

# Recent Discoveries and Advances for the Near-Earth Asteroid Tracking Program with the MSSS 1.2 Meter Telescope

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## 1. Abstract

Jet Propulsion Laboratory's (JPL) Near-Earth Asteroid Tracking (NEAT) program has two simultaneously-operating, autonomous search systems on two geographically-separated 1.2-m telescopes; one at the Maui Space Surveillance System (NEAT/MSSS) and the other on the Palomar Observatory's Oschin telescope (NEAT/Palomar). 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 AFRL's 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 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 and have use of the NEAT camera system for high priority satellite observations during bright time (parts of 12 nights each month) [1]. As of September 1, 2003 NEAT/MSSS has discovered 91 NEAs including 21 larger than 1-km, 15 Potentially Hazardous Asteroids (PHAs), 12 comets, and nearly 230,000 asteroid detections.

## 2. NEAT and NASA's Near-Earth Object Program

The objective of Near-Earth Asteroid Tracking (NEAT) Program is to discover Near-Earth Objects (NEOs) and to enable their further characterization. The NEO population consists of Near-Earth Asteroids (NEAs) and comets passing close to Earth. These discoveries are to fulfill the highest priority of NASA's NEO Observation Program which is "to primarily inventory the population of Near-Earth Objects and, secondarily, to characterize a representative sample of them." [2]. To put this into quantifiable terms, *it is to find > 90 % of Near-Earth Asteroids whose diameter is greater than 1 km by 2008.* [3]

NEAT discoveries contribute to three purposes: (1) statistical studies of all asteroid classes, enabling follow-up observations for physical characterizations including light curves, spectroscopy and radar, (2) determining the hazard to earth and (3) identifying candidates for space missions. In summary, the inventory aspect of the NEAT program addresses the question "*What are the population of objects that pass close to earth in the near-term?*" and the characterization, or science, addresses the question "*Is this population stable or are there mechanisms that continually replenish or drain this population which in turn could significantly modify the quantity and spatial distribution of NEOs in the long term?*"

NEAT currently operates with two autonomous search systems on two 1.2-m telescopes: (1) on the Maui Space Surveillance System, NEAT/MSSS, and (2) on the Palomar Observatory Oschin telescope, NEAT/Palomar. This report only details recent results utilizing the NEAT/MSSS telescope. NEAT/MSSS is operated as a partnership between NASA/JPL and the United States Air Force Research Laboratory (AFRL), utilizing AFRL's 1.2-m telescope on the 3000-m summit of Haleakala, Maui. 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 and have use of the NEAT camera system for high priority satellite observations [4].

## 3. History

JPL has collaborated successfully with the Air Force Maui Optical and Supercomputing (AMOS) site since 1993, when they performed follow-up observations of discoveries from Dr. Eleanor Helin's Palomar Planet Crossing Asteroid Survey [5] using their 1.6-meter telescope. With Dr. Helin serving as Principal Investigator, the NEAT project developed a CCD camera and a set of automated detection software for a system that began operating

in late 1995 on the Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) 1-m telescope at Haleakala, Maui. Helin [6] and Pravdo, et al. [7] described the attributes and capabilities of that system. In the period from March 1996 to August 1998, NEAT/GEODSS searched approximately 35,000 square deg of sky and detected 45 NEAs, with 26 larger than 1 km. After the USAF Space Command funded a focal reducer, the NEAT camera was transferred to MSSS in March 2000. Like the GEODSS system before it NEAT/MSSS is autonomous and remotely directed from JPL [8].

NEAT/MSSS achieved its first light in March, 2000. Now, 3.5 years later, it is a mature system and is contributing significantly to discoveries of NEAs and comets. Last year at this conference, we reported that MSSS had discovered 27 NEAs and 6 comets from January to mid-August. We report an additional 22 NEA's and 3 comets through August, 2003. More details of the discoveries of NEAT/MSSS are given in Section 11.

#### **4. 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 2.5-degree field of view needed for a survey instrument. Talent, et al. [8] describes the requirements. The NEAT/MSSS camera is installed at the prime focus and operates under pointing constraints of  $\pm 25$  degrees in declination.

The current NEAT/MSSS camera consists of a 4080 x 4080 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 per sec. The bandpass is about 0.40-0.85  $\mu\text{m}$  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.

#### **5. NEAT 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. 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  $\pm 15$  degrees from the galactic plane and  $\pm 30$  degrees from the Moon. The analysis software generates "patches", which are small 25 pixel sub-images ( $\sim 33$  arcsec per side) centered about candidate moving objects. The patches are returned nightly to JPL to be used in post-processing.

