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PURPOSE AND JUSTIFICATION

The purpose of the Spacewatch project is to explore the various populations of small objects throughout the solar system. Statistics on all classes of small bodies are needed to infer their physical and dynamical evolution. More Earth Approachers need to be found to assess the impact hazard. (We have adopted the term "Earth Approacher", EA, to include all those asteroids, nuclei of extinct short period comets, and short period comets that can approach close to Earth. The adjective "near" carries potential confusion, as we have found in communicating with the media, that the objects are always near Earth, following it like a cloud.) Persistent and voluminous accumulation of astrometry of incidentally observed main belt asteroids (MBAs) will eventually permit the Minor Planet Center (MPC) to determine the orbits of large numbers (tens of thousands) of asteroids. Such a large body of information will ultimately allow better resolution of orbit classes and the determinations of luminosity functions of the various classes. Comet and asteroid recoveries are essential services to planetary astronomy. Statistics of objects in the outer solar system (Centaurs, scattered-disk objects, and Trans-Neptunian Objects; TNOs) ultimately will tell part of the story of solar system evolution. Spacewatch led the development of sky surveying by electronic means and has acted as a responsible interface to the media and general public on this discipline and on the issue of the hazard from impacts by asteroids and comets.

BACKGROUND AND CURRENT STATUS

CCD scanning was developed by Spacewatch in the early 1980s, with improvements still being made. Spacewatch was the first astronomical group to use drift scanning with a CCD, first to use CCDs to survey the sky for comets and asteroids, first to do astrometry on an asteroid with a CCD (1984 JZ on 1984 Apr. 28; numbered (3325) after our observation), first to do targeted astrometry of an EA with a CCD (1983 TB, now known as (3200) Phaethon, on 1984 Sep. 22), first to discover an asteroid with a CCD (the Trojan (3801) Thrasymedes), first to discover an EA with a CCD (1989 UP), first to discover an EA with software (1990 SS; now (11885)), first to discover a comet with a CCD (1991x; modern designation 125P/1991 R2), and first to discover an asteroid known to be monolithic (1998 KY_{26}). At the time of this writing, Spacewatch still holds the records for discovering the smallest known asteroid (1993 KA_2; H=29), the closest known approach of any asteroid to the Earth (1994 XM_1; 105,000 km), the object with the most Earthlike orbit (1991 VG), the largest TNO other than Pluto (2000 WR_{106} = minor planet (20000)), and the asteroid most accessible to spacecraft (the rapid rotator 1998 KY_{26}). As of 2001 Jan. 12, Spacewatch had discovered 237 EAs, 15 Centaurs or scattered-disk objects, 17 comets, 7 TNOs, and rediscovered one lost comet (P/Spitaler in 1993). Spacewatch has also made a total of 4,255 astrometric observations of comets, recovered 61 comets, and has reported 315,308 astrometric detections of asteroids, mostly in the main belt, including more than 42,161 for which provisional designations have been credited by the MPC to Spacewatch. A total of 5,051 positions of EAs have been reported by Spacewatch since 1984.

processes that draw asteroids from the main belt into Earth-approaching orbits. Bottke *et al.* (2000a) also predict that most of the undiscovered EAs probably have more extreme values of *a, e,* and *i*. Thus to find the remaining objects, surveys will have to go fainter and be sensitive to slower angular motion, parameters that already distinguish Spacewatch from the other EA surveys.

Potentially Hazardous EAs:

Scotti discovered the closely-approaching EA 1997 XF_{11} that became the subject of media attention in March 1998 when the Minor Planet Center announced that in future decades it would approach so close to the Earth that the possibility of an impact could not be ruled out. Subsequent calculations and observations eliminated that alarm.

Because Spacewatch goes much fainter than other EA survey groups and Spacewatch observers can detect long, faint trails by visual inspection of the video display screen that software for starlike images can miss, detection of very nearby EAs is a characteristic of Spacewatch. Fourteen of the 24 closest observed approaches to Earth were made by objects discovered by Spacewatch. Among the 16 known asteroids with minimum orbital intersection distances (MOIDs) less than 0.001 AU, 5 were found by Spacewatch (Bowell and Koehn 2001). Five of the 49 approaches $\leq$0.02 AU from the Earth within the next hundred years will be made by EAs discovered by Spacewatch (MPC web site 2001 Jan. 17).

