OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **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 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).

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	grey	Jan–Jan	Jan–Jan	yes	no
2	90	PF	90Prime			2	grey	Feb–Feb	Feb–Feb	yes	no
3	90	PF	90Prime			2	grey	Mar–Mar	Mar–Mar	yes	no
4	90	PF	90Prime			2	grey	Apr–May	Apr–May	yes	no
5	90	PF	90Prime			2	grey	May–Jun	May–Jun	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Waxing moon gray time preferred. No need to avoid our time on the Mayall 4-m because we now have enough people to use both telescopes simultaneously.

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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	(Asteroids)			See target list 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.

Small NEOs: NASA wants astrometry of small NEOs to help predict impacts, and to provide near-term destinations for spacecraft. They want a small NEO suitable to bring back to cislunar space as a destination for human spaceflight (Chodas *et al.* 2013). Such long-range planning will require 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, an NEO takes typically 2-4 days after encounter, a longer interval than observations of most close approachers are made.

Dark Comet Candidates: Deep exposures of asteroids in comet-like orbits (low Jovian Tisserand orbital parameters *and* low Mean Orbital Intersection Distance with Jupiter "MOIDj") *and* with extremely low albedos using large telescopes and good angular resolution can reveal low-level comae and/or tails indicative of the sublimation of volatile material and the release of dust. Such discoveries result in the reclassification of asteroids into comets and drastically change the interpretation of both the infrared and visible-light flux detected from them (Bauer *et al.* 2011, 2012). We discovered main belt comet 238P/Read in incidental (non-optimized) 2-minute survey exposures with the Spacewatch 0.9-m telescope (Read *et al.* 2005). The finer image scale and larger aperture of the Bok telescope are better suited for *targeted* observations on objects "cherry-picked" for such detections according to albedo and orbital elements. We have reported sensitive nondetections of cometary features of some asteroids discovered by WISE that were suspected of being comets on the basis of their orbits, and measured cometary features of more than a dozen comets. Recently, outer solar system object 2014 PP69 has become brighter than expected and requires further monitoring.

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). The Table below summarizes 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 list the percentage 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

References:

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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=24. 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.

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. We average about two or three objects per hour and try to observe each object on both nights.

Inspection for Cometary Features: To detect faint cometary features we take more exposures than are required for astrometry and stack them all at the objects' rates.

Number of Nights Requested: Two grey nights per run will give us ~60 faint target-visits. Two-night runs are also compliant with the IAU/MPC rule that *Minor Planet Electronic Circulars* announcing exceptional recoveries of asteroids require such observations on two separate nights. We prefer waxing-moon time to get as many freshly discovered NEOs as possible.

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: "DCC" = Dark Comet Candidate suggested by low albedo; "loTj" = low Tisserand orbital parameter Tj *and* low MOID with respect to Jupiter's orbit suggestive of a previously unrecognized comet; "NEOWISE" = NEO detected by WISE needing astrometric followup; "NHATS" = "NEO Human Space Flight Accessible Targets Study" targets listed by JPL; "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.

Some of the Targets for First Quarter Moon, 2015 January

Desig.	Type	AbsMag	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs	Uncert Arcsec
K10B02L	DCC_LoTjMOID	16.4	06 43	+52	141	22.4	2014 Jan 10	1
K10N01W	DCC_LoTjMOID	17.1	08 33	+09	170	23.0	2010 Dec 7	278
K12XD4O	NHATS	23.9	08 52	+18	176	22.4	2014 Jan 9	2

K03M04J	NEOWISE	18.8	09 36	+21	165	23.1	2011 Jan 26	0
K14B08T	NHATS	25.0	14 20	+07	95	23.2	2014 Jan 29	379
K11G59P	NHATS	24.3	15 02	+56	102	22.8	2011 Apr 15	1700

Some of the Targets for First Quarter Moon, 2015 February

Desig.	Type	AbsMag	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs	Uncert Arcsec
F3201	Yarkovsky	19.3	04 14	+27	92	22.4	2014 Jan 3	0
K06O15G	NEOWISE	19.8	04 46	+19	98	22.4	2011 Jan 3	0
K10P66R	DCC_LoTjMOID	19.4	09 13	-09	154	21.1	2010 Nov 2	3800
K04E00B	DCC_LoTjMOID	17.2	10 34	+40	150	20.6	2010 Nov 7	1
K10KC7Y	DCC_LoTjMOID	17.0	13 08	+30	138	21.6	2014 May 15	0

