Near-Earth Asteroid Tracking with the Maui Space Surveillance System (NEAT/MSSS)

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1. Abstract

Over the last year the Jet Propulsion Laboratory's (JPL) Near-Earth Asteroid Tracking (NEAT) program has made significant progress and now consists of two simultaneously-operating, autonomous search systems on the 1.2-m (48") telescopes: on the Maui Space Surveillance System (NEAT/MSSS) and NEAT/Palomar on the Palomar Observatory's Oschin telescope. This paper will focus exclusively on the NEAT/MSSS system.

NEAT/MSSS is operated as a partnership between NASA/JPL and the United States Air Force Research Laboratory (AFRL), utilizing the AFRL 1.2-m telescope on the 3000-m summit of Haleakala, Maui. The USAF Space Command (SPCMD) contributed financial support to build and install the "NEAT focal reducer" on the MSSS 1.2-m telescope giving it a large field of view (2.5 square degrees), suitable for the near-earth object (NEO), both asteroids and comets, survey. This work was completed in February 2000. AFRL has made a commitment to NEAT/MSSS that allows NEAT to operate full time with the understanding that AFRL participate as partners in NEAT/MSSS and have use of the NEAT camera system for high priority satellite observations during bright time (parts of 12 nights each month). Currently, NEAT has discovered 42 NEAs including 12 larger than 1-km, 5 Potentially Hazardous Asteroids (PHAs), 6 comets, and nearly 25,000 asteroid detections since March 2000.

2. History

The NEAT system began operating in late 1995 on the Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) 1-m telescope at Haleakala, Maui. Helin [1] and Pravdo et al. [2] describe the attributes and capabilities of that system. A similar system with modifications is now operating at MSSS. It is autonomous and remotely directed from JPL. In the period from March 1996 to August 1998, NEAT/GEODSS searched approximately 35,000 deg^2 of sky and detected 45 NEAs, with 26 larger than 1 km.

NEAT/GEODSS operations terminated in 1998 and began transitioning to the MSSS 1.2-m which achieved first light in March 2000. Now, 17 months later, it is a mature system and is contributing significantly to discoveries of NEAs and comets. This year alone, 2001, MSSS has discovered 27 NEAs and 6 Comets. Cumulative results from the start of NEAT/MSSS in March 2000 to mid-August are 42 NEAs, 12 larger than 1 km in diameter and 5 potentially hazardous asteroids (PHAs). NEA detections, over this time period soared to 145 with 92 larger than 1 km. as shown in Fig. 1.

3. Hardware

The MSSS telescope used by NEAT is one arm of a twin-mounted 1.2-meter telescope. A focal reducer was developed by AFRL personnel to provide the wide field of view needed for a survey instrument. Talent et al [3] describes the requirements. NEAT/MSSS, with its new headring and focal reducer , achieved first light in March 2000. The camera is installed at prime focus. Over the past year and a half we have been operating under pointing constraints of +/-25 degree in declination.

The current NEAT/MSSS camera consists of a 4096 x 4096 charge-coupled device (CCD) with 15 micron square pixels, camera electronics, 2 thermoelectric coolers, and a mechanical shutter. The CCD is a front-side illuminated, commercial-off-the-shelf part manufactured by Fairchild Imaging. It features good cosmetic quality and low dark current, with less than 0.3% of the area unusable due to blemishes. Four output nodes or amplifiers read out each quadrant in parallel. The read noise is about 20 electrons at a readout speed of 200 kpixels s^{-1}. The bandpass is about 0.40-0.85 μm determined solely by the CCD response (i.e. no filters) and the optics. Using standard stars as calibrators, NEAT magnitudes are converted to V values with a precision of about 0.1 magnitudes.

