A SURPRISE AT THE BOTTOM OF THE MAIN SEQUENCE: RAPID ROTATION AND NO Hα EMISSION

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ABSTRACT

We report Keck Observatory high-resolution echelle spectra from 640–850 nm for eight stars near the faint end of the main sequence. These spectra are the highest resolution spectra of such late-type stars, and clearly resolve the TiO, VO, and atomic lines. The sample includes the field brown-dwarf candidate, BRI 0021-0214 (M9.5+). Very unexpectedly, it shows the most rapid rotation in the entire sample, v sin i = 40 km s⁻¹, which is 20× faster than typical field nonemission M stars. Equally surprising is that BRI 0021 exhibits no emission or absorption at Hα. We argue that this absence is not simply due to its cool photosphere, but that stellar activity declines in a fundamental way at the end of the main sequence. As it is the first very late M dwarf observed at high spectral resolution, BRI 0021 may be signaling a qualitative change in the angular momentum loss rate among the lowest mass stars. Conventionally, its rapid rotation would have marked BRI 0021 as very young, consistent with the selection effect which arises if the latest-type dwarfs are really brown dwarfs on cooling curves. In any case, it is unprecedented to find no sign of stellar activity in such a rapidly rotating convective star. We also discuss the possible conflict between this observation and the extremely strong Hα seen in another very cool star, PC 0025 +0447. Extrapolation of M–L relations for BRI 0021 yields M < 0.065 M⊙, and the other sample objects have expected masses near the H-burning limit. These include two Pleiades brown-dwarf candidates, four field M6 dwarfs and one late-type T Tauri star. The two Pleiades M6 dwarfs have v sin i of 26 and 37 km s⁻¹, Hα in emission, and radial velocities consistent with Pleiades membership. Similarly, the late-type T Tauri star has v sin i > 30 km s⁻¹ and Hα emission indicative of its youth. Two of the four late-type field dMe stars also exhibit rotation above 5 km s⁻¹, consistent with expectations. BRI 0021 has no measurable absorption due to lithium, indicating that it is likely to be more massive than 0.065 M⊙.

1. INTRODUCTION

The science of brown dwarfs remains void of confirmed representatives though many candidate brown dwarfs have been considered (e.g., Mould et al. 1994; Burrows & Liebert 1993; Tinney 1993; Kirkpatrick et al. 1993a; Graham et al. 1992). Radial velocity searches that are sensitive to brown dwarf companions having masses of >0.065 M⊙ have failed to reveal any confirmed examples (Campbell et al. 1988; Marcy & Benutz 1989; Latham et al. 1992; Cochran et al. 1991). Several lines of reasoning have emerged which suggest that the M dwarfs of latest spectral type are in fact not capable of burning hydrogen stably, and hence are either "transition" objects or bona fide brown dwarfs (Kirkpatrick 1994). Among these are the kinematics and galactic distribution of them which indicate youth, and extrapolation of the observed relation between mass and spectral type to the substellar regime (Kirkpatrick & McCarthy 1994). Spectroscopic tests are clearly needed to assess the brown-dwarf status of the faintest M dwarfs. Lithium burning is expected to occur only in the highest mass brown dwarfs; those with <0.060 M⊙ never achieve requisite central temperatures for Li burning, according to interior models (Magazzù et al. 1993; Nelson et al. 1993). Searches for lithium in brown dwarf candidates have so far all been unsuccessful (Marcy et al. 1994; Martin et al. 1994).

If the latest-type M dwarfs are young, chromospheric activity may, in principle, be useful to constrain their ages, as commonly done for late-type stars. This clock becomes questionable at the latest spectral types because of many uncertainties: the unknown survival of the magnetic dynamo, the unknown magnetic heating efficiency in the coolest atmospheres, and the lack of empirical calibration of age with chromospheric activity (see Giampapa & Liebert 1986). A future spectroscopic discriminant of brown dwarf status may lie in their surface gravities, which are predicted to increase by a factor of 3 between M = 0.04–0.07 M⊙ (Burrows et al. 1994). Gravity discrimination may be possible with high resolution spectra, by modeling the pressure broadening in line wings or by measuring molecular equilibria. This is difficult at present, pending superior atmospheric models (Allard 1994).

