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DETECTION OF Hα EMISSION IN A METHANE (T TYPE) BROWN DWARF

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ABSTRACT

We report the detection of Hα emission in the T dwarf (methane brown dwarf) 2MASSW J1237392+652615 over three days using the Keck Low Resolution Imaging Spectrograph. The measured line flux, $\log (L_{H\alpha}/L_{bol}) = -4.3$, is roughly consistent with early M dwarf activity levels and inconsistent with decreasing activity trends in late M and L dwarfs. Similar emission is not seen in two other T dwarfs. We speculate on several mechanisms that may be responsible for emission, including a strong magnetic field, continuous flaring, acoustic heat generation, and a close [$a \sim (4\text{–}20)R_J$] interacting binary, with the cooler component overflowing its Roche lobe. We suggest that the M9.5 Ve PC 0025+0447 could be a warm analog to 2MASS J1237+65 and may be powered by the latter mechanism.

Key words: stars: activity —
stars: individual (2MASSW J1237392+652615, SDSSp J162414.37+002915.6) —
stars: low mass, brown dwarfs

1. INTRODUCTION

Activity is an important parameter in the study of stellar populations. Numerous investigations of late-type (F–M) stars have shown correlations between emission (e.g., Ca II H and K lines, Mg II h and k lines, Balmer series) and fundamental parameters such as age, rotation, and metallicity (Hawley, Reid, & Gizis 2000). It is generally believed that the majority of this optical emission occurs in the chromosphere via collisional heating by ions and electrons along magnetic field lines. Indeed, this hypothesis is supported by the observed correlation of activity and rotation in late-type stars (Kraft 1967; Noyes et al. 1984; Basri 1987), which is expected if magnetic fields are generated by an internal dynamo (e.g., an α-Ω dynamo; Parker 1955). Decrease in activity as stars age can be attributed to spin-down due to angular momentum loss in stellar winds (Stauffer & Hartmann 1986).

As we examine cooler M and L dwarfs, however, these relations begin to break down. As stars become fully convective ($\sim 0.3\ M_\odot$), the α-Ω dynamo mechanism becomes ineffective, as it requires a low-buoyancy, radiative/convective boundary to anchor flux lines (Spiegel & Weiss 1980). However, the observed activity level remains roughly constant around this transition point (Hawley, Gizis, & Reid 1996), suggesting a turbulent dynamo as an alternate magnetic field source (Durney, De Young, & Roxburgh 1993). Indeed, flaring activity, which is magnetically driven, is seen in objects as late as M9.5 (Liebert et al. 1999; Reid et al. 1999), supporting the existence of substantial magnetic fields beyond the convective cutoff. Alternately, acoustic heating could sufficiently heat the chromosphere (Schrijver 1987; Mathioudakis & Doyle 1992) to produce a basal flux of Hα emission. In either case, Gizis et al. (2000) have shown that the fraction of objects with measurable emission rises to 100% at spectral type M7, then rapidly declines, so that no emission is seen in types L5 or later (Kirkpatrick et al. 2000). The decrease in (steady) activity even encompasses objects with rapid rotation (Basri & Marcy 1995; Tinney & Reid 1998), at odds with trends in hotter stars. Whether this drop in emission is due to ineffective chromospheric heating, decreased magnetic activity, or some other mechanism is unclear, but the end of the main sequence appears to mark a change in activity.

Based on the results of Gizis et al. (2000), we would not expect significant activity in T dwarfs, brown dwarfs that show CH_4 absorption bands at 1.6 and 2.2 μm (Kirkpatrick et al. 1999). Nonetheless, we have observed Hα in emission in the T dwarf 2MASSW J1237392+652615 (identified as 2MASS J1237+65 below; Burgasser et al. 1999), identified from the Two Micron All Sky Survey (Skrutskie et al. 1997). We describe the optical observations of this and two other T dwarfs in § 2; in § 3, we discuss the Hα detection in 2MASS J1237+65 and possible emission mechanisms; in § 4, we compare 2MASS J1237+65 with the unusual M9.5 Ve PC 0025+0447; we summarize our results in § 5.

