**OBSERVING REQUEST**
**University of Arizona Observatories**

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

# Spectropolarimetry of Asteroids and the Unusual (554) Peraga

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**CoI(s):** Bob McMillan (SO)

**Abstract of Scientific Justification**

We request four nights of time to continue observations of the linear polarization from asteroid surfaces. The two quantities of interest are the variations in linear polarization with respect to phase angle and wavelength. We choose to look at these quantities as a means to compare asteroids across across taxonomic classes. This will help to characterize regolith using polarimetry and improve our understanding of the complex light scattering that occurs. By the completion of the survey, we will look to determine if the wavelength dependence of polarization is driven purely by difference in albedo or by changes in composition. Our survey so far has conflicting results. Most recently, comparison of C- to Ch-type asteroids suggest that stronger wavelength dependences occur for the Ch-type, which suggests a composition basis for the variation. The primary target of interest for this run is (554) Peraga, which is a C-type asteroid which was measured to have atypical positive polarization at low phase angles. Later observations produced more typical polarizations. The current hypothesis for these results is a dichotomy of composition between hemispheres assuming the atypical values of polarization come from real effects. More observations will be taken to further assess the plausibility of the atypical, positive polarization. Observations in 2015A will take place near the ecliptic longitudes where the atypical polarization values were measured.

**Summary of observing runs requested for this project**

| | | | | | | | | Scheduling | | Sharing | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Run | Telescope | Cage | Instrument | PI | AO | Nights | Moon | Optimal | Acceptable | Poss. | Adv. |
| 1 | 90 | f/9 | SPOL | * | | 1 | grey | Jan | Jan-Apr | yes | yes |
| 2 | 90 | f/9 | SPOL | * | | 1 | grey | Feb | Feb-Mar | yes | yes |
| 3 | 90 | f/9 | SPOL | * | | 1 | grey | Mar | Feb-Mar | yes | yes |
| 4 | 90 | f/9 | SPOL | * | | 1 | grey | Apr | Jan-Apr | yes | yes |

**or:**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1a | 61 | f/13 | SPOL | * | | 1 | grey | Jan | Jan-Apr | yes | yes |
| 2a | 61 | f/13 | SPOL | * | | 1 | grey | Feb | Feb-Mar | yes | yes |
| 3a | 61 | f/13 | SPOL | * | | 1 | grey | Mar | Feb-Mar | yes | yes |
| 4a | 61 | f/13 | SPOL | * | | 1 | grey | Apr | Jan-Apr | yes | yes |

**Scheduling constraints and unusable dates** *(up to 4 lines)*: Each run should be scheduled contiguously with other SPOL programs, as requested by the instrument PI. Time on the Bok telescope is preferred given the faintness of some targets during these runs. We request to observe on February 10 and March 11 as they are best suited for observing our main target (554).

*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 | (207) Hedda | 05 21 | +28 | C-type V=14.3 Phase=24.9 |
| 2 | (133) Cyrene | 05 35 | +28 | S-type V=13.9 Phase=16.4 |
| 3 | (205) Martha | 06 53 | +09 | C-type V=14.0 Phase=17.5 |
| 4 | (431) Nephele | 07 33 | +22 | B-type V=14.5 Phase 11.9 |
| 5 | (335) Roberta | 08 53 | +16 | B-type V-13.2 Phase=9.8 |
| 6 | (554) Peraga | 10 18 | +07 | C-type V=11.8 Phase=3.0 |
| 7 | (76) Freia | 10 38 | +06 | C-type V=12.1 Phase 0.8 |
| 8 | | | | All Coordinates are for 2015 Mar 01 |

**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 |
|---|---|---|---|---|
| Chet Maleszewski | Robert McMillan | | no | yes |

**Scientific Justification**

We propose to measure the polarization of sunlight reflecting from asteroids over a wide range of phase angles (Sun–Target–Observer angle). The state of polarized light has been shown to vary based on the sunlight's incidence angle and the surface properties. From these measurements we can determine the components of linearly polarized light with electric vectors parallel and perpendicular to the scattering plane (Equation 1). A polarization vs. phase angle curve is constructed after many measurements throughout a wide range of phase angles. At high phase angles, there is a nearly linear increase in positive polarization (more light in the perpendicular state) as the phase angle increases. On the other hand, at low phase angles (between 0 and 20 degrees roughly) negative polarizations exist, which is primarily caused by multiple scatterings of the incident sunlight by the regolith.

