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SURVEYING WITH CHARGE COUPLED DEVICES

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SURVEYING WITH CHARGE COUPLED DEVICES

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SURVEYING WITH CHARGE-COUPLED DEVICES

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Abstract. The 0.91-m "Spacewatch Telescope" of the Steward Observatory of the University of Arizona on Kitt Peak is dedicated to scanning with charge-coupled devices (CCDs) during the dark half of the month. We explored six modes of using CCDs for searches of gamma-ray bursters, debris in geosynchronous space, satellites of asteroids, brown dwarfs, the tenth planet, comets, cometesimals, and various types of asteroids. In the process, we gained experience with cosmic rays and artifacts in CCD observations. Each of these topics is described. I especially note that the existence of cometesimals has not been confirmed by the Spacewatch Telescope, contrary to reports published by others.

This paper describes a new discipline in astrophysics, "scannerscopy," of surveying with a CCD rather than with photography at a Schmidt telescope.

It uses the CCD in scanning rather than in sequencing of stare exposures as is done at most observatories. This may save telescope time, and flat-fielding is rarely needed. Usually we turn the drive off, but the scanning can be done with the telescope slewing. In any case, the motion on the sky is precisely followed by slaving the charge transfer of the CCD to the drift rate of the image, while the CCD is read out continuously during the observing. Our primary application of CCD-scanning is on moving objects such as comets and asteroids. We also do routine astrometry with CCDs, in a transit method, and this yields a precision of better than ±0.7 arcsecs.

We presently use a Tektronix 2048 x 2048 CCD, 38 arcminutes wide, to a limiting magnitude of V = 20.5 (6-sigma detection). This is successful even for discovering rare and small near-Earth asteroids. 1990 UN with a diameter of 90 meters and 1991 BA at 9 meters are the smallest natural objects observed outside the Earth's atmosphere to date. In a month with good conditions we find typically 2,000 new main-belt asteroids and, on average, nearly two near-Earth asteroids. Only the latter are followed up with astrometry. The goal is to study magnitude-frequency relations, as well as to complete the inventory of dangerous impactors on Earth. We are designing a new CCD-scanning telescope to become an order-of-magnitude more effective in the discovery of elusive objects than the Spacewatch Telescope. The paper also describes possibilities with cameras on spacecraft that pass through the asteroid belt; thousands of small asteroids can be observed with the CCDs of CRAF and CASSINI.

1. Introduction

The long-range goal for the CCD-scanning techniques that will be described in this paper is to survey the solar system to completion: to what limiting magnitude do we know the populations of various objects, particularly the *faint ones such as* comets, asteroids and satellites that can be distinguished by their apparent motion with respect to the stars? Are there any more outer planets or distant objects such as Chiron? How does the magnitude-frequency relation in the asteroid belt compare with those of comets, Trojans, and near-Earth asteroids? The latter are especially interesting in their origin and collisional history, their potential for space resources, and their hazards to our own survival.

I did some surveying of asteroids, Trojans, comets and satellites with the Palomar 1.22-m Schmidt (van Houten et al. 1970, 1991; Gehrels 1977). For a continuation with new equipment in Arizona the primary question was what techniques to use. I decided not to resort to the techniques of the 1930s, by using photography on Schmidt telescopes, but to aim at the techniques of the 1990s that might have large CCDs and affordable computers to handle the data stream. A comparison of the Schmidt and a CCD scannerscope was made in Gehrels (1984a). The next step was then to work with a simple CCD-scanning system in order to gain experience with various applications, while the extensive computer programming was being done for the eventual automatic detection and astrometry of comets and asteroids. There also was a financial reason to do various tasks, namely to keep the project funded in its early stages, when asteroid hazards and mining were not yet popular topics. In any case, we were having fun with new ideas, as will be shown in Secs. 2-11.

For our own principal interest of observing comets and asteroids, the CCD has an advantage over photographic emulsion because it has a high quantum efficiency and wide wavelength range. On a long exposure with a Schmidt telescope an asteroid makes a trail, a spreading instead of integration; for the CCD the exposure time is shorter, and the asteroid is therefore detected more efficiently. Another advantage of the CCD is that the charge is accumulated linearly with integrated light flux -- it fills a pixel well linearly until the well-capacity is reached -- while photographic grain development changes non-linearly for fainter objects. Thus, with the CCD the threshold for object detection is more sharply defined than it is for emulsions; if an object is discovered near the detection threshold it does not need to be observed as long. Another advantage of the CCD over emulsion is that it does not have reciprocity failure. A long exposure on a faint object gives the same result as a short exposure on a proportionally bright object. Finally, the processing of CCD data can be made automatic and in real time with computer programming. This will be shown in this paper, especially in Sec. 13, to be a great asset when the programming is developed into a fine art.

There is a long history in astronomy of surveying with wide-angle cameras; historical precedent exists even for scanner-based systems. Indeed, the scanning that I will describe is similar to that done 90 years ago by George Ellery Hale with his original spectroheliograph, which matched the motion of the image plane to that of the photographic plate. The basis for CCD scanning is that the electronic signal charges can be transferred incrementally from one row of pixels to the next in a "bucket brigade" process. Engineers use the term Time Delay Integration (TDI) for this, but we prefer the simpler word "scanning." In any case, the rate of transfer is clocked to match precisely the rate at which the optical image of the star field moves across the CCD. This allows the CCD to be exposed and read out simultaneously and continuously for as long as the data collection system can store the accumulating scan.

Scanning can be done at rates from zero (a "stare" observation) to about 24 rows per second for our 2048 CCD, and faster by more advanced devices. An example of using stares and scans for the same objects is in Sec. 6. For stare observations, time must be taken from the observing to read the frames into the computer. This may require half of the observing time! Of course, the CCD also has an integration time; the first "ramp frame" has increasing integration for successive rows of pixels. If one needs the full field of the CCD, which occurs fully exposed on the frame after the ramp frame, and no additional frames, then too, half of the observing time is lost. But even with this loss, scanning has the advantage that each object is observed by all pixels in a column. Differences in pixel sensitivity are thereby averaged out, and "flat fielding" calibration is therefore not needed, except perhaps for high-precision photometry. Our astrometry (Sec. 11) is usually done with short scans, rather than with stare frames, because it is a smooth operation that does not require a great deal of typing header files.

For our developments of the new techniques, P. A. Strittmatter, as Director of the University of Arizona Observatories, assigned to us in 1981 the full-time use of the 0.91-m Newtonian telescope on Kitt Peak. Gradually a new name and concept emerged for the old reflector, "The Spacewatch Telescope," which will be described in Sec. 2. The name "Spacewatch" was first used during a NASA Advisory meeting at Wood's Hole in 1981, and was then suggested by A. B. Meinel for our program.

The Spacewatch Telescope is dedicated to two programs, namely for the CCD scanning and for a search for planets of other stars, which have myself and R. S. McMillan as their respective principal investigators. McMillan is also the Co-PI for the CCD scanning, and that facilitates our shared usage of the telescope. The two programs are philosophically related, namely in the exploration of abodes and future for life. The dark half of each month is used for the CCD scanning, while the search for planets of other stars is done during the half of the month centered around Full Moon. The radial-velocity program is described by McMillan et al. (1985, 1986b), McMillan and Smith (1987), and Smith and McMillan (1987). They have achieved unprecedented sensitivity to variations in Doppler shift. Systematic errors are at the 3-10 m/s level.

We were probably the first to have CCD-scanning in regular astronomical operation (Sec. 3), followed by the CCD Transit Instrument (CTI) of McGraw et al. (1986; also see Steward Obs. Preprints 382) which has a 1.82-m f/2.2 mirror in a stationary position, pointed near the zenith, using the Earth's rotation to scan the same strip of sky in different nights for stars that may vary in brightness and/or may have exceptional color. We have heard of earlier CCD scanning with periscopes on submarines, and in an experiment at the Anglo-Australian Telescope with a CCD that was moved in the focal plane while the telescope was driven at the sidereal rate (see Barbe, 1975, and p. 340 of Gehrels 1984a). We expect that CCD scanning will become popular in astronomy because of its advantages and capabilities (see Tyson, 1990).

On the Spacewatch Telescope we have used a 320 x 512 CCD in different modes on various objects, particularly in the early days when the extensive software for automatic detection of comets and asteroids was not yet completed. The early applications are described in Secs. 4-8. Another possible application on small asteroids is with CCD cameras mounted on spacecraft (Sec. 9). Our first scanning for comets and asteroids is described in Sec. 10, and astrometry for them in Sec. 11. Our new 2048 x 2048 CCD system will be described in Sec. 12. In Sec. 13, I give some background information on the hazard of near-Earth asteroids, and what can be done about it. That brings us to future plans, in Sec. 14. The paper concludes with a summary of various modes and applications for using CCDs (Sec. 15).

References to more detailed descriptions of our work are given in this review paper. General overviews of our CCD programs have been made by Gehrels (1981a, 1984b, 1985), and by Gehrels and McMillan (1982). Popular articles appeared in People Weekly of Nov. 19, 1984, in Gehrels (1988), and in Spacewatch Reports that we have issued in 1982, 1983, 1984, 1986 and 1991 specifically for a Spacewatch constituency of about 200 private and corporate donors. We also put out electronically mailed *Spacewatch Announcements* for discoveries of fast-moving objects to whoever wants to interact with observations of those objects.

