OBSERVING REQUEST
University of Arizona Observatories

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

Near-Infrared Photometry of TNOs and Centaurs in Support of Existing Spitzer Space Telescope Data

P.I.: Michael Mommert (NAU; *michael.mommert@nau.edu*; 928-523-5595)

CoI(s): Noemi Pinilla-Alonso (UTK), David E. Trilling (NAU), Josh P. Emery (UTK), Don McCarthy (SO), Craig Kulesa (SO), Cassandra Lejoly⋆ (NAU)

Abstract of Scientific Justification

Centaurs and Trans-Neptunian objects (TNOs) are icy small bodies that reside between the giant planets and beyond the orbit of Neptune, respectively. Their compositions, which include different ices (H_2O, CH_4, N_2, CH_3OH), organic material, and/or silicate minerals, provide important clues on the formation and evolution of the Solar System. In order to constrain the compositions of these objects, spectroscopic observations, which require large-scale telescopes due to the targets' faintness, are the usual approach. A much more efficient way to constrain their compositions is to combine photometric measurements taken in a number of near-infrared bands that are indicative of different surface materials. We have been measuring reflectances of TNOs and Centaurs with Spitzer/IRAC over several Spitzer cycles, yielding 3.6 and 4.5 μm photometry of 43 Centaurs and 140 TNOs. However, these measurements are meaningless without the availability of near-infrared photometric data, which are currently not available for 63 of these objects. *We propose to perform JHK photometry of 9 Centaurs and TNOs using 1.5 nights of 90"/PISCES and 11 hrs of UKIRT/WFCAM, in order to constrain the compositions of these objects.* This program is a continuation of a program that was awarded 10 hrs of UKIRT/WFCAM (u/14b/ua14) and 2 nights of 90"/PISCES in 2014B. The observations are necessary to constrain the compositions of these objects and will contribute to the understanding of their formation and evolution.

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	PISCES	*		1.5	bright	Jun–Jul	May–Jul	yes	no
2	UKIRT	PF	WFCAM			1.1	bright	Jan–Jul	Jan–Jul	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*:

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	119951 (2002 KX14)	∼16:50	∼-22	V∼ 20.29, 90" target
2	174567 Varda (2003 MW12)	∼17:09	∼-02	V∼ 20.29, 90" target
3	332685 (2009 HH36)	∼00:41	∼-20	V∼ 20.04, 90" target
4	143707 (2003 UY117)	∼02:22	∼+19	V∼ 21.48, UKIRT target
5	(2001 XD255)	∼08:30	∼+24	V∼ 21.49, UKIRT target
6	119979 (2002 WC19)	∼05:26	∼+18	V∼ 21.10, UKIRT target
7	(2003 WU172)	∼06:16	∼+27	V∼ 21.28, UKIRT target
8	(2011 FX62)	∼13:17	∼-27	V∼ 21.26, UKIRT target
9	(2005 CA79)	∼09:51	∼+25	V∼ 21.66, UKIRT target

Approval for Instrument Use from PI: see attached email from McCarthy

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
Cassandra Lejoly	Michael Mommert		no	no

Scientific Justification

Small bodies provide important clues on the formation and evolution of the Solar System. Two pristine small body populations are the Trans-Neptunian Objects (TNOs) and the Centaurs. TNOs reside on orbits outside the orbit of Neptune and can be considered remnants of the planetesimal disk from which the planets have formed. Due to their distance from the Sun, a considerable fraction of them has been found to harbor surface ices of different compositions. Centaurs are a short-lived, transitional population of icy small bodies moving between the giant planets. Centaurs that are not ejected from the Solar System in close encounters or resonances with the planets are driven into the inner Solar System, where they appear as comets due to the sublimation of their surface ices.

Visible light to near-infrared (NIR) spectra of the brightest TNOs and Centaurs have revealed a very diverse range of surface compositions, including H_2O, CH_4, N_2, CH_3OH, and a nearly ubiquitous low albedo component that could be macromolecular organic material (e.g., tholins) and/or silicate minerals (see, e.g., Barucci et al. 2008). The various volatiles and complex organic molecules relevant to TNOs and Centaurs produce diagnostic spectral signatures at $\lambda > 2.5$ μm (Figure 1, left).

