OBSERVING REQUEST
University of Arizona Observatories

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

Astrometry and Photometry of Faint, High Priority Solar System Objects

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CoI(s): Jeff Larsen (US Naval Academy), Jim Scotti (LPL/U. Az.)

Abstract of Scientific Justification

We request gray or bright time with 90Prime on the Bok 2.3-m telescope to improve knowledge of the orbits and magnitudes of high priority classes of Near Earth Objects (NEOs) and other small solar system bodies that cannot be reached with our (smaller) Spacewatch telescopes. Many asteroids and comets are being lost owing to insufficient followup astrometry, but only the most important ones can be followed with the limited resources available. It is better to follow objects longer during their discovery apparitions than to search tens of degrees of arc for them when they return years later, hence our need to reach fainter magnitudes soon after the objects' announcements. Objects flagged as high scientific priority and urgently in need of further observations include freshly discovered virtual impactors (VIs) and NEOs discovered by the recently reactivated NEOWISE spacecraft. Most of our targets are therefore unknown at the time of this proposal. Other targets include future targets of radar, NEOs previously detected by WISE with orbits or albedos suggesting potential for cometary activity, potential destinations for spacecraft, and returning NEOs with hard-won albedos and diameters previously determined by WISE. We report our observations promptly to the Minor Planet Center (MPC), who uses them to update their orbital elements. Our past use of the Bok telescope has been determined by the MPC to provide "dramatic improvement" to orbits (Spahr 2014 private communication). This proposal departs from our earlier ones in that we are willing to use bright time if gray or dark time is unavailable.

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			4	bright	Sep–Sep	Sep–Sep	yes	no
2	90	PF	90Prime			4	bright	Oct–Oct	Oct–Oct	yes	no
3	90	PF	90Prime			4	bright	Nov–Nov	Nov–Nov	yes	no
4	90	PF	90Prime			4	bright	Dec–Dec	Dec–Dec	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)***:** Dark or gray time is preferred but we can use bright time. Please keep us at least 3 nights away from full moon. Runs of 4 consecutive nights are preferred. Please avoid our nights on the Mayall and LBT.

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	(Asteroids)			See list of example targets below.

Approval for Instrument Use from PI: N/A

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 Case for Fainter Followup: Asteroids tend to be discovered near their brightest and most geometrically favorable appearances, so they tend to become fainter in the days and weeks following their discoveries. Also, most discoveries of asteroids are made near the limit of detection of the surveys that discover them, because fields of view sample larger volumes of space at greater distances. It follows that surveys that push their detections of asteroids to the limit of sensitivity cannot be expected to make enough followup observations during the normal course of their surveys, even if they revisit the same areas of the sky every few days. Recently discovered asteroids tend to drop below the limit of detection before enough observations spanning a long enough arc can be collected by repeating the same search patterns. Furthermore, a survey that attempts to follow up all its own discoveries by targeting specific objects with longer exposures would quickly become saturated with followup duty at the expense of its search pattern for new objects. On the other hand, specifically targeting followup observations on individual objects allows detection to dimmer limits and more prolonged tracking of asteroids' paths. Therefore, separate telescopes dedicated to followup and able to reach dim objects have been essential to the campaign.

Some important NEOs have slipped away before sufficient observations were made during their discovery apparitions. Those tend to be the ones with the more closely approaching, short-lived apparitions, and therefore in the most dangerous orbits. More than a third of Potentially Hazardous Asteroids (PHAs, asteroids with absolute visual magnitudes ≤ 22 and Mean Orbital Intersection Distances (MOIDs) with the Earth's orbit $\leq 0.05AU$) have not been observed after their discovery apparitions. Among NEOs with potential future close encounters with Earth, almost a third will be by objects that were observed during only their discovery apparitions. Lists of "Virtual Impactors" also call for better followup. NEODyS, the Near-Earth Object Dynamics group at the University of Pisa,currently lists many lost objects "large enough to reach the ground", some of which with absolute mag ≤ 22 were "stale" (discovery apparition expired). Immediate and intensive followup can prevent even big objects from being lost for a long time.