2. OPTICAL SPECTROSCOPY

2.1. *Observations*

2MASS J1237+65 was observed on three consecutive nights, 1999 July 16, 17, and 18 (UT) using the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck II 10 m Telescope. On each occasion, conditions were transparent, with seeing of 0″.8 to 1″.0, and we employed a 1″ wide slit. The target was acquired via blind offset from field stars, as it was invisible in the guiding imager. The July 16 and 17 observations were made using the 400 line mm^{-1} grating blazed at 8500 Å, covering the wavelength range 6300 to 10100 Å at 9 Å resolution. Total

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integrations of 4800 (1800 + 1800 + 1200) and 1800 s were obtained, respectively. The July 17 observation was plagued by poor target centering, reducing the observed flux by a factor of ~2; the data for this night are thus omitted, although Hα was detected. The July 18 observation was an 1800 s exposure using the 300 line mm^{-1} grating blazed at 5000 Å, covering 3800 to 8600 Å at 12 Å resolution. Additional 3600 and 2700 s observations (total integration time) of T dwarfs SDSSp J162414.37+002915.6 (identified as SDSS 1624+00 below; Strauss et al. 1999) and SDSSp J134646.45-003150.4 (identified as SDSS 1346-00 below; Tsvetanov et al. 2000) were made on July 16 and 17, using the 400 line mm^{-1} grating blazed at 8500 Å.

The data for all three objects were reduced and calibrated using standard IRAF routines[7]. A 1 s dark exposure was used to remove the bias, and quartz lamp flat-field exposures were used to normalize the response of the detector. The individual spectra were extracted using the APEXTRACT routine, allowing for slight curvature of the point-source dispersion line viewed through the LRIS optics. Because of the low flux levels of the T dwarf targets, we used an extraction template derived from observations of standard stars. Wavelength calibration was achieved using HgNeAr arc lamp exposures taken after each object exposure. Finally, the spectra were flux calibrated using observations of the DC white dwarf standard LTT 9491 (Hamuy et al. 1994). Data have not been corrected for telluric absorption, so the atmospheric H_2O bands at 8161–8282, 8950–9300, and 9300–9650 Å are still present in the spectra (telluric H_2O and O_2 bands are not visible shortward of 8000 Å because of low flux levels).

[7] IRAF is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

2.2. *Optical Spectra*

Spectra from 6300–10100 Å for all three objects are shown in Figure 1. Data blueward of 6300 Å are not shown, as our July 18 observations failed to detect any flux, continuum or emission, in this regime. Features identified by Oppenheimer et al. (1998) in Gl 229B are indicated. The optical spectrum of SDSS 1624+00 is discussed in detail in Liebert et al. (2000). Cs I lines at 8521 and 8943 Å are seen strongly in SDSS 1624+00, while both SDSS 1346-00 and 2MASS J1237+65 have progressively weaker lines. Broadened H_2O at 9250 Å and a weak CH_4 feature centered near 8950 Å are noted, both of which are stronger in 2MASS J1237+65 and SDSS 1346-00 than in SDSS 1624+00. The pressure-broadened resonant K I doublet at 7665 and 7699 Å, which is prominent in the spectra of L dwarfs (Kirkpatrick et al. 1999), is masking most of the flux between 7300 and 8100 Å in all three objects (Burrows, Marley, & Sharp 2000; Liebert et al. 2000). We note a feature in SDSS 1624+00 centered around 9900 Å that we identify as the 9896 Å 0-0 $A^4\Delta$-$X^4\Delta$ band of FeH, a feature that weakens from L6 V and later (Kirkpatrick et al. 1999). This detection supports the claims of Nakajima et al. (2000) and Liebert et al. (2000) that SDSS 1624+00 is probably warmer than Gl 229B, which shows no FeH band. Hydride bands in SDSS 1346-00 and 2MASS J1237+65 are either weak or absent, suggesting that they in turn are cooler than SDSS 1624+00. The remaining feature of interest, Hα emission at 6563 Å in 2MASS J1237+65, is the subject of the remainder of this article.

