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Overview

Spacewatch was begun in 1980; its purpose is to explore the various populations of small objects within the solar system. Spacewatch provides data for studies of comets and asteroids, finds potential targets for space missions, and provides information on the environmental problem of possible impacts. This grant provided some of the funds for the Spacewatch Project from December 1, 1985 through June 30, 1997. NASA has continued its support for this project under grant NAG5-4211.

Moving objects are discovered by scanning the sky with charge-coupled devices (CCDs) on the 0.9-meter Spacewatch Telescope of the University of Arizona on Kitt Peak (McMillan *et al.* 1986; Gehrels 1991; Scotti 1994). Each Spacewatch scan consists of three drift scan passes over an area of sky using a CCD filtered to a bandpass of 0.5-1.0 μm (approximately V+R+I with peak sensitivity at 0.7 μm). The effective exposure time for each pass is 143 seconds multiplied by the secant of the declination. The area covered by each scan is 32 arcminutes in declination by about 28 minutes of time in right ascension. The image scale is 1.05 arcseconds per pixel. Three passes take about 1.5 hours to complete and show motions of individual objects over a one hour time baseline. The limiting magnitude is about 21.5 in single scans.

CCD scanning was developed by Spacewatch in the early 1980s, with improvements still being made - particularly by bringing a new 1.8-m Spacewatch Telescope on line. In the meantime, we have been finding some 30,000 new asteroids per year and applying their statistics to the study of the collisional history of the solar system. As of the end of the observing run of May 1997, Spacewatch had found a total of 150 Near-Earth Asteroids (NEAs) and 8 new comets, and had recovered one lost comet (P/Spitaler in 1993). Spacewatch is also efficient in recovery of known comets and has detected and reported positions for more than 137,000 asteroids, mostly new ones in the main belt, including more than 10,882 asteroids designated by the Minor Planet Center (MPC).

Distinctions held by the Spacewatch group include:

- First to use CCD-scanning routinely in astronomy,
- First to use CCDs to survey the sky for comets and asteroids,
- First astronomical group to develop automated, real-time software for moving object detection,
- First to discover a near-Earth asteroid (1990 SS) by software,
- Detected about one-third of all near-Earth objects (NEOs) ever found,
- First to use a CCD to discover a comet (1991x, which was also the faintest comet at the time of discovery),
- Detected the smallest known asteroid (1993 KA2 with absolute magnitude H=29.2 which translates to 4-9 meters diameter, depending on whether it is an S or a C type),
- Detected the closest approach of any asteroid to the Earth (105,000 km; 1994 XM1),
- Discovered the S or C type asteroid with closest approach to the Sun (0.120 AU; 1995 CR),
- Discovered four of the seven known Centaur asteroids, which represent a newly-found population in the outer parts of the solar system.

Spacewatch discoveries contribute to the assessment of the impact hazard. This problem is studied in detail in the book *Hazards due to Comets and Asteroids* (Gehrels, ed. 1994). Spacewatch complements other surveys that have wider area coverage at brighter magnitude, by exploring the hazards of objects down to a diameter of 200 m (H > 22) that approach within 0.05 AU of the Earth's orbit.

Scientific Accomplishments

Near-Earth Asteroids: Spacewatch discovery tallies from the installation of our first big CCD in 1989 through 1997 May are summarized in the following Table, in which H designates absolute visual magnitude and "VFMO" stands for "very fast moving object", usually a very small asteroid approaching close to Earth.

	H<18.3	18.3≤H<23.3	H≥23.3	Total
Apollo	21	34	29(+3*)	84(+3*)
Amor	15	36	8	59
Aten	0	3	4	7
Total	36	73	41(+3*)	150(+3*)

(*) 3 VFMOs that were not designated by MPC.

Also 8 comets (5 periodic, 3 long period), 1 re-discovery, 4 Centaurs.

Apart from the hazard aspect, NEAs are important to find as potential targets for low-cost spacecraft missions. For example, Scotti used image subtraction in a dense Milky Way region for a difficult but successful recovery of a target candidate for Clementine 2 (1987 OA).

With continued systematic surveying, statistically strong inferences about the magnitude-frequency relation of NEAs will be possible. Rabinowitz (1993) showed a preliminary relation for the NEAs with a non-linearity starting for objects smaller than 0.10 km in diameter. A debate ensued, with a variety of interpretations, such as secondaries of impacts on the Moon. But a similar discontinuity was found by Davis *et al.* (1996 *Icarus*, **125**, 50-60) in the crater size distribution on Ida, so it may be a property of the statistics in the asteroid belt.

Main Belt Asteroids: Jedicke and Metcalfe completed a study of the magnitude-frequency relations for three distance zones in the asteroid belt (Jedicke and Metcalfe 1997). The de-biasing technique developed by Jedicke and Metcalfe has also been made available to Tim Spahr at the University of Florida for his dissertation on main-belt statistics (with Prof. S. F. Dermott). Spahr and Jedicke have applied these techniques together to derive the completion of the Palomar-Leiden Survey, which is about 96% over the apparent-magnitude range 16-19.

Centaurs: Spacewatch found its fourth new Centaur asteroid (the 7th overall) early in 1997. In their analysis of Spacewatch data, Jedicke and Herron (1997) found that the Centaurs, which move in orbits approximately between those of Saturn and Neptune, may have a population about as great as that of the main-belt asteroids.

History of Instrumentation

The stages of development of the Spacewatch Project through the duration of this grant are punctuated by significant upgrades to detectors, optics, and observing techniques. The 0.9-m telescope of the Steward Observatory on Kitt Peak was used throughout this period, with various Spacewatch CCDs at the f/5 Newtonian focus. This telescope had been turned over to us in 1981 in poor condition; in the years preceding this grant we had refurbished it and modernized its drives.

