OBSERVING REQUEST
University of Arizona Observatories

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

Evolutionary Analysis of Nearby Debris Disks

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Abstract of Scientific Justification

Debris disks are intimately linked to the formation and evolution of planetary systems and play a key role in the detection of planetary systems. The past thirty years of infrared astronomy have led to a large number of published debris disk discoveries, however, many of these efforts resulted in published candidate pools without further confirmation. It behooves us to constrain these stars in order to investigate the evolutionary status of planetary systems. By combing through ∼200 reviewed articles, we gathered a list of 910 claimed IR excess stars in the literature. Using a state-of-the-art photosphere fitting method that includes the AllWISE survey, we also selected 1030 Tycho-2 candidate infrared excess stars showing excess in at least one AllWISE passband. Through exhaustive vetting of these candidates, we created a list of 1100 high fidelity IR excess stars. We divided these stars into several groups according to dust luminosity and brightness for further characterization. The target sample presented in this proposal includes nearby (< 125 pc), faint ($m_V > 9$ mag) stars demonstrating infrared excess requiring the sensitivity of a large, world-class instrument to obtain high resolution optical spectroscopy enabling age diagnostics and the study of planetary evolution theories. We intend to gather age information using Li 6708Å absorption, Hα emission, and radial velocity measurements to gain insight into the relationship between the age of the star and its disk. In combination with facilities at the Lick Observatory, ANU, and DAO, this project seeks a comprehensive analysis of debris disks stars not yet completed on the large scale and the data obtained will provide evidence for or against relationships between the host star, the debris disk, and ultimately planetary formation.

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	Hectochelle			2	grey	Sep-Dec	Sep-Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: There are no scheduling constraints for this proposal and any available time can be used to observe this target sample in full or in part.

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	BD+19 2735	13:58:13.52	+19:17:11.59	V=9.36
2	HD 122851	14:04:22.97	-03:28:04.66	V=10.45
3	HD 149941	16:37:35.40	+07:17:03.40	V=9.22
4	J16064385-1908056	16:06:43.85	-19:08:05.81	V=12.69
5	HD 155906	17:14:26.41	-00:42:28.95	V=9.67
6	BD+85 286	17:25:07.45	+85:06:55.90	V=9.58
7	HD 338031	19:14:14.51	+24:45:57.86	V=10.23
8	HD 189002	19:58:25.59	-14:00:43.09	V=9.59
9	HD 356704	20:05:56.29	+12:41:07.82	V=9.46
10	TYC4246-319-1	20:43:50.96	+60:28:01.37	V=9.89
11	TYC3959-578-1	20:50:50.11	+57:28:20.16	V=10.39
12	BD+62 1895	21:07:16.81	+62:53:56.09	V=9.09
13	BD+57 2298	21:12:21.66	+57:49:08.11	V=10.4
14	TYC1112-317-1	21:06:23.95	+12:51:45.52	V=10.95
15	TYC1113-1057-1	21:13:03.33	+13:01:08.46	V=10.98
16	HD 215294	22:44:14.02	-09:01:23.97	V=9.04

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
Tara Cotten	I. Song		no	yes

Scientific Justification

The discovery of the first debris disk star, Vega (Aumann et al. 1984), demonstrated the capabilities of using infrared photometry as a tracer of debris in stellar systems. Since this finding, nearly 1000 journal articles have been published that discuss various aspects of debris disks from dust detections to direct imaging of planets. Debris disks have been shown to contain both small grains and larger, planetesimal sized objects similar to the Kuiper Belt of our Solar System (Wyatt 2008). Additionally, the dust seen in debris disks such as Vega requires the continual replenishment from larger bodies (Backman & Paresce 1993). Therefore, debris disks serve as the best targets for a study of the evolution of planetary systems, since they provide various environments across a multitude of ages (Zuckerman & Song 2004a).

