COMPUTER AIDED NEAR EARTH OBJECT DETECTION

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Abstract.
The Spacewatch program at the University of Arizona has pioneered automatic methods of detecting Near Earth Objects. Our software presently includes three modes of object detection : automatic motion identification; automatic streak identification; and visual streak identification. For automatic motion detection at sidereal drift rates, the 4σ detection threshold is near magnitude $V = 20.9$ for nearly stellar asteroid images. The automatic streak detection is able to locate streaks whose peak signal is above $\sim 4\sigma$ and whose length is longer than about 10 pixels. Some visually detected streaks have had peak signals near $\sim 1\sigma$.

Between 1990 September 25 and 1993 June 30, 45 new Near Earth asteroids, two comets and two Centaur's have been discovered with the system. An additional six comets, five Near Earth asteroids, and one Centaur were also "re–discovered". The system has directly detected for the first time Near Earth Objects in the complete size range from about 5 kilometers to about 5 meters. Each month ~2,000 main belt asteroids are also detected.

Future upgrades in both hardware, software, and telescope aperture may allow an order of magnitude increase in the rate of discovery of Near Earth Objects in the next several years. Several of the techniques proposed for the Spaceguard Survey have already been tested by Spacewatch, and others will need to be tested in the near future before such a survey can be implemented.

1. Introduction

The University of Arizona's 0.91-meter Spacewatch Telescope on Kitt Peak is being used during 18 nights centered on the new moon each lunation to survey for Near Earth Objects (NEOs). A Tektronix TK2048E thinned backside illuminated Charge Coupled Device (CCD) with 2048 $\times$ 2048 pixels of 24μm size is placed at the f/5 Newtonian focus. The resulting image scale is 1.076 arcseconds per pixel. The CCD is normally operated in slow scanning mode with the accumulating electronic charge being transferred along the CCD rows in sync with the drift of the sky across the CCD. Scans are then 2048 pixels high in declination and an arbitrary number of rows long in right ascension. A survey region consists of three scans ("passes") of the same length at the same location on the sky. Survey regions are usually selected near the opposition point and are normally done sequentially or by alternating passes from different survey regions. The resulting interval between passes is typically between thirty minutes and one hour. The field of view is ~32 arcminutes tall in declination and the sidereal drift time across the CCD is 147 seconds at the equator and varies with the secant of the declination. Survey regions of 10 frames in length result in 3.3 square degrees of area coverage every 1.5 hours. The limiting magnitude is $V_{lim} \sim 20.9$ at about 4σ for stellar images.

A. Milani et al. (eds.), Asteroids, Comets, Meteors 1993, 17–30.

Prior to the 1992 September observing run, a Tektronix TK2048 thick frontside illuminated CCD with 2048 × 2048 pixels of 27μm size was used. The lower quantum efficiency but larger pixels resulted in $V_{lim} \sim 20.5$, an image scale of 1.211 arcseconds per pixel, an integration time of 165 seconds at the equator and a field of view ~40 arcminutes tall.

2. Detection methods

The pedigree of our automated asteroid detection software includes analogs of the methods used in detection moving objects on photographic plates. For example, fast electronic blinking and registration and subtraction of pairs of frames were both used (for example, see Taff, 1981), but each of these methods rely on humans for the actual detection of the moving asteroid image.

The Moving Object Detection Program (MODP) was designed to combine automated detection methods with a real-time user interface (Rabinowitz, 1991). MODP includes three modes of object detection.

The automated motion detection method is used for detecting moving objects whose appearances are nearly stellar and whose rates of motion do not exceed about 1 degree per day. The first implementation of this method is described by McMillan, *et al.* (1986). Objects whose peak signals are above $\sim 3.5\sigma$ and whose rates of motion are below about 1.0 degrees per day are within the detection limits of automated motion detection. Near opposition, the orbital characteristics of a moving object correlate well with the resulting ecliptic angular rates of motion (Bowell, *et al.* 1990). The observer compares the observed rates of motion of a newly detected object with the results of a simulated sample of orbits at the observed opposition geometry (Rabinowitz, 1991; Scotti, *et al.* 1992).

Figure 1 shows an example of a simulated rate plot. Near Earth Asteroids (NEAs), even at the distance of the Main Belt can usually be distinguished by their ecliptic rates of motion alone. Figure 2 is a sample screen from MODP showing the third pass detection of 1991 VG, whose brightness was about $V = 20.8$ and whose rate of motion at discovery was $\sim 0.8^\circ/day$. Three typical main belt asteroids are also shown.

The automated streak detection method is used to detect relatively bright trailed images of fast moving nearby objects. This method is effective in identifying trails whose length is longer than about 10 pixels and whose peak signal is above $\sim 4\sigma$. Figure 3 is a sample screen from MODP showing the automated detection of 1992 JD which was magnitude $V = 16.7$ and moving $\sim 13.8^\circ/day$ at the time of discovery.