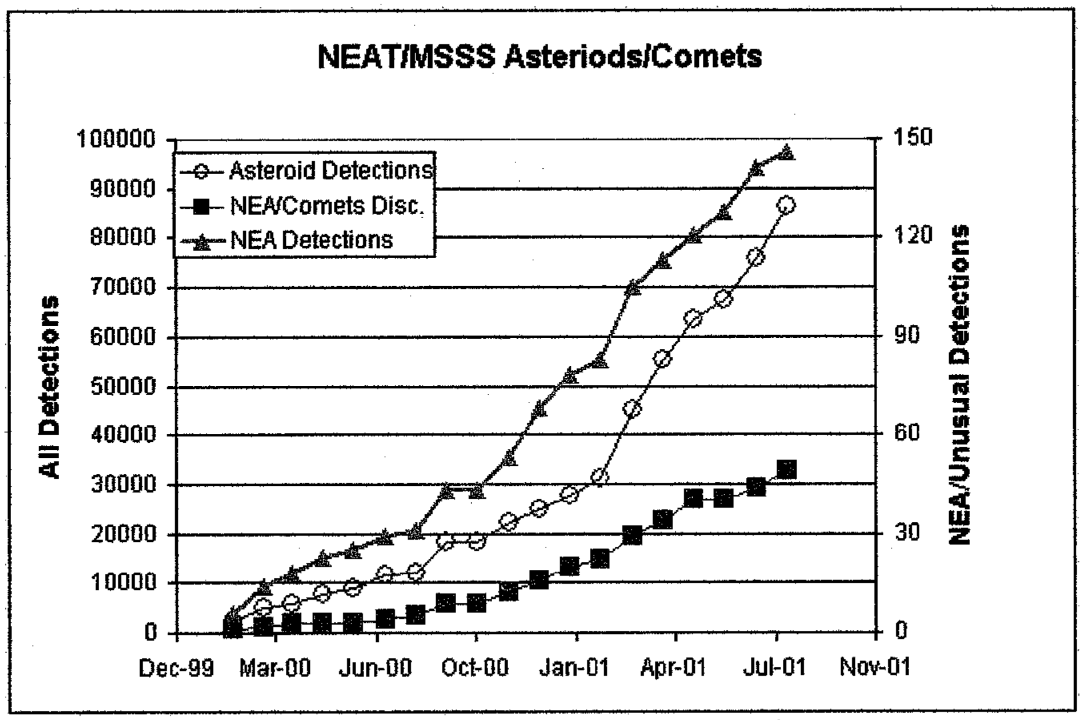

Fig. 1. NEAT/MSSS Asteroid and Comet Detections

A Sun Sparc 20 computer with 2 CPUs control all the operations functions with optical fibers to the camera and serial lines to the telescopes. A Sun E450 with 4 CPUs is the analysis, display, and communications computer. It has two 40 GB disk clusters to contain the image, data and analysis programs. A DLT tape is used as a backup archive device should the Internet not be available.

3.1 Observing Strategy

A typical night of observation of NEAT/MSSS begins with uploading from JPL an observing script which determines telescope pointings, integration times and the time separation between repeat visits, typically fifteen minutes, of each search field. Followup observations of objects discovered on previous nights are often included. Observations begin after nautical twilight. Fields are taken sequentially from the script, with software keeping track of observations completed until three images of each search field is obtained. The automated data analysis begins during the night, processing each triplet as it is completed. Search fields are typically along the ecliptic, with avoidance zones +/-15 degrees from the galactic plane and +/-30 degrees from the Moon. The analysis software generates "patches", which are small 25 pixel subimages centered about candidate moving objects. The patches are examined by eye at JPL to verify both the fast moving near-Earth objects and main-belt asteroids before submission of astrometry to the Minor Planet Center (MPC).

4. Detection Limits and Sky Coverage

The limiting magnitude of a NEA detection system is a complex function of rates of motion, exposure time, sky background, seeing, etc., and can vary greatly even within a single night of observation. Periodically we have calibrated system performance by imaging Landolt fields [4] as they transit but the most appropriate way to quantify the detection efficiency is to look at the magnitudes of our NEO discoveries. Fig. 2 plots the discovery magnitudes and rates of motion of the 42 new near-Earth asteroids and 6 comets found by the MSSS system over the past 17 months, as well as all NEA and comet detections though May 2001. The solid curve marks an approximate detection limit under exceptional conditions, with the system capable of going down to V=21 in a 60 sec exposure. A more typical detection limit (defined as an object having a 50% chance of being flagged as an NEO by the analysis software) would be V=19.7+/-0.3 for objects moving 2 degree day^{-1} or slower. This is a