Rotation, serving as an age indicator, may provide a test of brown dwarf status for the latest-type M dwarfs. All single dwarfs F5–M5 spin down presumably due to angular momentum loss in their stellar wind (Stauffer & Hartmann 1986). About one third of the late-type stars having Pleiades age (~70 Myr) exhibit equatorial velocity of tens of km s⁻¹, but most K dwarfs have v sin i < 10 km s⁻¹ by the age of the Hyades (~600 Myr, Stauffer et al. 1991, 1994). Field dM
stars (M0–M5) have average equatorial velocities of less than 2 \( \text{km s}^{-1} \) (Marcy & Chen 1992). Of the \( \sim 200 \) field M dwarfs stars measured by Stauffer & Hartmann (1986), only 11 of their 29 dMe stars had rotation detectable above their 10 \( \text{km s}^{-1} \) limit. Four of these lay between 15 and 20 \( \text{km s}^{-1} \). Marcy and Chen found 5 of 47 late-type stars rotating above their 3 \( \text{km s}^{-1} \) limit, 4 of which have \( \text{H}\alpha \) emission and none at all with \( v \sin i \) greater than 10 \( \text{km s}^{-1} \). Even HHJ and none at all with \( v \sin i \) greater than 10 \( \text{km s}^{-1} \). Even HHJ

\footnote{\text{Table 1. Program stars.}}

<table>
<thead>
<tr>
<th>Name</th>
<th>Other</th>
<th>( R ) (mag)</th>
<th>( I-K )</th>
<th>Exp. (s)</th>
<th>( v \sin i ) ( (\text{km s}^{-1}) )</th>
<th>( V_{\text{radial}} ) ( (\text{km s}^{-1}) )</th>
<th>( W_{\text{H}\alpha} ) (Å)</th>
<th>( W_{\text{H}\beta} ) (Å)</th>
<th>( W_{\text{Ca i}} ) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHS 36</td>
<td>Gl 406</td>
<td>11.6</td>
<td>3.31</td>
<td>120</td>
<td>(&lt; 3)</td>
<td>16.5</td>
<td>(-4.7)</td>
<td>0.53</td>
<td>0.14</td>
</tr>
<tr>
<td>LHS 248</td>
<td>Gl 1111</td>
<td>12.8</td>
<td>3.27</td>
<td>600</td>
<td>11( \pm 2.5)</td>
<td>8.7</td>
<td>(-4.3)</td>
<td>0.56</td>
<td>0.17</td>
</tr>
<tr>
<td>LHS 292</td>
<td>-</td>
<td>13.5</td>
<td>3.24</td>
<td>600</td>
<td>(&lt; 3)</td>
<td>-36.4</td>
<td>(-3.0)</td>
<td>0.51</td>
<td>0.31</td>
</tr>
<tr>
<td>LHS 1070</td>
<td>Gl 2005</td>
<td>13.7</td>
<td>3.40</td>
<td>600</td>
<td>8( \pm 2)</td>
<td>7.7</td>
<td>(-4.3)</td>
<td>0.40</td>
<td>0.14</td>
</tr>
<tr>
<td>HGU 3</td>
<td>-</td>
<td>19.6</td>
<td>3.30</td>
<td>10800</td>
<td>37( \pm 9)</td>
<td>8.4</td>
<td>(-4.4)</td>
<td>0.29</td>
<td>0.20</td>
</tr>
<tr>
<td>HGU 14</td>
<td>PPI 7</td>
<td>18.9</td>
<td>3.30</td>
<td>5866</td>
<td>26( \pm 5)</td>
<td>14.7</td>
<td>(-3.2)</td>
<td>0.11</td>
<td>0.19</td>
</tr>
<tr>
<td>UX Tau C</td>
<td>HBC 43</td>
<td>15</td>
<td>2.9</td>
<td>1800</td>
<td>(30\pm 8)</td>
<td>12.9</td>
<td>(&lt; 0.2)</td>
<td>1.08</td>
<td>0.72</td>
</tr>
</tbody>
</table>
| BRI 0021–0214 | LP 585–86 | 17.4 | 4.43 | 4800 | 40\( \pm 7\) | 165A (Zuckerman & Becklin 1992; Kirkpatrick et al. 1994).

