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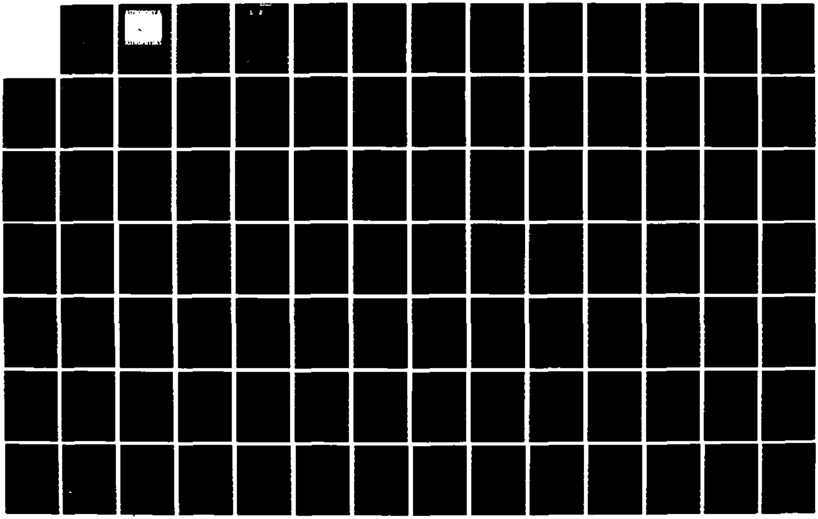

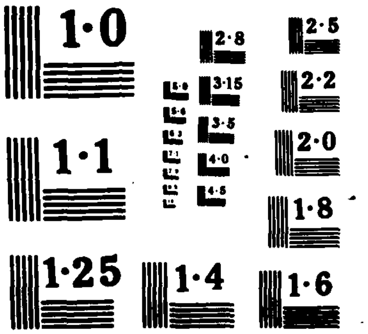
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ASTROPHYSICS

GEORGIA STATE UNIVERSITY

AD-A170 069

ASTRONOMICAL OBSERVATIONS BY SPECKLE INTERFEROMETRY

Final Report to Grant AFOSR-81-0161

Department of Physics and Astronomy
Georgia State University
Atlanta, Georgia 30303

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FINAL SCIENTIFIC REPORT

to the

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

for the interval

1 Jun 81 - 28 Feb 86

GRANT AFOSR-81-0161

ASTRONOMICAL OBSERVATIONS BY SPECKLE INTERFEROMETRY

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19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Speckle interferometry is a method permitting the extraction of spatial information from two dimensional images at scales down to the diffraction limit of the telescope in spite of severe blurring introduced by atmospheric turbulence. With existing large telescopes, speckle techniques thus permit resolution at spatial scales of 0.025 arcseconds rather than the 1 to 2 arcseconds associated with classical techniques. These methods are also characterized by enhanced measurement accuracy of the separation of closely spaced objects seen through the turbulent atmosphere. The speckle interferometry group at Georgia State University operates a highly sensitive speckle camera and ~~analysis~~ system incorporating an intensified charge-coupled device array as the primary imaging detector and a hardwired autocorrelator as a high speed data reduction processor operating at video rates. The analysis of the reduced data is carried out using a digital image —

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19. (Continued) processing system, provided with funding from the DOD-University Research Instrumentation Program. The Georgia State University speckle interferometry system is used regularly at the 4-meter telescope of the Kitt Peak National Observatory and the 1.8-meter telescope of the Lowell Observatory. The ~~scientific~~ goals of these ~~research~~ programs ~~have~~ include~~d~~: the detection of planetary mass objects in orbit about one component of a widely separated binary star system through the measurement of submotions in the otherwise elliptical motion of binary stars; the observation of asteroids with the goal of definitively answering the question of the duplicity of these primordial members of the solar system; the resolution of suspected structure in the nuclei of active galaxies and quasars; the reconstruction of truly diffraction limited images of a variety of astronomical objects; and, the generation of data applicable to a better understanding of the characteristics of atmospheric turbulence and its effects on high resolution imaging.

During the period of AFOSR support, observations were accumulated at approximately monthly intervals on the 1.8-meter telescope and three times per year on the 4-meter telescope. Speckle frames were recorded on video tapes at the Arizona sites and brought back to Atlanta for reduction and analysis until early 1985 when the autocorrelator was modified for real-time use at the telescope. An upgrading of the 1.8-meter telescope control system during 1985 improved the operational efficiency of that instrument. Considerable effort was expended in bringing the VAX 11/750 and its associated image processing hardware on line and in writing an extensive software package for the interactive analysis of speckle data. Both hardware and software oriented goals were met during late 1984, and the new image processing system provides a powerful facility for extracting diffraction limited measurements from speckle data. A fast background subtraction algorithm was found to give the most satisfactory correction for the component of atmospheric seeing which otherwise decreases the contrast in and biases the measurement of the binary star peak. The accuracy of measurement has been addressed through the goodness-of-fit to binary star autocorrelogram peaks and through the repeatibility of fits to series of data for the same object. A preliminary conclusion, subject to more extensive testing, is that we can indeed measure the geometry of binary stars with an accuracy approaching one tenth of a milliarcsecond, the level of accuracy at which one can expect a reasonable sensitivity to the detection of planetary mass submotions of binary star orbital motion. In connection with the problem of asteroid duplicity, we conclude that there are no clear examples of duplicity among this class of object. Support from the AFOSR has now resulted in the appearance of eighteen papers in the scientific literature from this program. These paers are included in an appendix to this final report.

ASTRONOMICAL OBSERVATIONS BY SPECKLE INTERFEROMETRY

A. RESEARCH OBJECTIVES

Between August 1981 and February 1986, speckle observations with the GSU speckle camera system were accumulated at the 1.8 meter Perkins telescope of the Lowell Observatory near Flagstaff, Arizona and the 4-meter telescope of the Kitt Peak National Observatory near Tucson. This collaboration involved GSU astronomers and Lowell Observatory astronomer Dr. Otto G. Franz with the following scientific problems being approached with AFOSR support:

1. The high accuracy of spatial separation measurements of the components of wide binary star systems by means of speckle interferometry was used to initiate a long-term search for submotions due to the Newtonian reaction of a star to an unseen, low-mass planetary or brown dwarf companion. Sixty-one binary stars within 25 parsecs of the sun comprise the observing program that was synoptically observed at nearly monthly intervals with the Perkins telescope.

2. The diffraction limited resolution of speckle interferometry as well as its relatively high sensitivity to large brightness differences was used to search for duplicity among asteroids. The question of asteroid duplicity has important implications to dynamical considerations of the formation of the solar system.

3. Speckle observations were obtained of selected extragalactic objects with unusually active and compact nuclei. The energetics of these active galaxies are thought to be driven by the accretion of nuclear material by

massive black holes. The detection of structure at the diffraction limit of large telescopes would place important physical constraints on the theoretical models of these objects.

4. Efforts toward the reconstruction of true diffraction-limited images of astronomical objects including binary stars, asteroids and planetary satellites were initiated with the addition of the image processing system provided by the DOD-University Research Instrumentation Program in 1983.

5. Although the above programs were primarily aimed at basic research in astronomy, the experience being gained in high resolution measurements through the turbulent atmosphere is directly relevant to the observation of military targets at high altitude. These observations are also providing a significant amount of data applicable to a better understanding of atmosphere turbulence.

B. RESEARCH ACCOMPLISHMENTS

1. Observing Opportunities

Observing time was supplied by the Lowell Observatory on a guaranteed basis to the scientific programs outlined above. During the term of this report, time on the 4-meter KPNO telescope was awarded on the basis of a competitive evaluation in which these programs, as well as a major binary star astrometry and photometry effort supported by the National Science Foundation, have been given "long term" status on that telescope. Our observing request to KPNO for long-term status, submitted in September 1984 was one of only three granted by the national observatory at the outset of their policy of giving such long-term allocations through the end of 1986. During the period of support through AFOSR-81-0161, observing time was allocated as follows:

	1.8-m Lowell		4-m KPNO	
	#Runs	#Nights	#Runs	#Nights
1981	5	27	0	0
1982	7	39	2	10
1983	12	67	3	17
1984	11	68	4	20
1985	7	35	2	16
1986	2	6	0	0
	44	242	11	63

The 1.8-m Perkins telescope near Flagstaff underwent a performance upgrading during 1984 consisting of a new microprocessor controlled driving and pointing system. These modification were particularly important to the planet search program with a resulting improvement in object acquisition time through better pointing accuracy.

2. Image Processing System and Data Analysis Procedures

A remarkable improvement in our data analysis capability was made with the installation of a VAX 11/750-based interactive image processing system provided with funding from the DOD-University Research Instrumentation Program. This system is described in our Final Report to AFOSR Grant 83-0257 dated 7 November 1984. An extensive software package, written in a menu oriented form, was made operational during late 1984. This package permits the reduction and analysis of speckle observations through the compensation of instrumental effects (such as fixed pattern signal, finite memory depth of the autocorrelation function accumulator, noise spikes and dropouts) and atmospheric effects (through the substraction of background seeing profiles by any one of several algorithms) and finally solving for the precise double star geometry (through two dimensional fits to image profiles). The software permits the user to tailor the analysis to the particular requirements of an observation.

The new system has increased not only our speed in handling the very large amounts of data generated by our program, it has also given us an increased sensitivity to the detection of faint companions in binary systems through the use of color contouring of intensities. The eye responds more readily to slight changes in color and intensity than just to gray levels alone. The image processing system should decrease the frequency of missed binaries by virtue of this trait. Other hardwired capabilities such as image zoom, threshholding and variable contouring also increase the sensitivity to binary star detection. A detailed description of the analysis procedures is given in our Annual Scientific Report for the period 1 June 1983 through 30 November 1984.

The reduction and analysis of speckle data requires an amount of time equal to about twice the time originally required to obtain the data at the telescope. Thus a single night's worth of observations requires approximately two eight hour days to completely process to binary star measurements. In early 1985, steps were taken to routinely employ the hardwired autocorrelator at the telescope and thus eliminate the use of video tape for other than archival purposes. This has not only significantly increased the overall efficiency of our effors but has improved data quality by eliminating from the process the effects of video tape noise and dynamic range compression.

3. Observational Precision and Accuracy

The attainment of fractional milli-arcsecond accuracy in the measurement of the relative separations of the components of binary stars has been of fundamental importance to the primary scientific goal of AFOSR sponsored speckle research at Georgia State University. We have initiated an analysis of our data in order to estimate the limiting astrometric accuracy.

A first approach to this problem was the application of repeatibility studies of the fits to autocorrelograms calculated from the same data sample. By using a sequence of video tape for a bright star we can be assured that multiple replays of this data through the hardwired autocorrelator will produce statistically independent vectorautocorrelograms since successive integrations are unlikely to be based upon identical samples of video frames when lists containing 1000 or more addresses are being grabbed. Fits to repetitions of an observational sequence are used to calculate a precision of fit defined as the standard deviation of the mean of the measured separations.

4. The Duplicity of Minor Planets

We have accumulated observations aimed at a definitive statement concerning the controversial question of the duplicity of minor planets. Observations were obtained (at opposition in most cases) of the following minor planets: 182 Elsa, 71 Niobe, 5 Astraea, 18 Melpomene, 9 Metis, 12 Victoria, 19 Fortuna, 14 Irene, 409 Aspasia, 28 Bellona, 114 Kassandra, 145 Adeona, 148 Gallia, 21 Lutetia, 115 Thyra, 15 Eunomia, 10 Hygiea, 11 Parthenope, 30 Urania, 38 Leda, 52 Europa, 76 Freia, 79 Eurynome, 87 Venetia, 709 Fringilla, 51 Nemausa, 53 Kalypso, 3 Juno, 44 Nysa, 4 Vesta, 2 Pallas, 40 Harmonia, 532 Herculina, 54 Alexandra, 287 Nephtys, 694 Ekard, 20 Massalia, Atalante, Hesperia, Amphitrite, Echo, Euterpe, Irene, Egeria, Ariadne, and Prokne. For most of these asteroids, data was collected at more than one epoch.

The analysis of these data shows no evidence of duplicity for any of the above asteroids. Our observations can set an upper limit of about 1.5 magnitudes on the brightness difference between primary and reputed secondary componentssz that might escape attention. These results combine with existing photometric studies to indicate that asteroid duplicity, if it exists in any case, is an extremely uncommon phenomenon.

C. PUBLICATIONS

The following publications were prepared with the support of AFOSR-81-0161:

"Masses and Luminosities of the Giant Spectroscopic/Speckle Interferometric Binaries Gamma Persei and Phi Cygni" H.A. McAlister, THE ASTRONOMICAL JOURNAL, 87, 563, 1982.

"Speckle Interferometric Measurements of Binary Stars. VII." H.A. McAlister and E.M. Hendry, THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 49, 267, 1982.

"Speckle Interferometry of the Spectroscopic Binary 94 Aquarii A" H.A. McAlister and W.I. Hartkopf, PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 94, 832, 1982.

"Speckle Interferometric Measurments of Binary Stars. VIII." H. A. McAlister, E.M. Hendry, W.I. Hartkopf, B.G. Campbell and F.C. Fekel, THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 51, 309, 1982.

"Speckle Imaging Through a Non-Redundant Aperture Mask" M.J. Price and M.R. Lawler, Final Report to GSU Subcontract to Science Applications, Inc., Tucson, Arizona, December, 1982.

"The Optical Variability and Spectrum of PKS 2155-304" H.R. Miller and H.A. McAlister, THE ASTROPHYSICAL JOURNAL, 272, 26, 1983.

"Photometry of the Newly Identified AM Herculis System CW 1103 + 254" H.R. Miller, MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, 201, 21p, 1982.

"The Optical Variability of Four Extragalactic Radio Sources" H.R. Miller, ASTRONOMY AND ASTROPHYSICS SUPPLEMENTS, 52, 289, 1983.

"The Variability of the Spectrum of Arakelian 120" B.M. Peterson, C.B. Foltz, H.R. Miller, R.M. Wagner, D.M. Wagner, D.M. Crenshaw, K.A. Meyers, and P.L. Byard, THE ASTRONOMICAL JOURNAL, 88, 926, 1983.

"Photoelectric Comparison Sequences in the Fields of Four BL. Lacertae Objects" H.R. Miller, T.L. Mullikin and B.G. McGimsey, THE ASTRONOMICAL JOURNAL, 88, 1301, 1983.

"Speckle Interferometric Measurements of Binary Stars. IX." H.A. McAlister, W.I. Hartkopf, E.M. Hendry, B. Gaston and F.C. Fekel, THE ASTRONOMICAL JOURNAL SUPPLEMENT SERIES, 54, 251, 1984.

"Binary Stars Unresolved by Speckle Interferometry. III." W.I. Hartkopf and H.A. McAlister, PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 96, 105, 1984.

"The True Nodal Quadrant of Capella" W.G. Bagnuolo and H.A. McAlister, PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 95, 992, 1983.

"Standard Stars for Binary Star Interferometry" H.A. McALister and W.I. Hartkopf, PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 95, 778, 1983.

"Catalog of Interferometric Measurements of Binary Stars" H.A. McAlister and W.I. Hartkopf, GSU Center for High Angular Resolution Astronomy, Contribution No. 1, 1984.

"Photoelectric Comparison Sequences in the Fields of B2 1308 + 326 and 1418 + 54" H.R. Miller, J.W. Wilson, J.L. Africano and R.J. Quigley,

"The Calibration of Interferometrically Determined Properties of Binary Stars," H.A. McAlister, CALIBRATION OF FUNDAMENTAL STELLAR QUANTITIES (Proceeding of IAU Symposium No. 111) ed by D.S. Hayes, et al (Dordrecht: Reidel), 97, 1985.

"High Angular Resolution Measurements of Stellar Properties" H.A. McAlister, ANNUAL REVIEW OF ASTRONOMY AND ASTROPHYSICS, 23, 59, 1985.

D. PAPERS PRESENTED AT MEETINGS

"Speckle Interferometry of Double Stars" H. A. McAlister, UA/AFOSR conference on Speckle Interferometry and Speckle Imaging, Tucson, AZ, April, 1983.

"Astronomical Speckle Interferometry" (Invited Paper), H. A. McAlister, Joint Topical Meeting on Information Processing in Astronomy and Optics sponsored by the American Astronomical Society and the Optical Society of America, St. Paul, MN, June 1983.

"Speckle Interferometry in Astrometry" (invited paper) H. A. McAlister, International Astronomical Union Symposium No. 109 on Astrometric Techniques, Gainesville, FL, January, 1984.

"First Results with the GSU ICCD Speckle Camera" W. I. Hartkopf, International Astronomical Union Symposium No. 109 on Astrometric Techniques, Gainesville, FL, January, 1984.

"Calibration in Interferometry" (Invited Paper) H. A. McAlister, International Astronomical Union Symposium No. 111 on Calibration of Fundamental Stellar Quantities, Como, Italy, May 1984.

"A Speckle Search for Minor Planet Satellites: Technique and Results," (Invited Paper) O. G. Franz, Symposium on New Directions in Asteroid and Comet Research, Astronomical Society of the Pacific, Flagstaff, Arizona, June 1985.

E. NEW INVENTIONS OR PATENTS

No new inventions or patents resulted from this research.

F. PROFESSIONAL PERSONNEL

The following personnel were associated with this research effort. Asterisks indicates those persons who contributed to this research but whose salaries were not supported by AFOSR funds.

Dr. Harold A. McAlister - Principal Investigator
Associate Professor, Georgia State University, Atlanta.

Dr. Otto G. Franz, Senior Investigator - Astronomer,
Lowell Observatory, Flagstaff.

*Dr. William I. Hartkopf - Senior Research Associate,
Georgia State University, Atlanta

*Dr. Paul C. Schmidtke - Image Processing Systems Manager,
Georgia State University, Atlanta

*Dr. Donald J. Hutter - Research Associate,
Georgia State University, Atlanta

Ms. Vera Golonka - Graduate Research Assistant,
Georgia State University, Atlanta

*Dr. Tor Vestin - Research Associate
Georgia State University, Atlanta

Dr. Michael J. Price - Senior Scientist
Science Applications, Inc., Tucson.

G. REPRINTS OF PUBLICATIONS

The remainder of this Final Report consists of reprints of the collected publications listed in Section C.

THE ASTRONOMICAL JOURNAL VOLUME 87, NUMBER 3 MARCH 1982

MASSES AND LUMINOSITIES FOR THE GIANT SPECTROSCOPIC/SPECKLE INTERFEROMETRIC BINARIES GAMMA PERSEI AND PHI CYGNI[a]

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ABSTRACT

Speckle interferometric measurements of the spectroscopic binaries γ Per and ϕ Cyg are combined with the spectroscopic orbits to determine the elements of the apparent orbits and the masses, distances, and luminosities of the four components. These two systems are of considerable interest because they contain highly evolved stars, and ϕ Cyg is a rare example of a binary star whose components are similarly evolved off the main sequence. The newly determined masses of $(2.50 \pm 0.09)M_\odot$ and $(2.39 \pm 0.08)M_\odot$ and distance of 71.9 ± 5.5 pc place the G8III–IV components of ϕ Cyg at the point of beginning the ascent of the red giant branch. The orbit of γ Per is confirmed to be highly inclined, and the masses of $4.7M_\odot$ and $2.8M_\odot$ and distance of 73.8 pc suggest that a classification of G8II–III + B9V is more appropriate than the existing classification of G8III + A3V. Atmospheric eclipses may be exhibited by γ Per at periastron passages.

I. INTRODUCTION

The shortage of mass and luminosity data for evolved stars has most recently been pointed out by Popper (1980), who concludes that the observational evidence, in spite of its scarcity, indicates that red giant masses are considerably in excess of $1M_\odot$. This conflicts with the conclusion of Scalo, Dominy, and Pumphrey (1978), who base their arguments on a frequency distribution deduced from visual binary data, that the average initial mass of red giants is in the range $(0.8–1.2)M_\odot$. Although selection effects favor the determination of red giant masses at the high-mass end of the true mass distribution, there is presently no luminosity class III star whose minimum mass is clearly within the range given by Scalo *et al.* (1978).

A high priority of the author's program of binary star speckle interferometry has been the resolution of spectroscopic systems containing giant stars. Double-lined systems are particularly important in such a program since the combined linear and angular information from the spectroscopic and speckle techniques not only provides the individual masses but also yields a direct determination of the distance to the system and hence the individual absolute magnitudes if the magnitude difference is available. The systems γ Per and ϕ Cyg have now had sufficient orbital coverage by speckle interferometry to warrant this kind of analysis.

The radial velocity of the star γ Per (HR 915) was discovered to be variable by Moore (Campbell 1909a), and elements for a long-period orbit were determined by McLaughlin (1948) from 56 velocity measurements from four observatories obtained irregularly between 1897 and 1947. Unfortunately, McLaughlin did not publish a detailed orbital analysis making it difficult to judge the reliability of the 14.6-yr orbital motion he determined. McLaughlin's elements are reproduced in Table I. In his extensive study of composite spectrum stars, Hynek (1938) included γ Per and gave spectral types of A + cF7. That the later-type star was a giant was evident from the very prominent contribution of that component in the violet region of the spectrum. On the basis of multicolor photometry, Bahng (1958) classified the system as G8III + A3V, while Cowley (1976) assigned it K0III + A2.

Wilson (1941) reported resolving γ Per using visual Michelson interferometry at four epochs in 1939 and

TABLE I. Spectroscopic elements of γ Per (McLaughlin 1948).

$p = 5350^{d}$
$= 14^{y}.65$
$e = 0.72$
$T = \text{JD } 2432263$
$= 1947.209$
$\omega_1 = 344°$
$\omega_2 = 164°$
$k_1 = 12.7$ km/s
$k_2 = 21.9$ km/s
$\gamma = +2.5$ km/s
$M_1 \sin^3 i = 4.72M_\odot$
$M_2 \sin^3 i = 2.74M_\odot$
$M_1/M_2 = 1.72$
$a_1 \sin i = 6.44 \times 10^8$ km
$a_2 \sin i = 1.11 \times 10^9$ km

---

[a] Astronomical Contributions from Georgia State University, No. 60.

[b] Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

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measured separations averaging 0″07 at a position angle of 49°. No further measurements were made until the system was resolved in 1973 using Labeyrie's technique of speckle interferometry (Labeyrie *et al.* 1974), and γ Per has come under regular speckle interferometric scrutiny only since 1975. Nevertheless, a sample of observations now exists which includes periastron passage and is sufficiently large to warrant a preliminary discussion of the relative orbit of γ Per and of the masses and luminosities obtained in combination with the spectroscopic elements.

The star ϕ Cyg (HR 7478) was found to have variable radial velocity by Plummer (Campbell 1909b), but more than half a century elapsed before a spectroscopic orbit of the system was determined by Rach and Herbig (1961). The object is generally considered to have spectral type G8 III–IV (Roman 1952). Rach and Herbig (1961) reported two sets of nearly identical strong and sharp lines and pointed out that ϕ Cyg is one of a small class of double-lined binaries in which both components are essentially equally evolved. Their spectroscopic elements are shown in Table II.

Since ϕ Cyg has a relatively long period, the possibility of direct resolution of this important system was recognized early in the author's program of binary star speckle interferometry, and the system was predicted to have a separation of 0″033, or near the diffraction limit of the 4-m Mayall reflector (McAlister 1976). The star was observed on four occasions during 1976–1977 and was consistently found to be unresolved. In July 1978, an observation did indicate marginal resolution for the first time (McAlister and Fekel 1980). Five additional observations showing resolution have been obtained and reduced to date. Although the angular separation of the components has indeed been found to be at the diffraction limit of the Mayall telescope, the small magnitude difference in the system leads to high fringe contrast in the composite spatial frequency power spectra of the speckle observations so that there is now no doubt as to the resolvability of ϕ Cyg.

Owing to the small number and limited distributions of the speckle measurements available, it was decided to adopt the spectroscopic elements P, T, and e and to use the speckle observations to obtain the unknown elements i, a'', and Ω. A simple way to proceed is then to use the equations

$$x = AX + FY, \tag{1}$$

and

$$y = BX + GY, \tag{2}$$

where $x = \rho \cos \theta$, $y = \rho \sin \theta$, $X = \cos E - e$, and $Y = (1 - e^2)^{1/2} \sin E$. The coefficients A, F, B, and G are the Thiele-Innes elements from which the classical elements can be determined (cf. Heintz 1978). Equations (1) and (2) were used to produce normal equations in a least-squares solution for the Thield-Innes elements. This procedure is particularly suited to the analysis of ϕ Cyg owing to the very high quality of the spectroscopic orbit of Rach and Herbig (1961).

II. THE OBSERVATIONS AND ORBIT OF γ Per

Table III contains 13 observations of the position angle and angular separation of γ Per obtained by the use of speckle interferometry between 1973.4 and 1980.8. R. H. Wilson (1941) reported successful resolution of the star, which was then known essentially only as a composite spectrum object, on four nights in 1939 using a visual Michelson interferometer with the 18-in. refractor of the Flower Observatory. Wilson's observations were as follows: 1939.724,, 52°1, 0″07; 1939.763, 63°0, 0″07; 1939.771, 45°9, 0″05″; and 1939.807, 36°7, 0″10. These measurements show a large dispersion in position angle even though they span only 2° of mean anomaly, and Wilson (1981) points out that, unknown to him until 1953, the Flower refractor objective was disassembled in 1936 and replaced without adequate care to ensure freedom from spurious effects in interferometer measurements of fringe visibility. Wilson's measurements do however show the proper quadrant, and it seems likely that he did indeed resolve the system in 1939. The first modern resolution was by Labeyrie *et al.* (1974), who estimated a Δm of 1–2 mag at a wavelength of 675 nm. The observations obtained during the author's program of speckle interferometry suggest a considerable decrease in Δm at 517 nm and 470 nm consistent with the composite spectral type arising from a cool giant in combination with a hot dwarf star. The descriptions of the circumstances of the individual speckle observations can be found in the original references shown in Table III.

Four epochs at which γ Per was found unresolved by speckle interferometry are also recorded in Table III. Wilson (1981) reported the star unresolved to his visual interferometer on 1954.678 and Couteau (1975) found it single in his micrometer on 1973.991. It seems likely that γ Per could be resolved by visual observers through much of its orbit by taking advantage of the decreasing Δm toward shorter wavelengths.

The new elements and their formal standard errors are given in Table IV. These errors are based only upon

TABLE II. Spectroscopic elements of ϕ Cyg (Rach and Herbig 1961).

$$\begin{aligned}
P &= 434^{d}086 \pm 0^{d}050 \text{ (s.e.)}\\
&= 1^{y}1885 \pm 0^{y}0001\\
e &= 0.516 \pm 0.003\\
T &= \text{JD } 2430837.64 \pm 0.42\\
&= 1943.306 \pm 0.001\\
\omega_1 &= 216^{\circ}5 \pm 0^{\circ}6\\
\omega_2 &= 36^{\circ}5 \pm 0^{\circ}6\\
K_1 &= 26.79 \pm 0.07 \text{ km/s}\\
K_2 &= 27.88 \pm 0.07 \text{ km/s}\\
\gamma &= +5.0 \text{ km/s}\\
M_1 \sin^3 i &= (2.36 \pm 0.02) M_{\odot}\\
M_2 \sin^3 i &= (2.26 \pm 0.02) M_{\odot}\\
M_1/M_2 &= 1.04 \pm 0.01\\
a_1 \sin i &= (1.370 \pm 0.005) \times 10^8 \text{ km}\\
a_2 \sin i &= (1.426 \pm 0.005) \times 10^8 \text{ km}
\end{aligned}$$

TABLE III. Speckle observations of γ Per.

Obs. No.	Epoch 1900.0 +	p.a.	Sep.	Reference
1	1973.45	59°0	0″193	Labeyrie *et al.* (1974)
2	75.6286	83.0	0.052	Blazit *et al.* (1977)
3	75.7816	51.0	0.041	Blazit *et al.* (1977)
4	75.9561	—	< 0.033	McAlister (1978)
5	76.8574	—	< 0.035	McAlister (1978)
6	76.9228	—	< 0.035	McAlister (1978)
7	77.0867	—	< 0.035	McAlister (1978)
8	77.7339	67.0	0.054	McAlister and Fekel (1980)
9	77.7420	65.4	0.058	McAlister and Fekel (1980)
10	77.9193	65.8	0.066	McAlister and Hendry (1981)
11	78.1490	66.5	0.091	McAlister and Fekel (1980)
12	78.6155	64.8	0.114	McAlister and Fekel (1980)
13	78.6182	64.7	0.115	McAlister and Fekel (1980)
14	79.0362	64.5	0.135	McAlister and Hendry (1982)
15	79.5326	64.2	0.154	McAlister and Hendry (1982)
16	79.7706	64.4	0.169	McAlister and Hendry (1982)
17	80.7235	64.7	0.200	McAlister (unpublished)

the fits to the equations of condition (1) and (2) and do not reflect any uncertainties in the spectroscopic elements which were published by McLaughlin (1948) without any error estimates.

The residuals to the newly determined apparent orbit are shown in Table V along with the mean and eccentric anomalies corresponding to the epochs of the observations in Table III. In Table V, the entries in the residuals columns for observations 4–7 are the predicted values of x and y at those epochs when γ Per was unresolved to speckle observers. Predicted angular separations for those four epochs are 0″003, 0″032, 0″027, and 0″013, respectively. The anticipated separations for the 1976 negative results are just at and below the diffraction limit for the 4-m telescope so that all of the negative speckle observations are consistent with the new elements. The four observations of Wilson (1941) at which he reported separations close to 0″1 all have predicted separations of 0″27 at a position angle near 63°. Those observations plus Wilson's negative result for 1954, which was slightly more than one revolution later, were very near apastron passages as predicted by McLaughlin's (1948) value of T. It is likely that careful visual inspection should have detected the secondary, particularly in blue light. However, it should once again be emphasized that McLaughlin's elements must be considered preliminary and that speckle measurements have not yet covered an apastron passage, next occuring on 1983.9, so that an uncertainty larger than the error shown in Table IV is likely for a''. It does not seem probable that this uncertainty can account for the discrepancy between Wilson's observations and the predicted values of separation. The predicted separation at the epoch of Couteau's (1975) visual attempt is 0″16. This small separation plus the nonzero Δm is consistent with Couteau's negative result.

The residuals in Table V show clear systematic effects probably due to the preliminary nature of the values of P, T, and e adopted here. Continued speckle observations will certainly give definitive values of the elements of the apparent orbit of γ Per, but it is particularly important that spectroscopists give careful attention to this system. The fair agreement between the spectroscopic and the newly determined values of ω are an indication of the consistency between the existing radial velocity material and the speckle observations.

III. THE γ Per SYSTEM

The very high inclination suspected by McLaughlin (1948) on the basis of large mass functions is confirmed in this analysis, and the individual masses are then found to be $M_1 = 4.73 M_\odot$ and $M_2 = 2.75 M_\odot$. The distance determined through the combination of a'' and i with the spectroscopic value of $(a_1 + a_2)\sin i$ is 73.8 pc. The error in the distance is at least 10% owing to the formal uncertainty in a'' and leads to a minimum error in the distance modulus of $\pm 0^m2$. The small formal uncertainty in i represents an insignificant contribution to the errors of the masses. Since the spectroscopic orbit is in need of reexamination, it is inappropriate to attempt the assigning of error estimates to the astrophysical parameters of γ Per which are summarized in Table VI.

The individual absolute visual magnitudes in Table VI were derived after adopting the value $\Delta m_v = 1^m4$ following the argument of Bahng (1958). The absolute magnitudes of the components are surprisingly bright, each component being more than a magnitude brighter

TABLE IV. Newly determined elements of γ Per.

$A = -0''.0723 \pm 0''.0035$
$F = -0''.0136 \pm 0''.0044$
$B = -0''.1409 \pm 0''.0048$
$G = -0''.0142 \pm 0''.0062$
$i = 88°.0 \pm 1°.8$
$a'' = 0''.159 \pm 0''.014$
$\Omega = 242.6$
$\omega = 353.2$

TABLE V. Residuals to the speckle observations of γ Per.

Obs. No.	Mean anomaly	Eccentric anomaly	Δx	Δy
1	284.8	246.9	+0.010	−0.000
2	338.4	304.3	−0.013	+0.021
3	342.1	310.9	+0.014	+0.015
4	346.5	320.0	(+0.003)	(−0.000)
5	8.7	28.2	(−0.016)	(−0.027)
6	10.3	32.4	(−0.014)	(−0.023)
7	14.3	41.8	(−0.008)	(−0.010)
8	30.1	68.5	+0.004	+0.009
9	30.3	68.7	+0.007	+0.012
10	34.7	74.4	+0.004	+0.006
11	40.3	81.1	+0.005	+0.014
12	51.8	93.0	+0.002	+0.004
13	51.8	93.0	+0.003	+0.005
14	62.1	102.4	−0.000	−0.000
15	74.3	112.4	−0.004	−0.007
16	80.1	116.9	−0.003	−0.004
17	103.6	133.5	−0.010	−0.011

than expected for spectral types A3V and G8III. A distance modulus of $m - M = +2^{m}8$ corresponding to a distance of 36 pc would be expected, but this would require the value of a'' to be doubled. Such a very large underestimation of a'' seems unlikely even for the preliminary nature of this discussion. The trigonometric parallax of γ Per is 0″011 (Jenkins 1952), which is very close to the parallax of 0″014 resulting from this study. However, the parallax is sufficiently small so that the true error of the trigonometric parallax may make this agreement fortuitous. The fact that γ Per has never been resolved as a visual binary lends further support to a small value of a''. Perhaps the strongest argument against the classification G8III and the resulting distance of <40 pc is that the luminosity of the primary would then correspond to the minimum luminosity in the post-main-sequence evolution of a $3M_\odot$ star, a value far too smal to be expected from a star of nearly $5M_\odot$ (cf. Fig. 4 of Iben 1967). On the other hand, the newly determined luminosity does fit rather well into the expected location on the evolutionary log L–log T_e diagram for a star of $4.75M_\odot$.

TABLE VI. Preliminary astrophysical parameters for γ Per.

$$M_1 = 4.73M_\odot$$
$$M_2 = 2.75M_\odot$$
$$d = 73.8 \text{ pc}$$
$$M_{v_1} = -1.1$$
$$M_{v_2} = +0.3$$

The discrepancy in the absolute magnitudes found here with those expected can be removed if the primary star is assigned a classification of G8II–III (Blaauw 1963) and if the secondary star is actually earlier than A3V or is itself also evolved. The mass of the secondary does seem somewhat large for a star of type A3V when compared with the results for reliable masses compiled by Popper (1980), and the secondary does fall in the theoretical main-sequence mass-luminosity relation shown by Iben (1965). Bahng (1958) found a particularly large disagreement with the observed colors when compared with the colors to be expected from the combination G8III + A0V. Since it is likely that the primary is actually cooler than implied by the classification G8III, the expected colors from the combination G8II–III + A0V tend to ameliorate the difficulty of a hotter secondary in the multicolor photometric classification. The value of M_{v_2} found here is appropriate to a secondary of type B9V (Allen 1973). The corresponding effective temperature would then imply that the secondary is nearing the end of its main-sequence evolution (Iben 1965).

If careful spectroscopic analysis rules out the supposition of a secondary as hot as B9, then the star must have already exhausted hydrogen in its core and is in the process of evolution towards the red giant branch. Comparison of evolutionary time scales for the two components argues against this possibility, however, because the primary should have completed its existence as a red giant long before the secondary ceases core hydrogen burning. We must therefore conclude that the best spectroscopic description for the γ Per system is G8II–III + B9V.

TABLE VII. Ephemeris for γ Per.

t	θ	ρ	t	θ	ρ
1982.0	62°0	0″249	1990.0	65°6	0″063
82.5	62.1	0.258	90.5	73.0	0.015
83.0	62.2	0.265	91.0	240.9	0.037
83.5	62.3	0.270	91.5	245.5	0.033
84.0	62.4	0.272	92.0	45.6	0.011
84.5	62.5	0.272	92.5	58.4	0.053
85.0	62.6	0.279	93.0	59.9	0.091
85.5	62.7	0.263	93.5	60.6	0.124
86.0	62.8	0.255	94.0	61.0	0.153
86.5	62.9	0.244	94.5	61.3	0.178
87.0	63.1	0.230	95.0	61.5	0.199
87.5	63.2	0.213	95.5	61.6	0.217
88.0	63.4	0.192	96.0	61.8	0.233
88.5	63.6	0.168	96.5	61.9	0.246
89.0	64.0	0.138	97.0	62.0	0.256
1989.5	64.5	0.104	1997.5	62.2	0.264

TABLE VIII. Speckle observations of ϕ Cyg.

Obs. No.	Epoch 1900.0	p.a.	Sep.	Reference
1	76.3018	—	$<0''.035$	McAlister (1978)
2	76.4494	—	<0.035	McAlister (1978)
3	76.4549	—	<0.035	McAlister (1978)
4	77.7330	—	<0.033	McAlister and Hendry (1981)
5	78.5412	$80^\circ.9$	0.030	McAlister and Fekel (1980)
6	79.3629	68.9	0.038	McAlister and Hendry (in preparation)
7	79.5294	74.3	0.038	McAlister and Hendry (in preparation)
8	79.7725	80.8	0.028	McAlister and Hendry (in preparation)
9	80.4795	70.6	0.033	McAlister (unpublished)
10	80.7173	77.1	0.036	McAlister (unpublished)

From the newly determined luminosities and the effective temperature appropriate to the spectral types G8II–III + B9V (Popper 1980), it can be found that the sum of the radii of the two components is approximately 30 solar radii. At a distance of 73.8 pc, this quantity subtends an angle of $0''.002$. The minimum separation of the system is just under $0''.003$, occurring at mean anomalies of $17^\circ.6$ and $347^\circ.2$ corresponding to 1977.225 and 1990.638. Since there is a chance of atmospheric eclipses, a photometric monitoring for the 1990 event would be of interest.

The newly determined elements demonstrate that γ Per should be resolvable to micrometer observers from the present time until late 1988 when the separation closes below $0''.16$. The system should reach a maximum separation of $0''.272$ in 1984. An ephemeris through one complete revolution commencing from 1982.0 is given in Table VII.

A third component in the system exists at a separation of 1 arcmin and has a visual magnitude of approximately + 11. This corresponds to a star of spectral type K2–K4V at the distance determined for the system. It might be pointed out that Scalo *et al.* (1978) mistakenly use this component as the source for the Δm recorded in their Table I.

IV. THE OBSERVATIONS AND ORBIT OF ϕ Cyg

Ten observations of ϕ Cyg are shown in Table VIII. All were obtained at the 4-m Mayall telescope at KPNO using the photographic speckle camera described by Breckinridge *et al.* (1979). No additional observations have been reported by other speckle observers.

TABLE IX. Newly determined elements of ϕ Cyg.

$A = -0''.0063 \pm 0''.0005$
$F = +0''.0068 \pm 0''.0013$
$B = -0''.0242 \pm 0''.0004$
$G = +0''.0058 \pm 0''.0012$
$i = 79^\circ.0 \pm 3^\circ.2$
$a'' = 0''.026 \pm 0''.002$
$\Omega = 252^\circ.2 \pm 2^\circ.2$
$\omega = 17^\circ.0 \pm 2^\circ.2$

The newly determined elements of the apparent orbit of ϕ Cyg are given in Table IX. Table X contains the mean and eccentric anomalies resulting from the spectroscopic time elements used to determine the X and Y values along with the residuals Δx and Δy. The dispersions among the residuals are $\sigma_{\Delta x} = \pm 0''.0015$ and $\sigma_{\Delta y} = \pm 0''.0014$. In Table X, the entries in the residuals columns for observations 1–4 are the predicted values of x and y at those epochs when ϕ Cyg was found to be unresolved. The predicted separation at those epochs are $0''.017$, $0''.005$, $0''.005$, and $0''.013$, respectively. These values are all well below the resolution limit of approximately $0''.030$ of the 4-m telescope, and the negative results are then consistent with the newly determined orbital elements.

Although the formal errors of the elements in Table IX are small, it should be emphasized that this is partly due to the small number of observations presently available. The value of ω derived from Thiele-Innes constants differs by 20° from that determined spectroscopically, and further observations must be accumulated before a definitive set of elements can be derived. The observations in Table VIII do sample rather well mean anomalies between 100° and 245° including two apastron passages, and it seems likely that the values of i and a'' will not change substantially as a result of future analyses. A change in i by $\pm 5^\circ$ will only alter the deduced masses by $\pm 5\%$. Popper (1980) pointed out that ϕ Cyg currently is the most favorable double-lined giant spectroscopic binary for which masses can be directly determined, and it seems probable that ϕ Cyg will join the relatively select group of stars whose masses have been accurately determined.

V. THE ϕ Cyg SYSTEM

The newly determined elements i and a'' allow the direct determination of the individual masses and the distance to the system when combined with the spectroscopically determined mass function and $(a_1 + a_2)$

TABLE X. Residuals to the speckle observations of ϕ Cyg.

Obs. No.	Mean anomaly	Eccentric anomaly	Δx	Δy
1	274°5	247°1	(+ 0″003)	(+ 0″017)
2	319.2	291.5	(− 0.005)	(− 0.010)
3	320.9	293.6	(− 0.005)	(− 0.002)
4	348.0	335.8	(− 0.005)	(− 0.012)
5	232.8	215.5	− 0.000	+ 0.000
6	121.7	140.6	+ 0.002	+ 0.001
7	172.1	174.8	0.000	− 0.001
8	245.8	224.8	+ 0.001	+ 0.001
9	99.9	124.5	− 0.001	+ 0.001
10	172.0	174.7	− 0.002	− 0.002

sin i. The masses are found to be $M_1 = (2.50 \pm 0.08) M_\odot$ and $M_2 = (2.30 \pm 0.08) M_\odot$, and the distance is 71.9 ± 5.5 pc corresponding to a trigonometric parallax of $0\overset{''}{.}014 \pm 0\overset{''}{.}001$. There is probably a small but nonzero magnitude difference as implied by the observation of Rach and Herbig (1961) that one component has slightly stronger lines than the other. However, we shall adopt here a value $\Delta m = 0$ until future observations with speckle cameras using linear detectors are available for photometric as well as astrometric use. The absolute visual magnitudes are thus $M_{v_1} = M_{v_2} = +1.1 \pm 0.2$, adopting $m_v = +4.64$ as the combined apparent magnitude. These parameters are summarized in Table XI.

An effective temperature of 4800 K is chosen as being consistent with the G8III–IV classification for ϕ Cyg (Allen 1973), and leads to a bolometric correction of -0.31 so that the components have absolute bolometric magnitudes of $+0.80$. Comparison with Fig. 1 of Iben (1967) shows that the components lie slightly above the evolutionary track for a $2.25 M_\odot$ star at the base of the red giant branch. A nonzero Δm will tend to raise the primary component in the direction consistent with an evolved star whose mass is between $2.25 M_\odot$ and $3.00 M_\odot$, as predicted by Fig. 4 of Iben (1967).

Thus the components of the ϕ Cyg system have crossed the Hertzsprung gap and are just beginning the ascent of the red giant branch. In view of the sensitivity of the atmospheric abundances of certain elements to convective mixing at this stage of stellar evolution, detailed spectroscopic analyses would be quite interesting. In the meantime, ϕ Cyg joins Capella as the only other double-lined spectroscopic binary containing nearly equal giant stars for which the masses can be directly determined and now provides the coolest giant stars with reliably known masses.

TABLE XI. Astrophysical parameters for ϕ Cyg.

$M_1 = (2.50 \pm 0.09) M_\odot$
$M_2 = (2.39 \pm 0.08) M_\odot$
$d = 71.9 \pm 5.5$ pc
$\pi = 0\overset{''}{.}0139 \pm 0\overset{''}{.}0011$
$M_{v_1} = +1.11 \pm 0.17$
$M_{v_2} = +1.11 \pm 0.17$

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SPECKLE INTERFEROMETRIC MEASUREMENTS OF BINARY STARS. VII.[1]

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ABSTRACT

Two hundred ninety-five measurements of 201 binary stars observed by means of speckle interferometry with the 4 m telescope at KPNO are presented. Binary stars directly resolved for the first time are HD 12483, HR 763 (31 Ari), HR 1043, HR 1411 (θ^1 Tau), HR 1569 (6 Ori), HR 1808 (115 Tau), HR 1876 (37 Ori), HR 2002 (132 Tau), HR 4365 (73 Leo), HD 163640, and HR 8119 (I Cep).

Subject headings: interferometry — stars: binaries — stars: visual multiples.

I. INTRODUCTION

This paper continues the series presenting the results from a program of binary star speckle interferometry based upon observations made at Kitt Peak National Observatory. (Paper VI is McAlister and Hendry 1982.) The previous papers in this series have presented 1138 measurements of binary stars, including the first direct resolution of 33 systems. Many of the objects which have been observed at every opportunity since late 1975 are showing significant orbital motions, and a number of resolved spectroscopic binaries are now amenable to combined spectroscopic/speckle interferometric studies. This kind of analysis, which has been a primary goal of this program since its inception, offers a direct method for determining the masses of the components of a system, the distance to the system, and thus the luminosities of the components if the object is a double-lined spectroscopic binary. Such analyses have most recently been completed for the giant system ϕ Cyg with a composite spectrum of G8 III+G8 III and for γ Per whose primary is concluded to be of type G8 II–III (McAlister 1982). A review summarizing the properties of the systems first directly resolved by speckle interferometry is in preparation.

II. THE OBSERVATIONS

The observations presented in Table 1 were obtained by the authors at the 4 m Mayall telescope on eight nights scheduled among four observing runs during 1979 using the KPNO photographic speckle camera. The 790 sets of observations contributing to this paper represent 39,500 exposures on 35 mm Tri-X film and were reduced to composite spatial frequency power spectra in the normal way. We have followed the procedure adopted in Paper VI of measuring binaries with separations in excess of 0".1 by means of the composite autocorrelation. All transformations using the coherent image processor were carried out by the second author, while all measurements of power spectra and autocorrelations were made by the first author using the two-coordinate Grant comparator at KPNO. The calibration for position angle and angular separation was obtained using the double-slit mask in the manner described in Paper I (McAlister 1977) and leads to error estimates of ±0°.2 and ±0.6% for systems with separations exceeding ~0".12 and ±2°.0 and ±5% for closer systems.

Table 1 contains 295 measurements of 201 binary stars, including the 11 newly resolved systems HD 12483, HR 763 (31 Ari), HR 1043, HR 1411 (θ^1 Tau), HR 1569 (6 Ori), HR 1808 (115 Tau), HR 1876 (37 Ori), HR 2002 (132 Tau), HR 4365 (73 Leo), HD 163640, and HR 8119 (I Cep). The entries for each system in Table 1 include the ADS number, the discovery designation, and the 1900.0 coordinates on the first line, and the epoch of observation, the position angle in degrees, and the angular separation in seconds of arc on subsequent lines. Reference to a note is given by a number to the right of the identification line.

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TABLE I

BINARY STAR SPECKLE INTERFEROMETRY MEASUREMENTS

ADS [illegible]	A 1803 AB	00122 +0819	
79.7730	120.4	0.167	
ADS 434	STT 12	00262 +5358	
79.7702	184.8	0.504	
HR 132	51 PSC	00272 +0624	
79.7702	96.6	0.244	
HR 233	-	00446 +6342	
79.7730	151.3	0.052	
ADS 746	STT 20 AB	00493 +1839	
79.7703	220.6	0.465	
ADS 755	STF 73 AB	00496 +2305	
79.7703	74.3	0.618	
ADS 784	BU 1099 AB	00508 +5950	
79.7703	308.6	0.186	
79.7730	309.6	0.182	
ADS 836	A 2901	00549 +6849	
79.7730	51.9	0.405	
ADS 940	STT 515	01037 +4643	
79.7703	139.6	0.474	
ADS 955	BU 303	01042 +2316	
79.7730	290.0	0.654	
ADS 1105	STF 115 AB	01170 +5737	
79.7730	138.2	0.304	
ADS 1123	BU 1163	01193 -0726	
79.7731	211.2	0.378	
ADS 1183	A 1910 AB	01242 +2219	
79.7730	132.4	0.131	
-	KUI 7	01326 -0955	
79.7731	124.0	0.102	
ADS 1473	HO 311	01456 +2409	
79.7731	227.5	0.104	
ADS 1598	BU 513 AB	01537 +7025	
79.7731	197.4	0.688	
-	HD 12483	01573 +0836	1.
79.7731	139.5	0.224	
ADS 1630	STT 38 BC	01578 +4151	
79.7732	109.9	0.576	
ADS 1709	STF 228	02076 +4701	
79.7732	266.8	1.038	
-	COU 79	02100 +2453	
79.5326	275.9	0.130	
79.7732	273.4	0.132	
	KUI 8	02229 +0131	
79.7732	32.5	0.511	
ADS 1938	STT 42 AB	02264 +5152	
79.7732	281.0	0.177	
HR 763	31 ARI	02312 +1200	2.
79.5326	152.9	0.078	
79.7733	148.0	0.076	
-	FIN 312	02347 -1218	
79.7733	189.3	0.097	
-	COU 1511	02352 +4027	
79.7732	91.6	0.156	
HR 788	12 PER	02359 +3946	3.
79.5299	96.2	0.052	
HR 793	MU ARI	02367 +1935	
79.5326	102.3	0.062	
79.7733	99.4	0.052	
ADS 2185	A 2906 AB	02458 +5235	
79.7732	148.2	0.116	
ADS 2200	BU 524 AB	02474 +3756	
79.0361	313.1	0.205	
79.5326	309.3	0.208	
79.7733	309.1	0.202	
ADS 2253	BU 525	02532 +2113	
79.7733	256.7	0.487	
ADS 2257	STF 333 AB	02535 +2056	
79.7733	27.2	1.490	
HR 915	GAMMA PER	02575 +5307	4.
79.0362	64.2	0.133	
79.5326	65.2	0.157	
79.7707	64.2	0.169	
ADS 2336	STF 346 AB	02596 +2452	
79.7733	58.6	0.206	
HR 936	BETA PER AB,C	03017 +4034	5.
79.0362	125.3	0.093	
79.5299	133.5	0.084	
HR 1043	HD 21427	03221 +5901	6.
79.7734	59.8	0.325	
-	COU 260	03223 +2007	
79.7733	22.2	0.228	
ADS 2616	STF 412	03285 +2408	
79.7734	6.3	0.595	
ADS 2628	BU 533	03294 +3121	
79.7734	43.1	1.114	
HR 1129		03373 +6302	
79.0362	5.0	0.071	
79.7707	7.3	0.065	
-	KUI 15	03466 +0615	
79.7734	209.1	0.655	
ADS 3064	A 1938	04082 +0728	
79.0364	258.6	0.093	
79.7708	293.1	0.112	
HR 1331	51 TAU	04125 +2120	
79.7735	304.3	0.090	
ADS 3172	STT 80	04166 +4212	
79.7734	161.0	0.381	
HR 1411	THETA 1 TAU	04229 +1544	7.
79.0364	2.0	0.116	
79.7708	0.0	0.144	
ADS 3358	BU 1295 AB	04320 +5317	
79.7734	148.8	0.253	
ADS 3358	STF AB,C	04320 +5310	
79.7734	226.4	0.840	
-	KUI 18	04336 -1430	
79.7734	97.8	0.167	
HR 1569	6 ORI	04492 +1116	8.
79.7708	4.8	0.334	
-	STT 97	04596 +2256	
79.7736	154.0	0.361	
ADS 3711	STT 98	05024 +0822	
79.7736	22.5	0.682	
ADS 3728	A 2636	05037 +0305	
79.7736	333.4	0.258	
ADS 3841	ALPHA AUR AP	05093 +4554	9.
79.0364	221.5	0.057	
79.7708	19.0	0.053	
HR 1798	ETA ORI AB,C	05194 -0229	10.
79.0364	118.5	0.053	
79.7736	111.4	0.037	
HR 1808	115 TAU	05213 +1753	11.
79.7736	80.4	0.095	
ADS 4115	STF 728	05254 +0552	
79.7736	49.4	0.966	
ADS 4134	HZ 42 AA	05269 -0022	12.
79.7709	144.9	0.208	
HR 1876	37 ORI	05293 +0925	13.
79.7709	20.3	0.053	
ADS 4208	STF 749 AB	05309 +2652	
79.7736	328.4	1.113	
ADS 4229	BU 1240 AB	05322 +3026	
79.0364	90.2	0.081	
79.7709	83.2	0.080	
ADS 4265	BU 1007	05355 +1629	
79.7736	239.1	0.348	
HR 2002	132 TAU	05429 +2443	14.
79.7736	126.3	0.043	
HR 2130	64 ORI	05575 +1942	15.
79.0364	55.4	0.048	
	KUI 23 AB	05580 +2316	
79.0364	231.3	0.134	
79.7709	257.9	0.104	
ADS 4890	FIN 331 AP	06116 +0959	
79.7709	258.9	0.102	
ADS 5103	BTZ AA	06230 +2017	16.
79.7709	122.1	0.095	
HR 2425	53 AUR	06320 +2904	17.
79.7709	61.0	0.067	
ADS 6185	STT 175 AB	07288 +3111	18.
79.7710	332.6	0.131	
ADS 6378	WRH 15 AB	07426 +2323	
79.0366	52.3	0.273	
79.7737	51.5	0.270	
	COU 929	07501 +2358	
79.7737	81.8	0.115	
ADS 6993	SP AB	08415 +0647	
79.0367	142.1	0.245	
	KUI 37	08542 +4211	
79.0367	35.2	0.695	
ADS 7158	A 1585	08568 +4733	
79.0367	286.6	0.284	
HR 3880	19 LEO	09420 +1202	19.
79.0368	203.5	0.135	
79.3593	202.5	0.140	
-	KUI 44	09442 +2139	
79.0368	210.2	0.280	
79.3593	211.[illegible]	0.274	
ADS 7545	STT 208	09453 +5432	
79.0369	95.5	0.229	
79.3593	98.8	0.223	
ADS 7651	KUI 48 AB	10025 +3206	
79.0369	168.5	0.214	
79.3593	169.4	0.216	

TABLE 1 *Continued*

ADS 7769		A 2570	10208 +0326	
	79.0370	306.7	0.363	
ADS 7780		HO 879	10221 +1713	
	79.0369	224.6	0.538	
ADS 7986		A 2768	10375 +0406	
	79.0370	205.7	0.182	
ADS 8086		BU 220	11075 -1757	
	79.0371	332.1	0.248	
HR 4365		73 LEO	11106 +1351	20.
	79.3621	99.8	0.068	
ADS 8189		STT 234	11254 +4150	
	79.0369	105.4	0.202	
	79.3620	109.5	0.215	
ADS 8231		STF 1555 AB	11310 +2820	
	79.0369	320.6	0.559	
	79.3621	323.2	0.559	
ADS 8249		STF 1559	11332 +6454	
	79.0369	1.6	0.350	
HR 4689		ETA VIR AA	12148 -0007	21.
	79.0371	228.6	0.101	
	79.3594	241.9	0.095	
	79.3622	240.9	0.095	
-		WRH	12301 +2310	
	79.3595	12.4	0.354	
HR 4963		THETA VIR	13049 -0500	22.
	79.3622	325.3	0.493	
	79.5317	325.5	0.493	
ADS 8804		STF 1728 AB	13051 +1803	
	79.3595	192.4	0.444	
-		FIN 350	13124 -0009	
	79.3622	38.3	0.085	
ADS 9301		A 570	14279 +2707	
	79.3597	34.3	0.182	
	79.5317	32.7	0.183	
ADS 9343		STF 1865 AB	14364 +1409	
	79.3597	305.0	1.033	
HR 5472		HD 129132	14359 +2224	
	79.3597	64.3	0.068	
	79.3624	65.4	0.066	
	79.5317	64.6	0.060	
ADS 9392		STF 1883	14439 +0622	
	79.3597	297.3	0.331	
ADS 9494		STF 1909	15005 +4803	
	79.5318	32.5	0.914	
-		COU 189	15075 +1921	
	79.3625	145.9	0.458	
ADS 9617		STF 1937 AB	15191 +3039	
	79.3625	305.6	0.371	
	79.5318	309.1	0.379	
HR 5747		BETA CRB	15237 +2927	23.
	79.0373	108.4	0.097	
	79.3597	83.5	0.063	
	79.3625	81.5	0.064	
	79.5290	61.2	0.059	
ADS 9688		A 1634 AB	15282 +4114	
	79.3597	206.2	0.064	
-		COU 610	15289 +3142	
	79.3625	202.9	0.672	
	79.5318	203.0	0.665	
ADS 9744		HU 580 AB	15371 +2000	
	79.3597	66.4	0.194	
	79.5290	65.9	0.197	
ADS 9757		STF 1967	15386 +2637	
	79.0373	126.0	0.324	
	79.3597	125.0	0.333	
	79.3625	125.7	0.333	
	79.5290	124.9	0.336	
ADS 9909		STF 1998 AB	15589 -1106	
	79.5291	20.2	1.117	
HR 5985		BETA SCO CE	15596 -1932	
	79.5290	18.1	0.168	
	79.5318	20.2	0.147	
ADS 9918		FIN 384 AP	16004 -0601	
	79.5291	328.9	0.056	
-		FIN 354	16067 +0958	
	79.5291	83.5	0.112	
ADS 10087		STF 2055 AB	16259 +0172	
	79.5291	9.0	1.235	
HR 6168		SIGMA HER	16309 +4239	
	79.3599	12.0	0.119	
	79.3625	12.6	0.115	
	79.5291	9.7	0.108	
	79.5318	10.3	0.112	
-		MLR 198	16442 +7404	
	79.3626	18.3	0.259	
ADS 10230		STT 315	16464 +0123	
	79.3599	28.0	0.138	
	79.5291	24.8	0.142	
ADS 10312		STF 214	16572 +0836	
	79.3627	186.2	1.292	
ADS 10360		HU 1176 AB	17045 +3604	
	79.3600	95.7	0.122	
	79.3626	95.1	0.123	
	79.5292	92.9	0.127	
ADS 10374		BU 1118 AB	17046 -1536	
	79.5320	265.9	0.335	
ADS 10531		HU 1179	17207 +3840	
	79.3626	92.2	0.058	
ADS 10598		STF 2173	17252 -0059	
	79.3627	174.8	0.428	
	79.5319	174.2	0.443	
ADS 10696		BU 631	17348 -0035	
	79.3627	203.2	0.060	
-		COU 114	17375 +2133	
	79.3627	28.7	0.311	
ADS 10795		STF 2215	17427 +1744	
	79.3626	268.0	0.573	
	79.5319	268.1	0.573	
-		COU 1145	17455 +3706	
	79.3626	57.5	0.114	
	79.5292	54.9	0.107	
-		FIN 381	17496 +1109	
	79.3627	185.6	0.068	
	79.5320	176.4	0.069	
ADS 10912		STF 2244	17570 +0005	
	79.3627	83.9	0.191	
	79.5319	82.4	0.197	
-		HD 163640	17520 +1821	24.
	79.3626	57.6	0.088	
ADS 11060		STT 341 AB	18016 +2126	25.
	79.3601	84.5	0.149	
	79.5293	85.4	0.170	
ADS 11111		STF 2281 AB	18046 +0359	
	79.3627	336.2	0.334	
	79.5320	335.3	0.332	
ADS 11123		STF 2289	18057 +1627	
	79.3627	222.2	1.224	
ADS 11149		B 2545 AB	18081 +3325	
	79.3601	42.4	0.091	
	79.3628	43.4	0.092	
	79.5293	41.8	0.095	
	79.5320	43.6	0.091	
ADS 11334		STF 2315 AB	18210 +2720	
	79.3628	130.9	0.635	
HR 6927		CHI DRA	8229 +7241	26.
	79.3600	238.7	0.095	
	79.3628	237.9	0.094	
	79.5321	54.4	0.094	
ADS 11479		STT 359	18334 +2331	
	79.3601	10.6	0.624	
	79.5321	10.3	0.615	
ADS 11468		A 1377 AB	18317 +5216	
	79.3628	93.3	0.266	
	79.5321	90.6	0.266	
ADS 11520		A 88 AB	18332 0317	
	79.7725	199.1	0.134	
ADS 11579		STF 2367 AB	18374 +3012	27.
	79.3601	29.4	0.060	
-		COU 1602	18363 +4050	
	79.3628	114.2	0.170	
ADS 11593		B 2546 AB	18365 +3439	
	79.3628	110.5	0.153	
	79.5293	110.5	0.150	
ADS 11640		FIN 332 AB	18406 +0524	
	79.3601	134.0	0.170	
	79.5321	133.2	0.151	
	79.7725	132.5	0.166	
ADS 11640		FIN 332 CD	18406 +0524	
	79.3601	150.5	0.119	
ADS 11842		A 2192	18508 +0319	
	79.3628	99.2	0.263	
ADS 11897		STF 2438	18558 +5805	
	79.3628	4.5	0.836	
ADS 12214		B 430	19094 -2526	
	79.5321	98.8	0.124	
HR 7417		BETA CYG A	19267 +2745	
	79.5295	181.2	0.424	
	79.7699	180.7	0.431	
ADS 12552		A 712	19282 +5626	
	79.7699	101.1	0.112	
HR 7441		9 CYG	19309 +2915	
	79.3601	358.4	0.037	
HR 7478		PHI CYG	19354 +2955	28.
	79.3629	68.9	0.038	
	79.5294	74.3	0.037	
	79.7725	80.5	0.029	

TABLE 1—*Continued*

-	KUI 93	19365 +1335	
79.7725	308.9	0.160	
HR 7536	DELTA SGE	19429 +1817	
79.3602	322.0	0.035	
ADS 12973	AGC 11 AB	19445 +1853	29.
79.7699	186.1	0.034	
ADS 13135	HU 687	19522 +5033	
79.7726	152.8	0.116	
ADS 13277	STT 395	19578 +2439	
79.5295	119.0	0.855	
ADS 13449	STF 2652	20074 +6147	
79.7726	222.6	0.308	
ADS 13572	STT 403 AB	20109 +4148	
79.7726	172.1	0.941	
ADS 13850	A 730	20230 +5916	
79.7726	329.4	0.229	
-	WRH AB	20300 +3454	
79.5295	97.8	0.290	
79.7699	97.3	0.284	
ADS 14073	BU 151 AB	20328 +1415	
79.5322	184.2	0.558	
79.7726	184.9	0.553	
HR 7906	ALPHA DEL AA	20350 +1534	
79.5295	345.7	0.185	
79.5323	346.4	0.181	
79.7700	342.9	0.180	
ADS 14296	STT 413 AB	20435 3607	
79.5323	17.2	0.844	
79.7699	16.3	0.850	
HR 7963	LAMBDA CYG	20435 +3607	30.
79.5323	7.6	0.051	
79.7699	3.2	0.048	
HR 7990	MU AQR	20473 -0922	
79.5324	141.8	0.056	
79.7700	136.7	0.058	
ADS 14412	A 751	20513 +5856	
79.7699	178.6	0.106	
ADS 14499	STF 2737 AB	20541 +0355	
79.5296	285.1	0.995	
-	KUI 102	20552 +0707	
79.5296	78.5	0.248	
79.7727	78.0	0.251	
-	COU 128	20575 +2316	
79.7727	134.7	0.198	
HR 8059	12 AQR	20588 -0613	
79.7700	158.7	0.071	
ADS 14585	BU 1138 AB	20593 +4527	
79.5324	171.3	0.115	
79.7700	175.7	0.117	
ADS 14761	HU 767	21088 +1534	
79.7700	355.1	0.104	
79.7700	354.0	0.099	
ADS 14749	STF 2780 AB	21093 +5935	
79.5297	216.7	1.054	
HR 8119	I CEP	21093 +5935	31.
79.5297	227.8	0.052	
ADS 14773	STT 535 AB	21096 +0936	
79.5296	17.9	0.261	
79.7700	15.4	0.227	
ADS 14784	STF 2783	21114 +5751	
79.7727	8.8	0.798	
ADS 14783	H 48	21117 +6400	
79.5324	253.2	0.558	
79.7727	253.0	0.557	
HR 8238	BETA CEP	21274 +7007	
79.5297	48.5	0.201	
79.7700	49.2	0.194	
ADS 15115	HU 371	21309 +2400	
79.5325	292.9	0.285	
79.7728	293.5	0.284	
-	KUI 108	21384 +4038	
79.5297	91.8	0.116	
79.7701	86.3	0.123	
ADS 15281	BU 989 AB	21401 +2511	32.
79.5297	301.4	0.134	
79.7701	296.9	0.158	
-	COU 14	21454 +1650	
79.5297	336.8	0.150	
79.7701	342.0	0.153	
ADS 15499	BU 275	21543 +6049	
79.7727	173.7	0.419	
HR 8417	XI CEP AA	22009 +6408	33.
79.3629	244.7	0.060	
79.5297	252.8	0.069	
79.7700	266.8	0.051	
-	COU 136	22054 +2238	
79.7728	47.7	0.376	
ADS 15902	BU 172 AB	22189 -0521	
79.7728	276.2	0.224	
ADS 15988	STF 2912	22249 +0355	
79.5297	117.2	0.812	
HR 8572	5 LAC	22283 +4712	
79.5298	43.8	0.124	
79.7701	44.9	0.122	
ADS 16011	HU 981	22270 +6107	
79.7727	222.5	0.324	
ADS 16057	STF 2924 AB	22301 +6923	
79.5297	87.0	0.482	
79.7728	87.3	0.482	
-	KUI 114	22356 -0404	
79.7728	333.3	0.065	
ADS 16173	HO 296 AB	22359 +1401	
79.5325	25.6	0.307	
79.7729	24.0	0.295	
HR 8650	ETA PEG	22383 +2942	
79.7729	359.4	0.043	
ADS 16214	STT 476 A,BC	22388 +4638	
79.7729	309.7	0.496	
HR 8704	74 AQR	22482 -1209	34.
79.5298	135.5	0.059	
79.7728	154.3	0.071	
ADS 16417	STT 536 AB	22535 +0850	
79.7728	347.9	0.195	
ADS 16428	STT 483	22542 +1112	
79.5325	294.7	0.600	
79.7728	296.9	0.605	
HR 8762	OMICRON AND	22573 +4147	
79.5298	0.6	0.316	
79.7701	0.4	0.327	
ADS 16467	BU 1147 AB	22580 +4213	
79.5325	334.0	0.402	
79.7729	335.6	0.406	
ADS 16497	A 417 AB	23000 -0814	
79.7728	193.7	0.181	
ADS 16530	HU 994	23038 +6306	
79.5325	126.7	0.205	
79.7729	127.8	0.204	
-	RST 3320	23046 -2300	
79.7730	327.3	0.302	
HR 8866	94 AQR AA	23138 -1400	35.
79.5299	289.9	0.153	
79.7702	310.7	0.158	
ADS 16708	HU 295	23174 -1536	
79.7702	100.4	0.434	
ADS 16731	STT 496	23196 +5659	
79.7729	119.8	0.280	
ADS 16836	BU 720	23290 +3047	
79.7701	78.8	0.504	
ADS 16877	STT 500 AB	23326 +4353	
79.7701	356.3	0.509	
HR 9003	PSI AND	23411 +4552	
79.5299	105.3	0.280	
79.7701	104.7	0.278	
ADS 17020	STT 507 AB	23438 +6420	
79.7729	305.3	0.714	
-	FIN 359	23478 -0343	
79.7702	62.5	0.096	

NOTES.—1. HD 12483 = SAO 110295 is directly resolved for the first time. The duplicity was noted by Edwards *et al.* 1980 who found a vector separation of 0".028 in direction 227°.5 on 1978 November 13. The present speckle observation is nearly perpendicular to the occultation vector separation and projects a separation of only 0".008 into direction 227°.5. Thus, the system has probably undergone some orbital motion in the year between the speckle and occultation measurements. Edwards *et al.* 1980 report a magnitude difference of 1.0 ± 0.2 mag in the blue, increasing to 2.0 ± 0.3 mag in the red.