Distribution of Sizes of MBAs and their Strengths:

The luminosity function of MBAs is relevant to physical studies of EAs because it is a cumulative record of collisional processing. Collisional processing depends on, among other things, the cohesiveness of asteroid material. Knowledge of the cohesion of EAs would guide methods to deflect their orbits and the design of mining techniques. Jedicke and Metcalfe (1998), analyzing Spacewatch observations of MBAs, found departures from a simple power law in their distribution of absolute magnitudes. The slope of this distribution and the kink at absolute magnitude $H \approx 13$ were then used by Durda, Greenberg, and Jedicke (1998) to derive information about the critical specific energy and the collisional processing of MBAs. This may have been the first empirical determination of the size-strength scaling relation for asteroidal material. It indicates that the transition between gravity-dominated and strength-dominated collision dynamics seems to lie in the vicinity of 150 m diameter where the critical specific energy, a measure of binding strength, is at a minimum. In other words, Durda, Greenberg, and Jedicke's (1998) results suggest that asteroids of 150 m diameter are the most weakly bound, with smaller objects being more monolithic and larger ones composed of pieces well under 150m in size, held together by mutual gravitation.

O'Brien and Greenberg (1999) point out that Durda *et al.'s* (1998) model for collisional evolution needs revision to bring it into agreement with cosmic-ray exposure ages of meteorites and the histories of cratering on asteroids (Chapman *et al.* 1996; Greenberg *et al.* 1994, 1996). However, Durda (1999 pers. comm.) says that the diameter at which the

Solar System. Finally, Jewitt and Luu found the first of the Kuiper Belt objects beyond the orbit of Neptune in 1992 (Jewitt and Luu 1995).

Recent dynamical studies by Levison and Duncan (1997), Malhotra (1995, 1996), Morbidelli *et al.* (1995), and Morbidelli (1997) have helped to define the expected distribution and dynamical structure of material in the 30 to 50 AU trans-Neptunian region while opening up a number of questions concerning, for example, the relative number of objects at the 2:3 and 1:2 mean-motion resonances with Neptune. While about 24% of the TNOs appear to be in or near the 2:3 mean-motion resonance, there have been only about 3% found to date at the 1:2 mean-motion resonance. Malhotra (1996) expected to find about equal numbers of objects at both resonances. One explanation for the discrepancy of these studies with observations is that Neptune is likely to have migrated out to its present location, causing some mean motion resonance to be depleted with respect to other resonances. Discovery of more objects beyond Neptune should provide additional constraints on these dynamical models. Weidenschilling (1997) and Kenyon and Luu (1998) have estimated the accretion rates and other initial conditions of the TNO region, while Stern (1995) and Davis and Farinella (1997) have provided models of collisional evolution of objects beyond Neptune which can be tested by direct measurement of the size distribution.

Knowledge of the size distributions of the TNOs may shed light on the characteristics of the primordial nebula and accretion of Neptune and of the TNOs. It has also been suggested by Stern (1996) that the region beyond about 50 AU may be unaffected by mean-motion resonances with Neptune and accretion may have continued up to the present time, resulting perhaps in the development of Pluto sized bodies in the 50-100 AU distance range which will be within the range of Spacewatch. On the other hand, the deep survey by Allen *et al.* (2000) suggests an edge to the Kuiper Belt at about 50 AU. Discovery or non-discovery of such bodies would yield important clues to the surface density of the primordial Solar nebula and on the initial conditions in the observed outer Solar System.