#### **6. Automated Near Real Time Object Detection**

The NEAT asteroid detection algorithm depends on the temporal displacement of the moving object in a field of "fixed stars". Typical temporal separation is 15-20 minutes for each frame and the collection of 3 frames provides a compromise between maximizing sky coverage per night and minimizing failures in the detection process. Failures in the process include missed detections because of such things as changes in seeing in one of the frames or occultations of the asteroid with nearby stars. Failures are also caused by "false detections" due to artifacts in the image such as cosmic ray hits. Failures are minimized by filter steps in the real time data processing stream, as much as practicable, but are often only eliminated in visual inspection in post processing at JPL. To facilitate the latter step a tool, patchview, shown in Fig 4, analyzes the "patches" around the putative discoveries. Upon completion of this step, the astrometry of both the fast moving near-Earth objects and main-belt asteroids, which are based on USNO A2 catalog stars [9], are submitted to the Minor Planet Center (MPC).

#### **7. 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 calibrate system performance by imaging Landolt fields [10] as they transit but the most appropriate way to quantify the detection efficiency is to look at the magnitudes of our NEO discoveries. Fig. 1 plots the discovery magnitudes

and rates of motion of the 91 Near-Earth asteroids and 12 comets found by the MSSS system over the past 3.5 years. The dotted line marks an approximate detection limit under exceptional conditions, with the system capable of going down to  $V=21$  in a 60 sec. exposure for a stationary object or 19.5 for an object moving up to 5 degrees per day. 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  $V=19.7\pm 0.3$  for objects moving 2 degree per day or slower.