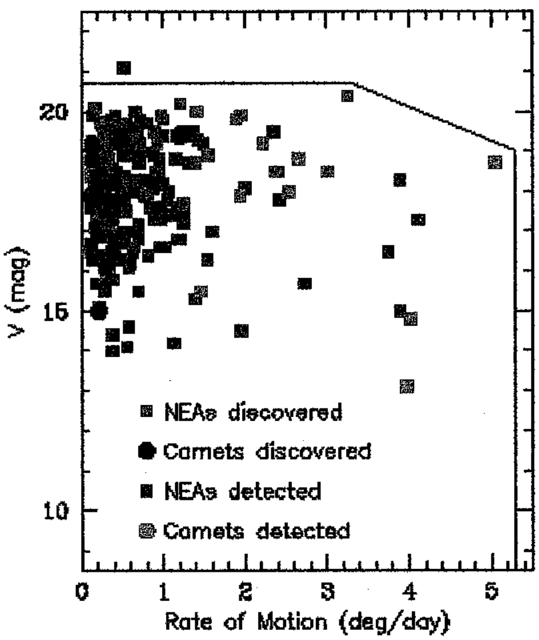

Fig. 2: Visual magnitude vs. rate of motion at time of detection. Solid curve illustrates the detection limit under exceptionally good conditions. A more typical limiting magnitude is 19.7.

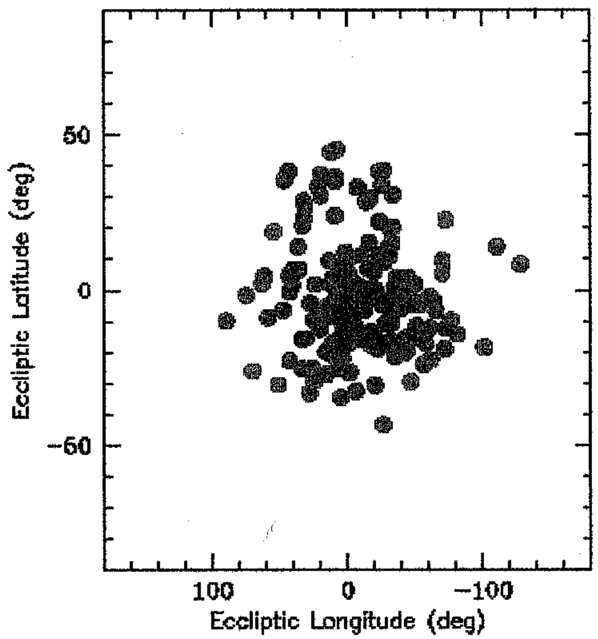

Figure 3. Ecliptic longitude and latitude of MSSS NEA detections. As expected, NEA's are discovered preferentially along the ecliptic. The mean ecliptic latitude less than zero is an artifact of our observing strategy, which focuses on regions in the southern sky less accessible to NEO search programs on the continental US.

modest improvement over NEAT incarnation at the GEODDS 1.0-m, which had a detection limit of 19.1 [5]. The position in the sky with respect to the opposition point for all NEAT/MSSS NEO detections is given in Fig. 3. As expected, objects are preferentially found near opposition, where NEO rates of motions are generally more distinguished from main-belt objects. There are also detections limits imposed by the analysis software, which is sensitive to asteroids moving up to 5.6 degree day^{-1}. Objects also must have a motion greater than 2 pixels between adjacent frame in the triplet, giving rise to a minimum rate of motion of approximately 0.09 degree day^{-1}. A consequence of this is that our analysis software will not flag objects moving at Kuiper Belt rates. We are engaged in implementing a distant object search using search fields imaged on weekly time scales, as developed by Larson et al. [6].

The monthly sky coverage and asteroid detection statistics for the NEAT/MSSS system is given in Fig. 4. The telescope has the ability to search approximately 55 deg^2 hour^{-1} with 20 sec exposures, extrapolating to 15000 deg^2 month^{-1} under ideal conditions. The actual sky coverage is a function of weather and the fraction of the month dedicated to NEO observations. We have maintained a schedule of approximately 8000 deg^2 $month^{-1}$ since 2001.