$$P = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}} \tag{1}$$

There are two main goals for the observations we are requesting. The first is to determine the polarimetric phase curve properties of individual objects. By doing so, we can estimate the albedo of said object and compare the produced polarimetric phase curves to similarly composed asteroids in order to see if there are any differences between them which need to be explained. Empirical relationships have been formed to compare albedos with various properties of the polarization curves described above. Results show that albedo as a function of the polarimetric phase curve properties (Cellino *et al.* 1999, Masiero *et al.* 2012). Comparisons of asteroids within the same taxonomic class have shown similar structure across the entire class. This suggests that factors specific to the asteroid such as grain size and microtopography do little to affect polarimetric phase curves. We target asteroids that are similar in composition but are classified in different groups (*e.g.* S-types and Q-types). From our knowledge of their composition from other means, and our observations, we can attempt to explain what causes variations in the observed polarization. We can extend this work to asteroid families, such as the Vestoids.

The second goal is to determine the wavelength dependence of a variety of asteroid compositions, as determined by asteroid taxonomy. Results from these observations may help constrain models that attempt to link various regolith properties with the complex light scattering at the surface which creates the net polarization we see across phase angle space. Belskaya *et al.* (2009) investigated wavelength dependence in Main Belt Asteroid (MBA) targets and found roughly linear trends. For C-type and S-type asteroids the slope of these trends increased as the phase angle also increased (Belskaya *et al.* 2009). The primary question that needs to be answered with our survey is whether the differing wavelength dependence is primarily driven by compositional differences or changes in albedo (as is seen in polarimetric phase curves).

For each observation conducted so far, a linear regression is implemented to determine the wavelength dependence of polarization, in a similar manner as Belskaya *et al.* Archived data of C-type asteroids analyzed by Belskaya *et al.* show that the linear polarization becomes more positive as wavelength increases. For the C-types observed so far by our program, this wavelength dependence trend holds. Figure 1 shows the wavelength dependence of polarization vs. phase angle for our current C- and Ch-type sample. A sharp increase in wavelength dependence occurs after 20 degrees phase angle, which is near the inversion angle for most asteroids. However, measurements at phase angles greater than 30 degrees are needed to confirm the turnoff. In addition, the Ch-type asteroids tend to have steeper wavelength dependences when compared to C-types at comparable phase angles. Once confirmed, this will be the first evidence that wavelength dependence varies as a function of subtle composition changes. On the contrary, our data from the S-, Q-, and V-type do not show significant changes in wavelength dependence with subtle composition change.

As opposed to previous semesters, we are returning to previously observed asteroids in order to improve the number of total observations for previously studied taxonomic classes. One of these objects, (554) Peraga, will be the focus of the semester's observations. This object has been measured to have positive polarizations at phase angles between 8 and 10 degrees (Zellner and Gradie, 1976). Typical C-type objects have polarizations between -1 and -2% at these phase angles. Later observations could not replicate these positive polarizations (Antonyuk and Kiselev, 2012). Both sets of observations can be seen in Figure 2. Assuming

