OBSERVING REQUEST
University of Arizona Observatories

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

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

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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* $\sim$40 *Centaurs and TNOs using 2 nights of MMT/MIMIRS or Magellan/FourStar, in order to constrain the compositions of these objects.* This program is a continuation of a project that has succesfully used smaller telescopes including Bok 90" and UKIRT. Here we focus on targets with $20.5 < V < 23$, a magnitude range that can be easily accessed with MMT or Magellan, but not with smaller telescopes. In order to increase the throughput of this program, we decide to measure JHK only for our brightest sample targets; for the fainter targets we derive K from JH observations using statistical methods. Our 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	MMT	f/5	MMIRS			2	bright	Sep	Sep-Dec	yes	no
2	Magellan	f/11	FourStar			2	bright	Sep	Sep-Oct	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Observations are not possible during most of August (IAU general assembly and work meeting) and the week of November 8–13 (Division of Planetary Science Meeting).

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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	**MMT targets**: (+ 40 more potential targets)			
2	(2000 CN105)	∼11:19	∼+6	V∼ 22.07
3	307261 (2002 MS4)	∼18:26	∼-7	V∼ 20.49
4	(2007 XV50)	∼04:40	∼+30	V∼ 21.65
5	88611 Teharonhiawako (2001 QT2	∼22:42	∼-6	V∼ 22.53
6	(2003 WU188)	∼07:15	∼+23	V∼ 22.09
7	(2001 QF298)	∼00:19	∼-6	V∼ 21.65
8	(2001 QX297)	∼23:07	∼-4	V∼ 22.76
9	(1996 TK66)	∼01:44	∼+9	V∼ 22.90
10	(2002 VT130)	∼04:59	∼+23	V∼ 22.19
11	(2001 QX322)	∼01:16	∼+30	V∼ 22.48
12	**Magellan targets**: (+ 42 more potential targets)			
13	(2010 FD49)	∼13:47	∼-4	V∼ 21.58
14	(2003 FF128)	∼15:39	∼-18	V∼ 22.08
15	(2008 LP17)	∼16:01	∼-18	V∼ 21.58
16	(2011 FX62)	∼13:33	∼-28	V∼ 21.34
17	187661 (2007 JG43)	∼19:53	∼-46	V∼ 21.88
18	(2007 UM126)	∼04:09	∼-17	V∼ 22.14
19	413666 (2005 VJ119)	∼16:46	∼-27	V∼ 22.86
20	148975 (2001 XA255)	∼17:36	∼-19	V∼ 22.57
21	(2010 BK118)	∼18:33	∼-56	V∼ 20.89
22	332685 (2009 HH36)	∼00:20	∼-21	V∼ 20.23

Approval for Instrument Use from PI: We contacted Brian McLeod, PI of MMIRS, who informed us that his endorsement is not necessary for this proposal.

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 surface properties of the faintest 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, which is shown in Figure 1 (top right). 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 2 nights of **either MMT/MMIRS or Magellan/FourStar** *to obtain JH and JHK photometry for a sample of ∼40 Spitzer-observed TNOs and Centaurs in order to constrain their surface compositions.*

Our targets are selected based on observability and $20.5 < V < 23$, a magnitude range that is inaccessible to smaller telescopes. All of our sample targets brighter than this range have already been observed with either 90"/PISCES or UKIRT/WFCAM. Moving on to larger apertures is the logical consequence. 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.

Our observing strategy for MMT or Magellan is such that we obtain JHK photometry for targets with $V < 22$ and JH photometry only for fainter targets; K magnitudes for the fainter targets are derived using an empirical relation between $J - K$ and $J - H$ colors of TNOs and Centaurs (Figure 1, bottom right). We use this statistical approach to obtain K magnitudes for fainter targets as we expect degraded accuracy for those targets anyway; in the case of $V < 22$ targets, we measure K, as we can derive accurate K magnitudes, which are crucial for the modeling, within reasonable amounts of time. We follow this strategy to minimize the time we spend on one target and to maximize the throughput of our program.