This is a review paper, but it also gives new information, namely on procedures in Secs 2, 3 and 11; CCD artifacts, Sec. 4, and not finding cometesimals (Sec. 8); scanning for geosynchronous objects (Sec. 6); the search for an outer planet or stellar companion of the Sun, and parallax observations in Sec. 7; and of our most recent work in Secs. 12-14.

2. Equipment and Procedures at the Spacewatch Telescope

Of the 19 telescope systems on and near Kitt Peak, the 0.91-m reflector is the only Newtonian, the only one with a glass mirror, and by far the most senior. Its unique features seem noteworthy especially because the most modern applications are feasible with the old telescope. It was ordered in the late 1910s from the Warner and Swasey Company in Cleveland, Ohio, by A. E. Douglass, who was then the only astronomer at the University of Arizona. The plaque at the base of the telescope gives 1921 as the date of completion. Douglass had obtained funding from Mrs. Lavinia Steward, so the telescope became the Steward Observatory on the campus of the University of Arizona in Tucson, where the original dome is still in use with a smaller reflector. Light pollution became too severe in Tucson such that E. F. Carpenter, then the observatory's director, and W. S. Fitch moved the telescope to Kitt Peak in 1964. On the local map for Kitt Peak the site is now indicated as that of "The Spacewatch Telescope."

The rotating part of the Spacewatch dome is double-walled, with an airgap in between. The outside is covered with aluminum paint. There is no catwalk, but, instead, there is a pulpit near the apex of the dome, which is a unique facility for checking sky conditions. Indeed, it is a place for observer euphoria (p. 310 of Gehrels 1988). It is made accessible by way of the stairs and platform structure that reach the Newtonian foci. We switch between the two programs by turning the Newtonian mirror to either the south port where the CCD is permanently mounted, or to the north port where there is a fiber optics head, also permanently mounted, which leads to a temperature-controlled spectrometer room on the ground floor for the search for planets of other stars. In a few urgent cases of astrometric follow-up for a fast-moving asteroid, the nights are conveniently shared by turning the Newtonian.

The control room for both programs is on the intermediate floor just below and behind the polar axis; it was previously called the "Coudé room." On this floor we also used to have a dish in the window for a microwave link to Tucson (Perry and McMillan 1984). There was a repeater station on Tumamoc Hill west of Tucson, but its microwave dishes were destroyed in 1989 by an aggressive environmental group, protesting the future observatory on Mount Graham. Fortunately, we do not depend on that microwave link since we now have a complete computer system (Sec. 12) in the Spacewatch dome. Furthermore, an *Ethernet* link is being installed which will allow us to monitor data and do astrometry in Tucson.

The primary telescope mirror is the original one; its parabolic figure was made by the famous optician John Brashaer. We experiment with ventilating the dome by bringing all of the inside to nearly ambient temperature. There is a large fan exhausting from the lowest floor, another one from the intermediate floor, and three small exhaust fans near the bottom of the closed-telescope tube. The ventilation tests are not conclusive, however, for the seeing appears to produce image diameters of 1 - 3 arcsecs during most nights. It is possible that we did not have precise enough control of the focus until we began to do it in October 1990 with a sensitive method which uses the charge tailing of the CCD (see below).

The diameter of the mirror is 0.927 m and we use the full aperture even though according to A.B. Meinel (personal communication 1987) the outer 0.02 m has a down-turned edge. The mirror is aluminized whenever the reflectivity in visible light has decreased to about 60%, which appears to happen about every three years. The most recent coating was applied in August 1989 by A. Bauer with the aluminizing facility of the Steward Observatory in Tucson. The thickness of the aluminum layer was then determined to be 95 nm.

The telescope is fork mounted. A cable is wound around the polar axle for a gravity preload eastward in right ascension. The preload in declination is an air piston pulling a cable wrapped around that axle; this was designed and built by M. Williams. As for the telescope drive, the original system had a centrifugal ball-governor driven by a weight on a cable and rewound by an electric motor about once per hour. This system is kept at the telescope as a possible future museum piece. In 1983/4, J. E. Frecker designed and built a versatile electronic drive which consists of DC servo motors, servo amplifiers, and a Z-80/S-100-bus computer. Seven sets of right ascension and declination can be pre-entered as convenient commands for our frequent resetting of the telescope and turning off the drive on various scan regions (Sec. 10). In turn, this drive system will be replaced by a modern digital servo controller card in a PC-AT computer, which is commercially available. All functions and safety limits will be accessible to software, and a hard-wired watchdog timer will disable telescope functions if the computer crashes or suffers a software bug.

The focusing mechanism was rebuilt by M. Williams, R. James, and M. L. Perry. It consists of a base plate for the CCD, now motor-driven and read out with a simple dial indicator. To find the proper focus setting we initiate in the control room the taking of five consecutive exposures while the drive is on. A computer program opens the shutter for a few seconds five times, for which we set five positions of the focus with the predicted one near the central image, and move the fields slightly in declination between the five exposures. In the display of the images, the proper focus is then easily seen. This is strikingly so for bright stars, magnitudes about 2-5, because their CCD charge-tailing in the right-ascension direction is strongly dependent on focus; the very longest bright spike is seen near the best focus. This method works only when the seeing is near the pixel size, so we get an impression of the seeing at the same time. When the seeing is poor the focus is found from the appearance of fainter stars in the frame. This observation also provides a check on the coordinate system of the drive mechanism, because we take the coordinates of the bright star from *The Astronomical Almanac*.

There is a peculiar trend of the focus readout during the night, indicating an apparent shortening of the telescope tube by about 1 mm, which would be excessive for steel contraction due to the typical drop in temperature of only about 5 degrees C during the night. The trend occurs even during nights of nearly constant air temperature. We do not understand what is the cause. E. Roemer pointed out that there may be a deformation of the mirror during the night, as is known for the 1-m reflector of the U.S. Naval Observatory near Flagstaff, Arizona.

The orientation of the CCD, that is the rotation about the optic axis, is determined by scanning at a rate which is grossly different from the proper one so that we see long star trails on the screen. Deviations from exactly east-west of these trails can be precisely measured and corrected, thanks to a rotation stage made by M. Williams; the deviation in the north-south direction tells us how to rotate the CCD. This procedure must be done twice, however, with the trail rate being much too fast as well as too slow. The orientation apparently depends upon the focus being precisely correct; the reason for this may be that the coma direction is reversed, or that the focusing motion is perhaps not exactly parallel to the optic axis. We have not found any hour-angle dependence of the orientation, even though a small effect is expected at extreme hour angles due to differential refraction. However, we do not normally scan at air masses greater than 2.0. This has been our firm policy even though estimates by B. G. Marsden indicate that we could go to larger air masses without appreciable decrease of precision in the astrometry described in Sec. 11.

The image scale and thus the scan rate has been determined by analyzing the declination "plate scales" from our astrometric solutions. They are independent of the chosen drift rate, while the plate scale in right ascension is convolved with the chosen drift rate to give an apparent plate scale. We now use the following relation. For one-by-one binning with the 2048 x 2048 CCD of Sec. 12 the dwell time per pixel is 0.080519/cos δ secs, where δ is the declination and 0.080519 ±0.000003 (prob. error) is the synodic image scale of the 2048 CCD in time seconds. We have not found any dependence of the scan rate on hour angle; again, this is probably because we do not scan at air masses greater than 2.0. The actual (sidereal) image scale is 1.002738 times larger. Measured in arcseconds, the pixel size is therefore 1.21109 ±0.00005. From this pixel size and knowing the outer dimension of the pixel area of the 2048 CCD to be 55.30 ±0.04 (p.e.) mm it follows that the focal length of the telescope is 4599 ± 3 (p.e.) mm. The scale is then 44.85 ± 0.03 arcsecs/mm, in fair agreement with the 44.8 arcsec/mm derived by W. J. Luyten (personal communication 1983), who used the telescope extensively for stellar proper motions in the 1930s in Tucson.

3. A 320 x 512 CCD System

We began with an RCA Model 53612 SID (Silicon Imaging Device) of 512 rows and 320 columns of pixels, a thinned, buried-channel, back-illuminated CCD; the read-out is in the 512-direction. The pixels are 30-micron squares with essentially no dead space between them. It is a good CCD, that was commercially available, with sufficient well-capacity of about 500,000 electrons per pixel to observe bright as well as faint objects, an important consideration for surveying of faint objects while bright stars cannot be avoided. J. E. Frecker installed the CCD in a simple but rugged RF-shielded housing (a coffee can) in a dry-ice chamber (styrofoam sheets glued together). It served us well for four years (McMillan et al., 1986a).

At the detector temperature, which we estimated to be at -50° C, considerably above that of dry ice in our admittedly preliminary setup, the readout noise was 120-150 electron-hole pairs per pixel per readout, and the thermal dark current 50 ehp/pixel/sec. The quantum efficiency of the 320 x 512 RCA CCD is reportedly about 70% over the wavelength range 0.4 - 0.8 microns.

At 6-sigma detection we found the limiting magnitude near $V = 19.6$, at an airmass of about 1.3; the magnitudes are always determined, still now with the 2048 CCD, near the center of the frame because that is where the objects are observed mostly, particularly when followed up after discovery. Our magnitudes are determined by making exposures or scans, similar to those on the objects in question, on known magnitude sequences. These are either Selected Areas with magnitudes provided by W. A. Baum (personal communication, 1970), or Naval Observatory Sequences provided by H. D. Ables and C. C. Dahn (personal communication, 1983), or as have been published by others for sequences such as near NGC 2264. There may be a small systematic error in our V magnitudes because we compare them with those published on the UBV system, while the sensitivity of the CCD, which is nearly always used without a filter, is wider and more red-sensitive than that of the V filter, and asteroids and comets are generally rather red (B-V about +0.8). We do, however, choose comparison stars with B-V about +0.8 from the above sources.