2. HR 763 = 31 Ari is directly resolved for the first time. Africano *et al.* 1978 detected an occultation secondary at a separation of 0".021 in the direction 265°.7 and noted a small magnitude difference. Fekel 1980 has detected the secondary spectroscopically and is accumulating observations toward a spectroscopic orbit. The system is of spectral type F7 V.

3. Residuals to the combined spectroscopic/interferometric orbit of McAlister 1978 are +0°.4, +0".002.

4. A combined spectroscopic/interferometric solution is in preparation and yields an inclination of 88° (McAlister 1982).

5. Residuals to the combined spectroscopic/interferometric orbit of Bonneau 1979 are +5°.0, +0".016 and −3°.7, −0".006.

6. HR 1043 = HD 21427 is resolved for the first time. This is a new component in the system ADS 2563 in which the AB separation exceeds 2". Abt and Biggs 1972 record one report of variable radial velocity. The power spectrum of this observation indicates a magnitude difference exceeding 1 mag, and this system should be a challenge for visual observers.

7. HR 1411 = θ^1 Tau is directly resolved for the first time. Occultation detections of the secondary have been reported by White 1979, Beavers and Eitter 1979, and Peterson *et al.* 1981 *a*, *b*. The latter authors derive colors consistent with a G2 V companion to the K0 IIIb primary and found $\Delta V = 3.5 \pm 0.1$ mag. Peterson *et al.* 1981*a* reconstruct actual θ, ρ measurements from two different observations to give $\theta = 160°.0 \pm 2°.1$ and $\rho = 0''.082 \pm 0''.004$ on 1980 January 27. Peterson *et al.* 1981*b* deduce considerable orbital motion from a second occultation observation on 1980 August 5. The two speckle measurements do suggest appreciable orbital motion, but further observations are required to see if these results are consistent with a 6000 day period suggested by Griffin and Gunn 1977 from radial velocity measures. The speckle observation on 1979.0364 is rather poor and results in considerable uncertainty in that measurement. Continued spectroscopic and interferometric measurements are clearly important.

8. HR 1569 = 6 Ori is reported as resolved for the first time, although Morgan and collaborators have apparently obtained a previous observation in 1978 (see A.A.O. Newsletter, No. 8, 1979 January). Abt and Biggs 1972 record two reports of variable radial velocity for this system.

9. Residuals to the interferometric orbit of McAlister 1981 are +1°.7, +0".002 and −0°.5, +0".001.

10. HR 1788 = η Ori is a long period spectroscopic binary which appears to be closing toward the diffraction limit of the 4 m telescope.

11. HR 1808 = 115 Tau is directly resolved for the first time. Africano *et al.* 1978 report an occultation observation clearly showing a secondary at a separation of 0".099 in direction 98°.1 on 1978 February 17. The present speckle observation projects a separation of 0".090 onto that direction. Africano *et al.* 1978 report a magnitude difference of 1.1 ± 0.1 mag at 423 nm, decreasing to 0.9 ± 0.1 mag in the red.

12. The new companion to δ Ori was first discovered by Heintz 1980 who found 1978.10: 147°.3, 0".15, and 1979.06: 137°.0, 0".16.

13. HR 1876 = 37 Ori is resolved for the first time. The object is a spectroscopic binary with $P = 8.4$ yr and spectral type B0 IV.

14. HR 2002 = 132 Tau is directly resolved for the first time. The star is of spectral type G8 III.

15. HR 2130 = 64 Ori has moved through 10° of position angle since its first resolution during this program on 1977.18. Fekel 1980 has found a period of ~13 yr, and it is probable that spectroscopic system is that which is resolved by speckle interferometry.

16. ADS 5103 seems to be gradually opening and may now be resolvable to visual observers.

17. HR 2425 = 53 Aur continues to show rapid orbital motion having moved through 60° of position angle in only 3 yr.

18. ADS 6185 has no visual orbit. The separation has increased from 0".046 to 0".131 in 3 yr with little change in position angle. The orbit is probably highly inclined.

19. HR 3880 = 19 Leo continues to open and may now be resolvable to visual observers.

20. HR 4365 = 73 Leo is resolved for the first time. Griffin 1966 suggested a period of a few years from spectroscopic observations and proposed, on the basis of colors, a secondary of type F1 V in addition to the K3 III primary. The magnitude difference for such a system would be $\Delta V = 2.9$ mag and $\Delta B = 1.9$ mag. The contrast in the power spectrum suggests a smaller Δm at 470 nm than that due to a secondary of type F1 V, and it may be that the secondary is hotter still than that suggested by Griffin 1966. Griffin also noted that the system would project a maximum separation of 0".06.

21. HR 4689 = η Vir has moved through 90° of position angle in 3.3 yr and is perhaps now closing in.

22. HR 4963 = θ Vir has shown surprisingly little motion in 3.5 yr.

23. HR 5747 = β CrB should have undergone periastron passage in 1980.181 (Neubauer 1944). Speckle observations are providing excellent coverage of this event.

24. The observation of HD 163640 reveals a newly resolved close companion to ADS 10905.

25. ADS 11060 underwent periastron passage on 1978.438 according to the new spectroscopic/visual orbit by Batten *et al.* 1979. Residuals to that orbit are −4°.3, +0".006 and −3°.7, +0".011.

26. Residuals to the combined spectroscopic/interferometric orbit of McAlister 1980*b* are +3°.0, +0".001; +2°.3, +0".003; and −1°.0, +0".003.

27. Batten 1981 has suggested that a revision in T from 1979.0 (Baize 1950) to 1980.7 better represents the spectroscopic observations. Using this revision to the elements of Baize, the residuals to this speckle observation are improved from −15°.2, +0".024 to +0°.9, +0".007.

28. A combined spectroscopic/interferometric study of the masses and luminosities of this double-lined giant system has been completed by McAlister 1982.

29. Finsen 1937 predicted $T = 1978.95$ from which residuals of −30°.9, −0".015 are found.

30. HR 7963 = λ Cyg has moved through 20° of position angle in 1 yr.

31. HR 8119 = 1 Cep is resolved for the first time. This is a new companion in the system ADS 14749.

32. Speckle interferometry has now followed this system through periastron passage.

33. Residuals to the orbit of McAlister 1980*a* are +1°.3, +0".006; −1°.5, +0".009; and −2°.4, −0".003.

34. HR 8704 = 74 Aqr has moved through 40° of position angle in 2 yr.

35. HR 8866 = 94 Aqr Aa has moved through 150° of position angle in 3 yr. The spectroscopic system analysed by Sarma 1961 has a period of 6.4 yr.

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SPECKLE INTERFEROMETRY OF THE SPECTROSCOPIC BINARY 94 AQUARII A[*]

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Five years of speckle observations of the spectroscopic binary 94 Aqr A are analyzed to determine the visual orbit of the Aa,b system. Eleven observations of angular separation and position angle yield the elements: $P = 6^{y}.216 \pm 0^{y}.080$, $T = 1980.840 \pm 0.024$, $e = 0.185 \pm 0.012$, $a = 0''.180 \pm 0''.003$, $i = 47^{\circ}.6 \pm 1^{\circ}.7$, $\omega = 209^{\circ}.8 \pm 1^{\circ}.9$, and $\Omega = 170^{\circ}.3 \pm 1^{\circ}.9$. The new elements agree resonably well with Sarma's (1961) spectroscopic elements, and combined with the trigonometric parallax of $0''.033$ yield masses of $3.0\ \mathfrak{M}_{\odot}$ and $1.2\ \mathfrak{M}_{\odot}$ and absolute magnitudes of $+3.1$ and $+4.6$ for the Aa and Ab components, respectively. Some inconsistency exists between the parallax-implied and published classifications of the B component, and a definitive study of the system must await the improvements offered by parallax determinations from space.

Key words: binary stars—interferometry—stellar masses and luminosities

I. Introduction

The star 94 Aquarii (HR 8866; $\alpha,\delta_{1900} = 23^{h}13^{m}.8, -14^{\circ}00'$) exhibits a separation of approximately 13 arc seconds. The components are thus sufficiently separated to be individually observed and have been classified as G5 IV and K V (Batten, Fletcher, and Mann 1978) with *V* magnitudes of 5.21 and 7.60 (Blanco et al. 1968). Campbell (1922) pointed out the variable velocity of the A component, and a long-period spectroscopic orbit was determined by Sarma (1961), based upon 32 spectrograms obtained between 1917 and 1958 at Lick Observatory. Sarma found what he considered to be an unusually large probable error for a single velocity of ± 1.2 km sec^{-1}, and although the spectroscopic observations cover more than six revolutions, Batten et al. (1978) consider the orbit poorly determined due to the unexpectedly large scatter about the radial-velocity curve. Sarma (1961) suggested that there may be a second velocity variation in the system but made no attempt to verify this possible explanation for the large velocity residuals.

Inspection of Sarma's residuals does leave the impression of systematic effects in the velocities. For example, the twelve observations between 1942.94 and 1949.70 have mean residuals of $+1.1 \pm 1.3$ (s.e.) km sec^{-1} while the seven determinations between 1949.70 and 1953.90 have mean residuals of -1.2 ± 0.8 km sec^{-1}. The time scale implied by this trend is too long for a hierarchical addition to the system and would thus hint that instrumental effects of some kind may be present in the observations. The elements of Sarma (1961) are reproduced in Table I where his probable errors have been converted to standard errors.

II. The Observations and the Apparent Orbit

The 6.4-year period of its spectroscopic orbit indicated 94 Aqr A to be a promising candidate for direct resolution by speckle interferometry (McAlister 1976), and the system was thought to have been first resolved in late 1976 from speckle photographs obtained at the 4-meter Mayall telescope (McAlister 1978). It was later found that the first resolution actually occurred earlier in 1976 from 2.1-m telescope speckle data that were given lower priority than the 4-m observations and were not reduced until 1981 (McAlister and Hendry 1982*a*). Eleven speckle observations of the system Aa,b have now been obtained and are recorded in Table II.

The observations on 1976.6137, 1977.6350, and 1977.9190 were obtained with the 2.1-m telescope while all others are from 4-m telescope speckle photographs. Since these measurements span nearly one revolution and because the photographic speckle program at Kitt Peak has now ended, it seems appropriate at this point to compare the speckle observations with the spectroscopic elements of 94 Aqr A.

The measurements in Table II were all reduced by the standard procedures of speckle interferometry (McAlister 1977). Composite spatial frequency power

TABLE I

Spectroscopic Elements of 94 Aqr Aa (Sarma 1961)

$P = 6.362 \pm 0.044$ (s.e.) years

$K = +5.5 \pm 0.6$ km/sec

$\gamma = +10.8$ km/sec

$e = 0.08 \pm 0.08$

$\omega = 225^{\circ}.7 \pm 66^{\circ}.4$

$T_0 = 1939.12 \pm 0.09$

$a \sin i = (1.75 \pm 0.19) \times 10^{8}$ km

$f(M) = 0.040 \pm 0.013$

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[*] *Astronomical Contributions from Georgia State University*, No. 61.

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TABLE II

Observations and Residuals

	Epoch 1900.0+	θ	ρ	Δθ	Δρ	Source
1.	76.6137	155°8	0″212	-2°3	+0″019	McAlister and Hendry 1982a
2.	76.8569	164.7	0.216	-1.1	+0.013	McAlister 1978
3.	77.4819	182.5	0.207	-1.3	+0.001	McAlister 1979
4.	77.6350	187.4	0.228	-1.0	+0.026	McAlister and Hendry 1982a
5.	77.9190	196.4	0.183	-1.2	-0.007	McAlister and Hendry 1982a
6.	78.6179	233.5	0.151	+5.6	+0.001	McAlister and Fekel 1980
7.	79.5299	289.9	0.153	-2.1	+0.023	McAlister and Hendry 1982b
8.	79.7702	310.7	0.158	+1.9	+0.021	McAlister and Hendry 1982b
9.	80.7232	359.8	0.142	-4.2	-0.000	McAlister et al 1982
10.	81.4738	70.9	0.092	+2.6	-0.015	McAlister et al 1982
11.	81.7007	90.0	0.111	-2.5	-0.000	McAlister et al 1982

spectra of the speckle photographs have consistently shown low fringe contrast and imply a Δm of 1–2 magnitudes in the Aa,b system. The accuracies of the individual measures in Table II are therefore rather poor compared to similarly obtained measurements of systems having small magnitude differences. The negative result obtained on 1976.9224 (McAlister 1978) is probably also due to the large value of Δm. No additional observations of 94 Aqr A have been reported by other speckle observers, and even though the separation sometimes exceeds 0.2 arc second it is not likely that the fainter Ab component could be detected by visual observers.

Elements of the apparent orbit were determined from standard equations of condition in rectangular coordinates (cf. Heintz 1978, eq. (36)) to iteratively solve for the Thiele-Innes elements A, B, F, and G simultaneously with the elements *P*, *T*, and *e*. The new elements along with their formal standard errors are given in Table III. The mean residuals from the newly determined orbit for the eleven observations are $<\Delta\theta> = -0°50 \pm 2°80$ and $<\Delta\rho> = 0''007 \pm 0''013$. Individual residuals are shown in Table II.

The new elements agree reasonably well with the spectroscopic elements of Sarma (1961). The interferometric period is 0.146 ± 0.091 years shorter than the spectroscopic period, leading to an increase in the mass sum of somewhat less than 5%. The orbit, shown in Figure 1, also appears to be slightly more eccentric than indicated by the radial-velocity variation.

TABLE III

New Elements for 94 Aqr Aa,b

P = 6.216 ± 0.080 (s.e.) years

T = 1980.840 ± 0.024

e = 0.185 ± 0.012

a = 0″180 ± 0″003

i = 47°6 ± 1°7

ω = 209°8 ± 1°9

Ω = 170°3 ± 1°9

A = +0″1644 ± 0″0024

F = -0″0705 ± 0″0030

B = +0″0331 ± 0″0024

G = +0″1190 ± 0″0030

III. Discussion

It is not possible to accurately determine the individual masses and luminosities of 94 Aqr A because the system is not double-lined, but the trigonometric parallax of 0″033 (Hoffleit 1964) is marginally significant and warrants a preliminary discussion of the physical parameters of the components. The distance combines with the an-

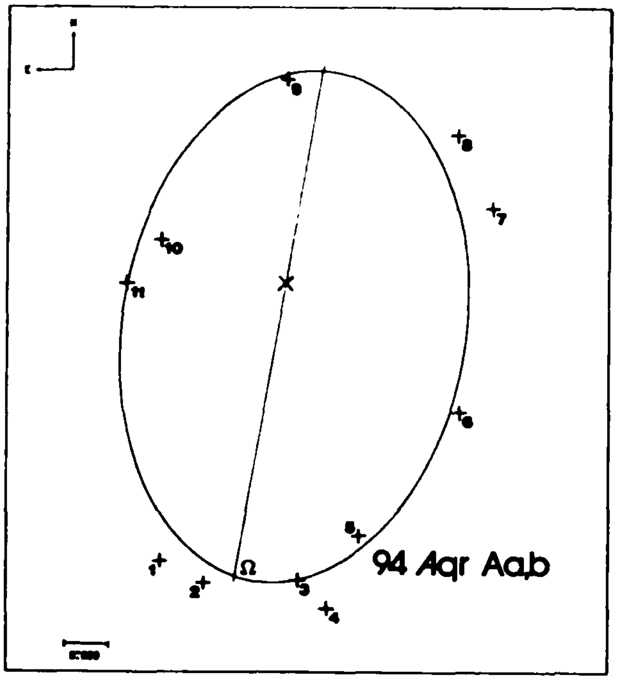

FIG. 1—Eleven speckle observations of the resolved spectroscopic binary 94 Aqr A are shown plotted against the newly determined apparent orbit.

gular semimajor axis to give a true semimajor axis of 6.56 A.U. and a resulting total mass of 4.2 solar masses. The newly determined inclination and the spectroscopic value of $a \sin i$ thus lead to a mass ratio of 0.4 and individual masses of $\mathfrak{M}_{\mathrm{Aa}} = 3.0$ and $\mathfrak{M}_{\mathrm{Ab}} = 1.2\ \mathfrak{M}_{\odot}$. If $\Delta m = 1.5$, then $V_{\mathrm{Aa}} = +5.5$, $V_{\mathrm{Ab}} = +7.0$, $M_{V\mathrm{Aa}} = +3.1$, and $M_{V\mathrm{Ab}} = +4.6$. These luminosities are consistent with spectral classifications of G5 IV and G0–G2 V for the components of 94 Aqr A. The trigonometric parallax implies that $M_{VB} = +5.2$, which corresponds more nearly to a classification of G5 V for the visual secondary than to the published K2 V classification. The absolute magnitude of $M_V = +6.5$ appropriate to K2 V leads to the unreasonably small mass sum of $\mathfrak{M}_{\mathrm{Aa}} + \mathfrak{M}_{\mathrm{Ab}} = 0.7\ \mathfrak{M}_{\odot}$; however, it may be that the visual secondary is itself a close binary containing two nearly equal K dwarfs.

Although considerable uncertainty presently exists in the masses of the components of 94 Aqr A, the luminosity of the star Aa agrees well with the value of $M_{V\mathrm{Aa}} = +3.2$ found by Roman (1952). Further progress on this system must await improvements in both the spectroscopic and interferometric orbits as well as in a redetermination of the parallax. Astrometric measurements from the *Hipparcos* satellite are very important for the complete elucidation of this system as well as for many other resolved spectroscopic binaries.

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SPECKLE INTERFEROMETRIC MEASUREMENTS OF BINARY STARS. VIII.[1]

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ABSTRACT

Six hundred measurements of 331 binary stars observed during 1980 by means of speckle interferometry with the 4 m telescope at KPNO are presented. Thirty-two systems are directly resolved for the first time. Newly resolved spectroscopic binaries include HR 2001, 53 Cam, HR 6388, HR 6469, 31 o^2 Cyg, HR 7922, and α Equ.

Subject headings: interferometry — stars: binaries — stars: visual multiples

This paper continues the series presenting the results from a program of binary star speckle interferometry based upon observations made at Kitt Peak National Observatory. (Paper VII is McAlister and Hendry 1982.) The previous papers of this series have presented 1433 measurements of binary stars, including the first direct resolution of 44 systems.

The observations presented in Table 3 were obtained during 1980 at the 4 m Mayall telescope as shown in Table 1. The 1920 sets of observations contributing to this paper represent 96,000 individual 35 mm Tri-X frames and were reduced to two-dimensional spatial frequency power spectra and autocorrelations in the manner adopted in Paper VII. The speckle photographs were normally taken at a wavelength of 470.5 nm.

Thirty-two systems directly resolved for the first time during 1980 are shown in Table 2. Specific notes concerning these newly resolved binaries may be found under their entries in Table 3. Table 3 contains 600 measurements of 331 binary stars. The entries for each system in Table 3 normally include the ADS number, the discovery designation, and the 1900 coordinates on the first line and the epoch of observation, the position angle in degrees, and the angular separation on subsequent lines. Alternative names are given for non-ADS systems. Reference to a note is given by a number to the right of the identification line.

TABLE 1

OBSERVING SUMMARY

UT Date	Number of Observations	Observer[a]
1980 Feb 26	126	C
1980 Feb 27 ...	153	C
1980 Feb 28	149	C
1980 Jun 23	148	M/H
1980 Jun 24 ...	163	M/H
1980 Jun 25 ...	158	M/H
1980 Jun 26	135	F
1980 Sep 19 ...	192	M
1980 Sep 20 ...	201	M
1980 Sep 21 ...	204	M
1980 Sep 22	152	F
1980 Sep 23	139	F

[a] C = B.G.C.; F = F.C. F.; H = E.M.H.; M = H. A. McA.

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TABLE 2

NEWLY RESOLVED BINARY STARS

Name	HR	HD	α (1900)	δ	ρ	Type[a]
...	178	3883	$0^h03^m63^s$	+2°4'05"	0".17	2
55 Cas	640	13474	0 20 66	+6 6 03	0.08	2
41 Ari	838	17573	0 24 41	+2 6 51	0.30	5
36 Tau	1252	25555	0 35 84	+2 3 50	0.04	2,3,5
τ Tau	1497	29763	0 43 63	+2 2 46	0.17	3
... ...	2001	38735	0 54 28	-1 0 34	0.16	1
40 Gem ...	2605	51688	0 65 33	+2 6 03	0.08	3
63 Gem ...	2846	58728	0 72 18	+2 1 39	0.04	3
68 Gem ...	2886	60107	0 72 79	+1 6 02	0.18	3
53 Cam ...	3109	65339	0 75 32	+6 0 36	0.04	1
...	4544	102928	1 14 59	-0 4 47	0.17	3,5
... ...	...	126269-70	1 41 94	+1 6 44	0.05	2,5
... ...	...	136406	1 51 54	-1 5 01	0.37	3
... ...	...	144641	1 60 18	2 1 09	0.12	3
... ...	6053	145997	1 60 89	1 8 17	0.09	3
... ...	...	155095	1 70 44	1 9 19	0.13	3
... ...	6388	155410	1 70 93	+4 0 54	0.04	1
... ...	6469	157482	1 71 85	+4 0 04	0.04	1
... ...	6560	159870	1 73 19	+5 7 38	0.16	5
...	...	171347	1 82 93	1 6 59	0.16	2
5 Aql	7059	173654	1 84 13	-0 1 04	0.13	2,5
...	...	178452-3	1 90 36	+1 2 06	0.12	2
...	...	184467	1 92 95	+5 8 24	0.11	2
... ...	...	190429	1 95 98	+3 5 45	0.12	6
31 Cyg	7735	192577	2 01 05	+4 6 26	0.04	1,4
23 Vul	7744	192806	2 01 16	+2 7 30	0.24	6
...	...	196088-9	2 03 00	+4 9 29	0.06	2
... ...	7922	197226	2 03 73	+3 8 43	0.12	1
α Equ ...	8131	202447	2 11 08	+0 4 05	0.10	1
...	8485	211073	2 20 96	+3 9 13	0.52	5
...	...	215318-9	2 23 92	+8 0 52	0.17	2
ψ Peg ...	9064	224427	2 35 27	+2 4 35	0.19	6

[a] (1) Spectroscopic binary, (2) composite spectrum binary, (3) occultation binary; (4) eclipsing binary; (5) variable radial velocity; (6) previously unknown binary

TABLE 3

BINARY STAR MEASURES

ADS 61	STF 3062	00010 +5753
80.7177	109°4	1″439
ADS 102	STF 2	00038 +7910
80.7203	25.4	0.621
80.7260	25.3	0.623
ADS 148	BU 1026	00069 +5304
80.7177	17.3	0.159
80.7259	19.5	0.159
ADS 197	A 1256 AB	00100 +4339
80.7177	59.5	0.154
ADS 207	STF 13	00106 +7624
80.7203	58.4	0.913
HR 108	β 1909	00233 -2053
80.7177	120.5	0.203
80.7231	120.5	0.204
ADS 434	STT 12	00262 +5358
80.7177	184.2	0.497
HR 132	51 Psc	00272 +0624
80.7178	95.5	0.236
80.7232	94.4	0.232
ADS 490	HO 212 AB	00301 -0409
80.4854	331.1	0.110
80.7204	357.4	0.132
80.7259	358.0	0.136
80.7287	357.9	0.136
ADS 520	BU 395	00327 -2519
80.7178	343.4	0.182
80.7232	342.5	0.202
HR 178	HD 3883	00363 +2405 (1)
80.7232	179.3	0.170
HR 233	HD 4775	00446 +6342 (2)
80.4854	127.3	0.037
80.7232	131.3	0.045
ADS 746	STT 20 AB	00493 +1839
80.7178	219.2	0.465
80.7232	218.7	0.466
ADS 755	STF 73 AB	00496 +2305
80.7178	76.8	0.628
80.7232	76.7	0.631
ADS 784	BU 1099 AB	00508 +5950
80.4853	301.1	0.195
80.7178	304.4	0.193
80.7233	304.5	0.196
ADS 836	A 2901	00549 +6849
80.7205	50.7	0.408
ADS 940	STT 515	01037 +4643
80.7179	137°8	0″480
ADS 955	BU 303	01042 +2316
80.7205	290.7	0.667
ADS 1105	STF 115 AB	01170 +5737
80.7178	136.4	0.269
ADS 1123	BU 1163	01193 -0726
80.7179	214.7	0.379
ADS 1183	A 1910 AB	01242 +2219
80.7259	130.5	0.132
ADS 1473	HO 311	01456 +2409 (3)
80.7290	240.6	0.073
ADS 1538	STF 186	01507 +0121
80.7234	54.9	1.315
+08°0316	HD 12483	01573 +0836
80.7205	138.7	0.227
80.7233	138.3	0.229
HR 640	55 Cas	02066 +6603 (4)
80.7204	9.7	0.077
80.7233	8.9	0.087
HR 657	COU 79	02100 +2453
80.7179	266.3	0.146
HD 15328	KUI 8	02229 +0131
80.7206	32.2	0.509
80.7234	37.4	0.513
ADS 1958	ES 620	02285 +5315
80.7205	20.3	0.705
HR 763	31 Ari	02312 +1200 (5)
80.7180	61.8	0.032
HR 781	FIN 312	02347 -1218 (6)
80.7180	357.0	0.087
80.7235	359.7	0.087
80.7261	357.3	0.087
HR 788	12 Per	02359 +3946 (7)
80.7180	45.0	0.036
HR 838	41 Ari	02441 +2651 (8)
80.7262	129.1	0.298
ADS 2185	A 2906 AB	02458 +5235
80.7180	141.1	0.129
80.7234	142.8	0.132
ADS 2200	BU 524 AB	02474 +3756
80.7180	304.6	0.205
80.7234	302.9	0.204
ADS 2253	BU 525	02532 +2113
80.7234	256°6	0″498
ADS 2257	STF 333 AB	02535 +2056
80.7235	26.7	1.488
HR 915	γ Per	02575 +5307 (9)
80.1532	64.9	0.181
80.7235	64.7	0.200
80.7260	65.1	0.207
80.7290	61.8	0.202
ADS 2336	STF 346 AB	02596 +2452
80.7180	60.5	0.211
80.7235	59.6	0.213
HR 936	β Per AB,C	03017 +4034 (10)
80.1532	131.6	0.073
ADS 2436	STT 52 AB	03088 +6517
80.7181	73.0	0.463
ADS 2616	STF 412	03285 +2408
80.7181	4.7	0.597
ADS 2628	BU 533	03294 +3121
80.7181	42.7	1.101
HR 1129	HD 23089	03373 +6302
80.1532	6.9	0.056
80.7181	6.8	0.054
80.7235	8.9	0.061
80.7290	7.1	0.064
HD 23387	COU 560	03397 +2402
80.7235	359.8	0.251
HD 24263	KUI 15	03466 +0614
80.1558	208.6	0.649
80.7207	207.8	0.650
HR 1252	36 Tau	03584 +2350 (11)
80.7208	152.7	0.041
ADS 3000	HU 1363	04026 -2216
80.7236	115.6	0.423
ADS 3064	A 1938	04082 +0728 (12)
80.7182	309.1	0.151
80.7237	308.8	0.149
80.7263	308.8	0.164
80.7291	310.7	0.153
HR 1331	51 Tau	04125 +2120 (13)
80.1532	285.9	0.075
80.7182	259.0	0.079
80.7263	255.8	0.085
80.7291	259.1	0.087

TABLE 3 – *Continued*

ADS 3172	STT 80	04166 +4212
80.7209	158°7	0″376
80.7263	159.3	0.380
ADS 3159	BU 744 AB	04174 -2558
80.7237	136.8	0.621
ADS 3182	HU 304	04184 +0914
80.7237	62.1	0.237
HR 1391	FIN 342 Aa	04199 +1543 (14)
80.1532	279.1	0.106
80.7291	267.0	0.095
ADS 3210	BU 1185	04200 +1838
80.7182	15.5	0.191
ADS 3230	BU 311	04227 -2418
80.7236	115.8	0.465
HR 1411	θ¹ Tau	04229 +1544 (15)
80.7182	355.1	0.136
ADS 3358	BU 1295 AB	04320 +5317
80.1558	148.0	0.254
80.7237	145.6	0.243
80.7263	143.8	0.247
80.7291	145.2	0.244
ADS 3358	STF 566 AB,C	04320 +5317
80.7291	225.2	0.818
ADS 3391	A 1013	04346 +5920 (16)
80.7237	[illegible]	[illegible]
HR 1497	τ Tau	04363 +2246 (17)
80.7210	23.5	0.173
HD 29961-2	DON 75	04382 -2110 (18)
80.7237	78.2	0.173
ADS 3475	BU 883 AB	04457 +1054
80.7236	47.5	0.266
ADS 3483	BU 552 AB	04462 +1329
80.7236	77.7	0.226
80.7291	78.4	0.221
-03°0928	RST 5501	04495 -0323
80.7237	46.6	0.309
HR 1589	STT 89	04520 +7355
80.7237	298.0	0.475
ADS 3588	BU 314 AB	04546 -1632
80.7237	176.1	0.140
80.7263	175.0	0.159
80.7291	175.1	0.146
ADS 3672	STT 95	04596 +1940
80.1559	305°3	0″939
HD 32641	STT 97	04596 +2256
80.1559	154.1	0.365
80.7209	151.9	0.363
ADS 3711	STT 98	05024 +0822
80.7209	18.0	0.675
ADS 3767	HU 33	05066 +0024
80.1587	18.2	0.109
ADS 3799	STT 517 AB	05083 +0151
80.1587	234.3	0.511
ADS 3841	α Aur Aa	05093 +4554 (19)
80.7183	247.0	0.052
80.7263	239.5	0.053
ADS 4020	A 848	05204 -0038
80.1587	156.5	0.208
ADS 4115	STF 728	05254 +0552
80.1587	49.4	0.966
ADS 4123	STF 729 AB	05260 +0313
80.1587	27.9	1.905
ADS 4134	HZ 42 Aa	05263 -0022
80.7183	143.9	0.217
80.7292	143.5	0.219
HR [illegible]	MLR 314	05270 +6638
80.1569	337.5	0.209
-04°1184	FIN 345	05304 -0429
80.7291	92.8	0.348
ADS 4208	STF 749 AB	05309 +2652
80.1588	328.5	1.126
ADS 4229	BU 1240 AB	05322 +3026 (20)
80.1534	78.4	0.087
80.7210	70.9	0.075
ADS 4265	BU 1007	05355 +1629
80.1587	238.3	0.348
ADS 4376	STF 3115	05396 +6246
80.1560	354.2	0.913
ADS 4392	STT 118 AB	05424 +2050
80.1588	316.8	0.285
HR 2001	HD 38735	05428 -1034 (21)
80.7291	104.0	0.159
ADS 4562	STF 784	05538 +8412
80.1560	298.7	0.483
ADS 4617	A 2715 AB	05569 +0939
80.7264	13°7	0″184
80.7292	13.9	0.184
HD 41116	KUI 23 AB	05580 +2316
80.1534	278.9	0.096
80.7210	303.4	0.114
80.7292	306.1	0.108
ADS 4768	BU 1058	06044 +2301
80.1560	240.9	0.245
HR 2236	RST 5225	06107 +0112
80.1588	201.6	0.236
ADS 4890	FIN 331 Aa	06116 +0959
80.1535	279.9	0.089
ADS 4950	STF 881 AB	06132 +5925
80.1560	132.1	0.700
ADS 4929	BU 895 AB	06136 +2828
80.1560	121.4	0.206
ADS 4951	A 2719	06149 +0746
80.1588	60.9	0.468
ADS 4971	A 2667	06162 +0219
80.1588	161.6	0.334
HR 2312	FIN 343	06201 +0133
80.1588	15.7	0.189
ADS 5103	BTZ Aa	06230 +2017
80.1536	123.7	0.092
80.7265	124.1	0.099
HR 2425	53 Aur	06320 +2904 (22)
80.1535	53.1	0.062
80.7210	37.4	0.057
80.7265	35.9	0.070
ADS 5289	STT 152	06332 +2821
80.1560	35.5	0.903
ADS 5447	STT 156	06416 +1818
80.1560	242.6	0.441
HR 2521	FIN 322	06442 -0210
80.1536	248.5	0.137
80.1588	248.6	0.141
80.7292	243.6	0.136
ADS 5514	STF 963 AB	06443 +5934
80.1560	252.6	0.298
80.7265	254.6	0.295
ADS 5586	STT 159 AB	06486 +5833
80.1560	42.4	0.629
80.7265	43.3	0.603

TABLE 3 – *Continued*

HR 2605	40 Gem	06533 +2603 (23)
80.1589	25°5	0"080
ADS 5871	STF 1037 AB	07066 +2724
80.1561	321.5	1.282
80.7292	321.0	1.284
ADS 5996	STF 1074 AB	07154 +0036
80.1561	168.1	0.679
HR 2846	63 Gem	07218 +2139 (24)
80.1588	168.0	0.044
HR 2886	68 Gem	07279 +1602 (25)
80.1588	89.2	0.184
ADS 6185	STT 175 AB	07288 +3111
80.1536	330.9	0.141
80.7292	330.7	0.151
ADS 6313	A 2534 AB,C	07380 +0026
80.1561	228.3	0.826
ADS 6354	HU 1247	07393 +6033
80.1561	323.8	0.185
ADS 6378	WRH 15 AB	07426 +2323
80.1561	52.3	0.274
ADS 6405	A 2880	07456 +0332
80.1562	273.8	0.147
80.1589	273.6	0.148
ADS 6412	BU 1195	07465 -0909
80.1562	91.0	0.216
80.1589	89.7	0.217
ADS 6420	BU 101	07471 -1338
80.1589	43.6	0.165
HR 3072	FIN 325	07479 -0510
80.1562	177.4	0.396
80.1589	177.3	0.399
HD 64704	COU 929	07501 +2358
80.1536	83.5	0.124
80.1588	85.5	0.120
ADS 6483	STT 185	07521 +0124
80.1562	53.3	0.229
80.1589	53.2	0.223
HR 3109	53 Cam	07532 +6036 (26)
80.1561	156.4	0.044
ADS 6549	STT 187	07579 +3319
80.1562	358.6	0.345
HR 3269	FIN 346	08146 +0415
80.1562	74.0	0.271
80.1589	73.6	0.271
ADS 6825	A 550	08227 -0405 (27)
80.1589	297°3	0"056
ADS 6828	A 551 AB	08234 -0211
80.1562	69.2	0.266
80.1589	69.0	0.266
ADS 6862	I 489	08270 -1914
80.1562	17.1	0.257
ADS 6993	SP AB	08415 +0647
80.1537	155.9	0.267
80.1589	156.1	0.266
ADS 7039	A 2473	08450 +1823
80.1563	41.1	0.322
HD 75974	COU 773	08482 +2021
80.1563	39.1	0.230
ADS 7082	A 2131 AB	08490 +2636
80.1563	168.9	0.336
HD 76943	KUI 37	08542 +4211
80.1563	25.5	0.740
ADS 7158	A 1585	08568 +4733
80.1563	287.2	0.285
80.1590	286.6	0.287
HR 3650	FIN 347 Aa	09068 +1525 (28)
80.1590	105.9	0.060
ADS 7334	A 1342 AB	09180 -0925
80.1538	15.4	0.171
ADS 7382	A 1588 AB	09224 -0847
80.1591	194.4	0.350
HR 3750	B 2530	09228 -0538
80.1564	161.0	0.188
ADS 7390	STF 1356	09231 +0930
80.1564	18.2	0.466
HR 3794	FIN 349	09275 +0218
80.1538	144.0	0.158
HR 3880	19 Leo	09420 +1202
80.1538	206.6	0.150
80.1592	206.3	0.133
HD 84739	COU 284	09421 +2104
80.1564	65.7	0.173
80.1590	66.7	0.171
HD 85040	KUI 44	09442 +2139
80.1564	211.2	0.271
ADS 7545	STT 208	09453 +5432
80.1565	105°2	0"224
ADS 7555	AC 5 AB	09476 -0738
80.1592	85.8	0.483
ADS 7651	KUI 48 AB	10025 +3206
80.1564	170.0	0.220
ADS 7662	A 2145	10038 +2049
80.1564	187.4	0.151
ADS 7674	HU 874	10063 +1351
80.1564	287.3	0.224
ADS 7704	STT 215	10108 +1814
80.1564	184.6	1.383
ADS 7769	A 2570	10208 +0326
80.1565	309.2	0.357
80.1593	309.7	0.365
ADS 7780	HU 879	10221 +3713
80.1538	228.0	0.532
80.1592	228.2	0.531
ADS 7896	A 2768	10375 +0406
80.1565	191.9	0.191
80.1593	191.9	0.199
ADS 7929	STT 229	10423 +4138
80.1565	282.0	0.791
ADS 8094	STF 1517	11084 +2041
80.1565	330.5	0.425
HR 4365	73 Leo	11106 +1351 (29)
80.1593	121.9	0.044
ADS 8189	STT 234	11254 +4150
80.1538	114.8	0.232
80.1592	115.5	0.234
80.4845	117.4	0.240
ADS 8197	STT 235	11267 +6138
80.1565	201.2	0.367
80.4845	206.0	0.372
ADS 8231	STF 1555 AB	11310 +2820
80.1565	323.8	0.573
HR 4544	HD 102928	11459 -0447 (30)
80.4817	43.7	0.173
ADS 8419	STF 3123 AB	12010 +6915
80.1567	349.9	0.133
80.1594	349.9	0.133
80.4791	345.8	0.132

TABLE 3 — *Continued*

HR 4689	η Vir Aa	12148 -0007 (31)
80.1539	278°.9	0″.070
80.1593	285.9	0.087
80.4763	292.6	0.093
80.4790	294.1	0.095
80.4817	291.7	0.093
HR 4789	WRH	12301 +2310
80.1566	11.8	0.358
80.1593	12.3	0.361
80.4790	11.9	0.358
ADS 8708	STT 256	12513 -0025
80.1565	95.0	0.961
80.4790	95.0	0.971
HD 112503	FIN 380	12552 +0850
80.1539	150.5	0.083
80.1593	149.5	0.084
80.4763	153.4	0.093
ADS 8759	BU 929	12587 -0308
80.1567	202.4	0.739
HR 4963	θ Vir Aa	13048 -0500 (32)
80.1538	327.1	0.498
80.1593	326.9	0.502
80.4790	326.7	0.494
80.4817	326.8	0.497
80.4846	326.3	0.496
ADS 8804	STF 1728 AB	13051 +1803
80.1539	192.6	0.509
80.1593	192.4	0.508
80.4763	193.1	0.526
80.4846	192.5	0.521
ADS 8863	A 2166	13154 +1818
80.1566	0.9	0.145
80.4817	2.0	0.142
ADS 8864	STF 1734	13156 +0328
80.1566	179.4	1.164
80.4790	179.7	1.145
ADS 8939	STT 269 AB	13283 +3525
80.1542	237.5	0.178
80.1594	237.1	0.183
80.4791	238.2	0.176
ADS 8974	STF 1768 AB	13330 +3648
80.1542	105.0	1.810
ADS 8987	BU 612 AB	13346 +1115
80.1595	185.4	0.224
80.4763	188.3	0.232
80.4818	187.9	0.233
ADS 9094	BU 1270	13588 +0858
80.1569	21.9	0.204
ADS 9174	STF 1816	14095 +2934
80.1567	88°.4	0″.792
ADS 9182	STF 1819	14103 +0336
80.1567	241.9	0.884
80.1595	241.7	0.887
80.4791	241.5	0.889
ADS 9247	BU 1111 BC	14185 +0854
80.4791	28.0	0.281
+16°2642	HD 126269-70	14194 +1644 (33)
80.1567	150.9	0.053
80.4791	154.0	0.053
ADS 9301	A 570	14279 +2707
80.1595	25.1	0.184
80.4764	21.0	0.179
80.4818	21.0	0.181
ADS 9329	STF 1863	14347 +5201
80.1545	68.1	0.652
80.1596	68.4	0.654
ADS 9343	STF 1865 AB	14364 +1409
80.1542	305.7	1.036
80.1595	306.0	1.034
80.4791	305.6	1.028
HR 5504	FIN 309	14405 -2042
80.4818	195.2	0.175
ADS 9378	STT 285	14417 +4248
80.1568	349.9	0.246
80.4764	347.3	0.250
80.4818	348.0	0.253
ADS 9392	STF 1883	14439 +0622
80.1567	298.1	0.359
80.1595	298.2	0.357
80.4791	297.1	0.369
ADS 9425	STT 288	14487 +1607
80.1545	173.0	1.441
80.1595	172.9	1.447
80.4791	173.6	1.434
ADS 9494	STF 1909	15005 +4803
80.1596	34.6	0.968
80.4764	35.3	0.986
ADS 9532	B 2351 Aa	15066 -1925
80.4764	34.8	0.151
HD 134943	COU 189	15075 +1921
80.1556	145.7	0.460
80.1597	145.4	0.461
ADS 9578	STF 1932	15140 +2712
80.1550	250°.9	1″.412
80.1596	250.4	1.413
80.4848	250.7	1.398
-14°4182	HD 136406	15154 -1501 (34)
80.4848	124.4	0.365
ADS 9617	STF 1937 AB	15191 +3039
80.1550	322.6	0.421
80.4765	328.1	0.443
ADS 9628	HU 149	15219 +5434
80.1545	274.2	0.596
80.1596	274.1	0.598
HR 5747	β CrB	15237 +2927
80.1597	344.9	0.080
80.4765	328.3	0.088
80.4819	328.3	0.099
80.4848	328.2	0.110
ADS 9688	A 1634 AB	15282 +4114
80.1543	15.4	0.060
80.1597	18.7	0.066
80.4764	10.2	0.058
HR 5778	COU 610	15289 +3142
80.1550	203.0	0.686
80.1596	203.2	0.684
80.4764	203.1	0.688
ADS 9716	STT 298 AB	15325 +4008
80.1569	34.9	0.683
ADS 9758	BU 619	15385 +1359
80.1556	2.6	0.698
80.1597	3.4	0.701
ADS 9757	STF 1967	15386 +2637
80.1539	125.0	0.354
80.1597	126.1	0.359
80.4765	125.0	0.365
80.4819	124.4	0.362
HR 5953	δ Sco	15545 -2220
80.4765	161.7	0.107
80.4849	159.3	0.121
ADS 9913	BU 947 AB	15596 -1932
80.4819	130.9	0.423
HR 5985	β Sco CE	15596 -1932
80.4765	31.7	0.105
ADS 9918	FIN 384 Aa	16004 -0601
80.1597	305.9	0.073
-21°4279	HD 144641	16018 -2109 (35)
80.4819	29.7	0.115

TABLE 3—*Continued*

ADS 9932	BU 949	16030 -0950
80.1568	192°0	0"385
HR 6032	FIN 354	16067 +0958
80.1597	85.0	0.120
80.4766	83.7	0.124
80.7225	81.1	0.110
HR 6053	HD 145997	16089 -1817 (36)
80.7255	0.1	0.085
HR 6084	σ Sco Aa	16151 -2521
80.4792	97.4	0.367
80.4819	97.9	0.367
HR 6148	β Her	16259 +2142 (37)
80.4820	67.1	0.086
ADS 10092	STF 3105	16264 -0650
80.1568	203.0	0.344
80.1597	206.7	0.324
HR 6168	σ Her	16309 +4239
80.1598	8.4	0.100
80.4766	7.2	0.081
80.4792	6.7	0.089
80.4849	359.2	0.093
80.7225	359.4	0.064
HD 151746	MLR 198	16442 +7404
80.4766	15.4	0.260
ADS 10230	STT 315	16464 +0123
80.1597	22.6	0.144
-19°4547	HD 155095	17044 -1919 (38)
80.7253	122.2	0.127
ADS 10360	HU 1176 AB	17045 +3604
80.1569	82.9	0.104
80.4792	74.3	0.099
80.7198	68.0	0.087
ADS 10374	BU 1118 AB	17046 -1536
80.4767	267.2	0.350
HR 6388	HD 155410	17093 +4054 (39)
80.4820	94.1	0.039
HR 6469	HD 157482	17135 +4004 (40)
80.4766	98.1	0.036
80.4820	85.7	0.047
ADS 10531	HU 1179	17207 +3840
80.4766	86.8	0.047
80.4792	85.3	0.046
80.7198	79.9	0.041
ADS 10598	STF 2173	17252 -0059
80.4767	169.4	0.542
80.7226	167.0	0.565
HR 6560	HD 159870	17319 +5738 (41)
80.4768	5°5	0"166
80.4822	3.8	0.157
80.4851	4.0	0.160
+46°2566	COU 1595	17336 +4546
80.7225	69.7	0.441
ADS 10696	BU 631	17348 -0035
80.4767	182.7	0.060
80.4793	184.7	0.060
80.4821	183.1	0.058
80.7198	177.0	0.058
HD 160935	COU 114	17375 +2133
80.4768	29.4	0.310
80.7254	29.2	0.307
ADS 10795	STF 2215	17427 +1744
80.4767	267.8	0.580
80.4821	268.1	0.574
80.7226	266.9	0.583
HD 162338	COU 1145	17455 +3706
80.4766	36.8	0.091
80.4792	38.2	0.100
80.7198	35.4	0.094
HR 6676	FIN 381	17496 +1109
80.4768	113.2	0.055
80.7171	79.0	0.062
ADS 10912	STF 2244	17520 +0005
80.4767	85.8	0.217
80.7226	86.9	0.225
ADS 10905	HD 163640	17520 +1821
80.4767	69.7	0.101
80.7226	62.8	0.090
ADS 11060	STT 341 AB	18016 +2126
80.4768	87.2	0.255
80.4792	86.7	0.253
80.4822	89.0	0.255
80.4851	88.0	0.256
80.7171	87.7	0.278
80.7199	88.3	0.278
80.7254	88.0	0.276
ADS 11111	STF 2281 AB	18046 +0359
80.4768	333.9	0.338
80.7171	331.5	0.344
ADS 11123	STF 2289	18057 +1627
80.7171	222.3	1.215
ADS 11149	B 2545 AB	18081 +3325
80.4768	48.3	0.091
80.4793	47.3	0.097
80.4822	48.5	0.102
80.7171	47.5	0.095
ADS 11324	AC 11	18198 -0138
80.7254	355°6	0"837
ADS 11339	BU 1203	18210 +0043
80.7199	141.4	0.400
ADS 11334	STF 2315 AB	18210 +2720
80.4768	131.3	0.645
80.7255	130.4	0.650
HR 6927	χ Dra	18229 +7241 (42)
80.4769	141.6	0.046
80.7172	219.0	0.136
80.7199	218.5	0.136
80.7255	220.0	0.136
-17°5245	HD 171347	18293 -1659 (43)
80.4822	144.5	0.156
ADS 11479	STT 359	18314 +2331
80.4794	10.6	0.643
80.7172	9.4	0.628
ADS 11468	A 1377 AB	18317 +5216
80.4769	95.5	0.264
80.4822	95.4	0.264
80.7172	95.8	0.266
ADS 11520	A 88 AB	18332 -0317
80.4795	186.7	0.151
80.7199	179.0	0.136
ADS 11524	HU 198	18336 +0845
80.4794	143.4	0.400
HD 172671	COU 1607	18363 +4050
80.4769	116.2	0.176
80.7172	112.3	0.191
ADS 11593	B 2546 Aa	18385 +3439
80.4768	114.7	0.153
80.4793	112.5	0.151
80.4822	113.2	0.151
80.4851	114.0	0.152
80.7172	113.9	0.157
ADS 11640	FIN 332 AB	18406 +0524
80.4769	131.4	0.173
80.7173	131.0	0.159
80.7199	131.8	0.169
ADS 11640	FIN 332 CD	18406 +0524
80.4769	150.2	0.124
HR 7059	5 Aql	18413 -0104 (44)
80.4794	7.7	0.127
ADS 11584	STT 363	18423 +7735
80.4769	152.2	0.167
80.4822	148.7	0.142

TABLE 3 – *Continued*

ADS 11842	A 2192	18508 +0319
80.4823	97°1	0"266
HD 176162	KUI 89	18538 -1258
80.4794	251.9	0.202
80.7226	252.9	0.199
ADS 11897	STF 2438	18558 +5805
80.4822	4.6	0.842
80.7172	3.3	0.837
+12°3818	HD 178452-3	19036 +1206 (45)
80.4794	148.5	0.118
ADS 12126	A 95	19056 -0735
80.7228	72.7	0.297
ADS 12160	HD 179558	19079 +1641
80.4823	138.0	0.680
ADS 12214	B 430	19094 -2526
80.7254	97.3	0.149
HR 7362	FIN 327	19192 -2442
80.7227	78.3	0.119
ADS 12366	BU 1129	19192 +5211
80.4769	5.9	0.121
80.7172	4.0	0.125
HR 7417	β^1 Cyg Aa	19267 +2745
80.4795	179.6	0.433
80.4823	180.0	0.428
80.4854	177.5	0.427
80.7255	177.8	0.429
ADS 12552	A 712	19282 +5626
80.4770	100.7	0.118
80.7173	94.5	0.129
+58°1929	HD 184467	19295 +5824 (46)
80.4797	74.2	0.117
80.7228	46.7	0.106
HR 7478	φ Cyg	19354 +2955 (47)
80.4795	70.6	0.033
80.4823	72.7	0.035
80.7173	77.1	0.036
80.7200	77.1	0.036
80.7255	74.7	0.040
HD 185936	KUI 93	19365 +1335
80.4769	308.5	0.163
ADS 12798	STT 382	19378 +2709
80.4796	332.2	0.326
ADS 12808	STT 380 AB	19379 +1135
80.4770	76.6	0.456
80.7173	76.9	0.455
HD 186307	KUI 94	19385 +4001
80.7199	154°8	0"210
ADS 12850	BU 658	19398 +2654
80.4824	105.3	0.363
80.7255	104.7	0.372
HR 7536	δ Sge	19429 +1817
80.4796	216.1	0.032
ADS 12973	AGC 11 AB	19445 +1853 (48)
80.4770	267.3	0.038
80.4796	261.6	0.036
80.4824	260.9	0.037
80.7256	304.5	0.173
ADS 13104	STF 2597	19500 -0700
80.4770	152.7	0.081
80.7227	139.1	0.075
HR 7637	FIN 378	19544 -1014
80.4770	111.7	0.235
ADS 13277	STT 395	19578 +2439
80.4770	120.2	0.866
80.7200	119.5	0.868
+35°3930	HD 190429	19598 +3545 (49)
80.4825	98.7	0.118
ADS 13449	STF 2652	20074 +6147
80.7228	222.1	0.303
HR 7735	31 o^1 Cyg	20105 +4626 (50)
80.4770	141.8	0.035
ADS 13572	STT 403 AB	20109 +4148
80.4797	171.8	0.939
80.7228	170.7	0.937
HR 7744	23 Vul	20116 +2730 (51)
80.7284	140.9	0.241
HR 7776	β Cap	20154 -1506 (52)
80.4771	31.0	0.073
80.4798	27.8	0.069
80.4825	33.7	0.060
ADS 13850	A 730	20230 +5916
80.4797	325.9	0.228
80.7228	327.5	0.235
HR 7837	FIN 336	20255 -1523
80.4772	203.1	0.121
80.7174	206.5	0.085
ADS 13944	A 1675	20265 +1528
80.4771	313.7	0.079
80.7257	0.[illegible]	0.114
HR 7866	WRH AB	20300 +3454
80.4770	98°8	0"278
80.4798	96.5	0.288
+49°3310	HD 196088-9	20300 +4929 (53)
80.4797	67.5	0.055
ADS 14073	BU 151 AB	20328 +1415
80.4770	188.3	0.531
80.4771	187.8	0.531
80.7200	187.7	0.517
80.7229	187.4	0.517
ADS 14099	HU 200 AB	20337 -1518
80.7174	110.6	0.354
HR 7906	α Del Aa	20350 +1534 (54)
80.4771	330.9	0.167
80.7229	326.8	0.160
HR 7922	HD 197226	20373 +3843 (55)
80.4797	100.5	0.121
ADS 14296	STT 413 AB	20435 +3607
80.4770	16.5	0.856
80.4797	14.9	0.856
80.7173	15.2	0.844
80.7257	15.0	0.845
HR 7963	λ Cyg	20435 +3607 (56)
80.4771	343.4	0.050
80.4797	338.0	0.043
80.4825	346.6	0.042
HR 7990	μ Aqr	20473 -0922
80.7174	138.5	0.045
ADS 14412	A 751	20513 +5856
80.4825	175.2	0.115
80.7173	167.4	0.125
HD 199942	KUI 102	20552 +0707
80.4771	73.9	0.259
80.7173	72.5	0.264
HR 8059	12 Aqr	20588 -0613 (57)
80.7257	76.8	0.087
ADS 14585	BU 1138 AB	20593 +4527
80.4772	174.6	0.115
80.4798	174.9	0.113
80.7202	174.5	0.106
80.7229	171.9	0.106
ADS 14761	HU 767	21088 +1534
80.4772	2.0	0.110
80.4798	3.6	0.112
80.7201	0.9	0.108
80.7230	1.6	0.114
80.7283	1.5	0.108

TABLE 3—*Continued*

ADS 14773	STT 535 AB	21096 +0936
80.4772	356°1	0″078
80.4798	355.3	0.074
HR 8131	α Equ	21108 +0405 (58)
80.4853	117.5	0.097
ADS 14784	STF 2783	21114 +5753
80.4926	8.8	0.791
ADS 14783	H 48	21117 +6400
80.4826	253.3	0.540
80.7202	253.8	0.534
ADS 14839	BU 163 AB	21138 +1109
80.4798	247.9	0.394
ADS 14893	A 617	21165 +0955
80.4798	297.6	0.099
80.7201	289.8	0.122
80.7256	289.0	0.119
HR 8238	β Cep	21274 +7007
80.4798	49.4	0.188
80.4852	49.6	0.191
80.7202	49.4	0.184
ADS 15115	HU 371	21309 +2400
80.4799	294.8	0.290
80.7175	295.5	0.290
ADS 15176	BU 1212 AB	21344 -0030
80.7229	236.3	0.323
+40°4615	KUI 108	21384 +4038
80.4799	75.8	0.131
80.4854	70.5	0.143
80.7202	72.1	0.137
80.7230	72.1	0.137
ADS 15281	BU 989 AB	21401 +2511
80.4799	285.0	0.187
80.4854	284.2	0.190
80.7174	280.9	0.188
80.7257	280.9	0.192
80.7285	281.9	0.189
HR 8344	COU 14	21454 +1650
80.4799	359.2	0.177
80.7230	0.9	0.186
ADS 15499	BU 275	21543 +6049
80.4826	173.4	0.421
80.7229	172.2	0.420
HR 8417	ε Cep Aa	22009 +6408 (59)
80.4772	292.8	0.067
80.4798	293.5	0.058
80.7202	304.9	0.045
HD 210444	COU 136	22054 +2238
80.4826	46°7	0″394
HR 8485	HD 211073	22096 +3913 (60)
80.7285	7.0	0.524
ADS 15902	BU 172 AB	22189 -0521
80.4799	270.4	0.210
80.7202	268.8	0.208
ADS 15988	STF 2912	22249 +0355
80.4799	117.7	0.801
80.7202	116.9	0.802
HR 8572	5 Lac	22253 +4712
80.4799	44.7	0.124
80.4853	45.7	0.115
80.7176	44.5	0.101
80.7286	41.1	0.111
ADS 16011	HU 981	22270 +6107
80.7229	222.2	0.323
ADS 16057	STF 2924 AB	22301 +6923
80.4798	87.7	0.478
80.7202	87.8	0.477
ADS 16173	HO 296 AB	22359 +1401
80.4799	17.2	0.258
80.7258	13.0	0.240
HR 8650	η Peg	22383 +2942
80.4799	38.6	0.041
ADS 16214	STT 476 A,BC	22388 +4638
80.7176	308.1	0.502
+80°0731	HD 215318-9	22392 +8052 (61)
80.7231	98.3	0.170
ADS 16345	BU 382 AB	22492 +4413
80.7202	206.4	0.930
HD 216879	COU 240	22515 +2225
80.7231	289.3	0.728
ADS 16417	STT 536 AB	22535 +0850
80.4799	347.8	0.259
80.7175	345.8	0.272
80.7231	345.7	0.271
80.7258	344.6	0.269
ADS 16428	STT 483	22542 +1112
80.4799	298.5	0.599
80.7175	298.3	0.607
HR 8762	ο And Aa	22573 +4147 (62)
80.4799	139.3	0.042
HR 8762	ο And AB	22573 +4147 (63)
80.4799	1°1	0″325
80.4853	359.7	0.331
80.7175	359.1	0.321
80.7203	359.1	0.320
ADS 16467	BU 1147 AB	22580 +4213
80.7176	335.3	0.410
80.7231	334.9	0.410
ADS 16497	A 417 AB	23000 -0814
80.4799	203.9	0.171
80.7175	206.1	0.160
ADS 16530	HU 994	23038 +6306
80.7176	125.5	0.199
80.7231	127.0	0.211
HR 8866	94 Aqr Aa	23138 -1400 (64)
80.7232	359.8	0.142
ADS 16708	HU 295	23174 -1536
80.7203	101.5	0.420
ADS 16800	BU 1266 AB	23255 +3017
80.7177	93.8	0.258
80.7231	93.8	0.260
80.7258	93.3	0.258
ADS 16836	BU 720	23290 +3047
80.7176	79.3	0.512
80.7231	79.3	0.515
ADS 16877	STT 500 AB	23326 +4353
80.7231	355.8	0.512
HR 9003	ψ And	23411 +4552
80.4799	106.3	0.284
ADS 17020	STT 507 AB	23438 +6420
80.7176	305.0	0.734
ADS 17030	A 424	23448 +2707
80.7203	103.8	0.188
HR 9041	FIN 359	23478 -0343
80.7177	58.5	0.097
80.7232	58.1	0.102
HR 9064	ψ Peg	23577 +2435 (65)
80.7287	54.1	0.191

NOTES TO TABLE 3

1. HR 178 = HD 3883 is directly resolved for the first time. Hynek 1938 listed the object as having a composite spectral type of A + F. The star is now generally classified as Am.

