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13. ABSTRACT ***(Maximum 200 words)***

Recent upgrades of the 10 micron interferometer have during 1997 been fully programmed, tested, and used. They provide improved tracking and stronger signals, and have been extensively used for new stellar measurements. Multiple shells around several stars have been found and analyzed, and movements or other changes with time are seen in the dust shells around some stars. Methods for compensating atmospheric fluctuations have been examined, and measurements of the vertical distribution of turbulence have been made with acoustic radar.

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Annual Technical Report on ONR Grant N00014-96-1-0737

for the Support of Infrared Spatial Interferometry

Introduction

The grant N00014-96-1-0737 began March 1, 1996. Its purpose is to develop infrared interferometry and to explore high precision astrometry in the 10 micron wavelength region by interferometric techniques. This involves study and measurement of atmospheric properties as well as development and testing of advanced interferometric equipment. The work is being carried out with the help of two 65 inch telescopes, stationed at the Mount Wilson Observatory, which can be separated by various baselines, and which contain HeNe laser interferometers to measure pathlength distance fluctuations near the ground. We report here the results of work during 1997.

Recent Technical Improvements

A number of changes and improvements were made in our interferometer during 1996 and 1997 which have enhanced our ability to measure and track the phase of stellar interference fringes. These include computer upgrades and substantial reprogramming of the operating programs, new tracking cameras for both telescopes which are sensitive to 2 micron infrared radiation, their programming to automatically track stars, and installation and testing of a tip-tilt system for fast correction of stellar motions due to seeing fluctuations.

The improved infrared cameras have enabled us to improve tracking and made possible measurements during the past year on stars which could previously not be measured properly.

The tip-tilt system, consisting of a small mirror near the telescope's focus which is piezoelectrically steered at frequencies as high as 70 Hz, has been proven to substantially improve performance under many seeing conditions. It automatically corrects fluctuations in the stellar position. This improved performance is shown quantitatively in Table 1, which provides numerical measures of the improved signals resulting from its use.

Table 1

Tracking Improvements Due to New Tip-tilt System

Date	Seeing Conditions	Ratio of α Ori's stellar signal for tip-tilt on vs off	
		Telescope 1	Telescope 2
12 Aug '97	medium good	1.31 1.12	1.45 1.16
13 Oct '97	medium	1.24	1.30
20 Oct '97	medium	1.16	1.33
02 Dec '97	poor	1.44 1.59	1.30 1.14
09 Dec '97	very poor	1.87 1.96	1.77 1.31

Grand average of signal improvement is a factor of 1.40 per telescope, or a factor of 1.96 in interference fringe power, which is proportional to the product of the two signals.

Illustrations of Recent Measurements and Results

With the equipment upgrading in 1997 we have obtained many new results on stars which will be published. Previous results have been written up and published during 1997, including papers on two stars showing striking discrete shells of emitted material, and the famous Mira, or o Ceti, which is well known to vary periodically, but which we show emits material quite differently on different cycles. This work is listed in three papers, numbers 2, 4, and 5 in our recent publication list for 1997. IR emission shells of the first two stars, NML Cygni and IK Tauri, are illustrated in Figs. 1 and 2. We have also shown that for some stars the dust composition changes synchronously with the phase of the star's intensity cycle, which typically has a period of about one year. This work is listed as number 6 in our publication list.

We have previously shown that much of the atmospheric turbulence which affects seeing occurs rather near the ground. About 60% of this turbulence is found, for example, within 30 or 40 meters from the ground when the seeing is reasonably good at our location on Mount Wilson. We have recently initiated collaboration with Dr. Don Walters of the Naval Postgraduate School at Monterey, Calif. His acoustic radar system has provided additional proof and illustration of the low-lying turbulence. The acoustic waves emitted at ground level are scattered back by atmospheric turbulence, and their time of arrival and intensity measured, giving a map of the turbulence distribution. Figures 3 and 4 illustrate this type of turbulence measurement. Figure 3 maps the turbulence during daytime and Fig. 4 that at night on particular occasions. We hope to make such acoustic measurements at a variety of locations on Mt. Wilson and to correlate them in some cases with direct seeing measurements and measurements of small and local temperature fluctuations in the atmosphere.

