OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** long-term⋆ **Proposal ID:** L84

The Catalina Sky Survey for Near-Earth Objects

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Abstract of Scientific Justification

We propose to continue our long-term program of discovering near-Earth asteroids and comets (NEOs) to fainter magnitude limits. Using the Mt. Lemmon 1.5-m prime focus camera (PFC) for 24 of the darkest nights of a lunation yields a significant extension of the volume of space surveyed for NEOs. In the past, new objects too faint for the usual astrometric follow-up by others were observed with the 1.5-m, but we will be using the refurbished 1-m telescope for faint follow-up that will permit increased survey coverage. The Catalina Sky Survey is a leading program in the congressionally-mandated NASA effort to discover and catalog all NEOs larger than 140 meters, and the 1.5-m is one of the most productive telescope currently used in the search, with discovery credit for 33 percent of all new NEOs discovered in 2013, and 25 percent so far in 2014. Notable discoveries so far in 2014 include near-Earth asteroid 2014 AA, which was discovered 24 hours prior to Earth impact over the Atlantic Ocean, only the second time such an event has been recorded (the first was 2008 TC3, also discovered at the 60”). The CSS is currently building a new large-format camera for the 1.5-m, which will increase the FOV from 1.2 to 5.0 square degrees. The optics are complete, the 10k x 10k detector has finally been delivered to the camera manufacturer for packaging and integration, and the opto-mechanical assembly is currently being fabricated by the Steward Observatory machine shop. On-sky commissioning is expected to begin by the end of the year.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	60”	PF	PFC	*		24	drk.gry	1/7-1/30		no	no
2	60”	PF	PFC	*		24	drk.gry	2/6-3/1		no	no
3	60”	PF	PFC	*		24	drk.gry	3/8-3/31		no	no
4	60”	PF	PFC	*		24	drk.gry	4/7-4/30		no	no
5	60”	PF	PFC	*		24	drk.gry	5/6-5/29		no	no
6	60”	PF	PFC	*		24	drk.gry	6/5-6/28		no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We are requesting 24 nights per lunation, centered on new moon. As usual, we are willing to accomodate Astronomy Camp dates.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	New NEOs	00:00:00.0	+00:00:00.0	

Approval for Instrument Use from PI: ______________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Why are Near Earth Objects important? The identification of the iridium anomaly at the Cretaceous-Tertiary boundary (Alvarez *et al.*, 1980, *Science*, 208, p. 1095) and associated Chicxulub impact crater (Hildebrand *et al.*, 1991, *Geology*, 19, p. 867) and possibly the Australian Bedout crater, (Becker *et al.*, 2004, *Science*, 306, p. 609) associated with the Permian-Triassic "great dying", strongly suggests that impacts by minor planets play an important role in the evolution of terrestrial life. Such impacts are a natural result of the accretionary process that formed the Earth and planets and continue today as demonstrated by many observed impacts at Jupiter, including D/Shoemaker-Levy 9. Although the collision frequency is much lower than in the past, the question is not whether there will be future impacts, but when. Clearly, any efforts to mitigate an impact is contingent on a complete understanding of orbital geometry, and this begins with discovery.

The Catalina Sky Survey. NASA's NEO Observations Program (NEOO) is a result of a 1998 congressional directive to conduct a program to identify at least 90 percent of bodies 1 km. or larger. Such impacts would have global consequences. (Morrison, 1992, *Spaceguard Survey Workshop Proceedings*). In 2005, the mandate was extended to search for NEOs down to 140 meters in diameter. The NEOO program supports two major surveys at the present time, including the Catalina Sky Survey, which is made up of the 0.7-m Catalina Schmidt (CSS, Minor Planet Center code 703), and the Mt. Lemmon 1.5-m (MLS, MPC code G96). The other major search effort is conducted with the Pan-STARRS 1 telescope, managed through the University of Hawaii's Institute for Astronomy. The practical result of this effort is the identification of *potentially hazardous objects*, or *PHAs*, a NEO subclass with a minimum orbital intersect distance with the Earth's orbit less than 0.05 AU and diameters larger than 140 meters. Such objects are particularly susceptible to future perturbations into Earth-intersecting orbits and the subject of the newer NASA congressional mandate (the 2005 Brown law).