2. HR 233 = HD 4775 has moved through 40° of position angle since its first resolution on 1978.615. A spectroscopic orbit with a period of $225^{\rm d}.7$ has been determined by Hendry 1981 who assigns a classification A + F2 V and points out that the system resolved by speckle interferometry probably is the composite spectrum pair. The $225^{\rm d}.7$ motion observed in the F2 V spectrum is therefore due to an unresolved third component in the system.

3. ADS 1473 = HO 311 may be approaching periastron. The system has not had an orbit determined.

4. HR 640 = 55 Cas is directly resolved for the first time. Hynek 1938 classified the composite spectrum as A2 + F2 V. No velocity variation has apparently been observed.

5. HR 763 = 31 Ari has moved through 90° of position angle since its first resolution on 1979.533, and speckle and spectroscopic observations suggest a period of 4 yr.

6. HR 781 = ε Cet = φ 312 has now been observed by speckle interferometry for two resolutions. The residuals to the orbit of Finsen 1970 are (+ 4°.3, + 0″.0010), (+ 5°.9, + 0″.009), and (+ 2°.9, + 0″.009) and indicate that minor revisions to Finsen's elements may be appropriate.

7. HR 788 = 12 Per is a spectroscopic binary with a period of 331 days. The elements of the apparent orbit have been determined by McAlister 1978*a*, and residuals to those elements are (+ 1°.9, 0″.000).

8. HR 838 = 41 Ari is directly resolved for the first time. The star is classified as B8 V, and Abt and Biggs 1972 note that the radial velocity is variable.

9. HR 915 = γ Per is a spectroscopic binary with a period of 14.6 yr. An analysis of this G8 II-III + B9 V system has been published by McAlister 1982 who found an inclination of 88° for the apparent orbit.

10. HR 936 = β Per AB,C has elements for its apparent orbit determined by Bonneau (1979) from which the present observation shows residuals of (− 2°.4, − 0″.003).

11. HR 1252 = 36 Tau is directly resolved for the first time. The spectrum is a composite A + F5 (Hynek 1938), and Abt and Biggs 1972 record one note of variable radial velocity. Occultation observations by Dunham *et al.* 1973 and by Eitter and Beavers 1977 combined to give a true separation and position angle of 0″.033 ± 0″.002 and 142° ± 3° on 1973 January 15. Thus, it seems likely that the component resolved here is the occultation secondary and that some orbital motion has occurred.

12. ADS 3064 = A 1938 has been observed through 250° of position angle since 1975.959 by speckle interferometry.

13. HR 1331 = 51 Tau is a Hyades spectroscopic binary which has moved through more than 200° of position angle since its first resolution on 1975.716.

14. HR 1391 = φ 342 is a close visual binary in the Hyades. Speckle and occultation observations should permit the accurate determination of the apparent orbit in the near future.

15. HR 1411 = θ^1 Tau is a Hyades spectroscopic binary which is exhibiting significant orbital motion.

16. ADS 3391 = A 1013 is a slowly moving visual binary which has closed from 0″.5 to less than 0″.1 since 1905.

17. HR 1497 = τ Tau is apparently directly resolved for the first time. This B3 V star is a member of the Cassiopeia-Taurus group. Jeffers, van den Bos, and Greeby 1963 list a companion at 0″.1 observed on four occasions between 1899 and 1909 by G. W. Hough who gave its magnitude as 8.6. Speckle interferometry would not routinely detect a companion with a Δm in excess of 4 mag. Dunham 1975 records that astronomers at the Cracow Observatory reported a secondary event observed visually during occultations in 1937 and 1947 giving a vector separation of 0″.1 at an assumed position angle of 90°.

18. HD 29961-2 = Don 75 is a close visual binary probably coinciding with Hynek's 1938 composite spectrum system of A3 + F5.

19. ADS 3841 = α Aur Aa = Capella has a new apparent orbit determination (McAlister 1981) from which the present observations have residuals of (+ 0°.1, + 0″.002) and (+ 0°.9, + 0″.001).

20. ADS 4229 = Bu 1240 AB is a rapidly moving visual binary which is being followed through a previously unresolved segment of its orbit.

21. HR 2001 = HD 38735 is directly resolved for the first time. Andersen and Nordström 1977 found the system to be a spectroscopic triple with the long-period system apparently resolved here.

22. HR 2425 = 53 Aur has moved through nearly 90° of position angle since its first resolution on 1976.860.

23. HR 2605 = 40 Gem is directly resolved for the first time. A visual occultation observation by E. Kharadze on 1971 April 2 indicated a companion with a vector separation of 0″.4 at a position angle of 20° (Dunham 1977*b*). The star is classified as B8 III and has no reported velocity variation (Abt and Biggs 1972).

24. HR 2846 = 63 Gem is directly resolved for the first time. Eitter and Beavers 1977 report an occultation secondary with a vector separation of 0″.047 at a position angle of 304° on 1972 November 24. This is likely to be the same object as is reported here. The star is classified as F5 IV-V and is a known quadruple. The companion described here and by Eitter and Beavers 1977 makes the system quintuple.

25. HR 2886 = 68 Gem is directly resolved for the first time. Dunham 1977*a* records that R. Sandy detected a secondary with a vector separation of 0″.15 at a position angle of 236° during an occultation on 1976 October 16. The star is classified as A1 V.

26. HR 3109 = 53 Cam is directly resolved for the first time. The star is a peculiar A star and a spectroscopic binary with a period of 6.5 yr (Scholz 1978). The companion reported here is very likely the spectroscopic binary.

27. ADS 6825 = A 550 is a visual binary whose separation has closed below 0″.1. The orbit of Baize 1980 predicts values of 311° and 0″.113 at this epoch.

28. HR 3650 = φ 347 is a rapidly moving system now observed by speckle interferometry for more than two revolutions. The orbit of Finsen 1966 predicts values of 220°.5 and 0″.066 at this epoch.

29. HR 4365 = 73 Leo has moved through 20° of position angle since its first resolution on 1979.362.

30. HR 4544 = HD 102928 is directly resolved for the first time. White 1982 reports an occultation secondary with a vector separation of 0″.035 at a position angle of 88″.5 on 1974 May 30. The star is classified K0 IV, and Abt and Biggs 1972 record one report of variable radial velocity.

31. HR 4689 = η Vir has moved through 140° of position angle since its first resolution on 1976.036.

32. HR 4963 = θ Vir continues to show only marginal motion since its first resolution on 1976.036.

33. + 16°2624 = HD 126269-70 is directly resolved for the first time. The star is a composite spectrum system with types A0 + F5 (Hynek 1938), and Abt and Biggs 1972 record one report of variable radial velocity.

34. − 14° 4182 = HD 136406 is directly resolved for the first time. Edwards *et al.* 1980 report a possible secondary with a vector separation of 0″246 at a position angle of 310°9 during an occultation on 1978 June 18. They estimate that $\Delta m = 1.1 + 0.5$.

35. − 21°4279 = HD 144641 is directly resolved for the first time. Oliver and Maloney 1975 report an occultation secondary which combined with an observation by Africano *et al.* 1976 to give a true separation of 0″078 at 150°5 on 1975 May 25. Africano *et al.* 1976 deduce a Δm of 1.4 ± 0.3 in the red and 1.0 ± 0.1 in the blue. If the occultation secondary coincides with the companion reported here, then the system has shown significant orbital motion since 1975.

36. HR 6053 = HD 145997 is directly resolved for the first time. Dunham 1977*c* records that R. Nolthenius observed an occultation secondary with a vector separation of 0″03 at position angle 324° on 1977 July 26. The star is of spectral type K2.

37. HR 6148 = β Her has been unresolved during the course of this program on numerous occasions (McAlister 1978*b*; McAlister and Hendry 1981). The system is a spectroscopic binary with a period of 1.1 yr and was first resolved by Blazit *et al.* 1977 who measured 78°0 and 0″043 on 1975.627 and reported a large red Δm.

38. − 19°4547 = HD 155095 is directly resolved for the first time. Dunham 1977*b* records that R. McNaught reported an occultation secondary with a vector separation of 0″1 at a position angle of 334° on 1977 March 12.

39. HR 6388 = HD 155410 is directly resolved for the first time. The object is a spectroscopic binary of type K3 III (Griffin 1978) with a period of 2.40 yr.

40. HR 6469 = HD 157482 is directly resolved for the first time. Bolton and Lyons 1982 report that this star is a spectroscopic triple system with the long period being ~ 5.3 yr.

41. HR 6560 = HD 159870 is directly resolved for the first time. The star is of spectral type F2, and Abt and Biggs 1972 record one report of variable radial velocity.

42. HR 6927 = χ Dra is a spectroscopic binary with a period of $280^{d}5$. Residuals to the apparent orbit of McAlister 1980*b* are (+ 15°4, + 0″016), (− 3°6, + 0″011), (− 4°3, + 0″010), and (− 3°2, + 0″009).

43. − 17°5245 = HD 171347 is directly resolved for the first time. The star is a composite spectrum object of type A2 + F (Kuhi 1963) and is noted by Schmidtke 1979 as being susceptible to lunar occultation.

44. HR 7059 = 5 Aql is directly resolved for the first time. The star is a composite spectrum system of types A0 + F2 (Hynek 1938). Although there is no note of variable radial velocity, the two measures recorded by Abt and Biggs 1972 differ by 33 $\mathrm{km\ s^{-1}}$.

45. + 12°3818 = HD 178452-3 is directly resolved for the first time. The star is a composite spectrum system of types A2 + G5 and is described by Hynek 1938 as having the color of a K0 V or G0 III star.

46. + 58°1929 = HD 184467 is directly resolved for the first time. This star was placed on the observing program at the suggestion of Batten 1980 who pointed out that the star is an IAU standard velocity object whose spectrum is composite.

47. HR 7478 = ϕ Cyg is a double-lined giant system whose masses and luminosities have been determined by a combined spectroscopic/interferometric analysis (McAlister 1982).

48. ADS 12973 = AGC 11 AB apparently underwent periastron passage in mid-1980. The system has a period of 22.8 yr with an orbital eccentricity of 0.85 (Finsen 1937). Speckle interferometry has now covered the orbit through 170° of position angle.

49. + 35°3930 = HD 190429 is directly resolved for the first time. This new component in the known quadruple system ADS 13312 probably belongs to the A component in the 2″ separation AB system.

50. HR 7735 = 31 o^2 Cyg is directly resolved for the first time. Breakiron 1978 pointed out that this star is often mistakenly called o^1 Cyg and that historically 30 Cyg and 31 Cyg have been referred to as o^1 Cyg and o^2 Cyg. This well-known astrometric, spectroscopic, and eclipsing ζ Aur type system has components of spectral type K4 IV and B4 V. A separate analysis of the star is in preparation.

51. HR 7744 = 23 Vul is directly resolved for the first time. The star is of spectral type K3 III, and Abt and Biggs 1972 report no velocity variations.

52. HR 7776 = β Cap is a spectroscopic binary which has been resolved with speckle interferometry by Blazit *et al.* 1977. Evans and Fekel 1979 determined elements for the apparent orbit from occultation measurements and classified the system as K0 II–III + B8 V. The speckle measure of Blazit *et al.* 1977 showed significant disagreement from this orbit, and the observations presented here have residuals of (+ 2°2, + 0″018), (− 1°0, + 0″014), and (+ 4°8, + 0″005).

53. + 49°3310 = HD 196088-9 is directly resolved for the first time. The star is a composite spectrum system of types A0 + G (Hynek 1938).

54. HR 7906 = α Del Aa has moved through nearly 70° of position angle since its first resolution by Wickes 1975 with a modified Michelson interferometer on 1974.65. The system continues to slowly close in separation.

55. HR 7922 = HD 197226 is directly resolved for the first time. The star is a spectroscopic binary of types B6 IV + B6 III with a period of $106^{d}3$ (Hube and Wolff 1979). Establishing the correspondence between the component reported here and the spectroscopic systems will require additional speckle observations.

56. HR 7963 = λ Cyg has moved through more than 40° of position angle since its first resolution on 1978.618.

57. HR 8059 = 12 Aqr has moved through more than 90° of position angle since its first resolution on 1978.618.

58. HR 8131 = α Equ is directly resolved for the first time. The star is a double-lined spectroscopic binary of types G2 III + A5 V having a period of 99 days (Stickland 1976). The correspondence between the component reported here and the spectroscopic system will require additional speckle observations.

59. HR 8417 = ξ Cep Aa is a spectroscopic binary with a period of 2.25 yr. The elements of the apparent orbit have been determined by McAlister 1980*a* and residuals to those elements are (− 1°2, + 0″007), (− 0°7, − 0″002), and (− 6°3, − 0″005).

60. HR 8485 = HD 211073 is directly resolved for the first time. The star is classified K3 III, and Abt and Biggs 1972 record two notes of variable radial velocity.

61. + 80°0731 = HD 215318-9 is directly resolved for the first time. The star is a composite spectrum system with types A5 + F8 (Hynek 1938).

62. HR 8762 = o And Aa has been resolved on two occasions by Blazit *et al.* 1977 but has not been previously seen on any of the 21 other measurements secured in this program. The observation reported here only marginally implies the presence of this component. The star o And is a Be star exhibiting a highly variable shell spectrum, and it is of considerable interest to know whether a close companion, such as that discussed here, might contribute to the shell episodes. It is here only assumed that this component is Aa and not Ba.

63. HR 8762 = o And AB continues to exhibit marginal orbital motion with only very small changes in θ and ρ.

64. HR 8866 = 94 Aqr Aa is a spectroscopic binary with a period of 6.4 yr. A combined spectroscopic/interferometric analysis has been completed by McAlister and Hartkopf 1982.

65. HR 9064 = ψ Peg is directly resolved for the first time. The system is of spectral type M3 III.

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THE OPTICAL VARIABILITY AND SPECTRUM OF PKS 2155-304[1]

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ABSTRACT

Photometry of the BL Lacertae object PKS 2155 - 304 has demonstrated that small-amplitude color variations accompany long-term trends in the optical variations of this object. These variations are similar to those found for the optically violent variable quasar 3C 446. These variations have been compared and found to agree well with a recent model suggested by Marscher. Spectroscopy of PKS 2155 - 304 has failed to confirm the identification of the [O III] features and the redshift reported by Charles, Thorstensen, and Bowyer.

Subject heading: BL Lacertae objects

I. INTRODUCTION

BL Lacertae objects are characterized by rapid, large-amplitude optical variability, significant polarization of their optical flux, and an absence of discrete features in their optical spectram. PKS 2155 - 304 has been suggested as a possible BL Lacertae object on the basis of the presence of a featureless optical spectrum obtained by Wade, Szkody, and Córdova (1979). This classification is supported by the observations of Schwartz *et al.* (1979) in which the soft X-ray source, H2155 - 304, was identified with this object. Griffiths *et al.* (1979) have detected both rapid optical variability and variability of the optical polarization for PKS 2155 - 304. The variability of PKS 2155 - 304 has been confirmed by Urry and Mushotsky (1981) who interpret their results to imply the presence of relativistic jets associated with this object. Charles, Thorstensen, and Bowyer (1979) have obtained spectroscopy of PKS 2155 - 304 and have detected a weak [O III] emission feature at a redshift of 0.17. Maraschi *et al.* (1980) tentatively confirm the existence of this [O III] feature in unpublished spectra which they have obtained. However, Snyder *et al.* (1980) have recently obtained a spectrum of PKS 2155 - 304 at higher resolution than that obtained by Charles, Thorstensen, and Bowyer (1979). They find no evidence for discrete features in the spectrum, in agreement with the earlier results of Wade, Szkody, and Córdova (1979). The purpose of the present paper is to present new photometry and spectroscopy of PKS 2155 - 304.

II. OBSERVATION AND RESULTS

PKS 2155 - 304 was observed 1980 June 7 with the Palomar 60 inch (1.5 m) telescope. The SIT spectrograph, located at the Cassegrain focus of the telescope, was used to obtain a spectrum of the object with a reciprocal dispersion of 285 Å mm^{-1}. A well-exposed spectrum was obtained with an exposure of 200 s. The useful range of the spectrogram is approximately 3500-6500 Å. The flux levels have been calibrated relative to observations of the standard stars of Oke (1974), and the wavelength scale calibrated by comparison with standard He and Ne sources. The spectrum of PKS 2155 - 304 is shown in Figure 1. We find no evidence for the lines of [O III] λ4959 and 5007 at a redshift of $z = 0.17$ which have been reported by Charles, Thorstensen, and Bowyer (1979). A single possible emission feature is observed in the spectrum of PKS 2155 - 304 at a wavelength of ~5375 Å. However this

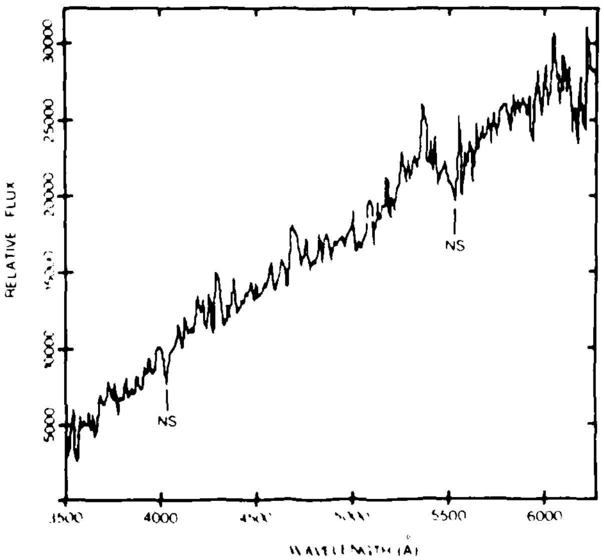

FIG. 1.—Spectrum of PKS 2155 - 304 obtained with the SIT spectrograph and 1.3 m telescope at Palomar Observatory on 1980 June 7. Features marked NS are due to improperly subtracted night sky lines.

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[4] Guest Observer, Lowell Observatory.

feature is only marginally significant and no reliable identification can be made. Margon (1981) has also obtained a spectrum of PKS 2155 − 304 using the 5 m Hale telescope on 1980 July 12 and has found no discrete features to be present in his spectrum of this object. Thus we are unable to confirm the redshift obtained by Charles, Thorstensen, and Bowyer (1979) for PKS 2155 − 304.

Photometric observations of PKS 2155 − 304 have been obtained using the No. 2 90 cm and 1.3 m telescopes at Kitt Peak National Observatory. A standard *UBV* filter set was used with the automated filter photometer equipped with a 1P21 photomultiplier for the observations made with the 90 cm telescope. The Mark 2 computer photometer equipped with a 1P21 photomultiplier and standard *UBV* filters was used for the observations made with the 1.3 m telescope. The extinction was determined each night and the transformation to the standard *UBV* system was made using the standard stars of Landolt (1973). The standard error for each observation of PKS 2155 − 304 was ≤0.01 mag in the *V* band and ≤0.02 mag in both $B-V$ and $U-B$.

The results of the photometric observations of PKS 2155 − 304 are summarized in Table 1. In column (1) is the date (UT) on which each observation was made; column (2), *V* magnitude of PKS 2155 − 304; column (3), $B-V$ color index; and in column (4), the $U-B$ color index. The photometric observations of PKS 2155 − 304 indicate that this object is variable on time scales ranging from days to years. Observations made on 1979 September 9 and 13 show the object to have $V = 13.37$ and color indices of $B-V = 0.35$ and $U-B = -0.73$. A general decline in brightness is observed to occur for this object from 1979 September to 1981 June with the object achieving a minimum observed magnitude of $V = 13.86$ and colors of $B-V = 0.28$ and $U-B = -0.77$ on 1981 June 7. PKS 2155 − 304 has been gradually brightening from 1981 June through the most recent observation of this object made 1982 November 15 when $V = 13.28$, $B-V = 0.36$ and $U-B = -0.70$. Photographic observations of PKS 2155 − 304 indicates that short-term variations on the time scale of weeks with a typical amplitude of $\Delta V \approx 0.25$ mag are superposed on the long-term variation in brightness (A. G. Smith, private communication).

TABLE 1

PHOTOMETRY OF PKS 2155 − 304

Date (UT) (1)	V (2)	B − V (3)	U − B (4)
1979 Sep 9	13.37	0.36	0.72
1979 Sep 13	13.38	0.34	0.74
1979 Nov 11	13.50	0.31	0.76
1979 Nov 12	13.52	0.32	0.79
1980 Jun 7	13.50[a]		
1980 Sep 22	13.63	0.30	0.75
1980 Sep 24	13.71	0.29	0.76
1981 Jun 6	13.86	0.28	0.77
1981 Jun 7	13.81	0.30	0.81
1981 Sep 21	13.73	0.29	0.77
1981 Nov 19	13.32	0.33	0.73
1981 Nov 21	13.37	0.35	0.71
1982 Oct 5	13.10[a]		
1982 Nov 15	13.28	0.36	0.70

[a] Visual estimates.

The photometric observations in Table 1 indicate that color variations accompany the long-term changes in luminosity. The mean color indices in 1979 September were $(B-V)_{\text{average}} = 0.35$ and $(U-B)_{\text{average}} = -0.73$. In 1981 June, the object was ~0.50 mag fainter, and the colors had changed to $(B-V)_{\text{average}} = 0.29$ and $(U-B)_{\text{average}} = -0.79$. Thus the object's colors and become bluer in both $(B-V)$ and $(U-B)$ as it faded in brightness. The most recent observations in 1982 November show the object to have brightened by ~0.60 mag and the colors to have become $(B-V) = 0.36$ and $(U-B) = -0.70$; i.e., it became redder as it brightened.

Sandage, Westphal, and Strittmatter (1966) and Miller and French (1978) have observed the optically violent variable quasar 3C 446, an object which has many properties in common with the BL Lacertae class of objects, and have found that the contrast between the emission lines and the continuum varies significantly. When the object is bright, the spectrum of 3C 446 resembles that of a BL Lacertae object, due to the fact that the continuum is much brighter and there is little or no contrast between the emission lines and the continuum. However, when 3C 446 is faint, the continuum is much fainter, and the emission lines are clearly visible and the object has a "typical" quasar spectrum. Sandage, Westphal, and Strittmatter (1966) pointed out that color variations also accompanied the overall variations in brightness for 3C 446. Recently Miller (1981) also observed and studied the optical variability of 3C 446. Sandage, Westphal, and Strittmatter (1966) and Miller (1981) both found color variations for 3C 446 similar to that reported in the present paper for PKS 2155 − 304, i.e., the colors became redder as the object brightened.

Marscher (1980) has proposed a model for optical variations observed in quasars and active galactic nuclei in which enhanced regions of synchrotron emission are produced by radiative thermal instabilities in relativistic flows. The rapid variability of PKS 2155 − 304, such as the 0.08 mag variation observed between 1980 September 22 and 24, suggests that the motion of the particles in the source region is likely to be relativistic. Marscher's model predicts that as the luminosity of the source increases, the nonthermal continuum should become steeper, i.e., the colors should become redder. This is what has been observed for PKS 2155 − 304.

Marscher's model predicts flux variations and the formation of knots in relativistic flows which are thought to occur in quasars and active galactic nuclei. The model also predicts that the knots can be responsible for the apparent superluminal motions observed in compact radio sources. Thus, VLBI observations of PKS 2155 − 304 during any radio event which may be related to the present mild outburst at optical wavelengths would be important in order to test this model.

The similarities between PKS 2155 − 304 and 3C 446 suggests that an optimum time to attempt to detect discrete emission features in the spectrum of PKS 2155 − 304 is when it is faint. Thus, spectroscopy of PKS 2155 − 304 when it is 14.0 mag or fainter would seem to have the greatest chance of successfully determining the redshift for this object.

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Photometry of the newly identified AM Herculis system: CW 1103 + 254

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Summary. Photoelectric photometry (*UBV*) is reported for the AM Her type system CW 1103 + 254. Rapid variability, super-imposed on a 113-min periodic variation is detected.

CW 1103 + 254 has recently been identified as a new AM Her variable by Stockman *et al.* (1982). This identification is based on the object having an emission-line spectrum which is similar to that of other AM Her systems, to the presence of linear and circular polarization which varies throughout each cycle, and to a light curve which is similar to that of previously identified AM Her systems. A finding chart for this object is given by Shore *et al.* (1982). The purpose of the present paper is to present the results of recent photometry for this object.

The photoelectric photometry was obtained using the 1.3-m telescope at Kitt Peak National Observatory. The Mark 2 computer photometer equipped with a 1P21 photomultiplier and standard *UBV* filters was used in the sky chopping mode for all the observations reported here. The observations have a minimum time resolution of 1 min in each colour. The extinction was determined each night, and the transformation to the standard *UBV* system was made using the equatorial standard stars of Landolt (1973).

CW 1103 + 254 was observed on the nights of 1982 April 19, 20 and 21. The results of those observations are shown in Figs 1, 2 and 3 respectively. The observations on each of those nights covers significantly more than one cycle of the object's variability. A period of 113.416 ± 0.002 min for this system was found based on the three night's observations shown in Figs 1–3. This period is in reasonable agreement with the period determined by Stockman *et al.* (1982) of 113.885 min. The slight difference in period may be either due to a real change in the period or due to the fact that the present period is determined from data obtained over a shorter time base than that of Stockman *et al.* Additional observations should clearly indicate whether a true change in period has occurred.

CW 1103 + 254 varies from a maximum of $V \simeq 15.25$ and fall to a minimum of $V \simeq 17.00$. The range is considerably smaller in the *B*-band ($\Delta B \simeq 0.75$ mag) and the *U*-band ($\Delta U \simeq 0.5$ mag). Considerable colour variations are also found to occur throughout the 113-min cycle. Near maximum light, $B-V \simeq 0.9$ and $U-B \simeq -0.85$, while near minimum light, the colours are $B-V \simeq 0.0$ and $U-B = -1.0$. These colours are in excellent agreement with those reported by Stockman *et al.* (1982) of $B-V=+1.0$, $U-B=-0.8$ in the bright phase and $B-V=-0.1$ and $U-B=-0.9$ in the faint phase.

The bright phase has a duration of 30–40 min which is a much smaller fraction of the total 113-min cycle than that observed for the bright phase of other AM Her systems, e.g. 2A 0311 – 227 (Warner 1980; Bond, Chanmugan & Grauer 1979). The maximum brightness achieved by the object is not rigorously repeatable, cycle to cycle, and may vary by as much as 0.25 mag in the V-band (see Figs 1 and 3). In addition, the faint phase achieves its minimum brightness at the end of the bright phase and exhibits a gradual brightening trend of typically $\Delta V \sim 0.25$ mag as one approaches the onset of the next bright phase. Similar gradients are also easily detectable in the B- and U-bands.

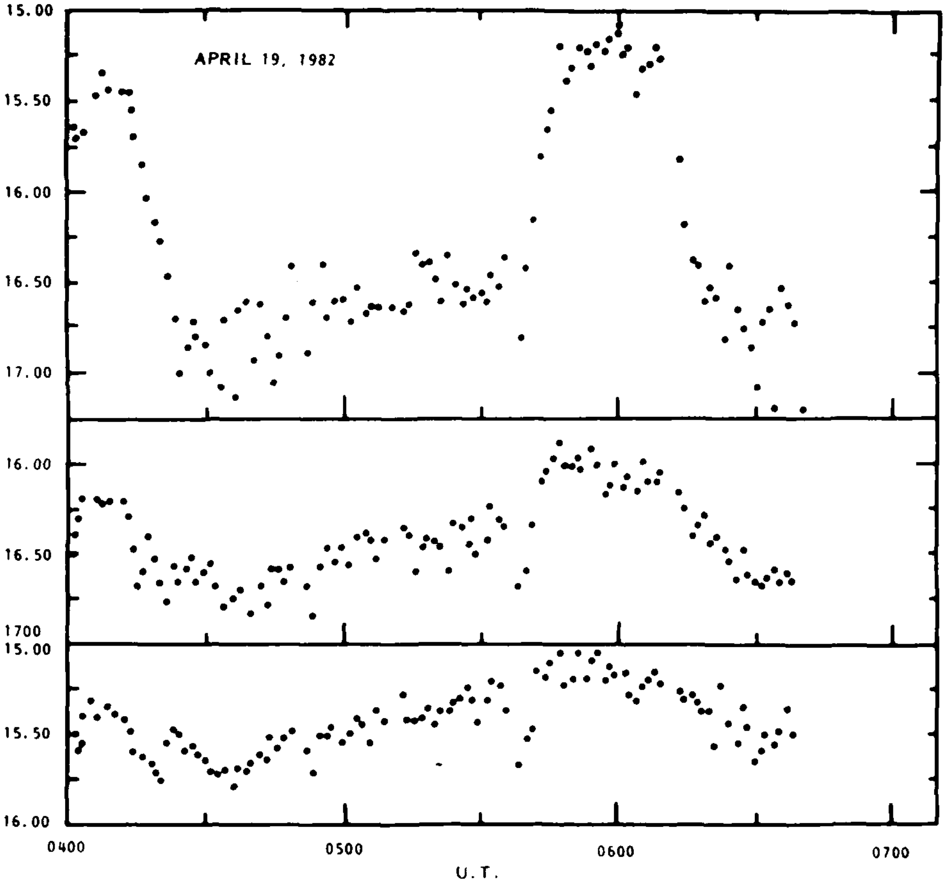

Figure 1. Light curve of CW 1103 + 254 on 1982 April 19 with 1-min time resolution.

Rapid short-term flickering with an amplitude of up to 0.5 mag is observed super-imposed on the 113-min cycle. Occasional 'glitches' in the variations are observed such as that found near 0538 UT, 1982 April 19 (Fig. 1). This phenomenon has also been detected by G. Schmidt (private communication) in his photometry of CW 1103 + 254. This effect is present in all three colours and is presumably due to inhomogeneities present in the accretion rate in this system. Additional observations of the 'glitch' phenomenon observed in this system should provide a better insight into the details of the physical processes producing this effect.

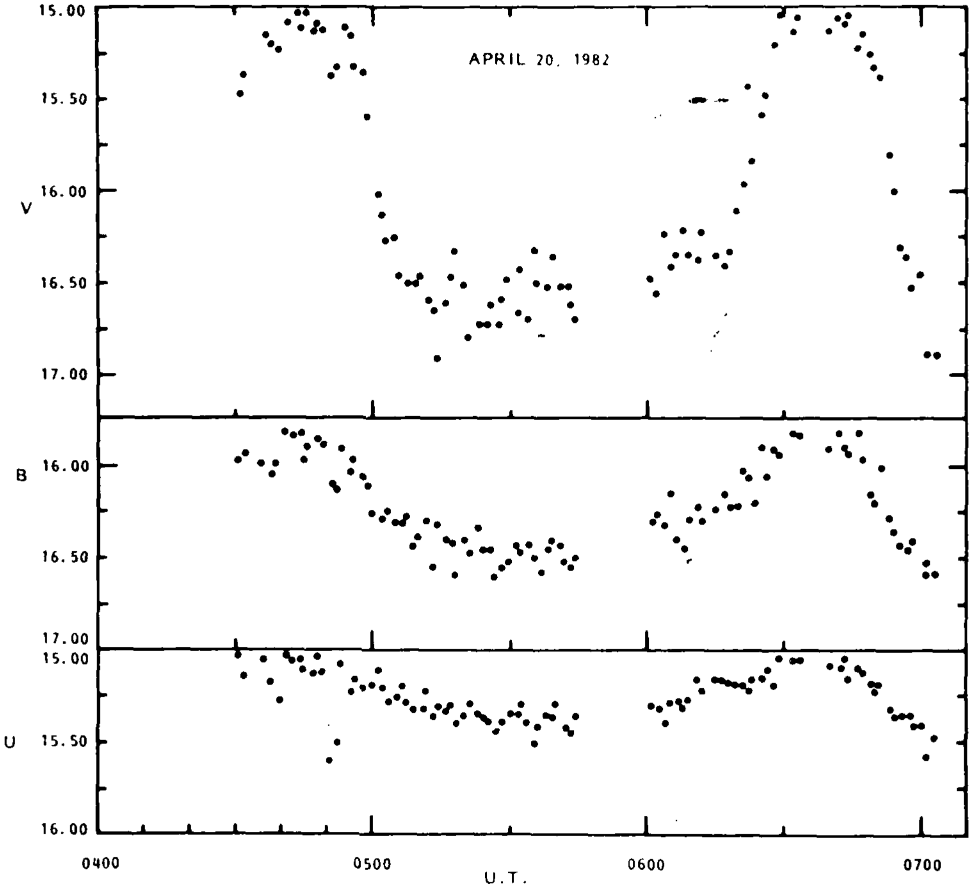

Figure 2. Light curve of CW 1103 + 254 on 1982 April 20 with 1-min time resolution.

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The author thanks Dr Craig Foltz for bringing this object to his attention and for providing a finding chart. The author thanks Dr Gary Schmidt for permission to quote his results prior to publication. The author also expresses his appreciation for useful discussions with Drs C. Foltz, G. Schmidt and H. Stockman. The author thanks Kitt Peak National Observatory for observing time. The work was supported by grants from the Dean's Research Fund at Georgia State University and the United States Air Force Office of Scientific Research, Grant 81-NP-014.

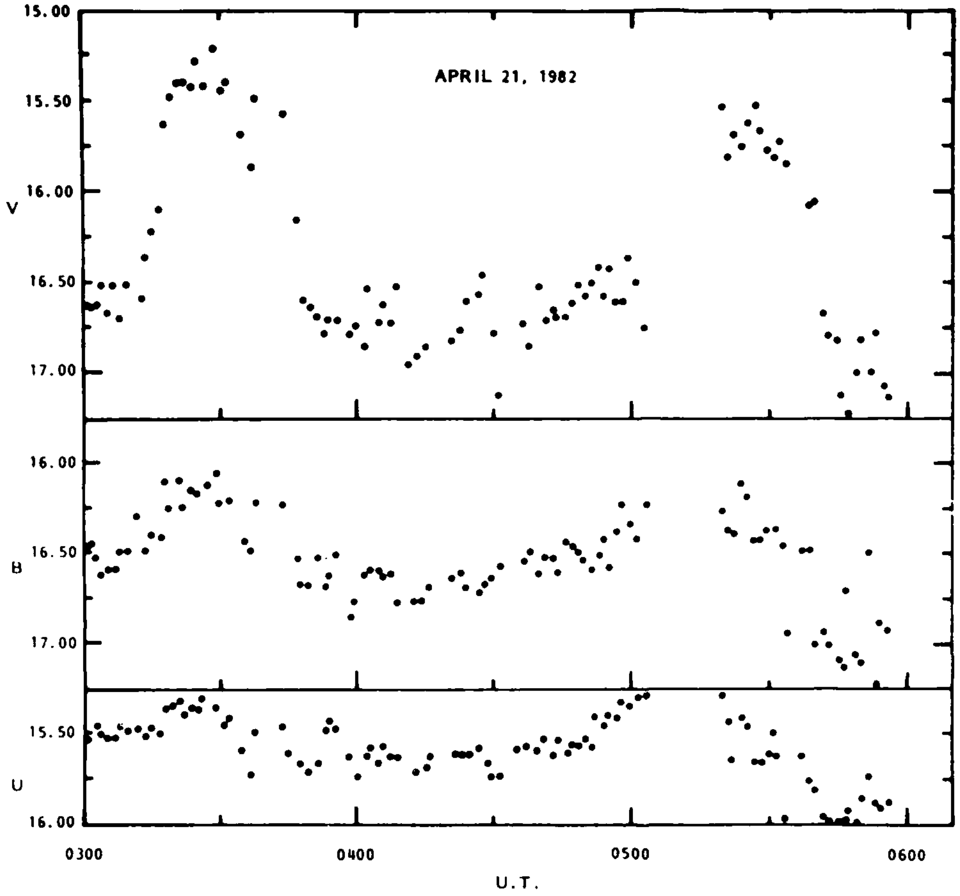

Figure 3. Light curve of CW 1103 + 254 on 1982 April 21 with 1-min time resolution.

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SUPPLEMENT SERIES

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The variability of the optical counterparts of four extragalactic radio sources (*)

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Summary. — The optical variability of four extragalactic radio sources has been studied using the archival plates at the Harvard College Observatory. Three of these sources, PKS 1123 + 264, B2 1132 + 303, and 4C 18.36, were conclusively found to exhibit significant optical variability. No conclusive evidence was found for optical variability for B2 1128 + 315 with a range $\Delta m < 0.3$ magnitude, based on a limited number of plates.

Key words : radio sources — photometry.

1. **Introduction.** — Variability in the optical flux of quasars and active galactic nuclei is a well-known property of this class of extra-galactic objects (e.g. Pollock *et al.*, 1979 ; Pica *et al.*, 1980 ; Gilmore, 1980). The optical variability can provide an important insight into the nature of the physical processes responsible for the high luminosity and rapid variability observed for these objects. The time scale of the variations (assuming relativistic effects are negligible) place constraints on the size of the active source region. The structure and shape of the light curve for these objects (i.e., periodic behavior, or comparison of the rate at which an object flares to the rate of decline) suggest or limit possible mechanisms which may be responsible for the activity. In order to study the optical variability of an object, it is important to obtain data on its brightness over as long a time base as possible. The archival plate collection of the Harvard College Observatory contains photometric plates covering most areas of the sky which were obtained beginning in the 1890's and continuing until the early 1950's. Since the early 1950's, the survey coverage has not been continuous. The purpose of the present investigation is to determine if the radio sources PKS 1123 + 264, B2 1128 + 315, B2 1132 + 303, and 4C 18.36 are optically variable, and if so, the nature of the variability.

2. **Data reduction and analysis.** — The optical data for these four objects was obtained from a search of high-quality patrol plates (i.e., the RL, RH, RB, and BM plates series which utilize telescopes with apertures of three and four inches) taken between 1928 and 1952.

Magnitudes for these objects are determined either by iris photometry of the object and nearby comparison stars or by visual interpolation between comparison stars located near the objects. The accuracy of the iris photometry was determined by constructing a calibration curve for each plate measured using the iris reading and the B magnitudes of the stars of the comparison sequence. The rms scatter of the comparison sequence about the calibration curve may then be used as an indication of the reliability of the magnitude for the source determined from that plate. Typically, the scatter of the comparison sequence about the calibration curve was ~0.1-0.2 magnitudes. The accuracy of visually interpolated magnitudes has been determined previously (Miller, 1975, 1977) by comparing the magnitudes obtained for an object using visual estimates with magnitudes determined using the iris photometer. The standard deviation of the difference between these earlier visual estimates and the magnitudes determined using the iris photometer was 0.16 magnitude. The results of an earlier study of the differences between visual estimates and magnitudes determined using the iris photometer yielded a value of 0.19 magnitude for the standard deviation. This value is slightly larger than that determined in the present investigation. However, this is in good agreement with similar investigations by Pollock (1975) and Angione (1973). Therefore, the typical uncertainty in the visual interpolated magnitudes is ~0.2-0.3 magnitude.

3. **Results.** — The results of the present investigation are summarized in table 1. The objects are listed with their 1950.0 coordinates and the total range in brightness (Δm) determined from a combination of archival plates and values previously published in the literature.

PKS 1123 + 264 was identified with a 17.5 magnitude object by Hoskins *et al.* (1974). This object is of particular interest since it is an example of an object at a moderately high redshift ($z = 2.341$; Peterson *et al.*, 1978) which exhibits significant optical variability. The light curve for this object is shown in figure 1. This object was detected on a total of nine plates. The maximum brightness observed was 15.8 which, when compared with the estimated brightness of the object on the Palomar Sky Survey print, yields a total observed range of $\Delta m \geqslant 1.7$ magnitudes. The time scale for the most rapid significant

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(*) Astronomical Contributions from Georgia State University, No. 67.

variation observed was ~1 year. This suggests an upper limit of ~1 Lyr on the dimensions of the source region assuming no relativistic motion of the material in the source region. These observations suggest that this object was in a brighter phase in the late 1930's than was observed during the mid to late 1940's. However, detailed trends are difficult to determine since the object was fainter than the plate limit throughout much of this time.

The optical counterpart for the radio source B2 1128 + 315 was identified by Fanti *et al.* (1975). The object has a redshift $z = 0.289$ (Wills and Wills, 1976). A search of archival plates provides no conclusive evidence for variability for this object. The total range for this object based on archival plates is $\Delta m = 0.30$ magnitudes (see Fig. 2). However, since this object is below the plate limit for a large number of plates, one cannot necessarily conclude that the object is not variable based solely on these archival plates.

The quasar B2 1132 + 303 was identified by Sandage *et al.* (1965) with an 18.24 magnitude object. A redshift of $z = 0.614$ was determined for B2 1132 + 303 by Lynds *et al.* (1966). The object was detected near the plate limit on a single plate taken in 1939. The estimated magnitude of the image on this plate is ~17.0 magnitudes. The uncertainties of this estimate are significantly greater than the typical uncertainties of most measurements discussed here. However, assuming that this estimate is reasonable, this object has a range of $\Delta m \geqslant 1.25$ magnitudes based on the comparison of this plate and the Palomar Sky Survey print. Current observations are necessary in order to confirm that this object is variable.

The radio source 4C 18.36 has been identified with a 17.5 magnitude source by Wills *et al.* (1973). Wills and Wills (1974) have determined a redshift of $z = 1.689$ for this object. This object was included in a survey by Uomoto *et al.* (1976) attempting to detect variable quasars. This object was found to be variable. A search of archival plates indicates that this object has twice in the past been as bright as 16.1 magnitudes. Comparison of these observations with the object's brightness on the Palomar Sky Survey (17.5) indicates a range of $\Delta m \geqslant 1.4$ magnitudes. The historical data does not indicate that large-amplitude rapid variability on the scales significantly shorter than three years are present. However, additional observations are necessary in order to confirm this behavior.

4. Conclusion.

— Two new optical sources, PKS 1123 + 264 and B2 1132 + 303, have been found to exhibit significant optical variations. In addition, the optical variability for a previously detected variable quasar, 4C 18.36, has been observed in more detail using archival plates, confirming the earlier detection of the optical variations. Additional observations of B2 1128 + 315 are necessary in order to define the nature of the variability for this object.

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TABLE I.

Radio Sources

Name	R.A. (1950.0)	DEC. (1950)	Δm
PKS 1123 + 264	$11^h\ 23^m\ 14^s.9$	$26^\circ\ 26'\ 49''.9$	1.70
B2 1128 + 315	$11^h\ 28^m\ 30^s.3$	$31^\circ\ 30'\ 40''.0$	0.30
B2 1132 + 305	$11^h\ 32^m\ 16^s.3$	$30^\circ\ 22'\ 01''.0$	1.25
4C 18.36	$13^h\ 08^m\ 29^s.5$	$18^\circ\ 15'\ 33''.8$	1.40

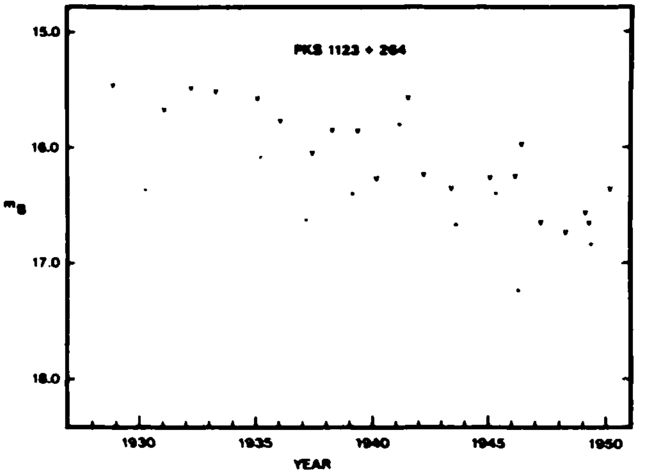

FIGURE 1. — The light curve of PKS 1123 + 264 from 1928 to 1952 determined from plates in the archive collection of the Harvard College Observatory. The symbol « v » indicates the plate limit when the object was too faint to be detected.

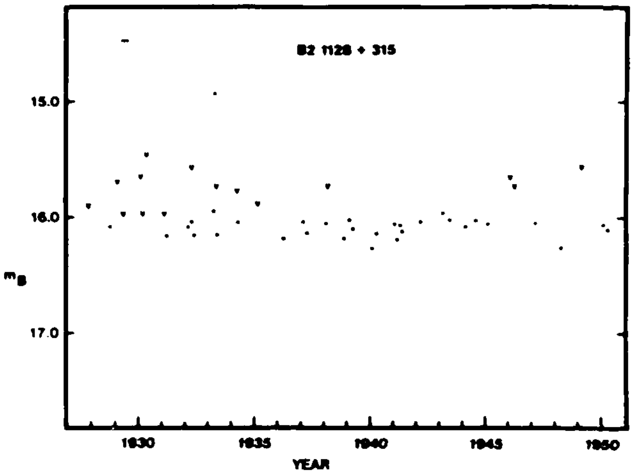

FIGURE 2. — The light curve of B2 1128 + 315 from 1928 to 1952 determined from plates in the archive collection of the Harvard College Observatory. The symbol « v » indicates the plate limit when the object was too faint to be detected.

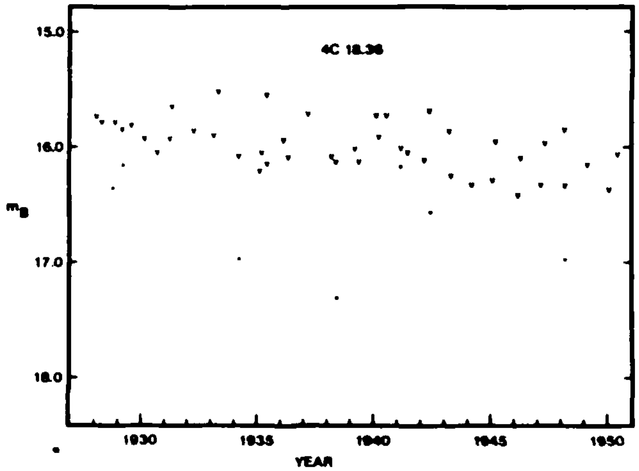

FIGURE 3. — The light curve of 4C 18.36 from 1928 to 1952 determined from plates in the archive collection of the Harvard College Observatory. The symbol « v » indicates the plate limit when the object was too faint to be detected.

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THE VARIABILITY OF THE SPECTRUM OF ARAKELIAN 120

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ABSTRACT

New spectroscopic and photometric observations of the variable Seyfert 1 galaxy Arakelian 120 are presented. These data are supplemented with published data from other sources. It is shown that Akn 120 exhibits both short-term and long-term variability, as do other Seyfert galaxies. The flux in the broad $H\beta$ emission line closely follows the optical continuum flux, which provides strong support for photoionization models and implies that the broad-line emitting region is very small (less than ~0.04 pc in extent).

I. INTRODUCTION

The Seyfert 1 galaxy Akn 120 was first identified in a search for high surface brightness galaxies (Arakelian 1975). It has been recognized as a highly variable source almost since its identification as an active galaxy (Lyutyi 1976). Miller (1979a) has examined the archive plates of the Harvard College Observatory and has determined that Akn 120 varies over a range $\Delta B > 2.1$ mag.

Moderate resolution optical spectroscopy has revealed that the permitted-line spectrum changes with time (Foltz *et al.* 1981; Kollatschny *et al.* 1981; Schulz and Rafanelli 1981). This is not surprising if the broad-line emitting region responds fairly rapidly to changes in the output of the nonthermal continuum source, which is presumably the principal source of ionizing radiation, and if the light-travel time across the broad-line region is less than the characteristic time scale for variability of the continuum source. Indeed, in general permitted line fluxes do seem to be correlated with changes in the continuum flux (Cherepashchuk and Lyutyi 1973; Peterson *et al.* 1982).

The response of the broad-line components of the emission lines in active galaxy spectra is of great interest for several reasons: (1) A close correlation between emission line and continuum fluxes argues very strongly that the emission-line region is photoionized. (2) The time scale for response of the emission lines to changes in the continuum flux sets significant limits on the size of the line-emitting region. (3) In principle, the temporal development of the changes in the broad emission lines can be used to determine the velocity field in the broad-line emitting region.

For a number of reasons, Akn 120 is an excellent candidate for a detailed study of spectral variability:

(1) Large amplitude changes in the brightness of the continuum source occur on a short time scale (less than several tens of days).

(2) Even at minimum brightness, Akn 120 is bright enough to be accessible to telescopes of modest aperture.

(3) The underlying (or host) galaxy is comparatively faint and the line-emitting regions are unresolved (Whittle 1982) so aperture effects should be negligible (Peterson and Collins 1983).

(4) The permitted lines are particularly broad (full width at zero intensity greater than ~1.0–1.5×10^4 km s^{-1}), so that some of the details of the line structure can be observed even at rather low resolution.

(5) It will be shown here that the broad emission lines respond rapidly to changes in the continuum flux, so it may be possible to determine the velocity field of the broad-line emitting region from a series of high-quality observations obtained in a single observing season.

In this contribution, new photometric and spectroscopic observations of Akn 120 are presented. These data, together with other observations taken from the literature, show that Akn 120 exhibits both long-term and short-term variability. The observations are found to be consistent with a very small (less than ~0.04 pc) broad-line emitting region which is photoionized by a variable continuum source which dominates the brightness of the galaxy.

TABLE I. New *UBV* measurements.

UT date (1)	Julian date (2440000 +) (2)	Telescope (3)	Aperture (arcsec) (4)	V (5)	$B-V$ (6)	$U-B$ (7)
1979 Apr 4	3967	0.91-m	15.5	13.52	0.42	− 0.76
1979 Sep 13	4129	0.91-m	15.5	14.04	0.57	− 0.74
1979 Nov 11	4188	1.3-m	14.2	13.79	0.38	− 0.82
1979 Nov 14	4191	1.3-m	14.2	13.63	0.39	− 0.79
1980 Jan 17	4255	0.91-m	15.5	13.69	0.37	− 0.75
1980 Feb 23	4292	1.3-m	14.2	13.18	0.38	− 0.83
1981 Mar 30	4693	1.3-m	14.2	13.21	0.44	− 0.76
1981 Sep 21	4868	0.91-m	15.5	13.55	0.37	− 0.75
1981 Sep 24	4871	0.91-m	15.5	13.59	0.40	− 0.72
1981 Sep 26	4873	0.91-m	15.5	13.54	0.42	− 0.72
1981 Nov 19	4927	1.3-m	14.2	13.49	0.39	− 0.80
1982 Apr 18	5077	1.3-m	14.2	13.66	0.35	− 0.79

II. PHOTOMETRY OF AKN 120

a) New Measurements

Photoelectric photometry was obtained on several occasions with the 1.3-m and 0.91-m telescopes at Kitt Peak National Observatory.* The Mark II photometer was used for observations on the 1.3-m telescope and the Automated Filter Photometer was used on the 0.91-m telescope. A 1P21 photomultiplier and standard *UBV* filters were employed in all cases. Instrumental calibrations are based on Miller's (1981) photoelectric sequence in the field of Akn 120. Integration times in each filter were sufficiently long that the fractional error $\sigma = [(\text{galaxy} + \text{sky}) + (\text{sky})]^{1/2}/[(\text{galaxy} + \text{sky}) - (\text{sky})]$ was less than 0.01.

Measurements obtained on 12 nights are given in Table I. The UT date of observation is given in column (1) and the Julian data is given in column (2). The telescope employed is given in column (3) and the projected diameter of the entrance aperture is listed in column (4). The measured values of V, $B-V$, and $U-B$ are given in columns (5), (6), and (7), respectively. No corrections for galactic extinction have been applied.

b) Photometry from Other Sources

In addition to the new measurements reported above, *UBV* measurements from other sources have been collected. These are listed in Table II. Column (1) gives the Julian data of observation. The projected diameter of the aperture through which the observations were made is given in column (2). The measured values of V, $B-V$, and $U-B$ are listed in columns (3), (4), and (5), respectively. The source from which the measurements are drawn is indicated in column (6).

