OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Recovery of Potentially Hazardous Asteroids

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CoI(s): Robert Crawford (Rincon Ranch Observatory), Mark Trueblood (Winer Observatory), David Bell (NOAO)

Abstract of Scientific Justification

We will search for selected Potentially Hazardous Asteroids (PHAs) whose positions on the sky have become very uncertain because they have not been observed in months to years. When the targets are located, astrometric observations will be taken over spans of three days and used to demonstrate their successful recovery. We will give priority to the subset of PHAs known as Virtual Impactors (VIs) because they have the potential to impact Earth this century. We will create an observational arc of one orbital period from discovery (or more). The result is greatly improved knowledge of the VI and PHA orbits and, for VIs, a greatly improved assessment of the risk of Earth impact this century. The recovery of a VI can remove it from the list of potential Earth Impactors. When conditions are favorable, we will attempt the recovery of VIs classified by NEODyS as "lost."

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	90"	PF	90Prime			3	dark	Jan–Jan	Jan–May	no	no
2	90"	PF	90Prime			3	dark	Mar–Mar	Feb–Jun	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: PI is not available Feb 5, Mar 14–15, or Apr 24–27. Co-Is are not available Feb 3 and Apr 17–24. Request that Run 1 and Run 2 be scheduled at least one lunation apart (near new moon in Jan and Mar, per Target List) to provide the maximum number of targets. Request no moon for at least half of each night.

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.

Targets depend on scheduled run dates. Examples are given below for our requested dates.
RA/Dec for moving targets depend on date/time observed.

Run 1 Dates Jan 16-24	Type,	Mag,	90P tiles on sky
2011 BT59	Lost VI,	V=22.8,	Up to 30 tiles
2014 MG68	VI arc ext.,	V=22.6,	7 tiles

Run 2 Dates Mar 16-22	Type,	Mag,	90P tiles on sky
2011 YV62	VI recovery,	V=24.1,	1 tile
2014 MG68	VI arc ext.,	V=23.8,	5 tiles

15-25 PHA targets will be available on any 2015A run dates with suitable lunar phase

Note: Based on NEOs discovered through August 2014. Additional VI and PHA targets will become available as a result of subsequent new discoveries.

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

The proposed work will recover high priority VIs and PHAs that have not been observed in several months to a year or more. Recovery is the final step in the observing process to fulfill the 2005 Congressional mandate to discover and assess 90 percent of all Near Earth Objects (NEOs) 140 meters in diameter or greater by 2020. The process begins with discovery and confirmation observations by others; this adds new objects to the known NEO population and permits an initial classification of some as VIs or PHAs. Arc extension observations during the remainder of the discovery apparition improve knowledge of the orbits (useful for later recovery) and can refine the initial risk classifications. The payoff comes when VIs and PHAs are recovered during a subsequent apparition. Recovery to create an observational arc of one orbital period (or longer) permits the size of the orbit and the object's location in the orbit to be much better determined, leading to a greatly improved impact risk assessment.

In past work using the KPNO 2.1-m telescope, this team recovered the VIs 2011 AX22 and 2011 BT15 (at the time, the object with the fifth highest Palermo Scale value; the Palermo Scale is a logarithmic estimate of the risk exceeding an established background) and the PHA 2008 AX1. Both 2011 AX22 and 2011 BT15 were removed from the list of virtual impactors thereby reducing the assessed risk of future Earth impact, while 2008 AX1 was confirmed as a PHA. We expect comparable results from the recovery of VIs and PHAs using the Bok Telescope.

Our targets are selected through a systematic review of the VI and PHA populations to identify recovery candidates that are observable with a given telescope and imager at a point in time. We prioritize candidates as follows: first, any VI that has not been observed in some time (recovery can remove it from the list of potential Impactors); and second, PHAs that have accumulated substantial ephemeris uncertainty (which is when the orbits can be improved the most).

