OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

Recovery of Potentially Hazardous Asteroids

P.I.: Larry Lebofsky (LPL; *lebofsky@lpl.arizona.edu*; 520-730-6128)

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

Abstract of Scientific Justification

We will attempt the recovery of 2011 YW10, a Virtual Impactor (VI) that has not been observed in more than three years since its discovery, if time can be granted during a date range in December 2015 when it can be observed using the Bok telescope. 2011 YW10 is an Aten asteroid (mean distance from the Sun of 0.86 AU) and crosses the orbits of Mercury, Venus, and Earth. It is observable in favorable circumstances only every 4 or 5 years. The successful recovery of this target will create an observational arc of nearly five complete orbital periods from discovery and will lead to a greatly improved assessment of the risk of Earth impact this century. The possible outcomes of a successful recovery range from removing 2011 YW10 from the VI list to its confirmation as a VI with a heightened risk of Earth impact. This will be a challenging recovery attempt made feasible under the circumstances by the relative brightness of the target during a short period of time and the 90Prime imager's large field of view. It is also an important recovery because it has potential Earth impacts in 2025 and 2030, only 10–15 years from now.

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	90"	PF	90Prime			2	dark	Dec 12–18	Dec 12–18	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We request 2 nights during the period Dec 12–18 to permit the recovery of 2011 YW10. If such time cannot be granted, no time on the Bok telescope should be allocated for this proposal because the planned recovery cannot be attempted.

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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	2011 YW10			12/12–18/2015 V $\sim$ 21.3

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 a high priority VI that has not been observed in the three years since its discovery. 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 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 and a reduced future growth rate for ephemeris errors.

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. The result of a successful VI recovery can range from removing the object from the VI list (as was true for 2011 AX22 and 2011 BT15) to its confirmation as a VI with a heightened risk of Earth impact.

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). Given the limited available time on Bok for community proposals in 2015B, we have requested time only for a VI recovery opportunity.

Semester 2015B has only one VI recovery opportunity within the range of the Bok telescope. We are requesting one run of two consecutive nights to comply with the established practice of the Minor Planet Center of requiring observations of the target on two closely-spaced nights. This run must be scheduled during the interval Dec 12–18. If such time cannot be granted, no time should be allocated on the Bok telescope for this proposal as the planned recovery cannot be attempted.

2011 YW10 is an Aten asteroid (mean distance from the Sun of 0.86 AU) and crosses the orbits of Mercury, Venus, and Earth). It is observable in favorable circumstances only every 4 to 5 years. It has H = 24.0 or 30–95 m diameter (depending on the albedo of the object), corresponding to ten times the mass of the Chelyabinsk NEO. It has a potential impact with Earth in 2025 with a nominal approach distance within three Earth radii and a second potential impact in 2030 with a nominal approach distance within 22 Earth radii. While the nominal orbit does not lead to an impact, the uncertainty in the orbit leaves open the possibility of impact during both approaches. If the recovery were to confirm the object as an impactor in 2025 or 2030, NASA and the worldwide space community would be hard pressed to mount a deflection mission in the 10–15 years remaining until impact. We believe that 2011 YW10 is an important target for this reason.

2011 YW10 will be a challenging recovery that will benefit from the 90Prime imager's large field of view. During the December window, it will culminate relatively low in the southern sky shortly after dark with a 2-sigma error ellipse covering one to two 90Prime fields of view; the waxing moon will approach the target during the window to reach first quarter on December 18. It will be moving on the sky at speeds up to 17" per minute – fast, but within the capability of the Bok telescope. The target's relative brightness ($V\sim21.3$) during this week in December and the 90Prime imager's one-degree field of view should make it possible to dig the target out of the brightening sky each night before it sets. It will be too faint for the Bok telescope the week before the December 12–18 window and will be lost in the glare of the moon a week after. A second recovery opportunity exists early in Semester 2016A, but the object will be much fainter ($V\geq23$).

We have used a V+R filter on the KPNO 2.1m to detect objects as faint as $V\sim23.5$ and have achieved a theoretical limiting magnitude of $V\sim24$ in long exposures. We request use of the new NOAO 5.75-inch

V+R filter to maximize our limiting magnitude. If this filter is not available, the ”Bob” filter designed by Robert McMillan will ensure detections at astrometric S/N ratios.

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. 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 (Mighell, 2012). We are confident that successful VI 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). 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. Figure 2 shows that recovery improves orbits to an extent that far exceeds what arc extension can accomplish. 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 and are at no risk of being lost.

References

1. 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.