Extrapolation of the mass–luminosity relations of Henry & McCarthy (1993), using Tinney’s photometry, indicates a mass of between 0.068 and 0.062 \( \text{M}_\odot \) for BRI 0021. Such objects are expected to undergo little hydrogen burning; their luminosities are produced partially by gravitational contraction.

Observations were made on 1993 Nov 11 UT with the W. M. Keck 10 m telescope on Mauna Kea using the HIRES echelle spectrometer (Vogt 1992). The instrument yielded 15 spectral orders from 640 to 860 nm (with gaps between orders), detected with a Tektronix 2048 \( \times \) 2048 \( \text{CCD} \) having pixels of 31 \( \mu\text{m} \). Data reduction was discussed by Marcy et al. (1994).

The wavelength scale was determined from a one second thorium–argon calibration lamp exposure. The IRAF routine IDENTIFY was used with a fourth-order Legendre polynomial fit in the dispersion direction, and a second-order Legendre polynomial fit in the cross-dispersion direction. The formal rms residuals in the dispersion direction were 0.03 \( \AA \), but the residuals at the edges of the individual orders were considerably worse, up to 0.5 \( \AA \). We thank Scott Träger of UC Santa Cruz for supplying this wavelength scale.

3. THE SPECTROSCOPIC RESULTS

3.1 Atomic Lines in Very Late-type M Dwarfs

Most of the spectrum of these stars is dominated by molecular features, particularly TiO and VO. We leave the discussion of these to a future paper, in which we will do detailed atmospheric modeling. For now, we discuss the few strong atomic features seen in our echelle format. The most striking of these is the \( \text{H}\alpha \) line (Fig. 1). In all but BRI 0021, this line is strongly in emission. As is true of many dM6 stars (Liebert et al. 1992), our field M6 dwarfs are dMe, and all our young M stars also show \( \text{H}\alpha \) emission. The field stars look like typical dMe stars at \( \text{H}\alpha \), with a fairly narrow, high contrast line often showing a central reversal (due to NLTE effects). We measured the equivalent widths of them using...
Fig. 1. The observed Hα line for all stars. Also visible is the Ca i line at 657.2 nm. All the stars are M6 V, except BRI 0021 (M9.5+) and possibly UX Tau C (M5?). Stars have been offset vertically for clarity, but have the same relative continuum scaling. Note the complete absence of any feature at Hα for BRI 0021.

For the LHS stars there is very little noise in the observed spectra; all the “ups and downs” are repeated in each star, and are real features. The (negative) Hα equivalent widths are listed in Table 1. For the more rapidly rotating stars, the molecular features are blended together with the Hα line, so we broadened a field star to help us choose consistent measurement points of the continuum near Hα. Prior to this guidance, the measured equivalent width was generally ~1 Å greater for the rapid rotators because of their apparently broad, low wings. The Hα line shapes are consistent with artificial rotational broadening of the field stars. There is no sign of emission or absorption at Hα in BRI 0021, to a limit of 0.2 Å. As discussed in the next subsection, this is completely unexpected given the v sin i of this star.