3. Hα IN 2MASS J1237+65

The Hα emission seen in 2MASS J1237+65 (Fig. 2) is quite unexpected, given the cool nature of this object, and great care was taken to verify its presence over three nights of observation. The emission spike was clearly seen in the raw data and is not spatially extended, thus ruling out the

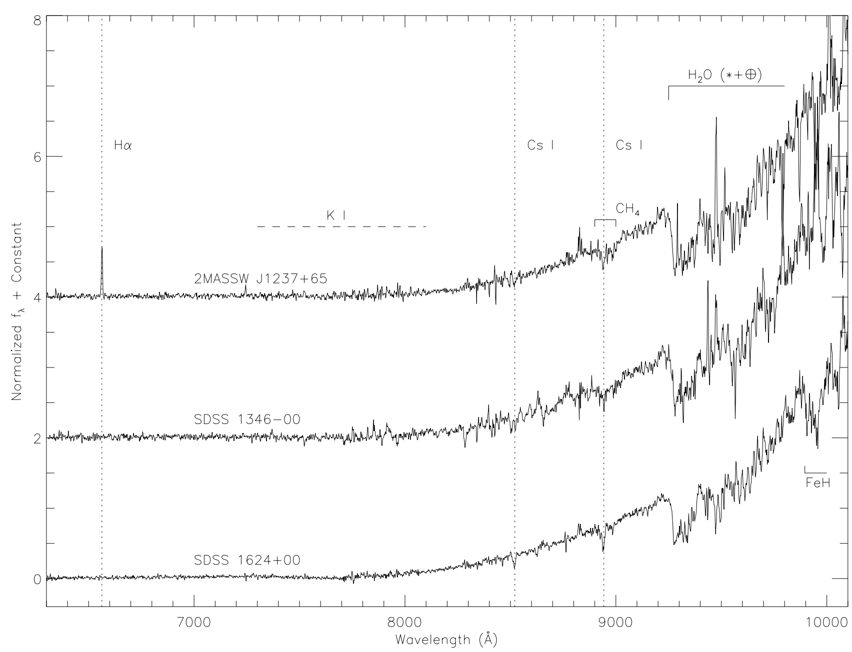

FIG. 1.—LRIS optical spectra of three T dwarfs, 2MASS J1237+65, SDSS 1346-00, and SDSS 1624+00, normalized at 9200 Å. Data for SDSS 1346-00 and 2MASS J1237+65 have been offset vertically by constants of 2 and 4, respectively. The following common features are shown: the K I resonant doublet (broadened to ~7300–8100 Å), Cs I (8521 and 8943 Å), CH_4 (8950 Å), and H_2O (9250 Å, stellar and telluric). The 0-0 $A^4\Delta$-$X^4\Delta$ band of FeH (9896 Å) in SDSS 1624+00 is also shown. Hα at 6563 Å is unambiguously seen in 2MASS J1237+65.

