OBSERVING REQUEST
University of Arizona Observatories

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

The first ever spectrum of a planet in the L-band: Probing the Atmosphere of the Planetary Mass Companion 2M1207b

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Abstract of Scientific Justification

The 2M1207 system consists of a primary brown dwarf with one of the lowest mass directly imaged companions. The companion, 2M1207b, has a mass of $\sim 5\ \mathrm{M_{Jup}}$, and is separated by 0.78” (41 AU at 53 pc). Its NIR-spectrum and Mid-IR photometry are peculiar, and share many characteristics with the planets in the HR 8799 system. Many investigators demonstrate that the spectra of these planetary mass companions are not consistent with the spectra of higher-mass field brown dwarfs at the same effective temperatures. Atmospheric models with non-equilibrium $\mathrm{CO/CH_4}$ chemistry and patchy high-altitude clouds have provided adequate fits to the spectra and photometric points, but remain relatively unconstrained. We propose to probe the non-equilibrium nature and patchiness of the atmosphere of 2M1207b using an $\mathrm{R} \sim 100$ L-band spectrum. The L-band spectral region is interesting to target because it includes the P, Q, and R branch methane transitions and because the broad flux level and slope across the band can be used to discriminate different levels of cloud patchiness and non-equilibrium chemistry. Since 2M1207b orbits a brown dwarf, it is well suited for early spectroscopic studies of planetary atmospheres because observational challenges arising from contrast are much less severe than in the case of a stellar host. Also, because of its position in the southern sky, 2M1207b can be targeted by MagAO/Clio2, currently the only instrument capable of making these observations. Recently, the new MagAO system facilitated a 10σ spatially resolved $3.3\ \mu\mathrm{m}$ image of 2M1207b in 53 minutes of exposure. Thus, the largest hurdles associated with resolving and detecting the source have already been overcome. A spectroscopic observation will require additional exposure time but has a high probability of success.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MAG2	AO	MagAO/Clio2	*	*	3	bright	Mar-May	Feb-June	yes	yes

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

no text past this line

A $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ 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	2M1207	12:07:33.5	-39:32:54.0	$L'_b = 15.3$, $\sim$5 M_{Jup}
2	guidestar	12:07:31.0	-39:32:28.2	$R = 14.2, \mathrm{sep} = 38$”
3	CT Cha b	11:04:08.4	-76:27:18.0	R_A=11, $L_b$$\sim$13.9, sep=2.7”, 17 M_{Jup}
4	HD 106906 b	12:17:53.2	-55:58:31.9	$R_A$$\sim$07, L_b=14.6, sep=7.1”, 11 M_{Jup}
5	GQ Lup B	15:49:12.1	-35:39:03.9	R_A=11, L_B=11.7, sep=0.6”, 22 M_{Jup}
6	1RXS 1609 b	16:09:30.3	-21:04:59.0	R_A=12, L_b=14.8, sep=2.2”, 08 M_{Jup}
7	GSC06214-00210 B	16:21:54.7	-20:43:09.2	R_A=12, L_B=13.8, sep=2.2”, 17 M_{Jup}
8	SCR 1845	18:45:05.30	-63:57:48.0	R_A=15, sep=1”, companion T6 type spectroscopic calibrator

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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
Jordan Stone	Josh Eisner		no	yes

Scientific Justification

The 2M1207 system is located at 53 pc (Biller and Close, 2007; Ducourant et al. 2008) in the TW Hya association. It consists of the first directly imaged planetary-mass companion, 2M1207b ($M \sim 5\ M_{Jup}$, Chauvin et al., 2004: Chauvin et al., 2005), orbiting a brown dwarf host. Given the low mass of the primary, and constraints on the mass of an early circumprimary disk, 2M1207b likely formed via a different mode than other planetary-mass companions in systems with more extreme mass ratios (Lodato and Clark, 2005). Even so, the J, H, and K band spectra and mid-IR SED of 2M1207b, share many characteristics peculiar to planetary atmospheres. The spectrum of 2M1207b is especially similar to the spectra of the planets in the HR 8799 system (Skemer et al., 2011; Barman et al., 2011a; Barman et al., 2011b; Skemer et al., 2012). Thus it appears that its young age and low mass have produced an atmosphere with planetary characteristics. Given the very small number of imaged planets, 2M1207b presents a rare opportunity to constrain planetary atmospheres.