In order to constrain the compositions of TNOs and Centaurs, spectroscopic observations are usually used, which require large-scale telescopes due to their faintness. A more effective approach to investigate the spectral properties of these objects is provided by the combination of NIR photometric observations in different bands. Figure 1 (left) shows that many of the absorption features of materials found on TNOs and Centaurs coincide with NIR photometric bands (namely, J, H, and K) and the bands of the Spitzer Infrared Array Camera (IRAC) centered at 3.6 and 4.5 μm. Spitzer/IRAC observations provide evidence of the presence of these materials on objects where visible and NIR observations alone do not offer a clear diagnostic. To exploit the promise of this wavelength range, we have been measuring reflectances of TNOs and Centaurs with Spitzer/IRAC over several Spitzer cycles, yielding 3.6 and 4.5 μm photometry of 43 Centaurs and 140 TNOs. *In order to be meaningful, the Spitzer data have to be combined with NIR photometry.* NIR data are required for two critical roles: (1) to provide the continuum from which absorptions will be measured, and (2) to broaden (in wavelength space) the lever arm for determining composition. The first of these roles is the most important, and perhaps the most obvious: an absorption band cannot be seen if there is no continuum level established. The second role, though a bit of a truism (more data are always better), is especially important for the very low spectral resolution broadband data we have to work with. While the Spitzer/IRAC photometry enables the detection of an absorption, it is nearly impossible to distinguish between the possible responsible species without the lever provided by shorter wavelength data. Our initial analysis method consists of combining J, H, K, 3.6, and 4.5 μm fluxes in color-color diagrams similar to those shown in Figure 1 (right) to identify possible ices on the surfaces. Comparison of the data with synthetic color indices, extracted from the reflectances of pure ices, enable us to identify which ices dominate the surface composition of these bodies. The NIR data are particularly sensitive to water ice, methanol, and methane.

This powerful color-color technique has been tested with great success by combining Spitzer/IRAC data with NIR photometry data (Emery et al. 2007, Wright et al. 2012, Pinilla-Alonso et al. 2013) and we can already present some intriguing results on the study of the surface composition of small icy bodies: (1) the first detection of water ice and the confirmation of methane on Sedna (Emery et al. 2007); (2) a suggestion of N_2, which is very difficult to detect, on TNO Quaoar (Dalle Ore et al. 2009); (3) the determination of a fairly homogeneous surface composition and the presence of volatiles and/or complex organics on the surfaces of cold classical objects, a TNO subpopulation (Wright et al. 2012).

The further exploitation of available Spitzer/IRAC observations of TNOs and Centaurs requires reliable NIR photometry of the remaining sample targets. At this moment, 63 out of 183 objects that have been observed with Spitzer have no or insufficient NIR photometry. NIR photometry in support of the Spitzer observations has been acquired in 2011B using Gemini/NIRI (see, e.g., Wright et al. 2012), as well as in 2013A. We have also used 90"/PISCES (2013B). The analysis of the data taken with 90"/PISCES shows that this combination only allows for reliable NIR photometry of the brightest targets in our sample. We have also been granted a total of 25 hrs of queue observing time at UKIRT in 2014A and 2014B (u/14a/ua15, PI: McCarthy, u/14b/ua14, PI: Mommert). Experiences made in our previous 90" and UKIRT observing runs have been taken into account in this continuation proposal.

We propose 1.5 nights (9 hrs) of 90"/PISCES and 11 hrs of UKIRT/WFCAM observations to obtain JHK photometry for a sample of 9 Spitzer-observed TNOs and Centaurs in order to constrain their surface compositions.

Our targets are selected based on observability and $V < 20.5$ for the 90", based on previous observing results. The UKIRT targets' apparent brightness ranges from 21.1 to 21.7 mag, a range that is easily accessible with UKIRT/WFCAM based on our previous observations. For the faintest targets we expect to require observation times of 3 hrs in the case of the 90" and 2 hrs in the case of UKIRT (including overhead). Note that spectroscopic observations of our targets would require the use of significantly larger telecopes with comparable or even longer exposure times for the same scientific outcome.

The data collected in previous semesters with UAO telescopes (2013B: 90"/PISCES, 2014A: UKIRT/WFCAM) are nearly fully reduced using a dedicated and mostly automated pipeline and NIR colors have been extracted. Colors for 7 sample targets are shown in Figure 1, right; the full sample of 14 targets will be published in early 2015 together with the results of the upcoming 2014B observations ($\sim$12 targets, 90"/PISCES, UKIRT/WFCAM), as well as additional data from previous Gemini/NIRI observing runs (18 targets, see Page 6 for details).

The results of this project are required to establish the largest database of TNO/Centaur compositions available, providing unique insights into the compositional distribution of this pristine population of objects. Note that, despite the fact that we observe moving objects, this program is not subject to timing constraints, since a sufficient number of accessible targets is available at any time during the acceptable part of the semester. If only part of the proposed observing time is available, only part of the sample presented here can be observed, reducing the outcome accordingly; the scientific success of this project, however, will not be jeopardized by such a reduction.