For the 320 x 512 CCD, McMillan designed an eyepiece and filter box. We can no longer use it for the large size of the 2048 CCD at the steep f/ratio of this telescope. However, the eyepiece was convenient in our early days when the telescope could not be set precisely with its mechanical drive system and dial readings. The blue filter is 1 mm BG12 + 1 mm BG18 + 2 mm GG385, green 2 mm GG495 + 1 mm BG18, and for yellow-red there is a GG495 filter. Our later scanning was not done at the original f/5, but at f/3.9 which was obtained with a lens (described in Sec. 11, below) mounted between the filter box and the CCD.

For the 320 x 512 CCD, J. E. Frecker built a system (Frecker et al. 1984) that controlled the timing of charge transfer and readout with an 8-bit Z-80 microprocessor and a Tektronix Model 620 x-y-z CRT monitor, while the data acquisition was done with a Data General Nova 1200 minicomputer left over from a previous project. The data were brought to Tucson -- usually on the morning shuttle van (see Gehrels 1988) of the Kitt Peak National Observatory -- in the form of 9-track tapes, and read and processed by our main computer, a Perkin-Elmer 3242 located in the Space Sciences

Building. This is a 32-bit processor and we have added to it such that it has 8 megabytes of memory, two tape drives, and 600 megabytes of disk storage. The system is a veritable workhorse, in use all day and most of the nights, also for other programs such as those of McMillan's radial-velocities, and of M. G. Tomasko and his associates, and for dissertations of students, who use it for modeling of aerosols in planetary atmospheres. Images can be displayed using a Grinnell-273 processing system with a resolution of 480 x 512 pixels, at 8 bits (256 grey levels) per pixel.

Programs were written by J. V. Scotti for the Perkin-Elmer to display and interact with the data using the Grinnell. The programs allow image centroiding and brightness determination, image shifting (for frame to frame registration of the images) and subtraction, background determination, and contrast enhancement. Flat-fielding of scans is neglected as unimportant for our applications (Sec. 1). A program for the detection of a moving object against a field of non-moving stars was written; the centroids of all the stars, galaxies, asteroids and other real and non-real images are found and listed and compared in three consecutive scans of the same region (Sec. 10). This sounds simple, perhaps, but tens of thousands of stars are thus kept track of in a half-hour scan with a 2048 CCD!

An astrometric reduction program (Sec. 11) takes as input a list of measured positions of reference stars and of the object for which the astrometry is being done, gives measured coordinates (in pixels) for all of them and then produces astrometric positions for the objects. D. J. Tholen, now at the University of Hawaii, provided an ephemeris program used in predicting the positions of an asteroid or comet once an orbit has been computed. More information on the computer programs is in McMillan et al.

(1986a).

The 320 x 512 CCD was installed on the Spacewatch Telescope in 1983, but the computer programs to do scanning on comets and asteroids were not yet tested and running until a year later. Since we still wanted to obtain experience with CCD observing in any case (see Sec. 1), we undertook various studies that will be described in Secs. 4-8.

4. Gamma Rays, Cosmic Rays, and Artifacts

During the early 1980s there was excitement regarding gamma-ray bursters that had originally been discovered on Venera and other spacecraft, but for which a few new discoveries were made of optical counterparts, for instance on photographic plates in the archives of the Harvard College Observatory. The physical nature of the sources was not clearly understood, however. Their distances were unknown, the bursts' repetition rate was highly uncertain, and the type of object producing the burst was not established. It seemed an important clue to obtain the frequency of optical counterparts, or at least establish an observational limit to their occurrence. The Spacewatch Telescope was therefore used, with the 320 x 512 CCD at f/5.

With the pixel size of 1.346 arcsec, the chip has 7.2 x 11.5 arcmins field of view. One of the nice features of CCD scanning is that it can be done at any orientation as well as at various rates of charge transfer. The CCD was therefore oriented the same as the error boxes of the sources, which happened to have also about the same dimensions as the above field of view. While the telescope was driven at sidereal rate, the CCD was slowly read out throughout the observation. This was accomplished, as usual, by shifting the electronic signal charges incrementally from one row of pixels to the next, resulting in trailed images of the stars.

It was our hope to observe a real transient event of sufficient duration, and with this scanning we would then determine that duration and possibly observe a lightcurve variation. The time resolutions were 0.25 or 0.36 sec per pixel; that is, every 0.25 or 0.36 sec all 512 rows were transferred by one row and 320 pixels were read out in the register at the end. The CCD output was watched in real time on the CRT monitor, which was then still located with the observer on the Newtonian platform. The output was also stored on digital tape which was analyzed later by visually inspecting each frame with the Grinnell system in Tucson.

The observing was done over the time interval October 1983 - April 1984, in part by my son Neil who is an astrophysicist at the Goddard Space Flight Center. It was on the following Gamma-ray Burst Sources (with the number of good hours of monitoring): GBS 2252-03 (24.4 hrs), GBS 1205+24 (4.1 hr), and GBS 1028+46 (23.6 hrs). No transient optical effects were detected. The limiting magnitudes were between about 15.8 and 17.0 depending on the duration the optical transients might have had. The V=15.8 optical limit corresponds to a gamma-ray fluence limit greater than 30 keV of about 10^{-9} ergs cm^{-2}; this limit is a factor of 100 lower than that of the best gamma-ray burst instruments on spacecraft.

The detailed report of this work was made by N. Gehrels et *al.* (1985). Our work may have been useful as a first reconnaissance for the surveying for optical transients that is to begin operation on Kitt Peak in 1991 with special sets of equipment of Goddard Space Flight Center (Teegarden et al., 1984) and Massachusetts Institute of Technology (Ricker et al., 1984).

We also gained a first reconnaissance with various types of artifacts. Any nearly-instantaneous effect such as cosmic rays would usually be contained in a single pixel or a few pixels only. We did observe such events and became proficient at recognizing them. They had some of the characteristics expected of a real optical transient, but were identified as background because they did not have a wide enough spread, perpendicular to the trails, to be consistent with the "seeing" profile caused by atmospheric turbulence of real gamma-ray bursters (also see Sec. 8). The most common were single-pixel events occurring at a rate of 1 to 2 per 100 secs over the 1.4 cm^2 active area of the CCD. The rate is consistent with the incident flux of cosmic-ray muons at the Earth's surface. A small number of two-pixel events were seen that we ascribe to muons depositing ionization energy near a boundary of two adjacent pixels.

There also were approximately ten background events of several saturated pixels in the trailing direction, again with only 1 to 2 pixels width in the perpendicular direction, thereby, again, not showing a seeing profile that is easily recognized by its fuzziness. These may be caused by natural radioactive decay in the window or substrate of the CCD. The decay deposits a large amount of ionization in one or two pixels which then spreads over the low potential barriers into the direction of the charge transfer. Similar spreading is commonly seen for bright stars on CCDs; for instance for a star just bright enough to saturate the CCD, the images are detectable over six or so pixels (see Fig. 1, Sec. 13).

5. Satellites of Asteroids

We searched for satellites of minor planets, "minor satellites," in

1984 because at that time there was excitement about their possible existence. Theories of solar-system formation with planetesimals collecting from interstellar dust and gas might predict that in the dense cloud of coagulating objects, satellites might have formed even for objects as small as asteroids. In the literature, there were some reports of satellites actually having been observed (see Van Flandern et al, 1979 for an overview).

In our paper (Gehrels et al., 1987) we first brought to the fore that in previous photographic observations as those of the Palomar-Leiden Survey (van Houten et al., 1970) such predicted outer satellites should have been found, but they were not.

We then reported observations made with the 320 x 512 CCD, at f-ratios ranging from 3.9 to 25 with various lenses on the Spacewatch Telescope, and from f/10 to f/70 at the 1.5-m Catalina reflector of the University of Arizona. These were all done in the stare mode, and reduced by subtracting pairs of exposures taken of the same field of view but separated in time, looking on the video screen of the Grinnell at the results of the subtraction.

The stars were superposed, the asteroid had moved with respect to the stars, but no other faint object with similar motion was seen, to limiting magnitudes that depended somewhat on the f-ratios. In any case, no satellite was found brighter than the 20th magnitude, which is larger than about 2 km in diameter. The extent of the search areas depended strongly on the f-ratio used; for 1 Ceres between 2.4 and 526 diameters was covered, and for 44 Nysa it was from 188 to 7753 times its diameter. The surveying was similarly done for 2 Pallas, 4 Vesta, 6 Hebe, 7 Iris, 8 Flora, 15

Eunomia, 29 Amphitrite, 41 Daphne; only a reconnaissance was made for 192 Nausika.

Thanks to the participation of J. D. Drummond as co-author, a good understanding was reached why no minor satellites were found in the photographic surveys, nor in this CCD search, nor in searches by other CCD observers. It appears that in the violent early days in the asteroid belt -- after satellite formation might have been possible when the frictional medium of the primeval solar nebula was still dense enough -- collisions dominated to the point of removing satellites of less than 30 km in diameter. Even satellites surviving the directly de-orbiting collisions would be subject to numerous minor collisions and perturbations, they would not achieve stable synchronous orbits. Only satellites larger than 30 km that reached such a stable orbit might survive today, but these we did not find. Based on the negative observational results, and noting the lack of huge asteroids that rotate slowly, due to synchronicity, it was concluded that no large satellites exist at appreciable distances. Only large satellites that are quite close to the parent bodies may be possible today -- the synchronicity there allowing normal rotation rates -- good candidates being expected near 624 Hektor and possibly 216 Kleopatra. Our work on the minor satellites was supported by the National Geographic Society (see Gehrels 1988).