Early attempts to characterize the atmosphere of 2M1207b produced adequate fits to J, H, and K band spectra using brown dwarf models with $T_{eff} = 1600$ K (Mohanty et al., 2007; Patience et al., 2010). It was immediately determined that the luminosity implied by the best-fit T_{eff} was much larger than what was measured (Mohanty et al., 2007). Since the distance to the 2M1207 system is well known and because degeneracy pressure provides a strong lower-limit to giant planet radii, the sub-luminous nature of 2M1207b cannot be explained by geometry. Two solutions were put forward to explain the under-luminosity. The original solution was to invoke an edge-on gray-extincting disk (Mohanty et al., 2007). A more exotic solution was suggested by Mamajek and Meyer (2007) who noted that a protoplanetary collision could produce a 1600 K atmosphere with a radius much smaller than R_{Jup}. Both of these solutions were deemed highly unlikely, especially in light of the discovery of similar atmospheric characteristics in the HR 8799 planets (Skemer et al. 2011; Barmann et al. 2011).

It appears that the low surface gravity implied by the young age and low-mass of directly imaged planets affects their atmospheres in ways which exhibit distinct spectral signatures from older more massive brown dwarfs at similar effective temperatures. An alternative solution to the luminosity problem is to model the atmosphere of 2M1207b using a much lower effective temperature and invoking a non-equilibrium CO/CH_4 ratio in the photosphere (Skemer et al., 2011; Barmann et al., 2011). In fact, chemical mixing from low levels in the planetary atmosphere can alter the CO/CH_4 ratio by delivering fresh CO faster than chemical reactions can proceed towards balance (Hubeny and Burrows, 2007; Barman et al. 2011). Fortney et al (2008) and Barman et al (2011) showed that the effects of atmospheric mixing from deep layers has a much stronger effect on the spectra of low surface gravity objects.

While invoking non-equilibrium mixtures of CO and CH_4 can provide adequate fits to the J, H, and K band spectra of 2M1207b and the HR 8799 planets, Skemer et al. (2012) showed that inhomogeneous cloud cover could also be used to explain the spectral slope of their photometric points across the L-band.

Models show that the $3 - 4\ \mu m$ spectral range is strongly affected by both CH_4 chemistry and cloud cover (see Figure 1). In order to better understand the nature of planetary atmospheres, a spectrum of this region will be invaluable in guiding more sophisticated modeling. No spectrum of a planetary mass companion yet exists in this spectral range, and MagAO/Clio2 is uniquely qualified for making the observation. 2M1207b is the prime target for making progress in this region. Since 2M1207b orbits a brown dwarf, the contrast between it and its primary is only ~ 4 magnitudes. This compares favorably to the HR 8799 planets which are ~ 10 magnitudes fainter than their primary. Further, a recent MagAO/Clio2 observation easily resolved the 0.78" binary, detecting 2M1207b at $10 - \sigma$ (see Figure 2). The detection was made through a filter with FWHM extending from 3.1-3.5 μm in 53 minutes. Since imaging has been demonstrated, the probability of a successful spectroscopic observation is very high. This is because the largest challenge for spectroscopy is getting the light through the slit. Now that we know this can be done, all that is left is integrating long enough to attain an acceptable signal-to-noise ratio. MagAO/Clio2 and 2M1207b present an excellent opportunity to constrain current models and make progress in the understanding of planetary atmospheres. Additionally, models of the 2M1207b spectrum exist for comparison to our data providing a rapid path from observations to publication.

