OBSERVING REQUEST
University of Arizona Observatories

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

Investigating the limits of multiple star formation and the origin of the brown dwarf desert

P.I.: Jennifer Patience (Arizona State University; *jennifer.patience@asu.edu*;)

CoI(s): Gaspard Duchêne (UC Berkeley), Rob De Rosa (UC Berkeley), J. Bulger (ASU), K. Ward-Duong⋆ (ASU), A. Rajan⋆ (ASU)

Abstract of Scientific Justification

We propose to use the MMT adaptive optics systems with ARIES to conduct a survey for the lowest mass stellar companions to B-type stars in three young nearby open clusters. The immediate objective of the project is to determine the frequency of "extreme" mass ratio systems ($q < 0.1$) among close visual binaries. Such systems are remarkably rare for solar-type stars ($\approx 1\%$), as indicated by the existence of the so-called brown dwarf desert. This phenomenon reveals a fundamental limit of the (multiple) star formation process which has two main possible interpretations: 1) an absolute companion mass limit that happens to roughly coincide with the substellar limit, or 2) a mass ratio limit, whereby accretion during the early stages of star formation precludes the existence of such asymmetric systems. The goal of this project is to take advantage of the independence of the mass ratio distribution with stellar mass to search for scaled up proxies of brown dwarf desert-like systems. By focusing on stars in the 3–8 $M_\odot$ range, we can unambiguously disentangle between the two possible scenarios. Thus, the proposed data will provide crucial limits of multiple star formation and on the origin of the brown dwarf desert. Here we propose to survey 60 B-type stars stars located in three nearby, young open clusters ($D \leq 350$ pc, 30–90 Myr).

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/30	ARIES	*	*	2.5	bright	Jan–Jan	Jan–Feb	no	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	α Per	03 22 00	+48 37 00	Open Cluster, 30 B-type stars
2	Collinder 65	05 26 05	+15 41 59	Open Cluster, 15 B-type stars
3	Platais 6	06 15 25	+03 55 12	Open Cluster, 15 B-type stars

Approval for Instrument Use from PI: 'See attached e-mail from Don 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
K. Ward-Duong	J. Patience	Jennifer Patience	no	no
A. Rajan	J. Patience	Jennifer Patience	no	no

Scientific Justification

This proposal aims at understanding one of the empirical limits of star formation, namely the formation of close visual binaries with extremely unbalanced mass ratios. These are extremely rare for solar-type stars but the fundamental reasons for this fact remain an open question, which we will tackle by searching for "scaled-up" systems consisting of low-mass companions to 3–8 $M_\odot$ stars.

Stellar multiplicity is thought to be the outcome of turbulent fragmentation of a collapsing prestellar core (Tohline 2002). Very low mass "seeds" (5–10 M_{Jup}) form and subsequently accrete from their parent core to reach their final mass. This inherently stochastic process is best probed by the ensemble population of multiple systems, i.e., the distribution of mass ratios ($q = M_2/M_1 \leq 1$). The observed distribution for visual binaries is remarkably uniform for stars with $0.3\,M_\odot \lesssim M_\star \lesssim 8\,M_\odot$ (Reggiani & Meyer 2013; Duchêne & Kraus 2013). This suggests that fragmentation and accretion on the seed binary proceed in a scale-free manner and can be studied by focusing on any population within this range (high-mass stars form through a different path; e.g., Zinnecker & Yorke 2007).

The brown dwarf (BD) desert is the remarkable dearth of 20–50 M_{Jup} companions to solar-type stars from short orbital periods to projected separations of at least 300 au [1] (e.g., Grether & Lineweaver 2006; Chauvin et al. 2010; Leconte et al. 2010). Besides confirming that planetary mass and stellar companions are physically distinct, the BD desert raises the question of the physical mechanism that sets a lower limit to the mass of stellar companions. **Is the conjunction of this limit with the stellar/substellar boundary a mere coincidence or a profoundly revealing fact?** Specifically, is the lower limit for stellar companions effectively set at around the substellar limit ("fixed mass" limit), or is it instead an indication that binaries simply cannot form with more extreme mass ratios ($q \lesssim 0.1$, "fixed q" limit)? Either way, this phenomenon points to a fundamental limit in the physics of (multiple) star formation that is not yet understood.