6. Geosynchronous Debris

The unique property of spacecraft in geosynchronous Earth orbit (GEO) to remain fixed over a geographic location, near zero latitude, makes this region of space a valuable resource. The question is, however, how polluted is it with debris -- artificial, natural, or both? The statistics of objects in GEO appear to be known to about V = 15 -- some 200 objects: a few communication and reconnaissance satellites, and other mostly inactive payloads and rocket bodies -- while the Spacewatch Telescope with the 320 x 512 CCD could extend this limit to about 19. Two surveys were therefore made with this system in order to sample the statistics of debris in these regions. It was done jointly with and paid for by colleagues at the Lyndon B. Johnson Space Center in Houston, Texas.

A first report was published by Gehrels and Vilas (1986). The declination was set at -5 deg 14.8 arcmins, allowing for the parallax of equatorial regions seen from Kitt Peak; the observations were made near the meridian of Kitt Peak, avoiding the shadow of the Earth, in March/April 1984. The first survey was made with the following sequence of stare exposures: an integration of 46 secs duration, followed by 36 seconds needed for recording the data on tape, followed by a second integration on the same region. During the readout of the second integration, the telescope was moved in hour angle to the position of the next, adjacent frame. The telescope drive was off during all of this work; stars were therefore trailed in the east-west direction, while round images were immediately recognized for active satellites being kept geostationary. A few trails for objects that were not exactly geostationary were also seen; these trails were irregular in brightness because they were caused by debris tumbling in space.

Each frame of data was visually examined for round images or trails, during the observing on the Newtonian platform, and later with the Grinnell system in Tucson for inspection down into the noise of the observations.

The limiting magnitude for round images was estimated to be V = 19.0. The total monitored sky area was 16.4 square degrees; it was done at f/5, as the f/3.9 focus was not yet available at that time. Ten objects were found, seven of which were geostationary satellites; they had apparent visual magnitudes brighter than 13.1; three of them were observed again on the following night. Three other objects, having magnitudes equal to or somewhat fainter than 13.7, showed appreciable motion in the north-south direction. These may have been debris from an explosion of a Soviet "Molniya" civilian satellite which had a highly eccentric orbit. The absence of fainter objects suggests that a gap in size exists between satellites or their debris and cometary/asteroidal grains having diameters in the millimeter range that are expected to exist there. An upper diameter limit of about 2.5 m -- at V = 19 and 37,240 km distance -- may be estimated for this size gap; the lower limit has not as yet been ascertained.

An engineering test and additional survey were made with a different technique (Vilas *et*. *al* 1991). Instead of the stare exposures, scanning is more efficient because the data readout is done during the observing. The CCD was turned 180 deg from its normal orientation, while the trailing rate was kept sidereal; the drive was on, also at sidereal rate. The two sidereal rates cancelled each other so as to observe geostationary objects, while the motion of the telescope provided the scanning. The area coverage was similar to that of the previous survey. No objects were found, which is not surprising as the regions for known satellites had been avoided, and Molniya events must be rare. Geosynchronous space is apparently still fairly clear.

7. Brown-Dwarf Companion or Distant Planet of the Sun

During the early 1980s an exciting possibility was being discussed: the Sun might have a faint stellar companion in eccentric orbit between about 10,000 and 174,000 AU, causing perturbations with a periodicity of about 28 My to the Oort cloud of comets when near perihelion . Some of these comets would eventually collide with the Earth, causing a shower of impacts, and this was reported to have been discovered in the geological record in terms of extinctions of life, with that periodicity of 28 My. The companion star was referred to as Nemesis, the Greek goddess of destruction, but I think of it as Shiva, the Indian deity who brings destruction and renewal, which is the case for geological discontinuities. The small mammals, our forebears, had greater opportunity to expand after extinction of the dinosaurs. This is not to say that the demise of the dinosaurs is entirely due to comet impact for they may have been on their way out already. Nor has it been established that the extinctions are periodic. This issue is keenly debated in a book edited by Smoluchowski et al. (1986).

A. H. Delsemme, one of the participants in the Smoluchowski volume, predicted (already in a personal communication of 1984) a region of the sky where Shiva might be found, namely about 400 square degrees, elongated rather perpendicular to the ecliptic, and centered near 17:30 right ascension and +15 deg declination. Delsemme had studied a set of 126 cometary orbits selected because they were the least influenced by the known planets, and yet their orbital angular momenta showed an appreciable anisotropy in a plane nearly perpendicular to the ecliptic. Such anisotropy would dissipate by orbital diffusion in 10-20 My, and it therefore could not be caused by galactic effects which have timescales of 100 My. Nor do gravitational perturbations by fast-moving stars or molecular clouds produce such anisotropy. A body was indicated that is near enough, one that is bound to the solar system. A strip of the sky centered on its derived orbit revealed an anomaly in the ratio of retrograde to prograde comets such that a position of the perihelion was indicated. Identification with the Shiva that might cause periodic cometary showers and extinctions of life forms was thereby proposed by Delsemme.

With the help of undergraduate student C. Lykins, we inspected the area of Delsemme's prediction with the catalogs of the Infrared Astronomical Satellite (IRAS), searching for possible candidates with the proper fluxes, namely those of sub-luminous stars, "brown dwarfs." Their characteristic decline at the short-wavelength end of the Planck curve would occur within the sensitivity range of the CCD. On each of the candidates, about 200 stars, we have therefore set the telescope briefly for exposures with the red and green and sometimes also the blue filter described in Sec. 3. The steep decline would have been easily recognized, but no clear identification was made.

For a few promising cases we made parallax measurements, which is also conveniently done with the CCD, namely by measuring relative positions with the centroiding technique described in Sec. 3. The positions of the candidate with respect to neighboring stars are measured to a precision of ±0.3 arcsecs (probable error) on stare exposures taken about five months apart. The two exposures are made at about the same hour angle, near the meridian, in order to minimize the effects of atmospheric refraction. Parallaxes can thereby be determined to a distance well beyond 200,000 AU.

A survey for the Tenth Planet is also made. If this one were found, we would also propose Shiva for its name, because it would be the body with high eccentricity and inclination proposed by Matese and Whitmire (see Smoluchowski et al., 1986) to be responsible for the extinctions, if these are indeed periodic. In a joint program with J. D. Anderson of the Jet Propulsion Laboratory (JPL), a region of the sky was surveyed where Shiva might be discovered. The region was identified through analysis of unsuccessful photographic surveying at the Lowell Observatory and elsewhere, of anomalies in the orbits of Uranus and Neptune, and of the trajectories of Pioneer 10 and 11 spacecraft. The survey was made through inspection of the IRAS catalogs by a JPL group, and photography of the region by Rick Hill and Gehrels with the Case/Kitt-Peak 0.6-m Schmidt. We are continuing with some Shiva surveying.

8. Frank's Cometesimals

Frank et al. (1986) saw black spots on images of the Earth, made with an ultraviolet imaging photometer on Dynamics Explorer I spacecraft. They concluded that the terrestrial atmosphere is being bombarded about 20 times per minute by 10-meter-sized comets. These would have to be exceptional objects, rather than regular comets, because their frequency would be at least 9 orders-of-magnitude larger than the magnitude-frequency relation for near-Earth comets and asteroids. The statistics are known from the work of Öpik, Wetherill, Kresák, Shoemaker and others; their results are shown in rounded numbers in Table 1. I kept this Table as it is easy to remember; it has been good for a decade. It is conservative, with the number of objects (second column) probably a factor of 1.7 ± 0.3 (p.e.) larger. These are, of course, the statistics at the present epoch; the possibility of long-term periodic variations was discussed in Sec. 7. About half of these objects are believed to be fragments from collisions in the asteroid belt, and the other half cometary cores. The numbers in the last column are given in terms of the energy expended at Hiroshima in August 1945, an equivalent of 13 kilotons of TNT, or 5 x 10^{20} ergs. The magnitude-frequency relation with a factor of 100 per factor 10 in size, a factor of 2.5 per magnitude interval, has not as yet been precisely established. Extrapolation to meteorite sizes gives the correct order of magnitude. For the asteroids in the main belt we know the factor to be about 100 (van Houten et al. 1970), but for near-Earth objects a refinement is needed. One of the goals for Spacewatch is to determine that factor.

In the meantime, we see in Table 1, at about 0.01 km size for the objects of Frank et al., a frequency of impacting the Earth about once per hundred years. This is a factor of 2 x 10^9 (if half of them are cometary cores) smaller than the 20 events per minute reported by them! One would therefore conclude that their objects are not comets, but, if real, some new type of solar-system population (the name "cometesimals" is sometimes used), with a size distribution of its own (see below). That would be interesting! In view of the importance of confirming such a new population, we made additional observations with C. M. Yeates of the Jet Propulsion Laboratory as guest investigator. Yeates paid for the observations and was present during about half of the observing, done during a total of about seven nights from October 1987 to April 1988. This observing was the last with the 320 x 512 CCD on the Spacewatch Telescope. It was done near the meridian of Kitt Peak, outside of the Earth's shadow, primarily in the directions of 160 deg east and west of the Sun, in the plane of the ecliptic. The telescope drive was turned off. The angular motion of the field of view corresponded to the expected motion of short-period comets at about 150,000 km distance. The f-ratio being 3.9, each field of view was 9.2 x 14.8 arcmins. Stare exposures were made of 12 secs duration over a total area of 7.6 sq. deg. The limiting magnitude for a non-trailed image was near V = 18.1 at 6 sigma. In April 1988 the exposures were made double, that is in immediate succession, observing the same field twice, before moving the telescope in hour angle to the adjacent field. All of this was carefully planned and analyzed by Yeates.