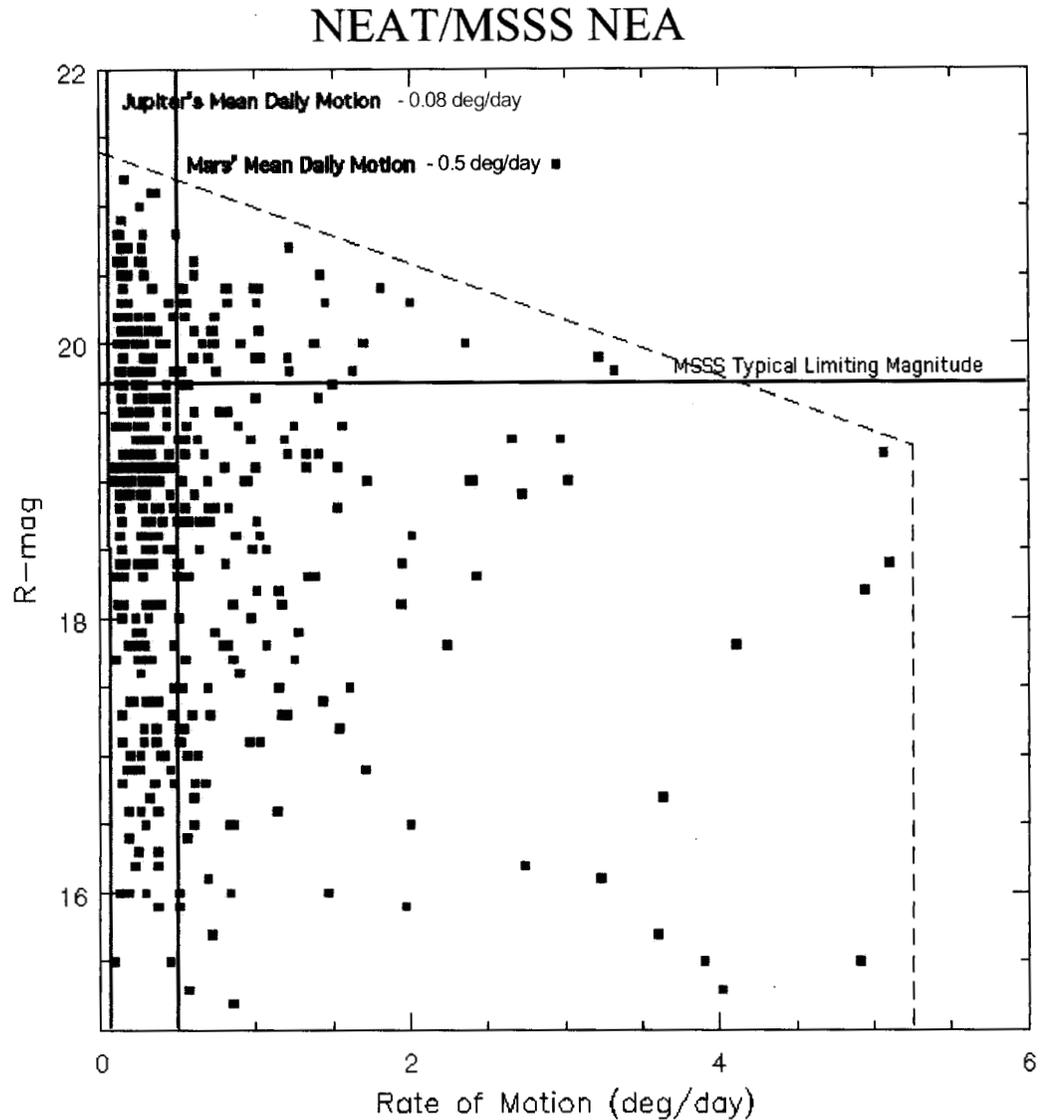


Fig. 1: Visual magnitude vs. rate of motion at the time of detection. The solid curve illustrates the detection limit for NEAT/MSSS under a typical limiting magnitude of 19.7. The dotted sloped line indicates the variation of limiting magnitude with degrees of motion under exceptionally good seeing conditions. The vertical blue line indicates the mean daily motion of Mars.

Fig 1 shows a significant discovery rate of NEOs at main-belt rates by the large number of discoveries between the Mars and Jupiter mean daily motions. There are detection limits imposed by the analysis software, which is sensitive to asteroids moving up to 5.6 degrees per day. Objects also must have a motion greater than 2 pixels between adjacent frames in the triplet, giving rise to a minimum rate of motion of approximately 0.09 degree

per day. A consequence of this is that our analysis software will not flag objects moving beyond the orbit of Jupiter.

NEAT/MSSS has the ability to search approximately 55 degrees per hour with 20 sec exposures which extrapolates to 15,000 degrees per month under ideal conditions. The actual sky coverage is a function of weather and the fraction of the month dedicated to NEO observations but we have maintained a schedule of approximately 10000 degrees per month since the beginning of this year. This arrangement has made NEAT/MSSS the third-most prolific discoverer of NEOs for 2003. [11]

### 8. Further Optimization

An extended baffle, to mitigate stray light and internal reflections from bright off-axis stars in the telescope optics was installed on NEATA/MSSS two years ago. Analysis revealed that the ghosts were not actually from off-axis stars but within the camera electronics. Recently, a fast algorithm was developed to locate and remove the ghosts from the object finding tables. Plans are also underway to secure an improved CCD chip and camera control board. As these improvements are implemented, AFRL will certify the system, as required by SPCMD, for satellite observations. Continuing improvements in the analysis software are being addressed, particularly in the area of post-processing.

### 9. Near-Earth Asteroids

The first asteroid, Ceres, was discovered by G. Piazzi in Palermo, Italy on January 1, 1801. The discovery came as a result of a prediction of the Titius-Bode law that there was a missing planet at approximately 2.8 AU from the sun, or between the orbits of Mars and Jupiter. The Titius-Bode equation,  $R=0.4 + 0.3 * 2^n$ , where R is the radius from the sun in AU and where n is an integer, from 0 upward, was a fairly accurate relationship for predicting the orbits of all the known planets in the 1700's except for n = 4. When Uranus was discovered in 1781, its distance was remarkably close to the value predicted by the equation where n = 7. This caused a systematic search for the planet at n=4 that resulted in the discovery of Ceres.

Tens of thousands of these bodies have now been found inside the orbit of Jupiter, but only about 100 are larger than 100 km. In 1898, the first Near-Earth Asteroid, 433 Eros, was found. As of September 1, 2003, nearly 2500 Near-Earth Asteroids have been detected as shown in Table 1. This table summarizes the discoveries by all observers [12].

Near-Earth Asteroids fall into 3 classes, or families, based on orbital dynamics (ephemerides) considerations: Atens, Apollos and Amors [13]. These names are approximately related to the first named body that defines the ephemerides. Fig. 3 shows a plot of the orbital characteristics of these 3 families and Table 1 shows the numbers discovered for each of these classes vs. time. As can be seen, an NEA is an asteroid that comes within 0.3 AU of earth's orbit plane. However, for the purpose of the NASA NEO program, the NEAs of interest are those having a diameter greater than 1 km. In Table 1 those objects are shown under the heading of NEA+18. If the asteroid's orbit passes within a 0.05 AU torus around earth's orbit, and has a diameter of 100 meters or more, then that NEA is called a Potentially Hazardous Asteroid (PHA). We know of 523 of these objects. Of those 523, 126 have a diameter greater than 1 km as shown under column PHA+18.