Also visible in Fig. 1 is an absorption line at 657.28 nm. We identify this as a ground state line of Ca I with a very low oscillator strength [log(gf)~—4.3; Kurucz & Peytremann 1975]. It is somewhat puzzling that this identification for the Sun shows a very similar equivalent width (Moore et al. 1966). It may be that the opacity in the pseudocontinuum due to TiO is sufficiently high compared to the line such that their ratio is similar to its solar value, despite the enormous increase of neutral calcium in such a cool star. As can be seen in Table 1, the M6 field stars have rather consistent equivalent widths. We measured these from the innermost maxima; the value for LHS 1070 is spuriously higher because the molecular features don’t show as much contrast, possibly due to its v sin i. It has also recently been announced that LHS 1070 is actually a close triple system (Leinert 1994). The T Tauri and Pleiades stars also show this Ca i line with a strength similar to that in the field M6 dwarfs. BRI 0021 has a noticeably stronger line, presumably because this calcium line arises from the ground state of a neutral species. Two components of the Ca ii infrared triplet are within our format; they are barely discernible in the M6 stars (except the presence of Hα emission), but slightly more obvious (with an emission core) in UX Tau C. We see no evidence of them in BRI 0021. Mould et al. (1994) did not see the Ca ii K line in the M9+ star PC 0025+0447, but there is an emission feature in their spectrum that might be the Ca i resonance line at 422.6 nm.

Another atomic line which is strong in very late-type stars is due to Rb i at 794.763 nm. This line is shown in Fig. 2 for all stars here, and its equivalent width is tabulated in Table 1. This is a resonance line, and it seems to be a good temperature diagnostic. The field M6 stars again show similar Rb i strengths, while both Pleiads are weaker. This is consistent with the suggestion of Marcy et al. (1994) that these stars should be moved to slightly higher effective temperatures. UX Tau C is very noticeably weaker still, leading us to believe that it is really a little hotter than M6. This is also suggested by the appearance of some of the longer wavelength molecular bands (we illustrate one later). The Rb i line is quite strong in BRI 0021. There are also some lines of Ti i (multiplet 33) which we see but do not display. The one at 842.651 nm is fairly clean and isolated, but the doublet at...
Fig. 2. The observed Rb i line at 794.76 nm. This appears to be the best atomic temperature diagnostic in our spectra.

843.496, 843.565 nm is confused with an overlying TiO band.

The strongest atomic feature in the spectrum is the resonance doublet of K I near 770 nm. Only the line at 769.898 is fully in our format; it is shown in Fig. 3. This is the analog of the Ca II K line for these stars, and for the first time we are aware of for dwarfs, a chromospheric reversal is seen in the line core (of three of the four field dMe stars). This line is in

Fig. 3. The observed K I resonance line at 769.9 nm. Note the chromospheric reversal in the center of the line for the lower three field dMe stars. Note also the smoothness of the outer wings in the rapid rotators (especially BRI 0021) compared with the field stars. This is due to rapid rotation, while the smoothness near the core for all stars is due to K I line opacity covering the other transitions. Note also the narrower line in UX Tau C.
emission in some high mass loss supergiants. Emission cores in neutral lines have been seen in flare stars (during quiescence), but only in the very blue part of the spectrum (Wilson 1961). Oddly, the strength of the $K\alpha$ reversal is not directly correlated with $He$ strength. The star without a reversal (LHS 36) is one of the slow rotators, but the other slow rotator does have a reversal. The reversal cannot be seen in the rapid rotators because of rotational smearing. UX Tau C again stands out as having a narrower and weaker $K\alpha$ line. Although it is likely to have the lowest gravity of our stars, we point out that the wings are primarily due to radiative damping. We take this as further evidence that this star may be a little hotter than the others.

Finally, we present the region of the $Li\,I$ resonance line at 670.78 nm in Fig. 4. The main scientific results from this have already been presented in Marcy et al. (1994). Our purpose here is to show the individual $M_6$ field stars, and the result for BRI 0021. Our limit for its lithium line is $\approx 200$ mÅ. This is based on imposing a synthetic $Li\,I$ feature on our slow rotator and applying artificial rotational broadening. We would expect the $Li$ resonance line to be even stronger in BRI 0021 at a given abundance than for UX Tau C. Thus, its absence in BRI 0021 is definitive: this star has destroyed its primordial lithium. The interpretation of this depletion is different than for the Pleiads, however, because we don’t know its age or mass. The theory (Nelson et al. 1993) suggests that a hard lower limit on its mass of 0.065 $M_\odot$ can be placed based on lithium destruction. This is just barely consistent with its mass as derived from an empirical relationship between mass and spectral type (Kirkpatrick & McCarthy 1994). It could have a mass between 0.065 $M_\odot$ and the hydrogen burning limit of 0.08 $M_\odot$ if it is older than about 200 Myr. There is nothing to suggest that it is younger than that, so the lithium test in this case does not rule out that BRI 0021 is a brown dwarf. Of course, hydrogen burning is not ruled out either.