There is a controversy about the interpretation; a comprehensive review of the situation has been written by Dessler (1991; also see Frank and Huyghe, 1990). Yeates and Frank released some of our CCD frames to science writers and reporters, claiming to see streaks due to cometesimals, without, however, our knowledge, let alone our concurrence. In their excitement, they even listed me as a coauthor without checking with me (Frank et al. 1988). When our group was finally given copies of the released images, we and other experienced CCD observers did not believe the streaks to be real. My judgment of the situation is based on four considerations:

1) The streaks look like artifacts because they do not show a seeing profile, as would be the case for any real image made through an astronomical telescope; the turbulence of the Earth's atmosphere usually causes at least some fuzziness of a real image, it is called "seeing," spread over more than one pixel (see Sec. 4).

2) All of the images claimed by Yeates and Frank to be real are found in the noise, in the background of the CCD readout. Yeates' statistical analysis does not seem to sufficiently take into account the instrumental

effects, and our CCDs are noisy, especially in stares rather than scans. We should take into account, however, that the human eye is good at detecting streaks (see end of Sec. 13).

3) If so many cometesimal events, found in the noise level of our CCD frames, were indeed real, I would expect some distribution in their size and distance so that, occasionally, an event of more convincing brightness occurs.

4) We have not seen the onset of the 10^9-factor increase that is mentioned at the beginning of this Section. In the surveying of Secs. 6 and 12 our sensitivity is close to the 10-meter size range.

These are admittedly qualitiative arguments. There is a way out of 4), and perhaps 3), namely if Frank's cometesimals would have a magnitude-frequency distribution of their own, and a narrow one at that. Near Tucson there are old volcanic mountains that have many ejecta on their slopes, vulcanic bombs. They are all of the same size, 0.4 m in diameter. Could it be that comets, with densities about 60 times lower than in terrestrial magma, eject bombs into the vacuum of space with 25 times greater size? Cometary bombs?

However, before believing the spectacular discovery of a new type of solar-system population, one would want to see at least a few indisputable images with fuzzy seeing profile. In our opinion, Frank's cometesimals have therefore not as yet been verified by the Spacewatch Telescope. It would be straightforward to make a proper observational test with a sufficiently extensive set of observations using a quieter CCD than ours.

9. Observing Small Asteroids from Spacecraft

The Galileo, Cassini, and Comet-Rendezvous Asteroid-Flyby (CRAF) missions are being planned for flying by known asteroids that are in the size range of tens to hundreds of kilometers. Based on the Spacewatch experience, a paper was written to examine the feasibility of also observing asteroids that are much smaller (Gehrels 1986). The conclusion is that thousands of small asteroids can be observed with the CCD cameras presently on GALILEO and planned for CASSINI and CRAF spacecraft. The paper has drawn attention internationally and was translated into Russian.

With modern data for the magnitude of the Sun it is found that

$$\log d = 3.130 - 0.2\,V(1,0) - 0.5\log p_V$$

where d is the diameter of the asteroid in km, and V(1,0) is the apparent magnitude of the asteroid on the UBV system, reduced to zero phase angle and 1 A.U. from the Sun and Earth and zero phase angle; p_V is the geometric albedo, which is the flux from the asteroid at zero phase divided by the flux that would be measured from a perfectly diffusing flat disk of the same diameter as that of the asteroid when oriented normal to the direction of the Sun and located at the position of the asteroid. With the best available data for the statistics of the asteroids in the main belt it follows that

$$\log \rho\,(V) = -3.86 + 0.395\,V$$

where ρ (V) is the number of asteroids brighter than V per $(AU)^3$ near the ecliptic. The probable error in the first term is on the order of ±0.12, and in the coefficient it is about ±0.004. This relation is one that can be determined more precisely with the CCDs on spacecraft.

The asteroid magnitude system that is expressed in terms of H can be converted with

$$V = H + 0.4$$

(Bowell, personal communication 1991) while, on average,

$$B - V = 0.8$$

in statistical analyses, when phase effects and color are unknown or can be neglected.

With the types of CCD cameras flown on modern missions through the asteroid belt, magnitude-density relations can be obtained for objects down to sizes of large meteorites. It is not even certain that the concentration toward the ecliptic plane is the same for large and small asteroids. Furthermore, if such observations were made when the spacecraft are in the asteroid belt at various distances from the Sun , a range of compositions could be sampled, from predominantly silicaceous at the inside of the belt to carbonaceous towards the outer regions, while there may also be different statistics in various parts of the belt. A wealth of basic information would become available, as when we did the Palomar-Leiden Survey (van Houten _et_ _al_. 1970).

It is also feasible to provide Earth-based support of the space missions, especially with a powerful 1.82-m Asteroid Telescope (Sec. 14). This could be for orbital identifications in order to make, from Earth and spacecraft both, detailed studies of a selected sample of objects. This could also help the pointing of the CCD cameras and other instruments on board the spacecraft. Physical studies would be attractive to make with instruments that are usually flown on spacecraft such as visible and near-infrared photometers, and for polarimetry near quarter phase. Such studies of objects with sizes down to the meter-size range are of primary importance to understanding the planetesimals that formed the solar system, the asteroids, meteorites, cometary cores; and their interrelations. These small ones are different, collisional debris most likely, from the ones we usually make physical studies for with telescopes on Earth.

10. Asteroid Surveying

From 1984 April 22 to 1986 March 2 we conducted a "First Spacewatch Survey" with the 320 x 512 CCD, for testing techniques of scanning and astrometry, while some of the work of the previous Sections was also done, such that we used almost all of the available dark time. I was the nearly-sole observer, leaving Scotti free for programming and astrometry, having a splendid time of it (see Gehrels 1988) and being teased at Kitt Peak with the title of "resident astronomer." The aim was to obtain useful results and get experience with scanning, in preparation for a CCD or an array of CCDs large enough to make surveying for near-Earth asteroids worthwhile (Secs. 12 and 13).

The survey was made with three consecutive scans of about half an hour each on the same region; semi-automatic processing software was now ready and used for the detection at the Perkin-Elmer (Sec. 3). New asteroids were readily found -- about 11 on a half-hour scan with the 320 x 512 CCD near opposition -- but we followed with astrometry only a few of them of special interest: a Trojan, a Hilda-type, a Phocaea-type, four Hungarias, and eight asteroids in the main belt. Such follow up of newly discovered objects is done with additional astrometry in the same and the next two months and the next two oppositions, or more.

The first asteroid followed over three oppositions for permanent numbering and to be named by us was 1985 VS = (3801) Thrasymedes, a Trojan. Shoemaker et al. (1989) recognized that the orbital elements of (3801) are similar to those of the larger Trojan (1583), such that it appears to be a fragment of (1583), and they used the similarity to confirm the existence of families among the Trojans. Our second asteroid to be followed was a Hilda at 3.96 AU, namely 1986 GW, which then became (4255) Spacewatch (see below).

11. Astrometry of Comets and Asteroids

For astrometry also we prefer CCD-scanning over stare-plus-read-out procedures, let alone photography, and we have shown that it works with a precision better than what used to be obtained for comets and asteroids with long-focus photography. Our astrometry was stimulated by the fact that during the years 1984-8 we used to receive from B. G. Marsden, Director of the Minor Planet Center in Cambridge, Massachusetts, each month a list of asteroids and comets most in need of positional measurements, elusive objects, too faint for astrometric programs elsewhere. From especially slow scans, and sometimes superposition of a few of these, Scotti, who makes all our astrometry reductions, could extend the limiting magnitude of the 320 x 512 CCD to V = 21.

The following results were obtained. Ninety-two asteroids were recovered for the Minor Planet Center; about 30 of these had been discovered in other surveys such as those at the Palomar Observatory. Seventy-two comets were observed for astrometry, usually in at least two nights; for 16 it was a "recovery," which is the first observation of an apparition, and these were reported in the IAU Circulars. All results have been published in the Minor Planet Circulars, about 1500 observations through 1988, when we suspended these observations in order to concentrate on the work reported in Secs. 12 and 13.

The astrometry is done with drive-off scanning over a pre-selected number of frames, which depends on the number of astrometric standards that are available. The drive is stopped a pre-calculated number of CCD frames ahead of the unknown, the Earth's rotation then brings the scan through the object, and we make certain that the total scan is long enough to have a sufficient number of astrometric reference stars in it. The method is in principle that of a transit telescope, but we stop the drive anywhere in the sky, not particularly near the meridian.

We prefer to use the AGK3 Catalog, which reaches, however, only to -2 deg in declination; south of that we have to use the SAO Catalog. We are in the process of adopting for astrometric reference the Guide Star Catalog of the Hubble Space Telescope; we will then need only one 2048 x 2048 pixel frame about the unknown, which is done through three scans each of two frames (there has to be a ramp frame to obtain a fully exposed second frame). Soon we will have automatic identification of standard stars and unknown objects, and automatic near-real-time reduction as well.