Table 1. Near Earth Object Statistics for Selected Years [12]

Date	NEC	Aten	Apollo	Amor	PHA+18	PHA	NEA+18	NEA	NEO
2003-09-01	49	187	1225	989	126	523	663	2402	2451
2002-09-01	46	157	1002	824	121	457	612	1983	2029
2001-08-01	43	111	700	601	97	332	495	1412	1455
1998-01-01	38	27	233	186	49	108	221	446	484
1970-01-01	29	1	13	14	8	11	24	28	57
1900-01-01	17	0	0	1	0	0	1	1	18

NEC = Near Earth Comets

PHA = Potentially Hazardous Asteroid

PHA+18 = Potentially Hazardous Asteroid > 1 km

NEA+18 = Near Earth Asteroid > 1 km

NEO = Total of all Near Earth Objects

# Near-Earth Asteroid Families

phi = 0.0  
theta = 0.0

Sep 1, 2002

### Aten Family:

$a < 1.0$  AU  
 $q > 0.983$  AU  
187 Known  
1st: 2026 Aten  
(1976AA) by E.F.Helin

### Apollo Family

$a > 1.0$  AU  
 $q < 1.017$  AU  
1225 Known  
1st: 1566 Icarus,  
(1949MA) by W. Baade

### Amor Family

$a > 1.0$  AU  
 $1.017 < q < 1.3$  AU  
989 Known  
1st: 433 Eros  
(1898DQ) by G. Witt

$a$  = semiMajor axis  
 $q$  = Perihelion Distance

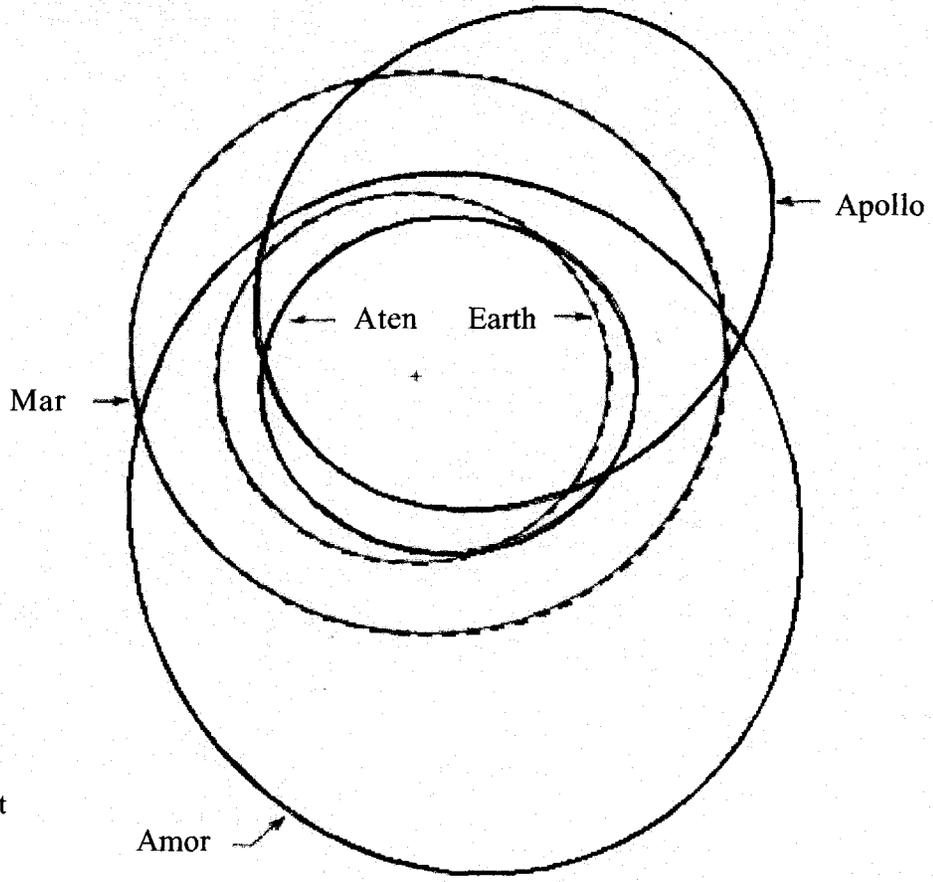


Fig 3. Orbit plots of Near-Earth Asteroid Families

## 10. NEO Population 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., [14] analyzed NEAT data obtained between March, 1996 to August, 1998. This represents approximately 35,000 square degrees of sky. He derived a new estimate of the number of kilometer-sized near-Earth asteroids to be  $700 \pm 230$ . This was significantly less than other estimates [15][16]. The sum total now discovered is 663 with 5 years left on the program. Such estimates will be significantly refined in the near future with the analysis of the more recent and complete NEAT/MSSS data.