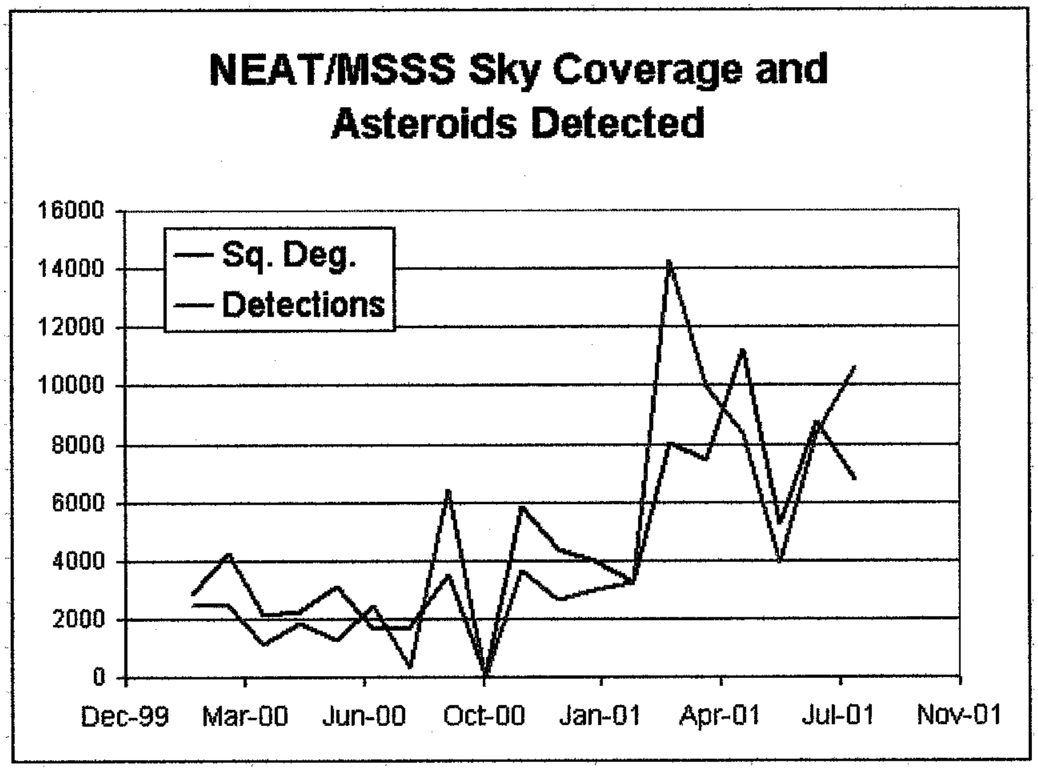

Fig. 4. NEAT/MSSS Sky Coverage and Asteroid Detections

5. Further Optimization

An extended baffle, to mitigate stray light during observations, has been built. This baffle will allow detection of fainter objects. Further work is being done on the mount control software. As a result, we expect faster telescope slew rates, expanding sky coverage and the ability to reach presently inaccessible parts of the sky. Purchased in 1994, the operations computer needs to be replaced. Plans are also underway to purchase an improved CCD chip. As these improvements are implemented, AFRL will certify the system, as required by SPCMD, for satellite observations. Continuing improvements in the analysis software will be addressed.

6. Discussion of Recent Discoveries

The following is a review of some interesting NEO discoveries made by NEAT/MSSS and illustrate the diversity of objects found by the search program. Table I gives a complete listing of NEAT/MSSS NEA discoveries.

The program's first discovery, 2000 ES70 was found on the second full day of observations and is a large, highly inclined Amor asteroid. Illustrating the synergy between the two NEAT observing sites, 2001 PJ is a small, Earth-grazing asteroid. After its discovery at MSSS, it was followed-up at NEAT/Palomar, to be an exclusive NEAT discovery with a published orbit Aug 4-6 based upon the two NEAT systems astrometry. A small number of NEOs cross deeply into the inner solar system (e.g. 3200 Phaethon). On April 30, NEAT discovered 2000 HD24, an 1-km Apollo asteroid with a Venus-crossing orbit.