The correlations of atmospheric density fluctuations near the ground, as measured by HeNe interferometers, is demonstrated in Fig. 5 with a presentation showing a method for correcting some of the fluctuations. This figure shows the "fringe" spectrum, with sidebands due to atmospheric fluctuations. Figure 5a is tho normal fringe spectrum showing normal sidebands on a 100 Hz fringe. Figure 5b shows the same spectrum after the fringe phase has been corrected by twice the total fluctuations measured by HeNe interferometers within the telescopes about 10 ft. above the ground. In effect, this attempts to compensate for the atmospheric fluctuations by extrapolating measurements near the ground to compensate both for fluctuations within the telescope and those along a path towards the star a distance of about 10 meters.

One can see from Figs. 5a and 5b that the slower fluctuations, producing the low frequency sidebands, are largely compensated and there is a clearer, stronger central spike. The more widely spaced sidebands are not improved because, in contrast to the slower fluctuations, the faster fluctuations measured at 10 feet above ground are not well correlated with those which are substantially higher above the ground. Although it would be desirable to compensate and cancel all sideband frequencies, for phase measurement of the interference fringe, compensation of the lower sideband frequencies is most important and this is achieved. Additional study of such compensation is needed, and we hope to do that.

Plans for the Coming Year

Along with plans for continued extensive stellar observations and further system improvements, we are expecting to set up at least one tall pole for precision measurement of small and local temperature fluctuations as a function of height above our observing position, and to examine correlations with the observed seeing. We plan more extensive acoustic radar measurements of turbulence as a function of atmospheric conditions and of location on Mount Wilson with respect to structures and wind directions there. We also are planning extension of our baselines to distances as long as 60 - 70 meters in order to measure stellar infrared sizes with improved precision.

Publications during 1997

1. "Contribution of laser technology to astronomy with emphasis on interferometry," C.H. Townes, *Laser Physics* 7, No. 1, 1 (1997).
2. "Non-uniform dust outflow observed around the infrared object NML Cygni," J.D. Monnier, W.C. Danchi, M. Bester, C.H. Townes, E. Lipman, P. Tuthill, T.R. Geballe, and D. Nishimoto, *ApJ* **481**, 420 (1997).
3. "A physicist courts astronomy," C.H. Townes, Prefatory Chapter of *Annual Review of Astronomy and Astrophysics*," Vol. 35 (1997).
4. "Multiple dust shells and motions around IK Tauri as seen by infrared interferometry," David D.S. Hale, M. Bester, W.C.Danchi, S. Hoss, E. Lipman, J.D. Monnier, P.G. Tuthill, C.H. Townes, M. Johnson, B. Lopez, and T.R. Geballe, *ApJ* **490**, 407 (1997).
5. "B. Lopez, W.C. Danchi, M. Bester, D.D.S. Hale, E.A. Lipman, J.D. Monnier, P.G. Tuthill, C.H. Townes, C.G. Degiacomi, T.R. Geballe, L.J. Greenhill, P. Cruzalebes, J. Lefevre, D. Mekarnia, J.A. Mattei, D. Nishimoto, and P.W. Kervin, "Non-spherical structures and temporal variations in the dust shell of o Ceti observed with a long baseline interferometer at 11 microns," *ApJ* 488, 807-826 (1997).
6. "Temporal variations of mid-IR spectra in late-type stars," J.D. Monnier, T.R. Geballe, and W.C. Danchi, accepted for publication in *ApJ*, 1998.

Additional publications in the proceedings of a 1996 conference

W.C. Danchi, B. Lopez, M. Bester, E.A. Lipman, J.D. Monnier, P.G. Tuthill, and C.H. Townes, "Secular variations and non-spherical structures in the dust shell of o Ceti observed with a long baseline interferometer at 11 μm," in *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 327 (1998).