Through examination of the connection between debris and planetesimals, Matthews et al. (2014) summarizes interesting trends between a disk and other physical parameters including multiplicity, metallicity, and stellar rotation. In particular, Maldonado et al. (2012) and Marshall et al. (2014) searched for a trend between debris disks and planets given their direct connection. Maldonado et al. reported that the presence of a planet dictated the metallicity, in agreement with Fischer & Valenti (2005) who pointed to a positive correlation between higher metallicity stars and planet host stars. Marshall et al. (2014) whose sample consisted of known exoplanet host stars, was limited by a small sample and unable to make any strong predictions. Rodriguez & Zuckerman (2012) approached the topic of multiplicity to better understand the nature of dust around multiple systems and with a sample of 28 sources they found a hint of multiple stars having more rapid disk dispersal rate. Further, Mizusawa et al. (2012) and references therein describe connections between the debris disks and the rotation of the host star. They found that rapid rotators have the highest percentage of excess but point out the necessity for better ages and metallicity measurements for many of their stars. These interesting results are limited by their small samples, thus, heralding the need for a larger sample in order for confirmation or refutation regarding the theories of star-disk-planet interactions.

Our creation of a large, comprehensive census of debris disks, began with the selection of over 200 publications which identify over 1200 infrared excess candidate stars. These studies used either pointed observations from telescopes such as *Spitzer* (Bryden et al. 2006; Chen et al. 2006) or all-sky surveys such as IRAS or WISE (Rhee et al. 2007; Patel et al. 2014) and many further restricted their samples based on spectral type (Smith & Wyatt 2010; Avenhaus et al. 2012), reliable distance using trigonometric parallax from the Hipparcos catalog (Wu et al. 2013), or cluster membership in order to invoke a reliable age estimate (Carpenter et al. 2009; Zuckerman et al. 2011) to name a few. To ensure the largest sample and include the most recent all-sky survey, AllWISE, we also cross-correlated the 2 million objects in the Tycho-2 catalog with the $\sim$ 750 million objects in the AllWISE catalog using a similar technique of Schneider et al. (2013). Through meticulous examinations of SEDs and AllWISE images we produced the most reliable, comprehensive list of 1700 infrared (IR, hereafter) excess stars to date (see experimental design a detailed procedure for selecting new IR excess stars). We created priority assignments based on fractional dust luminosity (defined as $\tau \equiv L_{IR}/L_*$), distance, evolutionary status and brightness such that this multi-facility project emphasizes the capability of each proposed instrument. Restricting the sample of 1100 stars to be within 125 pc and without previous archival optical spectra available yielded a sample of 598 stars. Following the incentive of obtaining age information for these targets, the proposed sample was restricted to F type or later stars and a brightness cut of visual magnitude$>$ 9 was applied since MMT can observe the faintest objects. Of the 150 stars, we propose to obtain spectra for 16 northern hemisphere IR excess stars which are observable from MMT.

Constraining the age of a star is known to be the most challenging piece of information to attain and yet it is the most necessary for an evolutionary analysis. We will use the age-dating schema of Zuckerman & Song (2004b; displayed in their Figures 3 and 5) by measuring the equivalent width (EW) of age indicators such as Li 6708Å and Hα (6563Å). Zuckerman & Song (2004b) compared the measured lines to a range of cluster ages for solar type stars to generate the best estimate of individual stellar ages. We will also use line measurements of the FWHM from the observed spectra and arc lamp to compare the broadening due to rotation of the star and the intrinsic broadening of the instrument. In this way, we will deduce a rotational velocity measurement. Finally, through observations of similar spectral type radial velocity standards, we will cross-correlate the observed spectra to obtain a radial velocity measurement which we will use to obtain

kinematic information for these Tycho-2 stars. The kinematic information will allow for cluster membership analysis only capable if a precise radial velocity measurement is available and kinematic analysis will further constrain/complement our age diagnostics. Since this is a multi-facility project, the optical spectra obtained for stars through other instruments should be similar because we are seeking comparable high resolution optical spectroscopy.