3.2 Rotation

The primary result of this paper concerns the projected rotation velocities ($v\sin i$) of the objects studied. The rotation of convective stars is known to decrease over time, providing an age indicator [see Catalano & Stauffer (1991) for reviews; Soderblom et al. (1993)]. In young clusters, the lowest mass stars lose their angular momentum more slowly than higher mass convective stars on the ZAMS. At the age of the Pleiades (~70 Myr), there is a population of very rapidly rotating low mass stars, which presumably have spun up during radiative pre-main sequence contraction and have not yet had time to spin back down. The spindown progresses down the main sequence beyond this age, so that by the age of the Hyades (600 Myr) most K stars are rotating at $\leq 10$ km s$^{-1}$. A small (undetermined) fraction of the M dwarfs in the Hyades have $v\sin i$ as high as 20 km s$^{-1}$ (Stauffer 1994).

Hyades M dwarfs show dispersion in $H\alpha$ emission strengths (Stauffer et al. 1991, 1994), as well as the directly detected rotational broadening, indicating that for very low mass stars the convergence to low rotation may take a billion years or so. This has supported the conventional wisdom that the dMe phenomenon occurs among stars not much older than 1 Gyr; indeed it is almost certain that they are dMe.
Fig. 5. Demonstration of the rotational broadening in late M stars. Each panel shows the spectrum of a program star (solid line) above LHS 292, our rotational standard which has been artificially broadened to an appropriate velocity (dotted line, offset by 0.4 continuum units). In the upper panels it is broadened to 10 km s\(^{-1}\), in the middle panels to 25 km s\(^{-1}\), and in the lower panels to 40 km s\(^{-1}\). This is only one of ten spectral regions used to determine values for \(v \sin \ i\).

because they are still rapidly rotating. Bopp & Fekel (1977) have proposed that rotation of 5 km s\(^{-1}\) is the trigger for Balmer emission in M stars (see also Bopp et al. 1981). One has to be careful at the latest spectral types, since the contrast between chromosphere and photosphere grows with cooler temperatures. The same intrinsic chromospheric strength can lead to H\(\alpha\) absorption at early M but emission at late M spectral types. This issue is discussed at length in Sec. 4.

We measure the rotation in each spectrum by comparison with a slowly rotating template, selected from our sample. Both LHS 292 and 36 have the sharpest lines; we used the former as our standard (so if it is rotating at more than 2 km s\(^{-1}\), our estimated velocities may be slightly low). There is an enormous amount of rotational information in our spectra, which are laced with molecular lines. Our procedure was to first artificially spin up our standard to a set of velocities from 2.5 to 60 km s\(^{-1}\) in intervals of 2.5 km s\(^{-1}\). We then chose 20 wavelengths intervals (2–3 nm wide each) located throughout our 15 spectral orders, which looked like they would be useful and were not contaminated by strong atomic lines or telluric features. We performed a cross correlation of the standard with the synthetic rotational spectra in each interval for each velocity.

We used a Gaussian fit to the cross-correlation function to characterize its resulting width, and plotted the behavior of this width as a function of rotational velocity in each interval. The relation between width and \(v \sin \ i\) varied, depending on the particulars of the molecular blending and line spacings. In certain intervals the behavior was far from the average. We selected the ten best intervals for use in our final calibration and then cross correlated the standard with each of the program stars. For each wavelength interval a fit to the width–velocity function for that interval (predetermined as above from LHS 292) was used to convert the measured cross-correlation width to a rotational velocity. The dispersion in these results among the wavelength intervals is used to estimate the error in \(v \sin \ i\).