The visual streak detection method allows the observer to detect the images of faint fast moving objects whose images are not bright enough to be detected automatically. MODP allows the observer to identify faint trailed images and to compute rates and predicted future positions for trails. The real-time response of the observer has allowed faint Very Fast Moving Objects (VFMO's) whose rates of motion have approached 100 degrees per day and whose peak signals have been $\leq 1\sigma$ to be followed (Scotti, *et al.* 1991; Rabinowitz, *et al.* 1993). Figure 4 shows eight trailed images of 1991 BA, a magnitude V=18.2 object moving $\sim 27.5^\circ/day$ at the time of discovery. It was observed over about 4.6 hours on 1991 January 18.

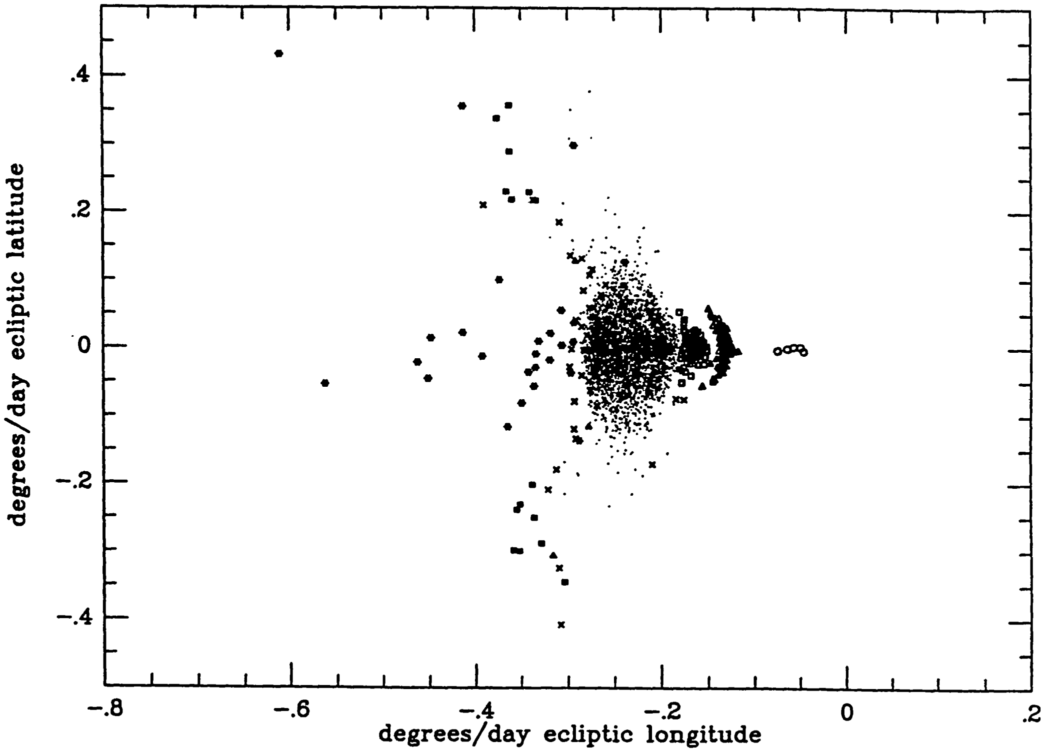

Fig. 1. A simulated rate plot of asteroids near opposition. Dots represent Main Belt asteroid rates, and (*) represent the rates of near Earth asteroids. (.) are main belt asteroids, (×) are Mars crossing asteroids, (□) are Hungaria type asteroids, (△) are Phocaea type asteroids, (□) are Hilda type asteroids, (△) are Trojan type asteroids and (o) are Centaur type asteroids.

3. Astrometry

During the first pass of a survey region, MODP identifies the images of Hubble Space Telescope Guide Star Catalog Stars ("GSC" stars hereafter, see Russell, *et al.* 1990) that are present within the scan and measures their locations. A linear least-squares solution of the measured pixel coordinates with respect to the apparent "of date" right ascension and declination are made for the set of identified GSC stars. Later, when measurements of an objects pixel coordinates are made, those coordinates can then be transformed into "astrometric" J2000 right ascension and declination. Figure 5 shows plots of a typical set of GSC star residuals with respect to the solution for that scan. One can often identify the original GSC plate boundaries in the residual plots. The scan to scan consistency of the GSC star measurements is ~ 0.1 arcseconds. The systematic trends in the residuals are reproducible from scan to scan.