Quantifying the Risk. Assessing the threat posed by a PHA requires predictions of its impact energy, which is determined by the object's mass and velocity. These characteristics can be obtained through three kinds of observations:

1. Discovery and follow-up astrometry (from discovery epoch, data mining of pre-discovery images, and arc extension from subsequent oppositions) to quantify impact probability and impact velocity.
2. Accurate time series photometry to determine size, shape, and spin vector. (In addition, density can be constrained using photometry of mutual events by secondary satellites in binary systems.)
3. Spectrophotometry to determine composition and inferred albedo from which one can estimate density.

For NEAs, these basic properties provide fundamental data that constrain models of origin, collisional history, and dynamical evolution from the main belt to the vicinity of the Earth. Similarly for comets, brightness data as a function of heliocentric distance provides information on formation environment and compositional evolution as volatiles are depleted by solar heating. Together, this information may also provide evidence that some asteroids are, in fact, extinct comets.

Physical Characterization. PHAs are usually identified within 48 hours of discovery, but observing geometry (proximity to the sun, speed of recession from Earth, etc.) can severely limit the observing window. It is essential to obtain physical observations close to the discovery epoch when objects are usually at their brightest for ground-based telescopes. Responding to such observing opportunities requires access to larger telescopes, such as the 1.5-m Mt. Lemmon facility, on short notice. This is a capability that characterization-only programs do not have, but we do.

Many NEOs come within range of radar time-delay/doppler observations that resolve shape, surface topography, and the satellites of binary systems. Crucial prerequisites to radar observations include precise astrometry to aid the targeting of narrow-beam radar systems and good-quality rotation periods to correctly interpret delay-Doppler data. Observations from ground-based systems are the predominate source for such information.

Rapid response follow up and physical observations with the 1.5-m has provided, and will continue to provide, an important capability for the NASA NEOO effort. Nevertheless, survey is the most productive part of our 1.5-m program, and in 2015, we will be transitioning all but the most difficult followup and characterization duties to a newly-refurbished 1-m telescope on Mt. Lemmon. Wider-field instruments, like the Catalina Schmidt telescope, do not have sufficient aperture for faint object follow up, and are more valuable if their survey cadences are not interrupted for such tasks.

Spinoff Science. In addition to addressing the needs of NASA's NEO search program, the participating surveys have provided an improved understanding of the distribution and sizes of a number of asteroid families. Today, over five million observations of minor planets are sent to the Minor Planet Center each year, the large majority of them coming from the Catalina and Pan-STARRS surveys. These observations have greatly increased the size and quality of the inventory of minor planets, including NEOs, and have allowed detailed studies of solar system evolution and dynamics. Examples of representative work in this area include studies of Jupiter migration (Franklin, *et al.*, *AJ*, 128, p. 1391); the dynamical evolution of asteroids by Yarkovsky thermal effects (Nesvorny and Bottke, *Icarus*, 170, p. 324); analysis of transient co-orbital motion (Brasser, *et al.*, *Icarus*, 171, p. 102); distribution of Trojans (Pal and Suli, *PADEU*, 14, p. 285); and others.

Of the 4 active NEO survey telescopes in operation, only the Mt. Lemmon 1.5-m telescope and Pan-STARRS 1 reach practical limiting magnitudes fainter V$\sim$21.0. The number of asteroids detected per square degree with the 1.5-m is nearly an order of magnitude greater than our 0.7-m Schmidt camera. We believe that in addition to the program of NEO survey, follow-up, and physical characterization studies proposed here, that our incidental observations will help to further improve the understanding of the histories and dynamics of minor planets at fainter apparent magnitudes.

Finally, since late 2007, we have collaborated with the Center for Advanced Computing Research at Caltech to use data from all three of our telescopes to discover a variety of stationary transients as the Catalina Real-time Transient Survey (CRTS). Notification is broadcast to the global astronomical community through the *VOevent* mechanism, and now an iPhone app written by the LSST group. Our collaboration has resulted in numerous Astronomical Telegrams and the discovery of over 8000 unique optical transients (Drake *et al.*, 2008, *BAAS 14, no.1*470.07, 421). About 1800 of these were supernovae, among them SN 2007fz, an extremely energetic SN. Additionally, there were 1000+ CVs, 2000+ AGN, and 300+ blazars. CRTS has recently published a catalog of 40 billion measurements of 500 million sources derived from the CSS data stream (http://nesssi.cacr.caltech.edu/DataRelease/).