Further observations of solar-type stars cannot resolve this ambiguity. Instead, the key idea behind this project consists in searching for extreme mass ratio companions to stars of different masses, for which the substellar boundary corresponds to a much different mass ratio. Low-mass stars seem to have a dearth of BD companion (e.g., Dieterich et al. 2012), hinting at a "fixed mass" limit, but detecting substellar objects around (on average very old) low-mass stars remains a steep observational challenge. Instead, **we propose to take the opposite route and to consider stars that are significantly more massive than the Sun, as a scaled-up proxy for BD-desert-like systems.**

Surveys of A- and F-type stars (1.5–2 $M_\odot$) have revealed a paucity of BD companions (e.g., Kouwenhoven et al. 2007; Janson et al. 2013), but the distinction between the "fixed mass" and "fixed q" scenarios is too narrow to be conclusive. To address this issue more effectively, **we propose to determine the mass ratio distribution of close visual binaries, and especially its low-q end, for 3–8 $M_\odot$ (B3 to A0) stars, for which the gap between the "fixed mass" and "fixed q" limits is broad enough for a statistically significant conclusion.** Past companion searches to B-type stars (e.g., Duchêne et al. 2001; Shatsky & Tokovinin 2002; Leconte et al. 2010; Janson et al. 2011) could only detect faint stellar companions outside of $1''$ ($\gtrsim$200 au), facing serious confusion issues and effectively probing a different separation range than that of the BD desert. Here we propose to take advantage of the remarkable PSF stability provided by the MMT adaptive optcs system to probe low-mass stellar companions within the central $1''$. A substantial population of companions in the 0.075–0.5 $M_\odot$ range (well above the $\sim$1% characterizing the BD desert for solar-type stars) will readily exclude the "fixed q" limit scenario. On the other hand, a rarity of such companions would indicate that the accretion phase that follows the formation of "seeds" functions as an efficient regulator, precluding the formation of extremely unequal systems.

To ensure sample homogeneity and to maximize linear resolution for this present proposal, we have selected three Northern open clusters which share similar distances and ages: α Per, Collinder 65 and Platais 6. These clusters are nearby ($\approx$180–350 pc; van Leeuwen 2009; Kharchenko et al. 2005), ensuring that the proposed observations will probe companions at projected separations $\approx$50–300 au, i.e., well within the BD desert range. Also, these clusters span a range of age from 30 to 90 Myr (Stauffer et al. 1999; Kharchenko et

[1] While "extreme" binary systems ($q < 0.1$) may be somewhat more common at even wider separations (Metchev & Hillenbrand 2009), we note that these systems may form through different processes.

al. 2005), i.e., young enough age that 3–8 $M_\odot$ stars are still on the Main Sequence, while their lowest mass companions are nearing the zero-age Main Sequence, which will enable a straightforward mass determination for the companions. Based on decades of studying these bright stars, the membership list of these clusters for intermediate- to high-mass stars is essentially complete and free of outliers. Specifically, we have used the following selection criteria: (extinction-corrected) $B - V \leq 0$ to select A0 and earlier -type stars; $R \leq 10$ to ensure good adaptive optics performance; and the absence of known close stellar companion in the Washington Double Star catalog as well as in archival HST and ground-based adaptive optics images to avoid adaptive optics guiding issues and saturation on bright companions. This leaves us with a list of 60 B3–A0 stars[2]. We will submit a proposal to observe B-type stars in three other clusters in semester 2015B to achieve sufficient statistical confidence. To place our results into a more global context, we also plan on surveying a significant population of field B-type stars, whose formation process may be different. In this proposal, we only plan on observing a few field stars when our targetted clusters are at too low elevations for good adaptive optics correction, but will later submit a dedicated proposal, based on a list of $\sim$100 field B-type stars within 100 pc of the Sun.