2. We acknowledge support through NASA Grant NNX13AK53G.

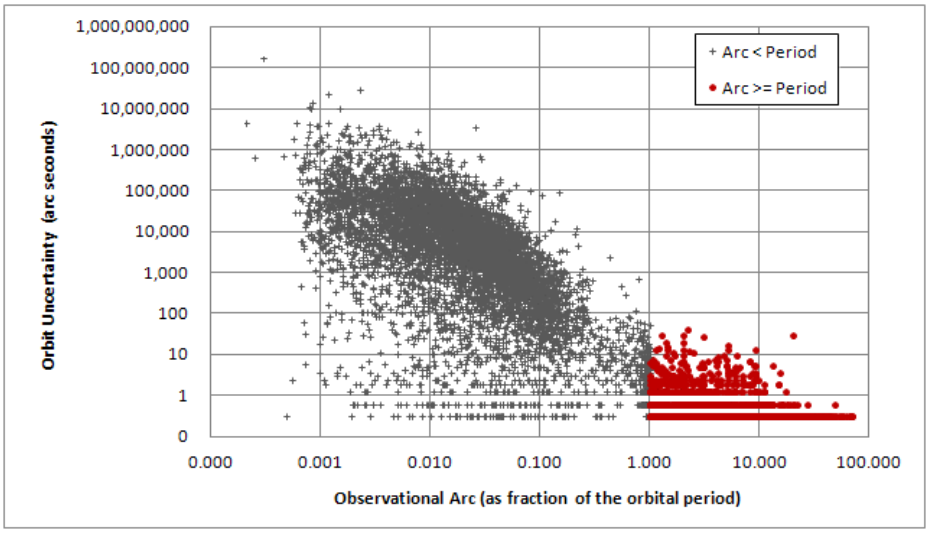

Figure 1: **Orbit uncertainty for NEOs.** The orbit uncertainty is a standardized measure equal to the ephemeris uncertainty (arc-seconds on the sky) if the NEO were observed at 0.7 AU with its motion vector perpendicular to the line of sight. On this basis, $1''$ corresponds to an uncertainty of 508 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.

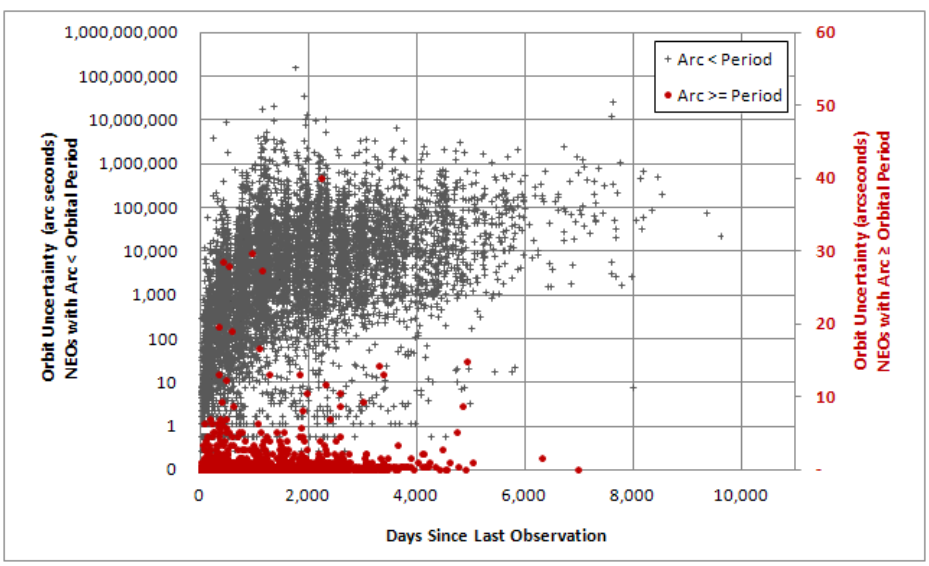

Figure 2: **The Impact of Recovery on Orbit Uncertainty.** Using the standardized measure from the first figure, orbit uncertainty increases dramatically with time for NEOs with observational arcs less than one period (left axis) when the objects are not re-observed. Arc extension during the discovery 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 can 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 makes 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 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 the MPC once enough data are obtained to demonstrate a successful recovery.

VI recovery 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.

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 an 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.

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 and another 6 nights in Semester 2015A for a similar program. Note that 3 of our nights in Semester 2015A are scheduled after this proposal is due, therefore we have no results of that run to report.
   (b) Nights requested: one run of 2 nights. Specifically, we request that our run be scheduled in the window Dec 12–18, 2015 to permit the recovery attempt for 2011 YW10. If the time in the interval requested cannot be granted, no time on the Bok telescope should be allocated for this proposal because the planned recovery cannot be attempted.
   (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 averaged 5-8 nights per semester on the KPNO 2.1-m since 2009 until it was closed in mid-2014 for a related NEO program. These 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 the 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 used the Bok 2.3-m telescope with the 90Prime instrument for two runs of three nights each (total 6 nights) in 2014B and one run of three nights in 2015A. These nights resulted in the following Minor Planet Electronic Circulars (MPECs):

Semester	MPEC	Objects
2014B	2014-U54	3
	2014-U67	10
	2014-W84	3
	2014-W103	6
2015A	2015-D02	1
	Total Objects	23