Many studies performed similar searches for IR excess to our Tycho-2 and AllWISE cross-correlation although any follow-up stellar information has yet to be assembled. Specifically, Patel et al. (2014) produced a sample of 220 stars with infrared excess in WISE within 75 pc of the Earth and Wu et al. (2013) found 141 nearby *Hipparcos* stars with WISE excess at 22μm, but were unable to advance understanding of the star-disk evolution with only dust information. Chen et al. (2014) marginally investigated the evolution of dust around a collection of stars limited by the requirement for available infrared spectroscopy from *Spitzer* IRS. With the release of the AllWISE all-sky mid-infrared mission and the advent of new infrared missions still a few years in the future, this study is a last chance to fully characterize an important sample of IR excess stars. The goal of characterizing this large debris disk population by obtaining stellar and age information would triple the number of well-studied disks and enable more realistic interpretations of the correlations discussed above as well as provide a better picture of the temporal evolution of dust. In particular, we will consider the possible relationship between stellar rotation and dustiness. In full, this project will comprise $>$1100 infrared excess stars of all spectral types, ages, metallicities, and dustiness in order to complete the census of nearby debris disk stars.

We have already begun the optical spectroscopy follow-up of a number of northern hemisphere targets displaying high fractional dust luminosity using the Lick Hamilton spectrograph. In addition, we have begun observations for the Southern Hemisphere targets through collaboration with S. Murphy and W. Lawson at ANU 2.3m. This proposal for the MMT Hectochelle optical spectra focuses on the faintest infrared excess stars from our census. Aquiring age, rotational, and radial velocity information for the proposed sample of stars will build upon previous studies and enhance candidate exoplanet searches and star-disk relationships. The spectroscopic information obtained in this proposal will be included in the dissertation of Tara Cotten which will offer a complete census of nearby debris disks with the intent of constraining the criteria for a bone-fide debris disk star and offering future exoplanet survey targets.

References

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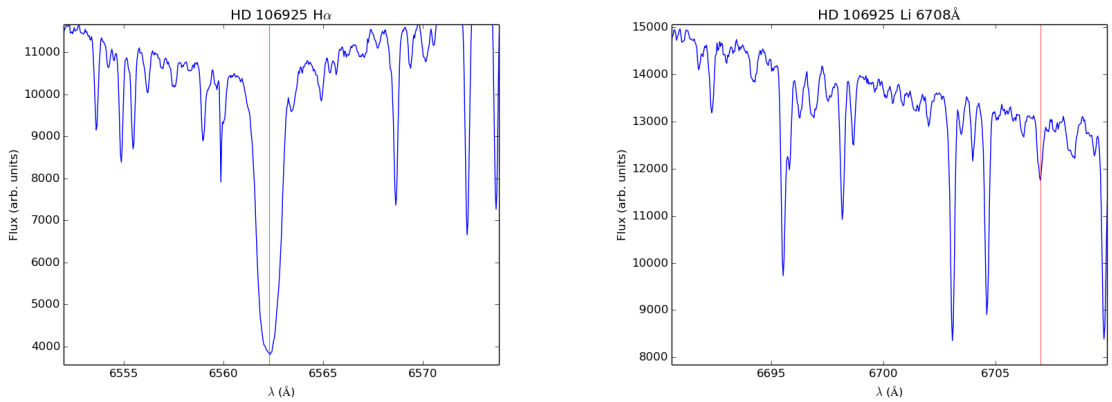

Figure 1: Spectra obtained during the previous trimester for target: HD106925. These spectra have not yet been flux calibrated through the use of our standard and so the flux is displayed in arbitrary units. This star is a G5 star and shows distinguishable Hα and Li 6708$\AA$ features above the noise. This is necessary for our age diagnostics for this star, which show that excess has no previous indication of age.