Semester 2015A has only two VI recovery opportunities (2015B will have a total of six). However, some 15 to 25 PHA recovery targets will be available on any given night during 2015A. As a result, we will gladly accept any dates within the semester that meet the lunar phase requirements (to ensure we are able to detect these faint objects). We are requesting two runs of three consecutive nights each, with the runs separated by at least one lunation (preferably two) in order to have the greatest diversity among targets. Per the established practice of the Minor Planet Center, a successful recovery is demonstrated by observing the target on two successive nights. We are requesting runs of three nights to permit the recovery of several-to-many objects, some of which will require a significant portion of a night to detect.

Our highest priority target for Run 1 is 2011 BT59, which is observable using the Bok telescope only near new moon in January 2015. This is a relatively large VI, H = 21.3 or 190–420 m in diameter (depending on the albedo of the object) discovered by Pan-STARRS in January 2011 that is projected to make close approaches to Earth in 2041, 2052, and 2091. The nominal approach distance in 2052 and 2091 is less than one Earth radius (implying an impact), but the distance is very uncertain because the object is not well localized in its orbit. The object is now classified as lost because the ephemeris uncertainty has grown to be large compared to a conventional field of view (FOV).

At new moon in January 2015, the usual linear treatment of ephemeris errors indicates that the two-sigma uncertainty for 2011 BT59 is an ellipse 22.5 degrees long and <2 arcminutes wide on the sky. With 90Prime's one degree FOV, some 25 to 30 tiles must be searched to find it with 95% probability. This is a large job, but it is feasible in a 3-night run (with good weather) because of the wide FOV. However, a more sophisticated "semi-linear" treatment (Milani, 1999) on NEODyS shows that this 30-tile area is merely a "sweet spot" along a much longer line of variations (LOV) and the object may not even be in the sky that night if it is on a different orbit. Although we have no guarantee of finding it, the recovery effort must begin with a search of the "sweet spot". The payoff from a successful recovery is also large – ranging anywhere from removing 2011 BT59 as a virtual impactor to confirming a likely impact – and is certain to greatly improve the current assessment of its impact risk. We are investigating the ephemeris probability densities on the sky as they translate from the probability grid in orbital element space that defines the LOV to guide our search pattern.

The January 2015 lunation is the last remaining opportunity for telescope recovery of this object. The ephemeris errors will have grown sufficiently by the 2018 and 2023 apparitions that it will no longer be feasible to attempt a telescope recovery and we will have to hope for its rediscovery by the ongoing surveys. To take advantage of this last remaining opportunity, we ask that the first run be scheduled in the window January 16–24, 2015 if possible.

We have used a V+R filter on the KPNO 2.1m to detect objects as faint as V $\sim$23.5 and have achieved a theoretical limiting magnitude of V $\sim$24 in long exposures. Most to all of the targets should be detectable using the Bok Telescope with the new NOAO 5.75-inch V+R filter under good to excellent conditions.

Recovery work is difficult because it entails observing objects (usually faint) when their ephemeris uncertainty has grown to be substantial. However, this is exactly when a new observation can do the most good because it will select among the variant orbits (aka "virtual asteroids") that are consistent with the observational history. This leads to much better knowledge of the orbit and, for VIs, to a greatly improved assessment of impact risk.

For example, our recovery of 2011 AX22 led to a large improvement in the mean anomaly and the *a* and *e* orbital elements. The distance of closest approach in May 2055 was moved away from Earth (possibly hitting the Earth) to $>$1 lunar distance (unlikely to hit the Earth). As a result of this orbital improvement, 2011 AX22 was downgraded from a VI to a PHA. The recovery of PHA 2008 OX1 extended its observational arc to 1,303 days – more than 2.5 orbital periods. It was confirmed as a PHA and its orbit was improved sufficiently to permit prediction of its sky position to within 1 arc-second over an interval of ten years into the future (Mighell et al, 2012).

All of the recovery candidates to be observed in this program will have ephemeris uncertainties of at least $100''$ on the sky and usually much larger at the time of observation. This could not be done on a telescope with a conventional (narrow) field of view. We are confident that successful recovery will translate into real benefits for orbits and impact risk assessment.