WISE Spacecraft Observations: The relationships between the mineralogical properties and orbits of asteroids are clues to their origins and subsequent processing. But albedos are generally difficult to determine in visible light. WISE (Wright *et al.* 2010) made a uniformly sensitive, all-sky thermal infrared survey of over 157,000 minor planets. Among these are nearly 600 NEOs for which WISE determined diameters and albedos ("NEOWISE"; Mainzer *et al.* 2011a,b,c,d, 2012a,b). After such hard-won physical parameters are determined, it is important that those objects be recoverable for further study. Even with only its two shorter wavelength infrared channels operating in the unrefrigerated telescope, the recently reactivated NEOWISE telescope still yields approximate albedos and diameters of asteroids. The NEOs it measures should be supported with accurate orbital elements.

Spacecraft Mission Targets: NASA wants astrometry of NEOs as potential rendezvous destinations for spacecraft. The orbital criteria for mission feasibility are low inclination with respect to the ecliptic, low eccentricity, and semimajor axis near 1 AU to minimize the velocity impulse required for transfer and rendezvous. However, semimajor axes near 1 AU correspond to long synodic periods. The fewer numbers of objects with the acceptable orbital elements also tend to leave only the smaller ones which are more numerous overall. The necessary long-range planning for a space mission requires much more accurate orbital elements than have been typical for small NEOs. Such objects need to be followed for longer time intervals immediately after their discoveries. "Small" means that discovery must occur while close to Earth, which usually means fast motion across the sky. These objects are also intrinsically faint, which results in short observation intervals and poor knowledge of their heliocentric orbital elements. Their faintness and short arcs of observation mean they are unlikely to be recovered on subsequent apparitions. Thus most previously discovered small NEOs are now lost. Followup for more prolonged intervals immediately after discovery are needed for closely- approaching NEOs and NEOs in Earthlike orbits to be recoverable on subsequent apparitions. Closely-approaching NEOs get fainter by 2-5 mags within days after their encounters with Earth. So targeted followup observations with longer exposure times and larger telescopes are needed to follow them at least until they are a couple of Hill radii from Earth ($\sim$0.02 AU). There the objects' trajectories recede out of their temporary hyperbolic paths with respect to Earth and the sun's gravity resumes being the dominant effect on their motion. At that distance the observations

consequently provide more leverage on the determination of the new post- encounter heliocentric orbital elements, which are needed to predict return apparitions. But to reach that distance from Earth, a NEO takes typically 2-4 days after encounter, a longer interval than observations of most close approachers can be made with 0.4-1.0 meter class telescopes.

Radar Targets: Radar observations of asteroids provide accurate orbits, size, spin vector, dielectric constant, and shape (Benner *et al.* 2013). However, to point and tune the receiver they need to know *a priori* the position to within 20 arcsec and the topocentric radial velocity. For up to date information they guide a campaign of ground-based optical astrometry.

Yarkovsky Effect: Rotation of asteroids causes spatially asymmetric thermal re-radiation of absorbed sunlight, yielding a net small thrust depending on the spin vector, albedo, diameter, and thermal inertia (Bottke *et al.* 2006). Only a few asteroids have orbits and physical properties known well enough to isolate this slow progression of orbital elements from other small, slow effects (Nugent *et al.* 2012). Such targets appear on our lists with ephemerides seemingly already accurate enough for everyday use, but the orbits of these objects require accurate monitoring for many years.

Effectiveness:) The MPC's recent analysis of our observations with the Mayall and Bok telescopes indicated that future ephemeris uncertainties dropped on average by a factor of 5 (T. Spahr 2014 private communication). In several cases the future ephemeris uncertainty was reduced by 2 orders of magnitude. We show positional uncertainties for each of the objects in the tables of example targets. A target with a listed ephemeris uncertainty of (say) 50 arcsec that is observed by us with our typical astrometric accuracy of 0.5 arcsec receives an improvement of a factor of 100 in ephemeris accuracy. The MPC further summarized how much our observations improve orbits (Williams 2014 private communication). We summarize results of the 72 PHAs we've observed with the Bok and Mayall telescopes since 2010 Jun 6. Statistics for PHAs can be assumed to be typical of other categories of our targets. For 38 of the 72 PHAs we added another observed opposition. Additionally, we consider the factor by which we increased the calendar span of observations, and the factors of improvement in the uncertainties of orbital elements, where "T" = time of perihelion passage, "Peri" = longitude of perihelion, "e" = eccentricity, "Node" = longitude of ascending node, "Incl" = inclination of the orbit with respect to the ecliptic, and "q" = perihelion distance. The tabulated numbers are the ratios of the uncertainties without our observations to the uncertainties obtained after including our observations. In most cases our observations improve knowledge of the elements. We extend arcs an average of a factor of 3.8 and reduce uncertainties of orbital elements by an average of a factor of 6. The most weakly constrained orbital element tends to be T; we reduce its uncertainty an average of a factor of 19.