The astrometric measurements of moderately bright asteroids produces residuals

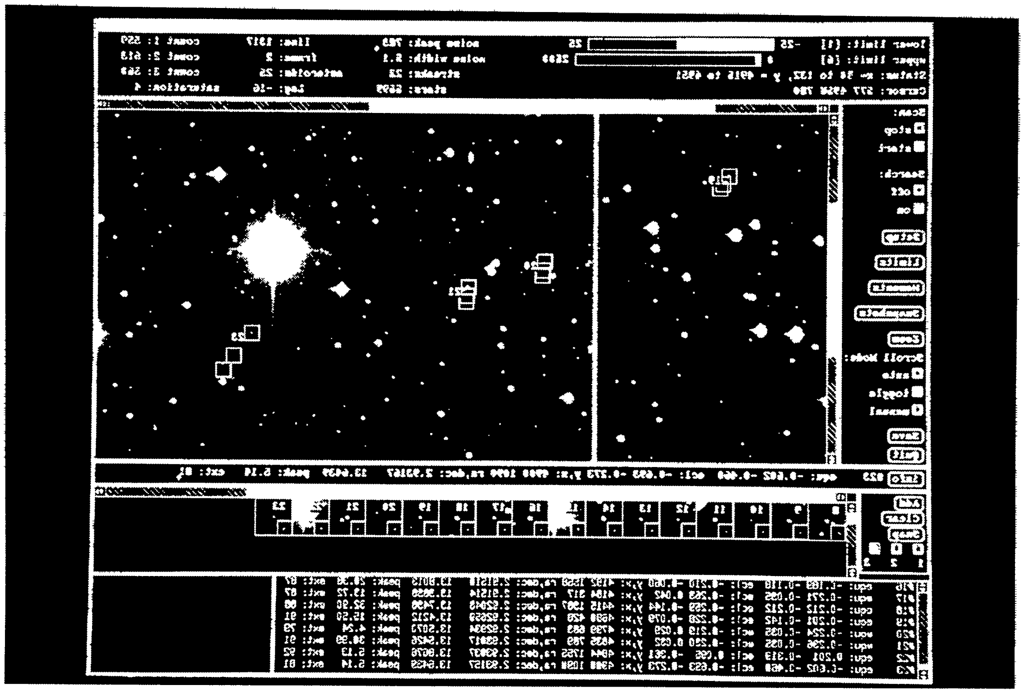

Fig. 2. The MODP display during the automated motion detection of asteroid 1991 VG. Three other main belt asteroids are also marked by MODP in the same display. The image of 1991 VG is indicated by the the small boxes widely spaced on the right. The narrower spaced boxes mark the 3 anonymous main belt asteroids.

on the order of a few tenths of an arcsecond. Table I shows parts of two typical pages from the Minor Planet Circulars showing the orbit solution and resulting residuals for two asteroids detected by Spacewatch. 1993 DT_1 is a case where all of the astrometry was produced completely hands-off with the observer only indicating that the object was real. All the measurements of the GSC stars and of the asteroid were made automatically. 1993 DT_1 was approximately magnitude V=19. (5693) 1993 EA is an NEA discovered and specifically followed up by Spacewatch. (5693) 1993 EA was about magnitude V=19 at the time of discovery and faded past V=20 during the last measurements reported in this sample. For bright objects ($V < 20$), the consistency of residuals during any night are within $\sim$ 0.2 arcseconds. For fainter objects ($V > 20$), the nightly consistency is within $\sim$ 0.6 arcseconds. The night-to-night consistency of residuals reflects the global precision of the GSC and is normally better than $\sim$ 1.0 arcseconds.

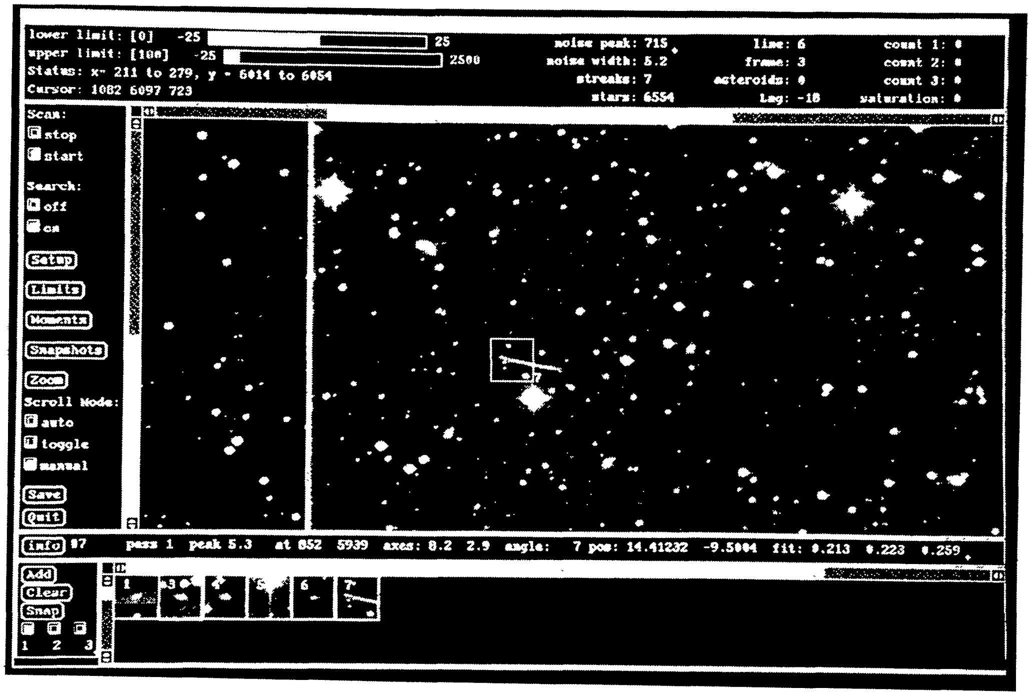

Fig. 3. The MODP display during the automated streak detection of asteroid 1992 JD.