Despite the shortcomings of the earlier versions of our CCD instrumentation, with every version an energetic observing effort was maintained, pushing the capabilities of the equipment to their limits and correspondingly the stamina of the observers.

1985-1988: An RCA SID 53612 thinned, back-illuminated CCD of 512×320 30μm pixels was used at dry ice temperature to recover asteroids and comets and to discover a number of main belt asteroids. During this epoch our techniques for scanning were refined and software to find moving objects and do astrometry on them was developed. Refinements were made, such as moving the observer and computer from the Newtonian platform to the "coude focus" (control room) on the floor below the dome, and compressing the image scale from f/5 to f/3.9 with a relay lens to cover more sky. The detector, although sensitive, was too small and noisy to find NEAs, so in 1985 a 2048×2048 CCD, 55×55 mm in size, was ordered from Tektronix.

1988-1989: In 1988 a large CCD of substandard quality was finally accepted from Tektronix at half price. The alternative of waiting 4 more years for a good, large CCD was unacceptable because we knew we needed to get on line with a larger CCD and develop the software and techniques. A new computer was procured and a postdoc, David Rabinowitz, was hired to program it and accelerate the Project development. A cryostat and an electronic system to control and read out the CCD were procured. These two items are still in service.

1989-1992: Spacewatch began finding NEAs as soon as the large CCD came on line, and was immediately competitive with the photographic surveys by Helin and Shoemaker. New real-time software, large area scans, and a high-quality image display transformed the role of the Spacewatch observer from a passive handler of tapes for analysis downtown to that of an active discoverer and interpreter of fascinating objects in near-real time.

1992-1995: In 1992 we finally received an acceptable CCD from Tektronix. It has 2048×2048 pixels that are 24μm square, making an image-sensing area 49×49 mm in size. This is still the largest thinned, backside-illuminated, antireflection-coated CCD available through retail purchase order. It was placed into service on the Spacewatch Telescope in September 1992 and is still operational. Its larger sensitivity and high fidelity image transfer function improved sensitivity a factor of two. Also in 1992 we began an effort to design and build a 1.8-m Spacewatch Telescope.

1995-1997: In 1995 a coma corrector was installed on the 0.9-m Spacewatch Telescope. This lens assembly eliminates coma and flattens the focal plane without distorting the field of view. Image quality became uniform across the field and the star images became more centrally concentrated, resulting in another half magnitude of sensitivity. At this time a new observing strategy was also introduced, in which the regions scanned by the first observer of each run are repeated by the second and third observers. Astrometry of many of the slow moving objects is thereby obtained at three epochs with intervals of between 5 and 9 days, varying according to weather. This adds much sensitivity to main belt and Trans-Neptunian Object (TNO) searches, since the times between the observations are increased by two orders of magnitude compared to three scans spanning only 1.5 hours.

New Telescope and Building: Also in 1997, fabrication and installation of the 1.8-m telescope and the construction of its building were completed. This will be the largest telescope in the world dedicated full time to the search for previously unknown members of the solar system. Its 1.8-m aperture, sensitive CCD, and dedication to surveying will extend all of Spacewatch's exploration of the solar system to exciting new limits.

Selected Relevant Publications

(1985-1997, in chronological order):

Starting with *Minor Planet Circular* 919 in 1984, Spacewatch has been reporting asteroid and comet observations on a monthly basis.

In *I.A.U. Circulars*, Spacewatch reports the recovery of comets and the discovery of interesting asteroids such as those of near-Earth asteroids 1989 UP and 1990 SS.

"Asteroids and Comets", 1985, T. Gehrels, *Physics Today,* **38**, No. 2, 32-41. (Included in *The Physics Teacher,* CD-ROM Toolkit.)

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"CCD Search for Geosynchronous Debris", 1986, T. Gehrels and F. Vilas, *Icarus,* **68,** 412-417.

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"Drift Scanning with a TK2048 CCD", 1990, T. Gehrels, R. S. McMillan, J. V. Scotti, and M. L. Perry, *Astron. Soc. of Pac. Conf. Ser.* **8,** "CCDs in Astronomy," ed. G. H. Jacoby (San Francisco: A.S.P.) 51-52.

"Scanning with Charge-Coupled Devices", 1991, T. Gehrels, *Space Science Reviews,* **58**, 347-375.

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"Computer Aided Near Earth Object Detection", 1994, J. V. Scotti, in *Asteroids, Comets, and Meteors 1993,* A. Milani *et al.,* Eds., Kluwer, 17-30.

"CCD Scanning for the Discovery of Comets and Asteroids", 1995, Gehrels, T., Jedicke, R., McMillan, R. S., Perry, M. L., Scotti, J. V., & Bressi, T. in *Proc. of the Planetary Defense Workshop,* Lawrence-Livermore National Laboratory CONF-9505266, pp. 125-127.

"Automated CCD Scanning for Near Earth Asteroids", 1995, R. Jedicke, in *New Developments in Array Technology and Applications,* A. G. Davis Philip *et al.* (Eds.) Kluwer, pp. 157-165.

"Orbital evolution of Comet 1995 O1 Hale-Bopp", 1996, M. E. Bailey, V. V. Emel'yanenko, G. Hahn, N. W. Harris, K. A. Hughes, K. Muinonen, and J. V. Scotti, *MNRAS,* **281,** 916-924.

"Detection of Near Earth Asteroids Based Upon Their Rates of Motion", 1996, R. Jedicke, *Astron. J.* **111**, 970-982.

"The Population of Near-Earth Objects Discovered by Spacewatch", 1996, T. Gehrels and R. Jedicke, *Earth, Moon, & Planets* **72,** 233-242.

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