NEAT/MSSS has discovered 5 potentially hazardous asteroids, marked as PHA in Table 1. A PHA is defined roughly as a object with an Absolute Magnitude H < 22 and whose orbit passes within 0.05 AU of the Earth's. Many of the objects will have spectacular apparitions in the not distant future, including 0.028 AU for 2000 QW7 in 2087, 0.030 AU for 2000 YV137 in 2167, and 0.032 AU for 2000 YF29 in 2136.

Table 1: NEAs DISCOVERED BY NEAT/MSSS
JANUARY 2000 - 15 AUGUST 2001

Desig.	NEAT ID	Disc.	Circumstances		Orbital Elements					
		Date	Motion	V	a	e	i	H	q	MPEC
2000:										
2000 ES70	JBHTAT	03/10	0.90	17.8	1.80	0.32	25.2	17.1	1.228	2000-E53
2000 HD24	JTRTZG	04/30	1.26	18.2	1.34	0.62	9.47	17.8	0.511	2000-J12
2000 PN8	KTI8QF	08/05	3.26	20.9	1.25	0.22	22.34	22.1	0.980	2000-P45
2000 QW7	L10QUN	08/26	3.98	13.6	1.95	0.47	4.17	19.5	1.035	PHA 00-Q32
2000 SD8	LA2364	09/20	0.94	19.7	1.13	0.32	6.64	20.7	0.774	2000-S40
2000 SE8	LA3EUM	09/20	2.54	18.5	2.51	0.59	0.65	23.4	1.017	2000-S41
2000 SQ43	LBX1ER	09/25	0.24	19.7	2.21	0.48	5.17	18.6	1.142	2000-S63
2000 SZ44	LC8J4P	09/26	0.65	19.8	2.51	0.52	5.79	20.5	1.207	2000-S69
2000 WX28	LXI24S	11/23	0.90	20.0	2.95	0.62	5.56	21.3	1.136	2000-W49
2000 WN107	LZLNS5	11/29	0.32	19.4	1.55	0.42	13.32	16.3	0.904	2000-X09
2000 XF44	M1QMNC	12/04	2.23	19.7	2.50	0.56	13.14	21.1	1.101	2000-X30
2000 YF29	M9Q2AA	12/26	0.56	18.0	1.49	0.37	6.29	20.2	0.938	PHA 01-A04
2000 YK29	M90PLN	12/24	0.64	17.1	1.38	0.13	15.22	18.1	1.200	2001-A08
2000 YL29	M9QJJA	12/26	0.18	20.6	1.55	0.33	21.54	15.7	1.042	2001-A09
2000 YV137	MBJ7U8	12/31	0.47	20.2	1.39	0.15	23.06	17.9	1.185	PHA 01-B22
2001:										
2001 BJ16	MI05VN	01/18	0.65	18.8	1.39	0.15	23.06	17.9	1.185	2001-B33
2001 BZ39	MIDP52	01/19	0.29	19.3	1.96	0.42	8.76	18.2	1.147	2001-B38
2001 BA40	MJTC4D	01/23	0.81	18.4	1.12	0.26	12.76	18.4	0.830	2001-B39
2001 DS8	MSSR6U	02/17	1.41	19.2	2.09	0.51	2.38	22.7	1.034	2001-D14
2001 EA16	MZBHNW	03/04	0.38	19.1	1.51	0.43	38.96	17.0	0.865	2001-F04
2001 EC16	N39H5T	03/15	1.47	16.0	1.35	0.36	4.79	22.3	0.856	2001-F07
2001 FP32	N50HKK	03/20	5.06	19.2	1.37	0.34	29.66	23.4	0.906	2001-F33
2001 FB90	N5BCOC	03/21	1.22	20.7	1.67	0.60	1.51	20.8	0.662	PHA 01-F45
2001 FF90	N769V2	03/26	0.55	20.2	2.61	0.63	23.65	16.6	0.956	2001-F49
2001 GS2	NE2XE1	04/14	1.95	18.4	1.78	0.38	18.71	20.0	1.101	2001-H07
2001 HG31	NHN4GG	04/24	0.32	19.5	2.57	0.52	5.88	16.0	1.242	2001-H48
2001 JL1	M03N44	05/11	0.57	18.7	2.57	0.53	27.01	16.6	1.210	2001-J29
2001 JM1	NOGH48	05/12	4.02	15.3	1.46	0.31	17.04	19.0	1.006	2001-J30
2001 JW1	NP84XD	05/14	3.02	19.0	1.18	0.07	35.45	20.3	1.097	2001-K04
2001 KO2	NRRF7F	05/21	2.66	19.3	2.62	0.62	12.12	20.2	0.989	2001-K21
2001 KO41	NSSQMF	05/24	0.28	19.7	2.04	0.44	5.07	20.6	1.134	2001-K35
2001 KZ66	NUJHOF	05/29	0.28	19.9	1.66	0.43	14.51	16.4	0.949	2001-K51
2001 LF	NWFN2K	06/03	0.94	19.0	1.80	0.34	17.99	17.2	1.195	2001-L26
2001 OT	OC8G2Y	07/16	1.56	19.4	0.93	0.32	12.12	21.2	0.634	2001-O10
2001 OD3	OC9XEE	07/16	0.99	20.4	2.52	0.50	14.89	18.8	1.250	2001-O13
2001 OC36	OFGI3B	07/25	2.38	19.0	1.41	0.48	2.29	22.9	0.732	2001-O42
2001 PJ	OJ0IYB	08/04	1.42	20.5	2.10	0.50	5.78	20.4	1.051	2001-P18
2001 PD1	OJ32C4	08/04	0.73	19.7	2.09	0.43	5.73	18.6	1.200	2001-P24
2001 PE1	OJR8MS	08/07	0.30	19.4	2.78	0.60	3.45	18.5	1.121	2001-P25
2001 PT9	OLNQ3I	08/11	1.17	19.9	1.46	0.45	7.20	20.2	0.800	PHA 01-P38
2001 PU9	OLW3KD	08/12	1.96	20.4	2.17	0.49	28.37	19.6	1.104	2001-P39
2001 PJ29	ON3MTH	08/15	1.90	20.3	1.45	0.39	6.68	22.6	0.880	2001-Q06