The attached figures demonstrate why arc extension during the discovery apparition is important (Figure 1) and why recovery of an NEO after one or more orbital periods leads to greatly improved orbits (Figure 2). Although one cannot easily predict the orbit improvement that a new observation will produce for any given object, Figure 1 makes it clear that extending the observed arc during the discovery apparition improves the orbit and will reduce ephemeris uncertainty at future dates. Arc extension enables future re-observation, including recoveries. However, Figure 2 shows that recovery improves orbits to an extent that far exceeds what arc extension can accomplish. Without further observation, the ephemeris uncertainty grows substantially over time for NEOs that have observed arcs shorter than one orbital period. When recovered to create an arc equal to one period or longer, NEOs can remain unobserved for decades into the future without accumulating appreciable ephemeris errors. They can be re-observed at any time if needed, and are at no risk of being lost.

In addition to our highest priority targets (VI recovery), based on past experience, there are likely to be 15–25 additional PHAs in need of further observation. This will completely fill the 3 nights of each of the two runs requested.

References

1. Andrea Milani, 1999, Icarus 137, 269–292.

2. Kenneth J. Mighell, Morgan Rehnberg, Robert Crawford, Mark Trueblood, and Larry A. Lebofsky, 2012, *PhAst: An IDL Astronomical Image Viewer Optimized for Astrometry of Near Earth Objects*, PASP, **124**, 1360-1368.

3. We acknowledge support through NASA Grant NNX13AK53G.

4. Since this team began observing, we have compiled a total of 98 Minor Planet Electronic Circulars (MPECs) issued by the Minor Planet Center covering 289 objects, including recent MPECs 2014-K29 and 2014-K57. The complete list of MPECs may be viewed at http://www.winer.org/Science/MPEC.php

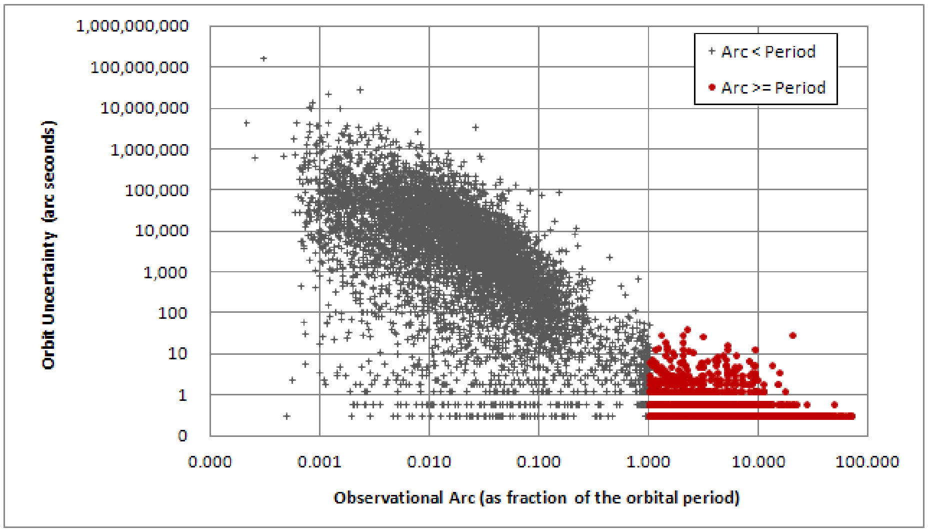

Figure 1: **Orbit uncertainty for NEOs.** The orbit uncertainty is a standardized measure equal to the ephemeris uncertainty (arc-seconds on the sky) if the NEO were observed at 0.7 AU with its motion vector perpendicular to the line of sight. On this basis, $1''$ corresponds to an uncertainty of 508 km in the position of the object along its orbit. The orbit uncertainty decreases as the observational arc increases. NEOs with arcs less than 10% of the orbital period (most of them) have large uncertainties, while NEOs that have been recovered (Arc $\geq$ Period) have low uncertainties. Arc extension observations during the discovery apparition shift NEOs to the right and down in the diagram. Note that the horizontal and vertical axes are logarithmic.