4. Survey results

4. 1. NEAR EARTH ASTEROIDS

Spacewatch discovered 1990 SS on 1990 September 25, making this the first fully automatic discovery of a NEA. During 29 lunations through 1993 June 30, a total of 45 new NEAs have been discovered with Spacewatch. Amongst the objects discovered by Spacewatch are the smallest asteroids ever detected and the objects making the closest observed approaches to the Earth. Five previously known NEAs were "re-discovered" during this time.

Figure 6 shows a histogram of the number of NEAs discovered per absolute magnitude, H. Spacewatch discoveries show a bimodal distribution of larger distant objects with a peak near $H = 21$ and a second peak of smaller nearby objects with a peak near $H = 27$. Spacewatch finds large NEAs far from the Earth and small NEAs close to the Earth. The first direct sampling of NEAs over the entire range $15 < H < 29$ has been made.

Table II shows the number of NEAs discovered during each of the first three years, scaled to a 10 month observing season (normally September through June), distributed according to the size of the object. The first VFMO was found in

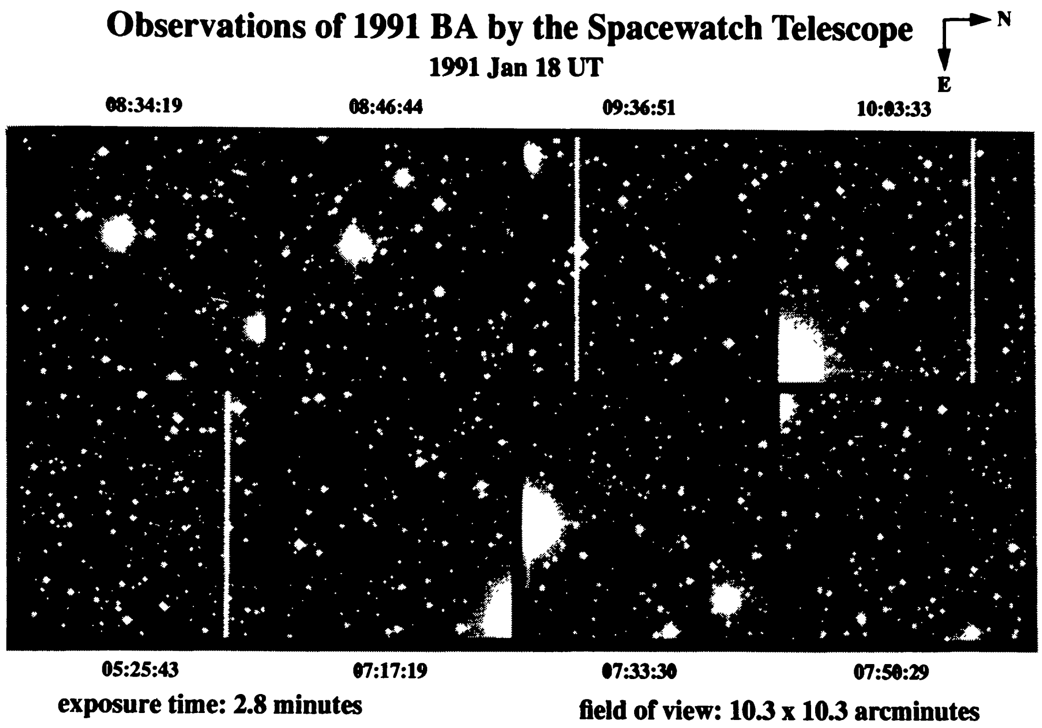

Fig. 4. The trailed image of 1991 BA from Scotti, *et al.* 1991.

January 1991, during the fifth month of the first season. More VFMOs may have been recognized during the first year had the significance of their long trailed images been recognized earlier. Also reflected in the table is a decreased discovery rate due to poorer weather conditions during the second season. The increased detection rate during the third season is due to the installation of a new thinned, backside illuminated Tektronix CCD with significantly higher quantum efficiency than that of our earlier detector.

The discovery of objects smaller than 100 meters diameter has led to the identification of an enhancement in the flux of small objects compared to an extrapolation of the magnitude/frequency of the larger NEAs down to the sizes of the small objects. These discoveries have allowed the first direct measurements of the magnitude/frequency distribution from the size of fireballs, to the smallest photographically discovered NEAs whose smallest object is estimated to be a few hundred meters in diameter and to the larger NEAs (Rabinowitz, 1992; 1993).