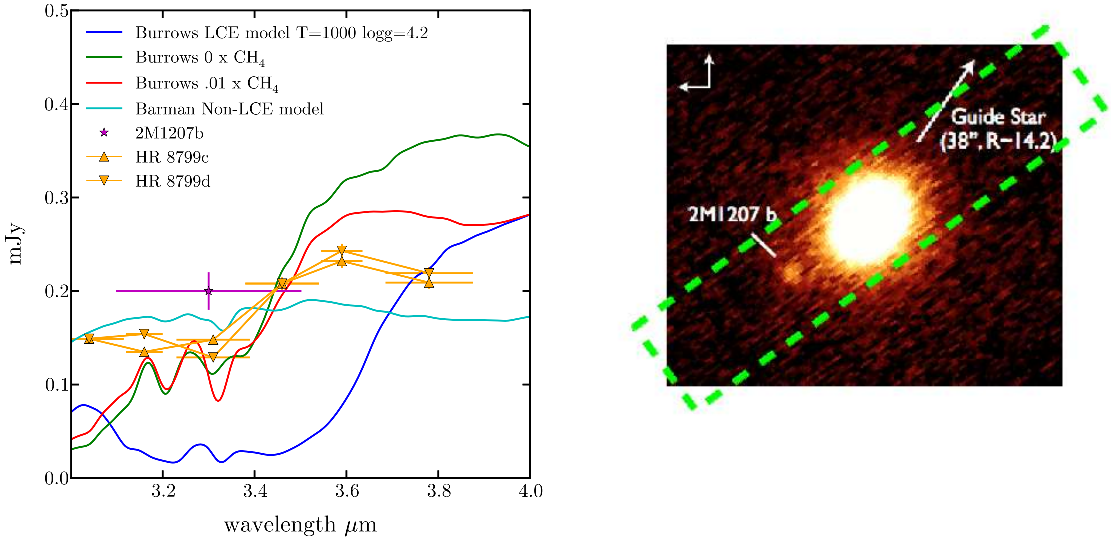

Figure 1: Left: The narrowband photometry from 3–4 μm of 2M1207b (magenta star) and HR 8799c and d (orange triangles, flux scaled to the distance of 2M1207b), overplotted on theoretical models for the shape of the L-band spectrum of 2M1207b. Horizontal bars on photometric points show the FWHM range of the narrowband filters. The photometry are not consistent with equilibrium models, but are better approximated by models with non-LCE chemistry. We expect that the spectrum of 2M1207b will be qualitatively similar to the shape suggested by the narrowband photometry of the HR 8799 planets, even though the objects may represent different evolutionary states.We propose to obtain the first spectrum of a planetary mass object in this critical range. Right: This MagAO/Clio2 image shows 2M1207b clearly separated from its host brown dwarf. The 10σ detection of 2M1207b, was made with 53 mins of exposure. Overlaid is an illustration of a slit, suggesting the orientation we will pursue, which will give us a spectrum of both sources. Since we will observe both sources simultaneously, the spectrum of 2M1207A can be used to help calibrate the spectrum of 2M1207b. This will be especially helpful for applying the telluric calibration and for monitoring differential slit loss.

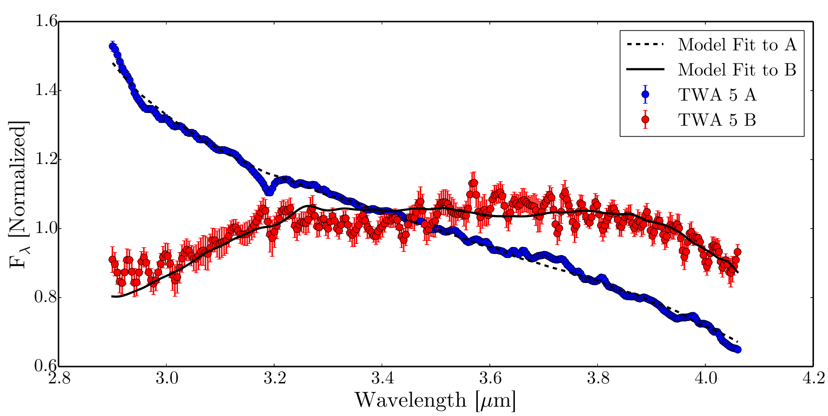

Figure 2: The L-band spectra of TWA5 A (blue, M2 type star) and TWA5 B (red, M8.5 brown dwarf) from our last run with MagAO/Clio2. The best fit atmospheric models to these spectra match the effective temperatures for these sources found with fits to shorter wavelength data. This demonstrates the functionality of the instrumental mode and our reduction pipeline.