Figure 5 shows one of the wavelength intervals for all the stars with detectable rotation. The lower line in each panel is the reference spectrum of the slow rotator LHS 292 spun up to an appropriate value. Note that there is a fairly good detailed fit in almost all cases. One would not expect perfect
agreement since the stars are not exactly the same; in particular, UX Tau C is likely to be hotter and BRI 0021 is certainly cooler than the rotational standard (LHS 292). Note the changes in TiO strengths at 844.2 and 845.1 nm; these bands are listed by Kirkpatrick et al. (1991) as "prominent in mid to late M stars." Since these bands saturate at the cool end, one expects less change there. The way in which the molecular features (which are ubiquitous and easily visible in the standard) are smoothed away, consistent with the appearance of the program objects, leads us to confidently ascribe the appearance of the spectra in the right panels of Figs. 1–4 to rapid rotation. We can think of no other means of achieving such smoothing and line widths.

In Table 1 our final determinations of \( \nu \sin i \) are listed. Recall that all program stars have H\( \alpha \) emission except BRI 0021. For the field dM6 stars, two of four have detectable rotation, namely LHS 248 (11 km s\(^{-1}\)) and LHS 1070 (8 km s\(^{-1}\)). We estimate our sensitivity limit to be about 3 km s\(^{-1}\). These two detections out of four late M dwarfs are statistically consistent with the results from Stauffer & Hartmann (1986). As mentioned above, it is easier for very late M stars to show emission because of their very cool photospheres; the relation of emission to rotation for this population is currently unknown. Stauffer & Hartmann only studied three stars with \( R - I \) greater than 1.5 (GI 406 has an \( R - I \) of 1.76) and got \( H\alpha \) measurements for none of those. A better sample for this purpose is in Giampapa & Liebert (1986), who found that half of their 15 stars M6 or later showed H\( \alpha \) emission. Liebert et al. (1992) used improved spectra to find that essentially all such stars have H\( \alpha \) emission. Neither study has rotational information.

We also observed three stars with known youth: the two Pleiades objects and the T Tauri star. These all are rotating substantially more rapidly than the field M6 stars, though their H\( \alpha \) lines are not stronger. This is likely due to the "saturation" effect for very active stars: increasing the rotation further does not increase the emission (for reasons not completely understood). Marcy et al. (1994) gave essentially the same value for \( \nu \sin i \) for UX Tau C, but did not appreciate that the two HHJ stars are also rapid rotators. The fact that the Pleiades stars are rotating as rapidly as the T Tauri star is not surprising given the rotation history of stars during their pre-main sequence and main sequence evolution.

Finally, a very surprising result is that BRI 0021 is the most rapid rotator of our sample, with \( \nu \sin i \) of 40 km s\(^{-1}\). As presented in Sec. 1, most M stars, especially field stars, are very slow rotators. Rapid rotation in BRI 0021 is especially surprising because of its lack of H\( \alpha \) emission. One expects a randomly chosen very late M star to be rather old (since they live for longer than the age of the galaxy), and the absence of H\( \alpha \) emission conventionally implies an age of well more than a billion years. Very rapid rotation, on the other hand, is conventionally thought to be a marker of youth. Even among young field H\( \alpha \) emission stars, however, \( \nu \sin i \) is known to exceed 20 km s\(^{-1}\) only in one case: GI 890 (Pettersen et al. 1987). We have considered many other mechanisms for broadening stellar lines to the extent observed, and can think of no explanation for the appearance of the spectrum other than rotational broadening. This result is so intriguing that we defer further discussion of it to Sec. 4.