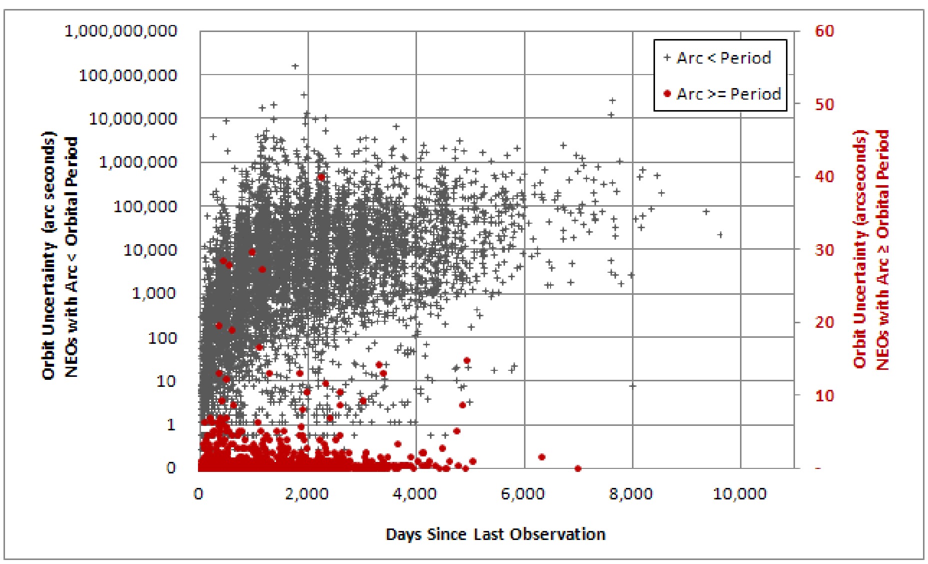

Figure 2: **The Impact of Recovery on Orbit Uncertainty.** Using the standardized measure from the first figure, orbit uncertainty increases dramatically with time for NEOs with observational arcs less than one period (left axis) when the objects are not re-observed. Arc extension during the discovery apparition is essential to prevent the effective “loss” of these objects. Once recovered by creating arcs of at least one orbital period (right axis), orbit uncertainty remains small without further observation even decades into the future. Note the logarithmic axis on the left and the linear axis of vastly smaller scale on the right.

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)***

Recovery candidates are usually faint because the new apparition is rarely as favorable as the discovery apparition. With few exceptions, NEO recovery can *only* be done with a 2-m class telescope (or larger). The Bok Telescope should be highly productive for this work because of its aperture and large field of view. Its limiting magnitude is about that of the KPNO 2.1-m, and the 90Prime imager's much larger field of view will make it feasible to search for VIs and PHAs whose ephemeris uncertainty has grown to as much as several degrees in the sky.

Our observing protocol was developed over a five year period to help us observe as many as two dozen NEOs in a given night. For past work, we developed observation planning software to determine the parameters for a moving object, including optimal times for observation during the night, integration time, non-sidereal tracking rates, interval between sets, etc. We use an S/N ratio of 10 to ensure that we can achieve high astrometric accuracy. Integration times range from as short as 30 seconds up to as long as 900 seconds. A minimum of three sets are taken to detect motion against the sky and more are taken should the target blend with a field star, cosmic ray hit, etc.

We reduce our data in real time as acquired, once a minimum of three sets are available for each object, and we normally submit astrometric observations to the IAU's Minor Planet Center (MPC) during the night the observations are made. In the summer of 2011, Trueblood and Crawford mentored a Research Experience for Undergraduates (REU) student, Morgan Rehnberg of Beloit College, to develop PhAst, a complete NEO photometry and astronomy data reduction package written in IDL (Mighell, 2012). We have used PhAst for data reduction since 2011B, and in the past year have modified it under NASA Grant NNX13AK53G to enhance its use for NEO recovery and to process MEF format images.