A useful by-product of the automated NEO search programs is the discovery of other classes of small solar system bodies. With the exception of the faint Kuiper Belt objects and the SOHO sun-grazing comets, these search programs have been the primary source of all new bodies, including main-belt asteroids, Centaurs, and comets. Over 24,000 main-belt detections have been submitted to the MPC by NEAT/MSSS in the past 17 months. More interesting are the six new NEAT/MSSS comets, as listed in Table 2. Four of these objects are periodic comets, with Jupiter-crossing orbits which bring them within the inner solar system, but two (C/2001 B2 and C/2001 O2) are non-periodic comets with perihelion outside the orbit of Jupiter. These objects are most likely recently perturbed from the Oort Cloud. Their strong activity at such large heliocentric distances must be powered by the sublimation of ices more volatile than water, such as C0, CO2, and/or N2. The NEAT/MSSS search for near-Earth objects can yield asteroids with orbits indistinguishable from Jupiter Family Comets, such as 2000 GH147, 2000 WX28, 2001 FF90, and 2001 OK17. These asteroids are likely the devolatilized cores of inactive comets and such objects shall prove invaluable in the understanding of the evolution of comets into asteroids and the true nature of the NEO population. It is important to stress that half our comets were discovered in the visual examination of the main-belt detections. Because we visually inspect each detection the software flags, we are able to detect comets moving at main-belt rates of motion. Fig. 5 illustrates what how a faint comet appears to the observer screening the detections. This visual verification is quite time consuming but it is perhaps the best way to find comets that may be identified as asteroidal by other detection program (e.g. P/2001 BB50 LINEAR-NEAT).