### 3.3 Radial Velocities

We established the radial velocities of the program stars by using the atomic features described in Sec. 3.1. We note that H\( \alpha \) did not seem to be preferentially shifted compared with the other lines. Barycentric corrections were computed for all objects, and the radial velocity (16.5 km s\(^{-1}\); Stauffer et al. 1994) for LHS 36 (GI 406) was used as the absolute standard. We preferred measuring atomic lines relative to GI 406 to using the absolute scale established from the ThAr lines, as their accuracy was not sufficient to give the most precise velocity. The barycentric velocities for each star are listed in Table 1. The errors in all cases are around 3 km s\(^{-1}\), judging from internal scatter among our diagnostic lines. We see that the HHJ stars are confirmed as Pleiads from this point of view as well; the mean cluster velocity is 5.9 km s\(^{-1}\) (Rosvick et al. 1992). Our velocity for HHJ 14 agrees with that of Stauffer et al. (1994). UX Tau C also has a velocity consistent with the known value for UX Tau A (and with Magazzù et al. 1991). BRI 0021 has a velocity consistent with the value of 16±10 km s\(^{-1}\) by Reid et al. (1994) obtained in 1992. This leads to the suggestion that none of these stars are part of a close spectroscopic binary system. In addition, we tested our two individual spectra of BRI 0021 for a velocity change during 90 min, and can rule out variations at a limit of 3 km s\(^{-1}\). Tidal synchronization by a close binary is ruled out for this star.

The velocities for the field stars can be combined with their known proper motion to yield information on their space velocities. Of particular note is that the space motion of BRI 0021 resembles that of the members of the young disk population. Such implied youth is consistent with the general observation by Kirkpatrick (1994) that the stars at the end of the main sequence generally have the character of a young population. Of course, the rapid rotation would conventionally provide an even more striking indication of youth.

### 4. DISCUSSION

By far our most intriguing result is the extremely rapid rotation (40 km s\(^{-1}\)) found in the coolest known single star, BRI 0021, accompanied by a complete lack of the chromospheric activity which is always seen in rapid rotators among the convective stars. Because rapid rotation is generally a sign of youth, this appears to provide, at first glance, dramatic support for the conjecture of Kirkpatrick (1994) and Hawkins & Bessell (1988) that the stars M7 or later may be brown dwarfs on cooling curves. In that case, we selectively detect the young ones because they fade out of sight when older. The lack of H\( \alpha \) emission, however, allows the possibility that the angular momentum history of the latest-type stars is fundamentally different, and that magnetic braking is greatly reduced in these stars. In that case, rapid rotation may not be a guarantee of youth. This scenario would suggest instead that either the interior of these stars is very different from earlier M stars in the context of a magnetic dynamo, or that the conversion of magnetic fields to surface activity is
drastically altered. The implication that they could be brown dwarfs is therefore very much alive, by virtue of the apparent qualitative change in the rotation–activity connection. Regardless of brown dwarf status, we apparently see in BRI 0021 a definitive case of the quenching of normal stellar activity at the end of the main sequence. Below we discuss, in turn, the implications of this observation for the study of stellar activity and detection of brown dwarfs.

To understand whether the lack of observed Hα emission in BRI 0021 is a result purely of its extraordinarily cool effective temperature, or due to a change in its magnetic activity, the most obvious starting point is other observations of very cool stars. Liebert et al. (1992) show that Hα emission is the norm (albeit with large scatter) for stars with $M_v > 16$, corresponding to spectral types M6 and later. This is surprising given the conventional picture that dMe stars are young, since surely some very low mass stars are old (but would be less surprising if, as conjectured above, the coolest stars are all in fact young). Indeed, Liebert et al. show that some of the cool dMe stars do not have the kinematics of the young disk, and Reid et al. (1994) discuss this issue in more detail. The latter authors are less certain about the kinematic separation, but tentatively conclude that photometrically selected faint stars (as opposed to those selected by proper motion) may be from a younger population. There is a great dispersion in the observed equivalent widths of Hα, but all the very cool stars in Liebert et al. show emission. We know of one extreme example which shows that there is a lower limit to the mass of objects with chromospheres. Jupiter can be regarded as a rapidly rotating, extremely low mass brown dwarf, which does not exhibit Hα emission or a chromosphere (although its effective temperature is sufficiently different from the stars we are talking about that the comparison may not be meaningful). It does, of course, possess a magnetic field.