## 11. Discussion of Recent Discoveries

Cumulative results from the start of NEAT/MSSS in March, 2000 through August, 2003 indicate 91 NEAs, with 21 larger than 1 km in diameter and 15 classified as potentially hazardous asteroids (PHAs). Total NEA detections over this time period, which include previously discovered objects, amounts to 242 with 142 larger than 1 km. The following discussion is a review of some of the more interesting NEO discoveries made by NEAT/MSSS and illustrate the diversity of objects found by the search program.

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. A small number of NEOs cross deeply into the inner solar system (e.g., 3200 Phaethon). On April 30 2001, NEAT discovered 2000 HD24, a 1-km Apollo asteroid with a Venus-crossing orbit.

NEAT/MSSS has discovered 21 potentially hazardous asteroids. At least 3 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.

Over 229,707 asteroid detections have been submitted to the MPC by NEAT/MSSS since March, 2000. More interesting are the nine new NEAT/MSSS comets, as listed in Table 2. Five of these objects are periodic comets, with Jupiter-crossing orbits, which bring them into the inner solar system. Four are non-periodic comets with three (C/2001 B2, C/2001 O2 and C2003 J1) having perihelion points outside the orbit of Jupiter. These latter objects are most likely 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 CO, CO<sub>2</sub>, and/or N<sub>2</sub>.

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.

NEAT/MSSS has discovered 12 comets during its operational life. Table 2 summarizes all of those discovered by NEAT/MSSS. It is important to stress that most of our comets were discovered by visual examination of the main-belt asteroids. Because we visually inspect each detection that the software flags, we have been able to detect comets. This visual verification is quite time consuming but it is presently the best way to distinguish from the asteroids discovered by the automated detection algorithms. The tool by which this is done, patchview, is illustrated for comet 2002 V1 in Fig 3. The images in the nine "patches" illustrate how the comet appears to the observer screening the detections. Note that the middle top image shows a nice point source in addition to the comet. This enhances the detection of the coma.

Within a few days after discovery it was predicted that comet 2002 V1 would make a close approach to the sun in mid-February, 2003. Fig 4 shows the orbit that was predicted shortly after discovery. As the orbit was refined, it showed that it would pass the sun by only 0.1 AU on Feb 17<sup>th</sup>. A request was made to ensure that SOHO project would be observing at the time of closest passage. A montage of 5 images were taken from Feb 17-19. The one taken at 5:54 UT on February is shown in Fig 5 near its closest approach. Serendipitously, at about that time, the sun emitted a Coronal Mass Ejection. See the story in [18].

During the year NEAT.MSSS found a fairly bright object (16.7 visual magnitude) on January 27, 2003 that proved to be the third stage of the Apollo 12 mission to the moon, launched on Nov 14, 1969. It is called J002E3 and has been occasionally been re-observed over the years. See further stories about it in [19].

NEAT/MSSS also detected 2003 GW, a rather large 2 km class Apollo asteroid on May 15, 2003. It was discovered as a faint 20.3 magnitude object moving at 0.8 degrees per day. It does not come within 0.05 AU of the earth so it is not potentially hazardous, but might serve as a NASA mission candidate.

## 12. 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 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) [17] maintains an active program of photometric follow-up of NEOs at the JPL Table Mountain Observatory with the emphasis on possible radar targets. For example, he has obtained B-R, V-R, and I-R colors of both 2000 QW7 and 2000 YF29. The spectral properties of near-Earth asteroids are diverse, with the colors of 2000 QW7 and 2000 YF29 consistent with a Q-type and D-type classifications, respectively.

### 13. Summary

JPL has had a long successful collaboration with the AMOS/MSSS, extending back to 1993 for follow-up operations with the AMOS 1.6-meter telescope and December, 1995 for 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, along with NEAT/Palomar, are the second most prolific discoverer of Near-Earth Objects.