This work is supported by a NASA Planetary Astronomy grant to Emery (UTK) and Trilling (NAU).

References:

Barucci, Brown, Emery, Merlin 2008, The Solar System Beyond Neptune, UoA Press, Tucson

Dalle Ore, Barucci, Emery et al. 2009, A&A, 501, 349

Emery, Dalle Ore, Cruikshank et al. 2007, DPS meeting #39, #49.08

Peixinho, Boehnhardt, Belskaya et al. 2004, Icarus 170

Pinilla-Alonso, Emery, Trilling et al. 2013, DPS meeting #45, #414.05

Wright, Emery, Cruikshank et al. 2012, DPS meeting #44, #405.03

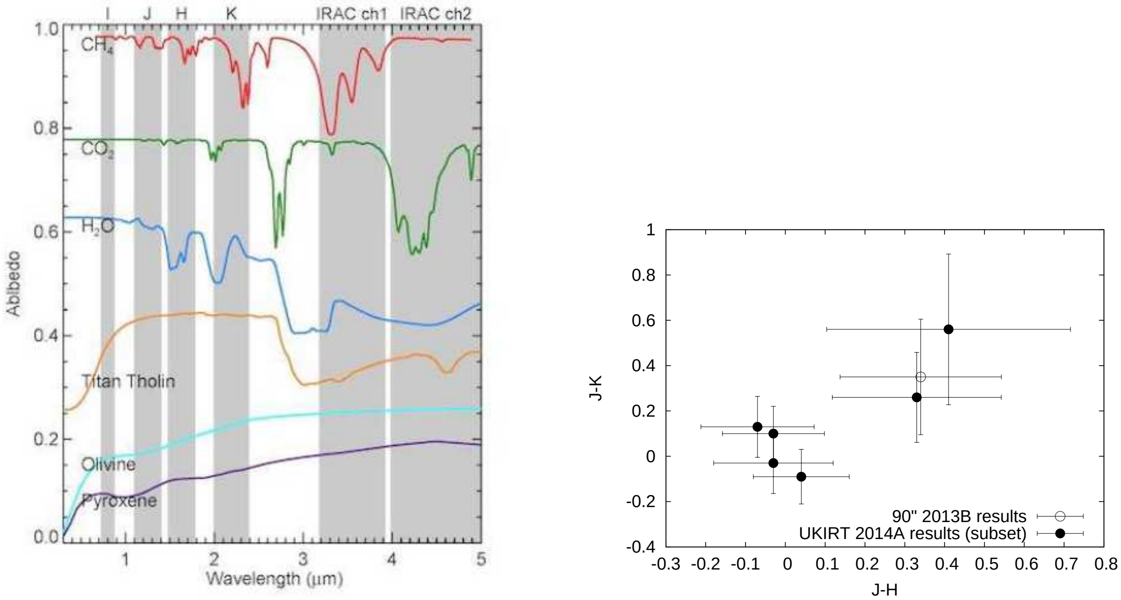

Figure 1: **Left:** Absorption spectra of CH_4, CO_2, and H_2O ices at 40 K, organic Titan tholin, and amorphous silicates olivine and pyroxene, offset in the vertical for clarity. Standard photometric filters I, J, H, K, and IRAC channels (grey bars) are shown for reference. The plot shows clear differences in the spectra of different materials in the J, H, K, Spitzer IRAC/ch1, and IRAC/ch2 bands. In order to properly identify these materials, photometry in all five bands is required. **Right:** Color-color representation of data gathered in 2013B and 2014A with 90"/PISCES and UKIRT/WFCAM (not complete). Note that despite the small sample size a trend is already visible in the data. The combination with Spitzer data will allow for constraining the compositions of these objects using other combinations of color-color plots. For instance, 'K-Spitzer Ch1' versus 'Spitzer Ch1-Spitzer Ch2' is diagnostic for silicates, water, methane, and complex organic materials.