Centaurs and Scattered-Disk Objects:

In their original definition, Centaurs were defined as asteroids or comet nuclei between the orbits of Jupiter and Neptune, each one crossing the orbit of at least one giant planet (Jedicke and Herron, 1997). The Centaurs were seen as dynamically derived from the Transneptunian population and it was hoped that observational limits to the Centaur population would provide complementary limits to the number of Centaurs in a steady-state model. Jedicke and Herron (1997) debiased early scans made with the 0.9 meter Spacewatch Telescope to establish an upper limit (2000) on the number of Centaurs in the absolute magnitude range $-4 < H < 10.5$. The implication is that although a transient population, the Centaurs may be as numerous as the MBAs over the same range of absolute magnitudes.

However, developments during this grant period have lead to the blurring of the distinction between Centaurs and "Scattered Disk" TNOs principally through Spacewatch discoveries of 1995 SN_{55} and 1999 TD_{10}, which can be argued to meet criteria set for both TNOs and 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 (Perry *et al.* 1998). "First Light" with it was accomplished during this grant period, including its first digital imagery of Earth-approaching asteroids. (Funds from this grant were not spent on the 1.8-m telescope; they are from NAG5-7854.)

Mosaic of CCDs: To increase the area covered by the 0.9-m telescope we have another grant from NASA (NAG5-7533) to pave the focal plane with a mosaic of four CCDs. We have taken delivery of four of Marconi Applied Technology's (formerly EEV, Inc.) 2048x4608 three-side buttable grade 1 CCDs with 13.5 μm pixels. They will be operated to the same limiting magnitude we have been reaching, to allow us to discover all of the same classes of moving objects, but at a much higher rate. The control and readout electronics are well along in development in our lab. We have received the field corrector lenses and the cryostat is nearly finished. The cell for the field corrector has been designed. The blank for the new primary mirror, needed to provide the appropriate focal length and figure for the required wide, flat, distortionless field of view, is being cast. Bids for polishing the mirror have been received. Fabrication of the mirror cell is 50% complete.

EDUCATION, PUBLIC OUTREACH, AND MEDIA CONTACT

These contributions by Spacewatchers are made without any compensation over and above regular University salaries.

Gehrels' educational contributions for the interval 1997 Dec. 1 through 2000 Nov. 30 began in the spring of 1998 with a presentation to the Tohono O'odham Tribal Council, and at Baboquivari High School in Sells, Tohono O'odham Nation, Arizona. In July and August 1998 he attended the American Geophysical Union (AGU) meeting in Taiwan. The statistics paper by Gehrels (1999) was the result of that trip. In Ahmedabad, India, Gehrels spoke before the UN Graduate School in Space Science with students from Bolivia, India, Indonesia, Mongolia, North Korea, Sri Lanka, and Uzbekistan; the paper by Bhandari and Gehrels (1999) was the result.

Gehrels also made two trips to schools in the Tohono O'odham Nation in the Spring of 1999. His trip of 1999 Sept. 23 - Oct. 9 was for a lecture in Los Angeles to the Space Frontier Foundation, two lectures in Bangalore, two in Ahmedabad, one in Amsterdam for the International Aeronautics Federation, and a presentation to Prince Bernhard of the Netherlands.

Gehrels served on the Dean's P&T committee, the Graduate Degree Certification committee, and as a Marshall at Commencements. He teaches "Universe and Humanity, Origin and Future," and is developing a textbook for that. He was specially invited to teach a UN Course at the Physical Research Laboratory in Ahmedabad, for graduate students from India, North Korea, Indonesia, Sri Lanka, Kazakhstan, Uzbekistan, Mongolia, Nepal and the Kyrgyz is funded by AFOSR. The purpose of this education is to develop the capability for astronomers in Mongolia to observe asteroids. This has been given a high priority by DoD/Pentagon.