We require more than four astrometric reference stars and inspect the residuals of each star in order to perhaps reject it as a standard; the cause is then most likely a poorly known proper motion. Even with the small 320 x 512 CCD there has usually been no problem in acquiring enough AGK3 or SAO stars per scan of 29 minutes. Near the galactic plane we used to scan only about 12 minutes and still had as many as eight reference stars.

The differences in right ascension are essentially obtained from time measurements, with the Earth's rotation being the precise clock. A linear least-squares solution is made to fit the observed pixel coordinates of the reference stars to their catalog coordinates. The determination yields separate solutions for right ascension and declination with separate slope (image scale) and intercept for each. There is no rotational transformation because any erroneous orientation angle of the CCD projected on the sky would simply widen all the images in the north/south direction. All observations in the scan are made at essentially the same zenith distance; the small corrections for refraction across the field are readily taken care of in the astrometric solution. We do not do astrometry at airmasses greater than 2.0, as was already mentioned in Sec. 3.

The astrometry with the 320 x 512 CCD as well as most of the work in previous sections was done using the f/3.9 lens mentioned in Sec. 2. This lens is of the type and quality used for xerographic and cinema copying, being aberration corrected for a nominal conjugate ratio of 1.0:1, achromatized, and anti-reflection coated. For our usage, at 1.3:1, the "seeing," CCD resolution, and telescope focusing "noise" are much larger than the point-spread function of this lens. In any case, effects of distortion and field curvature are independent of pixel location in the scan direction because the measured signal from each star is the result of the total accumulation of exposure as each star traverses the length of the whole CCD array. The effect of optical aberrations in the declination direction is smaller than the other sources of error.

The scans at f/3.9 were 9.2 arcmins wide and, at the equator, 29 mins long for 7.25 deg (including the ramp frame). The scan length is proportional to the secant of the declination; the 512 rows were traversed in 59 secs at the equator, at 30 deg declination it was 68 secs. Near the poles one cannot use the scanning method: at 60 deg declination there already is enough curvature to smear the star images in the north-south direction by about 0.9 arcsecs near the edges of the RCA CCD, because of the deviation of the parallel from a great circle.

The astrometry has been described in detail by Gehrels et al. (1986). The internal error of the method was determined from the residuals of reference stars in the SAO Catalog with respect to the positions determined by observation. We generally found the consistency to be better than ±0.7 arcsec, with respect to orbit calculations including observations from other observatories. Table 2 shows such residuals, taken from Minor Planet. Circ. 15396 for 1986 GW, now (4255) Spacewatch, the Hilda-type asteroid discovered in April 1986. The first column gives the date of observation (year, month, date), and the other two list the residuals in arcseconds for right ascension and declination. These are Spacewatch observations, except the first two and the last four. The mean absolute value for the residuals in right ascension is ±0.44 arcsec and in declination it is ±0.59 arcsec, for only the Spacewatch observations. We have checked a few times for systematic deviations in our residuals, with respect to those of other observers, and found none, to a precision of ±0.4 arcsec.

12. A 2048 x 2048 CCD System

We ordered a 2048 x 2048 CCD in 1986. A lower-grade discounted CCD was finally delivered in 1988. Prior to that delivery, in despair, we had looked into the possibility of installing an array of five 512 x 512 CCDs. The difficulty with that would have been to orient the CCDs to within a few arcminutes precision, and probably having to adjust the orientations inside the dewar while it would be cooled with liquid nitrogen. Our 2048 CCD arrived in the nick of time.

It is a "thick," front-illuminated Tektronix TK2048SP, S/N 1022-4, with pixel size 27 x 27 microns. The quantum efficiency of this type of Tektronix CCD is reportedly about 30% over the wavelength range 500 - 800 nm. Ours is cosmetically not bad, having most of its defects concentrated in about 150 columns near the north edge of the CCD (there was a similar range of defective rows near an edge of our 320 x 512 CCD). The camera system is a Princeton Scientific Instruments' Model V, with an Infrared Labs' liquid-nitrogen dewar, and an 80386-based, IBM PC-AT-compatible microcomputer for control and data acquisition. This was provided to us by the Defense Advanced Research Projects Agency (DARPA); the CCD had been paid for from private donations. Video display of selected parts of the 2048 x 2048 pixel image area is provided by a PC-Vision-Plus board in the computer. Since delivery of the system we have made extensive tests, first in the laboratory, and then at the Spacewatch Telescope beginning in January 1989. The readout rate can be as fast as 50,000 pixels/sec, or 84 secs per frame. The readout noise at -90 deg C, the temperature at which we keep the CCD, is about 15 electron-hole pairs per pixel per readout, as measured by Princeton Scientific Instruments. Further information on this CCD system is in Gehrels et al. (1990).

A motorized shutter was installed in front of the CCD by M. L. Perry. We still have a problem as outgassing appears to be taking place, probably from some grease inside the dewar. Pumping is therefore needed about every third day of operation. A turbo pump is now used, and a new dewar is on order.

A gas jet of air that has passed through a jar filled with a drying agent was installed by D. L. Rabinowitz in front of the Dewar window. Since the secondary mirror is shielded from fogging by the telescope tube, we can continue to observe even when the humidity reaches 100 percent.

The data from the 2048 CCD were at first recorded on a Digidata Gigastore tape drive that encodes digital information on a conventional VHS-format video tape; the data were further processed with the Perkin-Elmer 3242 and an 80386 PC-AT computer on the campus. This is not, however, fast enough for the full-time scanning which we are now doing. For such a large amount of data we needed further automation for image and motion recognition and for the processing of the scans. More equipment and another year and a half were needed. To meet the needs, the Defense-University Research Instrumentation Program (DURIP) provided a Solbourne workstation which has a Sun Unix operating system running on a multiple CPU architecture; this system can run four tasks in parallel.

The new equipment and computer programs are performing in a spectacular manner. Rabinowitz, Scotti and I are the observers, each taking about six nights per month. Three consecutive scans, each about half-an-hour, are made of the same strip of the sky, each time the drive of the telescope is turned off so that 7.5 degrees are scanned in right ascension. Allowing for defects near the edge, this CCD covers 38 arcmins in declination. During the first and second scans, the computer program made by Rabinowitz is at work to recognize trails of fast-moving asteroids. For the third scan, Scotti's program (Sec. 10) was modified by Rabinowitz in order to bring all objects that show consistent motion to the attention of the observer. This is done with a listing of the rate of motion, approximate brightness, position and time, etc. Figure 1 shows the part of the third scan in which Apollo asteroid 1990 SS was discovered.

The system is described in detail by Rabinowitz (1991). Its special strength is that it can detect objects such as near-Earth asteroids, especially when they show the effects of high inclination and/or when they are far away and moving as slowly as 0.05 deg/day. The observer can at a glance decide, from a diagram of ecliptic latitude versus longitude (Rabinowitz 1991), whether the object is a Jovian Trojan (or even slower), a main-belt asteroid, near the inside of the asteroid belt, just barely crossing the Mars orbit, or one that may come even closer to the Earth. It is noted, however, that such discrimination works only when the observations are made near opposition, within a region in ecliptic longitude that is opposite the Sun, where the motion of the object is primarily a reflex of the orbital motion of the Earth. Since the limiting magnitude of this system is about 20.5 (at 6-sigma detection), we find about 2,500 asteroids per lunation, which are mostly the ones in the main belt. Because they are so faint they are nearly all new findings. We let them go, however, because it would take too much time away from our scanning to get the astrometric observations required for precise orbits. Only the ones that appear by their angular velocity vectors to be near-Earth asteroids are followed up with such astrometry in the following weeks and months. From the data in Table 3 (see below) it appears that we are discovering, on average, nearly two near-Earth asteroids per lunation.

13. Near-Earth Asteroids

Until the arrival of the 2048 CCD the area coverage at the 0.91-m telescope was clearly too small to search for near-Earth asteroids. We had therefore in 1980 proposed a special 1.82-m scannerscope, and when that proposal was unsuccessful we resorted to the development of the new techniques. Now, with the 2048 CCD even at the old 0.91-m telescope, the first priority is to find near-Earth asteroids. Since the early 1980s the urgency of obtaining statistics for them has become better understood. They probably are extinct cometary cores as well as fragments of asteroids in the main belt. (For brevity we refer to them only as asteroids, and with "near-Earth" is meant all those with present perihelion distances less than 1.30 AU.) This is an important discipline because the asteroids and comets are planetesimals left over from the formation of the solar system. Space flight to the asteroids, and even sampling and mining missions, were already proposed in the 1970s. It has also become better understood that the near-Earth asteroids are a hazard to humanity. The following three paragraphs are based on notes from a rare gathering of experts discussing these hazards and the aims of "Spacewatch" programs, at Aspen, Colorado in 1982.

The hazard takes two forms: 1) the direct physical consequences of impact of bodies ranging in diameter from a few tens of meters to more than a kilometer, and 2) the chance that the effects of atmospheric entry and impact would be mistaken for a major attack by a nation capable of nuclear riposte. The probability of a natural catastrophic collision is low but finite (it is summarized in Table 1 in Sec. 8). The magnitude of the catastrophe, on the other hand, can be large. A 500-meter diameter asteroid impacting on land typically produces a crater about 10 km in diameter, and the region over which there would be general destruction of life is about 100 km in diameter; such impacts and larger ones are produced on the continents, on average, about once every 300,000 years. Twice as many impacts of comparable energy release occur in the oceans, generating large tidal waves and destructive effects on coastal areas. Impact craters 3 km in diameter and larger (destruction of life over a 30 km diameter area) are produced, on average, every 60,000 years. A 10-km asteroid may have eliminated 60% of the species in an impact about 65 million years ago; such a collision at the present time would probably eliminate all of humanity. However, if all of the near-Earth asteroids down to about 150 m diameter were detected and their orbits accurately determined -- as seems possible with a dedicated 1.82-m scannerscope (Sec. 14) -- the problem would no longer be statistical in nature; any collision that might occur in the following few decades could be forecast.