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

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

Hainaut, Boehnhardt, Protopapa 2012, A&A, 546, L115

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

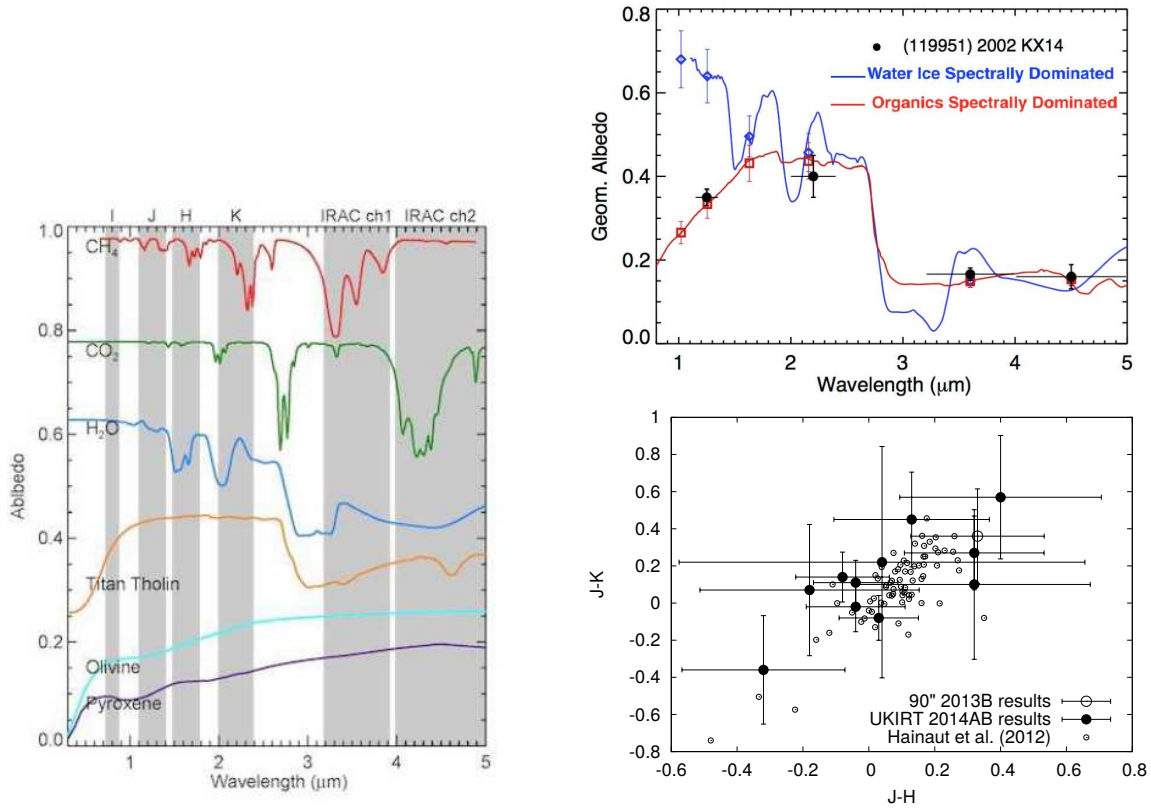

Figure 1: **Left:** Absorption spectra of CH_4, CO_2, and H_2O ices at 40 K, organic Titan tholin, and amorphous silicates olivine and pyroxene, offset in the vertical for clarity. Standard photometric filters I, J, H, K, and IRAC channels (grey bars) are shown for reference. The plot shows clear differences 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. **Top Right:** Mixing model for 2002 KX14, showing the importance of including NIR data in the modeling of Spitzer data to properly identify compositions. **Bottom Right:** Color-color representation of data gathered in 2013B, 2014A, and 2014B with 90"/PISCES and UKIRT/WFCAM. Note that despite the small sample size a trend is already visible in the data, which is even stronger after including data from the literature (Hainaut et al. 2012). For our faintest targets ($V > 22$), we will use this trend to statistically derive the target's brightness in K band from its J and H magnitudes.

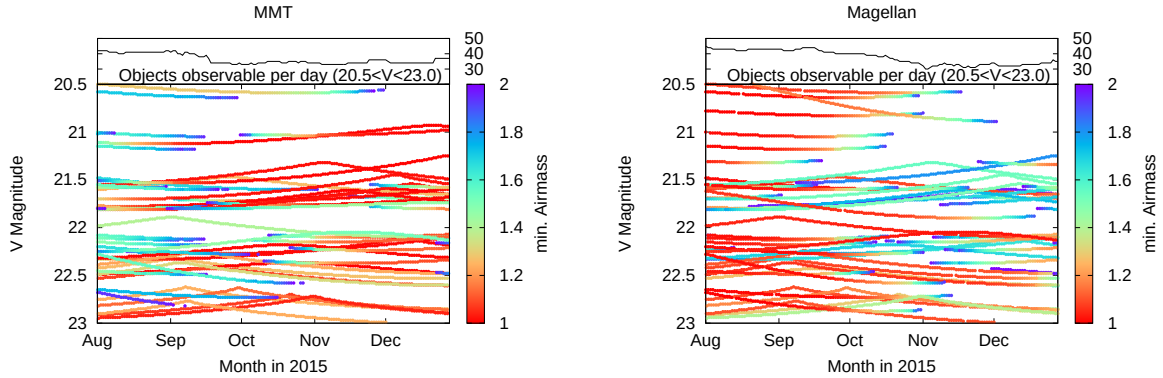

Figure 2: Target observability, apparent magnitude, and airmass distribution for our MMT (left) and Magellan (right) targets in 2015B. Observability has been derived using the JPL Horizons system; all targets have a positional uncertainty with the field of view radius and airmass < 2.0.