### 14. Acknowledgments

Observations made at the Maui Space Surveillance System (MSSS), Maui, Hawaii, USA are the result of collaboration between NASA/JPL/Caltech and Detachment 15 of the U. S. Air Force Research Laboratory, which owns and operates the MSSS. We wish to acknowledge and thank Paul Kervin, John Africano, Paul Sydney, Riki Maeda, and other staff without which NEAT/MSSS would not exist, as well as the generous support by the Air Force. The research described in this paper, was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Table 2: COMETS DISCOVERED BY NEAT/MSSS MARCH 2000 - 31 AUGUST 2003

NEAT/MSSS	Discovery Date	V Motion deg/day	Mag	a AU	e	i deg	q AU	MPC/Ref.
2001								
C/2001 B2 (NEAT)	1/24	0.22	15.5	---	1.00	150.60	5.306	42665
P/2001 BB50 (LINEAR-NEAT)	3/20	0.13	18.4	5.68	0.59	10.62	2.347	42665
P/2001 F1 (NEAT)	3/24*	0.14	19.7	6.45	0.36	19.09	4.153	42856
P/2001 J1 (NEAT)	5/11	1.21	19.9	3.88	0.76	10.16	0.937	42856
P/2001 K1 (NEAT)	5/20*	0.21	18.7	3.85	0.36	16.91	2.469	42856
C/2001 O2 (NEAT)	7/25*	0.14	19.3	---	1.00	101.12	6.818	43161
2002								
C/2002 K1 (NEAT)	5/16	0.32	19.6	----	1.00	88.22	3.243	46762
C/2002 K4 (NEAT)	5/27	0.41	18.5	----	1.00	95.94	2.742	46620
P/2002 O5 (NEAT)	7/30	1.36	17.2	2.87	0.59	20.3	1.173	47049
C/2002 V1 (NEAT)	11/6	0.45	17.3	----	1.00	81.71	0.099	48096
2003								
C/2003 H3 (NEAT)	4/30	0.30	17.2	----	1.00	42.81	2.901	49277
C/2003 J1 (NEAT)	5/13	0.12	19.4	----	0.99	98.32	5.125	49277

\* Discovered within Main-belt data.