Astronomy Camp. We provide support for the PFC when used by the adult and advanced-teen Astronomy Camps. As educational outreach, the capability of the camera and software provides a valuable tool to teach basic techniques in observational astronomy and allows campers to experience discovery firsthand. Astronomy Camp has been credited with the discovery of several new NEOs and main-belt asteroids. We provide an observer and checkout of camp staff as well as final verification of objects before submitting them to the MPC with Camp getting discovery credit. We also have a productive relationship with the Mt. Lemmon Sky Center, providing tours and talks about the asteroid survey work being conducted from Mt. Lemmon.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

NASA Investment. In response to the need for access to larger aperture and rapid response to obtain physical observations of NEOs, significant upgrades to the Mt. Lemmon 1.5-m have been funded by the NASA NEOO Program. New servo systems and a declination gear has facilitated the use of the UAO-standard PC/TCS control system that interfaces with a new prime focus camera control system. The cryogenically cooled prime focus camera contains a thinned, 2-channel 4k x 4K ImagerLabs CCD. A 3-element field corrector provides a 1.5 degree circular field that produces 1 arcsec pixels and a 1.2 square degree field at f/2.0. Thirty second unfiltered exposures record stars to V$\simeq$21.5 with S/N$\simeq$3. Elements of the experiment are astrometry for orbit determination (by the Minor Planet Center) and photometry to determine size, shape, spin state, and composition.

We have also upgraded, with NASA and U of A funding, the Internet link to both Mt. Bigelow and Mt. Lemmon. This has increased bandwidth by a factor of 10 or more, to 75 MBps, allowing us to provide half of our network capacity to the broader Steward community of users, including the 61-in telescope and the summit facilities. We have recently boosted the bandwidth even further by upgrading the radios, in anticipation of larger data rates from upgraded cameras.

As part of NASA's continued funding of our program to 2015, we will build a 10.5K x 10.5K CCD camera and reducing optics to increase our field by 4 times. Despite delays in the delivery of a science-grade detector to the camera manufacturer, we hope to begin commissioning of the new camera by late 2014 / early 2015.

Astrometry. Networked computers for acquisition, control, reduction, moving object detection and archiving are used to automate the task of sequencing the telescope and camera, flat fielding the images, extracting objects above a specified noise threshold, solving for and converting to standard equatorial coordinates, and identifying objects with consistent motion among four visits to a field. Twenty two square degrees can be surveyed in one hour. At the conclusion of the fourth visit, the software flags moving objects which are validated by visually blinking the images, and the astrometric positions (accuracy validated by the MPC to $\sim$0.1-0.2 arcsec using the UCAC4 catalog) are written to a file in a format compliant for reporting to the Minor Planet Center. Suspected new NEOs can be sent in immediately and flagged for follow up, while all other incidental astrometry of known objects are sent in at the end of the night. The survey mode is also used for follow up and second return recovery observations. With the fainter limit of the 1.5-m, we find an order of magnitude increase in the moving object density over the wide field 0.7 m Catalina Schmidt, most of which are fainter (more distant or smaller) objects.

Photometry. Background-subtracted aperture photometry is performed on all objects in the image above a specified noise threshold. Rotational light curves can be obtained for extended periods utilizing field stars to correct for variable extinction and to exclude measurements confused by nearby stars. For moving objects, the one-degree field has distinct advantages over the usual smaller-field systems by being able to utilize the same field reference standards for several hours. Rotational light curves observed over a range of observing geometries (especially those passing close to the earth) provides the means of measuring a range of cross sections from which the shape, spin axis orientation, and possible binary nature can be determined. We will attempt to observe light curves of several asteroids for which radar data exists but cannot be interpreted until a period is determined.