To support the proposed work, we have revised our observation planning software to model the Bok Telescope with 90Prime imager and its mosaic algorithm (which defines tiles on the sky for objects having high ephemeris uncertainty) to account for the gaps between sensors in the 2 x 2 array. We have also set up PhAst to process MEF format images from the 90Prime imager. In the proposed work we will reduce our data during the night to assure that we have located the target objects and we will submit our observations to MPC once enough data are obtained to demonstrate a successful recovery.

As can be noted from the target list, the VI observations are particularly challenging because of the targets' uncertainty on the sky. To make the search for these objects more efficient, we use a target's own motion rate to distinguish between it and other objects. We image each tile on the sky deeply while tracking non-sidereally at the target's expected motion rate and direction. We then look for the tile that contains an object with a circular PSF at the expected magnitude. Our software projects the 2-σ error ellipse from the NEODyS web site on our images, enabling a more efficient search. This tile is then re-imaged two or three times to detect motion on the sky and confirm the recovery. Still, it can require a significant portion of a night to detect a V = 23 object that could be in any of 7 tiles on the sky.

For example, for a 900 sec exposure for a V = 23 object, and adding an additional 5 minutes per pointing for a short offset (20 minutes per tile for pointing and integration) we expect a 7-tile object to require 140 minutes to find it plus an additional 60 minutes to complete the integrations, for a total of 200 minutes to cover 7 tiles. For 2011 BT59, we would need most of all three nights (while the object is up approximately 9 hours each night) to find it and to complete the observations.

To achieve the faint limiting magnitude needed to recover many of the VI and PHA candidates, we request use of the new NOAO V+R filter for our runs, if it is available. As noted in the Science Justification, we have achieved the needed object detection limit of V $\sim$23.5 in prior runs by using a V+R filter to give maximum contrast between the signal from a reflected solar spectrum and the sky background noise.

The target list above shows possible VI and PHA recovery targets for two run dates as examples. We will re-evaluate the list of recovery candidates once actual run dates are known. We will then update and optimize the target list in the week prior to each run.

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**)*

1. Project Nights

   (a) Nights already had for this project: 0 on UAO telescopes for this program, 6 on UAO telescopes in Semester 2014B for a similar program. Note that our UAO time in Semester 2014B is scheduled after this proposal is due, therefore we have no results of those runs to report.

   (b) Nights requested: two runs of 3 nights each (total of 6 nights), with the runs separated by at least one lunation (preferably two). Specifically, if possible, we request that Run 1 be scheduled in the window January 16–24, 2015 to permit the recovery attempt for 2011 BT59, and Run 2 be scheduled in the window March 16–22, 2015 to permit the recovery attempt for 2011 YV62.

   (c) Nights to complete project: Each run is a self contained project that is completed at the end of the run, or immediately thereafter, with submission of the recovery observations to the Minor Planet Center. We reduce our astrometric observations during the night to assure that we have found the targets and will submit the recovery observations when a sufficient arc on the sky is obtained (two successive nights, as required by the MPC for recoveries). On occasion, we will hold submission of observations for a few days after the run when additional data reduction or review is needed. Our data (with that of other observers) are published by the Minor Planet Center in regular MPECs (Minor Planet Electronic Circulars).

2. Nights on non-UAO telescopes: We have been averaging 5-8 nights per semester on the KPNO 2.1-m since 2009 for a related NEO program. The predecessor programs involved astrometric follow-up observations to confirm new NEO discoveries (in 2009) and to extend the observational arcs of VIs and PHAs (2010 and later). Although such work is still needed, we believe that a greater contribution can be made through VI and PHA recovery using the wide field of the Bok Telescope with 90Prime imager. On the Bok Telescope, we plan to focus on recovery of VIs and PHAs that were not possible, due to their large ephemeris errors, using the KPNO 2.1-m telescope.

3. We are not collaborating with other groups. We coordinate with other groups by reporting what we are observing on the Minor Planet Center's Follow-Up web page to avoid duplication of effort.

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)***

The PI and his team are scheduled to use the Bok 2.3-m telescope with the 90Prime instrument after this proposal is due to the TAC, for two runs of three nights each (total 6 nights). That will be the first use of this telescope by the PI during the last two years.