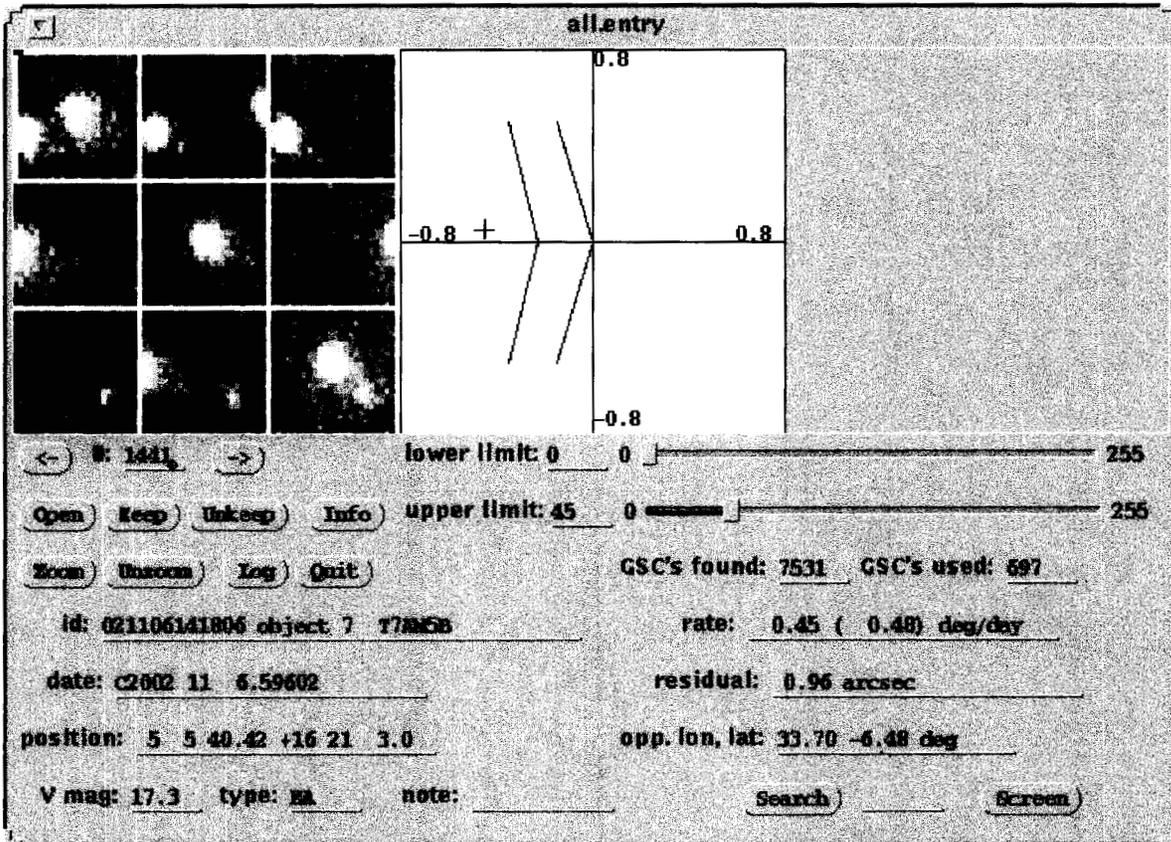


Fig 3. The patchview panel for Comet 2002 V1 discovered Nov 6, 2002



Fig. 4: Comet 2002 V1 NEAT, in its orbit on the night of discovery showing a predicted close passage by the sun on Feb 18, 2003. Orbit can be generated at: <http://neo.jpl.nasa.gov/orbits/>.