Table 1. Effects of observations by Spacewatch COD 695, 2010 Jun - 2014 May on Uncertainties of PHA Orbital Elements. by G. V. Williams, MPC. f(parameter) = uncert. before / uncert. after.

	% Span	f(T)	f(Peri)	f(e)	f(Node)	f(Incl)	f(q)
Minima	0.00	0.91	0.90	0.91	0.81	0.83	0.83
Maxima	4027.27	596.29	11.14	43.57	40.96	17.40	13.44
Averages	384.66	19.29	2.38	6.89	2.95	3.37	3.57

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McMillan, R. S., and the Spacewatch Team. 2007. Spacewatch preparations for the era of deep all-sky surveys. In *Proc. IAU Symp. 236: Near Earth Objects, our Celestial Neighbors - Opportunity and Risk*, A. Milani, G. Valsecchi, and D. Vokrouhlicky, Eds. (Cambridge U. Press), pp 329-340: http://spacewatch.lpl.arizona.edu/publications.shtml .

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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**)*

Orbit Improvement: Positions are measured to improve knowledge of orbits. Ephemeris uncertainties can be from tens to thousands of arcseconds, so astrometry to subarcsecond accuracy is a vast improvement over prior knowledge. Another measure of our contribution is the extension of time span of orbit knowledge. The target lists include the date the object was last observed. Asteroids with small uncertainties are on our lists for other reasons.

Astrometry: Astrometry to subarcsecond accuracy requires SNR=5 or better. That can be obtained as faint as V=23 in bright time. Because the targets are moving, we take a series of exposures of a few minutes' duration each, short enough to avoid significant trailing. Alternatively, in uncrowded fields we use nonsidereal tracking to accumulate signal into untrailed images of moving objects.

Photometry: "R" magnitudes are determined from known stars in our scientific target fields.

Number of WISE Targets: We are selecting from a priority list of about 600 objects, which includes all the NEOs detected by WISE as well as some other objects observed by WISE that should be inspected for traces of weak or intermittent cometary activity. Our lists of previously known objects sometimes show duplication between observing runs to ensure their recovery.

Usability of Bright Time: In view of the demand on dark and gray time with the Bok telescope we have investigated the usefulness of bright time at least 3 days away from full moon. Successful NEO obs have been made to V=21.5 with our 1.8-m telescope in light from a moon 3 days away from full. The Bok telescope should do better, not only because of the larger aperture but also with the help of the windscreens that we do not have at the 1.8-m. We ran KPNO's CCDTIME tool for the pessimistic parameters of R band, 2.1-m telescope, 0.6 arcsec/pixel, 2 arcsec seeing, airmass=2.0, and the moon 1 day from full. SNR equalled 5 at R = 23.2. Another reason to consider bright time is to provide better temporal coverage on NEO motions. On 2015 Feb 6 and 7, our observer with our 1.8-meter telescope recovered a number of NEOs as faint as V=21.5, yielding MPECs (Bressi 2015) that might not have been possible without our timely recoveries.

Number of MPC Targets: During one lunation, about 200 new NEOs are posted on the NEO Confirmation Page. This is the current statistic without accounting for the expected increase in discovery rate. For the telescopes larger than those of Spacewatch, we favor targets that grow fainter than apparent V=22 as they recede from Earth after discovery. That is about half of the objects. We also favor the 20% of the NEOs that the MPC designates as "Potentially Hazardous Asteroids" (PHAs), plus the NEOs of any size that are indicated by JPL to have potential close encounters with Earth. So we estimate 20-30 *new* objects will be in each of our Bok 2.3-m and Mayall 4-m target lists each lunation. In bright time we should average about one or two objects per hour.

Number of Nights Requested: Four bright nights per run will give us $\sim$20 faint target-visits.