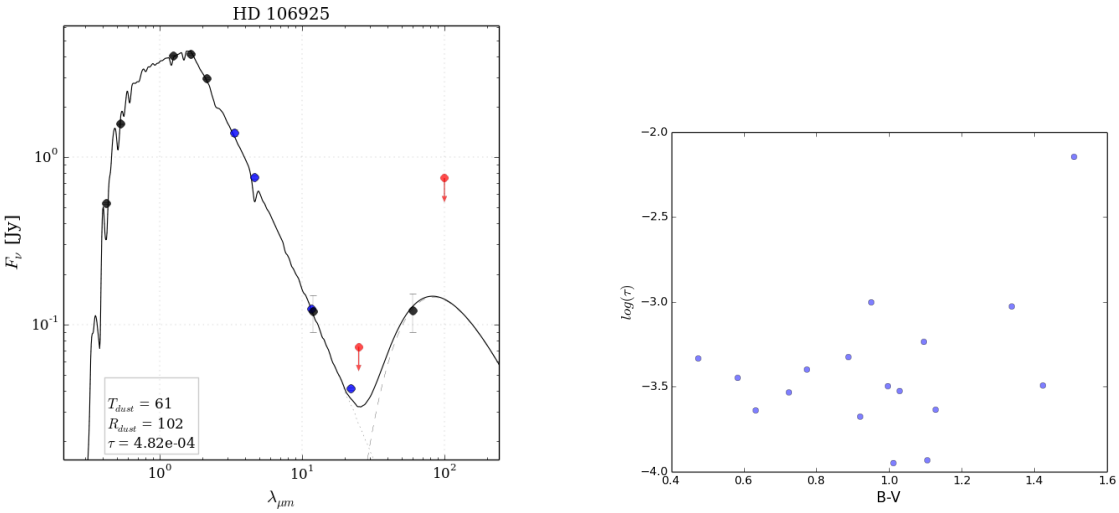

Figure 2: SED for the target already observed during the last trimester (left) and a plot of the various fractional dust luminosities for the stars proposed during this round (right). The SED shows photometry from Tycho B, V, 2MASS J, H, and K and WISE channels 1-4 as well as IRAS data and upper limits (from left to right). The plot of fractional luminosities shows the range of dust significance for these debris disk stars and also confirms that the targets are the correct spectral type to detect lithium in the photosphere and use it as an age indicator.

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)***

We propose to obtain high resolution optical spectrometry using Hectochelle for a distinct sample of high fidelity infrared excess stars lacking stellar, in particular, age, information. Initially, we collected $\sim$ 1200 stars published as infrared excess stars from almost 200 journal articles. Since each study used a different excess criteria we then confirmed infrared excess using our automated SED fitting tool and screened each star using the four AllWISE images. This secondary check of claimed infrared excess yielded a sample of 910 stars. To generate a complete survey of stars with infrared excess, we cross-correlated a nearby Tycho-2 sample using proper motion as a proxy for distance ($\mu \gtrsim$ 25 mas yr^{-1}) with the entire AllWISE catalog ($\sim$ 747 million objects). This sample was subject to having reliable AllWISE measurements in all four passbands and main sequence colors. Using the fully automated SED fitting tool, we selected 1030 stars with infrared excess at either the 12μm or 22μm passband and examined the AllWISE images to exclude all false positive detections such as a nearby contaminating source or spurious AllWISE photometry. The combination of these two searches produced a list of 1100 high fidelity infrared excess sources, excluding the number of duplicate stars expected from combining our two searches and also excluding stars demonstrating excess indicative of an early stage of star formation (i.e. T-Tauri). The remaining target selection cuts relevant for this proposal ensure a nearby (d$<$ 125 pc), faint ($V > 9$ mag), sample of F through M type stars without available optical spectra which would benefit from observations using the MMT Hectochelle instrument: this produced 150 objects. We narrowed the target list to 16 stars based on the observable northern hemisphere range available during the 2015B semester and targets not previously proposed to other instruments.

Using the Hectochelle instrument, we plan to obtain optical spectra at a resolution of R$\sim$ 30,000. To effectively obtain stellar parameters, we need to measure EWs with an uncertainty as small as $\pm$ 10 mÅ, which will also lead to radial velocity measurement errors of $\sim$1 km/s. Due to the size of the telescope, we have limited the sample by selecting those stars with V $>$9 mag which would require extremely long exposure times on a smaller telescope. An estimate of on source time for a typical object (V=12 mag) in the target sample would be up to an half hour under the condition of achieving a S/N $>$ 50. In addition to the expected overhead times which include slew, calibration exposures, and readout time (using the smallest binning option), we predict the faintest object can be observed in an hour. In total, we request 2 nights to complete the MMT Hectochelle observations taking into account the possibility for bad weather.