Table 2: COMETS DISCOVERED BY NEAT/MSSS 2000 - 15 AUGUST 2001

NEAT/MSSS	Discovery Date	Motion	V Mag	a	e	i	q	MPC/Ref.
C/2001 B2 (NEAT)	01/24	0.22	15.5	----	1.00	150.60	5.306	42665
P/2001 BB50 (LINEAR-NEAT)	03/20	0.13	18.4	5.68	0.59	10.62	2.347	42665
P/2001 F1 (NEAT)	03/24*	0.14	19.7	6.45	0.36	19.09	4.153	42856
P/2001 J1 (NEAT)	05/11	1.21	19.9	3.88	0.76	10.16	0.937	42856
P/2001 K1 (NEAT)	05/20*	0.21	18.7	3.85	0.36	16.91	2.469	42856
C/2001 O2 (NEAT)	07/25*	0.14	19.3	----	1.00	101.12	6.818	43161

* Discovered within Main-belt data

7. Multiple Use of NEAT/MSSS Data: *SkyMorph*

NEAT data are archived within days of receipt via the *SkyMorph* program (S. Pravdo, PI). *SkyMorph* is funded by NASA's Applied Information Systems Research Program and provides a publicly-accessible WWW site (http://skys.gsfc.nasa.gov/skymorph/skymorph.html) for NEAT images and objects information. The existing SkyMorph archive has already proven to be a major asset to the astronomy community. It is used for purposes as diverse as refining asteroid orbits and discovering supernovae. These data cover the dimension of time in a way that is unique among large optical databases: most of the sky is re-observed with the same instrument on time scales from hours, months, and years.

Pre-discoveries enable moderate and long-term extrapolations of NEO orbits both for space mission rendezvous planning and for hazard-to-the-Earth evaluation. A pre-discovery can extend the temporal baseline (data arc) by years without the necessity for awaiting any new observations of the object in question. A reason for non-detection of an asteroid in standard NEAT processing is that the object was not identified in *all* of the three triplet images, because, for example, it overlaid a star in one image. Even the relatively short baseline of NEAT, about 5.5 years, has resulted in many pre-discoveries. Approximately 50 pre-discoveries of asteroids per month are reported to the Minor Planet Center (MPC) using archived NEAT data.