One key advantage of studying 3–8 $M_\odot$ stars is that even extreme mass ratio systems have companions in the stellar regime, which translates into much less stringent requirements on the achieved contrast compared to previous searches for substellar companions. As shown in Fig. 1, a contrast of $\Delta K \approx 9$ mag is sufficient to detect almost all stellar companions to stars with $M \leq 7\,M_\odot$. Still, such contrasts were only accessible outside of $1''$ in previous surveys and only companions with masses $\gtrsim 0.7\,M_\odot$ could be detected closer in. In other words, while the challenge of detecting extreme stellar binary systems is a comparatively easy one (relative to current exoplanet imaging searches), it has not been possible to address it in the separation range of the BD desert with past instrumentation (see Fig. 2). The proposed observations, taking advantage of the high quality and great stability of the PSF produced by the MMT adaptive optics systems will fill in this critical gap and help address the fundamental question of the nature of the brown dwarf desert.

References:

Allard et al. 1997, ARAA, 35, 137
Chauvin et al. 2010, A&A, 509, A52
Dieterich et al. 2012, AJ, 144, 64
Duchêne et al. 2001, A&A, 379, 147
Duchêne et al. 2007, A&A, 476, 229
Duchêne et al. 2013, A&A, 555, A137
Duchêne & Kraus 2013, ARAA, 51, 269
Grether & Lineweaver 2006, ApJ, 640, 1051
Hunsch et al. 2003, ApJ, 698 1989
Janson et al. 2011, ApJ, 736, 89
Janson et al. 2013, ApJ, 773, 170
Kharchenko et al. 2005, A&A, 438, 1163
Kouwenhoven et al. 2007, A&A, 464, 581
Lafrenière et al. 2007, ApJ, 660, 770
Leconte et al. 2010, ApJ, 716, 1551
van Leeuwen 2009, A&A, 497, 209
Metchev & Hillenbrand 2009 , ApJS, 181, 62
Raghavan et al. 2010, ApJS, 190, 1
Reggiani & Meyer 2013, A&A, 553, A124
De Rosa et al. 2014, MNRAS, 437, 1216
Shatsky & Tokovinin 2002, A&A, 382, 92
Smiljanic et al. 2011, A&A, 535, A75
Stauffer et al. 1999, ApJ, 527, 219
Tohline 2002, ARAA, 40, 349
Zinnecker & Yorke 2007, ARAA, 45, 481

[2]The list can be provided as needed.

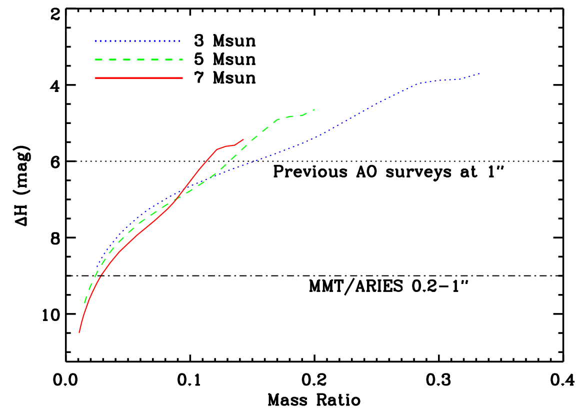

Figure 1: Relation between mass ratio K-band flux ratio for 3 $M_\odot$, 5 $M_\odot$ and 7 $M_\odot$ primary stars (blue, green and red curves, respectively) for an age of 50 Myr appropriate for our targets, based on the evolutionary models of Allard et al. (1997). Only stellar companions with masses in the 0.075–1 $M_\odot$ are shown here. The depth achieved by previous AO surveys of B-type stars at a separation of 1″ (Duchêne et al. 2001; Shatsky & Tokovinin 2002; neither could probe companions with $q \lesssim 0.1$ within 1″ of the target star) and the expected depth throughout the 0.″2–1″ range of of the MMT/ARIES observations proposed here are also indicated.