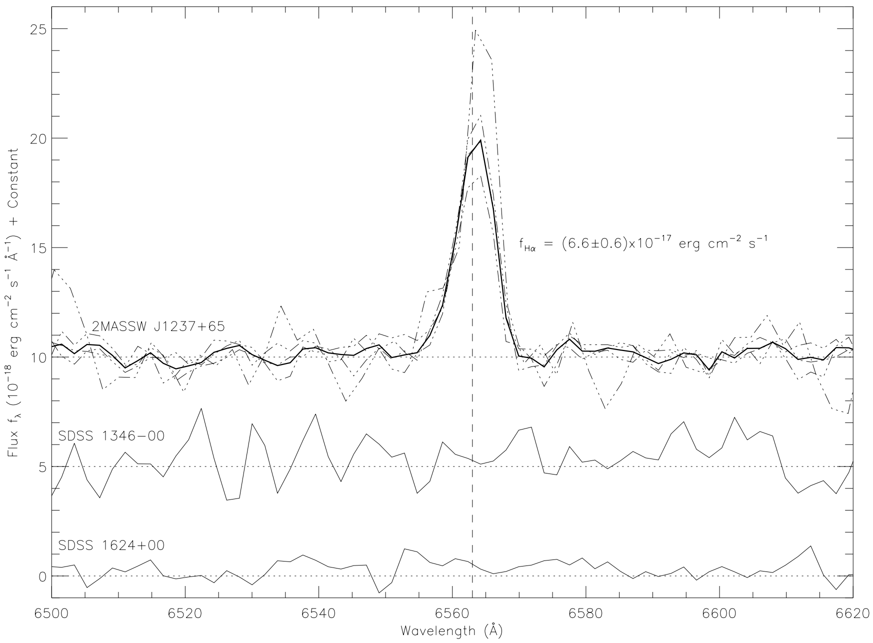

FIG. 2.—A close-up of the Hα feature in 2MASS J1237+65, showing four sets of observations for 2MASS J1237+65 (*dash-dotted lines*) and the mean from 1999 July 16 (UT) (*solid thick line*). Data for SDSS 1346-00 and SDSS 1624+00 are also shown. Zero levels are indicated by dotted lines, with SDSS 1346-00 and 2MASS J1237+65 offset vertically by constants of 5×10^{-18} and 10×10^{-18} ergs cm^{-2} s^{-1} Å^{-1}, respectively.

possibility of a background H I region or telluric emission. Hα emission was detected in five observations, spanning three nights and using two different instrument settings, with the emission FWHM equivalent to the instrumental resolution ($\sim$5 pixels). Hence, we can rule out the possibility of a chance cosmic ray. Finally, since no emission at 6563 Å is seen for the other T dwarfs, for which observations were reduced using the same bias and flat-field exposures, we can rule out detector features. The Hα emission line is thus quite real. Measurements of the Hα line for all three T dwarfs are listed in Table 1.

The integrated line luminosity at 6563 Å averaged over the three July 16 observations is $f_{H\alpha} = (6.6 \pm 0.6) \times 10^{-17}$ ergs cm^{-2} s^{-1}. An equivalent width measurement is not possible, as no continuum flux was detected in this spectral region. Note that there appears to be an increase in Hα flux on July 18 to $f_{H\alpha} = (8.5 \pm 0.3) \times 10^{-17}$ ergs cm^{-2} s^{-1}. We estimate the bolometric flux of 2MASS J1237+65 using the 2MASS J-band magnitude of 15.90 ± 0.06 and assuming a Gl 229B bolometric correction of $BC_J = 2.3$ (Matthews et al. 1996). This yields $m_{bol} = 18.2$ and $f_{bol} \approx 1.3 \times 10^{-12}$ ergs cm^{-2} s^{-1}; thus, $\log (f_{H\alpha}/f_{bol}) = \log (L_{H\alpha}/L_{bol}) \approx -4.3$. A limit on Hβ emission at 4861 Å is estimated at $f_{H\beta} \lesssim 2.0 \times 10^{-17}$ ergs cm^{-2} s^{-1}, resulting in a Balmer emission ratio on 1999 July 18 (UT) of $f_{H\beta}/f_{H\alpha} \lesssim 0.24$.

3.1. *Unusually Strong Magnetic Activity*

The detection of Hα is clearly inconsistent with the emission trend seen in objects later than L5 V and indeed in brown dwarfs in general (Gizis et al. 2000). The level of activity for 2MASS J1237+65 can be placed in context with other late-type emission-line objects by comparing relative

TABLE 1

EMISSION MEASUREMENTS FOR THREE T DWARFS

Object	Observation (UT) Date	Time	t_{int} (s)	$f_{H\alpha}$[a]	$\log (L_{H\alpha}/L_{bol})$[b]	$f_{H\beta}$[a]	$\log (L_{H\beta}/L_{bol})$[b]
2MASS J1237+65	1999 July 16	0621	1200	5.95 ± 0.13	-4.3	...	...
2MASS J1237+65	1999 July 16	0640	1800	7.06 ± 0.09	-4.3	...	...
2MASS J1237+65	1999 July 16	0715	1800	6.76 ± 0.04	-4.3	...	...
SDSS 1624+00	1999 July 16	0827	3600	<0.4[d]	< -5.7	...	...
SDSS 1346−00	1999 July 17	0700	2700	<0.7[d]	< -5.3	...	...
2MASS J1237+65[c]......	1999 July 17	0756	1800	1.68 ± 0.08	-4.9	...	...
2MASS J1237+65	1999 July 18	0639	1800	8.50 ± 0.30	-4.2	<2.0[d]	< -4.8

[a] In units of 10^{-17} ergs cm^{-2} s^{-1}.