McMillan gave video interviews for Phoenix commercial TV, UA News Services, the Tucson affiliates of NBC-TV and PBS-TV, and the RSK program of Sanyo Broadcasting Co. of Japan. He did an interview with reporter/still photographer Kazuya Nagase of Kyodo News of Japan. He contributed to press releases and interacted extensively with the press on the topics of Spacewatch's rediscovery of the long-lost asteroid (719) Albert and the Spacewatch discoveries of S/1999 J1 (a satellite of Jupiter) and 2000 WR_{106}, the brightest known TNO other than Pluto. McMillan and Montani hosted and assisted a still photography crew for *Worth Magazine* at the Spacewatch telescopes. McMillan also gave tours of the Spacewatch telescopes for participants of a Mars Conference, a meeting of chemists, an assemblage of UA Dept. Heads, an advisory board to the UA College of Science, the Japan Spaceguard Association, and (with Gehrels and Read) a United Kingdom Task Force on Near-Earth Objects. This latter helped that Task Force write a thorough and thoughtful report to Her Majesty's Government on the hazard of impacts by asteroids that was also well received internationally. McMillan's presentations at the Space Studies Institute in Princeton, NJ and the Colorado School of Mines in Golden, CO reached students and members of the general public in addition to professionals. With Mike Read he upgraded the Spacewatch web page, and granted permission for many organizations, including planetaria, to use images from the page for media productions. McMillan gave talks on Spacewatch to Prof. Steve Tegler's physics class at Northern Arizona University in Flagstaff, to the Saddlebrooke retirement community near Tucson, and a class of senior students at Tucson High Magnet School. McMillan also provided technical advice to two science fiction writers.

Scotti gave several public lectures in this time period, including the Annual Dinner Meeting of the Ottawa Centre of the Royal Astronomical Society of Canada in 1998 November, a guest presentation and question and answer session at Vail Middle School in 1999 May, two phone lecture and question and answer sessions with Edison High School (Fresno, CA), and a public lecture in 2000 April at the Pima Air and Space Museum.

Scotti's interaction with the press extended from phone interviews and conversations, to film interviews, to live radio call-in shows, magazine articles, and numerous web/e-mail related interactions, including several for stories in newspapers or web publications. These were mostly for the (719) Albert story, but there were also some on the impact hazard. He was interviewed on national TV in 1998 on the 1997 XF_{11} affair, and wrote an article on his discovery of that closely-approaching asteroid for *Sky and Telescope* magazine (Scotti 1998). Scotti did a radio interview on "Let's Talk Stars" on KTKT with David Levy on Sept. 12, 2000, a radio interview on KXAM (Phoenix) with Dr. Sky (Steve Cates) on Nov. 24, 2000, and a video interview for "Savage Planet". He was interviewed by Jim Erickson of *The Arizona Daily Star* for the (719) Albert story.