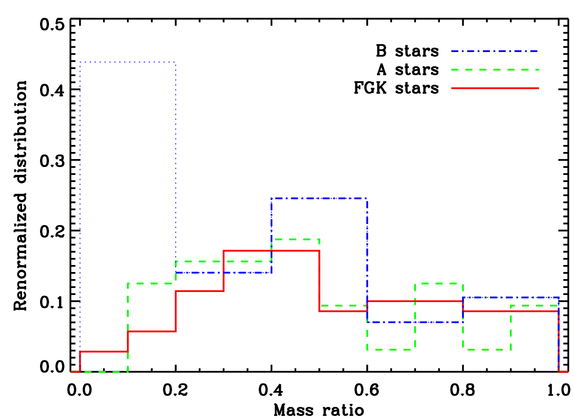

Figure 2: Mass ratio distribution for B-type, A-type and solar-type stars for visual binaries (blue, green and red histograms, respectively), renormalized over the whole [0,1] range for comparison purposes. The solar-type distribution (measured from 20 to 300 au; Raghavan et al. 2010) is the only one that is robustly estimated below q=0.1; the actual frequency of companions in this range is about 1–2% (Metchev & Hillenbrand 2009; Raghavan et al. 2010). The intermediate-mass stars distribution (measured from 20 to 125 au; De Rosa et al. 2014) is cut at the $q = 0.15$ completeness limit. Finally, the peak at low-q for B-type stars (Shatsky & Tokovinin 2002) is overwhelmingly dominated by companions outside of 300 au and severely affected by confusion and small number statistics. That survey is therefore not a reliable probe of extreme mass ratio systems.

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**)*

The immediate objective of our program, finding the lowest mass *stellar* companions within 300 au of B-type stars requires a combination of high spatial resolution and high contrast that has long proved too challenging. The former is now routinely delivered by adaptive optics systems on large ground-based telescopes, such as the MMT system in the near-infrared. High contrast, such as necessary to discover substellar and planetary companions to nearby stars has focused on projected separations beyond $1''$, combining coronagraphy with advanced PSF subtraction methods (such as spectral and angular differential imaging). With state-of-the-art instrumentation (including so-called "extreme" adaptive optics systems), it now possible to achieve contrast ratios $\Delta K \gtrsim 12$ mag within the central $1''$. This is much more than necessary for the present project, for which a contrast of $\Delta K \approx 9$ mag is sufficient to detect virtually all stellar companions to B-type stars given the age of the clusters under consideration (see Figure 1). Instead, we propose to take advantage of the extremely stable PSF provided by the MMT adaptive optics system to build up high signal-to-noise and to reduce speckle noise in the immediate vicinity of the star to enable effective PSF subtraction. Typical surveys for stellar multiplicity use $\sim$10 short, unsaturated exposures, yielding a contrast of 6 mag outside of $0\farcs3$ and 8 mag at $1''$ on 8m-class telescopes (e.g., Duchêne et al. 2001, 2007, 2013). To achieve the deeper contrast needed for this program, we will gather several tens of such exposures for each target, which will allow for a good suppression of quasi-static speckles and for high signal-to-noise in the PSF wings.

Our targets are bright at optical wavelengths ($R \lesssim 9$), ideal for adaptive optics guiding. We will conduct this survey in the K band, giving up the highest possible angular resolution in exchange for optimum quality and stability of the adaptive optics correction. Companions detected in real time will be followed-up with J and H observations to obtain color information, which will prove important to confirm the physical link with the primary target. The extreme mass ratio systems we are interested in, however, will most likely not be detected before post-processing and we will request dedicated follow-up time in another semester. Since our targets are relatively bright ($6 \lesssim K \lesssim 9$), there is a risk of saturating the target with broadband filter imaging. Depending on observing conditions and the availability of a faster readout mode, we will use either narrow band filter, a neutral density filter, and/or subaraay readout. It is important to conduct the entire survey with a single filter in order to build a large library of potential PSF stars. Ultimately, we anticipate spending 15 min clock time acquiring images of a given target.