The first analysis of the orbital characteristics of these small objects was done by modeling the detection biases of Spacewatch and comparing the orbits of the detected small objects with the orbits of objects with a simulated initial orbit distribution of the larger NEAs. The magnitude/frequency distribution of the small objects has suggested that their orbits are different than those of large NEAs. The

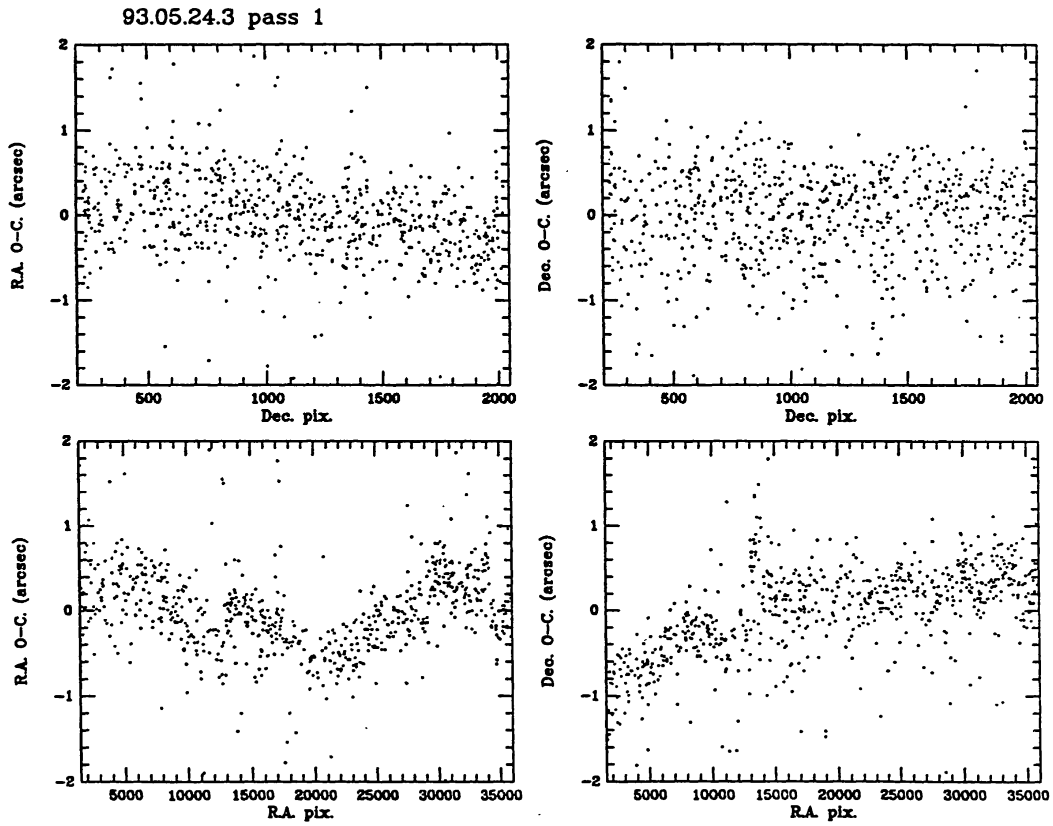

Fig. 5. GSC star residuals of a typical scan made on 1993 May 24. The right ascension and declination residuals are plotted against both the right ascension pixel position and the declination pixel position.

small NEAs appear to have lower orbital eccentricities and perihelia near the orbit of the Earth (Rabinowitz, 1993; Rabinowitz, *et al.* 1993).

Preliminary physical studies of some of the small NEAs also indicates that they have significantly different colors than the larger NEAs and main belt asteroids (Rabinowitz, *et al.* 1993).

4. 2. CENTAURS

Two new trans-Saturnian "Centaur" asteroids have been discovered by Spacewatch. (5145) Pholus (=1992 AD) was discovered on 1992 January 9 near its perihelion at 8.7 AU, just inside the distance of Saturn. On 1993 April 26, asteroid 1993 HA_2 was discovered just outside of its perihelion distance of 11.2 AU. Three weeks after the discovery of Pholus, (2060) Chiron was accidentally "re-discovered" and its subtle

TABLE I

Comparison of automated astrometry with orbit calculations. The residuals for each published observation of the object are shown with the date (YYMMDD), the observatory code (Spacewatch is identified by observatory code 691), and the right ascension and declination residuals in arcseconds.

M. P. C. 22 060 — 1993 MAY 6

1993 DT1 = 1981 JA6

Epoch 1993 Aug. 1.0 TT = JDT 2449200.5 — Williams

M	315.98082		(2000.0)	P	Q
n	0.23556870	Peri.	55.00602	-0.25802517	+0.96594907
a	2.5965159	Node	200.06695	-0.90357903	-0.24827420
e	0.2413425	Incl.	3.19364	-0.34200578	-0.07281694
P	4.18	H	15.0	G	0.15

Residuals in seconds of arc

810508	675	1.0-	0.1+	930303	691	0.4+	0.2-	930303	691	0.2-	0.4-
810509	675	1.0+	0.1-	930303	691	0.1-	0.1-	930319	691	0.2+	0.3+
930226	691	0.2+	0.3+	930303	691	0.2-	0.3-	930319	691	0.2-	0.0
930226	691	0.3-	0.2+	930303	691	0.1+	0.1-	930319	691	0.1+	0.2-
930226	691	0.1-	0.1+	930303	691	0.2+	0.3+				

M. P. C. 22 585 — 1993 SEPT. 30

(5693)* 1993 EA = 1984 AJ

Discovered 1993 Mar. 3 by Spacewatch at Kitt Peak.