In the cases where the measurements were made through relatively large apertures, a small correction for the effect of the underlying galaxy has been applied. The correction is derived from multiaperture observations of Lyutyi (1976, 1979). On the basis of Lyutyi's measurements through apertures 13.5 and 27 arcsec in diameter made on nine different nights, it is found that the contribution of the underlying galaxy is $V = 15.80 \pm 0.35$ mag, $B = 16.65 \pm 0.59$ mag, and $U = 16.37 \pm 1.77$ mag in the annulus bounded by the apertures. This contribution, which is assumed to be constant as the active nucleus changes, is subtracted from the 27-arcsec aperture measurements of Lyutyi (1976, 1979) and from the 25-arcsec aperture measurements of Dibai, Doroshenko, and Terebizh (1978), and Doroshenko and Terebizh (1981). In each case, the correction applied to the large aperture measurement is small (less than 0.25 mag in V, less than 0.20 mag in B, and less than 0.15 mag in U), since the brightness of the active nucleus overwhelms the brightness of the outer parts of the galaxy.

Measurements from more than one source are available for only four nights, and unfortunately the measurements are not in good agreement, particularly in the U bandpass. In some cases, the differences may be attributable in part to the use of different apertures. It is suspected, however, that the differences are due primarily to slight differences in the transmission curves of the nominally identical filters used by different observers. Clearly this is a strong possibility in U for those measurements in which the atmospheric cutoff defines the short-wavelength limit of the bandpass. In the case of the V and B filters, minor variations in the filter transmission in the vicinity of 5000 Å, where both filters transmit more than ~30% of the incident light, can have a pronounced effect on the flux measurements because of the presence of the strong (equivalent width ≃100 Å) redshifted Hβ line. Broadband photometric measurements of emission-line objects are always suspect because of such systematic effects and therefore comparison of data obtained with different systems must be viewed with great caution; it is assumed, however, that the data from individual sources are internally consistent.

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*Kitt Peak National Observatory is operated by the Association of Universities for Research in Astronomy under contract with the National Science Foundation.

TABLE II. *UBV* measurements from other sources.

Julian date (2440000 +) (1)	Aperture (arcsec) (2)	V (3)	$B-V$ (4)	$U-B$ (5)	Source[a] (6)	Aperture correction made (7)
2392	27	13.45	0.40	− 1.04	1	*x*
2396	13.5	13.54	0.35	− 0.98	1	
2415	27	13.63	0.29	− 1.03	1	*x*
2476	13.5	13.73	0.35	− 1.11	1	
2685	13.5	14.06	0.53	− 0.79	1	
2689	13.5	14.05	0.55	− 0.80	1	
2718	13.5	14.05	0.53	− 0.95	1	
2723	13.5	13.96	0.60	− 0.92	1	
2745	13.5	14.03	0.53	− 0.99	1	
2813	13.5	14.02	0.54	− 0.80	1	
2870	13.5	14.00	0.65	—	1	
3079	13.5	14.13	0.57	− 0.85:	1	
3110	25	14.02	0.64	− 0.74	2	*x*
3112	25	14.10	0.60	− 0.58	2	*x*
3131	25	14.27	0.51	− 0.62	2	*x*
3131	13.5	14.11	0.64	− 0.78	1	
3131	25	14.30	0.55	− 0.50	2	*x*
3159	25	14.16	0.51	− 0.48	2	*x*
3159	13.5	14.05	0.56	− 0.75	1	
3164	10	14.42	0.39	− 0.45	2	
3164	13.5	14.01	0.62	− 0.71	1	
3167	10	14.48	0.48	—	2	
3426	13.8	13.63	0.56	− 0.77	3	
3427	13.8	13.64	0.56	− 0.80	3	
3429	13.8	13.65	0.53	− 0.75	3	
3490	18	13.92	0.38	− 0.77	4	
3496	10	13.88	0.54	− 0.97	1	
3509	18	13.91	0.47	− 0.83	4	
3571	10	13.79	0.37	− 0.57:	1	
3571	15.6	13.33	0.57	− 0.74	3	
3573	10	13.73	0.41	− 0.88	1	
3775	14.2	13.86	0.66	− 0.78	3	
3776	14.2	13.86	0.65	− 0.78	3	
3778	14.2	13.88	0.66	− 0.77	3	
3967	15.5	13.52	0.42	− 0.76	3	
4226	25	13.72	0.29	− 0.53	5	*x*

[a] Sources: (1) Lyutyi (1976, 1979); (2) Dibai, Doroshenko, and Terebizh (1978); (3) Miller (1979b); (4) Puschell (1978), (5) Doroshenko and Terebizh (1981)

c) *Results*

The *V*, *B*, and *U* measurements listed in Tables I and II are plotted as a function of Julian date in Fig. 1. If the measurements from each source are indeed internally consistent, then it is clear that short time scale (tens of days) variations occur. Even if there are significant systematic differences among the various sources, it is still apparent that long-term variations (i.e., over a time scale of several years) also occur. This result is not particularly surprising since variability on multiple time scales has been reported for other Seyfert galaxies (Lyutyi 1977; Lyutyi and Oknyanski 1981).

The $B-V$ and $U-B$ color indices are plotted as a function of Julian data in Fig. 2. Despite the apparently large systematic errors in these data, it is nevertheless clear that Akn 120 is about 0.1–0.2 mag redder in $B-V$ when the active nucleus is particularly faint than it is at other times (see Fig. 1). The color difference is consistent with the relative contribution of the underlying galaxy (which is assumed to be a normal spiral) becoming more pronounced as the active nucleus decreases in brightness. The $U-B$ index is probably more strongly affected by systematic errors, but qualitatively these data show the same behavior as the $B-V$ data. It therefore does not appear to be necessary to require a change in the power-law index of the nonthermal continuum source as the brightness varies in order to account for the changes in the broadband color indices.

III. SPECTROSCOPIC OBSERVATIONS OF AKN 120

a) *IDS and Reticon Observations*

Scans of the spectral region around Hβ have been made on several occasions since the end of 1980. Our first few observations revealed that the Hβ profile had undergone a dramatic change since the November 1976 observations by Osterbrock and Phillips (1977) and the decrease in the equivalent widths of the [O III] $\lambda\lambda$ 4959, 5007 lines implies that the optical continuum flux had increased by a factor of about 4 (Foltz *et al.* 1981). These

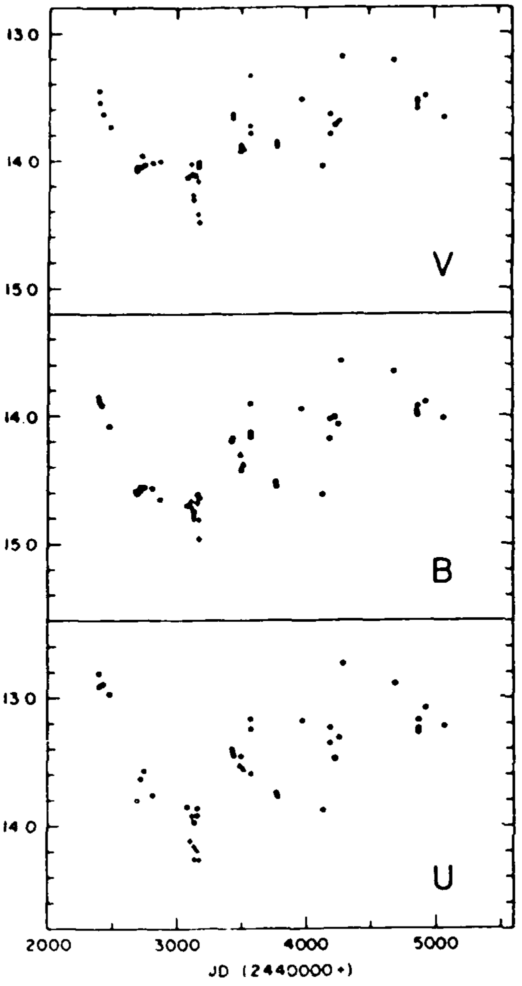

FIG. 1. *V*, *B*, and *U* magnitudes of Akn 120 are shown as a function of Julian date. Open circles are from Lyutyi (1976, 1979); crosses are from Dibai, Doroshenko, and Terebizh (1978); closed squares are from Doroshenko and Terebizh (1981); closed triangles are from Puschell (1978); closed circles are from Miller (1979b) and this work.

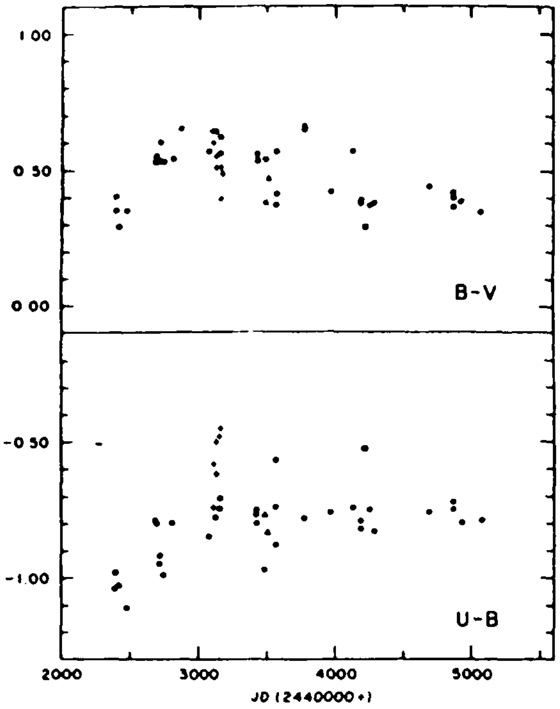

FIG. 2. The $B-V$ and $U-B$ color indices are shown as a function of Julian date. Symbols are defined in Fig. 1.

spectral changes were concurrently discovered by Kollatschny *et al.* (1981) and by Schulz and Rafanelli (1981). Monitoring of the spectrum has been continued in order to determine more about the response of the broad-line emitting region to changes in the continuum source.

Most of the new observations reported here were obtained with the Ohio State University image-dissector scanner (IDS; Byard *et al.* 1981) on the Perkins 1.8-m reflector of Ohio Wesleyan University and Ohio State University at Lowell Observatory. Three additional spectra were obtained with the Boller and Chivens spectrograph equipped with a photon-counting Reticon detector on the Steward Observatory 2.3-m telescope on Kitt Peak. Both detectors are dual-channel devices, allowing simultaneous observations of the night sky spectrum which is then subtracted from the galaxy spectrum. Standard stars were observed to determine the wavelength-dependent sensitivity of the detectors; accurate spectrophotometry was not attempted, however, since in several cases the aperture size is approximately the size of the seeing disk and since some of the observations were made under conditions of variable transparency. It should be noted, however, that aperture effects should be negligible in the case of Akn 120 because the line-emitting regions are unresolved (Whittle 1981), and the brightness of the active nucleus dominates the light from the galaxy even through large apertures (cf. Peterson and Collins 1983).

The appearance of the spectrum in October 1982 is shown in Fig. 3. The two strong features on either side of Hβ are the Fe II λ 4570 and Fe II $\lambda\lambda$ 5190, 5320 blends. The Hβ line appears to be asymmetric, with a broad low shelf on the red wing; this shelf is probably due to Fe II λ 4924 and Fe II λ 5018 rather than to excess Hβ emission at large relative redshift (Osterbrock and Shuder 1982). No attempt is made to subtract the possible contribution of Fe$^+$ emission from the Hβ line, though the weak, unidentified line at ~5050 Å (rest) has been excluded.

The [O III] $\lambda\lambda$ 4959, 5007 lines are superposed on the broad red wing of the Hβ feature. The flux in these lines is measured by interpolating the Hβ profile underneath each of these emission features with a straight line and

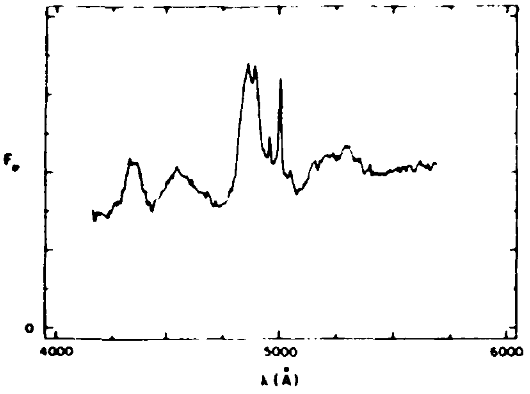

FIG. 3. An average of five scans of Akn 120 obtained over a two-week period in 1982 October with the Ohio State University IDS. These data represent a total integration time of approximately 7.5 hours. The data are plotted in relative energy units per unit frequency interval (energy s^{-1} cm^{-2} Hz^{-1}) *in the rest frame of Akn 120.*

then measuring the total flux above the interpolated profile. The flux and equivalent width of the Hβ feature are measured by identifying the lowest points of the depressions between the Fe II λ 4570 blend and Hβ and between Hβ and the Fe II λλ 5190, 5320 blend as continuum and interpolating between those points with a straight line. The total flux above this interpolated continuum, except for the flux in the [O III] lines, is then measured. While the true featureless continuum may lie below this level, it is found that in those observations which cover a large spectral range, this interpolated continuum (which corresponds to a power law) also intersects the lowest points in the spectrum shortward of Hγ, between Hγ and Fe II λ 4570, and longward of Fe II λλ 5190, 5320; it is therefore believed that this interpolation provides an adequate and repeatable representation of the continuum.

Relative line strengths (i.e., *F*(*H*β) = 1) and equivalent widths are given in Table III. Column (1) contains the UT date of observation and the Julian date is given in column (2). The telescope and instrument used are listed in columns (3) and (4), respectively. The projected size of the entrance aperture is given in column (5), and the aperture geometry is also noted. The equivalent width of the Hβ feature in the rest frame of Akn 120 ($z = 0.0325$, as determined from the centroids of the [O III] λλ 4959, 5007 lines) is given in column (6). The fluxes of [O III] λλ 4959 and [O III] λ 5007 relative to the Hβ flux are given in columns (7) and (8).

The IDS data obtained on 1981 January 11 and 1981 March 9 have been previously published (Foltz *et al.* 1981) and the Hβ line profiles from these nights and from 1980 November 9 are shown by Capriotti, Foltz, and Peterson (1982). The line strengths and equivalent widths have been remeasured choosing a continuum as described above and the values given here differ only slightly from those reported by Foltz *et al.*

b) Spectroscopic Observations from Other Sources

Spectroscopic observations of Akn 120 have also been published by other investigators. These measurements are listed in Table IV. The date or dates of observation are given as UT dates and Julian dates in columns (1) and (2), respectively. *The rest-frame equivalent width of* Hβ and the relative strengths of [O III] λλ 4959 and [O III] λ 5007 are given in columns (3)–(5), and the published reference is noted in column (6).

The data reported by Dibai, Doroshenko, and Terebizh (1978) are based on 24 image-tube spectrograms obtained during December 1973 and November–De-

TABLE III. New spectroscopic measurements.

UT date (1)	Julian date (2440000 +) (2)	Telescope (3)	Instrument (4)	Aperture (5)	$W_0(H\beta)$ (Å) (6)	$\frac{F([O\,III]\lambda\,4959)}{F(H\beta)}$ (7)	$\frac{F([O\,III]\lambda\,5007)}{F(H\beta)}$ (8)
1980 Nov 9	4552	Perkins 1.8-m	IDS	3″-square	94	0.041	0.122
1981 Jan 10	4614	1.8-m	IDS	3″-square	89	0.025	0.089
1981 Jan 11	4615	1.8-m	IDS	3″-square	86	0.017	0.084
1981 Mar 9	4672	1.8-m	IDS	3″-square	88	0.017	0.059
1981 Dec 29	4967	Steward 2.3-m	Reticon	2.5″-round	70	0.024	0.102
1982 Feb 22	5022	2.3-m	Reticon	2.5″-round	76	0.020	0.066
1982 Mar 28	5056	1.8-m	IDS	3″-square	118	0.020	0.056
1982 Aug 27	5208	1.8-m	IDS	7.5″-round	121	0.019	0.050
1982 Sep 19	5231	1.8-m	IDS	7.5″-round	110	0.024	0.072
1982 Oct 9	5251	1.8-m	IDS	3.5″-round	135	0.012	0.088
1982 Oct 10	5252	1.8-m	IDS	3.5″-round	129	0.023	0.097
1982 Oct 15	5257	1.8-m	IDS	3.5″-round	138	0.022	0.085
1982 Oct 19	5261	1.8-m	IDS	3.5″-round	127	0.030	0.099
1982 Oct 23	5265	1.8-m	IDS	3.5″-round	141	0.012	0.075
1982 Dec 27	5330	2.3-m	Reticon	2.5″-round	110	0.030	0.083

TABLE IV Spectroscopic measurements from other sources

UT date (1)	(2440000 +) (2)	$W_\lambda(\mathrm{H}\beta)$ (3)	$\frac{F([\mathrm{O\,III}]\lambda 4959)}{F(\mathrm{H}\beta)}$ (4)	$\frac{F([\mathrm{O\,III}]\lambda 5007)}{F(\mathrm{H}\beta)}$ (5)	Source* (6)
1974 Dec–1975 Dec	2382–2777	57	0.07	0.18	1
1976 Nov 22	3104	190	0.035	0.11	2
1979 Oct 22	4168	...	0.038	0.115	3
1980 Mar 11–15	4309–4313	112	0.043	0.12	4
1980 Nov 2	4545	...	0.054	0.161	3

*(1) Dibai, Doroshenko, and Terebizh (1978); (2) Osterbrock and Phillips (1977); (3) Kollatschny *et al.* (1981); (4) Schulz and Rafanelli (1981).

cember 1975. These authors claim that no significant spectral variations were detected during this time.

The equivalent width of Hβ is not given by Kollatschny *et al.* (1981) for either of their observations (these authors do, however, quote absolute flux measurements).

IV. ANALYSIS OF SPECTRAL VARIATIONS

a) Line Measurements and Internal Errors

In general, no attempt has been made to obtain accurate spectrophotometric observations of Akn 120. However, it is possible to determine the behavior of the optical continuum if it is assumed that the flux in the [O III] λλ 4959, 5007 lines is constant over several years. The low-density narrow-line emitting region is thought to be of order 100 pc in diameter (Walker 1968; Osterbrock 1978), and thus changes in the continuum flux will only affect the narrow-line region on a long time scale (Capriotti and Foltz 1982); it is therefore reasonable to assume, as a first approximation, that the forbidden line fluxes are constant over the time scales of interest here. This assumption is used frequently (Phillips 1978; Osterbrock and Shuder 1982; Peterson *et al.* 1982).

The forbidden O^{++} lines lie on the red wing of the Hβ feature, but the equivalent widths of these lines must be referred to the featureless continuum. A calculated [O III] λλ 4959, 5007 equivalent width,

$$W_c([\mathrm{O\,III}]) = W_0(\mathrm{H}\beta)\,\frac{F([\mathrm{O\,III}]\lambda 4959 + F([\mathrm{O\,III}]\lambda 5007)}{F(\mathrm{H}\beta)}$$

is therefore used (Peterson *et al.* 1982). Values of W_c([O III]) are given in Table V for all observations in Tables III and IV, except for the data obtained by Kollatschny *et al.* (1981), since no equivalent width measurements are available.

If it is assumed that the [O III] λλ 4959, 5007 flux is constant, then changes in the strength of these lines relative to Hβ indicate changes in the Hβ flux. The sum of the independent flux measurements of [O III] λλ 4959 and [O III] λ 5007 (hereafter referred to as F([O III]) is used to improve the statistical accuracy.

An estimate of the magnitude of the internal errors can be made by examining the five spectra obtained within a two-week period in October 1982. Random errors can be estimated by assuming that no real changes in the spectrum occurred during this period; since real changes may indeed occur on a time scale of two weeks, the error estimates derived in this way may be too large. The October data indicate that the continuum is measured consistently to within ~11% (rms) and the Hβ flux is measured to within ~16%. Measurement errors due to uncertain continuum placement have been estimated by repeated measurement of individual spectra by different observers, and these errors are smaller. For example, the F([O III])/F(Hβ) ratio is measured consistently to better than ~4%–11% and the Hβ equivalent width is repeatable to better than ~7%; this implies that the errors determined from data taken on different nights are not *too* large an overestimate of the internal errors.

An additional consistency check is provided by the fact that both the IDS and the Reticon scanner are dual-channel devices. Thus, each observation provides two independent scans, which are reduced separately and treated as independent data until the last step in which the two flux-calibrated scans are averaged. Measurements of the equivalent widths and line strengths in the separate scans are found to be identical to within the measurement errors quoted above.

TABLE V Calculated [O III] λλ 4959, 5007 equivalent widths.

Julian date (24440000 +)	W_c([O III])	Julian date (24440000 +)	W_c([O III])
2382–2777	14.2	5056	6.57
		5208	8.35
3104	27.6	5231	10.6
4309–4313	18.2	5251	13.5
4552	15.3	5252	15.4
4614	10.1	5257	14.7
4615	8.70	5261	16.3
4672	6.69	5265	12.3
4967	8.78	5330	12.4
5022	6.54		

The internal errors derived from the October 1982 data are probably appropriate for all of the new data presented here. Although Akn 120 was relatively faint at this time, the integration times were long (typically ~6000 s).

b) Results

The continuum brightness as determined from the calculated [O III] equivalent width W_c([O III]) and expressed in magnitudes relative to the November 1976 data of Osterbrock and Phillips (1977) is plotted as a function of Julian date in Fig. 4. Comparison of these data with the photometric data in Fig. 1 reveals that long-term trends seem to be reproduced—this gives us a great deal of confidence both in our assumption that the [O III] $\lambda\lambda$ 4959, 5007 flux is constant over several years and in the integrity of our reduction and measurement procedures.

In Fig. 5, the Hβ flux expressed in magnitudes relative to the [O III] flux is shown as a function of Julian date. These data show basically the same trends as the photoelectric photometry and the continuum measurements from the spectra, particularly in the later data. The earliest spectroscopic data shown here (Dibai, Doroshenko, and Terebizh 1978) do not seem to fit the general pattern at all, but these data are suspect in this context as they represent the average values determined over thirteen months of observation. The Hβ flux at the time the galaxy was observed by Osterbrock and Phillips (1977) seems inordinately high compared to the continuum magnitude determined from the same data, but this can be explained by the fact that the continuum rather suddenly decreased in brightness at about the time the Lick observations were made (see Fig. 1). The relatively high flux in Hβ is presumably because the decrease in the continuum had not been communicated to the entire broad-line emitting region when the Lick observations were made. This probably explains the extraordinarily large Hβ equivalent width which, if temporal variations are ignored, is apparently inconsistent with photoionization by a simple power-law spectrum (Puschell 1978). The inclusion of the Fe II $\lambda\lambda$ 4924 and Fe II λ 5018 flux in the Hβ measurement also probably contributes to the large value of the Hβ equivalent width.

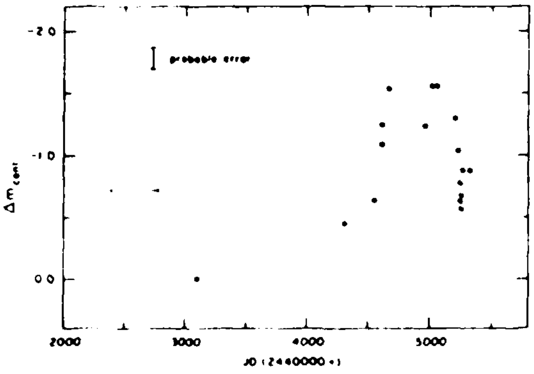

FIG. 4. Continuum magnitudes, as determined from the equivalent widths of [O III] $\lambda\lambda$ 4959, 5007 and referred to the Osterbrock and Phillips (1977) observations, are plotted as a function of Julian date. The probable error shown is derived from the October 1982 data, as explained in the text. The closed circles represent new data presented in this paper, the closed square is from Schulz and Rafanelli (1981), the open circle is from Osterbrock and Phillips (1977), and the horizontal bar represents the average value given by Dibai, Doroshenko, and Terebizh (1978).

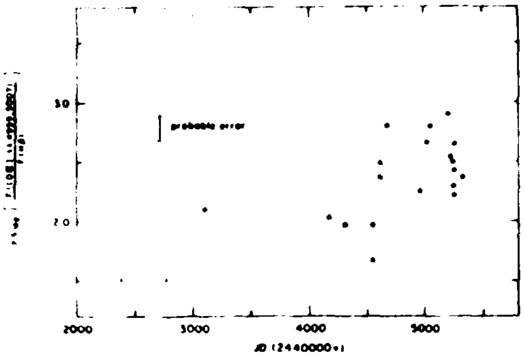

FIG. 5. The flux in the Hβ line is plotted in magnitudes, referred to the [O III] $\lambda\lambda$ 4959, 5007 flux, as a function of Julian date. The probable error is determined from the October 1982 observations (see text). The closed triangles represent data from Kollatschny *et al.* (1981); the other symbols are as defined in Fig. 4.

It is possible to obtain an estimate of the size of the broad-line emitting region by comparing the line measurements plotted in Fig. 5 with the continuum measurements plotted in Fig. 4. However, a longer temporal baseline is necessary for an accurate determination of the delay between continuum and emission line changes. It is nevertheless clear that the broad-line emitting region responds very rapidly to changes in the continuum level, and an upper limit $r < 50$ light days (~0.04 pc) seems consistent with all of the data (compare this to Miller's [1979b] upper limit of 0.02 pc for the size of the continuum source). On the basis of similar considerations, Cherepashchuk and Lyutyi (1973) derive sizes of 15–30 light days for the line-emitting regions in NGC 4151, 3516, and 1068, and it would not come as a surprise if future data reduce our upper limit of ~50 light days by a factor of 2 or more.

The amplitude of the Hβ variations (>1.3 mag) is close to the amplitude of the continuum variations (~1.8 mag) detected over the same time interval. This is indeed strong evidence that energy input to the broad-line emitting region is via photoionization. The amplitude of the line variations is expected to be smaller than the amplitude of the continuum variations unless the time scale for continuum changes greatly exceeds the light-travel time across the line-emitting region.

Finally, it is noted that while detailed profile information is generally not available, there are two peaks in the

Hβ profile located at approximately $+1800$ km s^{-1} and -1300 km s^{-1} relative to the rest system defined by the [O III] lines. These peaks are apparently stationary in wavelength, though their relative strength changes with time. This does not appear to be consistent with the ballistic outflow model (Capriotti, Foltz, and Peterson 1982), and our preliminary conclusion is that this particular model does not apply in this case.

V. SUMMARY

On the basis of the new spectroscopic and photometric measurements presented here and other measurements from published sources, several conclusions can be made:

(1) The optical continuum flux, as determined from the equivalent widths of the [O III] $\lambda\lambda$ 4959, 5007 lines, shows variations which appear to be consistent with the flux variations determined from broadband photometry. This supports our assumption that the forbidden-line fluxes are constant over several years and that those lines may be used as a flux benchmark in spectroscopic variability studies.

(2) Akn 120 exhibits both short and long time scale variability, as do other Seyfert galaxies (Lyutyi 1977; Lyutyi and Oknyanski 1981).

(3) The flux in the broad Hβ line varies with the optical continuum flux. The amplitude of the Hβ variations is only somewhat smaller than the amplitude of the continuum variations. This argues very strongly in support of photoionization of the broad-line emitting region by the continuum source.

(4) Changes in the Hβ flux closely follow changes in the optical continuum. The existing data are insufficient for an accurate determination of the delay between continuum and broad-line changes, but it is estimated that the delay is less than ~ 50 days, indicating that the size of broad-line emitting region is less than 0.04 pc.

(5) While the broadband photometric measurements are plagued by systematic effects, it is nevertheless clear that the continuum of Akn 120 is redder at minimum light. The changes in the broadband colors are attributable to the contribution of the underlying galaxy, and it does not appear to be necessary to require a change in the spectral index of the nonthermal source as the brightness of the source changes.

(6) Data obtained thus far are insufficient for determination of the velocity field in the broad-line emitting region. However, the fact that the two prominent peaks in the Hβ line are stationary in wavelength on a time scale much longer than the light-travel time across the broad-line region argues against the specific ballistic outflow model discussed by Capriotti, Foltz, and Peterson (1982).

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PHOTOELECTRIC COMPARISON SEQUENCES IN THE FIELDS OF FOUR BL LACERTAE OBJECTS[a]

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ABSTRACT

Photoelectric comparison sequences in the fields of four previously identified BL Lacertae objects have been calibrated in order to encourage long-term photometric studies of these objects.

I. INTRODUCTION

Rapid and large amplitude optical variability has long been established as a property of the BL Lacertae class of objects (Stein, O'Dell, and Strittmatter 1976). The optical variability is a property which has important implications for the physical nature of the nonthermal energy source associated with these objects. Thus, in order to encourage long-term monitoring and to photometrically calibrate speckle interferometric observations of these objects, photoelectric comparison sequences have been established in the fields near four of these objects.

The optical counterpart of the radio source 0109 + 22 was identified by Owen and Mufson (1977). Wills and Wills (1979) classified this object as a BL Lacertae object on the basis of the presence of a featureless optical spectrum. A search of archival plates at the Harvard College Observatory (Pica 1977) showed that this object has a total range of more than 3 mag. Recent photographic monitoring of this object (Pica *et al.* 1980) has demonstrated that this object is variable but with a range of less than 1.0 mag.

Kinman (1976) classified the radio source OF 038 (0422 + 004) as a BL Lacertae object. Eachus and Liller (private communication) examined archival plates at the Harvard College Observatory and found that this object has a range in excess of 3.0 mag. Recent photographic monitoring of this object (Pica *et al.* 1980) has shown that it has exhibited a range of approximately 2.0 mag since late 1976.

The BL Lacertae objects OI 090.4 and OJ-131 were identified by Tapia *et al.* (1977) on the basis of the presence of a high percentage of linear polarization in their optical flux. A search of archival plates at the Harvard College Observatory (Baumert 1980) demonstrated that both of these objects exhibit significant optical variability with time scales ranging from a few days to several decades.

Table I contains a list of the four BL Lacertae objects and their 1950.0 equatorial coordinates.

II. OBSERVATIONS

The photoelectric photometry was obtained at Kitt Peak National Observatory using the 0.9-m telescope and the 1.3-m telescope. The automated filter photometer equipped with a refrigerated 1P21 photomultiplier tube was used with all of the observations obtained with the 0.9-m telescope. This system uses a standard *UBV* filter set with a pulse counting system.

The Mark 2 computer photometer equipped with a 1P21 photomultiplier and standard *UBV* filters was used in the sky chopping mode for all observations obtained with the 1.3-m telescope. The extinction was determined each night, and the transformation to the standard *UBV* system was made using the equatorial standard stars of Landolt (1973). The standard error for each observation of each star in each color is <0.01 mag, except when the tabulated value in Table II is followed by a colon. If this is the case, then the standard error is <0.03 mag.

III. RESULTS

The comparison stars which were measured in the fields of these BL Lacertae objects are listed in Table II. Column 1 lists the star designation; column 2, the V magnitude; column 3, the $B-V$ color index; and column 4, the $U-B$ color index. The finding charts for the comparison sequences appear in Fig. 1. These charts were taken from the O prints of the Palomar Sky Survey. The sequence stars were chosen solely to provide an adequate range in brightness without regard to color. The

TABLE I. Equatorial coordinates for the BL Lacertae objects for which photoelectric sequences were determined.

Source	R.A. (1950.0)	Dec. (1950.0)
0109 + 22	$01^h\,09^m\,24^s0$	$+22^\circ\,28'\,44''5$
OF 038	$04^h\,22^m\,12^s9$	$+00^\circ\,29'\,00''0$
OI 090.4	$07^h\,54^m\,22^s6$	$+10^\circ\,04'\,38''7$
OJ − 131	$08^h\,18^m\,36^s2$	$-12^\circ\,49'\,24''9$

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[a] Astronomical Contribution of Georgia State University, No. 68.

[b] Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under contract with the National Science Foundation.

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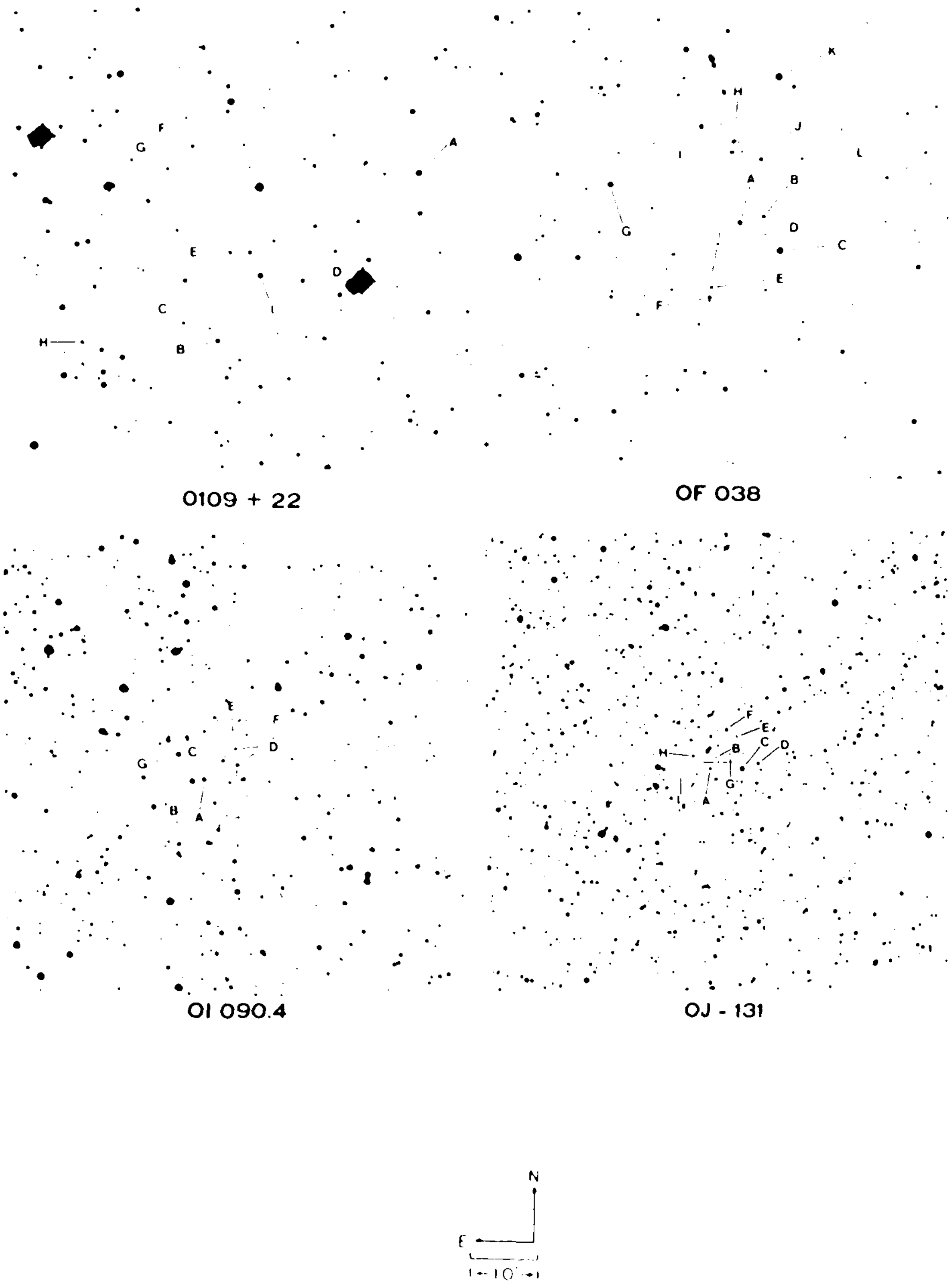
0109 + 22

OF 038

OI 090.4

OJ - 131

FIG. 1. Finding charts for the comparison sequences in the fields of the BL Lacertae objects. North is up and east is to the left. All charts are enlargements of the O prints of the National Geographic Society-Palomar Observatory Sky Survey.

TABLE II. Standard stars in the fields of BL Lacertae objects.

Star	V	$B-V$	$U-B$
		0109 + 22	
A	11.58	0.56	0.08
B	13.37	0.67	0.14
C	14.15	0.75	0.13
D	14.26	0.81	0.41
E	15.14	0.62	0.02
F	15.47	0.55	0.03
G	15.75	0.57	0.03
H	15.74	0.87	0.74:
I	12.37	0.74	0.20
		OF 038	
A	12.51	0.68	0.12
B	13.96	0.62	0.13
C	11.16	0.54	0.07
E	15.05	0.65	0.09
F	14.75	0.70	0.08
G	11.84	0.62	0.12
H	13.50	0.49	0.04
		OI 090.4	
A	14.44	0.49	0.06
B	12.96	0.63	0.09
C	14.71	0.81	0.45
D	15.87	0.49	0.08
F	15.91	0.74	0.14
G	13.21	0.67	0.32
		OJ-131	
A	15.43	0.59	0.31
C	12.12	0.68	0.30
D	14.31	0.38	0.05
E	16.68	0.48	...
F	14.19	0.65	0.13
H	15.61	0.53	0.25
I	16.89	1.05	...

sequence stars designated "A" and "B" in the field of OF 038 have also been observed by Kinman (private communication). Our observations of these two stars are in excellent agreement with his values for these stars which are: for star A: $V = 12.51$, $B - V = 0.66$, $U - B = +0.12$, and for star B: $V = 13.97$, $B - V = 0.64$, $U - B = 0.11$.

The author is grateful to Kitt Peak National Observatory for observing time. The author is also grateful to Dr. T. D. Kinman for communicating results prior to publication. This work was supported in part by grants from the Research Corporation, the Dean's Research Fund at Georgia State University, and the United States Air Force Office of Scientific Research, Grant 81-0161.

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SPECKLE INTERFEROMETRIC MEASUREMENTS OF BINARY STARS. IX.[1]

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ABSTRACT

Four hundred forty measurements of 232 binary stars observed during 1981 by means of speckle interferometry with the 4 m telescope at KPNO are represented. Newly resolved systems include ξ^1 Cet, ρ Her A, HD 187321, and 59 Cyg A.

Subject headings: interferometry — stars: binaries — stars: visual multiples

This paper continues the series presenting the results from a program of binary star speckle interferometry based upon observations made at Kitt Peak National Observatory. The previous papers of this series have presented 2033 measurements of binary stars including the first direct resolution of 76 systems.

The observations presented in Table 1 were obtained during 1981 at the 4 m Mayall telescope with the photographic speckle camera described by Breckinridge, McAlister, and Robinson (1979). The 1111 sets of observations which were accumulated for this paper represent nearly 56,000 individual 35 mm Tri-X frames and were reduced to two-dimensional spatial frequency power spectra and autocorrelations in the same manner as in Paper VIII (McAlister *et al.* 1983).

Table 1 contains 440 measurements of 232 binary stars with references to notes concerning certain systems. The table also contains the first direct measurements of the systems ξ^1 Cet, ρ Her A, HD 187321 and 59 Cyg A. The entry for each system in Table 1 normally includes the ADS number, the discovery designation, and the 1900 coordinates on the first line, and the epoch of observation, the position angle in degrees, and the angular separation in arc seconds on subsequent lines. Alternative names are given for non-ADS systems. References to notes are given on the identification lines.

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TABLE I

Binary Star Measures

ADS 61	STF 3062	00010 +5753
81.6981	110°0	1″403
ADS 102	STF 2	00038 +7910
81.6980	24.2	0.633
ADS 148	BU 1026	00069 +5304
81.7035	24.4	0.149
ADS 207	STF 13	00106 +7624
81.6980	56.5	0.908
ADS 434	STT 12	00262 +5358
81.7035	184.6	0.497
HR 132	51 Psc	00272 +0624
81.4629	93.8	0.216
81.4656	93.3	0.216
ADS 490	HO 212 AB	00301 -0409 (1)
81.4629	212.3	0.206
81.4656	213.4	0.200
81.7035	219.7	0.213
ADS 520	BU 395	00322 -2519
81.7035	34.9	0.157
ADS 746	STT 20 AB	00493 +1839
81.7035	217.1	0.460
ADS 755	STF 73 AB	00496 +2305
81.7035	80.0	0.624
ADS 784	BU 1099 AB	00508 +5950
81.7036	306.9	0.200
ADS 836	A 2901	00549 +6849
81.7036	50.[illegible]	0.405
ADS [illegible]	STT 515	01037 +4643
[illegible]	138.1	0.476
[illegible]	BU 303	01042 +2316
[illegible]	290.7	0.652
[illegible]	STF 115 AB	01170 +5737
[illegible]	135.5	0.206
[illegible]	A [illegible] AB	01242 +2219
[illegible]	124.5	0.112
[illegible]	123.4	0.118
ADS [illegible]	BU 870	01377 +5702
[illegible]	5.1	0.922
[illegible]	STF 186	01507 +0121
[illegible]	54.6	1.288
[illegible]	BU 513 AB	01537 +7025
[illegible]	204.0	0.730
ADS 1615	STF 202	01569 +0217
81.7009	283°1	1″923
ADS 1709	STF 228	02076 +4701
81.6981	267.3	1.039
HR 649	ξ^1 Cet	02077 +0823 (2)
81.7010	101.0	0.056
HR 657	COU 79	02100 +2453
81.6981	258.3	0.155
HR 719	KUI 8	02229 +0131
81.7010	32.6	0.511
HR 763	31 Ari	02312 +1200 (3)
81.4656	147.7	0 [illegible]6
81.7010	145.1	0 [illegible]
HR 781	FIN 312	02347 -1218
81.7011	118.1	0.127
HR 788	12 Per	02359 +3946 (4)
81.7010	20.2	0.051
ADS 2200	BU 524 AB	02474 +3756
81.7010	300.5	0.194
ADS 2253	BU 525	02532 +2113
81.6982	256.8	0.489
ADS 2257	STF 333 AB	02535 +2056
81.6982	26.5	1.483
HD 21437	COU 260	03223 +2007
81.7011	21.5	0.233
ADS 7545	STT 208	09453 +5432
81.4619	114.8	0.211
ADS 7780	HU 879	10221 +3713
81.4619	228.2	0.508
ADS 7896	A 2768	10375 +0406
81.4592	171.5	0.193
ADS 8094	STF 1517	11084 +2041
81.4592	328.7	0.424
ADS 8189	STT 234	11254 +4150
81.4619	120.5	0.268
ADS 8197	STT 235	11267 +6138
81.4593	218.6	0.394
ADS 8231	STF 1555 AB	11310 +2820
81.4592	322.8	0.582
ADS 8347	A 1777 AB	11499 +4702
81.4619	142.0	0.121
HR 4689	η Vir Aa	12148 -0007
81.4565	318°6	0″117
81.4620	317.7	0.116
81.4728	318.1	0.117
HR 4789	WRH	12301 +2310
81.4566	10.3	0.350
81.4674	11.1	0.354
ADS 8695	STF 1687 AB	12484 +2147
81.4620	164.5	1.027
81.4728	164.5	1.021
HD 112503	FIN 380	12522 +0850
81.4620	149.8	0.098
81.4728	151.0	0.100
ADS 8759	BU 929	12587 -0308
81.4701	201.6	0.731
HR 4963	θ Vir Aa	13048 -0500
81.4565	325.7	0.492
81.4593	326.4	0.492
81.4728	326.9	0.487
ADS 8804	STF 1728 AB	13051 +1803
81.4566	191.9	0.578
81.4620	192.1	0.581
81.4728	191.8	0.579
ADS 8864	STF 1734	13156 +0328
81.4620	178.3	1.141
ADS 8939	STT 269 AB	13283 +3525
81.4648	237.0	0.168
81.4728	238.6	0.160
ADS 8954	BU 932 AB	13294 -1242
81.4649	48.6	0.334
81.4701	47.0	0.347
ADS 8987	BU 612 AB	13346 +1115
81.4701	193.1	0.256
81.4728	193.6	0.258
HR 5178	KUI 65	13419 -0913
81.4649	63.1	0.352
81.4701	62.5	0.343
ADS 9174	STF 1816	14095 +2934
81.4649	88.4	0.763
81.4702	87.7	0.762
ADS 9182	STF 1819	14103 +0336
81.4675	238.4	0.880
ADS 9247	BU 1111 BC	14185 +0854
81.4566	31.0	0.291
81.4675	30.4	0.293

TABLE 1—*Continued*

ADS 9301	A 570	14279 +2707
81.4676	6°0	0"173
81.4702	6.7	0.175
81.4729	5.3	0.177
ADS 9329	STF 1863	14347 +5201
81.4649	67.8	0.644
81.4676	66.1	0.638
HR 5472	HD 129132	14358 +2224
81.4566	290.1	0.037
81.4675	292.4	0.035
81.4702	289.2	0.037
81.4729	294.6	0.039
ADS 9343	STF 1865 AB	14364 +1409
81.4649	304.5	1.011
81.4675	304.8	0.990
ADS 9378	STT 285	14417 +4248
81.4566	340.4	0.264
81.4702	341.6	0.258
81.4729	340.7	0.259
ADS 9392	STF 1883	14439 +0622
81.4566	294.3	0.400
81.4675	293.7	0.392
ADS 9425	STT 288	14487 +1607
81.4675	171.9	1.406
ADS 9494	STF 1909	15005 +4803
81.4621	36.3	1.058
81.4676	36.2	1.058
81.4729	36.3	1.056
ADS 9532	B 2351 Aa	15066 -1925
81.4702	23.8	0.158
HR 5654	COU 189	15075 +1921
81.4676	145.2	0.469
81.4702	145.1	0.457
ADS 9578	STF 1932	15140 +2712
81.4567	250.6	1.420
ADS 9617	STF 1937 AB	15191 +3039
81.4650	341.9	0.526
81.4676	341.7	0.527
81.4730	341.5	0.531
ADS 9628	HU 149	15219 +5434
81.4650	274.2	0.590
81.4676	272.2	0.585
HR 5747	β CrB	15237 +2927
81.4566	230.6	0.053
81.4676	226.0	0.055
81.4702	226.2	0.054
81.4730	226.5	0.054
ADS 9688	A 1634 AB	15282 +4114
81.4621	344°5	0"036
HR 5778	COU 610	15289 +3142
81.4650	202.6	0.688
81.4729	201.6	0.691
ADS 9716	STT 298 AB	15325 +4008
81.4702	38.7	0.601
ADS 9744	HU 580 AB	15371 +2000
81.4622	70.3	0.202
81.4702	69.0	0.200
ADS 9758	BU 619	15385 +1359
81.4622	2.5	0.694
81.4676	2.7	0.687
81.4703	2.3	0.695
ADS 9757	STF 1967	15386 +2637
81.4567	123.1	0.387
81.4676	122.9	0.382
81.4730	123.2	0.386
HR 5953	δ Sco	15545 -2220
81.4568	165.6	0.152
81.4622	166.5	0.152
81.4704	167.4	0.160
ADS 9913	BU 947 AB	15596 -1932
81.4677	95.5	0.363
HR 5985	β Sco CE	15596 -1932
81.4568	37.1	0.126
81.4677	37.1	0.112
81.4704	41.1	0.111
ADS 9918	FIN 384 Aa	16004 -0601
81.4677	273.8	0.062
81.4731	270.6	0.057
ADS 9932	BU 949	16030 -0950
81.4623	193.1	0.396
81.4704	192.8	0.402
HR 6032	FIN 354	16067 +0958
81.4568	84.1	0.119
81.4677	83.4	0.119
81.4731	83.4	0.119
HR 6084	σ Sco Aa	16151 -2521
81.4567	95.2	0.372
81.4704	97.1	0.369
81.4730	95.6	0.369
ADS 10052	STF 2054	16225 +6155
81.4731	353.3	1.070
ADS 10087	STF 2055 AB	16259 +0172
81.4731	12.3	1.271
HR 6168	σ Her	16309 +4239
81.4705	344°1	0"039
81.4731	343.1	0.042
ADS 10157	STF 2084	16375 +3147
81.4731	129.1	1.255
HR 6237	HD 151613	16434 +5658 (5)
81.4677	143.5	0.047
HD 151746	MLR 198	16442 +7404
81.4677	11.3	0.247
81.4731	11.6	0.241
ADS 10230	STT 315	16464 +0123
81.4568	5.5	0.167
81.4677	6.3	0.171
81.4731	6.0	0.167
ADS 10229	STF 2106	16464 +0935
81.4650	181.9	0.562
ADS 10257	BU 241	16496 -2124
81.4622	7.6	0.402
81.4704	7.4	0.397
ADS 10265	BU 1117	16508 -2259
81.4731	297.7	0.955
ADS 10279	STF 2118	16559 +6511
81.4731	69.1	1.131
ADS 10345	STF 2130 AB	17033 +5436
81.4732	43.1	2.113
ADS 10360	HU 1176 AB	17045 +3604
81.4569	41.0	0.075
81.4678	39.3	0.077
81.4706	40.2	0.072
81.4732	39.7	0.074
81.7000	28.7	0.072
ADS 10374	BU 1118 AB	17046 -1536
81.4569	264.0	0.357
81.4679	262.8	0.349
HR 6469	HD 157482	17185 +4004 (6)
81.4568	134.1	0.065
81.4678	134.2	0.061
81.4706	135.2	0.063
81.4732	135.6	0.062
HR 6485	ρ Her Aa	17202 +3714 (7)
81.4732	22.4	0.286
ADS 10531	HU 1179	17207 +3840 (8)
81.4706	50.4	0.035
81.6973	321.1	0.076

TABLE I - *Continued*

ADS 10598	STF 2173	17252 -0059
81.4569	165°8	0″636
81.4679	166.3	0.632
81.7001	164.5	0.654
HR 6560	HD 159870	17319 +5738
81.4680	1.2	0.161
81.4733	2.5	0.159
81.7001	0.6	0.157
ADS 10696	BU 631	17348 -0035
81.4679	166.6	0.064
81.4733	166.1	0.069
81.7001	164.1	0.070
HD 160935	COU 114	17375 +2133
81.4679	29.6	0.309
81.4707	30.4	0.304
81.7001	29.3	0.306
ADS 10795	STF 2215	17427 +1744
81.4569	266.7	0.571
81.4677	265.2	0.563
81.4732	266.6	0.570
81.7002	266.7	0.571
HD 162338	COU 1145	17455 +3706
81.4678	23.2	0.105
ADS 10850	STT 338 AB	17475 +1521
81.4679	352.5	0.843
81.7000	351.9	0.837
HR 6676	FIN 381	17496 +1109
81.4678	27.2	0.064
81.4707	35.0	0.070
81.7001	26.6	0.078
ADS 10912	STF 2244	17520 +0005
81.4678	86.5	0.236
81.7001	87.5	0.240
HD 163640	+18°3500	17520 +1821
81.4706	62.0	0.090
HR 6697	HD 163840	17531 +2401 (9)
81.4706	170.8	0.098
81.4732	171.8	0.114
81.7000	180.7	0.096
ADS 11060	STT 341 AB	18016 +2126
81.4568	88.8	0.318
81.4652	88.6	0.318
81.4679	88.6	0.323
81.4707	88.7	0.318
81.4733	89.2	0.324
81.7001	89.5	0.333
ADS 11111	STF 2281 AB	18046 +0359
81.4651	330°1	0″347
81.4679	331.4	0.342
81.4707	330.6	0.342
81.4733	331.1	0.348
81.7001	329.8	0.343
ADS 11127	BU 132	18053 -1952
81.4732	195.5	1.321
ADS 11123	STF 2289	18057 +1627
81.7001	221.1	1.221
ADS 11149	B 2545 AB	18081 +3325
81.4626	51.2	0.102
81.4680	50.1	0.103
81.4707	50.1	0.103
81.4733	50.9	0.102
81.7001	52.1	0.109
ADS 11149	HO 82 AB,C	18081 +3325
81.7001	38.4	0.771
HD 167570	17 Sgr	18107 -2034
81.4708	132.2	0.258
81.7028	131.7	0.274
ADS 11240	BU 639 AB	18128 -1840
81.4707	142.0	0.471
81.7028	143.4	0.474
ADS 11324	AC 11	18198 -0138
81.4732	356.4	0.846
ADS 11339	BU 1203	18210 +0043
81.4653	143.2	0.395
81.4681	142.6	0.392
81.7028	143.3	0.396
ADS 11334	STF 2315 AB	18210 +2720
81.4680	129.8	0.642
81.4707	130.2	0.628
81.7001	129.7	0.638
HR 6927	χ Dra	18229 +7241 (10)
81.4626	206.8	0.134
81.4652	216.7	0.130
81.4680	218.9	0.130
81.4734	218.8	0.139
81.7001	251.4	0.055
ADS 11479	STT 359	18314 +2331
81.4680	9.7	0.639
81.6975	10.0	0.636
ADS 11468	A 1377 AB	18317 +5216
81.4680	95.4	0.261
81.7002	96.1	0.261
ADS 11520	A 88 AB	18332 -0317
81.4626	166°0	0″123
81.4707	167.6	0.126
81.7028	160.2	0.113
ADS 11524	HU 198	18336 +0845
81.4653	137.5	0.448
HR 7017	COU 1607	18363 +4050
81.4680	115.0	0.171
81.6975	115.3	0.174
ADS 11558	STF 2368 AB	18366 +5215
81.7028	322.2	1.896
ADS 11593	B 2546 Aa	18385 +3439
81.4707	113.7	0.148
81.4733	114.3	0.153
81.7001	114.3	0.151
ADS 11640	FIN 332 CD	18406 +0524
81.4681	147.2	0.114
81.6975	145.0	0.120
ADS 11584	STT 363	18423 +7735
81.4680	153.5	0.151
81.7001	153.6	0.147
HR 7072	KUI 88	18429 -1842
81.4707	167.4	0.412
81.7028	166.9	0.412
ADS 11698	BU 971 AB	18449 +4919 (11)
81.4680	37.0	0.290
81.7001	36.1	0.285
ADS 11842	A 2192	18505 +0319
81.4734	94.9	0.268
81.6975	96.6	0.263
ADS 11871	BU 648 AB	18533 +3246
81.7002	45.5	1.160
HR 7166	KUI 89	18538 -1258
81.4625	256.7	0.190
81.4733	255.4	0.191
81.7028	257.6	0.188
ADS 11897	STF 2438	18558 +5805
81.4680	3.9	0.842
81.7001	3.9	0.840
ADS 12126	A 95	19056 -0735
81.4708	70.4	0.294
81.7004	72.3	0.291
ADS 12160	BU 139 AB	19081 +1641
81.6975	137.4	0.676
ADS 12214	B 430	19094 -25[illegible]
81.4626	101.9	0.172
81.4653	103.2	0.178
81.4736	103.0	0.173
81.7029	103.0	0.179

TABLE I *Continued*

HR 7362	FIN 327	19192 -2442
81.4735	78°9	0".118
81.7028	77.3	0.115
ADS 12366	BU 1129	19192 +5211
81.4626	3.8	0.130
81.7028	3.5	0.127
HR 7417	β^1 Cyg Aa	19267 +2745 (12)
81.4735	176.4	0.426
81.7003	175.3	0.423
ADS 12552	A 712	19282 +5626
81.4627	98.8	0.132
81.4683	98.6	0.128
81.7030	98.9	0.126
HD 184467	+58°1929	19295 +5824 (13)
81.4736	310.4	0.081
HR 7441	9 Cyg	19309 +2915 (14)
81.4626	204.6	0.029
81.4681	202.0	0.033
81.4735	204.2	0.033
81.7003	200.2	0.037
ADS 12741	STF 389	19338 -2339
81.4653	324.0	0.148
81.4735	324.4	0.143
81.7029	325.9	0.148
HR 7478	φ Cyg	19354 +2955 (15)
81.7003	78.7	0.039
HR 7486	KUI 93	19365 +1335
81.4627	308.0	0.169
81.4682	307.7	0.165
81.4735	307.6	0.168
81.7003	306.3	0.174
ADS 12798	STT 382	19378 +2709
81.4681	331.1	0.321
81.7003	331.2	0.323
ADS 12808	STT 380 AB	19379 +1135
81.4708	75.7	0.449
81.7003	75.9	0.449
HR 7499	KUI 94	19385 +4001
81.4735	152.3	0.206
81.7002	151.1	0.194
ADS 12850	BU 658	19393 +2654
81.4681	104.7	0.356
81.7003	104.2	0.362
HR 7536	δ Sge	19429 +1817
81.4627	169.4	0.048
ADS 12962	STF 2583 AB	19440 +1134
81.4734	107.7	1.428
HD 187321	+18°4252	19443 +1837 (16)
81.4682	96°8	0".408
81.7003	97.9	0.405
ADS 12973	AGC 11 AB	19445 +1853
81.4627	31.6	0.070
81.4682	30.3	0.071
81.4735	31.8	0.081
81.7003	27.0	0.083
HR 7592	DJU	19492 +2349
81.7003	244.1	1.084
ADS 13104	STF 2597	19500 -0700
81.4708	136.4	0.109
ADS 13135	HU 687	19522 +5033
81.7030	158.3	0.125
HR 7637	FIN 376	19544 -1014
81.4626	137.7	0.207
81.4709	136.9	0.205
81.4736	135.5	0.205
81.7029	144.4	0.190
ADS 13277	STT 395	19578 +2439
81.4654	120.0	0.857
81.4682	119.8	0.844
81.7029	119.3	0.855
ADS 13312	STF 2624 AB	19598 +3545
81.7029	174.2	1.969
ADS 13449	STF 2652	20074 +6147
81.4654	221.9	0.308
HR 7735	31 Cyg	20105 +4626 (17)
81.4683	131.6	0.026
ADS 13572	STT 403 AB	20109 +4148
81.4654	170.9	0.931
81.7030	171.3	0.935
HD 194359	COU 125	20202 +2357
81.6977	117.0	0.372
ADS 13850	A 730	20230 +5916
81.4654	327.9	0.230
81.4709	327.1	0.226
HR 7837	FIN 336	20255 -1523
81.4628	208.6	0.102
81.4737	209.9	0.090
ADS 13944	A 1675	20265 +1528
81.4628	72.5	0.067
81.4684	70.7	0.067
81.4737	71.7	0.070
81.6977	72.1	0.068
HR 7866	WRH AB	20300 +3454
81.4683	97°4	0".286
81.4736	96.3	0.279
HD 196088	+49°3310	20300 +4929 (18)
81.4709	76.3	0.051
ADS 14073	BU 151 AB	20328 +1415
81.4653	191.6	0.487
81.4682	191.5	0.483
81.4709	192.1	0.482
81.4736	191.3	0.484
81.6977	190.8	0.468
81.7004	192.7	0.470
ADS 14099	HU 200 AB	20337 -1518
81.4628	110.1	0.350
81.4737	109.8	0.349
HR 7906	α Del Aa	20350 +1534
81.4628	312.6	0.141
81.4683	312.7	0.137
81.4737	312.1	0.140
81.6977	305.7	0.142
HR 7922	HD 197226	20373 +3843 (19)
81.4709	98.8	0.109
ADS 14296	STT 413 AB	20435 +3607
81.4627	15.1	0.841
81.4736	15.0	0.840
81.6976	15.3	0.838
HR 7963	λ Cyg Aa	20435 +3607 (20)
81.4683	316.1	0.033
ADS 14412	A 751	20513 +5856
81.4627	166.1	0.129
81.4683	164.5	0.130
ADS 14499	STF 2737 AB	20541 +0355
81.4628	285.8	0.997
HR 8038	KUI 102	20552 +0707
81.4737	68.4	0.263
81.6978	66.3	0.269
HR 8047	59 Cyg Aa	20564 +4708 (21)
81.4710	58.1	0.215
81.7033	55.9	0.207
HD 200290	COU 128	20575 +2316
81.7033	136.5	0.193
HR 8060	FIN 328	20587 -2015
81.4737	161.5	0.303
HR 8059	12 Aqr	20588 -0613 (22)
81.4737	133.2	0.054

TABLE 1 - *Continued*

ADS 14585	BU 1138 AB	20593 +4527
81.4655	175°0	0″112
81.4710	175.1	0.115
81.7033	174.0	0.108
ADS 14648	BU 368 AB	21021 -0838
81.6978	90.8	0.255
ADS 14761	HU 767	21088 +1534
81.4628	10.5	0.112
81.4710	11 4	0.114
81.7033	13.3	0.109
HR 8119	I Cep	21093 +5935 (23)
81.7033	226.6	0.053
ADS 14773	STT 535 AB	21096 +0936
81.4628	202.6	0.131
81.4710	201.2	0.132
81.7032	194.1	0.097
ADS 14784	STF 2783	21114 +5753
81.7033	6.9	0.783
ADS 14839	BU 163 AB	21138 +1109 (24)
81.4628	248.6	0.336
81.4655	248.7	0.338
81.4710	247.1	0.330
81.7033	249.6	0.322
ADS 14893	A 617	21165 +0955
81.4628	280.9	0.157
81.4655	282.2	0.157
81.7033	279.9	0.159
HR 8238	β Cep	21274 +7007
81.4655	50 6	0.172
81.4711	48.4	0.175
ADS 15115	HU 371	21309 +2400
81.7005	295.2	0.288
ADS 15176	BU 1212 AB	21344 -0030
81.4737	236.5	0.337
81.7032	239.2	0.339
HR 8300	KUI 108	21384 +4038
81.4628	62.1	0.144
81.7005	61.8	0.151
ADS 15281	BU 989 AB	21401 +2511
81.4628	268.1	0.159
81.4711	265.8	0.153
81.4737	266.0	0.158
81.7005	262.0	0.143
HR 8344	COU 14	21454 +1650
81.4629	14.7	0.216
81.4737	13.8	0.214
81.7005	17.0	0.222
HR 8355	FIN 358	21482 -1047
81.4655	72°0	0″067
81.7006	75.3	0.076
ADS 15499	BU 275	21543 +6049
81.7033	172.6	0.421
HR 8417	ξ Cep Aa	22009 +6408 (25)
81.4656	227.8	0.062
81.4711	231.6	0.050
HD 210444	COU 136	22054 +2238
81.7005	44.1	0.425
ADS 15902	BU 172 AB	22189 -0521
81.7006	260.3	0.188
ADS 15971	STF 2909	22237 -0032
81.7034	218.3	1.648
ADS 15988	STF 2912	22249 +0355
81.7005	117.1	0.777
HR 8572	5 Lac	22253 +4712
81.4629	45.6	0.126
81.4738	43.5	0.114
ADS 16011	HU 981	22270 +6107
81.7033	220.7	0.321
ADS 16138	HO 295	22344 +4347
81.4655	330.9	0.134
81.4711	333.4	0.137
HR 8629	KUI 114	22356 -0404 (26)
81.4737	314.1	0.033
81.7006	103.7	0.048
ADS 16173	HO 296 AB	22359 +1401
81.6978	349.0	0.173
HD 215318	+80°731	22392 +8052
81.7006	98.6	0.147
ADS 16314	HO 482 AB	22466 +2552
81.6979	36.4	0.346
ADS 16317	STF 2950 AB	22475 +6110
81.7034	289.0	1.578
ADS 16417	STT 536 AB	22535 +0850
81.4629	346.6	0.310
81.4738	347.2	0.307
81.6978	345.4	0.314
ADS 16428	STT 483	22542 +1112
81.6978	299.2	0.592
HR 8762	o And AB	22573 +4147
81.4629	358°8	0″315
81.4738	359.6	0.315
81.6979	358.3	0.316
ADS 16467	BU 1147 AB	22580 +4213
81.6979	335.9	0.409
ADS 16497	A 417 AB	23000 -0814
81.4738	219.3	0.138
81.7006	227.3	0.137
ADS 16530	HU 994	23038 +6306
81.6979	126.4	0.208
HR 8817	RST 3320	23046 -2300
81.7034	321.2	0.290
ADS 16538	STT 489 AB	23047 +7451
81.7006	330.8	0.979
HR 8866	94 Aqr Aa	23138 -1400 (27)
81.4656	65.6	0.107
81.4738	70.1	0.109
81.7007	90.0	0.130
ADS 16708	HU 295	23174 -1536
81.7006	102.6	0.383
ADS 16731	STT 495	23196 +5659
81.6979	119.5	0.290
ADS 16800	BU 1266 AB	23255 +3017
81.4629	91.6	0.267
ADS 16836	BU 720	23290 +3047
81.6980	259.0	0.507
ADS 16877	STT 500 AB	23326 +4353
81.6980	356.3	0.508
HR 9003	ψ And Aa	23411 +4552
81.4738	103.8	0.290
81.6980	105.0	0.285
HR 9003	ψ And Ab	23411 +4552 (28)
81.4738	180.4	0.145
ADS 17020	STT 507 AB	23438 +6420
81.7006	306.1	0.714
ADS 17030	A 424	23448 +2707
81.6980	105.2	0.185
HR 9041	FIN 359	23478 -0343
81.4656	53.6	0.097
81.7007	49.3	0.098

NOTES TO TABLE I

1. ADS 490 = HO 212 AB is being followed spectroscopically by one of us (F.C.F.), and a preliminary spectroscopic orbit indicates $T = 1980.2$

2. HR 649 = ξ^1 Cet is a G6 II–III star for which Griffin 1979 reported a preliminary period of 1640^d for the spectroscopic orbit. Appleby 1980 included the star in his list of objects thought to be double on the basis of noninstantaneous disappearance during visual observation of a lunar occultation event. The object is directly resolved here for the first time.