We continue to improve the photometric accuracy our 1.5-m observations. The astrometric reference grid is also used for calibrating the photometric scale on a frame-by-frame basis using a subset of solar-like (G0-G5) stars defined by the 2MASS survey. We have installed a new scroll shutter that produces better flat fields with correspondingly better photometry. We routinely obtain absolute instrumental precision of 5 percent to V$\simeq$18.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This is a long-term project mandated by congress for the period 1998-2016, and now extended by Congress and budgeted by NASA through 2016 to discover and catalog all NEOs larger than 140m. We are now only one of two operational surveys being supported by the NEOO Program. Together with the CSS 0.7-m Schmidt, the 1.5-m has been a key part of the most successful NEO discovery program for nearly a decade. Success of this program is directly related to the amount of time on the sky and coverage obtained. The requested 24 nights per lunation is constrained by the number of observers on the CSS team. We started using the 1.5-m in late 2004, and are currently funded through mid-2015. Further funding has been requested to continue CSS operations through mid-2018.

Previous Use of Steward Facilities *List* ***all*** *allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command).* ***(up to one page)***

This is a continuation of a long term observing program begun in 2004. In 2013, 345 new NEOs were discovered with the Mt. Lemmon 1.5-m of which 20 are PHAs, 87 of which are larger than 140-m and 2 of which are larger than 1 km. The first NEO discovered in 2014 was found by the Mt. Lemmon 1.5-m (named 2014 AA), and was an exceptional discovery. Approximately 22 hours after discovery, the 3m object impacted the Earth over the Atlantic Ocean between Central America and West Africa. This is only the second time an asteroid has been detected in space prior to Earth impact.

Since we are discovering objects as faint as V$\simeq$22.0, we have had to perform our own follow up. Usually, this is first done on the discovery night (if there is enough time before twilight), followed by observations the next night weather permitting. We also routinely follow up all of our CSS (703) objects and the fainter objects from other surveys on the MPC NEO Confirmation Page. Mt. Lemmon positions are cited on a large percentage of Minor Planet Electronic Circulars when the objects are fainter than V$\simeq$20.

NEO discovery statistics from 2013, tabulated by the CfA Minor Planet Center, can be found in Table 1.

Survey	**PHAs**	**NEOS ($\gtrsim$140-m)**
PanSTARRS	32	358 (163)
MLS	20	345 (87)
CSS	17	235 (88)

Table 1: NEO Discovery Statistics for the major surveys in 2013

Each good night, we typically send in 10,000 - 20,000 astrometric positions of known and newly discovered asteroids to the CfA Minor Planet Center that are published in *Minor Planet Electronic Circulars*. Over 20 million astrometric observations are credited to the Mt. Lemmon 1.5-m since late 2004, along with over 30,000 numbered minor planet discoveries and many times that number of provisional discoveries.

On 2008 Oct. 8, we made the first discovery of a NEO that was predicted to impact the Earth before the fact with the Mt. Lemmon 1.5-m. The 3 m diameter 2008 TC3 mostly burned up in the earth's atmosphere over northern Sudan, but not before 586 astrometric positions, detailed lightcurve and a spectrum was obtained prior to entering the earth's shadow. A team from the University of Khartoum and NASA Ames recovered pieces of 2008 TC3 along the entry path. The Almahata Sitta meteorite turned out to be a very rare carbon-rich achondrite ureilite whose spectrum matched the one taken while in space (Jenniskens, *et al.*, *Nature* 458, p. 485j).

Other work from the 1.5-m includes measuring the YORP effect on the asteroid Itokawa (Durech, *et al.*, *A&A* 488, p. 345), and a statistical study of historical discovery data to quantify the number of objects interior to the Earth's orbit (Zavodny, *et al.*, *Icarus*, 198, 284Z).

Refereed papers published about CSS discoveries include:

Gal-Yam, A. *et al. Nature* 462, 624-627.

Drake, A. J., *et al. The Astrophysical Journal* 696, 870-884.

Drake, A. J.; Beshore, E.; Catelan, M.; Djorgovski, S. G.; Graham, M. J.; Kleinman, S. J.; Larson, S.; Mahabal, A.; Williams, R., *arXiv:1009.3048v1 [astro-ph.EP]*

A.J. Drake, S.G. Djorgovski, J.L. Prieto, A. Mahabal, D. Balam, R. Williams, M.J. Graham, M. Catelan, E. Beshore, S. Larson. *The Astrophysical Journal Letters*, 718, L127

Papers using CRTS data are too numerous to mention here, but are summarized at *http://crts.caltech.edu/pub.html* Many ATELS about CRTS discoveries can be viewed at *http://www.astronomerstelegram.org/*