SOHO Coronagraph image  
February 18, 2003 @ 0554 UT

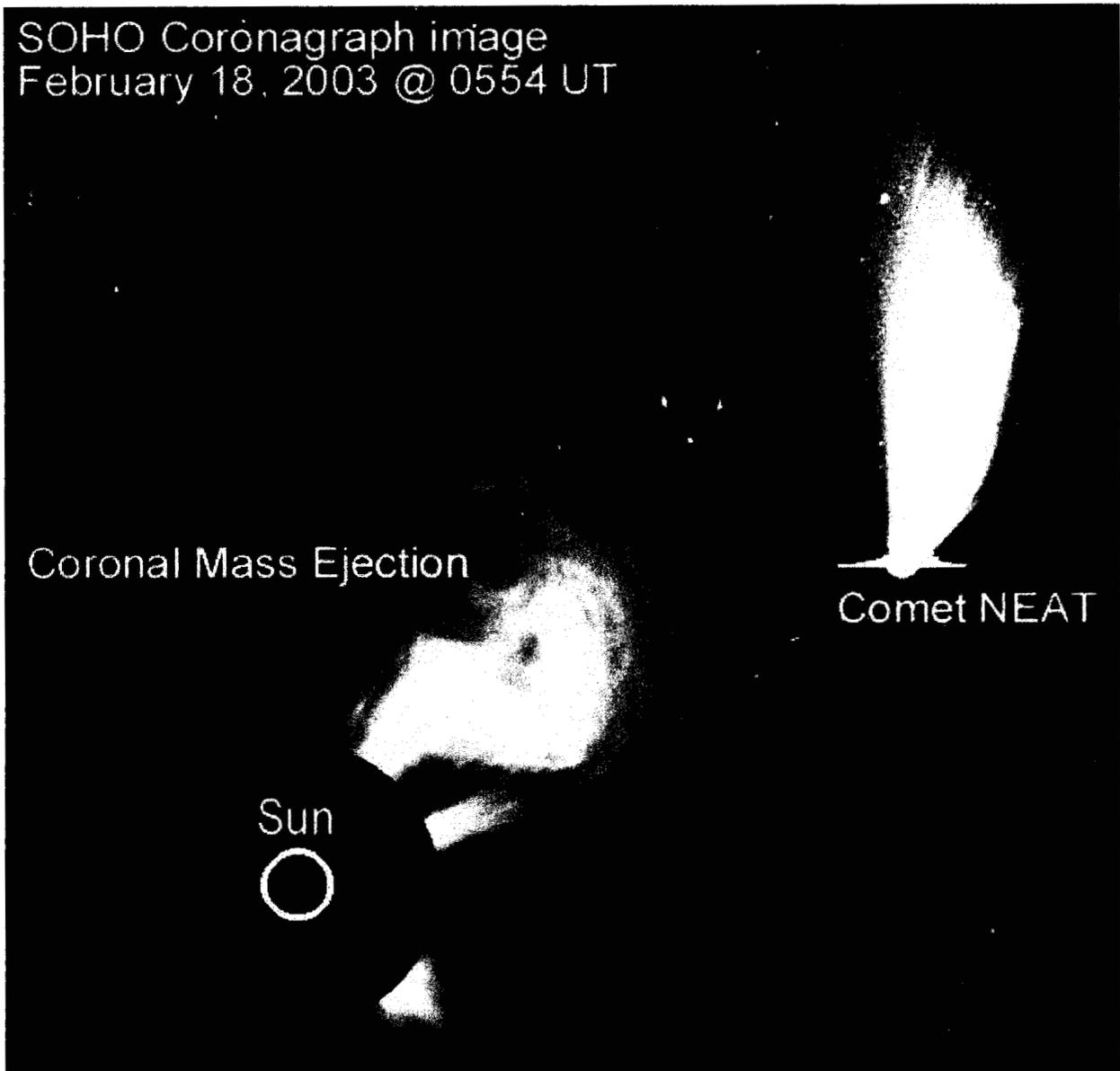


Fig. 5: Comet 2002 V1 NEAT, from the SOHO spacecraft at its closest approach (0.099 AU) from the sun on Feb 18, 2003. This picture shows the sun emitting a Coronal Mass Ejection in the general direction of the comet. This picture and others can be found at <http://soho.nascom.nasa.gov/hotshots>.

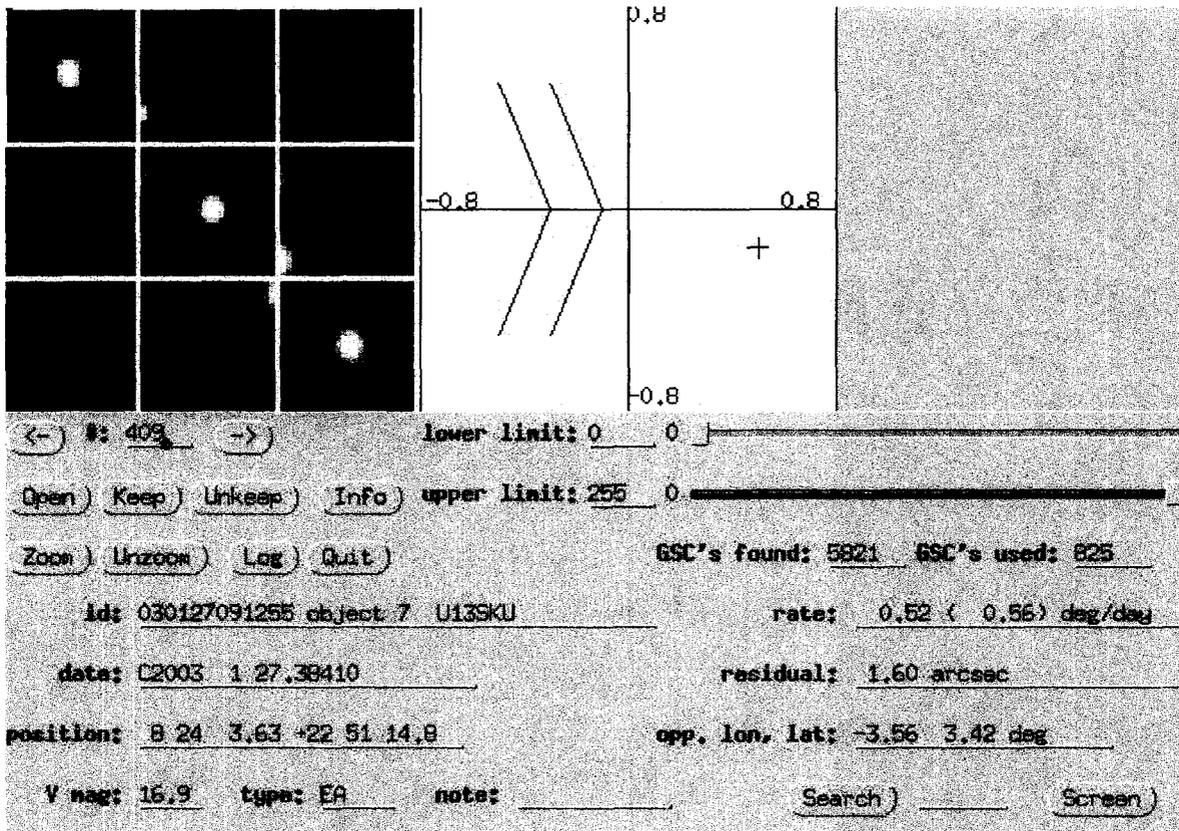


Fig. 6: The Apollo 12/Saturn third stage rocket captured as a 17<sup>th</sup> magnitude object on January 27, 2003.

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