3. HR 763 = 31 Ari may have completed one revolution during the 2.2 yr since its first resolution, and the quadrant adopted in these measures reflects this supposition.

4. HR 788 = 12 Per is a resolved spectroscopic binary with a period of 331^d. The residuals from the combined spectroscopic/interferometric orbit (McAlister 1978) are (−1°3, +0″002).

5. HR 6237 = HD 151613 is a spectroscopic binary with a period of 3.8 yr that was first resolved by this program on 1977.4813: 51°8, 0″041. It was unresolved on 1979.3625 and 1979.5291.

6. HR 6469 = HD 157482, a system first resolved by this program on 1980.4766, shows rapid orbital motion consistent with the 5.53 yr spectroscopic period determined by one of us (F.C.F.).

7. HR 6485 = ρ Her Aa is directly resolved here for the first time. The system is the primary component of the visual binary ADS 10526 and has a spectral type of F0 IV.

8. ADS 10531 = HU 1179 appears to have passed through periastron during 1981 and may now have sufficient separation to be measured by visual observers. The observation on 1981.4706 is at the diffraction limit of the Mayall telescope and may have errors as large as ±5° and ±0″005.

9. HR 6697 = HD 163840 was first resolved by this program on 1976.2965 and has been unresolved on eight occasions since that time. The object has been observed spectroscopically and astrometrically since it was reported as a previously overlooked nearby star (McAlister and Ianna 1974), and a preliminary study of the system has been made by Culver, Ianna, and McAlister 1980.

10. HR 6927 = χ Dra is a resolved spectroscopic/astrometric binary with a period of 280^d5. The residuals from the combined spectroscopic/interferometric orbit (McAlister 1980*a*) are (−14°1, +0″016), (−4°4, +0″011), (−2°4, +0″010), (−3°0, +0″017), and (+8°2, 0″000).

11. ADS 11698 = Bu 971 AB is a difficult visual system, due to a Δm of ~ 2 mag, which recently has been rarely observed. Thus, it is uncertain whether the several runs of negative results reported at various times after its discovery in 1879 imply a relatively short period, a rather eccentric orbit, or simply reflect its difficulty of measurement. Speckle observations during the past 4 yr show a constant position angle with a slow increase in separation.

12. HR 7417 = β^1 Cyg continues to show marginal orbital motion since it was first resolved by this program on 1977.3676: 186°2, 0″444.

13. HD 184467 = +58°1929 has moved through more than 120° of position angle since its first resolution on 1980.4797: 74°2, 0″117. The pair resolved here probably corresponds to the spectroscopic system of McClure 1983, having a period of 492^d.

14. HR 7441 = 9 Cyg is a single-lined spectroscopic binary classified as F5 + A0, with a period of 215^d5 (Hendry 1978). Previous measures of the resolved system have shown appreciable orbital motion, but it does not yet seem possible to determine the compatibility with Hendry's orbit. The system was last resolved on 1979.3601, and was definitely unresolved on 1979.7699. To be consistent with the observed trend in the motion, we have assumed a quadrant reversal between 1979 and 1981.

15. HR 7478 = ϕ Cyg is a double-lined spectroscopic binary with components of spectral type G8 III–IV. The residuals from the combined spectroscopic/interferometric orbit (McAlister 1982) are (+8°7, +0″005).

16. HD 187321-2 = +18°4252 is a composite spectrum binary (Hynek 1938) which is here directly resolved for the first time. The system has a spectral type of G0 + A, and Hynek noted the "star has the color of a giant G3."

17. HR 7735 = 31 Cyg was first resolved in the preceding paper of this series. The observation presented here is at the resolution limit of the Mayall telescope, but the composite power spectrum convincingly exhibits the expected appearance of a just-resolved binary.

18. HD 196088-9 = +49°3310 is a composite spectrum binary which has moved through nearly 10° of position angle since its first resolution by this program on 1980.4797.

19. HR 7922 = HD 197226 was first resolved by McAlister *et al.* 1983. The system measured here is probably not the 106^d3 spectroscopic binary of Hube and Wolff (1979), although it cannot be ruled out that the quadrant is actually reversed from that adopted here since the spectroscopic system would have gone through 3.41 revolutions in the time between the two observations reported in this series.

20. HR 7963 = λ Cyg Aa continues to show significant orbital motion and has moved through nearly 70° of position angle in 2.9 yr.

21. HR 8047 = 59 Cyg Aa is a B1.5 Ve star which has exhibited a remarkable series of shell episodes (see Underhill and Doazan 1982). The companion measured here has not been previously reported.

22. HR 8059 = 12 Aqr has moved through nearly 220° of position angle in the 2.9 yr since its first resolution by this program.

23. HR 8119 = I Cep has shown no significant orbital motion during the 2.2 yr since its first resolution by this program.

24. ADS 14839 = Bu 163 AB continues to decrease in separation. However, the rate of decrease in this highly eccentric system (e = 0.88) continues to be slower than predicted by the orbit of Heintz 1969. Thus, periastron and the nearly coincident nodal passage will occur later than 1985.5 by at least 1 yr.

25. HR 8417 = ξ Cep Aa is a double-lined spectroscopic binary with a period of 2.25 yr. The residuals from the apparent orbit determined from previous speckle observations (McAlister 1980*b*) are (−2°7, +0″015) and (+0°5, +0″003).

26. HR 8629 = Kui 114 apparently underwent periastron passage earlier than 1981.6 as predicted by Baize 1976. We found the system to be unresolved on 1980.49 and 1980.73, implying separations less than 0″030. The separation was increasing again between the two observations presented here.

27. HR 8866 = 94 Aqr Aa is a single-lined spectroscopic binary with a period of 6.36 yr. The residuals from the combined spectroscopic/interferometric orbit (McAlister and Hartkopf 1982) are (−1°8, 0″000), (+1°9, +0″002) and (−2°5, +0″019).

28. HR 9003 = ψ And A is a resolved composite spectrum system for which the Aa pair has been measured on numerous occasions since its first resolution by this program on 1976.8596. The measurement of a possible third Ab component reported here for the first time must be considered tentative since no other speckle observations, including the one on 1981.6980, have shown evidence for this component. The composite power spectrum for 1981.4738 does, however, rather clearly show two sets of fringes

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BINARY STARS UNRESOLVED BY SPECKLE INTERFEROMETRY. III*

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The epochs of 1164 speckle observations, obtained with the 4-meter Mayall telescope at KPNO during 1975–81, are given for 469 unresolved known or suspected binary stars.

Key words: binary stars – speckle interferometry

This is the third in a series of papers reporting observations of binary stars unresolved by speckle interferometry. All observations were obtained with the photographic speckle camera attached to the 4-meter Mayall reflector at Kitt Peak National Observatory (except as noted). As in the earlier papers (McAlister 1978; McAlister and Hendry 1981), only observations of adequate exposure time and atmospheric dispersion compensation are included.

The observations reported here were obtained over six years of speckle work at KPNO between September 1975 and September 1981. The stars included in this paper include visual binaries with eccentric orbits, occultation binaries, astrometric binaries, Hyades stars of known or suspected duplicity, and many long-period spectroscopic binaries. In total, some 1164 observations of 469 objects are tabulated below.

The resolution lower limit adopted by us is the Rayleigh limit of 1.22 λ/D, where λ is the passband center and D the telescope aperture. Several different filters have been used over the course of this project; the appropriate resolution limit is given for each observation in Table I.

Table I is arranged rather differently from tables in earlier papers of this series, in order to include information from past speckle observations. The first column contains three rows of information for each star—two names, plus the the star's position for epoch 1900.0. The second column also contains three rows of information—identification codes for binary types (defined at the end of the table), the range of dates for any published speckle observations, and the number of such observations (an asterisk following this number indicates that the star has never been resolved by speckle interferometry). Numbers in parentheses refer to notes following the table. Finally the third and fourth columns give the epoch of each unresolved observation and the corresponding resolution upper limit in arc milliseconds.

Information in the notes, unless otherwise stated, was taken from the *Bright Star Catalogue* (BSC, Hoffleit and Jaschek 1982), the Index Catalogue of Visual Double Stars (IDS, Jeffers, van den Bos, and Greeby 1963), the *New General Catalogue of Double Stars* (ADS, Aitken 1932), and the two earlier papers in this series. Occultation data were taken from lists provided by David Dunham and Nathaniel White, unless otherwise noted.

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TABLE I

Binary Stars Unresolved by Speckle Interferometry

HD 443 +64 0003 00039+6432	AS 75.7-76.9 3*	78.618 30
HR 130 κ Cas 00273+6223	SB,VAR	78.615 30
HR 154 π And 00315+3310	SB 76.0-76.9 4*	77.733 35 78.615 30 79.770 30 80.718 30 81.704 30
HR 163 ε And 00333+2846		80.726 30
HR 165 δ And 00340+3019	SB 76.9-76.9 3* (1)	77.733 35 78.539 30 79.770 30 80.718 30 80.726 30 81.704 30
HR 215 ζ And A 00420+2343	VAR,SB	80.726 30
HR 222 HD 4628 00432+0445	SB	75.960 33
HR 224 δ Psc 00435+0702	SB	80.726 30
HR 225 64 Psc A 00437+1624	SB	80.483 30 80.718 30 80.723 30
HR 233 HD 4775 00446+6342	SP 78.6-80.7 4 (2)	80.718 30 80.726 30 81.704 30
HR 244 HD 5015 00471+6035	SB 76.9-76.9 2* (3)	77.733 35 79.770 30 80.723 30
HR 265 28 Cas 00507+5839	NS	80.726 30
HR 271 η And 00519+2253	SB	80.726 30
HR 294 ε Psc 00577+0721	OC	80.718 30 80.723 30 80.726 30
HR 337 β And 01041+3505	SB (4)	80.726 30
HR 343 θ Cas 01050+5437	SB 75.7-76.9 4*	77.733 35 78.615 30 79.770 30 80.718 30 80.723 30
HR 348 HO 215 01056+3712	VIS 76.9-79.8 4* (5)	77.733 35 80.718 30 81.704 30
HR 351 χ Psc 01061+2030		76.857 35
HR 352 τ Psc 01062+2934	SB	76.860 35 76.923 35 77.733 35 79.773 30 80.718 30 80.723 30 80.726 30 81.701 30
HR 360 φ Psc 01083+2403	SB (6)	76.857 35 76.860 35 76.923 35 77.733 35 79.773 30 80.718 30 80.721 30 80.726 30
HR 383 υ Psc 01140+2644	SB	80.726 30
HR 427 38 Cas 01238+6945	SB 76.0-76.9 3*	78.618 30 81.704 30
HD 9313 +15 0227 01266+1532	SB	77.733 35 79.773 30
HD 9811 +64 0202 01308+6414	SP	80.723 30
HR 458 A υ And 01309+4054	SB 76.9-76.9 2*	77.733 35 78.615 30 80.723 30
HR 464 51 And 01319+4807		80.726 30
HR 469 χ And 01333+4353	SB	76.857 35 76.923 35 77.734 35 80.723 30
HR 489 ν Psc 01362+0459		80.726 30
HR 493 107 Psc 01370+1946	SB?	75.962 33
HR 496 φ Per 01374+5011	SB,VAR 75.7-76.9 4*	77.734 35 78.615 30 79.036 30 80.723 30
HR 510 ο Psc 01401+0839		80.726 30
HR 511 A HD 10780 01405+6322	AS 75.7-76.9 4*	80.721 30 80.723 30
HR 534 54 Cet 01456+[illegible]	OC,SB	80.723 30
HR 539 ζ Cet 0146[illegible]-1049	SB 75.7-79.8 5 (7)	80.718 30 80.721 30 80.726 30
HR 544 α Tri 01474+29[illegible]	SB	80.726 30
HR 545 γ¹ Ari 01481+1848	SB,VAR (8)	80.726 30
HR 546 γ² Ari 01480+1848	SB,VAR (9)	80.726 30
HR 549 ξ Psc 01484+0242	SB	76.923 35 77.734 35 79.773 30 80.721 30 80.723 30 81.701 30
HR 553 β Ari 01491+2[illegible]	SB,VAR 75.7-76.9 4*	77.734 35 78.618 30 79.773 30 80.718 30 80.723 30
HR 563 ι Ari 01519+172[illegible]	SB,OC 75.7-76.9 3* (10)	77.734 35 78.615 30 78.618 30 79.773 30 80.718 30 80.721 30
HR 603 γ¹ And 01578+4151	SB (11)	78.618 30
HD 12730 +07 0321 01597+0715	OC 76.9-76.9 2* (12)	77.734 35 78.618 30 79.773 30 80.718 30 80.723 30
HR 617 α Ari 02015+2259	SB	80.726 30
HR 619 HD 13018 02023+1733	OC (13)	79.773 30 80.718 30 80.723 30 81.701 30
HR 622 β Tri 02036+3431	SB,HY	80.726 30
HR 643 60 And 02069+4346	SB	76.857 35 76.923 35 77.734 35 80.723 30
HR 645 6 Per 02069+5036	SB 76.9-76.9 3*	79.773 30 80.718 30 80.723 30
HR 649 ξ¹ Cet 02077+0823	SB,OC 81.7-81.7 1 (14)	76.857 35 76.923 35 77.734 35 79.773 30 80.718 30 80.723 30
HR 664 γ Tri 02114+3323	SB	80.726 30
HR 676 HD 14262-3 02133+2242	SP	80.718 30 80.723 30
HD 15869 +15 0325 02280+1826	OC	81.701 30
HR 753 HD 16160 02306+0625	SB 75.7-76.9 4* (15)	78.615 30 79.773 30 80.721 30 80.723 30
HR 763 31 Ari 02312+1200	SB,OC 79.5-81.7 5 (16)	78.610 30 78.615 30 79.036 30 80.723 30 80.726 30 80.729 30
HD 16499 +11 0352 02337+1012	OC	81.701 30
HR 793 μ Ari 02367+1935	SB,OC 75.6-79.8 12 (17)	80.485 30 80.718 30 80.721 30 80.723 30 80.726 30
HR 804 γ Cet 02381+0249	NS (18)	80.721 30
HR 813 μ Cet 02395+0942	SB,OC,VAR 75.7-76.9 3* (19)	77.734 35 77.742 35 78.610 30 78.615 30 79.773 30 80.718 30
HD 17245-6 +43 0576 02410+4351	SP	80.718 30 80.723 30
HR 824 39 Ari 02420+2850		80.726 30
HD 17433 +30 0446 02427+3042	SB	75.719 33 81.701 30
HR 828 40 Ari 02429+1752	OC,SB (20)	80.72[illegible] 30 81.7[illegible] 30
HR 840 16 Per 02443+[illegible]	VAR	80.726 [illegible]
HR 843 17 Per [illegible]	VAR?	80.726 [illegible]
HR 854 τ Per [illegible]	SB 73.4-79.8 8 (21)	80.718 30 80.724 30 80.726 30

TABLE I (Continued)

HR 869 ρ^3 Ari 02508+173[illegible]	SB 76.9-76.9 2*	78.616 30 79.773 30 80.718 30 81.701 30
HR 915 τ Per 02575+5307	SB,VIS 73.4-80.9 23 (22)	76.860 35
HR 936 β Per AB,C 03017+4034	SB,AS 73.4-80.2 18 (23)	80.718 30 80.726 30
HR 938 53 Ari 03018+1730	OC,SB,VAR (24)	80.721 30
HR 941 κ Per 03028+4429	SB,HY (25)	76.857 35 76.860 35 76.923 35 79.771 30 80.718 30 80.724 30
HR 948 HD 19698 03052+1130	OC	81.701 30
HR 952 HD 19789 03059+1240	OC	81.701 30
HR 958 HD 19926 03071+0617	SP	79.771 30 80.721 30 80.724 30
HR 965 HD 20084 03086+8433	SP	80.721 30
HR 996 κ^1 Cet 03141+0300	VAR	75.960 33
HR 1030 o Tau 03194+084[illegible]	SB 76.[illegible]-76.9 3*	79.771 30 80.156 30 80.721 30 80.724 30
HR 1038 ξ Tau 03218+0923	SB (26)	77.734 35 80.718 30
HR 1048 66 Ari 03226+2227	OC,SB (27)	79.773 30 80.724 30
HR 1066 5 Tau 03254+1236	SB,OC 76.0-77.1 5* (28)	77.742 35 79.771 30 80.156 30 80.721 30
HD 21962 +16 0458 03273+1616	OC (29)	79.773 30 80.718 30
HR 1084 ϵ Eri 03282-0948	AS 75.6-77.1 6 (30)	80.721 30 80.724 30
+17 0593 SAO 93525 03322+1506	OC	80.721 30
HR 1110 HD 22695 03338+1613	OC (31)	80.724 30
HR 1140 16 Tau 03389+2359	OC,VAR? 75.7-76.9 4* (32)	77.742 35 79.771 30 80.718 30
HR 1142 17 Tau 03389+2348	OC,SB 76.0-76.9 3* (33)	77.742 35 79.771 30 80.718 30 80.724 30
HR 1144 18 Tau 03392+2431	OC,SB (34)	80.718 30 80.724 30 80.729 30
HR 1145 19 Tau 03393+2409	OC,SB 76.9-76.9 2* (35)	79.771 30 80.718 30 80.724 30
HR 1149 Cou 560 03399+2403	SB,OC 76.0-76.9 3* (36)	79.771 30 80.718 30 80.724 30
HR 1152 22 Tau 03401+2413	OC,SB (37)	80.718 30 80.724 30
HD 23568 +24 0562 03411+2413	OC 76.0-76.9 3* (38)	80.724 30
HD 23643 +23 0539 03415+2322		76.860 35
HR 1165 η Tau 03415+2348	OC,VAR? 76.0-76.9 4* (39)	79.771 30 80.718 30 80.724 30
HR 1172 HD 23753 03424+2307	OC,SB? (40)	80.718 30 80.724 30
HD 23822 +23 0556 03432+2334	OC 76.9-76.9 2* (41)	79.773 30 80.721 30 80.724 30
HR 1201 HD 24357 03475+1702	HY,VAR?	76.039 33
HR 1206 HD 24497 03487-1844	SP	80.721 30
HR 1233 HD 25102 03542+1003	HY,VAR	76.039 33
HR 1238 HD 25202 03551+1755	HY,SB	76.039 33
HR 1252 36 Tau 03584+2350	OC,SP 76.9-80.7 4 (42)	77.742 30 79.771 30
HR 1279 HD 26015 04020+1454	OC,HY (43)	76.039 33
HR 1280 HD 26038 04023+1704	OC (44)	80.721 30
HD 26345 +18 0594 04049+1810	HY	76.039 33
HD 26380 +15 0592 04052+1541	OC (45)	79.774 30 80.721 30
HR 1292 45 Tau 04060+0516	HY,SB?	76.039 33
HR 1303 μ Per A 04076+4809	SB,AS,VAR 75.7-76.9 4* (46)	79.771 30 80.156 30 80.721 30 80.726 30
HR 1306 52 Per 04081+4014	SB,SP 75.7-76.9 3*	79.771 30 80.156 30 80.721 30 80.726 30
HD 26737 +22 0657 04086+2212	HY	76.039 33
HD 26874 HY 162 04098+2034	HY	76.860 35
HR 1319 48 Tau 04101+1529	HY,SB	76.039 33
HR 1324 b Per 04107+50[illegible]	SB,HY,VAR [illegible] 1*	77.734 35 77.742 30 79.771 30 80.156 30
HR 1325 o^2 Eri 04105-0751	SB,VAR (47)	75.960 33
HR 1329 ω Tau 04114+2020	SB,OC 75.7-76.9 4* (48)	77.742 30 79.036 30 80.721 30
HD 27149 HY 23 04122+1800	SB,HY 76.9-76.9 1*	79.773 30 80.156 30
HR 1339 53 Tau 04135+2054	SP 76.0-76.9 3*	80.721 30
HD 27397 +13 0663 04143+1348	HY,VAR	76.039 33
HD 27429 +18 0624 04146+1830	HY	76.039 33
HD 27459 +14 0682 04149+1451	HY,VAR	76.039 33
HD 27524 +20 0740 04156+2048	HY	76.039 33
HD 27534 +18 0629 04157+1811	HY	76.039 33
HD 27561 +14 0687 04159+1410	HY	76.039 33
HR 1373 δ Tau 04172+1718	SB,HY,VAR 78.9-78.9 1* (49)	76.039 33 76.860 35 76.923 35 77.734 35 79.773 30 80.156 30 80.718 30
HR 1375 HD 27742 04176+2045	OC,VAR (50)	77.734 35 80.721 30
HR 1380 64 Tau 04183+1713	HY,SB	76.039 33
HR 1385 HD 27901 04191+1849	HY,SB?	76.039 33
HR 1387 κ^1 Tau 04194+2204	OC,HY,SB? (51)	76.039 33 77.734 35 80.721 30
HR 1388 κ^2 Tau 04195+2158	HY,VAR	76.039 33
HR 1389 δ^3 Tau 04197+1742	VIS,HY,SB (52)	76.039 33
HR 1392 υ Tau 04203+2235	OC,HY,SB (53)	76.039 33 76.860 35 76.923 35 79.771 30 80.721 30
HD 28033 +21 0644 04204+2115	HY	76.039 33
HR 1394 71 Tau 04206+1523	SB,OC,HY 76.9-77.1 3* (54)	76.039 33 79.036 30 79.771 30 80.156 30 80.718 30
HR 1399 72 Tau 04213+2246	OC,VAR	77.734 35 80.721 30
HR 1403 HD 28226 04221+2124	OC,HY,SB (55)	76.039 33 76.860 35 76.923 35 79.771 30 80.721 30
HR 1407 75 Tau 04227+1608	OC,HY,VAR (56)	80.721 30
HR 1408 76 Tau 04227+1431	HY,VAR	76.039 33

TABLE I (Continued)

HR 1409 74 Tau 04228+1857	HY	76.041 35
HR 1411 θ^1 Tau Aa 04229+1544	SB,OC,HY 79.0-79.9 1 (57)	76.041 35 76.860 35 76.923 35
HR 1412 θ^2 Tau 04230+1539	SB,OC,HY 78.7-78.7 1* (58)	76.041 35 80.718 30
HR 1414 79 Tau 04232+1250	HY,VAR?	76.040 35
HR 1422 80 Tau 04244+1525	HY,SB (59)	76.041 35
HR 1428 81 Tau 04249+1528	HY,VAR?	76.041 35
HR 1430 83 Tau 04250+1330	HY,VAR	76.041 35
HR 1444 ρ Tau 04282+1438	SB,HY 76.0-76.9 3*	76.041 35 79.774 30 80.156 30 80.721 30
HR 1454 58 Per 04298+4104	SB,AS 76.0-76.0 1*	79.774 30 80.156 30 80.721 30
HR 1472 89 Tau 04324+1550	HY,VAR	76.041 35
HR 1478 σ^1 Tau 04334+1536	SB,HY? 76.9-76.9 2* (60)	79.774 30 80.156 30 80.718 30
HR 1528 HD 30453 04428+3225	SP	79.774 30 80.721 30
HR 1543 π^3 Ori 04444+0647	SB,VAR	75.960 33
HR 1560 ω Eri 04470-0537	SB 76.9-76.9 1*	80.156 30 80.721 30
HD 31855 +45 1024 04540+4544	SP	80.724 30
HR 1605 ε Aur 04548+4341	SP,SB,VAR 76.0-76.0 1* (61)	79.771 30 80.156 30 80.724 30
HR 1612 ζ Aur 04555+4056	SB,VAR 76.0-76.0 1*	80.724 30 80.726 30 80.729 25
HR 1620 ι Tau 04571+2127	OC,HY (62)	80.721 30
HR 1637 9 Aur 04588+5128	SB	79.771 30 80.153 30 80.718 30
HD 32656 +26 0783 04597+2618	OC (63)	79.774 30
HR 1656 104 Tau 05015+1831	NS,VIS 76.0-79.8 5* (64)	77.742 30 79.036 30 80.153 30 80.726 30 80.729 30
HR 1660 105 Tau 05019+2134	OC,SB (65)	80.721 30
HR 1698 ρ Ori 05081+0245	SB 76.0-77.1 2*	79.771 30 80.153 30
HR 1788 η Ori Aab,c 05194-0229	SB 76.0-79.8 10 (66)	80.726 30
HR 1872 STT 110 05290+0342	VIS,SB 76.9-79.8 2* (67)	80.159 30
HR 1937 49 Ori 05340-0716	SB	79.771 30
HR 2013 HD 39004 05447+2756	OC,SB (68)	79.774 30
HR 2047 χ^1 Ori 05484+2015	OC,VIS,AS (69)	75.960 33 79.771 30 80.159 30 80.718 30
HR 2130 64 Ori 05575+1942	OC,SB 77.2-79.0 4 (70)	80.718 30 80.726 30
HR 2148 17 Lep 06005-1629	SB,VAR 76.0-76.0 1*	79.036 30
HR 2172 HD 42083 06037+5240	SB 76.9-77.1 2*	80.726 30 -
HR 2175 41 Aur 06039+4844	HY	76.860 35
HD 42417 MLR 316 06054+6610	VIS	80.156 30
HR 2298 ε Mon A 06185+0439	SB 76.0-76.9 2* (71)	78.149 30 80.156 30
HD 44780 +25 1255 06186+2506	SB	76.860 35 77.087 35
HR 2304 HD 44927 06195+2323	OC,SB? 76.9-79.8 4 (72)	80.729 30
HR 2356 β Mon A 06240-0658	SB,VIS (73)	79.771 30 80.159 30
HR 2421 γ Gem 06319+1629	SB,AS 76.0-76.9 3*	78.149 30 80.156 30
HD 48394 BAL 1018 06381+0005	VIS	80.156 30
HD 48953 +16 1273 06410+1653	OC,SP (74)	76.860 35
HR 2506 18 Mon 06426+0231	SB	76.860 35 78.149 30 80.156 30
+32 1424 Cou 1552 06460+3255	VIS	80.156 30
HR 2631 HD 52554 06566+1754	OC (75)	80.159 30
HR 2650 ξ Gem A 06582+2043	OC,SB (76)	80.159 30
HD 54986 +17 1518 07060+1709	OC (77)	80.159 30
HR 2763 54 Gem 07123+1643	NS,OC,SB (78)	80.159 30
HR 2777 δ Gem A 07142+2210	NS,SB,OC 76.9-77.1 3* (79)	78.146 30 79.036 30 80.159 30 80.729 30
HD 58061 VY CMa 07189-2534		76.860 35
HR 2854 γ CMi 07227+0908	SB 76.0-76.9 3*	78.146 30 80.159 30 80.729 30
HR 2861 65 Gem 07236+2807	SB 78.1-79.8 2 (80)	76.858 35 76.923 35 80.154 30 80.159 30 80.721 30 80.729 30
HR 2902 Boss 1985 07292-1418	SB,SP 76.3-77.1 2*	80.156 30
HR 2938 74 Gem 07337+1754	OC,SB? (81)	80.159 30
HR 2943 α CMi 07340+0528	NS (82)	75.960 33
HR 3003 81 Gem 07403+1845	SB,OC (83)	76.861 35 77.087 35 78.149 30 79.036 30 80.154 30 80.159 30
HR 3104 HD 65257 07528+1647	OC (84)	80.159 30
HD 65736 +18 1816 07549+1831	OC (85)	80.159 30
HR 3149 χ Gem 07574+2804	SB	76.858 35 76.923 35 77.087 35 78.147 30 80.156 30
HR 3209 ζ Cnc C 08065+1757	NS 76.9-76.9 1*	76.858 35 78.149 30
HR 3215 15 Cnc 08069+2957	SB	78.147 30 79.036 30 80.156 30
HR 3222 HD 68461 08073+1649	OC,SB (86)	80.159 30
HR 3279 HD 70442 08169-1946	SB,SP 76.0-76.9 3*	78.149 30 80.156 30
HD 70923 B 2527 08195-0049	VIS (87)	80.156 30
HR 3311 23 Cnc A 08207+2716	SB (88)	78.149 30
HR 3312 24 Cnc A 08207+2452	(89)	80.156 30
HR 3357 θ Cnc 08259+1826	OC,SB? (90)	76.858 35 76.923 35 78.147 30 80.159 30
HR 3376 HD 72505 08282+1336	OC (91)	80.159 30
HD 73666 40 Cnc 08344+2019	OL	76.923 35 78.149 30
HD 74155 +16 1802 08373+1648	OC	78.147 30
HR 3450 45 Cnc 08377+1302	SB,OC,SP 76.0-77.1 4* (92)	78.147 30 79.037 30 80.156 30
HR 3461 δ Cnc Aa 08390+1831	76.9-76.9 1* (93)	78.147 30 79.037 30
HR 3510 54 Cnc 08454+1543	OC (94)	76.861 35 76.923 35 80.159 30

TABLE I (Continued)

HR 3563 HO 252 08519+3037	VIS 76.9-78.1 2* (95)	80.156 30
HR 3626 75 Cnc 09029+2702	SB	80.154 30 80.159 30
HR 3627 WRH 16 09036+2227	OC,VIS,SB 76.3-78.1 4* (96)	79.037 30 80.156 30
HR 3640 WRH 17 09046+2224	OC,VIS,SB 76.3-76.9 3* (97)	80.156 30
HR 3690 38 Lyn 09126+3713	SB (98)	80.156 30
HR 3782 ξ Leo 09265+1144	OC (99)	80.159 30
HR 3800 10 LMi 09281+3650	76.9-76.9 1* (100)	78.147 30 79.037 30 80.154 30 80.159 30
HR 3805 HD 82674 09284-0645	SB	80.156 30
HR 3815 11 LMi 09296+3616	NS,SB? (101)	75.963 33 76.301 35 76.923 35 78.147 30
HR 3827 10 Leo 09319+0717	SB	76.858 35 76.924 35 80.156 30
HR 3852 ο Leo A 09358+1021	SB,OC 76.9-76.9 1* (102)	78.147 30
HD 83822 +09 2226 09359+0927	OC (103)	76.861 35 76.924 35 80.159 30
HD 87473 Cou 1569 10000+3441	VIS	80.156 30
HR 3975 WRH 18 10019+1715	VIS,SB,OC 76.3-76.4 2 (104)	76.861 35 78.147 30 79.037 30 80.159 30
HD 88230 GRB 1618 10051+4957	AS,NS	76.042 38 80.159 30
HD 88923 +46 1609 10103+4556	SP	80.159 30
HR 4055 RST 3688 10144-1202	VIS	79.037 30
HR 4101 45 Leo 10224+1016	SB (105)	79.362 30 80.159 30
HR 4132 HD 91312 10274+4056	SB 76.0-77.1 4* (106)	79.037 30 80.156 30
HR 4201 36 SEX 10400+0301	OC,SB (107)	79.037 30 79.362 30 80.157 30
HR 4249 HD 94363 10483-0143	SB (108)	79.037 30 80.159 30
HR 4253 Ma 5 10486-0135	VIS,SB? 76.3-79.4 3* (109)	79.037 30 80.157 30
HD 94515 +06 2368 10496+0623	OC (110)	80.157 30 80.485 25
HD 94738 +01 2502 10510+0058	OC (111)	80.157 30
HR 4291 58 Leo 10554+0409	OC,SB? (112)	80.157 30
HD 95735 LAL 21185 10578+3634	AS	79.359 30
HR 4365 73 Leo 11106+1351	SB 79.4-80.2 2 (113)	76.924 35 81.473 30
HR 4374 STF 1523 B 11128+3206	SB (114)	76.040 33 77.487 35 80.484 30
HR 4375 STF 1523 A 11128+3206	SB,AS 76.0-77.1 5* (115)	76.040 33
HR 4400 79 Leo 11189+0157	OC,SB? (116)	80.157 30
HR 4430 HD 99967 11250+4712	SB 76.0-77.1 3*	79.359 30 80.154 30
HD 100235 HU 1134 11269-3648	VIS 76.3-79.4 2* (117)	80.156 30 80.485 30
HR 4474 HD 101013 11325+51[illegible]	SB	77.087 35 79.359 30 80.154 30
HR 4496 61 UMa 11358+3446	SB	75.963 33 76.042 38 76.301 35
HR 4540 β Vir 11455+0219	SB	75.963 33 76.042 38 80.159 30
HR 4550 HD 103095 11475+3821	SB,VAR	79.037 30
HR 4589 π Vir 11557+0710	SB,OC 76.0-77.1 4* (118)	79.037 30 79.362 30 80.159 30
HD 105589 +00 2902 12043-0012	OC	80.157 30
HD 106384 -04 3235 12091-0510	OC (119)	80.159 30
HR 4668 HD 106760 12115+3337	SB,VAR 76.0-77.1 3*	78.150 30 79.360 30 80.154 30 80.159 30 80.482 30 81.467 30
HR 4680 HD 107054-5 12135+3048	SP,SB	80.157 30 80.482 30 81.467 30
HR 4695 16 Vir 12153+0352	OC,SB? (120)	78.150 30 79.359 30 80.157 30 80.479 30
HR 4707 12 Com 12175+2624	SB 76.0-79.5 5* (121)	77.486 35 79.359 30 80.154 30 80.159 30
HR 4719 HD 108007 12194+2608	VIS,SB (122)	80.157 30 81.467 30
HR 4785 β CVn 12290+4154	SB,VAR 76.0-79.5 8 (123)	78.150 30 80.159 30 80.479 30 81.467 30 81.473 30
HR 4896 HD 112048 12485-0341	SB	78.150 30 80.154 30 80.159 30 80.479 30
HR 4902 ψ Vir 12492-0900	OC 76.0-77.1 5* (124)	79.362 30
HR 4905 ε UMa 12496+5630	VAR,SB? 75.4-79.4 7 (125)	80.154 30 80.159 30 81.467 30
HD 112515 +46 1832 12522+4610	SP	80.157 30
HR 4983 β Com 13072+2824	SB?	76.040 33 76.299 35
HR 5014 Fin 350 13124-0009	VIS 76.3-79.4 9 (126)	80.159 30 80.476 30 80.482 30 81.470 30 81.473 30
HR 5055 ζ UMa B 13199+5527	SB,AS (127)	76.299 35 76.924 35 77.088 35 78.150 30 80.476 30 80.485 25 81.467 30
LFT 1034 GL 526 13408+1525	NS	80.157 30
HD 120901 DL Vir 13472-1813	SB	77.487 35 78.150 30 80.159 30 80.485 25 81.473 30
+47 2099 SAO 44780 13476+4648		76.858 35
HR 5235 η Boo 13499+1854	SB,NS 76.0-79.5 4*	76.299 35 78.150 30 79.360 30 80.154 30 80.159 30 80.482 30 81.473 30
HR 5323 14 Boo 14093+1326	SB 76.3-77.1 4*	78.150 30 79.360 30 80.154 30 80.159 30 80.476 30 80.482 30 81.473 30
HD 125229 +57 1499 14129+5711	SB	80.154 30
HR 5355 CS Vir 14131-1815	SB,VAR (128)	77.487 35 80.476 30 80.485 25
HD 126269-0 +16 2642 14194+1644	SP 80.2-80.5 2 (129)	81.473 30
HR 5435 γ Boo 14280+3845	SB 75.4-79.5 9 (130)	79.037 30 80.156 30 80.476 30 81.468 30 81.470 30 81.473 30
HR 5472 HD 129132 14358+2224	SB,NS? 76.0-81.5 17 (131)	80.160 30 80.485 25
HR 5475 π^1 Boo 14360+1651	HY,SB (132)	76.299 35
HR 5487 μ Vir 14378-0513	SB 76.3-77.1 4*	77.487 35
HR 5506 36 Boo A 14406+2730	SB (133)	79.532 30 80.154 30 81.470 30
HR 5531 α^2 Lib 14453-1538	OC,SB	79.537 30 80.485 25
HR 5538 39 Boo 14463+4908	SB (134)	79.188 57

TABLE I (Continued)

HR 5544 ξ Boo A 14468+1931	NS (135)	76.299 35
HR 5544 ξ Boo B 14468+1931	NS,AS 76.0-81.3 5* (136)	76.040 33 76.299 35 78.150 30 79.360 30 81.468 30
HR 5553 GL 567 14488+1933	SB,HY 79.5-79.5 1*	79.532 30 80.485 35 81.470 30
HR 5568 HD 131977 14517-2059	NS,SB (137)	76.299 35
HR 5633 HD 134064 15028+1850	VIS,SB 76.0-79.5 9* (138)	80.157 30 80.479 30 81.470 30
HD 134700 -15 4047 15062-1547	OC (139)	81.470 30
HD 135204 -00 2944 15088-0058	NS 76.3-79.4 4* (140)	77.481 35 80.160 30 80.476 30 81.468 30 81.470 30
HR 5676 χ Boo 15103+2932	SB?	77.487 35
HD 135774-5 +10 2818 15118+1005	SP	80.157 30 80.476 30 81.468 30
HR 5723 ε Lib 15188-0958	SB 76.3-76.5 3*	79.360 30 80.160 30
HR 5774 ν^2 Boo 15282+4114	VIS,SB? 75.6-81.5 8 (141)	77.481 35 78.147 30 78.614 30
HR 5834 ζ^2 CrB 15356+3658	SB (142)	76.296 35
HD 139691 WAK 1 CE 15363+3624	VIS 78.1-78.1 1* (143)	80.154 30 80.160 30
HD 140671 B 2367 15398-2226	VIS	80.482 30
HR 5868 λ Ser 15416+0740	SB 76.3-76.5 3*	77.481 35 78.147 30 79.360 30 79.529 30 80.160 30 80.477 30 80.485 25 81.470 30 81.473 30
HR 5914 χ Her 15493+4244	VAR	76.299 35
HR 5954 49 Lib 15547-1614	SB 76.3-76.5 3*	77.481 35 79.360 30
HR 5982 υ Her 15597+4619		76.299 35
HR 5983 HD 144208 15597+3654	SB 76.3-79.5 2*	77.487 35 78.150 30 78.617 30 79.529 30 80.160 30 80.477 30 80.725 30 81.470 30 81.473 30
HR 6005 HD 144889 16030+2205	SB	77.487 35 80.477 30 81.470 30 81.473 30
HR 6023 φ Her 16056+4512	SB,VAR	76.299 35
HR 6046 WRH 21 16082+3641	VIS,SB 76.3-79.5 3* (144)	76.457 35 77.487 35 78.617 30 79.360 30 79.363 30 79.529 30 80.157 30 80.160 30 80.725 30 81.473 30
HR 6053 HD 145997 16089-1817	OC (145)	80.485 30 81.470 30
HR 6064 σ CrB B 16109+3407	NS 81.4-81.4 1* (146)	80.157 30 80.160 30 80.479 30 80.725 30 81.468 30 81.473 30
HR 6103 ξ CrB 16182+3108	HY	76.299 35
HR 6117 ω Her 16208+1416	VAR,SB (147)	76.299 35
HR 6129 υ Oph 16224-0809	VIS,SB (148)	79.360 30
HR 6148 β Her 16259+2142	SB 75.6-79.5 11 (149)	78.615 30 80.477 30 80.485 25 80.723 30 81.468 30 81.471 30 81.473 30
HR 6168 σ Her 16309+4239	SP 72.3-81.5 24 (150)	81.468 30
HD 150365 -17 4616 16355-1752	OC (151)	80.485 30
HR 6237 HD 151613 16434+5658	SB 76.3-81.5 5 (152)	78.617 30 80.160 30 80.477 30 80.485 25 80.720 30
HR 6243 20 Oph 16443-1036	SB 76.3-76.5 2*	77.487 35 79.532 30 81.470 30
HR 6315 19 Dra 16555+6517	SB,VAR 76.3-76.3 2*	77.487 35 78.617 30 80.160 30
HD 154225 +40 3090 16590+4013	SP	80.157 30 80.479 30 80.482 30 80.485 25 80.723 30
HR 6388 HD 155410 17063+4054	SB 80.5-80.5 1 (153)	77.487 35 78.615 30 79.363 30 79.529 30 80.157 30 80.477 30 80.485 25 81.468 30 81.471 30 81.473 30
HD 156026 -26 12036 17100-2625		76.299 35
HR 6410 δ Her 17109+2457	SB 78.4-79.5 2 (154)	80.477 30 80.479 30 80.482 30 80.720 30 81.473 30 81.[illegible] 30
HR 6469 HD 157482 17185+4004	SB 80.5-81.5 6 (155)	80.723 30 80.725 30
HR 6497 HD 157978 17215+0741	SP 76.3-79.5 3* (156)	77.481 35 77.487 35 77.735 30 78.150 30 78.538 30 78.615 30 78.617 30 79.363 30 79.532 30 80.477 30 80.485 25 80.720 30 80.723 30 80.725 30 81.468 30 81.700 30
HR 6524 HD 158837 17264+0248	VIS,SB 76.5-79.5 6* (157)	80.477 30 80.723 30 81.468 30 81.700 30
HR 6588 ι Her 17366+4604	VIS,SB 75.6-79.5 4 (158)	78.147 30 78.538 30 78.609 30 78.615 30 80.160 30 80.482 30 80.720 30 81.468 30 81.471 30 81.473 30
HR 6661 Y Oph 17473-0607	SB,VAR	80.725 30
HD 163640 +18 3500 17520+1821	 79.4-81.5 5	78.617 30
HR 6692 HD 163685 17523-2845	OC (159)	77.487 35 80.482 30
HR 6697 HD 163840 17531+2401	SB 76.3-81.7 12 (160)	79.529 30 80.477 30 80.479 30 80.482 30 80.485 25 80.720 30
HR 6729 95 Her B 17573+2136	SB?	77.487 35 80.482 30
HR 6734 τ Oph A 17576-0811	NS,SB (161)	80.477 30
HR 6771 72 Oph 18026+0933	VIS 79.4-79.4 1* (162)	80.477 30 80.717 30 81.468 30 81.471 30 81.700 30
HR 6775 99 Her 18032+3033	NS,AS 75.7-76.5 5* (163)	77.481 35 79.363 30 79.529 30 80.477 30 80.725 30 81.468 30 81.471 30
HR 6812 μ Sgr A 18078-2105	OC,SB,VAR 78.7-78.7 1* (164)	80.482 30
HR 6902 HD 169689 18208+0759	SP	78.615 30 79.363 30 80.477 30 80.720 30 81.468 30 81.698 30
HR 6988 HD 171856 18319-2129	OC,SB (165)	80.482 30
HD 172806 +03 3777 18371+0356	SP	80.482 30
HD 172865 +30 3271 18374+3012	VIS 77.5-79.4 3 (166)	80.479 30 80.717 30 80.726 30 81.468 30 81.698 30

TABLE I (Continued)

HR 7063 β Sct 18419-0451	SB 76.3-79.5 4* (167)	78.615 30 79.363 30 80.720 30 81.471 30 81.703 30
HD 174016-7 +61 1771 18433+6150	SP	80.482 30
HR 7077 HD 174115 18437-1915	OC,VAR (168)	80.482 30 80.723 30 81.471 30
HR 7083 HD 174208 18443-0602	SB (169)	76.668 35 77.482 35 80.482 30 81.473 30
HR 7133 113 Her A 18505+2231	SB 79.5-79.5 1* (170)	77.487 35 77.733 35 77.736 20 78.538 30 79.532 30 80.720 30 80.726 25 81.468 30 81.698 30
HR 7135 HD 175515 18506+0629	SB	76.668 35 77.482 35 79.363 30 80.482 30 80.720 30 81.473 30 81.698 30
HR 7155 HD 175852 18522-2501	OC (171)	78.538 30
HR 7164 HD 176123 18536-1642	OC	81.703 30
HR 7165 FF Aql 18538+1714	SB,VAR (172)	80.725 30
HR 7176 ε Aql A 18551+1456	SB OC,SB?	76.668 35 77.482 35 79.363 30 80.720 30 81.473 30
HR 7195 HD 176704 18563-2459	OC (173)	78.538 30 81.703 30
HR 7205 HD 176903 18572-1915	OC (174)	80.723 30
HR 7209 14 Aql 18576-0351	VIS,SB?,HY 77.5-78.7 3* (175)	80.723 30 81.473 30
HD 176973 +18 3922 18576+1859	78.6-78.6 1* (176)	81.473 30
HD 178291 -19 5317 19029-1907	OC	81.703 30
HR 7265 HD 178555 19039-1958	VIS 76.3-81.4 5 (177)	81.473 30
HD 179143-4 +37 3357 19063+3738	SP	80.720 30 81.468 30 81.697 30
HR 7333 26 Aql 19152-0536	SB 78.7-79.5 2* (178)	76.668 35 80.723 30 81.471 30
HR 7342 υ Sgr 19160-1609	OC,SB,VAR (179)	76.668 35 79.532 30
HD 181731-2 +00 4182 19165+0019	SP	80.482 30
HR 7377 δ Aql Aa 19205+0255	AS,VAR 76.4-81.4 4 (180)	78.618 30 80.477 30 80.480 30 80.485 25 80.720 30 81.474 30
HR 7405 α Vul 19245+2428	SB?	80.728 30
HR 7418 β² Cyg 19267+2745	(181)	80.480 30 81.474 30
HD 184360 +20 4179 19289+2012	VIS (182)	77.482 35 80.482 30 81.700 30
HR 7441 9 Cyg 19309+2915	SB,VIS 76.3-81.7 12 (183)	76.449 35 76.668 35 80.480 30 80.482 30 80.717 30 80.726 30
HR 7466 WRH 23 Aa 19332+2907	VIS 76.5-79.8 4* (184)	76.668 35 80.480 30 81.468 30 81.700 30
HR 7476 54 Sgr A 19350-1631	OC,VAR (185)	80.723 30
HR 7478 φ Cyg 19354+2955	SB 76.3-81.7 14 (186)	81.468 30
HR 7479 α Sge 19356+1747	(187)	80.728 30
HR 7488 β Sge 19366+1715	(188)	80.728 30
HD 186745-6 +23 3760 19412+2342	SP,SB	80.482 30 81.700 30
HR 7536 δ Sge 19429+1817	SB,VAR 75.6-81.5 14 (189)	76.668 35 80.482 30 80.717 30 80.728 25
HD 187299 +24 3889 19442+2446	SB	78.615 30 80.717 30 81.468 30
HR 7546 AGC 11 AB 19445+1853	VIS 75.6-81.7 15 (190)	80.717 30
HR 7573 HD 187982 19478+2444	SP 76.4-76.4 1*	76.668 35 77.482 35 78.615 30 79.529 30 80.482 30 80.726 30 81.468 30 81.700 30
HR 7574 9 Sge 19479+1825	SB,VAR	77.487 35 78.615 30 81.468 30 81.474 30
HD 188262-3 +16 4053 19492+1631	SP	80.482 30
HR 7599 HD 188405 19500-0700	VIS 80.5-81.5 3 (191)	78.618 30
HD 188507 +22 3854 19504+2210	SB	76.668 35 77.487 35 80.480 30 81.468 30 81.703 30
HR 7609 S Sge 19515+1622	SB,VAR	80.725 30
HD 188827 -15 5513 19519-1543	OC	81.703 30
HR 7614 61 Sgr 19523-1545	SB	80.482 30
HR 7635 γ Sge 19533+1913	HY	80.728 30
HR 7653 NT Vul 19570+2729	SB,VAR 76.4-76.4 1*	76.668 35 77.487 35 78.618 30 79.529 30 79.773 30 80.480 30 80.728 30 81.468 30 81.474 30 81.703 30
HR 7658 HD 190009 19578-2253	OC,SB	81.703 30
HR 7678 HD 190603 20007+3156	SB,VAR (192)	77.487 35 78.615 30 79.530 30 79.773 30 80.480 30 80.717 30 81.468 30 81.703 30
HD 190916 +35 3953 20022+3530	SB (193)	77.487 35 79.532 30 80.480 30 81.468 30 81.703 30
HD 191566-7 +35 3994 20055+3511	SP (194)	80.485 30 80.723 30
HD 191766 +29 3926 20065+2959	SP	81.703 30
HR 7735 31 Cyg 20105+4626	SB,VIS,AS 76.4-81.5 9 (195)	76.668 35 80.723 30 81.474 30
HR 7751 32 Cyg 20124+4724	SB,VAR 76.5-79.5 2* (196)	77.487 35 78.538 30 78.610 30 79.773 30 80.480 30 80.723 30 80.726 25 81.468 30 81.703 30
HR 7770 35 Cyg 20148+3440	SB	76.668 35 77.487 35 79.773 30 80.480 30 80.717 30 81.468 30 81.703 30
HD 193410-1 +29 3989 20151+2911	SP	81.698 30
HR 7774 HD 193472 20153+1314	SB,VAR	76.668 35 78.615 30 79.530 30 79.773 30 80.480 30 80.723 30 81.471 30
HR 7775 HD 193452 20152-1506	OC (197)	78.538 30 80.485 30 80.723 30
HD 194121 -14 5734 20186-1426	OC (198)	80.482 30
HR 7806 39 Cyg 20199+3152		80.728 30
HD 194558 +39 4172 20212+3950	VIS 79.8-79.8 1* (199)	80.723 30

TABLE I (Continued)

HR 7850 θ Cep 20279+6239	SB 76.3-76.5 3*	77.487 35 78.618 30 79.773 30 80.480 30 80.723 30
HR 7852 ε Del 20284+1058	SB	80.728 30
HR 7871 ζ Del 20306+1420	SB,VAR?	80.728 30
HR 7895 HD 196753-4 20342+2320	SP,SB	80.723 30
HR 7921 49 Cyg A 20370+3157	SP 79.5-79.5 1 (200)	80.477 30 80.480 30 80.717 30 81.468 30 81.474 30 81.698 30
HR 7928 δ Del 20388+1443	SB,VAR	80.728 30
HD 197593 -16 5690 20396-1610	OC	80.483 30
HD 197684 +11 4368 20402+1157		81.698 30
HR 7939 30 Vul 20405+2455	SB	79.530 30 79.773 30 81.471 30 81.474 30 81.698 30
HR 7942 52 Cyg 20415+3021	(201)	80.728 30
HR 7948 γ² Del 20420+1546	SB? (202)	80.728 30
HR 7949 ε Cyg A 20422+3336	SB (203)	79.531 30 79.773 30 80.480 30 80.728 30 81.471 30
HR 7950 ε Aqr 20423-0952	SB?	80.482 30
HD 198287 +38 4235 20442+3855	VIS 78.6-81.4 1* (204)	80.480 30 80.720 30
HR 7977 55 Cyg A 20455+4545	SB,VAR (205)	77.487 35 78.615 30 79.532 30 79.773 30 80.480 30 80.717 30 81.471 30
HR 8007 BW Vul 20501+2809	SB,VAR	81.471 30 81.698 30
HD 199318-9 +14 4478 20517+1426	SP	81.703 30
HD 199394 +45 3327 20517+4558		80.726 30
HR 8050 HD 200245 20572+2807	VIS 76.6-76.6 1 (206)	80.477 30
HD 200428-9 +15 4320 20583+1522	SP	81.703 30
HR 8060 Fin 328 20587-2015	NS,VIS 76.5-81.5 4 (207)	80.477 30
HR 8086 61 Cyg B 21024+3815	VAR (208)	75.718 33 76.455 35 79.530 30
HD 201270-1 +45 3410 21033+4516	SP	80.483 30 81.703 30
HR 8115 ζ Cyg 21087+2949	SB	76.858 35 77.487 35 79.530 30 79.773 30 80.483 30 80.720 30 80.726 30
HR 8116 HD 202128 21088+1534	VIS,SB 77.5-81.7 13 (209)	77.635 67
HR 8123 δ Equ 21096+0936	NS,SB,VIS 75.5-81.7 17 (210)	80.728 30
HR 8131 α Equ 21108+0405	SB,SP 76.4-78.7 4* (211)	78.538 30 78.615 30 80.720 30 81.471 30 81.703 30
HD 202466 D 24 21109-0938	VIS 78.6-78.6 1* (212)	80.717 30
HR 8137 30 Cap 21123-1824	OC,SB? (213)	78.615 30 80.483 30 80.723 30
HR 8143 σ Cyg 21135+3859	SB	80.729 30
HR 8146 υ Cyg 21138+3429	SB (214)	80.729 30
HD 202929 WRH 21139-1328	VIS (215)	80.477 30 80.723 30 81.703 30
HR 8157 V1334 Cyg 21154+3719	VIS,SB,VAR 76.9-81.4 4* (216)	77.487 35 78.618 30 80.477 30 80.720 30 81.703 30
HR 8173 1 Peg 21175+1923	SB	80.729 30
HD 204971 -12 6026 21269-1243	OC	81.703 30
HR 8242 HD 205114-5 21281+5211	SP	80.483 30 80.720 30
HR 8264 ξ Aqr 21324-0818	SB,OC 75.7-78.7 4 (217)	76.859 35 78.615 30 79.773 30 80.485 30 80.718 30
HR 8279 9 Cep 21352+6138	B,VAR	77.487 35 80.483 30 80.720 30
HR 8295 44 Cap 21376-1451	OC	81.703 30
HR 8308 ε Peg 21393+0925	VAR (218)	80.726 25
HD 2068[illegible] -19 582[illegible] 21396-[illegible]	OC (219)	[illegible]
HR 83[illegible] 9 Peg [illegible]	VAR	[illegible]
HD 207936 -11 5690 21477-1102	[illegible]	[illegible]
HR 8355 Fin 358 21482-1007	VIS,OC 76.6-81.7 4 (220)	77.487 35 78.618 30 80.723 30
HD 208253 +51 2727 21498+5112	SP	80.483 30
HR 8383 VV Cep 21538+6309	SB,AS,VAR 75.7-79.5 6* (221)	77.487 35 79.773 30 80.720 30
HR 8454 π² Peg 22055+3241		80.729 30
HR 8465 ζ Cep 22074+5743	SB (222)	80.729 30
HD 210845 -12 6209 22081-1225	OC (223)	80.483 30
HR 8494 ε Cep 22114+5633	SB,VAR	80.729 30
HR 8498 1 Lac 22116+3715		80.729 30
HR 8518 γ Aqr A 22165-0153	SB 76.9-76.9 2* (224)	78.615 30 79.530 30 80.717 30 81.701 30
HR 8530 HD 212320 22183-0742	OC	81.701 30
HR 8538 β Lac 22196+5144		80.729 30
HR 8541 4 Lac 22205+4858		80.729 30
HR 8579 6 Lac 22262+4237	SB	80.729 30
HR 8580 HD 213428 22261-0325	SB	76.859 35 79.773 30 80.485 30 80.717 30 80.720 30 81.701 30
HD 214608 +43 4260 22344+4347	VIS 78.6-81.5 3 (225)	80.483 30 80.485 30 80.723 30
HR 8629 Kui 114 22356-0404	OC,VIS 76.6-81.7 11 (226)	80.485 30 80.726 30
HR 8632 11 Lac 22361+4345	HY	80.729 30
HR 8650 η Peg 22383+2942	SB,AS 75.8-80.5 12 (227)	80.485 25 80.718 30 80.720 30 81.474 30
HR 8665 ξ Peg A 22417+1139	SB	80.729 30
HD 215708 -03 5505 22420-0314	OC (228)	79.773 30 80.723 30
HR 8684 μ Peg 22452+24[illegible]		80.729 30
HD 216931 [illegible] [illegible]-0347	OC (229)	80.483 30 80.720 30 80.723 30
HR 8731 EW Lac 22527+4809	SP,SB	81.474 30 81.698 30
HR 8734 HD 217107 22531-0256	OC (230)	80.720 30 80.720 30
HR 8775 β Peg 22589+2733	VAR SB (231)	80.729 30
HR 8796 56 Peg 23022+2456	SB	80.726 30

TABLE I (Continued)

HR 8832 HD 219134 23085+5637	AS,VAR 76.9-76.9 1*	76.857 76.860 78.615 79.773 80.718 80.723	35 35 30 30 30 30
HD 219512 +34 4883 23112+3451	SP	80.718 80.723	30 30
HR 8858 ψ² Aqr 23127-0944	OC,SB?	81.701	30
HR 8879 HD 220035 23155-0627	OC	81.701	30
HR 8880 τ Peg 23157+2312	VAR,SB	80.729	30
HR 8893 66 Peg 23180+1146	VIS 76.9-79.8 4* (232)	80.718 80.723 81.698	30 30 30
HR 8905 υ Peg 23204+2251	HY	80.729	30
HD 221600 -05 6011 23283-0457	OC	81.703	30
HR 8940 71 Peg 23285+2157	SP,VAR 76.9-76.9 2*	78.615 79.530 80.718 80.723 81.698	30 30 30 30 30
HD 221914 +17 4946 23310+1753	AS	76.857	35
HR 8954 16 Psc 23313+0133	OC,SB (233)	76.857 76.922 78.539 78.615 79.773 80.718 81.701	35 35 30 30 30 30 30
HR 8961 λ And 23327+4555	SB,VAR 76.9-76.9 3*	78.539 78.615 79.530 79.770 80.723	30 30 30 30 30
HD 223617 +01 4786 23460+0141		80.726	30
HR 9038 HD 223778 23476+7459	NS,SB (234)	79.773 80.723	30 30
HR 9071 σ Cas B 23539+5512	SP,SB (235)	78.615 79.773 80.718	30 30 30
HD 224661 -06 6335 23545-0627	OC	81.703	30
HD 224945 -03 5750 23569-0319	OC	81.703	30

Binary star identification codes are as follows:

AS = astrometric binary
HY = Hyades member and known or suspected binary
NS = nearby star
OC = occultation binary
OL = overluminous star
SB = spectroscopic binary or variable radial velocity
SP = spectrum binary
VAR = star of variable magnitude
VIS = visual binary

NOTES TO TABLE I

(1) ADS 548A.