504-516.
Marsden, B. G. 2000. *http://cfa-www.harvard.edu/cfa/ps/pressinfo/200TNOs.html*
McMillan, R. S., T. Gehrels, J. V. Scotti and J. E Frecker 1986. Use of a scanning CCD to discriminate asteroid images moving against a background of stars. In *Instrumentation in Astronomy:* Proc. S.P.I.E. **627** (D. L. Crawford, Ed.), *VI 141-154.*
McMillan, R. S. and J. A. Larsen 2000. Discovery of Trans-Neptunian Object 2000 WR_{106}. *Minor Planet Electronic Circ.* 2000-X02.
McMillan, R. S., and C. P. Stoll 1982. Software simulations of the detection of rapidly moving asteroids by a charge-coupled device. *Proc. SPIE* **331,** *Instrumentation in Astronomy IV,* 104-112.
Melosh, H. J., and E. V. Ryan 1997. Asteroids: Shattered but not dispersed. *Icarus* **129,** 562-564.
Morbidelli, A. 1997. Chaotic diffusion and the origin of comets from the 2/3 resonance in the Kuiper belt. *Icarus* **127,** 1-12.
Morbidelli, A., F. Thomas, and M. Moons 1995. The resonant structure of the Kuiper belt and the dynamics of the first five trans-Neptunian objects. *Icarus* **118,** 322-340.
O'Brien, D. P., and R. Greenberg 1999. Tiny asteroids: Three contradictory lines of evidence for their numbers. Abstract. *B. A. A. S.* **31,** 1091.
Ostro, S. J., P. Pravec, L. A. M. Benner, R. S. Hudson, L. Šarounová, M. D. Hicks, D. L. Rabinowitz, J. V. Scotti, D. J. Tholen, M. Wolf, R. F. Jurgens, M. L. Thomas, J. D. Giorgini, P. W. Chodas, D. K. Yeomans, R. Rose, R. Frye, K. D. Rosema, R. Winkler, & M. A. Slade. 1999. Radar and optical observations of asteroid 1998 KY_{26}. *Science,* **285,** 557-559.
Perry, M. L., and J. E. Frecker 1991. The drive system of the Spacewatch CCD-scanning telescope. *Bull. Amer. Astron. Soc.* **23,** 875.
Perry, M. L., T. H. Bressi, R. S. McMillan, A. F. Tubbiolo, and L. D. Barr 1998. The 1.8m Spacewatch telescope motion control system. *Proc. SPIE* **3351,** *Telescope Control Systems III,* 450-465.
Pravec, P., C. Hergenrother, R. Whiteley, L. Šarounová, P. Kušnirák, and M. Wolf 2000. Fast rotating asteroids 1999 TY_2, 1999 SF_{10}, and 1998 WB_2. *Icarus,* **147,** 477-486.
Rabinowitz, D. L. 1991. Detection of Earth-approaching asteroids in near real time. *Astron. J.* **101,** 1518-1529.
Rabinowitz, D., E. Helin, K. Lawrence, and S. Pravdo 2000. A reduced estimate of the number of kilometre-sized near-Earth asteroids. *Nature* **403,** 165-166.
Scotti, J. V. 1994. Computer aided near Earth object detection. in *Asteroids, Comets, and Meteors 1993,* A. Milani *et al.,* eds., Kluwer, 17-30.
Stern, S. A. 1995. Collisional time scales in the Kuiper disk and their implications. *Astron. J.* **110,** 856-868.
Stern, S. A. 1996. On the collisional environment, accretion timescales, and architecture of the massive, primordial Kuiper disk. *Astron. J.* **112,** 1203-1211.
Tombaugh, C. W. 1961. The trans-Neptunian planet search. In *Planets and Satellites* (G. P. Kuiper and B. M. Middlehurst, Eds.) pp. 12-30. Univ. of Chicago, Chicago.
Weidenschilling, S.J. 1997. The origin of comets in the solar nebula: A unified model. *Icarus,* **127,** 290-306.

Gehrels, T., and E. Echternach 1999. Beautiful but dangerous. *Zenit* **10:**416-423 (in Dutch).

Gehrels, T., and L. Ksanfomality 2000. The search for Earth-approaching comets and asteriods. *Solar System Research,* **34,** 37-48.

Gehrels, T., and P. Massey 2000. Discovery and confirmation of Comet P/2000 S4. *IAU Circ.* 7502.

Hergenrother, C., M. Tichy, J. Ticha, Klet, and **J. V. Scotti.** 1999. Observation of Comet P/1999 RO28 (LONEOS). *IAU Circ.* 7253.

Jedicke, R. and **J. D. Herron** 1997. Observational constraints on the Centaur population. *Icarus* **127**, 494-507.

Jedicke, R., and **T. S. Metcalfe** 1998. The orbital and absolute magnitude distribution of main belt asteroids. *Icarus* **131,** 245-260.

Larsen, J. A. 1997. Discovery and confirmation of Comet 1997 V1. *IAU Circ.* 6767.

Larsen, J. A. 1998. Discovery and Confirmation of the Comet C/1998 M3. *IAU Circ.* 6951.

Larsen, J. A. 1998. Observation of Comet 1998 U4. *IAU Circ.* 7042.

Larsen, J. A. 1998. Spacewatch survey for bright Kuiper-belt objects. Abstract of paper presented at the Kuiper Belt Workshop at Lowell Observatory, Sept. 2-5, 1998.

Larsen, J. A. 1998. The Spacewatch survey for bright Kuiper belt objects. Abstract. *Bull. Amer. Astron. Soc.* **30,** 1113.

Larsen, J. A. 2000. The Spacewatch Outer Solar System Survey. In *Massive Stellar Clusters,* Astron. Soc. Pacific Conference Series, in press.