Id. B. G. Marsden (MPC 22060)

Epoch 1993 Aug. 1.0 TT = JDT 2449200.5 — Marsden

M	284.81470		(2000.0)	P	Q
n	0.68703159	Peri.	258.60945	+0.99360789	+0.07144495
a	1.2719936	Node	97.24980	-0.03233376	+0.92191972
e	0.5854749	Incl.	5.05463	-0.10815676	+0.38073566
P	1.43	H	17.0	G	0.15

Residuals in seconds of arc

840110	675	0.8-	1.4+	890513	413	(1.7+	3.8-)	930413	691	0.1-	0.6-
840110	675	1.1+	0.1-	890513	413	0.8-	0.1+	930413	691	0.4-	0.1-
860408	413	1.3-	0.2+	930303	691	0.1+	0.4-	930427	691	0.3-	0.5-
860413	413	1.7+	1.1-	930303	691	0.1+	0.6-	930427	691	0.4-	0.4-
860413	413	0.3+	0.9+	930303	691	0.2+	0.5-	930511	413	1.3+	0.6+
860413	413	0.1+	1.0-	930303	691	0.2+	0.6-	930514	691	0.6-	0.2-
860413	413	0.5+	0.4-	930303	691	0.2+	0.5-	930514	691	0.6-	0.3-
890414	413	0.5+	0.9-	930303	691	0.0	0.3-	930514	691	0.1+	0.4+
890414	413	0.5-	0.9+	930304	691	0.0	0.2-	930526	691	0.8-	0.4+
890502	675	(3.7+	3.6-)	930304	691	0.1+	0.3-	930526	691	0.7-	0.5+
890502	675	(1.8+	3.6-)	930304	691	0.1-	0.3-	930526	691	0.4-	0.0
890503	675	(0.2-	3.6-)	930319	691	0.2+	0.4+	930617	691	0.7-	0.6-
890503	675	(8.8+	9.3-)	930319	691	0.0	0.2+	930617	691	1.1-	0.9-
890504	675	1.4+	1.7+	930319	691	0.0	0.3+	930617	691	1.3-	0.6-
890504	675	0.0	1.4+	930413	691	0.2-	0.7-				

cometary appearance was recognized at the time of observation.

Pholus has been found to be extraordinarily red, possibly indicating that this object is a primordial object or an object unmodified by close approaches to the sun

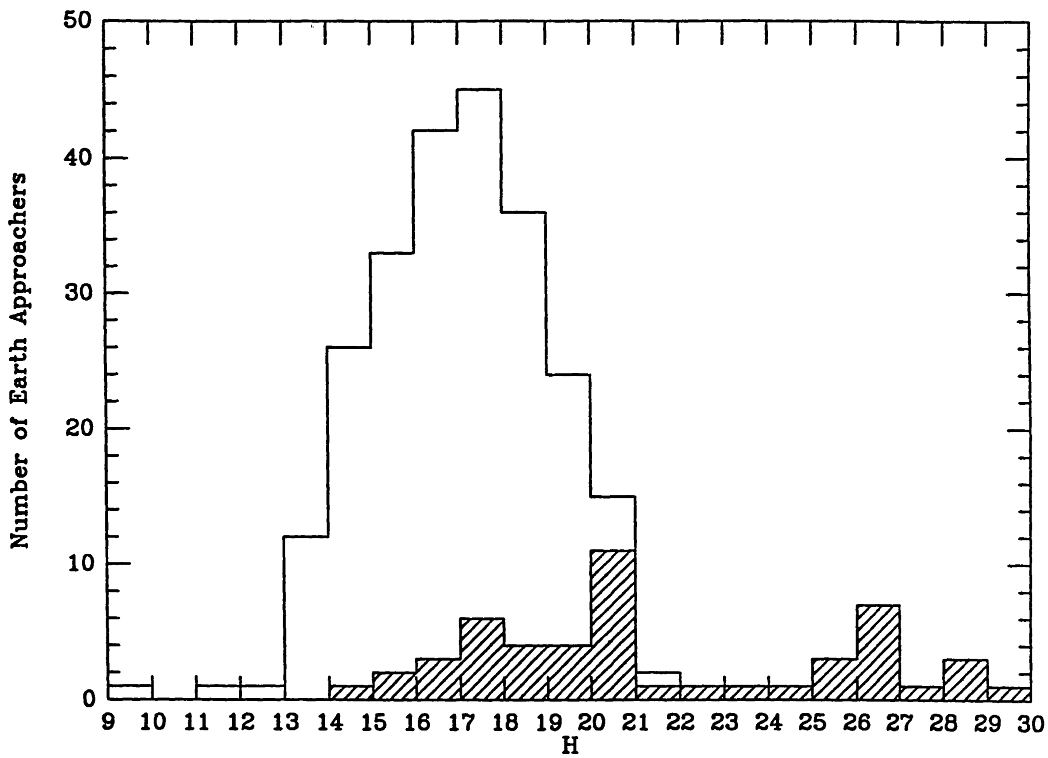

Fig. 6. Histogram of the number of all NEAs and of NEAs discovered with Spacewatch with respect to their measured absolute magnitude, H. Spacewatch NEAs are indicated by the cross-hatched region.