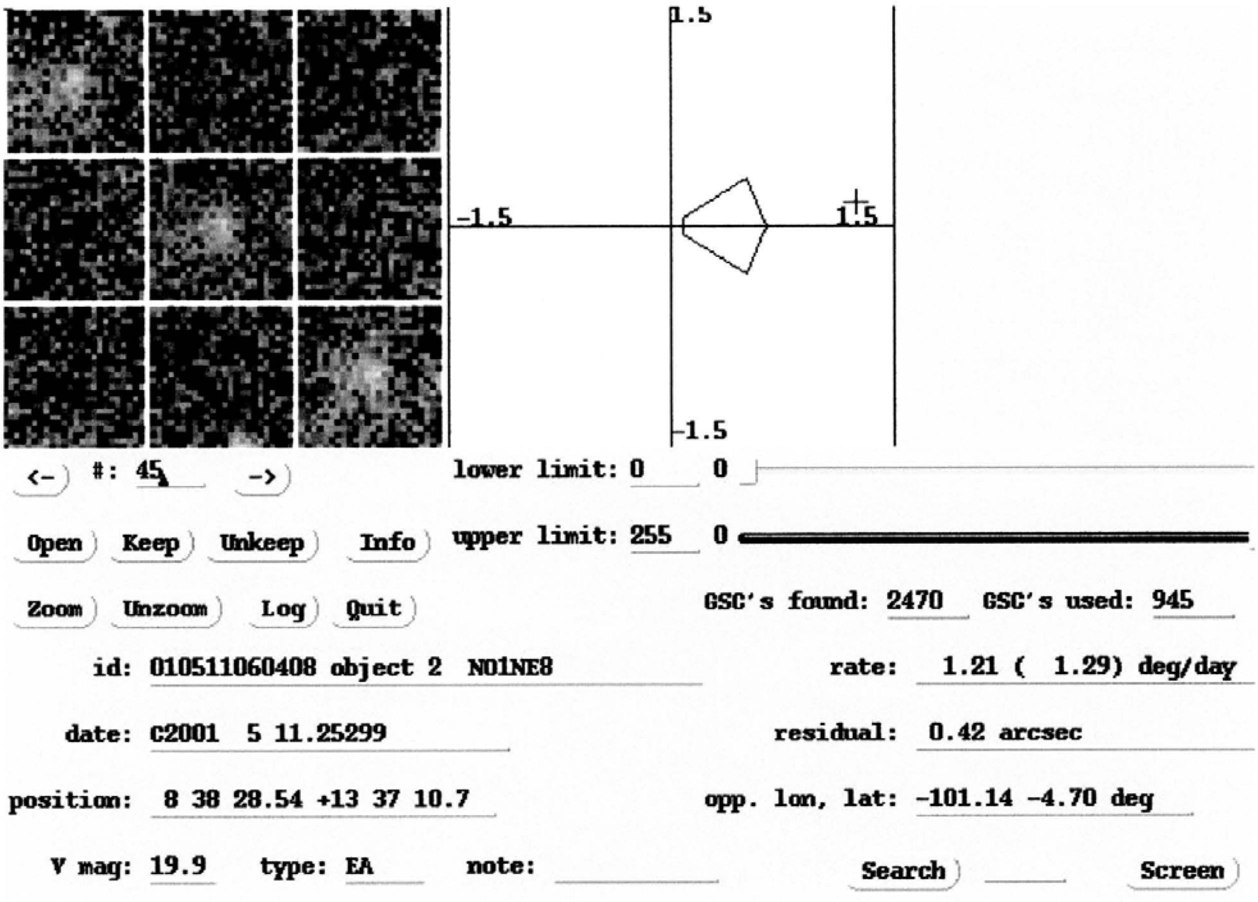

Fig. 5: Comet 2001 J1, discovered 11 May 2001 with NEAT/MSSS, is a faint Earth-crossing Jupiter-Family Comet.

Moving farther into the solar system, the bright Trans-Neptunian Object (TNO) 2000 EB_{173} [7] was recovered in part with NEAT archived data. The discovery of slow-moving objects, TNOs and others, is a still unexploited use of the SkyMorph database.

The SkyMorph project has supported and continues to support other scientists in their research with the database. For example, SkyMorph has been used to discover 5 supernovae. The Supernova Cosmology Project at the Lawrence Berkeley National Laboratory has chosen NEAT data for their nearby and mid-distance supernovae searches and characterization. NEAT/MSSS has provided ~50 candidates for degenerate dwarf binary systems, an elusive but perhaps important gravitational wave sources.

7.1 Physical Studies of MSSS Asteroids

By increasing the number of known near-Earth asteroids, NEAT/MSSS has greatly facilitated physical studies of this important class of solar system objects, especially the very small and fast moving objects which tend to be quickly fade after discovery. Several of the recent close-approaching MSSS asteroids have been imaged by JPL's Planetary Radar team lead by Steve Ostro, including 2000 QW7, 2000 YF29 and 2001 EC16. One of the co-authors (Hicks) [8] maintains an active program of photometric followup of NEOs at the JPL Table Mountain Facility with the emphasis on possible radar target and was able to obtain B-R,V-R, and I-R colors of both 2000 QW7 and 2000 YF29. Observations of 2001 EC16 were unfortunately clouded out. The spectral properties of near-Earth asteroids are diverse, with the colors of 2000 QW7 and 2000 YF29 consistent with a Q-type D-type classification, respectively.

7.2 NEO Size Distribution

The discovery statistics of an automated NEO detection program can be used to constrain size and orbit-dependent trends within the NEO population. Recently Rabinowitz et al. [5] analyzed NEAT data obtained between March 1996 to August 1998, representing approximately 35,000 square degrees of sky, deriving a new estimate on the number of kilometer-sized near-Earth asteroids. They determined that there were 700+/-230 near-Earth asteroids with an absolute magnitude, H, less than 18, approximately half of previous estimates. Such estimates will be significantly refined with the analysis of the more recent and complete NEAT/MSSS data.

8. Summary

JPL has had a long successful collaboration with the AMOS/MSSS, extending back to Dec. 1995 with the NEAT/GEODSS program. The dual use of the NEAT camera as both a discovery/survey instrument as well as satellite detection system serves NASA's goal of detecting NEOs greater than 1-km as well as the Air Force satellite tracking mission. NEAT/MSSS with NEAT/Palomar in recent months has been dominate source of NEAs and comet discoveries.

9. Acknowledgments

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