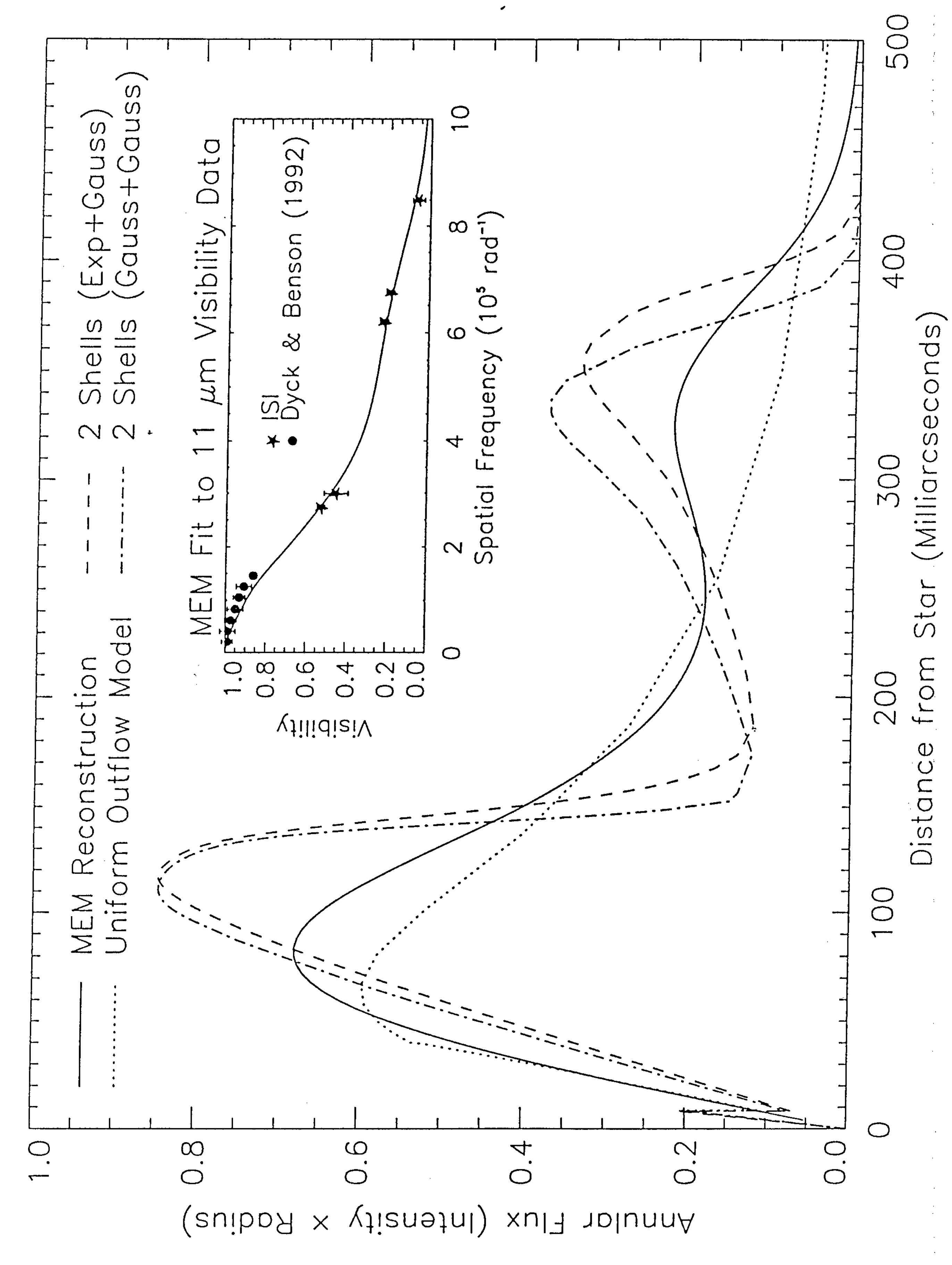
Peter Tuthill, John Monnier, William Danchi, and Chris Haniff, "Morphologies of dusty circumstellar envelopes," in *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 322 (1998).

J.D. Monnier, M. Bester, W.C. Danchi, M.A. Johnson, E.A. Lipman, C.H. Townes, P.G. Tuthill, and T.R. Geballe, "Observations and modeling of the nonuniform dust outflow around the red supergiant NML Cygni," in *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 329 (1998).

C. Townes, M. Bester, W. Danchi, D. Hale, E. Lipman, J. Monnier, and P. Tuthill, "Mid-infrared spatial interferometry on late-type stars and their circumstellar environments," *A Half Center of Stellar Pulsation Interpretations: A Tribute to A.N. Cox, ASP Conference Series* Vol. 135, eds. P.A. Bradley and J.A. Guzik, ASP Press, p. 316 (1998).