[b] Assuming $BC_J = 2.3$ (Matthews et al. 1996). J-band magnitudes for the Sloan objects taken from Strauss et al. (1999) and Tsvetanov et al. (2000).

[c] The object appears to have been improperly placed in the slit for this observation, so that the entire spectrum is depressed by a factor of ≈ 2. Data are included only to show detection of Hα.

[d] Upper limits based on the continuum noise and spectral resolution of 9 Å (Hα) and 12 Å (Hβ).

flux emitted through the Hα line. Hawley et al. (1996) find a mean log $(L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}) \approx -3.8$ for field dMe stars with $M_{\mathrm{bol}} < 12$ (spectral type M5 V or earlier), while Gizis et al. (2000) show that this falls to below -5 for L dwarfs. Hence, even the activity level of 2MASS J1237+65 is inconsistent with these trends, while SDSS 1346-00 and SDSS 1624+00 have upper limits of log $(L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}) \approx -5.3$ and -5.7, respectively. Does 2MASS J1237+65 have an unusually strong magnetic field, perhaps powered by a dynamo mechanism different than that of M and L dwarfs? Further examination of activity statistics in this cool regime are clearly needed.

3.2. *Flaring*

While sustained activity may appear to diminish toward later spectral types, flaring does not. A good example of this is BRI 0021-0214, a rapid M9.5 V rotator (Basri & Marcy 1995), which in quiescence shows little or no Hα emission (Basri & Marcy 1995; Tinney, Delfosse, & Forveille 1997; Tinney & Reid 1998), yet was seen to flare by Reid et al. (1999) with log $(L_{\mathrm{H}\alpha}/L_{\mathrm{bol}}) = -4.2$, similar to 2MASS J1237+65. The BRI 0021-0214 flare also showed no continuum emission, again similar to the activity in 2MASS J1237+65. While flaring has not yet been observed in L dwarfs, the occurrence of flares in the latest M dwarfs (Reid et al. 1999; Liebert et al. 1999; Fleming, Giampapa, & Schmitt 2000) suggests that they may simply have not yet been observed. However, most strong M dwarf flares persist only a few hours (Hawley & Petterson 1991), while smaller flares (which would show weaker continuum emission) have timescales on the order of minutes (Nelson et al. 1986). Thus, prolonged emission of 2MASS J1237+65 requires either a continuous flaring mechanism or fortuitous timing on our part. Further observations of the emission line are warranted to investigate the temporal behavior of this emission.

3.3. *Acoustic Flux*

Schrijver (1987) first pointed out that a minimum basal flux seen in late-type stars could be attributed to chromospheric heating from acoustic waves. We can estimate the amount of acoustic flux from 2MASS J1237+65 by extrapolating the models of Ulmschneider, Theurer, & Musielak (1996), which improved on pivotal work done by Bohn (1984). Estimating $T_{\mathrm{eff}} \approx 1000$ K, log $g \approx 5$ (where g is in centimeters per second squared), and using the scaling $F_{\mathrm{ac}} \sim T_{\mathrm{eff}}^{20}$ (where "ac" stands for acoustic) from the coolest points in their Table 1, we estimate $F_{\mathrm{ac}} \approx 4 \times 10^{-8}$ ergs cm^{-2} s^{-1}, or log $(L_{\mathrm{ac}}/L_{\mathrm{bol}}) \approx -15$, well below the observed activity level. As such, acoustic energy is not likely the source of activity in 2MASS J1237+65.