Age diagnostics performed on each infrared excess star in our high fidelity sample will produce the largest scale study of the temporal evolution of disks. The sample proposed here enables a complete the sample of the faintest northern hemisphere infrared excess stars which lack accurate stellar properties necessary for a full characterization. By obtaining the EW of Li 6708Å and Hα we propose to obtain age information regarding these debris disk systems and better constrain the evolution of circumstellar material surrounding these stars. We will use the OB26 filter centered on 6707Å for the detection of both lines simultaneously. Rotational velocity, $v \sin i$, will be measured through analysis of the spectral lines using IRAF to measure the broadening produced by the rotational velocity compared to instrumental broadening measured through the calibration (ThAr) lamp and to search for doublets produced by multiplicity. Lastly, comparison radial velocity standard stars will be observed and then compared to the target spectra we obtain here. Under the conditions for high S/N, we plan to obtain radial velocities accurate to within 10km/s for stars which have no prior radial velocity information.

In addition to the spectra obtained in this proposal, we will complete the characterization of these debris disk stars by simultaneously obtaining spectra through collaborative efforts using ANU, Lick Observatory, and DAO. The debris disks presented in this proposal will finalize observations for the remaining northern hemisphere sample, thus contributing significantly to the goal of accumulating a comprehensive picture of debris disks.

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**)*

1 - UAO Telescope Time
This project was given 2 nights of UAO time prior to this proposal. We estimate 2 nights of observing to acquire high resolution optical spectrometry of 16 high fidelity infrared excess stars in addition to a couple of radial velocity standards (not included in the target list) should be sufficient. The proposed number of observation nights includes a 30% bad weather estimate. We estimate a similar number of nights during the final trimester of UAO time

2 - non-UAO Telescope Time
Currently, our collaborators through the University of California system are pursuing roughly 63 additional bright northern hemisphere infrared excess stars. Northern, bright (visual magnitude < 7) will be observed during 4 nights this quarter using DAO to complete the stellar characterization for this infrared excess sample. Previous observations yielded over 30 useful spectra for the brightest objects and a large contribution to the final sample. We have acquired 4 nights of DAO time again this semester for the brightest targets in the sample, which has surprisingly high resolution, because these stars would be overkill for a larger telescope and the observations would be dominated by overhead times. In addition, through Australian collaboration, we intend to obtain spectra for the remaining southern hemisphere targets (43% of our final sample which lacks optical spectra) using the ANU 2.3m telescope. In addition to these observations, a total of 447 stars with archival optical spectroscopic data using instruments such as FEROS, UVES, HARPS, ELODIE, SOPHIE, and Hamilton will be examined in order to measure the stellar parameters discussed above. The UAO observations obtained in this proposal will complete the northern hemisphere census of nearby debris disk stars.

3 - Collaborations This project is a long-standing collaborative effort between ASU, UGA, and other partner institutions. J. Patience has been involved with this study in the characterization of a large group of infrared excess stars, and her students at ASU (A. Rajan, K. Ward-Duong) will participate in the data reduction and analysis with T. Cotten, graduate student of I. Song at UGA. T. Cotten will have a lead role in publications from this survey, including outstanding targets, as part of her dissertation project. S. Murphy and W. Lawson are in collaboration through the use of the ANU Observatory 2.3m Telescope in Australia. Finally, C. Melis and B. Zuckerman have been participating in this project from the beginning and observing northern hemisphere stars when available. The amalgamation of these observations as well as archival data will be summarized in a paper written by T. Cotten following the completion of these observations.

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**)*

The previous proposal through UAO was allocated 2 nights in the month of February during 2015A under program number 291. These two nights contained just over 5 hours of observational time, under which 12 targets were observed. The data for these targets are in the process of being reduced, however, one target HD 106925 has been included in Figure 1 demonstrating the ability to successfully measure Hα and Li. The spectra presented have not yet been fully reduced (i.e.. lacking necessary flux calibration) but the ability to distinguish Hα and Li from the continuum is evident.