W.C. Danchi, P.G. Tuthill, M. Bester, E.A. Lipman, J.M. Monnier, and C.H. Townes, "IR imaging of circumstellar environments," in *Cool Star 10, ASP Conference Proceedings*, eds. Bob Donahue and Jay Bookbinder (1998).

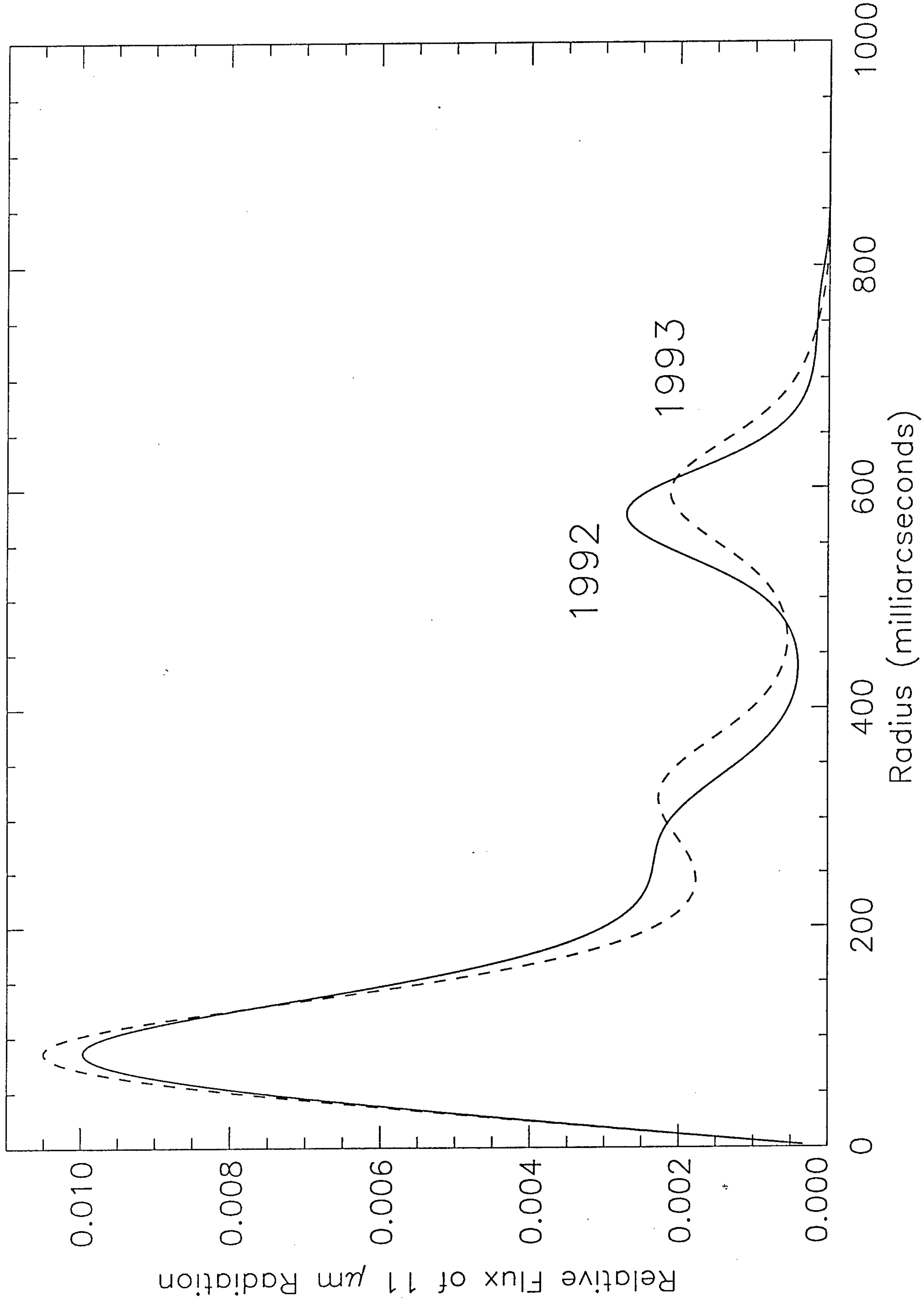
Figure 1. Models of radial distribution of 11 μm radiation around the star NML Cygnus, showing two separate dust shells. The various models assume various possible detailed shapes of each shell.