With sufficient advance warning, such a collision could be averted by modifying the orbit of the asteroid. A change of only a fraction of a meter per second in the velocity of the asteroid is sufficient to steer it away from collision with the Earth, provided this change is made a few years prior to the projected encounter. Such a change can be accomplished by generating a properly directed explosion on the asteroid; the velocity is changed by recoil from the crater ejecta. A 10 kiloton TNT-equivalent device would produce a crater adequate to appreciably deflect a 1-km diameter asteroid from a centered collision with Earth; 10 tons of high explosive could adequately deflect a 100-m asteroid. An impact aversion mission could probably be carried out by means of a single mission with the projected launch and spacecraft capability of NASA.

A 150-m stony asteroid (3.5 g cm^{-3} density) impacting the Earth at a typical velocity of 22 km s^{-1} delivers 790 megatons TNT equivalent energy. There are probably some 25,000 near-Earth asteroids 150 m in diameter or larger. This is an estimate; none have been observed as small as 150 m (in 1982, but see below). Among these, however, several must make very close approaches (less than a few million kilometers) to Earth each year. (1989 FC, for instance, passed the Earth on 23 March 1989 at about 750,000 km; its diameter is 0.3 km; 1991 BA at 171,000 km on 18 January 1991, diameter 9 km; see Table 3, below.) Nature thus provides impacts on Earth at a sufficiently high rate for these to be of concern for direct physical consequences, or accidentally triggering a nuclear counter attack. A 25-m diameter asteroid will enter the Earth's atmosphere about once per century; this frequency estimate is conservative -- it may be too low. Generally such an object will break up low in the atmosphere, releasing several megatons TNT-equivalent energy in an atmospheric shock wave and a burst of visual and infrared radiation. A comparable event, which released 12 to 15 megatons TNT-equivalent energy, occurred over Siberia in 1908. The forest was ignited out to a distance of 15 km from the center, flattened by the shockwave out to about 20 km, and some trees were knocked over out to 40 km. If such an event occurred today, the perception of it by a human observer within a few tens of km from the center might be that one had experienced the airburst of a nuclear weapon. In a world in which the number of nations possessing nuclear weapons is increasing, it is not clear what the response might be from an unsophisticated nuclear nation if it were unexpectedly subjected to a multi-megaton shock wave from the impact of such an asteroid. The best strategy to avoid international miscalculation would be to provide advance warning and identification of the natural event. Ideally, such warning would facilitate evacuation and prevent loss of lives. As the number of near-Earth asteroids a few tens of meters in diameter is in the range of one million to ten million, and as these objects are detectable only when relatively close to Earth, there is little likelihood that more than a small fraction would be discovered in the near future. However, they could eventually be detected by infrared satellite systems, as they approach Earth, and tracked accurately from one to a few weeks prior to encounter. Thus warning of a collision with useful lead time appears technically feasible. To begin with, however, it is essential to study these topics on the basis of the best possible magnitude-frequency relations, and with a development program of techniques for sky surveying in order to find nearly all near-Earth asteroids larger than 150 m.

I reproduced the above three paragraphs because so little has been published to date on the hazard aspect, but it is not to over-emphasize this as the reason for our CCD scanning. My own interests as a planetary scientist are primarily in the planetesimal aspect mentioned above. The mining aspects are also important, of course.

Presently, about 150 near-Earth asteroids are known. We have made estimates for the number of near-Earth asteroids and comets the 2048 CCD on the Spacewatch Telescope should discover in its present mode of operation, with the drive turned off for scanning (see Rabinowitz 1991). They were made in comparison with the Palomar 0.46-m Schmidt where for a limiting magnitude of about 17, C. S. and E. M. Shoemaker found half a dozen new Earth-approaching asteroids, 8 to 10 Mars crossers, and several comets from surveying over approximately 30,000 square degrees per year (Shoemaker, Abstract of Uppsala meeting, 1985; they have improved the limiting magnitude since then and the yield has increased accordingly, but we used the numbers as documented in 1985).

It seems qualitatively confirmed by an independent estimate, namely from a surveying program for comets (Gehrels, 1981b) at the Palomar 1.22-m Schmidt with a limiting magnitude near V = 19.3, which showed that one needs to survey about 600 square degrees, near opposition, in order to make a discovery of a comet. In summary, we might expect from the intensive Second Spacewatch Survey (see below), approximately 18 (±3 prob. error) new Earth-approaching asteroids, 27 Mars crossers, and 8 comets per year, provided a factor of 2.5 in the magnitude-frequency relations is valid (Sec. 8). We do not, however, follow up the Mars crossers with astrometry. The full comet detection will occur only after our computerized program for that is in place. The present visual inspection of frames that scroll by quickly is no match for the thorough blinking described in Gehrels (1981b).

The prediction of 1.8 near-Earth asteroids per good month of scanning seems fulfilled by our discoveries, which are summarized in the present Table 3. This is of the greatest importance because the findings then confirm a factor of 2.5 or more in the magnitude-frequency law of near-Earth asteroids. We should soon be able to establish the law more precisely. The following are the new results obtained with the 2048 CCD and Solbourne computer.

On October 27, 1989, our first near-Earth asteroid, 1989 UP, was discovered; this marked the beginning of the Second Spacewatch Survey. However, the main, computerized part of the survey was begun only after completion of Rabinowitz's and Scotti's software for image and motion detection. The techniques and programs are being refined still now. Apollo Asteroid 1989 UP had been found through visual recognition of a trail on the Solbourne screen by Rabinowitz and Scotti, and reported in IAU Circular 4887. Its perihelion distance is 0.98 AU, indicating that it is gravitationally controlled by the Earth and may eventually impact. Aphelion is in the middle of the asteroid belt where it probably originated. Its mean diameter is 0.3 km; that is in the lowest 10% of the sizes of near-Earth asteroids before Spacewatch. W. Wisniewski (personal communication, 1989) observed a lightcurve amplitude of more than a magnitude. It is therefore an elongated object, probably a fragment of a collision in the asteroid belt.

Automatic operation began in September 1990, a run with poor weather, but near-Earth asteroid 1990 SS was discovered, an Apollo. October 1990 had exquisite conditions, and four new ones were discovered. In addition, we re-discovered 1990 UP, 1865 Cerberus, and periodic comet Kopff. Table 3 lists our new objects; this listing will be upgraded through galley proof of this paper. The diameters are based on a straight average for carbonaceous and silicaceous reflectivity yielding a diameter of 0.09 km for 1990 UN (Bowell, personal communication 1991). 1990 UN was announced as the smallest natural object observed outside the Earth's atmosphere (*IAU Circ*. 5130). Then came 1991 BA with 9-m diameter (*IAU Circ*. 5172); this was not discovered by the software, however, but by eye as a faint trail. 1990 UP has a peculiar orbit, close to Mars' distance, and a period of rotation of about 16 hours (Wisniewski, personal communication 1990), possibly slowed by multiple collisions from the usual 2-6 hours for these objects. Or, it may be an extinct cometary core, as it has a high inclination, and its rotation rate was then controlled by outgassing. We still have not learned how to distinguish such cores from fragments of collisions in the asteroid belt.

Finally we note that 1989 UP and 1991 BN meet the criteria for future sample-return and mining missions, namely: low delta-V in terms of low inclination and occasional proximity to Earth, and being bright enough so that the orbit can be determined precisely. 1991 BA, on the other hand, was unique, a record, in several ways: the detection of the long trail, of at least 100 pixels, was done near the 1-sigma brightness level, as only the eye can do; it is by far the smallest asteroid known; and it made the closest approach to Earth by an asteroid known so far (170,000 km on 1991 Jan. 18.72 UT).

14. Future Developments

The present CCD system and 0.91-m Spacewatch Telescope are not optimum for the discovery of near-Earth asteroids. The exposure for scanning one frame is 165 secs, at an average declination of 10 deg, and this is too long for proper discovery of fast, trailing objects. Objects closer than Mars move faster than 0.3 deg/day at opposition. Their exposure then extends to more than 1.7 pixels. A trail is a waste of telescope time; the exception to this statement is for detection by eye (see end of Sec. 13). An optimum system for discovering near-Earth asteroids therefore has the integration (drift) time of the sky across the CCD reduced, by moving the telescope at least a factor 1.7 faster than sidereal rate, while clocking the CCD faster, to match the sky drift, with processing of the data also fast enough. The time taken by a near-Earth asteroid to move one pixel ought to be the same as the exposure time of one frame. The principal advantage then is an increase in area coverage. Our next development is therefore to speed things up, to move the 0.91-m Spacewatch Telescope at the maximum rate that the present 2048 CCD and Solbourne Computer can handle. It appears that the CCD allows a factor of almost two faster readout, and that the computer needs to be enhanced.