(2) This system has been only marginally resolved over 2 years of speckle interferometry. The last resolved measurements in 1980.5 and 80.7 gave separations of 0".037 and 0".045, respectively.

(3) ADS 721A.

(4) ADS 949A.

(5) The BSC notes that this object is probably single.

(6) ADS 995A.

(7) Component A of a wide visual double is a spectroscopic binary of period 4.5 years. The pair was resolved once by Koechlin et al (1979), with a separation of 0".055.

(8) ADS 1507B. Pleiades member.

(9) ADS 1507A. Pleiades member.

(10) Occultation measurements give a vector separation = 0".01.

(11) ADS 1630A.

(12) A visual occultation measurement gave a vector separation of 0".4.

(13) An occultation in 1973.0 gave a vector separation = 0".030 for this pair (Evans 1982).

(14) This object was resolved in 1981.7 at 0".056, a separation of 0".012 is predicted by spectroscopic analysis.

(15) The BSC notes a companion at 2" separation, with Δm = 5.

(16) The system closed from 0".076 in 1979.8 to 0".032 in 80.7, then reopened to 0".096 by 81.5. An occultation in 1977.7 gave a vector separation of 0".0213 (Evans 1982).

(17) ADS 2062A was found by occultation to be triple, with ρ's of 0".06 and 0".2, and Δm's of 0.8 and 1.8, respectively. We have observed this system for more than 5 years; it was unresolved from 1976.9 to 1977.1.

(18) ADS 2080A. The AB pair have a separation of 2".8 and a Δm of 2.7, so would be extremely difficult to observe by the speckle technique.

(19) Occultation vector separation = 0".05; member of Hyades moving group and spectroscopic binary of period 3.3 years.

(20) This probable Hyades member was observed in a 1968.6 occultation to have a vector separation of 0".2.

(21) This eccentric, highly inclined system (e = 0.73, i = 95°) has a period = 4.15 years and is only resolvable over part of its orbit. The pair was resolved as late as 1978.6, but unresolved in 1979.8.

(22) This 14.6-year spectroscopic binary (e = 0.72, i = 88°) was resolved by Labeyrie et al (1974) at 0".193 in 1973.4, but rapidly closed to under 0".033 by 76.0. It was again resolved in 77.7 and has increased in separation to 0".216 at its last observation.

(23) Algol. Bonneau's (1979) orbit predicts separations of 0".041 and 0".042 at these two respective dates.

(24) A visual occultation in 1975.59 gave a vector separation of 0".03.

(25) ADS 2368.

(26) Short period spectroscopic triple system.

(27) ADS 2552A; vector separation = 0".010 in 1973.0 (Evans 1982).

(28) This 2.63-year period spectroscopic binary has a vector separation of 0".011.

(29) A 1977.2 occultation gave a vector separation of 0".035 (Evans 1982).

(30) This 2.5-year astrometric binary was resolved in 1975.6 (ρ = 0".048), but has been unresolved since that time. Speckle observations are incompatible with the astrometric orbit of van de Kamp (1974) and probably refer to a 3rd component of the system.

(31) ADS 2661A. The vector separation in a 1977.1 visual occultation was 0".3.

(32) Pleiades member; vector separation = 0".0062.

(33) Electra. This Pleiades member had a vector separation of 0".010 and a Δm of 3.4 in 1972 (Evans 1982).

NOTES TO TABLE I (Continued)

(34) Pleiades member.

(35) The spectroscopic period for this Pleiades binary is 3.59 years; vector separation in 1969.7 was 0".010 (Evans 1982).

(36) Pleiades member; vector separation = 0".003.

(37) Pleiades member. A visual occultation gave a vector separation of 0".1.

(38) A 197[illegible] occultation gave a vector separation of 0".299 (Evans 1982).

(39) Vector separations of 0".031, 0".0017, and 0".00[illegible] were measured in 1971.8, 72.[illegible], and 72.2, respectively (Evans 1982).

(40) Pleiades member; variable?

(41) Vector separation = 0".0093 in 1973.1 (Evans 1982).

(42) The A component of ADS 2965 was resolved once in 1980.7, with $\rho = 0''.041$. Occultation measurements made in 1973.0 (Evans 1982) combine to give a separation of 0".033.

(43) ADS 2999A. Variable?

(44) ADS 3006A. A grazing visual occultation in 1977.2 gave a vector separation of 0".05 for the primary and 4".4 for the visual AB pair.

(45) Separation = 0".075 in 1979.0, based on occultation measurements by Evans (1982) and Radick and Lien (1982).

(46) ADS 3071A is a 0.8-year spectroscopic binary of separation 0".019, so far unresolved by speckle interferometry.

(47) ADS 3093C.

(48) Vector separation = 0".05.

(49) The primary is an occultation double of separation 0".04 and $\Delta m \approx 9$.

(50) A grazing visual occultation in 1975.2 gave a vector separation of 0".15.

(51) A 1974.3 visual occultation gave a vector separation of 0".1.

(52) ADS 3206.

(53) Vector separation = [illegible].

(54) Vector separation = 0".0089 in 80.[illegible] (Peterson et al. 1981).

(55) Vector separation = [illegible].

(56) Vector separation = 0".024 in 1979.2 (Evans 1982).

(57) This pair was resolved at 0".086 in 1979.1 by Hege et al. (1981).

(58) Separation in 1980.[illegible] was about 0".121, based on three occultation measurements by Evans and Edwards (1980), Peterson et al. (1981), and Evans (1982).

(59) ADS 3264A.

(60) Vector separation 0".0115.

(61) ADS 3605A is a 27-year SB, with a = 0".014.

(62) A visual occultation gave a vector separation of 0".1 in 1956.0.

(63) Vector separation in 1972.0 was 0".076 (Evans 1982).

(64) ADS 3701. Finsen and Worley's (1970) "highly conjectural" orbits predict that this pair should be easily resolved. Wilson (1936) determined a separation of 0".09 in 1934.9.

(65) Visual occultation measurements give a vector separation of 0".3 in 1974.8.

(66) ADS 4002A is a triple system, unresolved over most of its 9.2-year orbit. It was last resolved in 1979.8, with $\rho = 0''.017$.

(67) This object is a suspected visual double of separation 0".4. The IDS contains only one observation and rejects this reported duplicity, however.

(68) The reality of this occultation binary (vector separation 0".01) has been questioned.

(69) This pair is also a composite spectrum binary, a nearby star, and a possible triple system. The astrometric separation is 0".[illegible].

(70) Occultation triple. The close pair has a vector separation of 0".0014; the wider pair had a separation of 0".[illegible] in 1976.1, based on occultation measurements (Evans 1982; Dunham). This second pair closed from 0".066 in 1977.2 to 0".048 in 1979.0 (with a possible marginal resolution in 1977.8).

(71) ADS 5012A.

(72) This pair was resolved from 1976.9 to 78.1, but unresolved in 1979.8.

(73) ADS 5107A.

(74) Vector separation is 0".05.

(75) A grazing visual occultation gave a vector separation of 0".020 in 1975.8.

(76) A visual occultation in 1973.9 gave a vector separation of 0".1.

(77) A grazing visual occultation in 1977.3 yielded a vector separation of 0".05.

(78) ADS 5961A is an occultation double, with separation 0".045 in 1977.3.

(79) ADS 5983A is a 6.1-year spectroscopic binary, as yet unresolved by speckle interferometry. Occultation data have cast some question on the SB character of this pair.

(80) This pair was marginally resolved (0".038) in 1978.1, and unresolved in 1979.8.

(81) Vector separation = 0".03 in 1975.1, from a grazing visual occultation.

(82) ADS 6251A.

(83) A visual occultation in 1955.2 gave a vector separation of 0".1.

(84) A visual occultation in 1974.9 gave a vector separation of 0".2.

(85) Vector separation = 0".05, from a visual occultation measurement in 1971.3.

(86) Suspected occultation double, of vector separation 0".011 (White 1977).

(87) B 2527. Finsen measures from 1951 to 1959 were all less than 0".1 for this pair.

(88) ADS 6515A.

(89) ADS 6[illegible]A.

(90) Vector separation from a visual occultation of this pair was 0".3.

(91) A visual occultation in 1975.4 gave a vector separation of 0".1.

(92) Vector separation = 0".05.

(93) Merrill (1922) suspected this object to be double in his interferometric observations with the Mt. Wilson 100-inch.

(94) Vector separation = 0".05.

(95) ADS 7[illegible]. The IDS notes that this object is a rapidly moving binary, frequently unresolved.

(96) This pair was unresolved by Finsen's eyepiece interferometer in 1954 (Finsen 1977). Visual occultation measurements give a vector separation of 0".1.

(97) Unresolved by Finsen (1977) on 1954.33 ($\rho < 0''.108$).

(98) ADS 7292A is a spectroscopic binary, while AB are a visual pair of $\rho = 2''.7$. A rather large Δm of 2.1 magnitudes makes this wide pair difficult to observe, however.

(99) Vector separation = 0".0066 in 1973.2 (Evans 1982), while a grazing visual occultation on 1978.7 gave a vector separation of 0".1.

(100) Duplicity was suspected by Merrill in 1922, but is as yet unconfirmed by speckle interferometry.

(101) ADS [illegible]44.

(102) ADS [illegible]48[illegible]A is a spectroscopic binary and an occultation double of vector separation 0".004. Duplicity was first suspected by Merrill (1922).

(103) A visual occultation measurement in 1974.[illegible] gave a vector separation of 0".[illegible].

(104) This pair was unresolved in 1976.3, but resolved by Blazit et al. (1977a) in 1976.4 at $\rho = 0''.039$. Finsen (1977) was unable to resolve the stars in 1954.40 ($\rho < 0''.097$). An occultation of this pair gave a vector separation = 0".097.

(105) ADS [illegible]78.

(106) ADS [illegible]826A.

(107) Vector separation = [illegible].

(108) ADS [illegible]96[illegible].

NOTES TO TABLE I (Continued)

(109) The IDS lists a single observation of this object, made in 1843, which found a separation of 0".4. The object was later observed to be single by Burnham.

(110) Vector separation = 0".034 in 1979.3 (Evans 1982).

(111) Vector separation = 0".012 in 1974.4 (Evans 1982).

(112) A visual occultation gave a vector separation of 0".1 in 1971.3.

(113) This pair was resolved at 0".068 in 1979.4, and at 0".044 in 1980.2.

(114) ADS 8119B.

(115) ADS 8119A is a 1.8 year period spectroscopic binary, with a = 0".055.

(116) Vector separation = 0".0034 in 1970.4.

(117) ADS 8198. The IDS notes that the orbit is probably highly inclined. The stars were unresolved in 1925.

(118) Vector separation = 0".011.

(119) Vector separation from a visual occultation in 1976.4 was 0".1.

(120) A visual occultation gave a vector separation of 0".6 for this pair.

(121) ADS 8530A is a 1.1-year SB and member of the Coma cluster.

(122) ADS 8539A.

(123) This pair was resolved in 1978.4 (ρ = 0".110) by Blazit et al (1977b), but has otherwise been unresolved by speckle interferometry. With a spectroscopic orbital period of 6.7 years, this pair should become resolvable again in the near future.

(124) Vector separation = 0".040.

(125) These stars were resolved once in 1975.4 (ρ = 0".053) by Morgan et al (1976), but have been unresolved since that time. The system is noted to have variable radial velocity (Abt and Biggs 1972) and was suspected of being binary by Merrill (1922).

(126) At the time of the last resolved observation in 1979.4, this system had ρ = 0".085 and was rapidly closing.

(127) ADS 8891B is listed in the BSC as an astrometric binary of period 57 years and a = 0".13, and also as a spectroscopic binary of period 0.5 years.

(128) This Pleiades member is a 4.5-year SB.

(129) Separations in 1980.2 and 80.5 were 0".053.

(130) ADS 9300. This pair was resolved once in 1975.4 by Morgan et al (1978), with ρ = 0".069, but has been unresolved since 1977.1.

(131) This pair, after being unresolved from 1976.0 to 77.1, steadily increased in separation to 0".080 in 1978.6, then closed in to marginal resolution from 1980.5 to 81.5.

(132) ADS 9338A.

(133) ADS 9372A.

(134) ADS 9406B

(135) ADS 9413A.

(136) ADS 9413B.

(137) ADS 9446A.

(138) ADS 9505. Although Eggen's (1946) orbit says that this system is resolvable over most of its orbit (the predicted separation in 1981.47 is 0".101, for example), this binary has never been resolved by speckle interferometry in the dozen times it has been observed since 1976.0.

(139) Vector separation = 0".0541 in 1977.6 (Evans 1982).

(140) ADS 9544. The IDS lists this as a close, rapidly moving system, with separation 0".1 in 1958. Speckle measurements have as yet been unable to resolve this system.

(141) ADS 9688 closed in from 1975.6 to 76.5, was unresolved in 1977.1, and was resolved again in 1979.4. As of 1981.5 the system was again nearing the limit of our resolution.

(142) ADS 9717A.

(143) ADS 9731. Walker (1972) found a separation of 0".1 for this pair, but so far speckle interferometry has not been able to confirm this value.

(144) Observations listed in the IDS for 1937 and 1940 found separations of 0".1, while the object was observed to be single in 1949 and 1950.

(145) A visual occultation in 1977.6 gsve a vector separation of 0".03.

(146) ADS 9979B.

(147) ADS 10054A.

(148) RST 3949A.

(149) This pair was resolved by Blazit et al (1977a) in 1975.6 (ρ = 0".043), but has been unresolved since that time.

(150) This object, incorrectly listed as τ Her in Paper I, was first resolved in 1972.28 by Labeyrie at al (1974), with ρ = 0".115. The pair closed to under 0".035 in 1976.3, opened back up to 0".119 by 79.4, and reclosed by mid 1981.

(151) A visual occultation in 1979.5 gave a vector separation of 0".04.

(152) This pair has dipped above and below our limit of resolution several times over 5 years of speckle observations: it was resolved in 1977.5 and 81.5, but single in 76.3, 79.4, and 79.5. Abt and Levy (1974) have determined a 3.8-year period spectroscopic orbit for this system.

(153) This system was marginally resolved in 1980.5.

(154) ADS 10424 was resolved in 1978.4, but unresolved by 79.5.

(155) This system underwent a large change in angle between the years 1980.5 (θ = 85°.7, ρ = 0".047) and 81.5 (θ = 134°.1, ρ = 0".065), and may have gone through closest approach at this time.

(156) Spectroscopic triple system, with 3.2-year and 3.76-day periods.

(157) ADS 10607 was listed in the IDS as single in 1957 and 1959 although numerous observations between 1911 and 1955 did resolve the stars at 0".1 separation.

(158) This system was resolved once in 1975.6 by Blazit et al (1977a).

(159) Vector separation = 0".3, from a visual occultation.

(160) These stars were first resolved in 1976.3 with ρ = 0".110, then remained unresolved for over 5 years until a separation of 0".098 was measured in 1981.5. Interestingly, this interval is just twice the preliminary orbital period of 940 days determined by Culver et al (1980).

(161) ADS 11005A.

(162) ADS 11076. A note in the BSC reads as follows: "Component B in notes to ADS 11076 not assigned letter: doubtful, *separation 0".1 if real*".

(163) ADS 11077. The AB pair (separation ~ 1".7) has a large Δm of 3.4 magnitudes, so is not observable. We have so far been unable to resolve the astrometric companion of one of the components, either.

(164) Occultation binary, vector separation 0".011. The Δm for this binary is 2.9 magnitudes, so this is a difficult object to observe by speckle interferometry.

(165) A visual occultation in 1925.4 gave a vector separation of 0".1.

(166) ADS 11579. This system closed from 0".11 to 0".05 during the years 1977.5 to 79.4. The 90-year orbit of Baize (1950) predicts a closest apparent separation of ~0".016 in 1978.8, but speckle measurements suggest that closest approach occurred in about 1980.2.

(167) This pair is a 2.3-year period spectroscopic binary.

(168) A visual occultation measurement in 1976.6 gave a vector separation of 0".2.

(169) ADS 11719A is a 2.4-year period spectroscopic binary.

(170) ADS 11820A has a spectroscopic period of 0.7 years.

(171) A visual occultation gave a vector separation of 0".1.

(172) ADS 11884A is a 3.9-year period SB. The radial velocity may vary on a timescale of 11.3 years.

(173) Vector separation = 0".1.

(174) Vector separation = 0".1, from a visual occultation observation made in 1975.8.

(175) A 3105. The IDS notes: "Rapidly moving binary, position angles scattered, distance 0".1". The BSC lists a separation of 0".099.

(176) ADS 11957Aa.

(177) ADS 12096. The BSC lists this object as double with a = 0".129. Finsen (1977) reported the object as single on eight occasions from 1950 to 1963. Speckle observations from 1976.3 to 78.6 were also unable to resolve the pair. Starikova and Tokovinin (1982) did measure a separation of 0".105 in 1981.4, however.

NOTES TO TABLE I (Continued)

(178) This pair is a highly eccentric spectroscopic binary, of period 0.7 years.

(179) Vector separation = 0".011; period for the SB = 138 days.

(180) The BSC lists the A component of δ Aql as a 3.4-year astrometric binary, with a = 0".058. The pair has been resolved only once by speckle: ρ = 0".132 in 1979.5 (Koechlin et al 1979). Osvalds' (1958) orbit predicts that all these observations should be resolved.

(181) ADS 12540B = Albireo.

(182) ADS 12594. The IDS reports a separation of 0".4 for 1920.83, with the note "Chandon suspects"

(183) This system dips above and below our limit of resolution over a period of ~3 to 4 years. The stars were unresolved from 1976.3 to 76.4 and again in 79.8, but barely resolved from 1977.5 to 79.4 and after 81.5. The spectroscopic period is 4.7 years.

(184) ADS 12696.

(185) A visual occultation observation gave a vector separation of 0".1.

(186) This pair was unresolved from 1976.3 to 77.7, and only marginally resolved from 1978.5 to 81.7. The spectroscopic period is 1.2 years.

(187) ADS 12766A.

(188) Pleiades member.

(189) This system has a very eccentric apparent orbit of period 10.2 years, and is unresolvable over part of that orbit.

(190) ADS 12973 was marginally resolved in 1980.5 and 81.4, with a large angular change in the interim. Speckle observations indicate that modifications are needed to Finsen's (1937) orbital elements.

(191) ADS 13104. These stars have steadily decreased in separation for over 150 years, according to observations dating as far back as 1826 in the ADS and IDS. After reaching minimum separation in about mid-1978, they opened up to about 0".1 by mid-1981.

(192) ADS 13335A.

(193) ADS 13374A.

(194) ADS 13429A.

(195) ADS 13554A is a 10.4-year SB, unresolved from 1976.4 to 79.5, then marginally resolved in 1980.5 and 81.5. The Δm for this eclipsing system is 2.6 magnitudes, and Wilson's (1950, 1955) observations are considered suspect.

(196) Variable and spectroscopic periods are 3.1 years, with a 1.1-year period also possible.

(197) ADS 13717A is the B component of a multiple system with HR 7776. BC had a separation of ~0".022 in 1977.5 (from occultation data of Radick and Lien 1980 and Evans 1982); AB have a separation of 0".9, but a Δm of ~4, making speckle observations virtually impossible. Component A is an occultation binary of visual vector separation 0".05 in 1976.9.

(198) A visual occultation measurement gives a vector separation of 0".05.

(199) ADS 13833. The ADS lists a separation of 0".25 in 1886.8, opening to 0".34 in 1906.34. By 1953 the stars had closed to 0".1 and the IDS lists the pair as single or round from 1953 to 1960.

(200) ADS 14158A. The AB components form a visual pair of ρ = 2".5 and Δm ≈ 2.3. The IDS says that component A is a composite spectrum binary found single by WRH. It was resolved at 0".244 by Koechlin et al (1979) in 1979.5. The B component is a spectroscopic binary.

(201) ADS 14259A.

(202) ADS 14279A.

(203) ADS 14274A.

(204) ADS 14314AB. The IDS notes that the pair appeared single in 1960.

(205) ADS 14337A.

(206) ADS 14565. This pair was resolved at 0".226 in 76.6, while the BSC lists a separation of 0".110. A note in the IDS says: "Too close after 1952. No certain change in angle"

(207) This system has a highly eccentric apparent orbit, with ρ closing from 0".112 in 1976.6 to <0".041 in 1978.8 (Koechlin et al 1979), then opening to 0".103 by 1981.5

(208) ADS 14636B.

(209) ADS 14761. This 34.4-year binary was unresolved in 1977.5 and resolved in 78.6 at 0".071. This 2.1-meter observation was included to set an upper limit to ρ during the time interval between these published observations

(210) ADS 14773. Components of this highly inclined (i = 100°) system are briefly unresolvable by speckle interferometry. Measurements are in reasonably good agreement with the 5.7-year orbit of Luyten and Ebbighausen (1934)

(211) Note in BSC: "Separation 0".08. May be single star.". Note in IDS: "Spectrum composite. WRH checks for duplicity (in 1949). Single.".

(212) The IDS lists separations of 0".5 in 1876 and 0".3 in 1923, with a Δm ≈ 2. A note in the IDS states that the duplicity is doubtful, however.

(213) Vector separation = 0".1, from a visual occultation.

(214) ADS 14831A

(215) Note in IDS: "Checked for duplicity (in 1949). Single.".

(216) ADS 14859. This is listed in the IDS as a rapidly moving pair, unresolved on numerous occasions. The BSC gives a separation of 0".130 and a period of 32 years.

(217) The vector separation of this pair is 0".02. The stars were marginally resolved in 1977.5 (ρ = 0".033), but otherwise unresolved by speckle interferometry. Failure to resolve these two stars may be due in part to their large Δm, estimated at about 2 to 3 magnitudes.

(218) ADS 15268A.

(219) Vector separation in 1977.0 was 0".062 (Evans 1982).

(220) This binary has a highly elliptical apparent orbit. The stars were resolved in 1976.6 and 81.5 (0".096 and 0".067 separation, respectively) but unresolved in 1976.9. An occultation in 1978.4 yielded a vector separation of 0".0358 (Radick and Lien 1980).

(221) This 20.34-year spectroscopic and astrometric binary has a = 0".034.

(222) Red star Pleiades group.

(223) Vector separation = 0".004 in 1970.9 (Evans 1982).

(224) ADS 15864A.

(225) ADS 16138. This highly inclined system (P = 30 years, i = 85°) underwent a quadrant change in 1980, becoming temporarily unresolvable. These observations, as well as the resolved measurements of 1978.6 and 81.5, are in reasonable agreement with the orbit of Cester (1962).

(226) The orbit of Baize (1976) predicts a closest approach (ρ = 0".026) in 1981.6. Speckle measurements on either side of this date (0".065 in 1979.8, 0".048 in 81.7) suggest that closest approach actually occurred in about 1981.8. Occultation measurements in 1973 and 1974 (Evans 1982, Dunham) suggest a possible 3rd component.

(227) ADS 16211A was resolved in 1975.8, unresolved from 1976.4 to 78.6, then resolved again from 79.8 to 80.5. Speckle measurements are in poor agreement with van de Kamp's (1957) orbital solution, which predicts that the pair is never resolvable by existing telescopes.

(228) Vector separation = 0".009 in 1975.9 (Evans 1982).

(229) ADS 16392A.

(230) A grazing visual occultation in 1976.5 gave a vector separation of 0".02.

(231) ADS 16483A.

(232) ADS 16715. Interferometric double.

(233) Vector separation = 0".011.

(234) ADS 17062A

(235) ADS 17140B.

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[illegible]

THE TRUE NODAL QUADRANT OF CAPELLA*

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I. Introduction

The absolute orbit of the binary system comprising Capella is known with high accuracy from the spectroscopic orbit of Batten and Erceg (1975) and the apparent orbit of McAlister (1981). Indeed the apparent orbit of Capella probably qualifies as the most accurately determined orbit for a resolved binary system due to the large number of revolutions over which the system was measured by a variety of interferometric techniques. Capella is thus the only system whose orbit can serve as an external calibration object for binary star interferometry.

In spite of this agreeable situation, the ambiguity of the proper quadrant for the longitude of the ascending node Ω has apparently never been settled. In the pioneering discussion of Anderson (1920), the method of eliminating the 180° quadrant uncertainty is described in principle, but one only assumes that Anderson was able to settle upon the correct quadrant when confronted with the small Δm exhibited by the essentially coequally evolved stars of Capella. It will be seen from the present analysis that, contrary to intervening studies, Anderson did indeed place the secondary at the appropriate position angle. Subsequent interferometric measurements by Merrill (1922) likewise contain no specific comment about quadrant determination, and it may be that *Merrill's 1921 results simply reflect the adoption of* the quadrant chosen by Anderson less than two years earlier. Capella was not resolved again for nearly half a century until Kulagin (1970) observed the system some 167 revolutions after Merrill's last measure on 1921 April 1. Kulagin pointed out the 180° ambiguity of position angle measurement considered by many to be inherent in interferometric observations and thus adopted the quadrant of Anderson (1920). Fortunately, an amount of time similar to that separating Kulagin's and Merrill's measurements elapsed after the 1968–69 Pulkova results, and Capella continues to be regularly observed by the technique of speckle interferometry since the first measurements of Labeyrie et al. (1974) in 1971. A complete listing of all reliable interferometric results for Capella is given by McAlister (1981).

Actual quadrant *determinations have been given by* Heintz (1975) and by Koechlin, Bonneau and Vakili (1979). In an astrometric analysis, Heintz (1975) found a photocentric semimajor axis of 0″008 ± 0″005 with an orientation implying that the node lies in the first quadrant. The large relative error in the photocentric scale makes this only a marginal determination. Koechlin et al. (1979) observed Capella with a two-telescope interferometer using a baseline of 13.8 meters. Visual measurements *of the fringe visibility on two nights* permitted an analysis of the true orientation indicative of a nodal quadrant in agreement with Heintz (1975). McAlister (1981) adopted the quadrant found by Heintz (1975) and Koechlin et al. (1979) and reversed the Mount Wilson position angles.

Resolution of the quadrant ambiguity for Capella is made particularly difficult because of the small magnitude difference between the components. From an analysis of the secondary spectrum, Wright (1954) found Δm = 0.25 magnitude corresponding to an intensity ratio I_2/I_1 = 0.79. Bagnuolo (1983) has analyzed video speckle observations of Capella furnished by E. K. Hege and found Δm = 0.21 ± 0.04 magnitude using a variation of the "shift and add" (SAA) algorithm described by Bates and Cady (1980). This analysis implied that the secondary was nearly 180° away from the position angle predicted by the orbit of McAlister (1981). Unfortunately the absolute orientation of these data was not known with sufficient certainty to warrant a definitive statement concerning Ω. We present here an analysis of photographic speckle observations of Capella from which we have been able to establish the correct nodal quadrant.

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*[illegible] No. [illegible]

II. Analysis

Eight photographic speckle transparencies obtained by McAlister (1977) on 1976 December 3 were analyzed. Because of the nonlinearities and adjacency effects inherent in photography, quantative estimates of Δm are not expected, rather the goal was simply to resolve the 180° position angle ambiguity. Care accordingly was *taken to preserve the absolute orientation of the data*.

A. *Frame Intensity Digitization*

The frames were digitized in 256 × 256 square pixels 20 μm on a side with 10-bit resolution in density (steps of 0.005) by means of a microdensitometer. The area covered on each frame was about 1″54, centered on the apparent light centroid.

The transformation of pixel density (D) to intensity (I) was the next step. The first method assumed, following (Goodman 1968), that the combined gamma for the two-stage photographic process is about 2.0 (where $\gamma_1 \sim$ 2–3, $\gamma_2 \sim 1$) and extrapolated the toe of the curve to give zero intensity for the lowest pixels in the frame (D = *600 units*). *A variation of this method was to assume a* constant fog in the central region of the frames, which will be processed further. The zero-intensity pixels have D = 450. A third method was a fit demanding that the distribution of intensities should match a theoretical distribution based upon a double-star intensity ratio of 0.82 ($\gamma \sim 1.5$). Finally as a check on the reduction process, an (unrealistic) linear fit in the D,I plane (roughly equivalent to γ = 3.2) was used. Figure 1 is a plot of the transformations used.

B. *Shift-And-Add Analysis*

The frames were next analyzed by a variation of the SAA algorithm used by Bagnuolo (1983). This procedure produces a composite image containing "center", "principal", and "ghost" spots by "*shift-and-adding*" about the brightest (or dimmest) pixels of a frame. For superposition about the brightest pixels the center and principal spots tend to form a replica of the double star. "Wrong-way" superpositions tend to produce the ghost spot. In principle, resolution of the position angle ambiguity is accomplished by simply identifying the brighter, i.e., the principal spot, of the two outer spots.

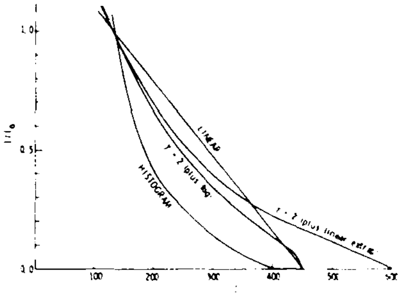

Fig. 1. Transformations of digitized density (D) to intensity (I), where for convenience I_0 was set at 200 units.

In each frame a 160 × 160 pixel area about the intensity centroid was used for further analysis. The frames were rectified for the overall (Gaussian) falloff in intensity with distance from the center. The half-power point, 111 pixels from center, was estimated by summing the centered frames into a single "long-exposure".

The shift-and-add superpositions were done for the top 1% and bottom 4% of the pixels (in intensity) in a central 133 × 133 pixel region, producing 27 × 27 pixel composite images. These levels were chosen to permit unambiguous determination of Ω.

The 27 × 27 pixels composite images were further analyzed by 13 parameter least-squares fits which included the following parameters:

1. overall tilt of the form $a_1x + a_2y + a_3xy$ (3 parameters),
2. (x,y) position of the principal spot (2 parameters),
3. heights and widths of the principal, ghost, and center spots, assuming Gaussian shapes. (The principal and ghost spots are assumed to have the same width.) Because of the possibility of a small noise spike, the central five pixels were not fitted (five parameters).
4. the background, assuming a Gaussian plus constant model (three parameters).

Figure 2 presents a typical result for the top 1% superposition, where the first transformation mentioned above was used. Both the fitted background and the central spot have been removed. The figure clearly shows that the principal spot, and hence the secondary stellar companion, lies in the south direction, with a position angle of about 186° instead of 19° predicted by McAlister's (1981) orbit. Thus, the original orientation of Anderson is verified. The additional 13° discrepancy is not considered *significant because the exact position angles of the* frames were not calculated for this analysis.

Table 1 summarizes the SAA results. In it are listed the relative intensities of the spots, their widths, and the estimated *rms* deviations of the residuals, s. The last column gives the difference between the principal and ghost spots in units of s, and is thus a conservative estimate because it assumes that each spot rests upon only two independent pixels of noise and that there are no large-scale axially symmetric features in the residuals. As can be seen, the direction determined by the high-pixel super-

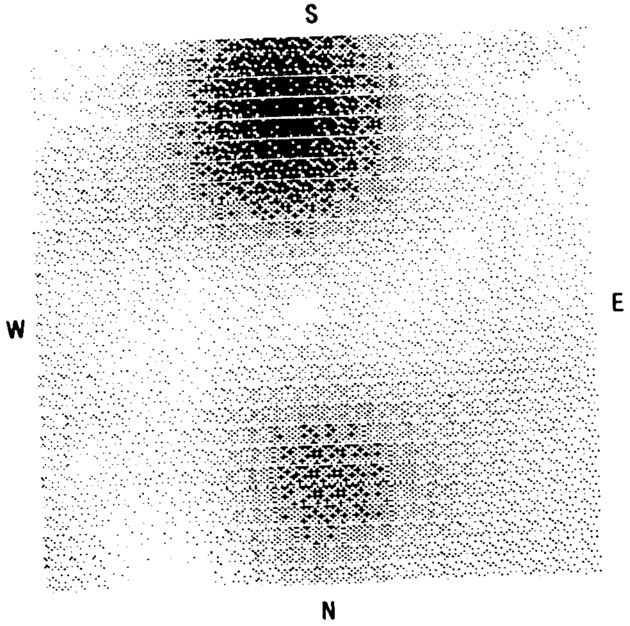

Fig. [illegible] The principal and ghost spots from the top 1% SAA are shown after the center spot and background have been subtracted. A 64-level gray scale has been used. The location of the principal spot to the south indicates that the fainter component of Capella was to the south of the brighter component at the epoch observed here.

TABLE I

SAA Results (Center Spot Height = 100)

Pixels	D.I Trans	[illegible]	[illegible]	θ	δ	δ/[illegible]	[illegible]	z
top [illegible]	[illegible]	3.946	[illegible]324	[illegible]	[illegible]	0.464	[illegible]	[illegible]
top [illegible]%	γ = 2	3.939	1.30	56.95	33.27	0.497	4.922	7.00
	γ = 2 + fog	3.975	1.314	66.48	34.43	0.518	4.980	6.44
	histogram	3.959	1.316	66.84	34.65	0.518	4.977	6.46
	linear	4.165	1.484	57.28	38.75	0.576	4.961	5.74
bottom 4.%	γ = 2	4.889	4.226	-37.5[illegible]	42.86	[illegible]	[illegible]	3.60
	γ = 2 + fog	4.830	4.134	-36.78	-40.01	1.087	[illegible]	2.71
	histogram	4.936	4.163	-37.49	-41.68	1.117	1.038	4.03
	linear	4.673	1.728	-34.77	-35.[illegible]	1.004	[illegible]	0.09

position has a very high degree of confidence.

The low-pixel superpositions produce "negative" spots and according of theory, Bagnuolo (1982), the most negative of the outer spots is in a direction opposite to the true position angle. These results therefore corroborate the direction found from the high-pixel SAA but with lower confidence. They also seem to be more dependent on the D,I transfer function chosen.

C. *Screened-Shift-and-Add Analysis*

The concept of SAA may be extended by requiring that the background about bright speckles be minimal. This procedure, hereafter referred to as "screened-shift-and-add" (SSAA), is a quantative procedure of searching for isolated "uncorrupted" speckle pairs on a double-star speckle frame.

The SSAA procedure starts with a digitized frame which is sampled at intervals given by the separation of the components determined by SAA. The sampling resulted in production of 1080 strips of data 15 points long. The separation between points of adjacent strips was at least 1.1 Airy radii.

Each data strip was examined for patterns of four adjacent points of the form $I_1 < x < h > I_2$ or $I_1 < h > x > I_2$ where $h \geq a\langle I\rangle$ and I_1 and $I_2 \leq h/b$, where $\langle I\rangle$ is average intensity and x is an unrestricted intensity. Parameters a and b are set low enough to generate a significant number of isolated bright speckles.

The composite four-point image produced by summing all occurrences satisfying the above conditions may be denoted by L_1, H_1, H_2, L_2. An estimate, r, of the intensity ratio may be made from the background subtracted ratio of H_1 to H_2, i.e., $r = (H_1 - \bar{L})/(H_2 - \bar{L})$ where $\bar{L} = (L_1 + L_2)/2$. More importantly for this case, the procedure also determines a dominant direction because the lesser of H_1, H_2 is in the direction of the true position angle. As a check on the precision of this procedure one can also define quantities r_i for each occurrance and estimate their dispersion.

Table II shows the SSAA results for the $\gamma = 2$ transfer function and several values of parameters a and b. As in Table I, one can define significance values, z, in units of the estimated standard deviations s. It can be seen that the direction found is highly significant. Indeed, even the distribution of "right way" "wrong way" occurances (N_r, N_w) is significant. The bottom of the table shows results using the linear transfer function and showing that even with this assumption the results are significant.

III. Conclusion

The results presented here unambiguously indicate that on 1976 December 3, the fainter star in the Capella system was to the south of the brighter component. The speckle observations contributing to this conclusion were obtained at a wavelength of 5520 Angstroms where the G5 III star is brighter. We thus conclude that the correct nodal quadrant for Capella is that given by Anderson (1920) and that the value for the longitude of the ascending node as determined by McAlister (1981) should be amended to Ω = 220°2. With data that can be more accurately calibrated for intensity such as that produced by speckle cameras using solid-state detectors, the shift-and-add algorithm is likely to be a valuable tool in determining astrophysically useful magnitude and color differences among the components of binary systems having separations down to the diffraction limits of large telescopes.

TABLE II

SSAA Results

Trans	a	b	N_r	N_w	r	s	z
γ = 2	1.3	0.0	[illegible]	161	0.894	0.160	13.80
		1.0	243	154	0.910	0.163	11.00
		1.5	93	55	0.890	0.124	10.84
	1.4	0.0	118	65	0.892	0.119	12.28
		1.0	108	65	0.900	0.121	10.87
		1.5	50	35	0.918	0.082	9.18
	1.5	1.0	43	27	0.911	0.103	7.23
	1.55	0.0	29	14	0.875	0.107	7.66
linear	1.3	1.0	209	125	0.902	0.142	12.56
		1.5	205	116	0.897	0.134	13.73
	1.4	1.0	99	45	0.907	0.115	9.30
		1.5	87	42	0.906	0.112	9.49
		2.0	71	36	0.911	0.108	8.56
	1.5	1.0	37	13	0.859	0.100	10.00
		1.5	36	12	0.861	0.092	10.45
	1.6	1.0	15	7	0.762	0.068:	14.69:

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STANDARD STARS FOR BINARY-STAR INTERFEROMETRY*

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We present a list of 26 binary star systems that propose that they be adopted as standards by all interferometric observers of binary stars. This will permit the discovery and elimination of systematic effects among observers and will also provide a readily available means of calibration.

Key words: binary stars — interferometry — standard stars

I. Introduction

In the course of compiling a catalog of interferometric measurements of binary stars (McAlister and Hartkopf 1983), we have been struck by the difficulty of comparing the results from two or more groups of observers in order to search for systematic effects that may exist in these measures. There are occasional hints that such discrepancies do exist, but we have not found it practicable to establish any corrections which might at least put all interferometric observers on the same "system." This is due to many reasons: the small number of groups working in the field, the small probability of two groups having nearly simultaneous access to the few large telescopes accessible to them, the large number of potential systems in both hemispheres from which to choose, etc. Little can be done to alleviate most of these obstacles, but a significant step in the right direction will be made if all interferometric observers of binary stars will agree to observe a small set of standard systems at every possible opportunity. The purposes of this paper are thus to propose a set of standard binary stars generally accessible to all observers, both in terms of declination and angular separation, and to recommend that these objects be given high priority in the various binary-star interferometry programs currently underway or planned for the future.

II. Discussion

Two systems which have been extensively observed by many teams are Capella and β Cephei. An intercomparison of the results from various groups using several different interferometric techniques was made in the orbital analysis of Capella by McAlister (1981). It was there suggested that the system's motion is now well enough known so that Capella may qualify as the only binary system whose dynamical motion can be used as an accurate external calibration for interferometric observations. Unfortunately, Capella never exhibits an angular separation greater than about 0.055 and thus is only resolvable by telescopes with apertures in excess of 2.5 meters (in the case of speckle interferometry) and is only accurately measurable by 4-meter class instruments. Thus we conclude that there is no system whose orbital elements can furnish general and accurate calibration potential. Although accurate calibration is not the primary purpose of the list of standard binaries proposed here, some observers may find these systems useful for that purpose, particularly when it is not feasible to secure an independent calibration at a telescope one is using as a visitor. It is surprising how rarely are effective focal lengths known to within 5%.

The other system which has received wide speckle interferometric attention is β Cep for which the observations are shown in Figure 1. This binary has been observed by the C.E.R.G.A. group (e.g., Bonneau et al. 1980) using telescopes ranging from 4 to 5 meters in aperture for observations prior to 1977 down to 1.9 meters in aperture after that date; by the Imperial College group (Morgan et al. 1978; Morgan, Beckmann, and Scadden 1980) using the 2.5-meter Isaac Newton telescope; by the University of Erlangen-Nurnberg group (Weigelt 1978) on one occasion using a 1-meter telescope; by the Special Astrophysical Observatory (U.S.S.R.) group (Dudinov et al. 1982) on one occasion using the 6-meter telescope; and by the Georgia State University group (e.g., McAlister et al. 1983) using the 2.1-meter (open circles in Fig. 1) and 4-meter (filled circles) KPNO telescopes. The observations clearly show the ten years' worth of orbital motion, as well as scatter not always attributable to small apertures and hence low intrinsic accuracy. This may well be the case with the measurement by Weigelt (1978). In contrast, the 10° position angle discrepancy for the 1975.55 result obtained by the Imperial College observers is probably the result of a systematic effect suggested and later confirmed by that group (Morgan et al. 1978, 1982).

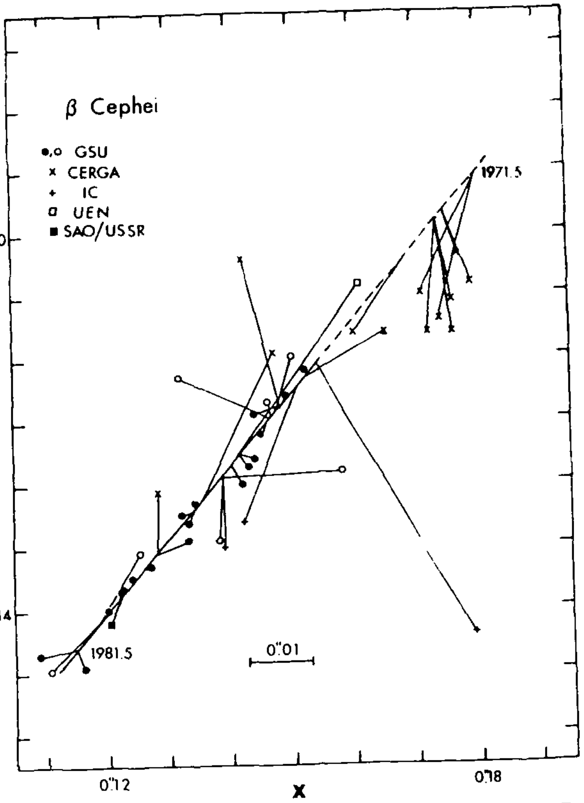

FIG. 1—Speckle observations of the binary star β Cep obtained by five different groups between 1971 and 1981 are shown. The solid line is a fit to the GSU KPNO 4-meter observations (filled circles), and the dashed line is an extrapolation back in time to the epochs of the early CERGA observations. The observations are plotted in cartesian coordinates instead of the usual position angle and angular separation.

The orbital motion of β Cep has been modeled to first order by a linear fit to the GSU KPNO 4-meter observations as shown by the solid line in Figure 1. An extrapolation back to the earlier C.E.R.G.A. results is shown by the dashed extension of the solid line. The departure of the early results from this extrapolation is no doubt partly, or perhaps primarily, due to elliptical motion although the curvature in the orbit prior to 1975 that is required to fit the observations seems too abrupt in light of subsequent motion to be fully due to inadequate modeling. The dispersion in the 4-meter observations used to determine the linear fit is ± 0°55 in position angle and ± 0.″0026 in angular separation. Our 2.1-meter data have dispersions of ± 2°2 and ± 0.″0094. The values for the 4-meter measures approach the limiting accuracies of ± 0°2 and ± 0.6% originally estimated for the 4-meter speckle results (McAlister 1977). As might be expected, larger telescopes give more accurate results for binary-star speckle interferometry than do smaller telescopes. It might also be pointed out that the scatters in the θ and ρ directions for the 4-meter observations are of comparable size, as is also the case for the 2.1-meter measures.

The binary star θ Virginis has been regularly observed by us since its first resolution in early 1976 (McAlister 1977) and is included in our proposed list of standard

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*Astronomical Contribution from Georgia State University No. 73

systems. *It is an excellent object for this purpose*, having moved through only 3° of position angle with essentially fixed separation over a five-year interval. A linear fit to our 19 4-meter speckle observations of θ Vir shows dispersions of ± 0°53 and ± 0″0048 corresponding to a precision of 1%. This system was used as an external calibration object in a series of speckle measurements from the KPNO 2.1-meter telescope (McAlister and Hendry 1982).

The three binary systems whose observations are briefly discussed above are examples of what may be learned about systematic effects within and among the results of different observers. In order to greatly expand the possibilities of such discussions, we have selected 26 binary-star systems which could constitute a set of standard systems for interferometric observers. These objects, which are presented in Table 1, were chosen first on the basis of being uniformly distributed along the celestial equator and have an average declination of +4°7. They are thus easily accessible to observers in both hemispheres. Current angular separations range from 0″24 to 0″82 with usually only very gradual orbital motion. Table 1 lists various identifications, accurate 1950.0 coordinates, the combined visual magnitude, the magnitude difference, the number of interferometric observations recorded in the catalog of McAlister and Hartkopf (1983), the epochs of the first and latest published observations, the average position angle and angular separation over these epochs with dispersions that have been divided by $(t_l - t_f)$ as indicators of annual orbital motion, and a reference to any existing orbit.

III. Conclusion

We encourage the adoption of the objects in Table I as a set of standard systems for binary-star interferometry. This will be a major step toward the identification of systematic effects that now are only suspected to exist between different observers and different techniques. It will also permit a reliable means of calibration when circumstances at the telescope prohibit an accurate independent calibration.

The authors would be happy to provide a copy of their *Catalog of Interferometric Measurements of Binary Stars* to interested investigators.

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TABLE I

STANDARD STARS FOR BINARY STAR INTERFEROMETRY

HR	ADS/Name	SAO	α (1950)	δ (1950)	m	Δm	N_{obs}	t_f (1900+)	t_l (1900+)	<P.A.>	<Sep.>	comment
132	51 Psc	109262	00ʰ29ᵐ48ˢ8	+06°40′47″	5.7	0.7	6	77.7	81.5	95°4±0°6	0″236±0″005	no orbit
404	1123	129277	01 21 49.6	-07 10 30	5.9	0.2	14	75.6	80.9	217.2 0.8	0.346 0.009	P = 16.1 yr (Finsen 1973)
719	Kui 8	110542	02 25 24.9	+01 44 16	6.5	0.4	12	76.9	81.7	32.5 0.2	0.510 0.001	no orbit
1199	Kui 15	111469	03 49 20.1	+06 23 10	5.7	0.1	8	76.9	80.9	208.4 0.2	0.645 0.003	no orbit
-	Stt 97	76954	05 02 36.5	+22 59 38	6.7	1.5	8	76.9	80.9	153.4 0.3	0.362 0.001	no orbit
1946	4265	94759	05 38 24.2	+16 30 35	4.9	0.4	10	76.9	80.9	237.9 0.2	0.347 0.001	P = 95.4 yr (Valbousquet 1980)
2678	5795 AB	152394	07 04 19.8	-11 12 57	5.4	1.3	4	76.9	80.9	116.5 0.2	0.557 0.002	no orbit
2982	6313 AB,C	115839	07 40 31.4	+00 18 33	6.2	1.8	5	76.3	80.2	228.5 0.4	0.818 0.008	no orbit
3269	Fin 346	116630	08 17 12.2	+04 06 23	6.1	0.0	9	76.9	80.9	74.9 0.4	0.274 0.003	no orbit
3744	7382 AB	136861	09 24 47.6	-09 00 21	6.5	0.0	4	76.9	80.2	196.2 0.5	0.349 0.001	no orbit
4347	8086	156528	11 10 01.4	-18 13 39	6.1	0.4	10	76.0	81.4	333.3 0.4	0.250 0.004	P = 233 yr (Heintz 1968)
4789	Wrh	82390	12 32 21.6	+22 54 15	4.8	2.4	10	76.3	81.5	12.4 0.3	0.356 0.001	no orbit
4963	θ Vir Aa	139189	13 07 21.5	-05 16 21	4.4	1.5	27	76.0	81.5	325.3 0.2	0.495 0.001	no orbit
-	9392	120673	14 46 24.2	+06 09 46	6.7	0.0	8	78.3	81.5	296.5 0.8	0.363 0.010	P = 228 yr (Feierman 1969)
5654	Cou 189	101429	15 09 47.7	+19 09 47	5.9	1.9	8	78.1	81.5	145.5 0.1	0.461 0.003	no orbit
5850	9758	101699	15 40 50.3	+13 49 33	6.4	1.0	9	76.4	81.5	2.5 0.1	0.682 0.003	no orbit
-	9932	140981	16 05 42.9	-09 58 09	6.9	0.3	6	78.6	81.5	192.5 0.3	0.384 0.007	P = 55.0 yr (Wilson 1940)
6627	10795	103106	17 44 55.5	+17 42 51	5.7	1.3	12	78.3	81.7	267.5 0.3	0.574 0.002	no orbit
6795	11111 AB	123187	18 07 04.6	+03 59 00	5.7	1.2	12	78.3	81.7	333.3 1.0	0.339 0.002	P = 270 yr (Heintz 1968)
7285	12160 AB	104602	19 10 19.8	+16 45 40	6.7	1.3	4	76.6	81.7	137.9 0.1	0.681 0.001	no orbit
7497	12808 AB	105168	19 40 12.8	+11 42 27	5.3	1.2	8	76.5	81.7	76.3 0.1	0.456 0.001	no orbit
7882	14073 AB	106316	20 35 12.2	+14 25 12	3.6	1.0	24	75.6	81.7	182.5 1.5	0.538 0.008	P = 26.6 yr (Couteau 1962)
-	14648 Aa	145118	21 04 45.8	-08 26 13	8.1	0.3	2	78.6	81.7	90.7 0.1	0.256 0.001	no orbit
8566	15998	127551	22 27 26.2	+04 10 38	5.5	1.4	10	76.6	81.7	117.1 0.1	0.818 0.005	P = 140 yr (Knipe 1960)
8739	16428	108307	22 56 41.6	+11 27 40	5.8	1.3	8	78.6	81.7	297.3 0.5	0.600 0.002	P = 270 yr (Valbousquet 1981)
8890	16708	165658	23ʰ20ᵐ02ˢ0	-15°18′50″	5.2	0.7	6	76.5	81.7	102°0±0°2	0″412±0″003	P = 63.2 yr (van den Bos 1953)

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Photoelectric comparison sequences in the fields of B2 1308 + 326 and 1418 + 54 (*)

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Summary. — Photoelectric *UBV* comparison sequences have been established in the fields of two violently variable BL Lacertae objects : B2 1308 + 326 and 1418 + 54 (= OQ 530). The sequences will provide accurate standards with which to calibrate the photographic photometry of each of these objects.

Key words : photometry — BL Lacertae objects.

1. Introduction.

The optical variability of BL Lacertae objects provides a clue to the nature of the physical process which is producing the extreme luminosities observed for these objects. The long term nature of the optical variability can most effectively be studied by continuous photographic monitoring programs using telescopes of modest aperture. In order to aid the accurate photographic photometry for members of this class of violently variable objects, the fields of the objects of interest must be calibrated photometrically. The fields of two violently variable BL Lacertae objects were selected to be calibrated : B2 1308 + 326 and 1418 + 54 (= OQ 530).

B2 1308 + 326 has exhibited several major outbursts in recent years (e.g. Moore *et al.*, 1980 ; Puschell *et al.*, 1979). The total range observed for this object exceeds 5 mag and rapid changes of the order of 0.5 magnitude on the time scale of a few days have been observed on several occasions. The BL Lacertae object 1418 + 54 has been found to have a history of large amplitude variations with a total range exceeding 4.8 mag (Miller, 1978). However, no major outbursts have been reported for this object recently.

The history of violent variability observed for both of these objects suggested that calibrated comparison stars in the fields of each of these objects would be very useful in studies of the trends in their long term variability. We report here the comparison sequences which were measured in the fields of each of these objects.

2. Observations and results.

The photoelectric photometry was obtained at Kitt Peak National Observatory from April 1981 through June 1983. The observations were made using either the 0.9 meter telescope or the 1.3 meter telescope. The automated filter photometer equipped with a standard three color (*UBV*) filter set was used with a refrigerated 1P21 photomultiplier tube and pulse counting system for the observations which were made with the 0.9 meter telescope. The Mark 2 computer photometer equipped with a 1P21 photomultiplier tube and standard *UBV* filters was used for the observations made with the 1.3 meter telescope. The extinction was determined each night, and the transformation to the standard *UBV* system was made using the equational standard stars of Landolt (1973). The standard error for each observations is less than 0.01 mag in *V* and less than 0.22 mag in each color unless the *V*-magnitude and the colors are followed by a colon. Then the errors are 0.02 mag and 0.044 mag in *V* and each of the colors respectively.

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Table I. — *Comparison stars.*

Star	V	B-V	U-B
B2 1308 + 326			
A	13.02	0.52	-0.05
B	12.70	0.66	0.25
C	13.50	0.71	0.32
D	13.85	0.67	0.40
E	16.74:	0.57:	0.02:
F	14.33	0.39	0.06
G	16.44:	0.62:	-0.14:
1418 + 54			
A	9.27	0.55	0.05
B	12.81	0.88	0.56
C	14.29	0.62	0.13
D	13.66	0.55	-0.03
E	15.89	0.80:	1.14:
F	10:55	0.40	-0.02
G	14.94	0.53	-0.02

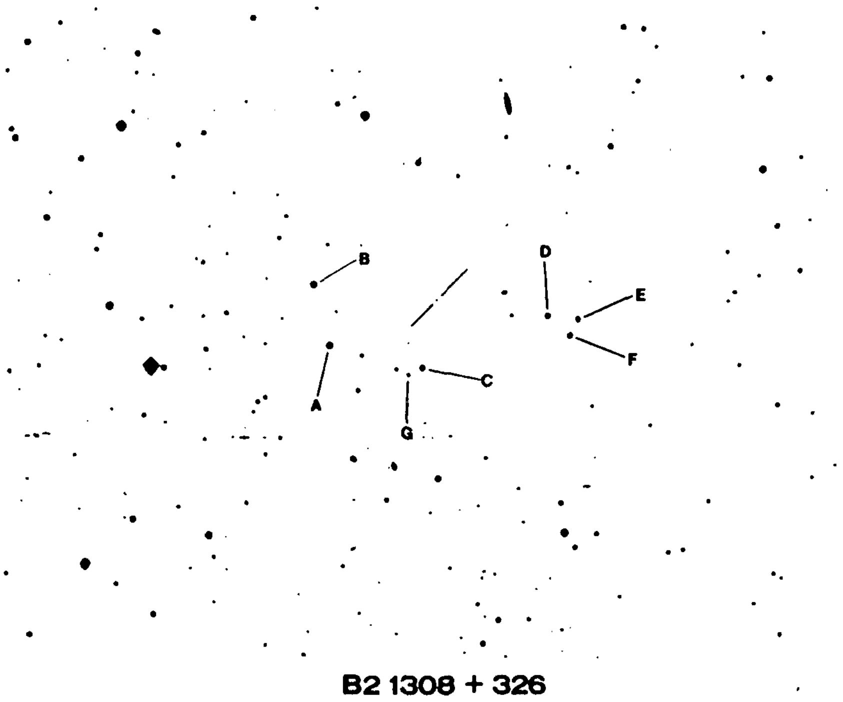

FIGURE 1. — Finding chart for the comparison sequence in the field of B2 1308 + 326. The positions of the sources are indicated by the line pairs and the sequence stars by letters. The chart is 50 arc minutes across and is oriented with north at the top and east to the left.