Our observing strategy will use the fixed pupil orientation (and its associated pattern of quasi-static speckles) to improve the quality of PSF subtraction. With observations of 60 targets of similar brightness, our observations will enable a LOCI-like PSF subtraction (Lafrenière et al. 2007) which will substantially improve the achievable contrast even in the central arcsecond. We emphasize again that the performance requirements for this project are much less stringent than those of recent surveys for substellar and planetary-mass companions. The performance required here is best matched to the capabilities of the MMT AO system.

While our observing strategy will result in field rotation, we are not designing the program to use the angular differential imaging technique, since most stars will not be observed with enough field rotation (as we follow the cluster through transit, only a few sources will have significant rotation in 15 min clock-time). Therefore, we do not expect to gain significantly from this approach overall. Considering the large-scale survey nature of the project, a full angular differential imaging approach would be prohibitive.

Since our targets are bright and observations will be conducted on-axis (with dithers of a few arcsecond), we do not anticipate any complication beyond nominal overheads (primarily 15 min for the acquisition of each target. With 60 targets, we thus request about 30h of telescope time, or six half-nights. The ideal schedule is January (first half-nights), so that we can track the targets at the highest possible elevation. Observations in February could be acceptable, with the last two hours of the half-night devoted to observations of field B-type stars in order to compare their proposerties to their clustered counterparts.

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 is the first time we propose to conduct this project. In order to observe B-type stars in other nearby open clusters, as well as among a similar-sized sample of field B-type stars, we anticipate requested an additional 7–8 nights over the course of the next 3 three semesters. Particularly interesting systems, with companions just above the substellar limit will warrant additional follow-up (spectroscopic and/or photometric) observations, which will be requested separately.

2 non-UAO Telescope Time

A parallel proposal is being submitted to the Lick Observatory requesting time with the Lick AO system. The Lick is for the nearer and the MMT is for the farther away targets.

3– Collaborators

Patience and her group are involved in several large survey programs – The **VAST** (Volume-limited A-STar) snapshot survey, and the **IDPS** (International Deep Planet Search) current AO system survey. Patience is the PI of the VAST survey which combined AO telescope access across a partnership of $\sim$10 collaborators to observe $\sim$250 A-stars. Patience is a co-I of the IDPS survey, which targets $\sim$250 young M-B stars, with primary responsibilities related to the B/A-star sample.The "Taurus Boundary of Stellar/Substellar" (TBOSS) collaboration. The collaboration is lead by Arizona State (PI: J. Patience). The **BAM** (Brown dwarf Atmosphere Monitoring) Project. Patience is a co-I of the BAM program that was extended to observe fainter brown dwarfs at the MMT. Publications and papers in progress from these surveys are listed below. Patience, De Rosa, Rajan, and Ward-Duong are Co-Is of the recently initiated **LEECH** LBT survey and the upcoming **GPIES** Gemini survey for imaged planets in the North and South, and her group has contributed to defining the target sets for both programs and some early observations with both instruments.

VAST publications thus far are primarily student/postdoc-led: De Rosa et al. 2011 [**X-ray A-stars**], De Rosa et al. 2012 [**A-star orbits**], De Rosa et al. 2014, [**A-star binary statistics**], De Rosa et al. 2014 [**A-star brown dwarf detection**], Patience et al. 2014, in prep [**A-star debris disk binaries**], Schneider et al. 2014, in prep [**A-star binary age estimates**]. The IDPS A-star subset has been published by a postdoc working with Patience: Vigan et al. 2012 [**IDPS A-star initial results**]. The TBOSS publications thus far are student-led: Bulger et al. 2014 [**Herschel Disk Study**], accepted A&A. Rajan et al. 2014 [**TY pilot study**], received referee report; Wilson, Rajan, Patience 2014 [**LT large scale survey**], 2014, A&A, 566, 111.