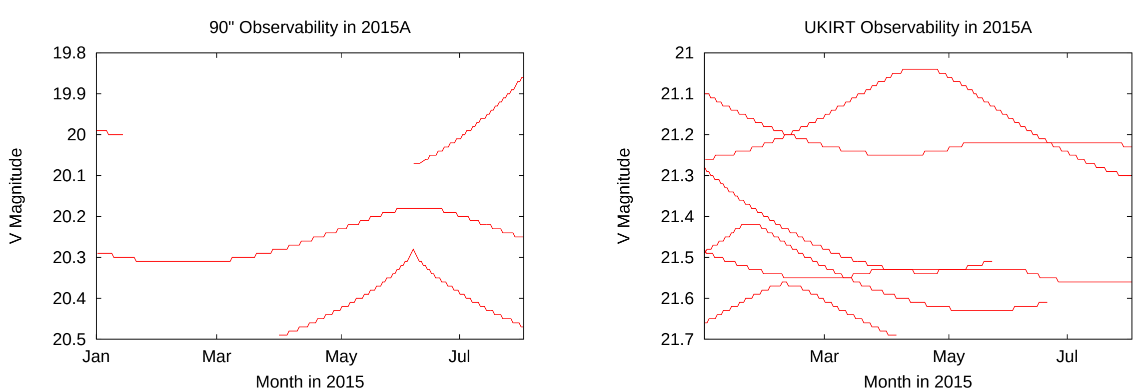

Figure 2: Target observability and apparent magnitude for 90" and UKIRT targets in 2015A. Objects shown in the plot are listed in the target list. Observability has been derived using the JPL Horizons system; all targets have a positional uncertainty of less than 2' and airmass < 2.0.

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)***

For our analysis, we require photometry in J, H, and K. K is critical to establish the reflectance continuum, J and H are required to resolve degeneracies between signatures of ices and organic material and to improve the identification of material mixtures (see Figure 1). *Our minimum science requirement is a high-quality (SNR>10) J, H, and K-band photometric measurement.*

Based on our previous experiences, we utilize a (JKJHJKJ) filter sequence, which allows us to use the high cadence of the J-band integrations to normalize the data for systematic variations in the object's brightness (e.g., its lightcurve) for the brightest targets. In the case of fainter targets, all available image data in one band are aligned in the moving frame of the target in order to improve the signal-to-noise ratio of the detection. Photometric calibration will be achieved using 2MASS stars in the field; these stars will be used to fully characterize the temporal and spatial variations of the sky. In order to properly calibrate the K-band data to the photometric Spitzer data we require photometric nights or nights with a stable, but thin layer of cirrus. Bright nights fully satisfy our needs, as well as seeing up to 2.0″ (or even more) is acceptable. Our targets are slowly moving objects (∼4"/hr); non-sidereal tracking might be useful but is not required. Guiding is not required.

90"/PISCES: Based on our past experiences with 90"/PISCES in 2013B, we require 2.0 hrs of observing time ([15, 15, 90] min in [J, H, Ks]) to achieve SNR=10 in J, H, and Ks for a V∼20 target. There are 3 targets observable from Kitt Peak during the optimal window (see Figure 2 and attached target list). Given the fact that 2/3 of our targets are fainter than $V = 20$ and some targets have high airmass values (airmass ~ 2), we schedule a total observing time of 3 hrs per target, including overhead for telescope pointing and focussing. In order to observe all targets accessible in the optimal window, we require 9 hrs of observing time. Since astronomical dark time during our optimal window is only ∼6 hrs, we ask for a total of 1.5 nights. Mommert, Pinilla-Alonso, and Kulesa are certified on 90"/PISCES; McCarthy is PI of PISCES.

UKIRT/WFCAM: From our past experience with UKIRT/WFCAM we schedule a conservative total of 1.8 hrs for the observation of a V=21.5 target (2.0 hrs for V=21.7), achieving SNR=10 in J, H, and K. In order to observe all 6 UKIRT targets, we require a total of 11 hrs of UKIRT observing time.

Minimum Schedulable Blocks (MSBs) for our 2014A and 2014B UKIRT observations have been designed in collaboration with WFCAM instrument and data reduction scientists. All observations consist of dithered 5s frames in the moving frame of the target. Proper dithering (3.2″stepsize) provides the opportunity to produce skyflat images that significantly improve the data quality. For all observations, the target is centered on WFCAM camera 3, which provides the best sensitivity and detector homogeneity.

Fully automated data reduction and analysis pipelines for data from both telescopes are available. The data analysis pipeline uses an automated World Coordinate System registration and stacks the images in the frame of the background ("skycoadd" image) and in the moving frame of the targets ("comove" image). The skycoadd image is used for photometric calibration: 2MASS stars are automatically detected and their known magnitudes are used to determine the zero point magnitude of the image. The calibrated brightness of the target is measured in the comove image, using the derived zero point magnitude. The NIR photometry is then combined with the Spitzer observations into color-color plots as shown in Figure 1. For several representative objects we analyze the NIR-Spitzer data with radiative transfer models in order to investigate possible surface compositions.