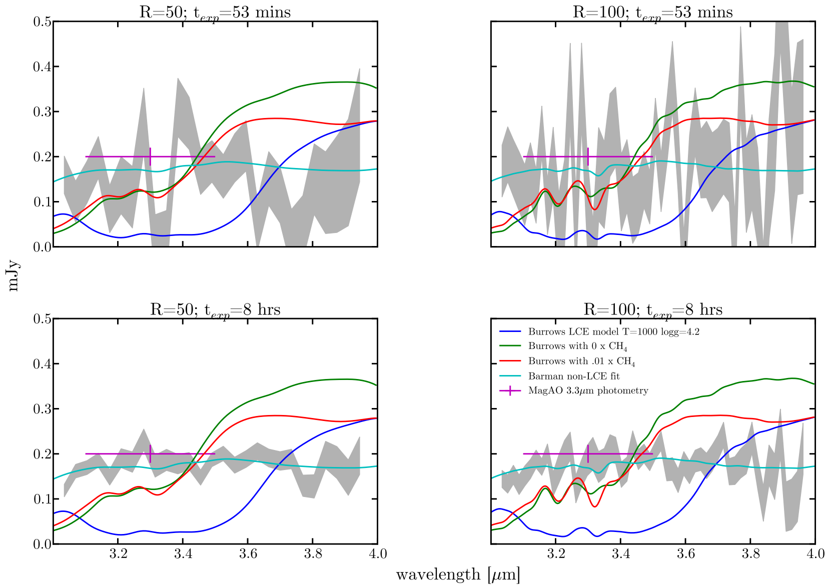

Figure 3: In each panel above, we plot the same four model spectra (green, red, blue, and cyan curves) and measured 3.3 μm photometric point (magenta crosshair, showing the FWHM of the filter and the 1σ photometric error). The left column of plots shows R=50, and the right column shows R=100. The gray swath in each panel covers the 1σ error interval around a simulated observation and illustrates our expected performance given the background flux rate observed in the 3.3 μm observation and assuming a source spectrum shaped like that from the Barman et al. 2011 fit. The top row of plots show our expected performance after 53 mins of integration. The bottom row of plots show our expected performance after 8 hrs of integration.

References

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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)***

MagAO/Clio2 is currently the only instrument capable of obtaining a low-resolution L-band spectrum in the southern hemisphere. It is in a unique position to make high impact spectroscopic observations of 2M1207b.

Clio has two filter wheels allowing us to put both the prism and a broadband filter in the beam. For our observations we will use an L filter to reject light outside our region of interest. This will provide two important benefits. First, in rejecting the short wavelength light, which does not get strongly dispersed by the prism, we reduce the cross-talk on the detector. Second, by rejecting the long wavelength light we reduce contamination of our spectra which can occur when light is diffracted into the field of view by the slit.

We will use the wide slit (3λ/D; 12 pixels) on Clio to minimize slit losses, which can vary with wavelength when using adaptive optics. Clio's prism disperses $\sim 0.0037\mu$m/pixel at $3.5\ \mu\mathrm{m}$. In the case where the slit is bigger than the diffraction-limit, diffraction sets the spectral resolution. For Clio, the 6.5m diffraction limit is ~ 4 pixels, implying a spectral resolution of ~ 230 at $3.5\ \mu$m. For these observations, we will bin our data to a lower spectral resolution to gain S/N. We will align the slit along the position angle of the binary system. This will provide us with a spectrum of both sources. Having the spectrum of the primary will be valuable for calibration purposes. For example, in tracking the effects of differential slit loss and for wavelength calibration.