Target Tables: Most of our targets will be objects not yet discovered, but the Tables show examples of previously known objects of importance. When we have to observe through clouds or bad seeing we select brighter targets among the same scientific categories. We permit objects to appear more than once on some lists to emphasize the multiple reasons for their importance. We have recovered asteroids with elongations as close as 46 degrees from the Sun. The shorthand notations, not all of which we use in every semester, are: "NEOWISE" = NEO detected by WISE needing astrometric followup; "Rendezvous" = Potential destination for spacecraft; "PHA" = Potentially Hazardous Asteroid; "Radar" = object scheduled to be observed by radar; "Uncert" = 3-sigma ephemeris uncertainty in arcseconds projected on the sky; "VI" = "Virtual Impactor" indicating that the object has potential future close encounters with Earth. "Yarkovsky" = A candidate for measurement of the Yarkovsky effect.

Table 2. Example Targets for 2015B Bright Time with 90Prime, in order of “Best Date”.

Desig.	Type	AbsMag	Best Date Year Mon dd	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs Year Mon dd	Uncert +/-3sig
K11Y74U	Rendezvous	22.9	2015 Sep 14	22 45	-02	146	23.2	2012 Jul 23	430
K04M03O	Rendezvous	22.2	2015 Sep 15	20 55	-11	122	23.1	2014 Dec 10	3
K10H33D	NEOWISE	18.3	2015 Oct 5	23 40	-10	117	23.2	2014 Feb 24	2
K10C00M	NEOWISE	18.4	2015 Oct 6	23 48	-10	117	23.2	2010 Jun 18	7
K12K06C	Rendezvous	21.7	2015 Oct 18	23 51	+02	92	22.7	2012 Jul 21	2
K15DF5P	Rendezvous	21.6	2015 Oct 30	22 47	-20	107	23.1	2015 Mar 16	530
K10V72C	Rendezvous	23.1	2015 Nov 5	03 25	+10	114	22.9	2010 Dec 7	2319
K14C14F	NEOWISE	18.1	2015 Nov 21	02 34	+26	86	23.0	2014 Oct 26	11
K10K10P	NEOWISE	23.4	2015 Nov 23	00 25	+09	89	22.2	2010 Jul 1	3200
K13W44U	NEOWISE	21.0	2015 Nov 26	11 10	+16	64	22.8	2014 Jun 25	47
K10EB9X	NEOWISE	19.4	2015 Nov 30	20 24	-09	60	22.9	2013 Aug 30	4
K05F03C	Radar	19.1	2015 Dec 1	07 59	+09	150	23.2	2008 Jan 18	2
K13E20M	Rendezvous	19.8	2015 Dec 5	21 08	-24	60	22.1	2013 May 15	2
K11Y62T	Rendezvous	22.4	2015 Dec 9	10 51	+22	141	22.9	2012 Feb 13	700
K10G25F	NEOWISE	19.1	2015 Dec 15	09 24	+54	137	22.5	2015 Mar 10	18
J94U00G	Radar	21.0	2015 Dec 15	09 57	+25	150	22.2	2012 Oct 21	7
K03G00A	Rendezvous	21.1	2015 Dec 19	10 02	+04	151	22.8	2012 Dec 13	2
K11D00U	Radar	21.1	2015 Dec 21	09 53	+08	168	22.9	2011 Dec 29	85
K09W00A	NEOWISE	21.2	2015 Dec 24	23 00	+09	70	22.3	2010 May 9	70
K02X38Y	Rendezvous	22.9	2015 Dec 26	01 34	-01	95	22.1	2010 Feb 20	16
K13CC9E	Rendezvous	22.0	2015 Dec 28	07 33	+32	160	23.2	2013 Aug 28	259
K10D77H	NEOWISE	21.8	2015 Dec 29	09 54	+41	156	22.2	2010 Jun 6	3200
K09C00V	Rendezvous	24.3	2015 Dec 30	03 44	+24	104	22.6	2009 Sep 7	260
K06X04P	VI	23.9	2015 Dec 29	11 34	+03	108	22.8	2007 Jan 24	3600
K11Y10W	VI	24.0	2016 Jan 5	02 34	+16	115	23.0	2012 Jan 3	800
K00H74D	NEOWISE	18.0	2016 Jan 11	01 06	-17	67	22.7	2010 Jun 27	2
K11E00K	Rendezvous	22.4	2016 Jan 15	00 57	-16	80	23.0	2011 Mar 29	2500

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**)*

UAO Nights, Past, Present, and Future: So far, 94 nights with 90Prime in 2010A-2015A have been scheduled for this project. All astrometric data were reduced and mailed to the MPC. We hope that our recoveries of NEOs with 90Prime for a few nights every lunation will continue as long as our funding does because the pace of discoveries continues to increase. (We are currently funded through 2018 Mar.)