3.4. *An Interacting Binary*

Finally, it is possible that 2MASS J1237+65 is active as a result of a binary interaction with an equal-magnitude or fainter companion. The binarity of brown dwarfs is well established (Martín et al. 1998; Basri & Martín 1999; Koerner et al. 1999), and the identification of three equal-magnitude binaries in an L dwarf sample of 10 by Koerner et al. (1999) is consistent with the binary fraction seen in late main-sequence stars (~35%; Fischer & Marcy 1992; Henry & McCarthy 1993). Hence, it is reasonable to consider that 2MASS J1237+65 could itself be double. In this case, the companion would have to be of equal mass or smaller, as

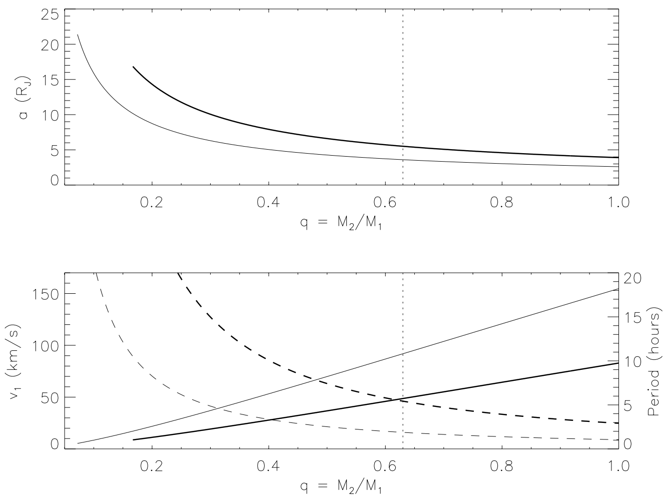

FIG. 3.— (*a*) Orbital separation, *a*, vs. mass ratio, $q = M_1/M_2$, for a brown dwarf binary, showing the maximum separation at which the secondary mass fills its Roche lobe for primary masses of 30 M_{J} (*thick line*) and 70 M_{J} (*thin line*). The dotted boundary indicates the maximum $q = 0.63$ required for sustained mass loss. (*b*) Maximum primary radial velocities (*solid lines*) and orbital periods (*dashed lines*) for a Roche lobe–filling secondary, for primary masses of 30 M_{J} (*thick lines*) and 70 $\mathrm{M_J}$ (*thin lines*). The limit $q = 0.63$ is indicated as above.

the optical continuum shows no evidence of a warmer component nor any significant variation over three days.

An unusual feature of brown dwarf binaries is the possibility of sustained Roche lobe overflow. Because of its degenerate interior, if a brown dwarf loses mass on a dynamical timescale [$\tau \sim (R^3/GM)^{1/2} \sim 1$ hr], its radius increases approximately as $d\ln R/d\ln M \approx -1/3$ when its mass lies in the range 5–70 M_{J} (Burrows & Liebert 1993)[8]. Sustained conservative mass transfer then occurs if the change in the Roche lobe of the secondary satisfies

$$\frac{d\ln R_L}{d\ln M_2} = \frac{8}{3}q - \frac{4}{3} - (q+1) \times \frac{0.4q^{2/3} + \frac{1}{3}q^{1/3}(1+q^{1/3})^{-1}}{0.6q^{2/3} + \ln(1+q^{1/3})} < -\frac{1}{3}\,. \quad (1)$$

We have taken $q = M_1/M_2$ as the mass fraction, M_1 and M_2 the primary and secondary masses, and R_L the secondary Roche lobe radius, as approximated by Eggleton (1983)

$$R_L = a\,\frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}\,. \quad (2)$$

Here a is the binary separation. Equation (1) is satisfied when $q < 0.63$. We have calculated possible brown dwarf binary separations, periods, and edge-on primary radial velocities as a function of q (Fig. 3) for primary masses $M_1 = 30$ and 70 M_{J} and

$$R_L = R_2 = \frac{\pi M_{\mathrm{Jup}}^{-1/3}}{(1 + 1.8M_{\mathrm{Jup}}^{-1/2})^{4/3}}\,R_{\mathrm{Jup}} \quad (3)$$

(Zapolsky & Salpeter 1969). M_{Jup} and $\mathrm{R_{Jup}}$ are the mass and radius of the secondary in units normalized to Jupiter. This rough model shows that sustained outflow requires a