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**)*

As part of this project, we have been awarded 4 bright nights of 90"/PISCES (November 17-20, 2013, PI: Trilling) in 2013B for a pilot study. Out of 4 nights, we could use only 2 nights due to weather. As it turned out, the combination 90"/PISCES does only allow for reliable NIR photometry of the brightest of our targets. Hence, we were able to obtain scientifically useful data for only one object (Figure 1, right). We have also been awarded 2 bright nights of 90"/PISCES in 2014B (December, 8-9, 2014, PI: Mommert). In those upcoming 2014B observation run we will focus on the 5 currently brightest targets in our sample, making use of experiences made in 2013B. In this proposal we ask for 1.5 nights of 90"/PISCES in 2015B, which allows us to observe 3 of our brightest sample targets.

Furthermore, we have been awarded 15 hrs (30 hrs requested) of UKIRT/WFCAM for the same project in 2014A (u/14a/ua15, PI: McCarthy) and 10 hrs (10 hrs requested) in 2014B (u/14b/ua14, PI: Mommert). UKIRT/WFCAM allows for observing significantly fainter targets than 90"/PISCES. Observations in 2014A had a completion rate of 99%, 13 targets have been succesfully observed and most of them reduced (Figure 1, right). Observations in 2014B have not yet started due to the unavailability of WFCAM on the telescope, but we plan to be able to observe 7–8 targets.

We have been awarded a total of 30 hours of Gemini-N/NIRI (PI: Emery) queue time in 2011B (12 targets observed) and 2013A (6 targets). The NIRI data have been reduced, but due to flaws in the reduction process, a re-reduction is necessary, which will be led by master graduate student Lejoly. For 2014B, we have been awarded 19 hrs of Gemini-S/Flamingo (PI: Pinilla-Alonso) in which we plan to observe 12 of our faintest targets. Gemini-S/Flamingo is our only asset in the southern hemisphere, providing access to a number of low-Declination targets. Furthermore, both Gemini telescopes provide access to the faintest targets in our sample.

UKIRT and Gemini mostly share the same target list. Due to the large number of accessible targets, duplicate observations can be ruled out. Only the brightest targets in our sample are accessible with 90"/PISCES. The simultaneous use of UKIRT, Gemini, and the 90" increases the rate at which this project advances. In order to complete this program, we anticipate to need approximately 2 more semesters, given we are awarded the observing time proposed for in this proposal (9 targets) and additional time on the Gemini telescopes ($\sim$15 targets).

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**)*

⋆ 90"/PISCES: The data reduction and analysis of our 2013B observing run (4 nights, 2 nights with useful conditions) has been completed for all data, providing crucial information for the planning of further observations with 90"/PISCES. Our 2014B observing run will take place in early December 2014. The results of both observing runs will be published together with the results of the 2014B UKIRT run (see below) in early 2015. A data reduction and analysis pipeline for 90"/PISCES is available.

⋆ UKIRT/WFCAM: The data reduction and analysis of our 2014A observations (15 hrs, 13 targets, completion rate 99%) has been mostly completed. A full reduction pipeline is available. Observations in 2014B (10 hrs, 7–8 targets) have not yet started due to the unavailability of WFCAM on the telescope. The results of both observing runs will be published together with the results of the 2014B 90" run in early 2015.

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Re: UAO proposal draft: NIR photometry of TNOs and Centaurs

Don McCarthy [dwmccarthy@gmail.com]

Sent: Friday, September 26, 2014 10:37 AM
To: Michael Mommert
Cc: Craig Kulesa [ckulesa@as.arizona.edu]

Hi Michael,

Craig and I are happy to support your use of PISCES on the 90" to observe those outer Solar System objects.

Don

On Thu, Sep 25, 2014 at 4:14 PM, Michael Mommert <Michael.Mommert@nau.edu> wrote:

Hi Don,

could you please send me the email before tomorrow noon? I would like to submit the proposal...

Michael

- -

Michael Mommert
Post-Doctoral Researcher

Department of Physics and Astronomy
Northern Arizona University
PO Box 6010
Flagstaff, AZ 86011

Phone: 928-523-5595

- -

From: Michael Mommert
Sent: Wednesday, September 24, 2014 4:12 PM
To: dmccarthy@as.arizona.edu; dwmccarthy@gmail.com
Subject: RE: UAO proposal draft: NIR photometry of TNOs and Centaurs

Hi Don, another reminder. I would like to mail the proposal on Friday, if possible.

Thanks,
Michael

- -

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- -

From: Michael Mommert