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)***

Companion Search - Allocations and Papers:

Magellan: 2013B - FourStar search for companions to GPI targets - *PI: Patience (2 nights)* - not useful
MMT: 2013A-UAO-S2 - ARIES A-star companion follow-up - *PI: De Rosa (4 half-nights)* - 50% useful, **2013B-UAO-S2 - ARIES A-star companion follow-up** - *PI: De Rosa (1 night)* - 75% useful, **2013C-UAO-S10 - ARIES A-star companion follow-up** - *PI: De Rosa (2 nights)* - 75% 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 accepted - Sample for follow-up projects, including LBT proposal

⋆ **Ward-Duong et al. 2014**, *A Direct Imaging Study to Search for and to Characterize Planetary Mass Companions*, 2014 IAUS, 299, 74 - Includes MMT data

⋆ **Ward-Duong et al. 2014**, *The M-dwarfs in Multiples (MinMs) survey - I. Stellar multiplicity among low-mass stars within 15 pc*, MNRAS, submitted - Includes MMT data

⋆ **Skemer et al. 2014** *LEECH: A 100 Night Exoplanet Imaging Survey at the LBT*, 2014 IAUS, 299, 70

Companion Characterization - Allocations and Papers:

LBT: 2013A - Thermal-IR measurements of substellar companions: - *PI: Patience (1 night)* - 50% useful

MMT: 2013C-UAO-S11 - ARIES Substellar spectroscopic characterization - *PI: Ward-Duong (2 nights)* - 0% useful, **2014A-UAO-S1 - ARIES Substellar spectroscopic 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, accepted - Characterization most similar to MMT proposal, includes MMT data

• **De Rosa et al. 2014**, *The VAST survey - V. Confirmation observations of low-mass companions to nearby A-type stars*, MNRAS - Analysis of MMT data complete, paper in progress

• **Maire et al. 2014**, *The LEECH Exoplanet Imaging Survey. Further constraints on the planet architecture HR 8799 system*, A&A, in prep

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Brown dwarf Atmosphere Monitoring - Allocations and Papers:

MMT: 2012A-UAO-S3 - SWIRC Brown dwarf variability monitoring - *PI: Patience (2 nights)* - 75% useful, **2013A-UAO-S99 - SWIRC Brown dwarf variability monitoring** - *PI: Rajan (2 nights)* - 0% useful.

• **Rajan et al. 2014**, *Searching for Photometric Variability across the L, T & Y Dwarf Sequence*, 2014 IAUS, 299, 301 - Includes MMT data

• **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. 2014**, *The Brown-dwarf Atmosphere Monitoring (BAM) Project II: Multi-epoch monitoring of extremely cool brown dwarfs*, MNRAS, submitted - Includes MMT data

• **Burgasser et al. 2014**, *Splinter Session on Cool Cloudy Atmospheres: Theory and Observations*, Cool Stars 18, submitted - Includes MMT data

From: Don McCarthy <dwmccarthy@gmail.com>
Subject: **Re: proposals**
Date: 28 September 2014 21:47:44 MST
To: Jennifer Patience <Jennifer.Patience@asu.edu>
Cc: Craig Kulesa <ckulesa@as.arizona.edu>

OK, Jenny!

FYI, the new detector in ARIES is still undergoing some tests and is not yet ready for prime time. So, we continue to swap the same detector between ARIES and PISCES. Thus, the two instruments cannot be scheduled close in time.

Don

On Sun, Sep 28, 2014 at 9:18 PM, Jennifer Patience <Jennifer.Patience@asu.edu> wrote:

> Hi, Don. My students and I are working on proposals for the upcoming deadline. Will PISCES be available at the MMT? If possible, we would like to submit an MMT/PISCES proposal for brown dwarf monitoring as part of one of my students (Abhi Rajan) thesis projects. We would also like to submit AO ARIES proposals for companion search and characterization observations continuing our ongoing projects (part of the thesis for Kim Ward-Duong). As always, we are happy to include you and Craig in all the results.
>
> -- Jenny