[8] $M_{\mathrm{J}} = 1.9 \times 10^{30}$ $g = 0.00095$ $M_\odot$, $R_{\mathrm{J}} = 7.1 \times 10^9$ cm $= 0.10$ $R_\odot$ (Allen 1973).

separation $a \lesssim (4\text{–}20)R_J$ (Fig. 3*a*). This close separation may seem problematic; however, the brown dwarf spectroscopic binary PPl 15 has been shown to have an orbital separation of about $60R_J$ (Basri & Martín 1999). Note that this scenario results in at least partial eclipsing for orbital inclination $i \gtrsim 70°$, suggesting that photometric monitoring could detect a transit event in a period of ~1–10 hr. Alternatively, radial velocity monitoring of the Hα line can produce a measurable variation [$v_1 \approx$ (10–90) sin i km s^{-1}] over this period.

The emission mechanism from overflow accretion is uncertain, as a hot accretion disk is ruled out by the lack of thermal continuum. Ionization along a shock front or magnetic streaming onto the primary's pole are possibilities. Nonetheless, we find this an intriguing and, more importantly, observationally constrainable hypothesis.

4. PC 0025+0447: AN ANALOG?

A possible analog to 2MASS J1237+65 is the much warmer M9.5 Ve PC 0025+0447, which was identified by Schneider et al. (1991) in a search for high-redshift quasars because of its unusually strong Balmer line emission. The contribution of Hα luminosity to total luminosity [$\log(L_{H\alpha}/L_{bol}) = -3.4$; Schneider et al. 1991] is a full order of magnitude stronger in this object than 2MASS J1237+65 and appears to be steady over a timescale of at least 7–8 yr, with no indication of flaring activity (Schneider et al. 1991; Mould et al. 1994; Martín, Basri, & Zapatero Osorio 1999). Both Schneider et al. (1991) and Martín et al. (1999) argue that PC 0025+0447 is a young (600 Myr) brown dwarf; if this is the case, then it is possible that 2MASS J1237+65 is an evolved version of this object that has slowly declined in activity with age. Martín et al. (1999) propose various mechanisms for the activity in PC 0025+0447, including sustained flaring and emission from a highly active, low-density corona. Mould et al. (1994), however, based on significant Li depletion, argue against PC 0025+0447 being a brown dwarf and propose that it is a Hyades-age (~700 Myr) main-sequence star with normal photospheric thermal emission.

We propose a scenario in which PC 0025+0447 is itself an interacting binary, consisting of an ~0.1 $M_\odot$ M dwarf and a brown dwarf companion losing mass to the primary. This scenario provides a natural explanation for the observed phenomena: Roche lobe overflow from the companion provides a steady Hα emission source, accretion may lead to the observed variable veiling of the M dwarf spectrum (Martín et al. 1999), and the accreted material from the brown dwarf companion may retain lithium at primordial abundance, leading to the intermittent appearance of the Li 6707 Å absorption seen by Martín et al. (1999), without requiring modification of the measured trigonometric parallax. Extrapolation from Figure 3 leads to similar maximal separations [$(3\text{–}25)R_J$] and periods (1–14 hr) as for 2MASS J1237+65. Unfortunately, despite many photometric and spectroscopic observations of PC 0025+0447, no time-resolved data are available to constrain this hypothesis. More detailed modeling is required to determine the feasibility of these mechanisms.

5. SUMMARY

We have reported the detection of Hα emission in the T dwarf 2MASS J1237+65 at the level $\log(L_{H\alpha}/L_{bol}) = -4.3$. This emission is intriguing, as it is a salient exception to the cool dwarf temperature-activity relations identified thus far. We have proposed various activity mechanisms, including a strong magnetic field, continuous flaring, and an interacting brown dwarf binary, but these are speculative guesses at best. Comparison can be drawn with the M9.5 Ve PC 0025+0447, which, if it is a brown dwarf, could be a warm analog to 2MASS J1237+65. Both objects could also be close binary systems with lower mass brown dwarf companions, that are steadily transferring mass to their primaries by Roche lobe overflow. Nonetheless, the mechanism for both objects remains unclear. Further investigation of the temporal stability of the Hα line in 2MASS J1237+65 and searches for emission in other T dwarfs are clearly warranted.

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