TABLE II

Table of the number of NEAs discovered per size per ten month observing season. Large refers to objects with diameter $D > 1.0$ km ($H < 18.3$), medium refers to 1.0 km $> D > 0.1$ km ($18.3 > H > 23.3$), and small refers to $D < 0.1$ km ($H > 23.3$).

	#	large	medium	small
1990–1991	16	8	6	2
1991–1992	12	3	2	7
1992–1993	24	6	9	9

(Mueller, *et al.* 1992; Fink, *et al.* 1992; Buie and Bus, 1992). No evidence has yet been found for cometary outgassing by Pholus (Zellner, *et al.* 1992). 1993 HA_2 has also recently been found to be extremely red, perhaps redder than Pholus (Tholen, 1993).

The dynamical evolution of Pholus is chaotic and presently under the control of

Saturn. It is presently in the 1 : 3 mean-motion resonance with Saturn. The half-life to ejection from the solar system is about 2 Myrs. The probability of Pholus-like orbits to evolve to (or from) a Jupiter-family short period comet orbit is about 40% and about 1–2% per million years evolve to Earth crossing orbits (Asher and Steel, 1993; Bailey, *et al.* 1993; Bailey, *et al.* 1994a;).

These Centaurs may be the largest members of a population of objects in intermediate orbits between the Jupiter Family comets and the Kuiper disk or Oort cloud. The possible significance of one of these large objects becoming a Jupiter Family comet or even a NEA has only begun to be considered (Bailey, *et al.* 1994b)

4. 3. COMETS

Two new comets have been discovered during the course of the Spacewatch Survey and six other comets (not including the re-discovery of Chiron) were also rediscovered. The long faint tail of comet P/Spacewatch (1991x) was recognized by the observer on 1991 September 8. The comet was nearly a year past perihelion and its total coma magnitude was near V=21, making it the faintest comet yet at the time of discovery. Comet Spacewatch (1992h) was discovered on 1992 May 1. This comet was the first new comet discovered automatically by Spacewatch. It was detected by its motion and the extremely subtle coma was only recognized by the observer. Spacewatch software is not yet able to discriminate comets by their appearance.

A preliminary estimate of the number of comets that Spacewatch should have detected suggests that there should have been at least twice as many comets discovered than have actually been found. This discrepancy is still not understood.

4. 4. MAIN BELT ASTEROIDS

The automatic motion detection software finds between 15 and 30 asteroids per square degree when surveying close to the opposition point and an average of about 10 to 15 asteroids per square degree during a month of surveying at a large range of opposition geometries. The automated astrometry discussed in section 3 has allowed completely automatic, hands off astrometry of every asteroid detected. Normally, astrometric measurements are made for each of the 3 images of each asteroid detection. Approximately 2000 asteroid detections are thus made available each month to the Minor Planet Center. Approximately 20% of these objects have been identified either with known asteroids or with other objects detected by Spacewatch (Williams, 1992). These observations can also be made available to other researchers.

5. Future Directions

5. 1. PHYSICAL AND ASTROMETRIC FOLLOW-UP

The rate at which NEA's are being detected has been increasing over the past 10 years from 7 in 1983 up to nearly 40 in 1993. That rate should increase to about 300 per year within 5–10 years as planned survey programs and improvements to

existing survey programs are implemented. There will be a corresponding increase in the need for astrometric and physical follow-up on these new objects in order to characterize their dynamical evolution and hazard to the Earth, and to study their composition and origin.

The projected area coverage of these near term surveys will not allow complete astrometric follow-up to be built into the survey strategy. An astrometric follow-up strategy needs to consider the brightness distribution of the discovered NEA's, the requirements for adequate orbit determination so that at least the largest detected objects can be recovered at some time in the future, and the limited time before the object becomes unavailable due to its faintness or its viewing geometry. In order to maximize the discovery rate, the survey telescopes should not contribute significant follow-up observations. Dedicated astrometric follow-up telescopes with apertures comparable to the survey telescopes should be used.

In order to estimate the magnitude of astrometric follow-up required in the near term, we assume that new NEA's are identified by their rates of motion near opposition as they are presently found by Spacewatch and that about half of the objects to be followed are objects with rates at the margins of the range expected for NEA's, and will turn out not to be NEA's. The objects which are not found to be NEA's are assumed to require only 2 observations in addition to the discovery observation in the discovery lunation and 2 additional observations the following lunation. NEA's are assumed to be observed twice in the discovery lunation, twice in the following lunation, and once in each of two subsequent lunations. Using reasonable integration times with an unfiltered Tektronix 2048 $\times$ 2048 pixel CCD array and accounting for its long readout time, this astrometric follow-up program would keep a 0.9 meter telescope occupied full time for about 10 nights per lunation. A 1.8 meter telescope would be occupied full time for about 7 nights per lunation.