Larsen, J., R. S. McMillan, J. V. Scotti, M. Hicks, R. Fevig, and G. V. Williams 2000. Discovery and Confirmation of Asteroid (719) Albert = 2000 JW8. *IAU Circ.* 7420.

Larsen, J. A., *et al.* 2000. Image motion package for asteroids, comets, and transneptunians. In preparation.

Larsen, J. A., and the Spacewatch Team 2000. The preservation and enhancement of the Spacewatch data archives. Abstract. *Bull. Amer. Astron. Soc.* **32,** 1018.

Larsen, J. A., A. E. Gleason, N. M. Danzl, A. S. Descour, R. S. McMillan, T. Gehrels, R. Jedicke, J. L. Montani, and J. V. Scotti 2001. The Spacewatch wide area survey for bright Centaurs and Transneptunian objects. *Astron. J.*, **121,** 562-579.

Montani, J. L., S. Kern and W. Shook 2000. Discovery and confirmation of Comet C/2000 A1 (Montani). *IAU Circ.* 7346.

Morbidelli, A., W. F. Bottke, **R. Jedicke,** B. Gladman, J.-M. Petit 1999. The debiased distribution of NEAs. Abstract. *Bull. Amer. Astron. Soc.* **31,** 1116.

Ostro, S. J., P. Pravec, L. A. M. Benner, R. S. Hudson, L. Šarounová, M. D. Hicks, D. L. Rabinowitz, **J. V. Scotti,** D. J. Tholen, M. Wolf, R. F. Jurgens, M. L. Thomas, J. D. Giorgini, P. W. Chodas, D. K. Yeomans, R. Rose, R. Frye, K. D. Rosema, R. Winkler, & M. A. Slade. 1999. Radar and optical observations of asteroid 1998 KY_{26}. *Science,* **285,** 557-559.

Perry, M. L., T. H. Bressi, R. S. McMillan, A. F. Tubbiolo, and L. D. Barr 1998. The 1.8m Spacewatch telescope motion control system. *Proc. SPIE* **3351,** *Telescope Control Systems III,* 450-465.

Scotti, J. V. 1997. Recovery of Comet P/1997 X2 (Kowal-Vavrova). *IAU Circ.* 6784.

Scotti, J. V. 1998. Discovery and confirmation of asteroid 1997 XF11. *IAU Circ.* 6837.

Scotti, J. V. 1998. Recovery of Comet P/1998 K4 (Mueller 3). *IAU Circ.* 6919.

Scotti, J. V. 1998. Recovery of Comet P/1998 O1 (Shoemaker-Levy 7). *IAU Circ.* 6979.

Scotti, J. V. 1998. Fleeting expectations: The tale of an asteroid. Sky and Telescope **96,** No. 1, 30-34.

Scotti, J. V., T. Kohima, T. Seki, C. Jacques, P. J. Shelus, A. Sugie, A. Asami 1999. Observation of Comet C/1999 D1 (Hermann). *IAU Circ.* 7112.

Scotti, J. V. 1999. Recovery of Comet P/1999 R2 (Ge-Wang). *IAU Circ.* 7255.

Scotti, J. V., T. B. Spahr, **R. S. McMillan, J. A. Larsen, J. Montani, A. E. Gleason and T. Gehrels** 2000. Discovery and Confirmation of Jovian Satellite S/1999 J 1. *IAU Circ.* 7460.

Scotti, J. V. 2000. Discovery of Comet P/2000 Y3. *IAU Circ.* 7552.

Supernova Cosmology Project, **R. S. McMillan, T. Gehrels, J. A. Larsen, J. L. Montani, J. V. Scotti, N. Danzl and A. Gleason** 1999. Discovery and confirmation of Supernovae 1999be and 1999bf. *IAU Circ.* 7134.

Tubbiolo, A. F. 2000. Discovery of Comet C/2000 Y1. *IAU Circ.* 7544.

Wisniewski, W. Z.†, T. M. Michalowski, A. W. Harris, and **R. S. McMillan** 1997. Photometric observations of 125 asteroids. *Icarus* **126,** 395-449.