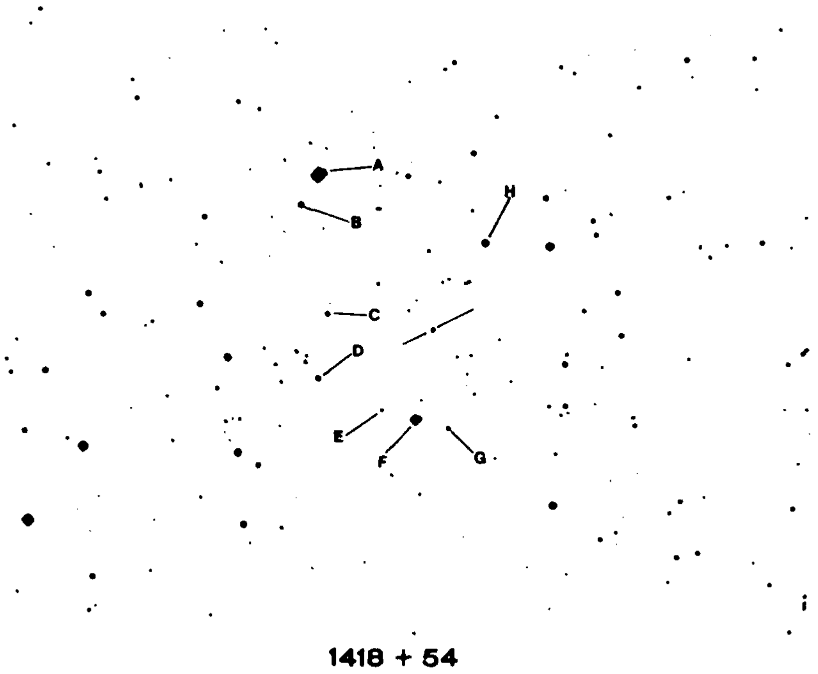

FIGURE 2. — Finding chart for the comparison sequence in the field of 1418 + 54 (= OQ 530). The position of the sources is indicated by the line pairs and the sequence stars by letters. The chart is 50 arc minutes across and is oriented with north at the top and east to the left.

THE CALIBRATION OF INTERFEROMETRICALLY DETERMINED PROPERTIES OF BINARY STARS

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ABSTRACT. With the advent of speckle interferometry, high angular resolution has begun to play a routine role in the study of binary stars. Speckle and other interferometric techniques not only bring enhanced resolution to this classic and fundamental field but provide an equally important gain in observational accuracy. These methods also offer the potential for performing accurate differential photometry for binary stars of very small angular separation. This paper reviews the achievements of modern interferometric techniques in measuring stellar masses and luminosities and discusses the special calibration problems encountered in binary star interferometry. The future possibilities for very high angular resolution studies of close binaries are also described.

1. INTRODUCTION

Interferometry has been applied intermittently to the examination and measurement of close visual binaries (where the word "visual" is used here in the context of direct resolution by any means) since Anderson and Merrill used Michelson interferometry at Mt. Wilson during 1919-21 primarily for resolving Capella (Merrill 1922). It was not until speckle interferometry was first proposed by A. Labeyrie (1970) and subsequently demonstrated by Labeyrie and his collaborators (Gezari et al. 1972) that an interferometric technique of exceptional accuracy was routinely applied to a wide sample of binary stars. Visual interferometry, particularly as developed and pursued by W. S. Finsen at Johannesburg (Finsen 1971), provided a gain in resolution while maintaining the same level of accuracy as micrometry. A photoelectric version of Michelson interferometry provided promising initial results (Wickes and Dicke 1973), but no sustained effort using that approach followed upon the initial success. For a complete listing of modern interferometric approaches to binary star astrometry, the reader is directed to the catalog of McAlister and Hartkopf (1984), hereafter referred to as MH.

D. S. Hayes et al. (eds.), Calibration of Fundamental Stellar Quantities, 97–[illegible].

Speckle interferometry employing photon detecting cameras at 4-meter class telescopes is capable of resolving 15th magnitude binaries with separations down to 0".025. Most of the speckle results have so far been for objects brighter than 8th magnitude, and there is much useful work to be done in this regime, but it is likely that further speckle programs will push resolution toward a significantly fainter limit and give greater emphasis on employing analysis procedures capable of extracting differential photometric information from speckle pictures. The potential in this latter area has already been demonstrated, and a great deal of very useful information is likely to follow in the coming few years as close visual pairs are resolved photometrically as well as spatially.

Relatively few in number but important results have come from long baseline optical interferometry to date. As has been pointed out many times, the principal reason for the short supply of accurately known stellar masses and luminosities is not due to any paucity of binary stars. It is instead the result of the inability of any one technique to determine all the necesary parameters and the shortage of systems amenable to study by more than one technique. Where speckle interferometry using single telescopes has increased the overlap between visual and spectroscopic binaries, long baseline interferometry will subject virtually every spectroscopic binary to direct resolution.

Interferometric measurements of binary stars can be expected to make substantial contributions to the calibration of stellar masses and luminosities. When long baseline instruments are fully functional, we can look forward to direct measurements of the diameters of the individual components of binaries and hence to major contributions in calibrating emergent fluxes and effective temperatures of stars of known mass. Obtaining such complete and fundamentally important data for stars should serve as strong motivation to the few groups around the world who are working in the extremely challenging area of long baseline optical interferometry.

2. INTERFEROMETRICALLY DETERMINED MASSES AND LUMINOSITIES

The contributions to the empirical mass-luminosity relation made from combining interferometric and spectroscopic observations are shown in Figure 1 in which are also plotted the points considered to be reliable by Popper (1980). The values for α Virginis were determined with the intensity interferometer at Narrabri (Herbison-Evans et al 1971) which concurrently determined the angular diameter of α Vir A. The orbital solution of α Aurigae by Merrill (1922), which has been only slightly modified by extensive modern measurements (McAlister 1981), and its combination with spectroscopic data is discussed by Batten et al (1978). Speckle interferometry has been responsible for the remaining additions to the mass-luminosity relation in Figure 1 with specific references to the individual studies available from MH. Popper (1980) considered only the analyses of α Aur, α Vir and 12 Per

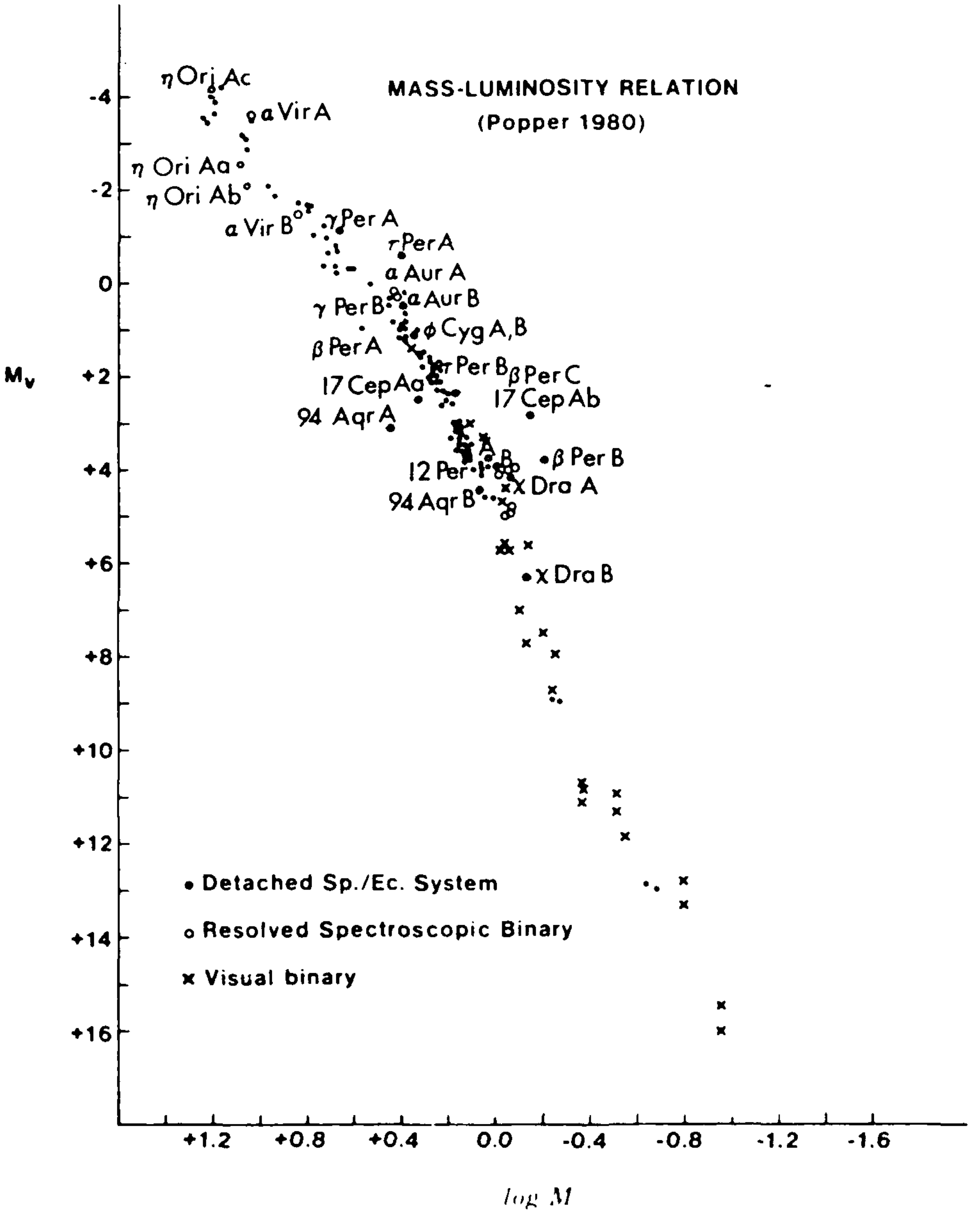

FIG. 1. Points added to the empirical mass-luminosity relation by interferometry are shown plotted against reliable other determinations as given by Popper (1980). Complete references to the individual analyses can be found in the catalog of McAlister and Hartkopf (1984).

to be sufficiently free from significant future revisions to be considered reliable. Analyses too recent to be included in Popper's review for χ Dra and ϕ Cyg yielded formal errors in the masses of less than 10%. It is possible that the spectroscopic mass ratio for χ Dra may be revised (F. C. Fekel, private communication) thus affecting the conclusion that the components are excessively luminous for their masses. The mass ratio for ϕ Cyg should be less of a problem since the components are of similar luminosity and the velocities are relatively free of blending effects. In this case, however, the system always has a separation less than $0\overset{''}{.}04$ and is frequently unresolved. The residuals to the six existing speckle measurements of ϕCyg are no greater than $0\overset{''}{.}002$ and it seems unlikely that the orbital elements will change appreciably as further observations are accumulated.

Interferometric techniques capable of $0\overset{''}{.}025$ resolution are likely to continue to yield new masses and luminosities as spectroscopic binaries with long period orbits receive sufficient coverage of their relative visual orbits. Such systems often need modern spectroscopic observations, particularly to determine mass ratios, and small velocity amplitudes make this a challenging task. Of the 118 binaries newly resolved by interferometry which are listed in Table I (see MH for a complete list of references), 39 are spectroscopic systems of which 11 are double-lined. It is probable and certainly highly desirable that the fraction of spectroscopic binaries in this sample could be increased or that at least the mass ratios determined for systems exhibiting high eccentricity as they undergo periastron passage. Parallaxes forthcoming from the HIPPARCOS mission would then fill in the missing information for mass determinations.

As of early 1984, there were 3363 measurements of 824 systems derived from accurate interferometric observations with an additional 1863 negative examinations for duplicity (see MH). The mean measured separation is $0\overset{''}{.}32$ while the median is $0\overset{''}{.}21$. Thirty eight percent of the measurements are of separations no larger than $0\overset{''}{.}16$ and thus could not be generally provided by any other technique in standard usage. The remaining measurements have accuracies significantly improved over those obtained by other techniques for binary star astrometry. More than 90 percent of these data are from speckle interferometry with the majority being for systems in the northern hemisphere. Although the existing programs of binary star interferometry seem to be healthy and likely to continue, the field is by no means overcrowded. A program resident in the southern hemisphere would be especially welcome.

TABLE I.

Binary Stars First Directly Resolved by Interferometry

Name		<,>	MK Type	Name		<,>	MK Type
HR [illegible]	[illegible] Psc	[illegible]	B9V	HR 5953	Sco	0.16	B0IV
HR 178	-	0.17	A7m	HR 5985	Sco	0.11	B2IV-V
HR 233	-	0.06	B9V + G0III-IV	HD 144641	-	0.12	G5
HR 439	-	0.13	K0Ib + B9V	HR 6084	Sco	0.37	B8Vp
HR 483	-	0.55	G1.5V	HR 6148	β Her	0.09	G8III
HR 539	Cet	0.06	K0III	HR 6168	Her	0.04	B9V
HD 12483	-	0.23	G5	HR 6237	-	0.05	F2V
HR 640	55 Cas	0.10	B9V + G0II-III	HD 155095	-	0.13	B8
HR 645	6 Per	0.04	G8III	HR 6388	-	0.04	K3III
HR 649	Cet	0.06	G6II-III	HR 6396	ζ Dra	0.05	B6III
HR 763	31 Ari	0.08	F7V	HR 6410	Her	0.10	A3IV
HR 788	12 Per	0.05	F9V	HR 6469	-	0.06	F9V
HR 793	Ari	0.05	A0V	HR 6485	ο Her	0.29	B9III
HR 825	-	0.19	A5Ia	HR 6560	-	0.16	A5V + G5III
HR 838	41 Ari	0.30	B8V	HR 6588	Her	0.16	B3IV
HR 854	Per	0.05	G4III + A4V	HD 163640	-	0.09	A2
HR 915	Per	0.22	G8III + A2V	HR 6697	-	0.10	G2V
HR 936	β Per	0.07	B8V	HR 6742	W Sgr	0.12	F8Ib
HR 1010	ζ² Ret	0.05	G2V	HR 6779	ο Her	0.06	B9V
HR 1084	Eri	0.05	K2V	HD 167570	17 Sgr	0.27	A3 + G5
HR 1129	-	0.06	G0III + A3V	HR 6927	χ Dra	0.06	F7V
HR 1252	36 Tau	0.04	G0III + A4V	HD 171347	-	0.16	A2
HR 1331	51 Tau	0.09	F0V	HR 7059	5 Aql	0.13	A2V
HR 1346	γ Tau	0.40	K0III	HD 178452	-	0.12	A2 + G5
HD 283571	RY Tau	0.04	-	HR 72	ι Lyr	0.08	B6IV
HR 1411	θ¹ Tau	0.15	K0III	HR 7377	δ Aql	0.13	F3IV
HR 1497	τ Tau	0.17	B3V	HR 7417	β¹ Cyg	0.42	K0III + B9V
HR 1569	6 Ori	0.33	A3V	HD 184467	-	0.08	K0
HR 1708	α Aur	0.05	G5III + G0III	HR 7441	9 Cyg	0.04	A0 + F5
HR 1788	η Ori	0.05	B1V	HR 7478	φ Cyg	0.04	G8III + G8III
HR 1808	115 Tau	0.09	B5V	HR 7536	δ Sge	0.05	M2II + A0V
HR 1876	37 Ori	0.05	B0III	HD 187321	-	0.40	A + G0
HD 37514-5	-	0.14	A + G	HD 190429	-	0.12	Oe
HR 2001	-	0.16	A4V	HR 7735	31 Cyg	0.03	K2II + B3V
HR 2002	132 Tau	0.04	G8III	HR 7744	23 Vul	0.24	K3III
HR 2130	64 Ori	0.05	B8III	HR 7776	β Cap	0.06	K0II-III + B8V
HD 41600	-	0.10	B9	HD 196088	-	0.05	A0 + G
HR 2304	-	0.04	A2V	HR 7906	α Del	0.14	B9IV
HR 2425	53 Aur	0.06	B9	HR 7921	49 Cyg	0.24	G8IIb
HR 2605	40 Gem	0.08	B8III	HR 7922	-	0.11	B6III
HD 52822-3	-	0.16	F5 + A	HR 7963	λ Cyg	0.03	B6IV
HR 2846	63 Gem	0.04	F5V + F5V	HR 7990	μ Aqr	0.04	A3m
HR 2861	65 Gem	0.04	K2III + K5III	HR 8047	59 Cyg	0.21	B1e
HR 2886	68 Gem	0.13	A1V	HR 8059	12 Aqr	0.05	G4III
HR 3109	53 Cam	0.04	A2p	HR 8119	I Cep	0.05	B0II
HR 3485	δ Vel	0.62	A1V	HR 8164	-	0.10	M1Ib + B2V
HR 3880	19 Leo	0.13	A7V	HR 8238	β Cep	0.18	B1III
+20°2465	Gl 388	0.08	M4Ve	HR 8264	ζ Aqr	0.03	A7V
HR 4365	73 Leo	0.04	K3III	HR 8417	ξ Cep	0.05	A3m
HR4544	-	0.17	K0III	HR 8485	-	0.52	K3III
HR 4689	η Vir	0.12	A2IV	HR 8558	ζ¹ Aqr	0.06	F6IV
HR 4785	CVn	0.11	G0V	HR 8572	5 Lac	0.11	K7Ib + A8V
HR 4905	UMa	0.05	A0p	HR 8650	η Peg	0.04	GII-III + F
HR 4963	Vir	0.49	A1IV + Am	HD 215318	-	0.15	F8 + A5
HD 126269	-	0.05	F5 + A0	HR 8704	74 Aqr	0.07	B9III
HR 5435	Boo	0.07	A7III	HR 8762	And	0.33	B5III + A2p
HR 5472	-	0.04	F3V	HR 8866	94 Aqr	0.13	G5IV
HD 136406	-	0.36	K0	HR 9003	ψ And	0.28	G5Ib + A0V
HR 5747	CrB	0.05	A8III	HR 9064	ψ Peg	0.19	M3III

3. THE ACCURACY OF INTERFEROMETRY

The effects of systematic errors in angular separation measurements on mass and distance determinations for spectroscopic binaries resolved by interferometry depend upon the specific manner in which the data from the two complementary techinques are combined. The propagation of a relative scale error into the errors for the masses with a factor of three increase from Kepler's Third Law does not usually occur since the interferometry is most often used to solve for the inclination factor in the spectroscopically determined values for $M\sin^3 i$. The error in the distance determination would be linearly related to a scale error, and thus the luminosities would have relative errors sensitive to scale errors by a factor of two.

Interferometric measurements are of potentially very high accuracy and hence deserve high weight in the solution of a binary star orbit. With the current sample of several thousand measurements, it is possible to judge the level of accuracy of the data within and among the various groups of observers employing interferometric techniques. An earlier discussion of this topic (McAlister 1978) concluded that there is little evidence for significant systematic errors in speckle observations when compared to orbits of high quality. This has also been indicated more recently by Worley (1983) who found average residuals for 170 speckle observations from orbits of high quality of

$$\langle \rho\Delta\theta \rangle = +0''.001 \pm 0''.007$$

$$\langle \Delta\rho \rangle = -0''.009 \pm 0''.015$$

It is interesting to note that the dispersion is twice as large in the separations as it is in the position angles. In both cases the dispersions are significantly larger than the mean differences. As will be seen later, this unfortunately does not imply that such orbits should be used for calibration purposes. Furthermore, comparison of speckle and micrometer measurements obtained nearly simultaneously shows no significant systematic difference at the limit of accuracy set by the micrometry. For 31 pairs of observations in the sense (visual-speckle) Worley (1983) found

$$\langle \Delta\theta \rangle = +0^\circ.34 \pm 3^\circ.06$$
$$\langle \Delta\rho \rangle = -0''.021 \pm 0''.042$$

for $$\langle \rho \rangle = 0''.38 \pm 0''.19$$

The dispersion in the diffences represents about 11 percent of the average separation and is probably inherent in the micrometer measures of such close pairs. Speckle interferometry should be routinely capable of measuring such separations to better than 1 percent accuracy, as speckle results are essentially derived from measuring the separation of two Airy disks having diameters on the order of $0''.03$. A level of 1 percent accuracy for binaries with separations of $0''.4$ essentially requires the centroiding on an Airy disk to an accuracy of about 10 percent. There is really little excuse for doing much poorer than this.

To assess the internal accuracy of interferometric measurements it is most profitable to examine the results for systems which have been extensively observed by various groups. Unfortunately such systems are rare. One binary star which has received a great deal of attention by interferometrists is β Cephei for which 42 measurements have been made between 1971 and 1981 by five different groups using at least six different telescopes. During that time span, β Cep closed in separation from about $0''.25$ to $0''.17$ while remaining nearly fixed in position angle. Figure 2 is a representation of these measurements in Cartesian coordinates. The solid line in Figure 2 is a linear fit to the GSU/KPNO 4-meter observations (filled circles) while the dashed line is an extrapolation ignoring elliptical motion back to the early French speckle results. In this straightforward attempt to compensate for orbital motion, the 18 GSU/KPNO 4-meter measurements show dispersions in angular separation of $\pm0''.0026$ and in position angle of $\pm0^\circ.55$. The 7 GSU/KPNO 2.1-meter measurements show a degradation in accuracy with dispersions of $\pm0''.0094$ and $\pm2^\circ.2$. While the 4-meter speckle observations approach a 1 percent level of accuracy, the 2.1-meter results emphasize the advantage of using the largest possible telescopes for speckle interferometry, not just to achieve the highest resolution but also to obtain the greatest accuracy.

The system comprising the star θ Virginis has been extensively observed in the course of the GSU speckle program but very little by other observers. A linear fit to 19 GSU/KPNO 4-meter measurements shows dispersions of $\pm0''.0048$ and $\pm0^\circ.53$ and are again at the 1 percent level for this system which has an average separation of $0''.495$.

It is seen that speckle interferometry can (and indeed should) achieve an internal accuracy of 1 percent. Although a perusal of the data in MH shows scattered indications of systematic differences among the observers, there does not yet exist sufficient overlap in the data to bring all interferometric results on a "system" that appears to be free of systematic error. The effects of these errors on the calibration of stellar masses and luminosities are certainly no worse (and perhaps considerably better if the consumer scrutinizes the data carefully) than the complementary spectroscopic, micrometer and astrometric material that joins with the interferometric results to yield fundamental astrophysical parameters.

4. CALIBRATION OF SPECKLE INTERFEROMETRIC OBSERVATIONS

4.1 Background

This section will concentrate primarily on observations of binary stars by speckle interferometry although discussions of standard stars and standard orbits pertain to any high angular resolution technique.

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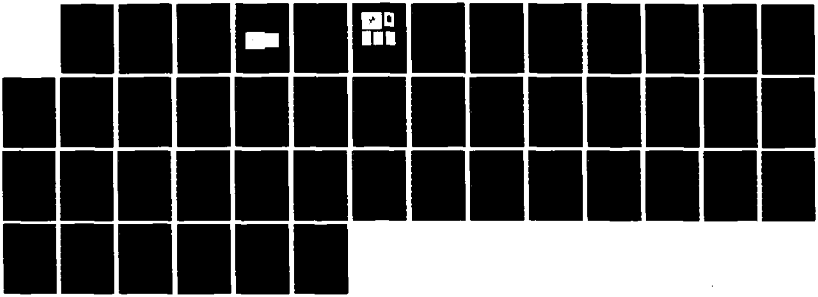

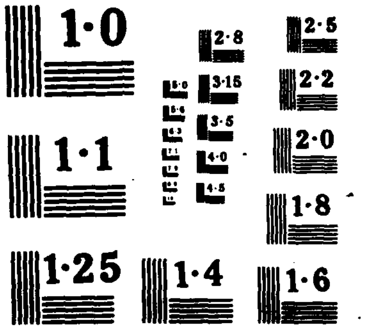
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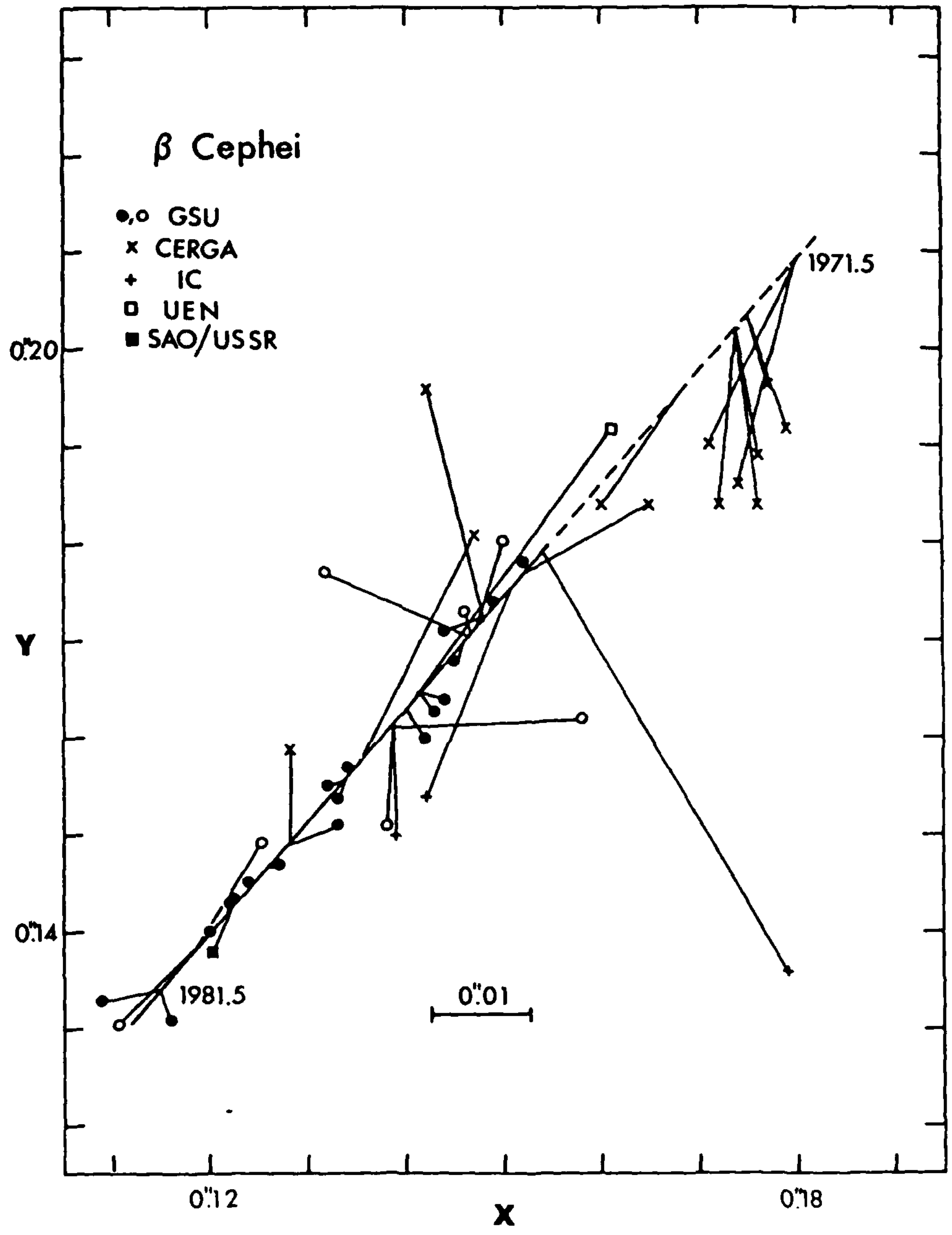


FIG. 2. Speckle interferometric measurements of the binary star β Cep are shown for the interval 1971-82 during which time the separation closed from 0"26 to 0"17 with little change in position angle.

Because of its straightforward applicability speckle interferometry is more likely to be widely applied to high angular resolution measurements than other techniques, particularly long baseline optical interferometry, and there is a significant body of data from speckle work which can be used as a solid basis for this discussion. Reviews of speckle interferometry are given by Bates (1982), Dainty (1975), Worden (1977), Labeyrie (1978) and McAlister (1983).

Speckle pictures (or interferograms as some prefer to call them) are obtained during short time exposures which freeze the instantaneous effects of atmospheric turbulence. Speckle interferometry is essentially an examination of the spatial frequencies present in a speckle picture with the frequency cutoff determined by the aperture of the telescope. This permits the method to make diffraction limited measurements of spatial structure. If in one dimension O(x) is the instantaneous object intensity, then the instantaneous image intensity will be given by

$$I(x') = \int O(x)P(x'-x)dx$$

where P(x') is the instantaneous point spread function induced by atmospheric and telescopic effects. Taking the Fourier transform of this equation utilizes the convolution theorem to deconvolve the atmospheric and instrumental effects to obtain

$$i(u) = o(u)T(u)$$

where i(u) and o(u) are Fourier transforms of the image and object intensities and T(u) is the instantaneous transfer function and is the Fourier transform of the point spread function. The squared modulus of T(u) is the modulation transfer function (MTF) and it is the average value of the MTF which is normally utilized in speckle interferometry where the power spectrum

$$W(u) = \langle |i(u)|^2 \rangle = |o(u)|^2 \langle |T(u)|^2 \rangle$$

is calculated or determined in an analog fashion from a series of speckle pictures of an object.

An alternate and entirely equivalent processing procedure operating in the spatial rather than spatial frequency domain utilizes the average autocorrelation of the instantaneous image intensities

$$C(x) = \langle \int I(x') \, I(x'-x)dx' \rangle \, .$$

Dainty (1974) describes the effects of the transfer function on C(x) and shows that atmospheric seeing completely dominates over telescope aberrations under typical conditions. Figure 3 summarizes the analysis approaches of speckle interferometry to the special problem of binary star astrometry and Figure 4 shows a single speckle picture of α Aur with a composite autocorrelation of many such

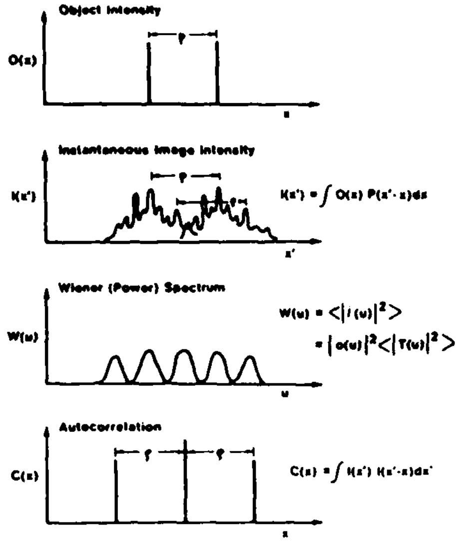


FIG. 3. A summary of the origin of speckle patterns and the analysis of speckle data for binary stars using either power spectrum or autocorrelation analysis is shown.

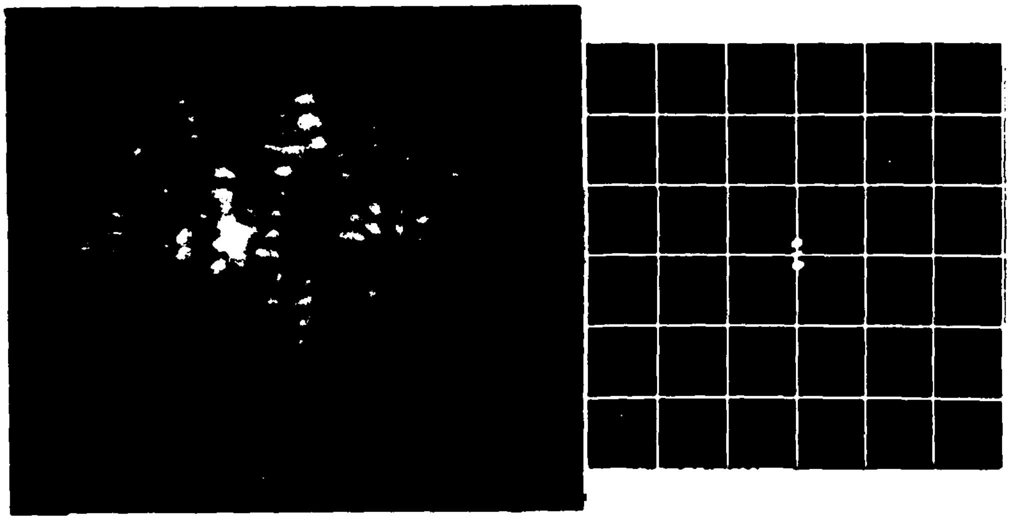


FIG. 4. A speckle picture of α Aur obtained with the GSU ICCD speckle camera at the KPNO 4-meter telescope in January 1984 is shown on the left where the picture is approximately 1" across. Individual pairs of speckles clearly show the 0".05 binary nature of the star oriented in the north-south direction. The picture on the right is the output from the hardwired digital vector-autocorrelator in use at GSU to reduce speckle data.

pictures produced by a hardwired vector autocorrelator at GSU.

4.2 Atmospheric Effects

The atmosphere limits the applicability and accuracy of binary star speckle interferometry by the effect of non-isoplanicity and by introducing a major seeing component into W(u) or C(x). The limits of isoplanicity are under normal circumstances sufficient to permit separation measurements of up to several arcseconds - well into the realm of standard micrometer and photographic techniques - although the detailed influence of the transition from isoplanicity to non-isoplancity (which is equivalent to considering the transition from very high correlation to very low correlation between the speckle images of the components of a binary) has by no means been thoroughly studied. It is expected that loss of complete isoplanicity decreases the precision with which separations can be measured and may introduce systematic errors into differential photometry, but these effects enter at separations larger than those normally measured by speckle interferometry.

Atmospheric seeing effects are definitely of concern, however, and must be considered in the measurement of binary star separations, stellar angular diameters and differential photometric properties. Figure 5 is a representation of the analysis of a sequence of digital speckle pictures of the binary star ADS 4241 taken with the GSU ICCD speckle camera (McAlister et al 1982) at the KPNO 4-meter telescope in January 1984. ADS 4241 has an approximate angular separation at that epoch of 0"25. In Figure 5, the practiced eye can perhaps pick out the double speckled structure in the picture which is about 1"5 x 1"3 in size. Figure 5(b) is an integrated vector autocorrelogram of about 10 seconds of a stream of pictures of ADS 4241 recorded at 30 pictures per second. Contours show the overall structure of the seeing component which dominates the autocorrelogram as well as the two spikes indicative of the double star geometry at position angles of about 150° and 330°. A first approach at compensating for the seeing component is shown in Figure 5(c) which is the result of rotating the autocorrelogram 90° in position angle and subtracting it from the unrotated original version. This procedure would adequately subtract out the seeing component if the autocorrelogram were perfectly axially symmetric about the zero spatial component. Unfortunately, this is essentially never the case due to telescope aberrations, atmospheric dispersion, detector effects, etc., but this "rotation" algorithm is useful in locating the binary star spikes which are often small effects on the overall seeing slope. The radial profiles in Figure 5 (d) represent cuts through the autocorrelogram of 5(b) where the central profile passes through an estimate of the coordinates of the double star spike and the upper and lower profiles are cut in counterclockwise and clockwise directions at 30° intervals from the spike. The central profile clearly shows the asymetry of the spike resting on the sloping background of the seeing component. In order to compensate for seeing, third order polynomial fits to the top and

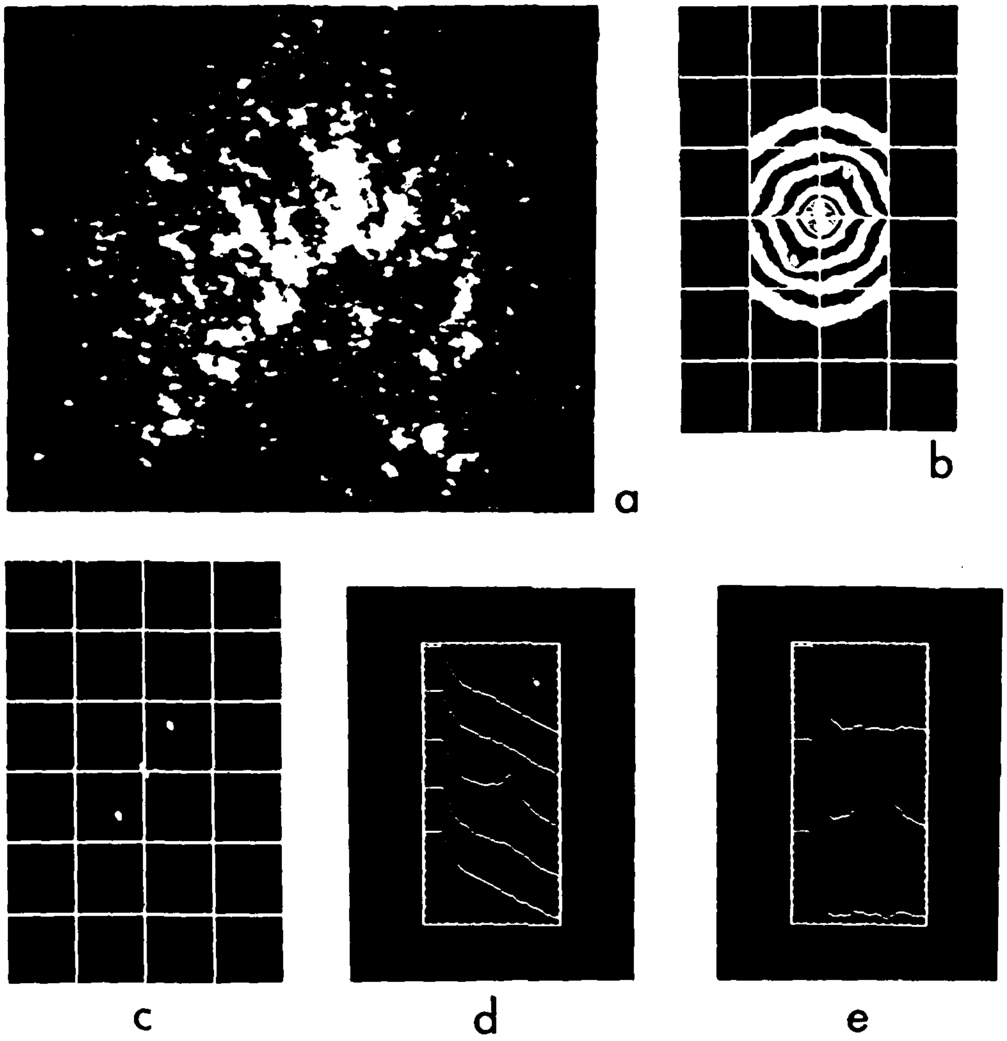


FIG. 5. A single speckle picture is shown in (a) of the 0″.25 binary ADS 4241 taken with the GSU speckle camera at the KPNO 4-meter telescope in January 1984. The integrated autocorrelogram is shown in (b) and indicates the broad seeing induced component. The result of approximately correcting for seeing by rotating the autocorrelogram by 90° and subtracting it from the original is shown in (c). Radial profiles through the double star spike in the autocorrelogram and through the adjacent regions are shown in (d) and (e) before and after a more precise seeing correction.

bottom profiles over a radial range encompassing the radial location of the spike in 5(d) were used to subtract out the sloping background by interpolating the coefficients of the polynomials to every point in the autocorrelogram between the two outer radial cuts. Figure 5(e) shows the resulting seeing corrected profiles which have been rescaled in intensity. In this case, the r.m.s. fluctuations in the background are at a level of 50 units in the relative intensity scale while the intensity of the binary star spike is approximately 2800 units. Centroiding the tops of the spikes in 5(d) and 5(e) shows a 5 percent increase in the separations deduced from the seeing corrected spike in comparison to the uncorrected spike with little effect on the position angle. This is precisely as would be expected and shows that failure to correct for atmospheric seeing effects in speckle interferometry can easily lead to systematic errors in separation measurements that could propagate to 15 percent errors in mass determinations.

One should ideally compensate for seeing effects by observing a nearby single star as close in time as possible to the program star observation. In practice this tends rarely to produce satisfactory compensation because of non-stationary seeing conditions and variations in the instrumental response and in the analysis of the separate data sets. This is more of a problem where the goal is to measure angular diameters or extended structures where the precise shape of the seeing corrected autocorrelogram is needed than in the case of binary star measurement where the background is only to be flattened. Seeing similarly affects measurements of fringe spacings made from power spectra. The systematic effect on the final separation measurement is, however, significantly reduced because the fringe spacing is a differential measure from a set of fringes which all tend to be shifted toward the central fringe by similar amounts, at least to first order. (McAlister 1978).

4.3 Angular Scale Determination

In transforming the linear measurement from an autocorrelogram or power spectrum of speckle data to an angular separation on the sky with an accuracy of 1 percent or better is somewhat of a challenge. Few large telescopes have had their focal lengths determined with this accuracy and so a laboratory measurement of the magnification of a speckle camera system is usually insufficient.

A very effective way of measuring the scale in the focal plane of the speckle camera is to turn the telescope into a Michelson interferometer by placing a double slit mask over the entrance aperture. This may be cumbersome for telescopes of large aperture, and it is possible to select an intermediate pupil at which such a mask can be placed. The projection effects of extrapolating this mask onto the entrance pupil require a knowledge of the focal length of the telescope and the location of the mask in the beam. This procedure was followed for the 4-meter telescope on Kitt Peak (McAlister 1977) and allowed a scale and orientation calibration with limiting accuracies of ±0.6

percent in angular separation and ±0°2 in position angle. The double slit calibration mask has been used during more than 25 observing runs on that telescope with two speckle camera systems and has permitted us to establish what we believe to be a very uniform geometric calibration for our series of binary star speckle measures.

4.4 Calibration Standard Stars

A purely internal scale calibration procedure is ideally desirable but is occasionally not practicable. This is particularly the case where itinerant instruments are used at remote telescopes on a visiting basis, a circumstance which is now almost standard practice. This brings up the question of standard stars or standard orbits. It seems a pity when one uses techniques with potential high accuracy of angular measure to flip through a catalog, pick out a convenient binary star and adopt its published separation as a scale calibration. This can result (and has!) in scale errors of 50 percent or worse.

Choosing binary star orbits, even those which can be judged as definitive on the basis of orbital coverage, as standards for scale determination can also be treacherous. Comparison of the "Fourth Catalog of Orbits of Visual Binary Stars" (Worley and Heintz 1983) with the catalog of interferometric measurements (MH) shows 21 systems having definitive orbits which have received modern attention from interferometry. Table II contains a summary of the residuals to seven of these orbits for which there are more than a handful of interferometric measurements. If we consider only the GSU/KPNO measurements, which probably have the most uniform internal calibration, then it is seen that three of the orbits in Table 2 (ADS 1598, 9617, 11060) yield average residuals insignificantly differing from their dispersions and within 2 percent of the average separations of the systems. The remaining four orbits (ADS 1123, 6650, 8804, 14073) show statistically significant systematic residuals ranging from -6.7 to +8.8 percent of the average separations observed. In every case there is no indication of any significant systematic problems with position angles. This result does not contradict the conclusion of Worley (1983) quoted in Section 3 since the average percentage residual in the separations for the orbits in Table II is only +0.8 percent. Although there is no overall systematic trend between interferometric measurements and orbital ephemerides, there are strong differences when one considers orbits on an individual basis. Unfortunately, the latter procedure is what one follows in selecting orbits for calibration purposes. To further complicate matters, it can be expected that the degree of agreement with a particular orbit may vary with mean anomaly.

One orbit which perhaps can be used for calibration purposes is that of α Aur as shown in Figure 6 (McAlister 1981). Residuals to that orbit for 56 observations using four different interferometric techniques by seven different observing teams are

TABLE II. Average Residuals of Speckle Observations to Definitive Orbits

ADS	<Δρ> All (N) GSU (N)	<ρ> Δρ/ρ	<Δθ> All (N) GSU (N)
1123	+0''025±0''013(14)	0''296	+0°5±2°1
	+0.026±0.009(9)	+8.8%	-0.2±1.5
1598	-0.005±0.008(11)	0.665	-0.5±1.3
	-0.003±0.004(10)	-0.5%	-0.2±0.9
6650	-0.044±0.015(14)	0.852	-0.9±1.6
	-0.046±0.007(8)	-5.4%	-0.5±0.7
8804	+0.032±0.019(25)	0.389	+1.0±1.6
	+0.033±0.006(19)	+8.5%	+1.2±0.5
9617	-0.005±0.010(12)	0.453	+1.0±1.5
	-0.008±0.006(10)	-1.8%	+0.8±0.9
11060	+0.004±0.005(20)	0.343	+0.1±0.8
	+0.003±0.003(16)	+0.9%	+0.1±0.7
14073	-0.036±0.012(27)	0.569	-1.0±2.9
	-0''038±0''005(18)	-6.7%	-0°1±0°9

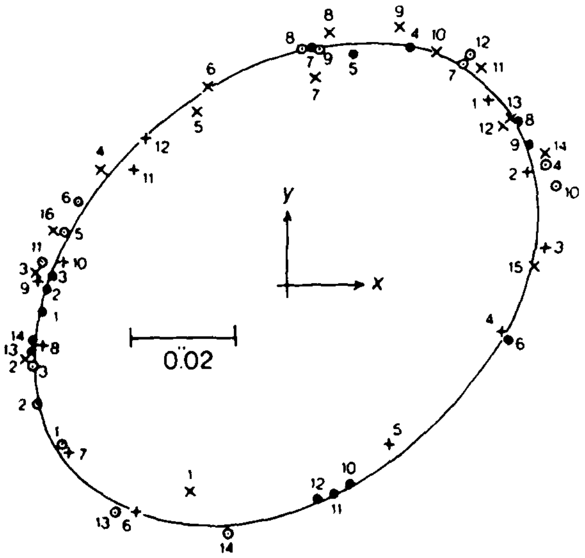


FIG. 6. Measurements from four interferometric techniques of the resolved spectroscopic binary α Aur are shown along with the apparent relative orbit (from McAlister 1981)

$$\langle \Delta\theta \rangle = -\,0^{\circ}.06 \pm 2^{\circ}.14$$
$$\langle \Delta\rho \rangle = +\,0''.0001 \pm 0''.0021$$

and the internal error of the calculated semimajor axis is +0.0001. Further thought shows that even this orbit is not well suited to calibration since only the largest telescopes can resolve it in the first place and then measure it with an accuracy of ±0".002 which is already about 4 percent of the average separation of 0".055. An accuracy of 1 percent is beyond reach if Capella is the only source of calibration. It must be concluded, therefore, that there are presently no binary star orbits which can be used unequivocally for calibrating angular scale to an accuracy of 1 percent.

As an alternative to standard orbits, it has been suggested (McAlister and Hartkopf 1983) that all interferometric observers adopt a set of standard stars for binary star interferometry. This list is reproduced here in Table III. Extensive observation of these objects will eventually lead to standard orbits in some cases. It will more generally define a set of slowly moving systems, such as θ Virginis, whose geometry can be frequently measured by (hopefully) several groups employing independent scale calibration. These objects, which are distributed all over the sky, can thus serve as tie-in stars to a system of accurate absolute angular calibration.

4.5 Photometric Calibration

Interferometric techniques offer the potential for performing photometry of the individual components of close visual binaries. This is extremely important since no other technique, except for the highly restricted method of lunar occulations, can obtain this information over the separation regime accessible to interferometry. Several approaches have been tried for speckle interferometry using actual data (Hege et al 1983, Cocke et al 1983, Bagnuolo 1983, Weigelt and Wirnitzer 1983, and Baguolo and McAlister 1983) and all rely upon the ability to perform accurate intensity calibration of speckle pictures. With the increasing use of solid state detectors in speckle cameras, such calibration is certainly feasible. Although "speckle photometry" is still in a developmental stage, there is every reason to believe that accurate photometry will be forthcoming for the components of binary systems once generally considered to be beyond the reach of photometric resolution.

5. POTENTIAL FROM VERY HIGH ANGULAR RESOLUTION INTERFEROMETRY

While interferometry using single telescope apertures has definitely enhanced the potential of binary star astrometry, the application of long baseline interferometry will quite literally revolutionize the field. Simple inspection of Kepler's Third Law shows that, for a given distance, an increase in limiting resolution from 0".025 as in the case of speckle interferometery at a 4-meter telescope

TABLE III

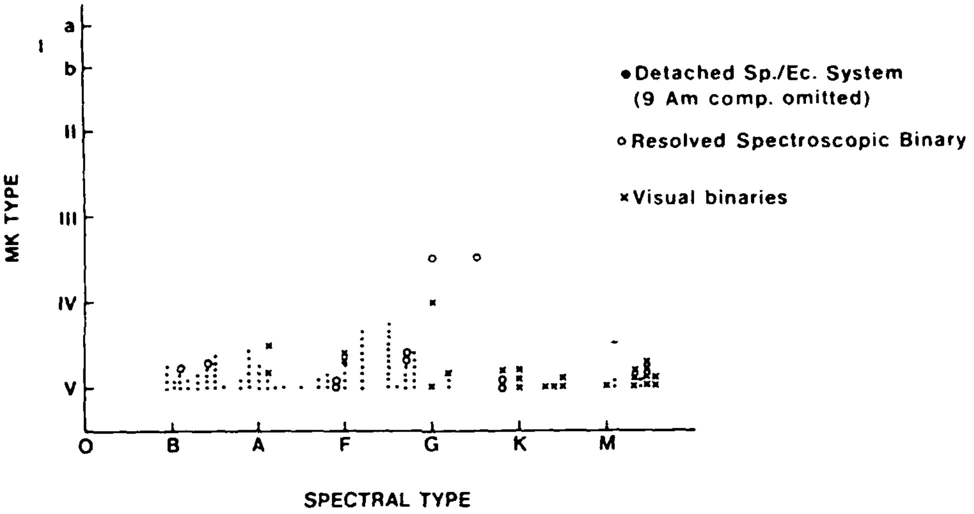
Standard Stars for Binary Star Interferometry

HR	ADS/Name	SAO	α	δ	m	Δm	N_{obs}	t_f	t_l	<P.A.>	<Sep.>	comment
			1950					1900+				
132	51 Psc	109262	$00^{h}29^{m}48^{s}.8$	+06°40'47"	5.7	0.7	6	77.7	81.5	95°.4±0°.6	0".236±0".005	no orbit
404	1123	129277	01 21 49.6	-07 10 30	5.9	0.2	14	75.6	80.9	217.2 0.8	0.346 0.009	P = 16.1 yr
719	Kui 8	110542	02 25 24.9	+01 44 16	6.5	0.4	12	76.9	81.7	32.5 0.2	0.510 0.001	no orbit
1199	Kui 15	111469	03 49 20.1	+06 23 10	5.7	0.1	8	76.9	80.9	208.4 0.2	0.645 0.003	no orbit
-	Stt 97	76954	05 02 36.5	+22 59 38	6.7	1.5	8	76.9	80.9	153.4 0.3	0.362 0.001	no orbit
1946	4265	94759	05 38 24.2	+16 30 35	4.9	0.4	10	76.9	80.9	237.9 0.2	0.347 0.001	P = 95.4 yr
2678	5795 AB	152394	07 04 19.8	-11 12 57	5.4	1.3	4	76.9	80.9	116.5 0.2	0.557 0.002	no orbit
2982	6313 AB,C	115839	07 40 31.4	+00 18 33	6.2	1.8	5	76.3	80.2	228.5 0.4	0.818 0.008	no orbit
3269	Fin 346	116630	08 17 12.2	+04 06 23	6.1	0.0	9	76.9	80.9	74.9 0.4	0.274 0.003	no orbit
3744	7382 AB	136861	09 24 47.6	-09 00 21	6.5	0.0	4	76.9	80.2	196.2 0.5	0.349 0.001	no orbit
4347	8086	156528	11 10 01.4	-18 13 39	6.1	0.4	10	76.0	81.4	333.3 0.4	0.250 0.004	P = 233 yr
4789	Wrh	82390	12 32 21.6	+22 54 15	4.8	2.4	10	76.3	81.5	12.4 0.3	0.356 0.001	no orbit
4963	θ Vir Aa	139189	13 07 21.5	-05 16 21	4.4	1.5	27	76.0	81.5	325.3 0.2	0.495 0.001	no orbit
-	9392	120673	14 46 24.2	+06 09 46	6.7	0.0	8	78.3	81.5	296.5 0.8	0.363 0.010	P = 228 yr
5654	Cou 189	101429	15 09 47.7	+19 09 47	5.9	1.9	8	78.1	81.5	145.5 0.1	0.461 0.003	no orbit
5850	9758	101699	15 40 50.3	+13 49 33	6.4	1.0	9	76.4	81.5	2.5 0.1	0.682 0.003	no orbit
-	9932	140981	16 05 42.9	-09 58 09	6.9	0.3	6	78.6	81.5	192.5 0.3	0.384 0.007	P = 55.0 yr
6627	10795	103106	17 44 55.5	+17 42 51	5.7	1.3	12	78.3	81.7	267.5 0.3	0.574 0.002	no orbit
6795	11111 AB	123187	18 07 04.6	+03 59 00	5.7	1.2	12	78.3	81.7	333.3 1.0	0.339 0.002	P = 270 yr
7285	12160 AB	104602	19 10 19.8	+16 45 40	6.7	1.3	4	76.6	81.7	137.9 0.1	0.681 0.001	no orbit
7497	12808 AB	105168	19 40 12.8	+11 42 27	5.3	1.2	8	76.5	81.7	76.3 0.1	0.456 0.001	no orbit
7882	14073 AB	106316	20 35 12.2	+14 25 12	3.6	1.0	24	75.6	81.7	182.5 1.5	0.538 0.008	P = 26.6 yr
-	14648 Aa	145118	21 04 45.8	-08 26 13	8.1	0.3	2	78.6	81.7	90.7 0.1	0.256 0.001	no orbit
8566	15988	127551	22 27 26.2	+04 10 38	5.5	1.4	10	76.6	81.7	117.1 0.1	0.818 0.005	P = 140 yr
8739	16428	108307	22 56 41.6	+11 27 40	5.8	1.3	8	78.6	81.7	297.3 0.5	0.600 0.002	P = 270 yr
8890	16708	165658	$23^{h}20^{m}02^{s}.0$	-15°18'50"	5.2	0.7	6	76.5	81.7	102°.0±0°.2	0".412±0".003	P = 63.2 yr

to the $0''.0002$ limit as an example for an interferometer with a 300-meter baseline results in a gain in sensitivity to shorter periods by a factor of $(0''.025/0''.0002)^{3/2} \geq 1400$. Where speckle interferometry now resolves systems having periods of years, a long baseline interferometer will resolve binaries having periods of hours! A two solar mass binary at a distance of 100 pc could be resolved as long as the period exceeded 18 hours corresponding to a semi-major axis of only 0.020 A.U. A system of the same total mass could be resolved from a distance of 1000 pc with a period as short as 23 days.

Observations of double-lined spectroscopic binaries offer the most promising returns from very-high angular resolution interferometry of binary stars. Distances determined for these objects are independent of the effects of interstellar extinction (and can in fact be used as a probe of the interstellar medium) and can potentially penetrate to distances well beyond the effective limit for trigonometric parallaxes while preserving the directness and uniqueness of a simple geometric technique. Single-lined spectroscopic binaries do not so easily yield a complete set of orbital and physical parameters since the linear scale of the relative orbit is not obtainable from the radial velocities of just one component. If the trigonometric parallax is known and the apparent orbit is determined interferometrically then the resulting mass sum can be combined with the spectroscopically determined mass function to give the individual masses. The HIPPARCOS astrometry satellite should eventually provide parallaxes of great value in this application.

By determining spectroscopic parallaxes for the objects included in the "Seventh Catalogue of the Orbital Elements of Spectroscopic Binary Systems" of Batten et al.(1978), Halbwachs (1981) calculated the expected angular separations at nodal passages. Of the 978 member systems in the catalogue, 683 binaries or 70% of the entire sample are predicted to have nodal separations exceeding $0''.0002$ and would thus be good candidates for resolution by an interferometer having a baseline of 300 meters. Conservatively considering only double-lined systems as prime candidates due to their anticipated small magnitude differences and limiting the program to objects north of declination -20°, we find a sample of 180 double-lined spectroscopic binaries likely to be resolved by a 300 meter baseline interferometer. Of these, 102 systems are predicted to have separations greater than $0''.0010$ and are almost certain to be resolved. Figure 7 presents a histogram of this last sample as a function of the MK spectral types available for the objects compared to the distribution currently available for the mass-luminosity relation. Important aspects of Figure 7 are the new large numbers of early type main sequence components as well as the substantial collection of evolved stars for which masses, luminosities and in many cases effective temperatures could become available.



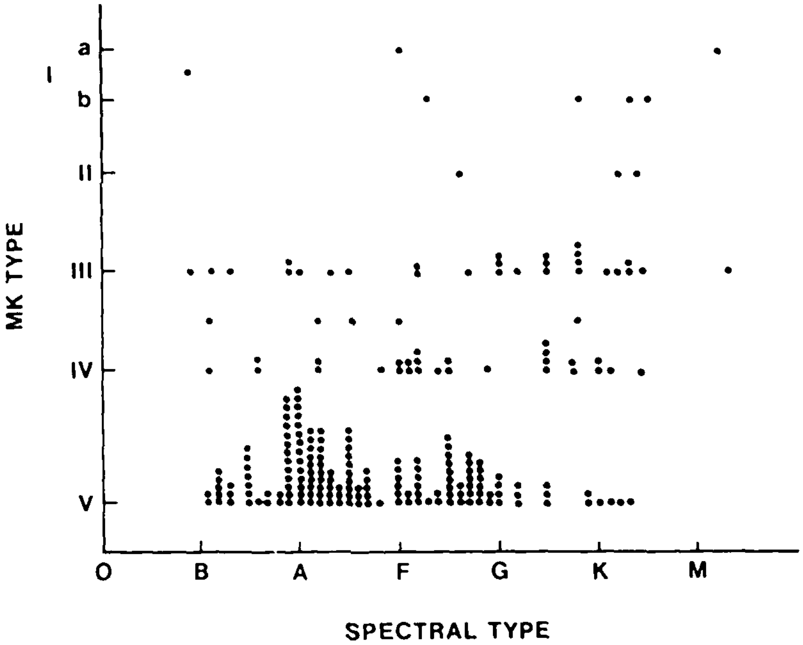


FIG. 7. The distribution of MK spectral types among the components of binaries considered by Popper (1980) as having reliably determined masses is shown in the upper histogram. The lower histogram shows the distribution of the components of double-lined spectroscopic binaries from the catalog of Batten et al (1978) which can be expected to have angular separations exceeding 0".0010 and thus be excellent candidates for long baseline optical interferometry.

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DISCUSSION

EVANS: Dr. Davis has emphasized the limitations of the occultation method and while, I agree with him, I feel I must emphasize what has been achieved so far. It has produced the major proportion of measured angular diameters. In some favorable cases, such as Alpha Tauri, where the repeatability of occulation observations has produced some twenty results; the mean value is uncertain by less than half a percent. The observed values range down, for later types, well below those values accessible to the speckle interferometrists. The observations do not require large telescopes, complicated equipment or large amounts of time so that even amateurs with relatively small telescopes can contribute. The possibility of multicolor observations on the same occasion is of value in the detection of possible variations with wavelength. As to errors: these are proportionally greater the smaller the star observed, but one needs to approach published values with reserve since methods of reduction vary quite widely. The quotation of the formal errors of a multiparameter fit usually give an unduly optimistic view of the situation. One should try a variety of trial diameters near the result of a multiparameter fit and assess critically the range over which diameter values might be acceptable. In certain cases there is no well defined best fit.