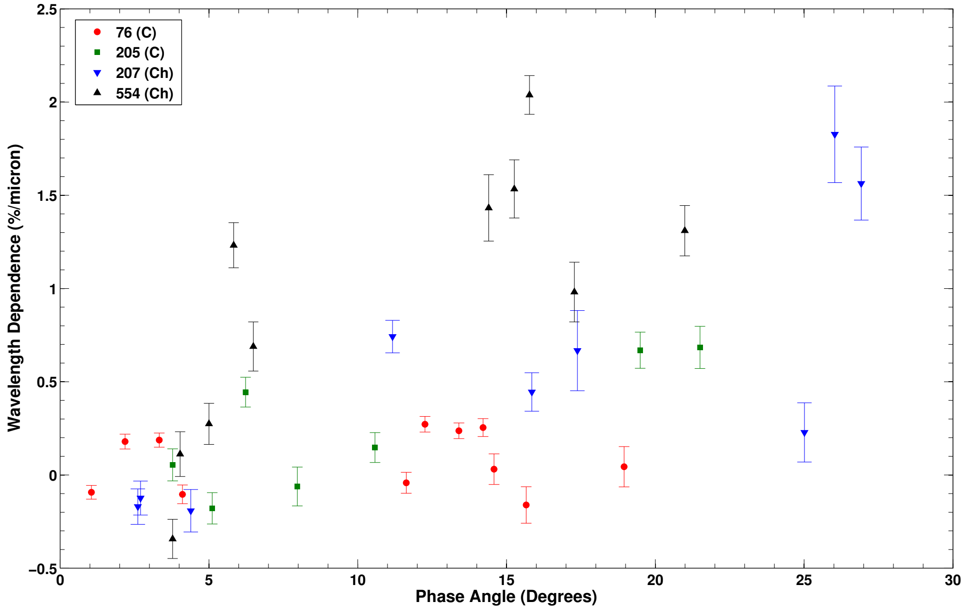


Figure 1: Plot of the wavelength dependence of linear polarization vs. phase angle for C- and Ch-type objects that we have observed in 2013. Initial results suggest that the Ch-type objects have stronger wavelength dependences compared to the C-types.

the effects measured by Zellner and Gradie are real, the most likely explanation is a dichotomy in composition across Peraga's surface. The previous two sets of observations were taken at nearly opposite ecliptic longitudes. This suggests composition differences on opposite hemispheres; the more atypical regolith may only be observable at certain epochs, given a particular rotation axis. Our previous observations of Peraga (not shown) suggest negative polarizations at an ecliptic longitude near 220. In another attempt to confirm the Zellner data, this semester we will observe Peraga between 150 and 160 degrees ecliptic longitude. Peraga is available for observation in the 8-10 degree phase angle range on February 6-8 and March 11-13. We request the grey time around these dates (Feb 10 and Mar 11) in order to observe at these phase angles. Note that February 7-9 falls in bright time, which would hinder the other SPOL programs; we request to start on February 10 as a result.

Antonyuk K. A. and N. N. Kiselev, 2012. *Solar System Research* **46**. 54-56.

Belskaya I. N., *et al.* 2009. *Icarus*, **199**, 97-105. http://adsabs.harvard.edu/abs/2009Icar..199...97B

Cellino A., *et al.* 1999. *Icarus*, **138**, 129-140. http://adsabs.harvard.edu/abs/1999Icar..138..129C

Masiero J., *et al.* 2012 *ApJ*, **749**, article id. 104. http://adsabs.harvard.edu/abs/2012ApJ...749..104M

Zellner B. and J. Gradie. 1976. *AJ* **4**, 262-280.

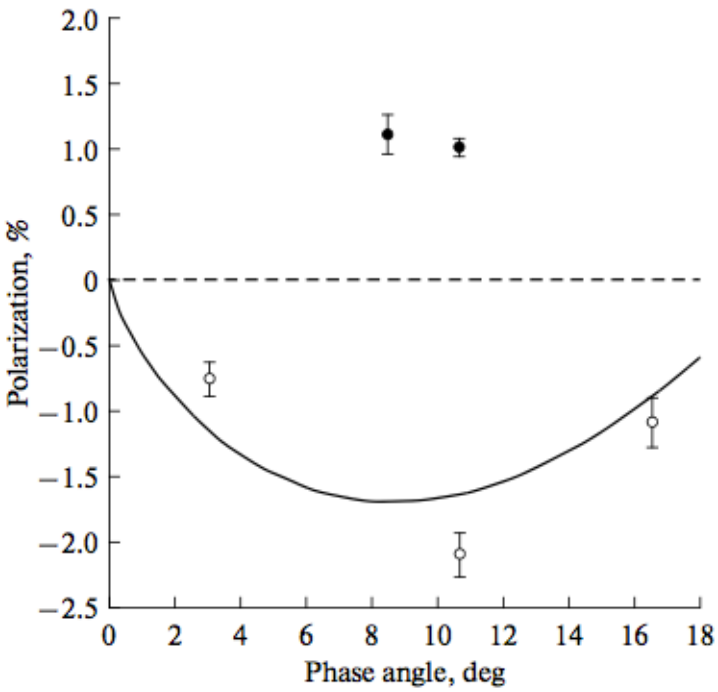


Figure 2: Previous polarimetric observations (polarization vs. phase angle) of the C-type asteroid (554) Peraga. The data show unusual positive polarization between 8 and 10 degrees phase angle. Typical C-type measurements have negative values in this angle range, represented by the solid line. Figure replicated as shown in Antonyuk and Kiselev 2012.