Mayall 4-m Time: Since mid-2010 through 2015A we have been scheduled for 35 nights with the Mayall 4-m telescope for this same work, reaching down to V magnitude 24 (Scotti *et al.* 2014). In the last 2 years we have received 25 nights with the Mayall. All astrometric data to date have been reduced and mailed to the MPC. We continue to propose for about 6 nights per semester with the Mayall, but like the Bok, we will be willing to accept brighter time than before.

LBT Proposal: We are requesting two half-nights with the LBT in 2015B to recover some especially important and faint asteroids that JPL lists as having possible close encounters with Earth. Overlap of target lists between 90Prime (bright) and LBT (dark) will be negligible, but there may be about half a magnitude of overlap of the lists for the Mayall and the LBT.

Overall Astrometric Output: Our campaign in the last 2 years with the Bok and Mayall has yielded 1272 lines of astrometry on 181 different NEOs, including 79 PHAs, plus 34 observations of comets. We made 363 observations of PHAs with $V \geq 22$. Our average extension of calendar span on large PHAs (with absolute magnitude ≤ 17.75) is 6 months, which is twice as long as the next most effective observing station delivers on such objects.

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**)*

⋆ **90Prime:** The 2.3-m Bok telescope of Steward Observatory has been used with the 90Prime camera on a regular basis for this work since 2010 (Scotti *et al.* 2014). Through 2015A we've received 94 nights; 39 of them in the last 2 years. All astrometric data to date have been reduced and accepted by the MPC.

⋆ **Spacewatch:** We conduct an intensive program of followup astrometry of faint asteroids and comets with the 0.9-m telescope of Steward Observatory and the Spacewatch II 1.8-m telescope of LPL on Kitt Peak (McMillan *et al.* 2007, 2010, 2012, 2013, 2014). The 0.9-meter telescope with its mosaic of CCDs covers 2.9 square degrees of sky in one exposure, and can detect asteroids as "faint" as V=21.5 with SNR=3. The Spacewatch 1.8-meter telescope has a smaller FOV but can reach V=22.6 with low SNR when conditions permit. These telescopes are the workhorses for astrometric recovery, having contributed twice as many observations of NEOs discovered by the WISE spacecraft within 2 weeks of their discovery in 2010 than any other followup station (McMillan *et al.* 2010). Recent results are listed at http://spacewatch.lpl.arizona.edu . In 2011 we installed a new CCD on our 1.8-meter telescope that allows us to observe 50 % more objects per unit time with half the astrometric residual as before. The annual average number of 3-pass tracklet detections of NEOs by Spacewatch is ∼2,800 of ∼1,000 different NEOs, including 177 different PHAs per year. Spacewatch observations have contributed to the removal of half of the objects that were retired from JPL's impact risk list. We make twice as many measurements of PHAs while they are fainter than V=22 than the next most productive astrometry group. Per year we observe about 35 radar targets, 50 NEOs that were measured by NEOWISE, and 100 potential rendezvous destinations. We also average 400 observations of comets per year. Since 2004 we have increased our efficiency by a factor of six in terms of observations per unit personnel work year by means of new hardware, software, and the automation of the 0.9-m telescope. In 2013 we received a grant to upgrade our 0.9-m telescope and develop a public archive of our image data.

⋆ **Previously Awarded Time for Asteroid Polarimetry:** Observations of polarization of asteroids are in support of Chet Maleszewski's PhD dissertation. He has received observing time from 2012A through 2014B with Paul Smith using SPOL on the Bok and Kuiper telescopes, with a total of 22 nights in 2013-2014 plus some observations donated by Smith in 2011C and 2015A. About 300 observations of taxonomically classified asteroids have been made for polarization and its dependences on wavelength, phase angle, and taxonomic type. The project has now progressed into the reduction and interpretation phase. Data from 2011C through 2014A are reduced. The 2014A data were presented at the DPS meeting in 2014. The 2013 data were presented at the AGU meeting, comparing the B-types and C-types.