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, left). We aim for SNR=10 in each of these bands.

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 ($\sim$4"/hr); non-sidereal tracking might be useful but is not required. Guiding is not required.

In the past semesters (2013B–2015A) we have used 90"/PISCES and UKIRT/WFCAM to observe all available target samples with $V < 20.5$. In this program we propose for observations of the fainter targets in our sample using MMT/MMIRS *or* Magellan/FourStar. We investigated the visibility of our sample targets for both observatories using the JPL/NASA Horizons system and plot the brightness distribution and the number of available targets per night in Figure 2. We only consider targets with airmass < 2.0 and positional uncertainties within the field of view radius. In order to minimize the time spent per target and maximize the throughput of this program, we decided to observe targets with $V < 22$ in JHK bands and targets with $V > 22$ only in J and H band. We use this approach as we anticipate increased uncertainties for our faintest targets, especially in the time-consuming K band. Using a simple relation derived from existing data (Figure 1, bottom right), we can obtain statistical K magnitudes with slightly degraded quality from J and H bands. Hence, this approach allows for a significantly higher throughput of our program compared to JHK observations for each target. We estimate the performance and the throughput for both observatories in the following using conservative color estimates for our targets ($J = H = K = V - 2$):

Based on the MMIRS and FourStar exposure time calculators, we require $\sim$[1,3,10] min of exposure time to obtain SNR=10 in the [J,H,K/Ks] filter for a $V = 22$ target for both observatories. For $V = 23$, we only require 5 min in J and 10 min in H band. Including pointing and focussing, we will not spend more than 30 min on each target, allowing us to observe of the order of 40 targets in two nights. Note that more than 40 targets are observable in the optimal periods indicated above for both observatories; in the acceptable period, >30 targets are observable per night (Figure 2, left). Remaining observing time will be spend on improving the quality of our measurements by increasing total integration times per target and obtaining direct measurements of K for our fainter targets (SNR=10 in K takes $\sim$45 min for $V = 23$ targets).

After the default data reduction, the data will be processed in our sophisticated data analysis pipeline that has been used in the past for data from both 90" and UKIRT. 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), which were cancelled and turned into 90Prime observations, due to the unavailability of PISCES. Furthermore, we have been awarded 2 nights of MMT/ARIES times for this program in 2015A (TBS time). Unfortunately, ARIES was placed at the f/15 focus, which is highly undesirable for our needs. The data reduction and analysis has been completed. In this program, we ask for 2 nights of MMT/MMIRS or Magellan/FourStar.

Furthermore, we have been awarded 15 hrs (30 hrs requested) of UKIRT/WFCAM for the same project in 2014A (u/14a/ua15, PI: McCarthy), 10 hrs (10 hrs requested) in 2014B (u/14b/ua14, PI: Mommert), and 10 hrs (10 hrs requested) in 2015A (u/15a/ua07, 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 had a completion rate of 98% (6 targets observed).

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 is currently performed by master graduate student Lejoly. For 2014B, we have been awarded 19 hrs of Gemini-S/Flamingo (PI: Pinilla-Alonso, 8 targets observed, reduction in progress).

If we are granted the proposed two nights of MMT/MMIRS or Magellan/FourStar, we have observed all targets in our sample with $V < 23$. For the remaining targets in our sample, we will propose observations at Gemini or similarly large observatories in the future.

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 has been converted into a 90”/90Prime run, during which we took optical colors for Centaurs in our sample to supplement our NIR data. Data reduction and analysis are mostly completed.
- ⋆ MMT: Our 2015A MMT/ARIES observations have been processed and analyzed. However, as a result of the telescope setup (f/15), which is undesirable for our purposes due to the small field of view and the large point spread function, our data and the data calibration quality is highly degraded (large PSF, faint targets) for most of our observations. Note that the field of view for both FourStar and MMIRS are significantly larger than for our ARIES observations.
- ⋆ 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, 6 targets, completion rate 98%) have been concluded; we are currently waiting for the CASU data reduction to finish. Our 2015A observations (10 hrs, $\sim$5 targets) have not yet been started due to bad weather and the unavailability of WFCAM on UKIRT.

The results of all of our observing runs will be published summer 2015 by master graduate student Lejoly.