MEM Reconstruction
Uniform Outflow Model
2 Shells (Exp+Gauss)
2 Shells (Gauss+Gauss)
MEM Fit to 11 μm Visibility Data
ISI
Dyck & Benson (1992)
Visibility
Spatial Frequency (10⁵ rad⁻¹)
Annular Flux (Intensity x Radius)
Distance from Star (Milliarcseconds)

Figure 1

Figure 2. Models of radial distribution of 11 μm radiation around the star IK Tau for two different years, 1992 and 1993. These show 3 separate dust shells. The interferometry measurements show there has been some movement in the dust shells during one year's time. This motion agrees with measured gas velocities and distance to the star.



Relative Flux of 11 μm Radiation
0.000
0.002
0.004
0.006
0.008
0.010
Radius (milliarcseconds)
0
200
400
600
800
1000
1992
1993

Figure 2

Figure 3. Atmospheric turbulence as a function of height (the ordinate) and of time in seconds (the abscissa). Measurements were made during daytime, and show severe turbulence to altitudes of about 40 meters.

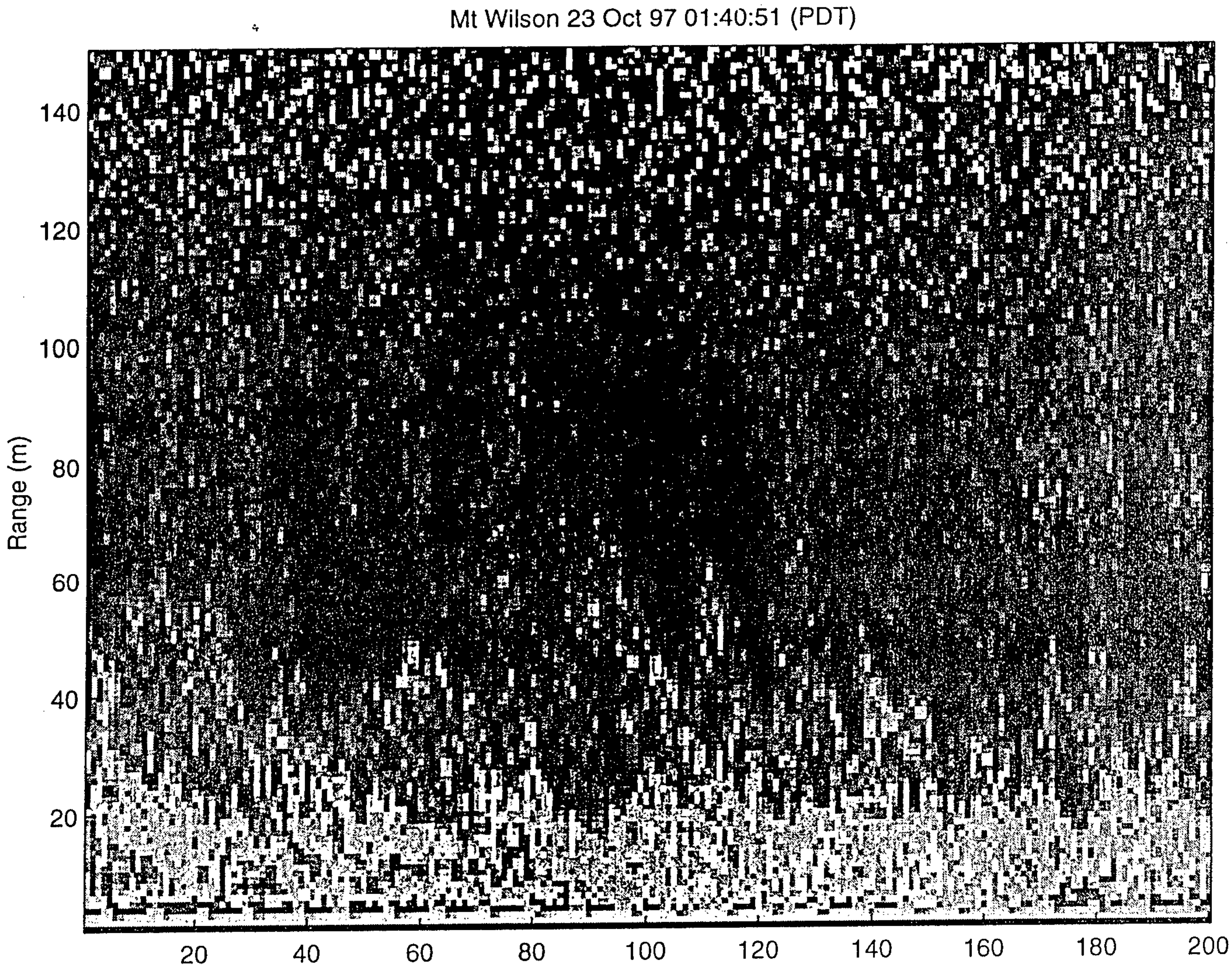

Mt Wilson 23 Oct 97 01:40:51 (PDT)
Range (m)
140
120
100
80
60
40
20
20
40
60
80
100
120
140
160
180
200

Figure 3

Figure 4. Atmospheric turbulence as a function of height (the ordinate) and of time in seconds (the abscissa). Measurements were made at dusk during a time of exceptionally good seeing and little turbulence.