We are planning a major refurbishment of CCD, computer equipment, radial-velocity spectrometer, and telescope mirror. The mirror is of lightweight construction with 1.82-m diameter, F/2.7. It consists of quartz, a front plate of about 1.6 cm and backplate 2.5 cm thickness, which are held together at 22.7-cm distance by orthogonal rows of ribs which are 0.7 cm thick and spaced at 7.6 cm distance. It is therefore called an "eggcrate" structure, weighing 500 kg. Laminated strongly so as to be able to withstand the vibrations of a launch, it was originally designed for use on spacecraft. The mirror was assigned to me in 1970 for an Asteroid Telescope by A. B. Meinel, who was then the Director of the Optical Sciences Center at the University of Arizona. When delays occurred in that plan, I loaned the mirror to the Multi-Mirror Telescope (see Gehrels 1988). The MMT now has a spare seventh mirror so the loaner is ready to be returned. Our "new" mirror, therefore, already comes with a proud record in astrophysics.

The fork of the ensemble may simply replace the present fork of the 0.91-cm tube. It looks likely that the new ensemble is light enough so that we may keep the 1921 base and polar axis, which are excellent hardware. We will need an automatic dome follower, an improved CCD system, and a new radial-velocity spectrometer. The CCD system is under study; it should transfer the charges and process that data-stream quickly, while having high quantum-efficiency and well-capacity. Cameras are already commercially available with 2048 x 2048 CCD, 9-micron pixels, quantum efficiency near 40%, and read-out rates near 500,000 pix/sec. The state of the art has changed greatly since we waited two years for delivery of our first 2048 CCD! The pixel size of 9 microns may be too small but other CCDs may soon be available, with 4096 pixels, for instance. In any case, the size of the CCD is not a predominant parameter for area coverage, nor is the f/ratio of the telescope, but the speed with which the system can scan is of primary importance.

We are aiming at a discovery rate an order of magnitude greater than with the present 2048 CCD on the 0.91-m telescope; the possibilities are reviewed by Rabinowitz (1991). The gains may come from moving the telescope (a factor of at least 1.7), a better CCD (factor of at least 1.5), and the larger telescope (factor of 3, allowing for effects of sky background). It is not merely the increase in discovery rate that is important, but also the ability to follow up discovered objects as they get fainter, farther away from opposition. Furthermore, the new telescope will be used in a variety of applications on faint and/or moving objects, including the discovery of planets of other stars. For the spectrometer, the aim is at improving its efficiency towards limiting magnitude $B = 9$ for surveying some 150 stars instead of the present $B = 5.5$ and 16 stars. The larger telescope will allow observation of the nearest stars, which tend to be intrinsically faint. The increased collecting area and improved guiding capability will allow radial-velocity measurements of most of the stars that are in astrometric planet-detection programs. Combination of astrometry and radial-velocity data on the same systems will help determine whether stars have more than one planet orbiting them.

A CCD-scanning telescope is also being planned by the Indian Institute of Astrophysics at Bangalore, with our support and with sponsorship of the Smithsonian Institution. A 1.27-m mirror is available and the dome is being built at the Kavalur Observatory, to the southeast of Bangalore; eventually the project may be moved to a drier site farther north.

The 1.27 and 1.82-meter scannerscopes will provide a choice for studying different types of objects, ranging from distant planets to hazardous asteroids. For the 0.91-m Spacewatch Telescope we are already able to detect 150-m objects out to 0.35 AU from Earth. The new facilities will provide greater completion of discovery as well as security for human life by an order of magnitude. The telescopes can support space missions and they are likely to find the optimum classes of objects for space resources, as well as low-delta-V candidates; fuel savings could be greater than the costs of the projects.

15. Summary of Modes for CCD Operation

The CCD is a versatile device as its readout rate and its orientation on the telescope can both be varied and precisely controlled. Thus we have used and developed six modes of operation as is described in this paper. We summarize them as follows:

1. **Driving the telescope at sidereal rate and no transfer of the CCD charges during the exposure.** This is the mode most commonly used by other CCD observers; we call it the "stare" mode, and use it for focussing (Sec. 2), in the search for satellites of asteroids (Sec. 5) and for Shiva, including parallax measurements (Sec. 7). Other examples are McMillan's

radial-velocity spectrometer (references in Sec. 2) and Wisniewski's CCD photometry of faint asteroids, successful even in crowded star fields and non-photometric skies (Wisniewski and McMillan 1987).

2. **Drive off, and no transfer of the charges.** The applications were to search in geostationary regions (Sec. 6), and for Frank's cometesimals (Sec. 8).
3. **Driving at sidereal rate, but continuously transferring the charges at an especially selected rate.** This is the technique used for the search of optical flashes from gamma-ray bursters described in Sec. 4. This was the first time we turned the CCD in order to scan in another direction than in our usual orientation for moving the charges from east to west.
4. **Drive on, with the transfer of the charges exactly sidereal, but the CCD turned 180 degrees.** This is a special modification of the above. The second search for geostationary debris was done this way (see end of Sec. 6).
5. **Drive off, with the transfer of the charges exactly matching the scanning on the sky.** This is the mode extensively used for CCD surveying and astrometry with the Spacewatch Telescope (Secs. 10, 11, and 13).
6. **Drive on, at whatever rate is best for the scanning, with the transfer of the charges exactly matching the scanning on the sky.** For finding and doing astrometry on exceptionally faint objects, we have a routine with the telescope driving westward but not as fast as the sidereal rate. The gain has been almost a factor of 3; occasionally we superpose three of those scans for even fainter limiting magnitude (Sec. 11). For the increase in area coverage this seems to be our mode of the future, as is explained in Sec. 14.

16. Acknowledgments

When I say "we" in this paper, I refer to our small crew for the CCD scanning, which has diverse but nicely matched talents. R. S. McMillan oversees all instrumental development. J. E. Frecker made most of our electronics, until his departure in 1987, when M. L. Perry took over, also for all mechanical maintenance and development. J. V. Scotti has done most of the computer programming, and he is responsible for our astrometry. D. L. Rabinowitz joined us in 1989, with his making image and trail recognition automatic as a major accomplishment. I thank them all for the cordial and efficient manner of working together.

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Fig. 1. Discovery frame of 1990 SS, at 1990 Sept. 25.24335 UT; (1950) $00^h\ 04^m\ 29.4^s$, + 02° 40′ 01.4″. This is on the third scan, on which boxes are made by the computer system about the image of the moving object and also about the positions it had on the second and first scans. The difference in rate of motion is clearly seen between 1990 SS and the main-belt asteroid on the right. That is how the discovery is made, at a glance. The bright streak is due to a hot pixel. Also seen is the charge tailing of bright stars. North is to the right and East is down.

[Note to Press: Please don't lose the fainter boxes in photographic reproduction.]

Table 1

Approximate Statistics for Near-Earth Objects

Diameter (km)	No. of Objects	Impact Probability (Once per no. of years)	Impact Energy (In "Hiroshimas")
10	10	10^8	10^9
1	10^3	10^6	10^6
0.1	10^5	10^4	10^3
0.01	10^7	10^2	1

Table 2

Residuals in arcsecs for asteroid (4255) Spacewatch

Date	Δ R.A.	Δ Dec.	Date	Δ R.A.	Δ Dec.	Date	Δ R.A.	Δ Dec.
770211	-1.6	-1.4	860501	+0.1	+0.6	860608	+0.8	+0.5
770212	+0.4	-2.5	860501	-0.8	+0.2	860608	+0.7	-0.2
860404	-0.4	-1.2	860514	0.0	0.0	870523	-0.2	+0.3
860404	-0.6	-0.7	860514	0.0	-0.8	870523	+0.2	0.0
860404	-1.1	-0.8	860514	-0.2	-0.3	870523	-0.3	-0.7
860409	+0.2	+0.2	860517	0.0	+1.0	870524	+0.6	-1.7
860409	+1.0	+0.1	860517	-0.6	+0.3	870524	+0.2	-1.6
860409	+0.4	+0.8	860517	-0.2	+0.5	870524	-0.4	-0.9
860415	+0.4	+0.8	860607	+0.4	+0.3	880914	-0.7	+1.2
860415	+0.8	+0.8	860607	+0.2	-0.1	880915	-0.1	+0.4
860415	+0.5	+1.1	860607	+0.7	+1.0	881006	+0.7	+0.3
860501	-0.9	+0.1	860608	+0.2	-0.1	881007	-0.1	-1.3

Table 3. Discoveries of the Second Spacewatch Survey

Identification	Perihelion distance (AU)	Aphelion distance (AU)	Incli. nation (deg)	Dia-meter (km)	Date of discovery	Remarks
1989 UP	0.98	2.7	3.9	0.3	89.10.27	elongated; perihelion at Earth orbit
1990 SS	0.87	3.0	25.4	1.0	90.09.25	
1990 TG1	0.78	4.1	8.9	4.3	90.10.14	
1990 UN	0.81	2.6	3.7	0.09	90.10.22	small (H=23.5)
1990 UO	0.31	2.1	27.4	0.3	90.10.22	perihelion at Mercury orbit
1990 UP	1.11	1.6	28.7	0.3	90.10.24	slow rotation
1990 VA	0.72	1.2	14.1	2.3	90.11.09	Aten; perihelion at Venus orbit
1991 AM	0.53	2.7	29.6	2.2	91.01.14	crosses Venus orbit
1991 BA	0.71:	3.8	2.0	0.009	91.01.18	smallest object found so far
1991 BN	0.88	2.0	3.3	0.4	91.01.19	

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SURVEYING WITH CCD

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