Some of the Targets for First Quarter Moon, 2015 March

Desig.	Type	AbsMag	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs	Uncert Arcsec
K10A79G	DCC_LoTjMOID	20.2	07 35	+67	95	23.5	2010 Mar 24	N/A
K10X69P	NEOWISE	21.4	11 37	-08	168	23.0	2011 Jan 31	1
K10D21M	DCC_LoTjMOID	20.3	12 08	+03	174	21.7	2014 Jul 29	1
K08A28T	NEOWISE	18.4	12 27	+09	169	22.4	2012 May 20	3
K11E04X	NHATS	24.5	15 57	-06	126	22.4	2011 Mar 26	4000

Some of the Targets for First Quarter Moon, 2015 April

Desig.	Type	AbsMag	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs	Uncert Arcsec
K10NB7W	NEOWISE	18.2	10 41	+03	126	22.8	2011 Jan 21	0

Some of the Targets for First Quarter Moon, 2015 May

Desig.	Type	AbsMag	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs	Uncert Arcsec
K10Y03D	NEOWISE	19.4	09 48	-16	93	22.4	2011 Apr 4	4200
K14E24K	Radar	23.2	10 33	-20	104	22.1	2014 Jul 3	8
Z7439	Radar	19.1	12 01	+38	99	22.0	2014 Jul 29	1
K10G62X	DCC_LoTjMOID	20.2	13 44	+30	119	19.9	2010 Jul 15	4000

Some of the Targets for First Quarter Moon, 2015 June

Desig.	Type	AbsMag	RA hh mm	Dec deg	Elong deg	Vmag	Last Obs	Uncert Arcsec
46P	Comet,Radar	N/A	15 46	-15	146	22.3	2014 Apr 29	N/A

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, 88 nights with 90Prime in 2010A-2014B have occurred for this project, including 6 nights in the future of this proposal. All astrometric data were reduced and mailed to the MPC. In this proposal we ask for five runs of 2 nights each. Our recoveries of NEOs with 90Prime for a few nights every lunation should continue as long as our funding does because the pace of discoveries continues to increase. (We are currently funded through 2017 July.)

Mayall 4-m Time: Since mid-2010 through 2014B we have been scheduled for 33 nights with the Mayall 4-m telescope for this same work, reaching down to V magnitude 24.4. All astrometric data to date have been reduced and mailed to the MPC.

Overall Astrometric Output: Our campaign since 2010 with the Bok and Mayall has yielded 1316 lines of astrometry on 207 different NEOs, including 84 PHAs, plus 39 observations of comets. We made 343 observations of PHAs with $V \geq 22$. Our average extension of calendar span on large PHAs (with absolute magnitude ≤ 17.75) is 184 days, which is 2x longer than the next most effective observing station on such objects.

Taxonomic Photometry: In addition to astrometry, considerable observing time with the Mayall and Bok telescopes on the above-listed nights has been used for multifilter (UBVRIz) taxonomic photometry of NEOs for which the NEOWISE mission has also determined albedos and diameters. Standardized high precision V-band photometry of such objects establishes the albedo near the peak of incident solar flux, which reckons in modeling their thermal properties. These observations are valuable because the delivery of asteroids from the main belt to Earth-crossing orbits depends on albedo, size, and composition. Measurements of mineralogical classes by means of taxonomic photometry can thus help refine understanding of the filtering involved in asteroid transport. Due to the faintness of the targets and time limitations, the program typically used (at least) BVR photometry to classify the objects using the method of Dandy *et al.* (2003). Although less accurate and potentially more ambiguous than the Bus-DeMeo or Tholen systems, it is significantly easier to obtain for faint asteroids but still allows sorting into major taxonomic groups. These data required more complex reductions and are now nearly completed.

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. Through 2014B we've received 88 nights. All astrometric data to date have been reduced and mailed to 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). 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 $\sim$2,800 of $\sim$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. Last year we received a grant to upgrade our 0.9-m telescope and develop a public archive of image data dating back to 1990.

⋆ **Previously Awarded Time for Asteroid Polarimetry:** These observations are in support of Chet Maleszewski's PhD dissertation. He has received one night of observing time per lunation since 2012A using SPOL on the Bok and Kuiper telescopes. 240 observations of taxonomically classified asteroids have been made, reduced, and analyzed for linear polarization and its dependences on wavelength and phase angle. Preliminary results on asteroids Ganymed and Heracles were presented at the 2012 AGU Fall meeting. Aggregate data for the S- and Q-types were presented at the 2013 DPS meeting and results on the V-types were presented at the 2013 AGU Fall meeting. A poster for the 2014 DPS meeting and papers are in preparation.