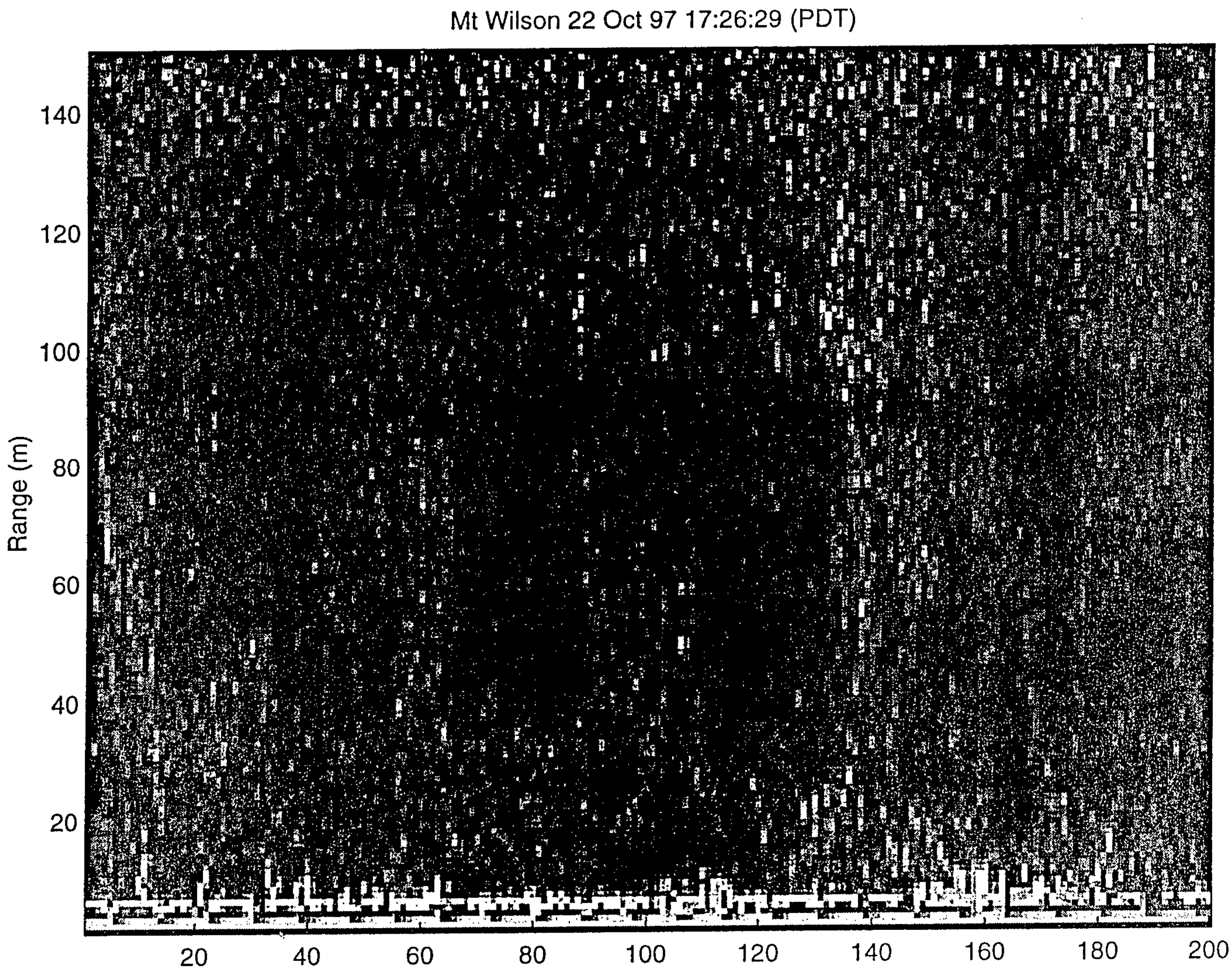

Mt Wilson 22 Oct 97 17:26:29 (PDT)
Range (m)
140
120
100
80
60
40
20
20
40
60
80
100
120
140
160
180
200

Figure 4

Figures 5a and 5b. Figure 5a is the normal spectrum of an interference fringe showing sidebands around the 100 Hz fringe due to