Follow-up of objects in order to determine color and light curves requires much more telescope time than that required for astrometry. Filtered photometry could be combined with astrometric follow-up, but the increased exposure times required will frequently result in trailed reference stars, degrading the astrometry. A larger aperture would be preferable and the additional load would saturate the monthly load on a single 1.8 meter telescope dedicated to doing the astrometric follow-up and a minimal program of photometric follow-up. Ideally, several larger aperture telescopes outfitted with CCDs would share the load and be distributed globally for better coverage and weather insurance.

5. 2. THE SPACEGUARD SURVEY

Many of the necessary methods that will be required to implement a survey to locate the most dangerous NEOs have been demonstrated by Spacewatch. In the process, a number of challenges have also been identified.

As proposed by the Spaceguard Report (Morrison, 1992; Morrison and Chapman, 1993), the Spaceguard survey would be comprised of six 2-3 meter class telescopes outfitted with CCD detectors. The goal of the Spaceguard survey would be to detect the majority of NEAs larger than $\sim$ 1 km in a reasonable interval of time ($\sim$ 20 years). The Spaceguard survey would detect about 2 orders of magnitude more NEAs each month than are presently being found. Although the Spaceguard

survey has not been funded and is not likely to be implemented exactly as described by Morrison (1992), it serves as a useful model for future NEO survey programs.

In order to be most effective, these telescopes will have to make the best use of the focal plane and field of view by incorporating large acreage CCD's and/or CCD mosaics with the highest detective quantum efficiencies and an optimal image scale (Morrison, 1992). Presently, scanning CCDs may produce the most efficient use of observing time due to the relatively long readout times of currently available astronomical quality large format CCDs. Faster readout times might make staring efficient as long as the problem of flat fielding the CCD is properly addressed. Faster scanning readout with the telescope moving along a great circle will require processing of tens of Gigabytes of raw data per night at each telescope. About 2000 main belt asteroids and 4 NEAs would be found each night with each telescope, resulting in the need for extensive follow-up support either by the survey telescope or by dedicated follow-up telescopes. With the full complement of six telescopes, extensive coordination will be required so that the survey and follow-up proceeds most efficiently with the least duplication of effort. If all six telescopes are available, there will be enough sky coverage to build most of the follow-up into the survey strategy by multiple coverage. If, however, there is not enough sky coverage, then the follow-up will greatly tax the system (see section 5. 1.).

Surveying should cover the area of opposition at least to ± 30 degrees in ecliptic longitude and ± 60 degrees in ecliptic latitude. In order to locate the Athens and to locate any previously unknown classes of objects, surveying far from opposition should also be done (Morrison, 1992). Dangerous comets, for example, will require maximal sky coverage and their danger will persist even after all of the dangerous NEAs have been identified (Marsden and Steel, 1994).

During a Spaceguard Survey, the majority of NEA detections will be of objects smaller than about 1 km diameter. A significant number of detectable NEAs will be VFMOs whose diameters are under 100 meters and which are passing through the neighborhood of the Earth-Moon system. The study of these objects will be very attractive to the researcher who is interested in studying the entire solar system, but the follow-up of such objects will drain the resources of the Spaceguard network if the best orbital data are desired. A decision will have to be made early on for each object. In general, perhaps objects whose estimated diameters are $\ll 1$ km should not be followed, or only a random subset should be followed if such a survey is to be successful in finding objects with diameters larger than 1 kilometer.

6. Summary

The Spacewatch project has demonstrated the feasibility of automated NEO detection. Fainter detection limits and inherently higher detective quantum efficiencies of CCDs with respect to traditional photographic detection methods for NEAs has more than compensated for the limited field of view of the physically much smaller detectors.

The foreseeable improvements in both telescopes and detectors can produce an order of magnitude increase in the rate of discovery of NEOs in the next few years. An additional order of magnitude is possible with a modest additional improve-

ment in telescopes and detectors as recommended by the Spaceguard Report. The improvements are within our present technological capabilities.

Continued discovery of NEOs with Spacewatch will allow not only the detection of potentially hazardous large NEOs, but also may unlock the new puzzle of the origins of the small NEOs that thus far have only been detectable by Spacewatch, and may also produce discoveries of other classes of solar system objects. Other automated NEO detection systems have been started and may come on line in the near future, in particular project EUNEASO (Hahn and Maury, 1993). Others are in their initial design stages or are awaiting funding (For example, see Steel, *et al.* 1993).

With some modification of the survey technique, the large members of the population of the outer solar system can also be studied as the discovery of the Centaurs have indicated. Understanding of the characteristics of this population will aid in the understanding of the evolution of objects from the outer solar system into the observed comet population and perhaps also the observed NEA population.

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