**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)***

To measure the trend of linear polarization and its wavelength dependence with respect to phase angle, it is necessary to measure the polarization on multiple nights throughout the year. Phase angles and the location of the polarization plane will be calculated using ephemeris programs such as those provided by the Minor Planet Center and JPL HORIZONS. The SPOL polarimeter makes use of a wave plate to measure the polarization at various angles. Measurements will be taken over a wavelength range of 4000-7550 angstroms. The SPOL reduction package will take the data and determine the Stokes parameters Q and U, from which the linear polarization can be calculated. During observations we will have the telescope track at the rate of the target's motion. If necessary, multiple cycles of observations can be made and combined during reduction. Bias and flat frames will be taken during each run, along with polarimetric standards.

In order to accurately fit the polarimetric phase curves, the uncertainties in polarization should be under 0.05 percent. Assuming the uncertainty in polarization is analogous to uncertainty in photon statistics, the needed SNR over a particular bandpass is SNR=2000. We estimate this corresponds to a photon count of 8E6 per bandpass. This will easily be achieved over the 4000-7550 angstrom data. However, narrow bandpasses of $\sim$ 200 angstroms within the data will be used to determine the wavelength dependencies; this will affect the necessary amount of exposure time.

To maximize the number of observations produced, we will limit the wall clock time on each object per night to around eighty minutes. A target that requires 120 seconds of exposure time per waveplate position will take approximately seventy-five minutes of wall clock time. Targets will be observed between 10 and 15 magnitude in V. The error estimates will increase by a factor of $\sqrt{2}$ when observing on Kuiper as opposed to Bok. By choosing brighter targets, we can produce similar results on the Kuiper telescope; Bok telescope time is still preferred in order to obtain high SNR and increase the possibility of observing more objects per night. For similar reasons, dark time is requested when receiving time on the Kuiper.

The majority of the data collected will be from (554) Peraga. Other previously observed asteroid targets are included in the target list as backup targets. All observations will be added to the polarimetry survey we have been conducting since 2012.

**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**)*

Thirty-two nights of observing time have been awarded to this program since September 2011. This is the last proposal for this polarimetric survey, which will contribute to Maleszewski's dissertation research. We ask for four nights in this proposal.

**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)***

⋆ **Previously Awarded Time for Asteroid Polarimetry** We have requested and received one night of observing time per lunation since 2012A. A total of 240 observations of taxonomically classified asteroids have been made between 2012A and 2013B (22 A, 53 B, 37 C, 9 Q, 80 S, and 39 V). Observations of four X-type asteroids, one B-type, and one C-type asteroid were conducted during 2014A. All data from 2012A-2013B has been reduced and analyzed to measure the linear polarization and wavelength dependence. Reduction of the 2014A data will be completed in October and presented at the 2014 DPS and AGU meetings.

Preliminary results of data from asteroids Ganymed and Heracles were presented at the 2012 AGU Fall Meeting. Results combining the S-type and Q-type data were then presented at the 2013 DPS meeting in Denver. V-type observations were first presented at the 2013 AGU Fall Meeting. Publications for the S-types, Q-types and V-types are in prep.

http://adsabs.harvard.edu/abs/2013DPS....4520814M
http://adsabs.harvard.edu/abs/2013AGUFM.P42B..07M

**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.

**UAO Time Awarded for Photometry and Astrometric Followup:** The 2.3-m Bok telescope of Steward Observatory has been used with the 90Prime camera on a regular basis in support of the Spacewatch program since 2010. Through 2014B we've received 88 nights. All astrometric data to date have been reduced and mailed to the Minor Planet Center (MPC).

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