atmospheric fluctuations. Figure 5b are the same results with some of the fluctuations compensated by HeNe laser measurements near the ground. The 100 Hz central spike is clearly improved.

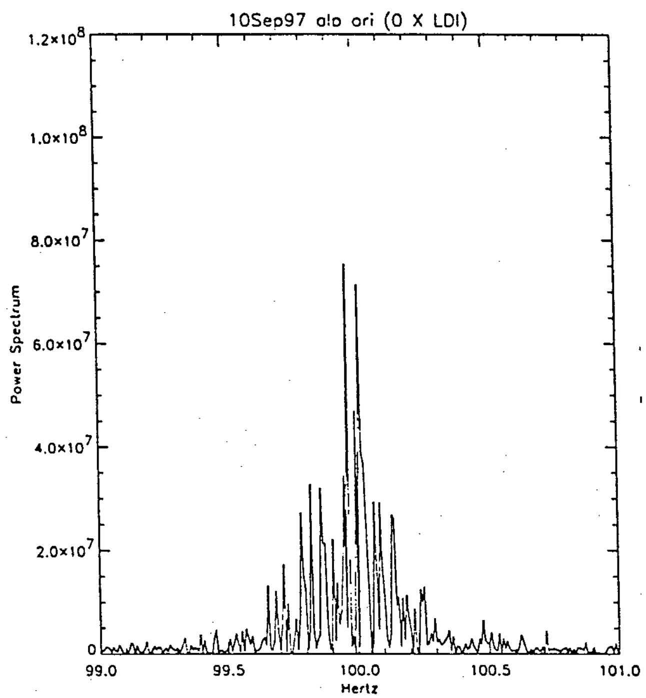


Figure 5a

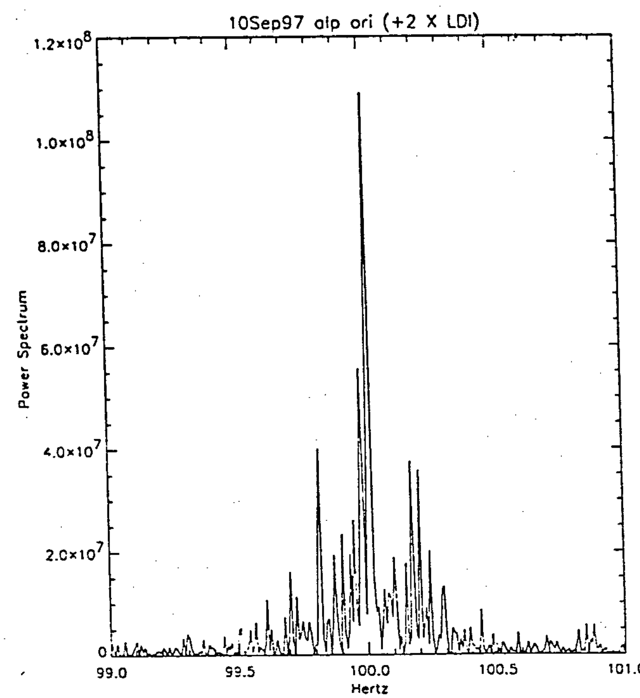


Figure 5b