We have simulated a spectroscopic observation of 2M1207b in order to determine the exposure time needed to provide adequate signal-to-noise to inform models and to give us a chance to detect the Q-branch methane bandhead at 3.3 microns. To produce these simulations, we have used the background flux rate measured in the 3.3 micron photometric observation. We model the source spectrum using the best-fit model from Barman et al 2011. While we expect the Mid-IR spectrum of this young low-mass sources could be different, the photometric measurement ensures that the average S/N ratio in the band is robust. Figure 3 shows our simulated observation of 2M1207b. With eight hours on-source we can get a high quality R~ 50 spectrum. If we get less data we can bin to lower spectral resolution and still produce a prominant result. We expect this observation will need $\sim 100\%$ overhead time judging from our experience making the 3.3 micron photometric measurement.

2M1207b is observable in the first half of the night during the months of May and June and we prefer to be allocated first-half nights for this program. This will provide us with the maximum amount of time with 2M1207b at low airmass and additionally will provide greater opportunity for good seeing.

We were awarded 1.5 nights of time for this program in 2014A. We lost one night to clouds and our remaining half night had worse-than-average seeing and we could not lock on the faint guidestar for 2M1207b. We were successful in targeting brighter on-axis targets. We have now demonstrated that the instrument and our pipeline are capable of delivering accurate spectra of substellar companions to late-type stars (Figure 2).

Given our experience with bad weather and poor seeing last run, we have adjusted our request. In order to ensure an adequate interval of good conditions, we include 2M1207b in a larger list of young substellar companions and ask for additional nights. We estimate from experience at Magellan that $\sim 50\%$ of the time will be high enough quality to observe 2M1207b. The other 50% of the time should be adequate for observing targets with brighter guidestars.

We plan to observe 2M1207b whenever conditions allow. Whenever the seeing is less stable, we will target objects with brighter less challenging guidestars. The other targets on our list are valuable for furthering our parallel program with MagAO. That program seeks to understand the evolution of the L-band spectra of young substellar companions in sequences of both mass and age. Thus, all the requested time will be spent making important observations producing valuable results.

As discussed above, we need a total of 16 hours of good conditions to make the first ever spectrum of a planet in the L-band. Given our experience with the fraction of time at Magellan when conditions are adequate we ask for 32 hours, or 3 nights.

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**)*

We were awarded 1.5 nights to observe 2M1207b in 2014A. We were unable to target 2M1207b due to clouds and poor seeing. Here we again propose to observe 2M1207b and we ask for more time to ensure that we have an adequate interval of good seeing to make the first L-band spectrum of a planet. We have also included additional targets with bright guidestars which we can observe when conditions are less than optimal. These additional targets will be very valuable for our parallel program and will help us to interpret the spectrum of 2M1207b.

We also applied for, and were awarded, 1.5 nights to initiate a program to survey young substellar companions to nearby stars. That run is in scheduled in November.

Two hours were used to obtain 3.3 μm photometry of 2M1207b. Additionally, we were awarded 1.5 nights to observe 2M1207b in 2014A. That time was mostly lost to bad weather and poor seeing, though some bright and less challenging targets were observed.

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**)*

One and one-half nights were awarded for a parallel program to use MagAO/Clio2 to observe substellar companions to nearby stars in 2014B. The target list includes relatively young and old sources and sources spanning the mass range from 13–30 Mjup. This run is scheduled for November 13-15.

⋆ One and one-half nights were awarded for this program in 2014A. Cloudy weather prevented observing for one night and worse-than-average seeing prevented the AO system from functioning on the faint guidestar used to target 2M1207b for half of a night. Spectra were obtained for brighter sources which the AO system could handle given the conditions. Those data are reduced and a paper is currently being constructed to report them.

⋆ The 3.3 μm photometry of 2M1207b will appears in the Astrophysical Journal: Andrew J. Skemer et al. 2014 ApJ 792 17

Three engineering nights to commission a new detector in ARIES in October 2013 were lost because the instrument was not ready

Two more nights were allocated to JS in May of 2013. Those nights were lost due to power failure at the observatory.

Two nights were allocated to JS in October of 2012 to use the ARIES spectrograph at the MMT. Data from that run have been published in the Astrophysical Journal: Jordan M. Stone et al. 2014 ApJ 792 56