Debris disks and evolutionary analysis - Allocations and Papers:
MMT: 2015A-UAO-S291 - Evolutionary Analysis of Nearby Debris Disks - *PI: Patience (2 nights)* - 100% (estimated from preliminary data reduction).
⋆ **Bulger et al. 2013**, *Submillimeter observations of IRAS and WISE debris disk candidates*, A&A, 556, 119 - Debris disk identification project that includes MMT data.

Companion Search - Allocations and Papers:
LBT: 2015A-UAO LBT low mass Taurus companion search - *PI: Patience (1.5 nights)* - 60% useful.
Magellan: 2014B-UAO - MagAO GPI target companion search - *PI: Ward-Duong (2 nights)* - 100% useful, **2013B-UAO - FourStar GPI target companion search** - *PI: Patience (2 nights)* - not useful.
MMT: 2015A-UAO-S236 - ARIES B-star companion search - *PI: Patience (3 nights)* - 15% useful, **2015A-UAO-S239 - ARIES M-star companion search** - *PI: Ward-Duong (2 nights)* - 60% useful, **2014B-UAO-S39 - ARIES M-star comp. search** - *PI: Ward-Duong (4 nights)* - 20% useful, **2013A-UAO-S2 - ARIES A-star companion follow-up** - *PI: De Rosa (4 half-nights)* - 50% useful.
•**Patience et al. 2014**, *The TBOSS (Taurus Boundary of Stellar/Substellar) Survey of Disk Properties*, 2014 IAUS, 299, 224 - Sample for follow-up projects, including LBT proposal.
•**Bulger et al. 2014**, *The Taurus Boundary of Stellar/Substellar (TBOSS) Survey I: far-IR disk emission measured with Herschel*, A&A, 570, 29 - Sample for follow-up projects, including LBT proposal.
•**Ward-Duong et al. 2015**, *The M-dwarfs in Multiples (MinMs) survey - I. Stellar multiplicity among low-mass stars within 15 pc*, MNRAS, in press - Includes MMT data.
Companion Characterization - Allocations and Papers:
LBT: 2013A - Thermal-IR substellar companion measurements: - *PI: Patience (1 night)* - 50% useful.
MMT: 2015A-UAO-S240 - ARIES substellar spec. characterization - *PI: Rajan (1 night)* - 80% useful, **2013C-UAO-S11 - ARIES substellar spec. characterization** - *PI: Ward-Duong (2 nights)* - 0% useful, **2014A-UAO-S1 - ARIES substellar spec. characterization** - *PI: De Rosa (4 nights)* - 25% useful.
• **De Rosa et al. 2014**, *Debris Disks and Multiplicity within the 75pc Volume-limited A-Star (VAST) Survey* 2014 IAUS, 299, 334 - Includes MMT data.
• **De Rosa et al. 2014**, *The VAST survey - IV. A wide brown dwarf companion to the A3V star ζ Delphini*, MNRAS, 445, 3694 - Characterization most similar to MMT proposal, includes MMT data.
• **Maire et al. 2015**, *The LEECH Exoplanet Imaging Survey. Further constraints on the planet architecture HR 8799 system*, A&A, in press.
Brown dwarf Atmosphere Monitoring - Allocations and Papers:
MMT: 2012A-UAO-S3 - SWIRC brown dwarf (BD) variability monitoring - *PI: Patience (2 nights)* - 75% useful, **2013A-UAO-S99 - SWIRC BD variability monitoring** - *PI: Rajan (2 nights)* - 0% useful.
• **Wilson, Rajan, and Patience 2014**, *The Brown-dwarf Atmosphere Monitoring (BAM) Project I: Multi-epoch monitoring of extremely cool brown dwarfs*, A&A, 566, 111 - The paper established the code and observing practices for all current and future BAM projects, including the MMT proposal.
• **Rajan et al. 2015**, *The Brown-dwarf Atmosphere Monitoring (BAM) Project II: Multi-epoch monitoring of extremely cool brown dwarfs*, MNRAS, 448, 3775 - Includes MMT data.