The occultation program has a future in the detection of close binaries, which in favorable cases are much closer than those accessible by speckle interferometry. Magnitude and color differences can be obtained from single observations and in some cases the ambiguity of quadrant of the speckle results can be removed. If numerous observations of the same system on the same or different occasions are available, conventional data for the separation and position angle can be derived and orbital elements improved or even derived. It is notable that the histogram of separations for A-type binaries differs from that given Dr. McAlister. For example, for the brighter A-type stars where observational selection is less severe, the numbers increase quite sharply for separations starting at the point where his begin to fall off.

FRACASSINI: As regards the discovery of double stars by means of interferometry, I will ask something about the problem of Alpha Lyrae. In one of the first publications of the Narrabri researchers, Prof. Hanbury-Brown mentioned the problem of Alpha Lyrae, whose effective temperature, derived from angular diameter measures, is lower than that of Alpha Canis Majoris in spite of its earlier spectral type. In this connection Prof. Hanbury Brown mentioned the hypothesis by Petrie of the duplicity of Alpha Lyrae. That is not a trivial problem for the researchers of the Department of Physics at the University of Milan and their colleagues of Brera-Merate Observatory who have proposed Alpha Lyrae as a standard for the calibration of angular diameter determinations and, as I. N. Glushneva will say in her paper, this star is carefully studied by the researchers at the Sternberg State observatory in Moscow. Is there any news about this problem?

McALISTER: We have observed Alpha Lyrae on several occasions with our speckle camera and find no evidence of a companion. Our detectibility would be restricted to separations in excess of about 0.03 arcseconds and a magnitude difference less than about two magnitudes. Within these constraints, then Alpha Lyrae appears to be single to us.

BATTEN: High-dispersion observations of Alpha Lyrae at Victoria reveal no sign of variation in the radial velocity.

POPPER: I was disappointed that you did not discuss the application of your technique to the determination of color indices and magnitude differences (as described in your abstract) in binaries with good orbits. This information is often lacking so that fundamental properties of the components are not well known (but see K. D. Rakos, Astron. Astrophys. Suppl. 47, 221). At this time, this use of speckle observations could be of equal or greater importance than the astrometric results.

McALISTER: I did not say much about photometric determination from speckle interferometry because at the present time there are very few solid results available for demonstration. There are several very promising algorithms for extracting differential photometry from speckle data, as mentioned in my paper, and I believe that this potential may even be more important than the accurate astrometry speckle is providing. One member of our speckle group is devoting a major part of his time to implementing these algorithms and we aim, ultimately, at providing a catalogue of magnitude differences and color indices for binaries with separations of a few arcseconds down to about 0.03 arcseconds.

POPPER: Perhaps the most interesting result thus far from your work is for Chi Dra. The revised orbit, combined with published radial velocities, leads to a mass for the F7 V primary considerably less than one solar mass. No other late F star with well-determined properties has such a low mass. A critical observation is the radial velocity separation of the components. A very preliminary result by Tomkin and

Fekel at McDonald Observatory shows that the spectral lines of the components are not clearly resolved except possibly at maximum separation. An underestimate of the separation by 1 or 2 km/s could remove much of the discrepancy in the mass of the primary, which has been interpreted as a consequence of a non-standard chemical composition. We await the results of further observations by Tomkin and Fekel.

McALISTER: I am glad to hear that a revised mass ratio for Chi Dra may be forthcoming. That, coupled with the more recent speckle results, will certainly warrant a re-analysis of this now puzzling system and may indeed show that it is not anomalous as it now appears.

STRAND: What is the limiting magnitude with the CCD system?

McALISTER: 15th mag.

STRAND: I believe that you will be able to obtain measures of G 107-70, the close binary with white dwarf components, for which we now have a very precise orbit except for the value of the semi-major axis, which is of the order of 0.6" from 61-inch plates. With a parallax known to 1%, combined with a speckle interferometric measurement of separation, the system will give masses with a precision of a few percent.

McALISTER: We have not yet made a deliberate attempt to measure very faint binaries, but I do recall that we have very nice results on a 15th magnitude system, which I believe is Ross 29. I do not remember if GL 107-70 is on our program, but I will certainly see that it is added if it is not already there.

GARRISON: I would like to second what was said by Dr. Popper about providing photometric information and to encourage you to extend your work to overlap with some the area-scanner work in the region of separations of 1 - 5 seconds of arc.

Chris Corbally at Toronto (now at the Vatican Observatory) finished a thesis last year in which he studied MK types for close visual binaries with separations of 1 - 5 seconds. The only photometric data available for comparison with his types are from the area scanner work of Hurly and of Rakos. Unfortunately there is little overlap between these two sources and they disagree with each other in those few stars. We can get good MK types for stars as close as 1" in good seeing, so this is important for studies of stellar evolution theories.

HEINTZ: The inclination usually is (along with the eccentricity) the element least reliably defined in astrometric (unresolved) orbits. I have a photographic series on Chi Draconis which I expect to complete shortly.

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HIGH ANGULAR RESOLUTION MEASUREMENTS OF STELLAR PROPERTIES

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1. INTRODUCTION

The technological advances of the 1970s have given us the means to widely exploit techniques for high angular resolution astronomy that have been with us in some cases for a century or more. This review describes the scientific progress made thus far in applying high angular resolution in the visible and infrared regions to the fundamental determination of the properties of stars and outlines the future scientific potential of the very high angular resolution to be obtained from multiple telescope interferometers. If we define high angular resolution simply as the extraction of spatial information on scales smaller than the seeing limit, then we must recognize the impressive results of the visual binary star observers who routinely measure angular separations at or below the Rayleigh limit, probably through the mental processing of speckle phenomena. For the purposes of this review, high angular resolution is defined in the context of interferometric or occultation observations employing impersonal data acquisition and analysis. It should be emphasized that the accuracy of a high angular resolution measurement is as important as the resolution itself and sometimes leads to a significant extension in the effective resolving power of a method.

Many fine reviews have appeared in recent years that elucidate the details of the techniques for high angular resolution astronomy. While this review concentrates on scientific results, it is worthwhile to present a selection of these technical descriptions. General discussions of interferometric techniques have been given by Labeyrie (114, 115), while Worden (235), Bates

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(23), and Dainty (47) have concentrated on speckle interferometry and speckle imaging methods. The monograph on intensity interferometry by Hanbury Brown (90) is the definitive treatment of that approach. Tango & Twiss (202) have discussed the theoretical basis for a modern Michelson interferometer employing two telescopes, and Davis (51) has given the design details of a prototype long-baseline interferometer now being tested at the University of Sydney. Shao & Staelin (193) have described their long-baseline facility aimed at high-precision astrometry. The critically important effects of atmospheric turbulence in optical astronomy have been discussed by Roddier (184) and Woolf (232). IAU Colloquium No. 50 on "High Angular Resolution Stellar Interferometry" had numerous contributions from all areas of interferometry; references to specific papers are given throughout this review. There have been no recent reviews of lunar occultation methods, and the early formative contributions of Nather & Evans (166) and Evans (65) still serve as foundations for lunar occultation work. The IAU joint discussion on photoelectric occultation observations published in Volume 2 of *Highlights in Astronomy* gives a broad review of the field at its inception.

2. HIGH ANGULAR RESOLUTION MEASUREMENTS OF BINARY STARS

2.1 *General Comments*

Binary stars remain the sole fundamental source for the determination of stellar masses, and there presently exists an enormous body of observational data pertaining to these objects and accumulated by a variety of mostly classical techniques. In the *Washington Double Star Catalog* (available from the Strasbourg and Greenbelt data centers) and the companion *Observations Catalog* of visual binary stars (both of which are maintained by C. E. Worley at the US Naval Observatory), there are currently some 400,000 measurements of 73,610 binary systems (C. E. Worley, private communication). Almost 80% of these observations are from visual micrometry. From this impressive collection there have been 928 determinations of orbits for 847 systems as reported in the orbit catalog of Heintz & Worley (102); 180 of these orbits are classified as being of good or definitive quality. The catalog of spectroscopic binaries of Batten et al. (25) lists 978 orbit determinations, of which nearly one third are for double-lined systems and one fourth are considered as being of good or definitive quality. Only a handful of these objects have been resolved as visual binaries. The radial velocity bibliography of Abt & Biggs (1) lists a significantly larger number of stars shown or suspected to have variable radial velocity, with duplicity as one possible explanation. Such objects are good candidates for attempted resolution by nonclassical methods.

Popper (172) has critically reviewed the current status of our knowledge of stellar masses. His discussion emphasizes the long-standing problems in double-star astronomy that no single technique is capable of deriving a complete dynamical description of a binary star system and that the selection effects inherent in the various observational techniques permit only a small fraction of systems to be amenable to complementary approaches. This is most strikingly the case among the visual binaries that require parallaxes and mass ratios; the former properties are usually derived from long-focus astrometry, while the latter are normally found from astrometry or spectroscopy in the case of highly eccentric visual orbits. Popper (172) finds only 14 visual systems whose individual components have mass determinations with accuracies better than 15%. This tremendous discrepancy between potential and accomplishment in masses derived from visual binaries is entirely due to the extreme difficulty in determining parallaxes and mass ratios for these systems by classical means. Many authors look toward space astrometry and advances in ground-based spectroscopic techniques for a solution to this impasse. No doubt much progress can be made in this area, but it is likely that the vast majority of visual binary discoveries will contribute to our knowledge of the statistical frequency of these objects, rather than to the collection of fundamental astrophysical data.

High-resolution observations of binary stars are most valuable where they can immediately provide the complementary information needed for explicit mass determination. The most clear-cut example of this is in the case of the direct resolution of double-lined spectroscopic binaries. Here angular scale information combines with spectroscopically determined linear scale information to yield the value of the orbital inclination otherwise missing from the spectroscopic analysis. A direct measurement of the distance to the double-lined binary also falls out of the solution. Thus, if we assume the availability of a magnitude difference, the individual absolute magnitudes as well as the individual masses can be determined for double-lined spectroscopic binaries. In order for the resolution of single-lined systems to yield complete mass and luminosity data, an independently determined parallax must be available. The potential for the resolution of spectroscopic binaries by interferometric techniques has been discussed by McAlister (128) and by Halbwachs (89). By calculating expected angular separations of spectroscopic binaries at nodal passages in order to alleviate the effects of the unknown inclination, these authors produced lists of spectroscopic systems approachable at various limiting resolutions. The effectiveness of this procedure is shown by the subsequent resolution by speckle interferometry of 7 of the 13 double-lined and 13 of the 59 single-lined candidate stars given by McAlister (128).

High-resolution observations of close visual binaries are of secondary importance compared with the resolution of spectroscopic binaries, but they are of primary importance to visual double-star astronomy because of the significant gain in accuracy compared with micrometer results and because of the more complete orbital coverage available by high-resolution techniques. Examples of visual binaries that have been followed through periastron passage or through previously unresolved orbital segments by speckle interferometry are ADS 4229, ADS 6825, ADS 10531, and ADS 12473, for which interferometric observations are given in the catalog of McAlister & Hartkopf (144). The analysis of the evolved system ADS 11579 by Batten et al. (24) incorporates speckle observations obtained at previously unresolved mean anomalies. Modern interferometric observations are providing the means for significantly improving the quality of orbit determinations for close, rapidly moving visual binaries.

In addition to high angular resolution, interferometric and lunar occultation techniques have the important capability for providing differential photometric measurements within binary star systems, thus yielding individual colors as well as masses. In this context, it is worth quoting Popper (172): "Masses are of little interest, however, without knowledge of other fundamental properties of the stars, which are usually determinable if the masses are." It is likely that an increased emphasis on accurate differential photometry from high-resolution techniques will make at least as important a contribution to binary star astronomy and the determination of fundamental stellar quantities as will the high resolution itself.

2.2 *Interferometric Measurements of Binary Stars*

It has not commonly been noted [Heintz (101)] that it was Karl Schwarzschild who in 1895 [Schwarzschild (190)] made the first measurements of binary stars employing the then radically new technique of Michelson interferometry only four years after Michelson himself measured the angular diameters of the Galilean satellites of Jupiter [Michelson (162)]. The technique languished until 1919, when Anderson (5) and Merrill (161) employed Anderson's version of Michelson interferometry to resolve the spectroscopic system comprising Capella. Finsen (80) traced the subsequent intermittent use of the technique, pointing out the irony of its application with generally small apertures. He also warned the consumer against taking all published results at face value (77; see also 209, 210). A monumental series of visual interferometer results was obtained by Finsen with an "eyepiece interferometer" of his own design and construction and used at the 26-inch refractor in Johannesburg during a 15-year period (78, 79). Finsen's program yielded some 6000 measures of southern binary stars, including more than 70 previously unresolved systems culled from his survey of over 8000 stars to a limiting magnitude of $V = +6.5$ (extended to $+7.5$ for high proper motion objects) in the declination zone $+20°$ to $-75°$. Finsen's work is by far the most productive program of interferometry carried out in any area of astronomical research. Other, more brief programs of visual binary star interferometry were conducted at the Lick Observatory (36-inch) during 1939–1941 by Jeffers (106), at Catania (13-inch) during 1922–1923 by Maggini (126), and at the Flower Observatory (18-inch) during 1934–1935 and 1949–1954 by Wilson (230, 231).

A photoelectric modernization of the Anderson-Finsen version of the Michelson interferometer was devised and demonstrated by Wickes & Dicke (227, 228). This approach offers the significant improvements over visual interferometry of being impersonal and yielding magnitude differences. The instrument was applied to a small number of field visual binaries (including the first direct resolution of the systems α Del A and the Population II star μ Cas) and several Hyades binaries (225, 226), but its use was discontinued after this promising beginning. A modified version of the Wickes-Dicke interferometer has been developed by Tokovinin (203), who calls the device a "phase-grating stellar interferometer." Tokovinin (204, 205) has subsequently initiated a productive program of binary star interferometry using telescopes with apertures ranging from 0.6 to 2.6 m. Tokovinin's instrument has the potential for extracting magnitude differences, although the photometric results are not yet considered reliable. The initial results from this program, which include three newly resolved bright B stars (196), appear to be in excellent agreement with speckle observations taken at similar epochs (206).

Michelson interferometry of binary stars employing two widely separated apertures has been successfully carried out only by Kulagin (111), who built a special periscopic instrument at Pulkovo, and by Blazit et al. (33) and Koechlin et al. (110), who used the two-telescope interferometer at CERGA (113, 115). Both instruments produced observations of the Capella system; indeed, the Pulkovo instrument was apparently discontinued after observing Capella through only one revolution. The CERGA interferometer has resolved the disks of the individual components of Capella as well. The intensity interferometer at Narrabri (90) was used to resolve the binary systems γ^2 Vel [Hanbury Brown et al. (92)] and α Vir [Herbison-Evans et al. (103)]. Twiss & Tango (208) described a 1.87-m baseline Michelson interferometer to be dedicated to binary star observations and capable of 0.015-arcsec resolution, but the project was unfortunately discontinued. Davis (49) considered the general application of long-baseline interferometry to binary star astrometry in which magnitude differences as well as angular diameters for one or both components can be determined in addition to the measurement of orbital motion. The Narrabri study of α Vir is to date the only such application of long-baseline interferometry in which masses, luminosities, and emergent fluxes have been directly measured, but similar binary star studies will be a major scientific goal for the on-going long-baseline program at the University of Sydney and the recently initiated Georgia State University effort.

Since the mid-1970s, speckle interferometry has become the major interferometric technique applied to binary stars. Following the invention of speckle interferometry by Labeyrie (112), Gezari et al. (85) demonstrated its applicability to binary stars with measurements from the 5-m Hale telescope of the angular separations of Capella and the newly resolved system β Cep. These observations were rediscussed in a second paper from this group [Labeyrie et al. (116)] in which six additional spectroscopic binaries, including the astrometric companion to Algol, were resolved for the first time. Following these pioneering efforts, speckle programs primarily directed toward binary stars were initiated in England at Imperial College (164, 165), in France at CERGA (32, 39a), and in the United States at Georgia State University (131, 145), where the quoted references indicate the initial and most recent results from these three groups. In addition to their normal program of observations, the English group has also published specific discussions of their results for the binary nature of the central star in the Red Rectangle, HD 44179 (160), and a preliminary survey for duplicity among Southern Hemisphere reference stars provisionally chosen to link the astrometric reference frames of the *HIPPARCOS* satellite and Space Telescope (7). The French group now collaborates with Soviet astronomers (10, 11), following the first applications of speckle interferometry on the 6-m telescope by Balega & Tikhonov (9) and Dudinov et al. (55). The speckle group at Georgia State University (GSU) has published a large number of negative results in a separate series of three papers, the latest being that of Hartkopf & McAlister (96).

Other groups that have contributed speckle measurements of binary stars, although not specifically as their primary scientific goal, are in West Germany at the University of Erlangen-Nurnberg (215, 219) and in the United States at the Steward Observatory (98, 99).

A catalog of interferometric measurements of binary stars has been compiled by McAlister & Hartkopf (144) and includes all modern results as well as the 1919–1921 Mount Wilson observations. The catalog contains references to 46 source publications, and it is thus unnecessary to repeat that complete listing here. It omits the extensive series of visual interferometer measurements by W. S. Finsen, as they can be found in an orderly series of papers in the *Union Observatory* (later *Republic Observatory*) *Circulars*. Thus the following discussion does not consider Finsen's results or the results of others using visual interferometry at small telescopes and thus inevitably achieving considerably lower resolution and accuracy than the modern techniques.

At the end of 1983, there were 3363 measurements of 824 binary stars obtained by "modern" interferometric methods and 1863 negative examinations for duplicity. The great majority of these results are from speckle interferometry. The mean measured angular separation in this sample is 0.32 arcsec, while the median is 0.21 arcsec; 20% of the measurements are for systems having separations of less than 0.1 arcsec. Some 120 systems were directly resolved, in the sense of explicitly measuring angular separation and true position angle, for the first time. Of these, 10 are double-lined and 28 are single-lined spectroscopic binaries, while another 21 show composite spectra and are at least potential candidates for detailed radial velocity studies.

The high accuracy of interferometric results is of considerable importance and justifies observing visual binaries with separations in the range of 0.3 to 1.0 arcsec interferometrically rather than by visual micrometry. Investigations have shown (132, 142) that accuracies approaching ±1 milliarcsec are routinely attainable by speckle interferometry, provided that careful calibration data are secured at the telescope. Indeed, accuracies an order of magnitude better than this are being approached for the wide binaries on the GSU/Lowell Observatory planet search program (143), in which high accuracy is the primary observational goal. At a 4-m aperture telescope, speckles are approximately 0.030 arcsec in diameter, and separation measurements reaching ±1 milliarcsec accuracy require a precision of only 3% in centroiding autocorrelation peaks. It is an injudicious use of large-telescope time to produce results of lower quality. It may be noted that computers of orbital elements of visual binary stars generally do not take advantage of the enhanced accuracy of interferometric measurements, as shown by the relatively large residuals these data are often permitted to have. Orbit computers should still approach these observations conservatively, as there are a variety of telescope sizes and calibration procedures behind the observations, but there is now sufficient coverage in many cases so that a judgment of accuracy can be made. In order to improve the accuracy of interferometric measures of binary stars and to permit greater intercomparison of results from different observers, a list of "standard" binaries has been suggested by McAlister & Hartkopf (142). The calibration of interferometric observations of binaries for instrumental and atmospheric effects has been discussed by McAlister (140).

Infrared speckle interferometry carried out by means of one-dimensional scans is beginning to provide results for cool companions to stars. A particularly interesting program for the detection of low-mass astrometric companions of nearby stars is being carried out at Kitt Peak (KPNO) and

Steward observatories by D. W. McCarthy. McCarthy et al. (155) report a detection of the astrometric companion to ζ Aqr B at the *K* and *L* photometric bands and deduce a color temperature of 1440 ± 200 K for this previously unseen star. Weigelt (216) had previously reported a companion to ζ Aqr A seen by him at visible wavelengths by means of speckle holography. This object was not detected by McCarthy et al. (155), nor is it reported in five other visible speckle observations (144). Other direct IR detections of low-mass companions have been given by McCarthy (148) and Lippincott et al. (123). A program of infrared speckle interferometry from Mauna Kea has led to the discovery of a stellar companion to T Tauri by Dyck et al. (59) that is responsible for the infrared excess previously thought to be due to an optically thick dust shell surrounding the presumed single star. Subsequent observations at 2- and 6-cm wavelengths using the VLA (189) have confirmed the duplicity of T Tauri and removed the quadrant ambiguity from the speckle data.

Beckers (29) has suggested a variation of Labeyrie's speckle interferometry in which speckle frames are simultaneously recorded in a narrow spectral feature and in the adjacent continuum. Beckers' "differential speckle interferometry" then takes advantage of the inherent precision of speckle methods in order to measure small shifts in the relative locations of corresponding speckles seen in and out of the absorption features arising from Doppler-shifted "photocenters." The method has the potential for indirectly resolving spectroscopic binaries down to submilliarcsecond separations and for measuring true rotational velocities and linear diameters of stars. A demonstration of the potential of Beckers' method has been given by Aime et al. (3).

The technique of "speckle holography," originally suggested by Bates et al. (21), has been applied to multiple star systems by Weigelt (212, 214, 218). This method, which relies on the presence of an additional point source within the isoplanatic patch to essentially deconvolve the atmospheric and instrumental point spread function, is of limited astronomical use because of the rarity of triple systems in which all three stars are separately resolved and lie in the same isoplanatic patch. A generally more applicable variation of speckle holography called "speckle masking" has been suggested by Weigelt (213, 218) and demonstrated by Weigelt & Wirnitzer (219). This computation-intensive approach has the important capability of diffraction-limited imagery of binary stars in which quadrant ambiguities are eliminated and true intensity ratios are obtainable.

2.3 *Occultation Measurements of Binary Stars*

The historical background of the application of lunar occultations to binary star astronomy has been summarized elsewhere (166). For many decades, visual observations were made in attempts to see multiple disappearances or fadings - useful indicators of possible duplicity (6)—but the modern use of photoelectric detectors and high-speed data recording provided the means for obtaining quantitative measures from these events. The pioneering efforts of D. S. Evans and R. E. Nather (65, 166) are largely responsible for bringing to occultation work the status of a powerful and reliable tool for high angular resolution astronomy. For the study of binary stars, the method has obvious advantages and disadvantages, the latter primarily due to the unique and fleeting circumstances surrounding each event. The advantages of unsurpassed resolution achieved with small telescopes by means of straightforward equipment contrast remarkably with interferometric methods that have effective resolution limits for single telescopes an order of magnitude less than the occultation method. Lunar occultations offer their greatest contribution to binary star astronomy through the systematic survey for new binaries, which can be followed up at will by other techniques (as speckle interferometry has done for some 25 occultation binaries), and by providing a means for measuring differential magnitudes and colors with astrophysically useful accuracies. Notwithstanding the limitation to only about 10% of the sky, the greatest drawback of occultation studies is the restriction of measuring only the component of separation projected perpendicular to the local lunar limb—the so-called vector separation—rather than the true angular separation of a binary star. The combined efforts of several occultation observing groups occasionally overcome this limitation through the triangulation of vector separations obtained along different projection angles.

Active occultation programs giving emphasis to all binary star opportunities have been carried out at the following observatories (where, again, only the first and most recent summary publications are referenced): McDonald Observatory (66, 74), Fick Observatory (62, 63), Prairie Observatory (173–175), Cloudcroft Observatory (176, 178), Lowell Observatory (see, for example, 223), and KPNO (188). Additional photoelectric occultation series from less extensive programs have also been published (35, 52, 97). Numerous reports of visual occultation timings in which duplicity has been suspected may be found in the International Occultation Timing Association's Newsletter. Special attention to occultations of star clusters has been given to the Hyades (see discussion below), the Pleiades (18, 20), and Praesepe (171) clusters.

Evans (67) has presented a catalog of occultation observations that have been obtained photoelectrically prior to 1981. The catalog contains 312 vector separation measures for 224 binaries. These measures result from a total of 3074 stars whose occultations have been observed, implying a duplicity detection rate of 7%. For stars brighter than $V = +6.7$, 17% of the

342 candidates were measured as double. Evans (67) showed that the lower duplicity rate observed for fainter A-type stars, whose average distance is about three times that of the observed sample of bright A stars, coincides with expectations if the occultation detections are complete to their limiting resolutions and the binary frequency of A stars is uniform. It was also pointed out that contact angle affects the detection of duplicity in a manner that allows an estimate of the frequency of missed detections at small contact angles when the lunar limb is effectively moving much faster than at high contact angles.

The mean measured vector separation in the Evans catalog is 0.26 arcsec, decreasing to 0.15 arcsec for stars of $V < +6.7$ mag. The internal error estimates are typically 1 to 3 milliarcsec. Nearly one third of the measured vector separations are less than 0.030 arcsec (the practical limit for speckle interferometry), while 11% are less than 0.010 arcsec. This highest-resolution category is of limited astrometric use, since errors are typically 10 to 30% of the measurement. It is difficult to intercompare the observational data in order to check for consistency between observers because of the minimum requirement of three simultaneous measurements for different geographic locations for an evaluation of the scatter in those data; such a situation happens only rarely. It is possible to compare occultation and speckle measurements of the same objects observed at similar epochs. A comparison of 33 commonly observed binary separations with epoch differences of less than 0.5 yr shows an average separation measurement difference of -0.007 ± 0.045 arcsec in the sense of occultation − speckle, where each direct speckle measurement has been projected onto the position angle of the corresponding occultation observation. If 4 differences are dropped on the basis of being in excess of 1.5 times the standard deviation, then the mean difference becomes -0.010 ± 0.020 arcsec. The situation improves further if interpolation to the observed occultation epoch is applied to the speckle data, where for 44 commonly observed separations the mean difference becomes -0.006 ± 0.035 arcsec, improving to -0.008 ± 0.015 arcsec when 4 large differences are omitted. The average separation in this last comparison sample is 0.15 arcsec. There is clearly no detectable systematic difference between occultation and speckle measurements. The dispersion in the differences is, however, significantly larger than the accuracies claimed for both techniques, a situation at least partly due to intervening orbital motion.

Potentially the most important information from occultations are magnitude differences. The Evans catalog (67) reports 269 measurements of ΔB for 202 systems and 140 measurements of ΔR for 105 systems. The average estimated error for the 249 ΔB determinations for which error estimates are given is ± 0.38 mag, with 23% of the error estimates being at or better than ±0.1 mag. Only 15% of the 126 ΔR measurements possessing error estimates are of this quality, having an average estimated error of ±0.47 mag. If we consider only stars brighter than $V = +6.7$, the average error for 85 ΔB determinations with error estimates is ±0.29 mag, with nearly 50% of ±0.1 mag quality. For 56 determinations of ΔR, 30% are of this high quality, with an average error estimate of ±0.28 mag. Routine gathering of Δm's of the highest attainable accuracy is clearly a challenge to occultation observers.

2.4 *Some Specific Binary Systems*

The following binary stars have received particular attention in the course of applying high angular resolution techniques to objects that are most likely to yield fundamental parameters.

2.4.1 HR 321 (μ Cas) The Population II binary μ Cas has long been a challenge to binary star observers due to the large Δm predicted by the astrometric orbit (122). Although the angular separation of the components is roughly 1 arcsec, the secondary contributes only about 1% of the system's light in visible regions. McCarthy (149) has used the advantages of infrared speckle interferometry to increase the relative brightness of the secondary to about 5% of that of the primary, causing a visibility modulation of about 10%. These results confirm the previous marginal resolutions at visible wavelengths (100, 225, 228) and provide mass determinations with uncertainties of ±25%. The orbit is still known with too little precision to contribute new data to the question of the primordial helium abundance.

2.4.2 HR 788 (12 Per) The mass and luminosity values determined by McAlister (133) from speckle observations of this 331-day double-lined spectroscopic binary were considered by Popper (172) as belonging to a sample of only five resolved spectroscopic binaries with well-determined masses. Results for the two components, both of slightly earlier spectral type than the Sun, fit the empirical mass-luminosity relation quite well.

2.4.3 HR 854 (τ Per) This 4.15-yr spectroscopic binary contains stars of types G5 III and A5 V. A combined spectroscopic and speckle interferometric analysis by McAlister (138) yielded the orbital inclination and semimajor axis and showed that astrophysically consistent luminosity values result from assumed masses. Explicitly determined masses and luminosities must await an improvement in the parallax or a measurement of the mass ratio.

2.4.4 HR 915 (γ Per) This 14.6-yr double-lined spectroscopic binary was found to present a nearly edge-on orbit from speckle observations that also directly determined the masses and luminosities for both components (139). The astrophysical parameters suggest a spectral classification of G8 II–III

+ B9 V rather than the previously estimated types of G8 III + A3 V. It was also suggested that there is a chance of an atmospheric eclipse at the next occasion of minimum angular separation (occurring in 1990).

2.4.5 HYADES BINARIES: HR 1331, HR 1391, HR 1411, AND HD 28363 High-resolution observations of binary stars in the Hyades are of importance, particularly if these stars are also spectroscopic binaries, in that they provide input to the on-going question of the cluster distance modulus and mass-luminosity relation in a manner independent of the standard astrometric procedures. It should be kept in mind that the significant dispersion in the individual distances to Hyades stars must be dealt with when members are used individually to determine cluster parameters. As demonstrated by VandenBerg & Bridges (211), theoretical models of a metallicity-dependent ZAMS for the Hyades can be used with considerable sensitivity to determine the cluster distance by means of a consistency match with the masses of Hyades binaries. This approach currently indicates a cluster distance modulus of 3.42 mag, in good agreement with the result of McClure (157) for the spectroscopic and eclipsing Hyades binary vB 22. McAlister (130) combined two speckle observations of the 11-yr single-lined spectroscopic binary HR 1331 (51 Tau) with the marginally determined spectroscopic elements and found that if one assumes a normal mass-luminosity relation, then a cluster distance modulus of 3.25 results. This system has been observed through more than one-half revolution by speckle interferometry and should soon possess one of the best-determined apparent orbits of any Hyades binary. HR 1391 (70 Tau) has been resolved by both speckle and occultation observers. Its status as the most puzzling of the Hyades binaries has been rediscussed by Evans (68), who clearly pointed out the discrepancy between the modern measurements and the visual interferometer results of Finsen (82). Evans concluded that an orbital period of 11.4 yr best fits the data and that a distance modulus of 4.0 mag, corresponding to the star being over 40% more distant than the cluster center from the Sun, leads to internally consistent masses, luminosities, and spectral types. The existing magnitude difference from occultation data and further high-resolution measurements of the orbital geometry are crucial to a final solution to this problem. Evans (68) also discussed the status of the information gleaned from occultation and speckle observations of the Hyades binaries HR 1411 (θ^1 Tau) and HD 28363 (ADS 3248). Orbital analyses for these systems lead to preliminary values for the Hyades distance modulus of 3.12 and 3.19. Occultation observers who have given particular emphasis to such important Hyades events have reported their results in a number of papers (26, 73, 76, 169, 170, 173, 175–177, 222).

2.4.6 HR 1708 (α Aur) No other star has received as much attention from interferometrists as has Capella. First resolved by Anderson (5) and Merrill

(161), it has intermittently been observed during some 200 revolutions of its 105-day orbit by numerous groups. Orbital elements derived from 56 reliable observations between 1920 and 1979 were redetermined by McAlister (137) independent of any input from spectroscopy [unlike the previous solution of Finsen (81)] and probably represent the most accurately determined set of apparent elements of any binary star. The orbit of Capella has been considered to be the only one capable of producing ephemerides suitable for the calibration of interferometric techniques (142). The uncertainty in the orbital inclination now leads to an error of less than 1% in the masses and thus improves the situation from that which existed at the time of Popper's (172) discussion. Blazit et al. (33) measured the angular diameters of the components with the CERGA two-telescope interferometer, finding values of approximately 5 milliarcsec with considerable uncertainty. From the geometrically determined distance of 13 pc and the scale-dependent values of the radii given by Popper (172), one expects angular diameters of about 3 and 5 milliarcsec for the G0 III and G5 III components of Capella. The true quadrant of the ascending node of the orbit has been determined by Bagnuolo & McAlister (8) by applying the "shift-and-add" algorithm of Bates & Cady (22) to a series of photographic speckle frames.

2.4.7 HR 1788 (η Ori) The 9.2-yr spectroscopic system associated with the B1 V primary component of the visual triple ADS 4002 has been resolved by speckle interferometry. A preliminary analysis (129) in which the 9.2-yr pair was assumed to be coplanar with an 8-day eclipsing system also associated with η Ori A was used to derive masses for all three stars comprising η Ori A, as well as to give a direct measure of the distance to the object and hence the individual stellar luminosities. With a total of 40 solar masses invested in the three stars, this preliminary result represents the most massive system for which masses and luminosities have been determined directly without reference to a temperature calibration.

2.4.8 HD 38268 (R136a) This is the object suspected to be the central ionizing source of the Tarantula nebula in the Large Magellanic Cloud and suggested as being supermassive in nature (40). Weigelt (217, 218) examined this object with speckle interferometry and arrived at a preliminary result that R136a was at least binary, with a separation of 0.46 arcsec. Meaburn et al. (159) reobserved the object by speckle interferometry and concluded that it was single in nature. This conflicting situation was settled by Worley (236), who pointed out that R. T. A. Innes and W. H. van den Bos both reported visual measurements in the mid-1920s of a companion having a separation of approximately 0.5 arcsec. Worley added two modern micrometer measures confirming the duplicity, indicating little or no orbital motion, and providing an estimated Δm of approximately 1 mag.

Worley did not see the more distant objects reported by van den Bos; rather, he noted that "the appearance under high power was one of a complicated nebulosity with numerous condensations." At the distance of the Large Magellanic Cloud, a binary system having a total mass of 3000 $M_\odot$ and presenting an angular separation of 0.5 arcsec would have an approximate orbital period approaching 1 Myr. The observed lack of orbital motion thus cannot be used to argue against the supermassive nature of these objects.

2.4.9 HR 3207 (γ^2 Vel) This WC8-type star was observed with the Narrabri intensity interferometer, and an analysis of the measured correlations by Hanbury Brown et al. (92) in combination with spectroscopic and photometric data yielded the distance, radius, luminosity, and emergent flux of the Wolf-Rayet star, as well as the radius and monochromatic emergent flux of the emission region of the star. The observations also permitted the determination of the angular size of the semimajor axis of the 79-day spectroscopic orbit, which combined with an assumed inclination and the spectroscopically determined $a \sin i$ to give the distance of γ^2 Vel. The interferometric observations were not sufficiently extensive to explicitly determine the orbital inclination as in the case of α Vir.

2.4.10 HR 5056 (α Vir) The 4-day spectroscopic system comprising Spica was studied using intensity interferometry by Herbison-Evans et al. (103), who determined not only the previously unknown geometric orbital elements but also the angular diameter of the primary star itself. This type of analysis, in which a complete astrophysical description of a star is deduced, is a major scientific justification for future long-baseline interferometers. The mass determinations for α Vir by Herbison-Evans et al. (103) are considered by Popper (172) to be well determined, and the primary component is the only star whose mass, luminosity, and effective temperature have been determined strictly fundamentally. Improvements in these values would result primarily from a better determination of the spectroscopic orbit of the secondary and a more accurate measurement of the magnitude difference in the system.

2.4.11 HR 5984 (β Sco) This multiple star system has had a fascinating history of occultations, first by Jupiter and Io (19, 105), which led to mass and angular diameter measures for some components of the system (64), and later by the Moon (69, 187). Through the combination of observations obtained from six different geographic locations in 1975 and 1976, Evans et al. (70) calculated the true double-star geometry of the AB and AC subsystems as well as the magnitude differences. This calculation shows the desirability of multiple observers pursuing occultation programs. The AB system is a previously observed visual binary that has also been measured by speckle interferometry, but orbital motion prevents a comparison between the occultation and speckle results. Many speckle observations have been accumulated for the 0.1-arcsec pair CE, which also shows significant orbital motion and for which nearly concurrent speckle and occultation measures show good agreement.

2.4.12 VB 8 Harrington et al. (95b) detected a very low mass companion to the low-luminosity star VB 8 by means of an astrometric analysis of photographic plates. A mass of a few millisuns was suggested, although more plate material is needed in order to establish the elements of the photocentric orbit. McCarthy et al. (156a) have reported a direct detection of the companion to VB 8 by means of speckle interferometry in the near-infrared. This is likely to be the lowest mass stellar object to be directly detected. The temperature of VB 8B was inferred by McCarthy et al. from the observed visibility curve, which shows a maximum depression from unit visibility of approximately 6% at 1.6 μm and 12% at 2.2 μm. The exact nature of VB 8B awaits higher signal-to-noise observations so that it can be more accurately placed on the two-color diagram. McCarthy et al. were unable to detect the astrometric companion to VB 10, found by Harrington et al. to have a period of approximately 4.9 yr. This implies that VB 10B is cooler and less massive than VB 8B.

2.4.13 HR 6927 (χ Dra) This spectroscopic/astrometric binary, with a period of just 281 days, was first directly resolved by Labeyrie et al. (116) using speckle interferometry. A subsequent analysis by McAlister (135) showed that the orbital inclination was significantly greater than the astrometric result, with a subsequent marked decrease in the masses. This system is noteworthy for having a primary star whose mass is less than the Sun's and yet whose luminosity appears to be significantly greater. This situation may be partly due to line-blanketing effects, but a final conclusion concerning the star's excess luminosity must await a spectroscopic redetermination of the mass ratio.

2.4.14 HR 7478 (ϕ Cyg) With a period of 434 days, ϕ Cyg is the only other *double-lined spectroscopic* binary besides Capella to have nearly coequally evolved giant components that have been directly resolved by high-resolution techniques. The masses determined from speckle interferometry and spectroscopy (139) are of sufficient accuracy to satisfy the criteria of Popper (172) for well-determined masses.

2.4.15 HR 7776 (β Cap) Evans & Fekel (71) employed in the case of β Cap a technique whereby vector separations and position angles from lunar occultations of binary stars can be made to iteratively converge to a uniquely determined apparent orbit. They combined newly obtained radial velocities, primarily aimed at deducing the orbital motions of the secondary component, with the occultation results to yield masses and luminosities for the K0 II–III and B8 V components of the long-period spectroscopic system and to set an upper limit on the mass of the short-period, probably late G-type companion to β Cap B. Evans (68) rediscussed this analysis in light of subsequent speckle observations and pointed out the rather large scatter in a series of three speckle measurements by McAlister et al. (146) taken on three consecutive nights. Although unexplained discrepancies may exist, it should be noted that the large zenith distance and magnitude difference of nearly 2 mag for β Cap AB do not make this a favorable object for speckle observation.

2.4.16 HR 8417 (ζ Cep) The A3+F7 stars comprising this 2.2-yr double-lined spectroscopic binary have had masses and luminosities determined from a combined spectroscopic and speckle interferometric analysis (136). Line-blending effects result in as yet only preliminary values for the masses, but the secondary appears to be undermassive for its luminosity. Sufficient speckle observations exist to produce a well-determined apparent orbit.

2.4.17 HR 8866 (94 Aqr) Five years of speckle observations of this 6.4-yr single-lined spectroscopic binary were used to determine apparent orbital elements for the first time (141). These agreed reasonably well with existing spectroscopic elements. Acceptance of a marginally useful trigonometric parallax yields preliminary masses and luminosities consistent with spectral types of G5 IV and G0–G2 V. This is a prime example of the benefits that could be gained from space astrometry with the *HIPPARCOS* satellite.

3. THE DIRECT MEASUREMENT OF STELLAR ANGULAR DIAMETERS

3.1 *General Comments*

The absolute monochromatic flux emitted at the surface of a star can be determined fundamentally by measuring the flux received from the star and the angular diameter of the star corrected for limb darkening. The effective temperature can also be determined by integrating the absolute monochromatic flux over the spectrum. The current status of the calibration of effective temperatures and the measurement and availability of angular diameters was discussed in detail during IAU Symposium No. 111 on the "Calibration of Fundamental Stellar Quantities" held in Como, Italy, in

May 1984. Davis (50) has reviewed the available data for angular diameters and showed that only for 32 stars have accuracies at the level of ±5% been achieved. The direct confrontation of stellar atmospheres theory with empirically determined radiative properties of stars thus remains quite limited.

The history of the direct measurement of stellar angular diameters parallels that already described for interferometric observations of binary stars and has been discussed elsewhere at length (see, for example, 53, 90). At the time when speckle interferometry was first proposed by Labeyrie (112), only a handful of results from occultations and from the Narrabri intensity interferometer (90) had been added to the half-century-old data from Mount Wilson. There are presently more than 150 measured angular diameters, with the majority derived from lunar occultation observations of cool giant stars. Because nature has provided us with stars whose angular diameters are all well below 0.1 arcsec, it has been the rule for observing programs to operate near their resolution cutoffs. Thus the press toward higher resolution has always been particularly characteristic of efforts to measure the angular diameters of stars.

Of the 111 stars tabulated by Davis (50) for which angular diameters have been determined with accuracies of ±20% or better, 31 have spectral types in the range of O5 and F8 and only 10 stars are of luminosity class V. The remaining stars lie between G8 and M8 and are all evolved objects. A striking gap in our knowledge of stellar angular diameters exists for all luminosity classes from late-A to late-G types, where only three determinations exist and only one (that for Procyon) is known with high accuracy.

Although the fundamental calibration of stellar angular diameters is tied to only a very limited collection of measurements, the situation is not as precarious as it might seem, and plans for future high angular resolution facilities promise very significant gains in this area. The increased supply of data for cool stars derived from occultation observations resulted in the refinement by T. G. Barnes and D. S. Evans of the correlation between a visual surface brightness parameter, calculated only from the unreddened V magnitude and the angular diameter, and the $B-V$ index originally discussed by Wesselink (221). The Barnes-Evans relation (13–15, 17, 167) shows a tight correlation across all spectral and luminosity classes, including variable stars and stars of type S and C, between this visual surface brightness parameter and the $(V-R)_0$ color index. In their papers describing the development of this relation, Barnes and his collaborators have summarized the angular diameter data then available to them, and they have converted the assumed limb-darkening law used by the original sources (most often a linear limb-darkening coefficient of $U = 0$ or 1) to those obtained from model stellar atmospheres grids (17). The Barnes-Evans relation has subsequently been used to determine the expansion rate and distance of the nova V1500 Cygni (12), the distances of Cepheid variables (16, 86), the linear radii of nearby stars (118), and the distances to eclipsing binaries (119, 120).

The indirect determination of angular diameters and effective temperatures by means of comparison of observed fluxes and model stellar atmospheres is being pursued by Blackwell and his collaborators (30, 31) in a manner similar to that originally proposed by Gray (88). This method shows a small systematic disagreement with the Barnes-Evans relation (17) and presently gives angular diameters about 4% larger than the Narrabri values (50). Such methods can ultimately be considered entirely reliable only when they can be compared with an expanded sample of fundamentally determined angular diameters of high accuracy. A catalog of all angular diameters, including those determined by indirect means, has been published by Fracassini et al. (84).

3.2 *Interferometric Measurements of Angular Diameters*

Interferometric methods have furnished angular diameters for some 60 stars. These results have been derived in the optical from intensity interferometry, Michelson (or amplitude) interferometry, speckle interferometry, and long-baseline interferometry with the CERGA two-telescope facility. The latter instrument has also been used for infrared measurements, as have the techniques of Michelson, speckle, and heterodyne interferometry. Unlike the occultation technique, interferometric methods utilizing a single-aperture telescope have little potential for expanding the collection of stars with measured angular diameters, and we must look to long-baseline interferometry for gains in this important area. Summary discussions of the status of interferometric measurements have been presented by Davis (48, 50).

The program of the Narrabri intensity interferometer was directed toward obtaining the first measurements of the angular diameters and effective temperatures of hot stars of all luminosity classes, including main sequence stars. Hanbury Brown (90) has extensively described the Narrabri facility, the procedures for the acquisition and analysis of data, and the details of the final results. Angular diameters were measured for 32 stars brighter than $B = +2.5$ in the spectral class range O5 to F8 (93). The average measured angular diameter was 1.7 milliarcsec, with an average accuracy of ±0.11 milliarcsec (or ±6.4%) and a limiting accuracy of ±0.03 milliarcsec. Sixteen of these stars were of luminosity class V or IV, 7 were class II or III, and 7 were class Ia or Ib. One Wolf-Rayet star (γ^2 Vel) was measured, as was one O5f star (ζ Pup). Effective temperatures were empirically determined for 5 stars, the hottest being 11,250 ± 460 K for the B8 Ia star β Ori, and radii were calculated for 15 stars whose parallaxes were either known trigonometrically or could be otherwise inferred. Nine stars were found to show effects of multiplicity in their correlation measurements from the intensity interferometer, and 4 of these were rejected from the angular diameter program on the basis of exceptionally bright secondaries. One of these "rejects," δ Vel, was subsequently confirmed as a binary by speckle interferometry (201). Hanbury Brown (91) discussed the Narrabri results from the particular points of view of accuracy and their role in calibrating fundamental stellar properties. Analyses of the limb darkening of Sirius (94), mass loss from Rigel (95), and rotation of Altair (90) were carried out with marginally significant results; these results serve primarily to point the way to what can be done by future long-baseline work. The Narrabri intensity interferometer was an essentially unique example of a major facility in optical astronomy that had a highly specific scientific goal and that was shut down after that goal was achieved.

Amplitude interferometry as originally practiced by Michelson led to results for 7 stars (163, 168), most notably for Betelgeuse, that have errors in the range of 10 to 20%. A version of the Michelson interferometer was developed by Currie and his collaborators, and results for 12 late-type giant and supergiant stars have been published (45, 46). The average measured angular diameter was 25.8 milliarcsec, with an average internal error of ± 4.1 milliarcsec (or ± 16%). Separate external errors were presented for comparisons made with results from other techniques.

Speckle interferometric measurements of angular diameters of cool, evolved stars have been presented in a number of papers, usually using either the original power spectrum analysis of Labeyrie (112), as followed by Gezari et al. (85), Blazit et al. (32), Bonneau & Labeyrie (36), Labeyrie et al. (117), Ricort et al. (179), Balega et al. (10), and Bonneau et al. (39), or the speckle superposition method first applied by Lynds et al. (125) to a reconstructed image of Betelgeuse, as has been done by McDonnell & Bates (158), Wilkerson & Worden (229), Worden (233, 234), Welter & Worden (220), Christou & Worden (43), and Goldberg et al. (87).

Long-baseline interferometry employing the CERGA two-telescope Michelson interferometer in the optical has been carried out by Blazit et al. (33), Bonneau et al. (38), and Faucherre et al. (75). Di Benedetto & Conti (54) have used this instrument for infrared measurements of angular diameters. Other infrared observations involving stellar angular diameters are mentioned elsewhere in this article and are based upon Michelson, heterodyne, and speckle interferometry. Roddier & Roddier (186) have obtained observations of Betelgeuse using their rotation-shearing interferometer. Indeed, Betelgeuse has been the star most commonly observed by interferometrists as an extended source.

The degree of overlap in the results within and among the various interferometric techniques remains quite limited; this situation has recently been summarized by Davis (50), who concluded that aside from a few discordant results, the agreement in the measurements is consistent with the published error estimates. Obvious discrepancies exist between the speckle and amplitude interferometry values for α Her and ρ Per (46, 109, 220, 233), both of which have angular diameters close to the resolution limits of these methods.

3.3 *Occultation Measurements of Angular Diameters*

The programs previously mentioned as being active in the discovery and measurement of binary stars during lunar occultations are also actively pursuing the measurement of stellar angular diameters. Most of these groups publish their diameter measures in the same series as their double-star results, with the exception of the Iowa State University group, whose first and most recent papers are those of Beavers et al. (27, 28) and which have included 37 angular diameter determinations for 20 stars. The average of the estimated internal errors for these measurements is ± 1.4 milliarcsec (or 26%) for an average measured diameter of 5.3 milliarcsec. The University of Texas group has published 31 determinations for 22 stars with average angular diameter of 7.8 milliarcsec and average estimated error of ± 1.3 milliarcsec (or ± 17%). The University of Illinois series produced 8 measurements averaging 8.5 milliarcsec and ± 2.6 milliarcsec (or ± 30%) errors, and the Cloudcroft program led to 11 measurements averaging 7.2 milliarcsec and ± 0.9 milliarcsec (or ± 12%) errors. The overall average angular diameter determined by these four major groups was 6.7 milliarcsec, with an average error of ± 1.4 milliarcsec representing ± 21% of the angular diameter. These four groups have published a total of 17 angular diameters for 9 stars for which estimated errors are less than 10%; 8 of these values are for Aldebaran. Ridgway (180) has extensively reviewed the progress made in determining angular diameters from lunar occultations.

The most productive program of occultation angular diameter determinations has been that of Ridgway and his collaborators, who have made measurements in the near-infrared of cool giant stars and extremely cool stars identified primarily as infrared sources (see 181, 183 for first and most recent references in this series). This group has published more than 100 angular diameter measurements, with an average overall accuracy of ± 11%. Although the majority of their results were from the 1.3-m KPNO telescope, their experience with the 4-m telescope has shown that the advantages of large aperture, specifically the increased light-gathering power and decreased scintillation, more than offset the deleterious effects of time smearing and produce superior results for diameters in excess of 2.7 milliarcsec. Infrared measurements of cool giants offer the astrophysical advantage of measuring the diameter closer to the flux maximum and the logistical advantage of permitting daytime observations for a significant increase in event opportunities.

Ridgway et al. (182) examined the then available sample of 66 measurements for the 24 stars for which more than one occultation measurement had been made in order to investigate the validity of the published error estimates. By calculating the variance from the mean expected for each measurement of a particular object and comparing it with the actual difference from the mean, Ridgway et al. (182) considered the overall statistical properties of the error estimates. They clearly showed that, except for Mira-type stars, the frequency distribution of the ratio of actual to expected deviations was a normal distribution consistent with entirely random errors, and thus that the published error estimates are overall reliable indicators of accuracy. Additional conclusions were that in about 4% of the cases, observational effects of an unknown sort may enter into the method, and that in some cases, especially for the Mira-type stars, temporal surface variations on the star produce exceptionally large discrepancies.

The question of the accuracy of angular diameter measurements has been addressed by a number of authors in the case of Aldebaran (K5 III), a star that has undergone an especially well-observed series of occultations. Evans & Edwards (72) selected 10 measurements from the then available sample of more than 20 and deduced an unweighted mean angular diameter for a fully limb-darkened disk of 19.9 ± 0.3 milliarcsec. They concluded that there was no evidence for any variation in diameter over the wavelength range 0.43–0.70 μm. Evans & Edwards (72) also stressed the absence of abnormalities from the occultation traces of Aldebaran, which had been noted in most of the events associated with a previous occultation of Antares (M1.5 Iab); they insisted that nonuniform stellar surface illumination rather than lunar limb effects was responsible for those peculiarities. Ridgway et al. (183) reexamined the Aldebaran data in light of their 14 new measurements from 0.4 to 3.8 μm and concluded that there is evidence of a wavelength variation of diameter that is at least as pronounced as that predicted from theory. They adopted a weighted mean angular diameter of 20.88 ± 0.10 milliarcsec incorporating limb-darkening effects. Most recently, White & Kreidl (224) reported 11 observations of 6 events observed in Strömgren *y* or *b* bandpasses and determined a mean limb-darkened value of 20.45 ± 0.46 milliarcsec from 21 selected measurements between 0.4 and 0.9 μm wavelengths. The occultation angular diameter for Aldebaran is thus known with an accuracy at least as good as the best-determined intensity interferometer results.

4. INTERFEROMETRIC OBSERVATIONS IN THE INFRARED

Speckle interferometry carried out in the visible region of the spectrum offers a factor of 50–100 gain in resolution when a 4-m class telescope is utilized under typical seeing conditions of 2 arcsec. In the infrared, the diffraction limit and typical seeing conditions converge at a wavelength of about 10 μm, and at 2.2 μm the speckle approach provides a resolution gain by only a factor of about 10 or less at the excellent sites currently being utilized by telescopes optimized for infrared work. In obtaining high-resolution scans of molecular cloud sources, Dyck (56) and Dyck & Staude (58) found that with slow scans in which system noise dominated speckle noise, the seeing conditions on Mauna Kea permitted resolution favorably comparable to that from speckle interferometry. As Dainty (47) has pointed out, this loss in resolution leverage with interferometry is more than compensated by the gain in numbers of extended cool objects available to resolution by infrared speckle interferometry compared with the number of objects available to visible speckle interferometry.

Technology has limited infrared speckle interferometry thus far to one-dimensional scanning techniques, where an image is scanned over a narrow slit at a frequency higher than the atmospheric redistribution time. Two-dimensional infrared speckle interferometry can be expected in the future as gains are made in detector development (195). Without employing interferometry, Bloemhof et al. (34) applied a one-dimensional array of detectors to 10-μm observations to directly obtain diffraction-limited scans of the dust shells of α Ori and α Sco. Particular instrumental configurations for infrared speckle interferometry along with observational and analysis procedures have been described by Sibille et al. (194), Selby et al. (191), Howell et al. (104), Dyck & Howell (57), McCarthy et al. (156), and Aime et al. (2).

Other interferometric methods that have been developed in the infrared include the incoherent spatial interferometer of Low and his colleagues (124, 150, 152), the two-telescope heterodyne interferometer of Townes and his colleagues (108, 197), and the use of the CERGA two-telescope interferometer for long-baseline observations in the infrared (54). The spatial interferometer has been used on the Steward Observatory 2.5-m telescope, the KPNO 4-m telescope, and the Multiple Mirror Telescope with its baseline of 6.9 m. Heterodyne interferometry has been carried out using the 5.5-m baseline provided by the twin McMath auxiliary telescopes on Kitt Peak.

Infrared interferometry has provided new high angular resolution information in areas spanning the entire stellar evolutionary time scale. The protostellar objects BN, VY CMa, W3 IRS-5, GL 2591, GL 490, S140 IRS-1, Mon R2 IRS-2&3, and the controversial object MWC 349 have had angular diameters or upper limits to diameters determined and in some cases shown to be double or even triple objects, as demonstrated by McCarthy (147) in the case of Mon R2 IRS-3, or to possess core–halo-type structures (41, 57, 83, 104, 127, 151). The object IRc2 has been resolved by Chelli et al. (42) and shown to have a complicated structure and to be the exciting source of the Kleinmann-Low nebula in Orion. Jiang et al. (107) resolved the optically thin dust shell surrounding a luminous early B-type star that together comprise the object NGC 2024 No. 2. The resolution of T Tauri as a binary star by Dyck et al. (59) has already been mentioned, as has the detection of several low-mass companions to nearby stars by McCarthy and collaborators. The carbon star IRC + 10216, the brightest non–solar system object at 5 μm, is a highly evolved object suffering extensive mass loss. The structure of the dust shell surrounding IRC + 10216 has been resolved by several groups (60, 150, 151, 154, 200), with the general conclusion that the source is highly elliptical, possibly indicative of a nearby edge-on disk structure. The compact structure of IRC + 10216 was first resolved by the lunar occultation measurements in the infrared by Toombs et al. (207). Their results were combined with the interferometric measurements of McCarthy and collaborators by Crabtree & Martin (44) to generate a single dust component model. Interferometric results for other evolved stars (including the Mira-type variables *o* Ceti, χ Cyg, R Leo, and R Cas; the highly reddened M giant NML Cyg; and supergiant stars possessing extensive dust shells) have been published (41, 83, 104, 127, 151, 153, 198, 199). Allen et al. (4) and Dyck et al. (61) have resolved the dust shell around the WC9 star Ve 2-45. Di Benedetto & Conti (54) employed the two-telescope CERGA interferometer at 2.2 μm with baselines up to 32 m to measure the angular diameters of 5 giant stars. Their results compare well with existing visible wavelength interferometric and occultation measurements.

5. FUTURE POSSIBILITIES

New ground-based facilities for very high angular resolution astronomy employing long-baseline interferometry are currently being planned and/or constructed by several groups (51, 113, 115, 121, 192, and unpublished plans by the group at Georgia State University), and a variety of space-based interferometer configurations have been proposed in a preliminary manner to American and European space agencies (see *Bull. Am. Astron. Soc.* 16 : 557–559). Baselines ranging from several hundred meters on the ground up to tens of kilometers in space imply resolutions in the range of 100 down to a few microarcseconds. If such instruments reach their expected sensitivities, they will trigger a revolution in how astronomers view the Universe. At a resolution of 1 microarcsec, we could resolve detail on the surfaces of nearby stars at the level at which we can now observe the Sun. Such dramatic improvements in what we can directly observe may well alter the very nature of astronomical science.

The scientific possibilities for submilliarcsecond ground-based interferometry have been addressed by several authors (48, 50, 124, 134, 185), with applications to single and double stars in the visible region and to infrared observations of broad classes of objects. The scientific return from the highest-resolution space interferometry has not yet been estimated in detail. Davis (48) has shown that a baseline of 1 km and a limiting sensitivity approaching $V = +7$ are sufficient to resolve significant numbers of stars of all spectral types. Limiting accuracies in angular diameter measurements of $\pm 1\%$ are needed if these values are to have the greatest astrophysical impact. Davis (48) also described the potential for determining absolute radii and luminosities of stars, for measuring stellar limb darkening, rotation, winds, and emission shells, for probing interstellar extinction, for recalibrating the Cepheid period-luminosity relation, and for searching for structure in active galactic nuclei and quasars. Through the direct resolution of spectroscopic binaries in which one or both component disks are also resolvable, a complete astrophysical description (including mass, radius, and luminosity) of a star can be obtained.

Long-baseline interferometry will break the logjam of potentially known stellar masses. For example, 70% of the spectroscopic systems in the Batten et al. (25) catalog are potentially resolvable with a baseline of 300 m, with 180 double-lined systems having anticipated separations in excess of 1 milliarcsec. Such a baseline could resolve binaries with a gain in sensitivity to orbital period of a factor of nearly 1800 over what currently can be done with speckle interferometry. A 2 $M_\odot$ binary at a distance of 100 pc could be resolved with a period as short as 13 h.

Assuming long-baseline instruments can employ large apertures in order to reach magnitudes characteristic of the brightest extragalactic objects, we may resolve structures of subparsec size at distances corresponding to a redshift $z = 0.1$. Thus, optical measurements with resolution comparable to radio VLBI will provide important new insights into the mechanisms underlying the energetics of these objects. For nearby galaxies, long-baseline optical interferometry can search for duplicity among the brightest stars and measure the size of planetary nebulae. The discoveries to be made from long-baseline interferometry in the infrared are perhaps the most unpredictable and so are among the most exciting.

As next-generation telescopes are pushing the technological limits of light-gathering power, it is extremely important that complementary directions in angular resolution are also being pursued. During the coming decade, very high angular resolution techniques promise unprecedented gains in studying the "microscopic" properties of astronomical objects in the Universe.

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