No doubt the visibility of Hα in very cool stars is due in part to the “contrast effect”: their photospheres become increasingly faint in the $R$ band, while a chromosphere remains hot. We have studied this question by taking the upper envelope of the Hα equivalent widths for field M stars in Liebert et al. [Fig. 6(a) solid line], and converting them to Hα luminosities by multiplying by an estimate of the continuum luminosity around Hα. This we estimate from data in Kirkpatrick et al. (1993a,b) which provide examples of $M_v$, $M_1$, $T$, and $L_{bol}$ for a set of spectral types among late M stars. We estimated the luminosity at Hα by using the spectra in Fig. 3 of Kirkpatrick et al. (1993b). Assuming the I band flux is dominated by the flux peak around 810 nm, we took the ratio of the observed flux there to the flux at 656 nm in each spectrum. We fit this ratio as a quadratic function of $M_1$ and thereby inferred a (normalized) luminosity at Hα for each $M_1$.

Because the photospheric luminosity is dropping rapidly, very cool stars which have a constant chromospheric filling factor (and surface flux) would exhibit a much more dramatic rise in Hα equivalent widths [Fig. 6(a) dashed line] than is actually observed. This implies the chromospheres must actually be weakening, along with the photospheric flux. Figure 6(b) shows that the Hα luminosity itself plummets in the late M stars, by two orders of magnitude from M3 to M9. We are generous at M9, estimating the upper envelope in equivalent width at 14 Å, while the only actual datum in Liebert et al. is less than 3 Å. A related analysis has been done for the earlier M stars by Young et al. (1989). Our chosen envelope is above the low mass Pleiades stars of Stauffer et al. (1994), which have only modest Hα equivalent widths. The actual decline in Hα luminosity may well be steeper.

If Hα is saturated along the upper envelope, then the luminosity will be limited by the decreasing radius of these stars. It is common to discuss activity efficiencies as a ratio of line emission with the bolometric luminosity of the star. Figure 6(b) shows this quantity for Hα. Despite its common usage, it is not clear that the bolometric luminosity of a star has much to do with the production of nonradiative heating in its outer atmosphere. We believe a better measure of activity efficiency is the surface flux itself; by “saturated” chromospheres we mean that surface flux should reach a constant maximum value. In practice, surface flux can be found by simply scaling the ratio of Hα to bolometric luminosity by a factor of $T^4$. Figure 6(b) shows that the surface...
flux in Hα drops by more than an order of magnitude at the bottom of the main sequence. Recall that this is inferred from our chosen upper envelope of equivalent widths; the actual drop could be steeper. Stauffer et al. (1994) also note a puzzling upper limit to Hα equivalent widths in very low mass stars in the Pleiades and Hyades (our measurements of HHJ 3 and 14 support that). The equivalent widths do not continue an apparent rise seen at earlier spectral types, but flatten out at about 5 Å in the Pleiades and 10 Å in the Hyades. The rapid rotation of BRI 0021 and HHJ 3 and 14 makes it clear that this behavior is not because of slow rotation among the faintest stars. Furthermore, this envelope does not change between the ages of the Pleiades and Hyades.

Giampapa & Liebert (1986) point out that an absence of Hα emission can be interpreted in two ways. A very cool star might lack absorption and emission because there is no opacity in the Balmer transitions. This would imply no chromosphere, and one would normally expect the star to be a very slow rotator. The other possibility is that Hα absorption is filled in by moderate emission; this would normally imply a rotation rate of a few km s⁻¹. They were unable to distinguish between these two possibilities for their nonemission stars because they didn’t have sufficient signal to noise to rule out slight emission, and could not measure their rotation.

For spectra of our quality, it would take quite a coincidence to fill Hα in just enough to yield no feature at all. The lack of an Hα feature (in absorption or emission) indicates the absence of a chromosphere in BRI 0021. Byrne (1993) has shown that at least some of the earlier M stars without emission are actually deficient in chromospheric activity, rather than having the right conditions to just fill it in. Presumably these are slow rotators, although this must be tested. By contrast, there have been no predictions for an absence of emission in very rapid rotators among M dwarfs. BRI 0021 is now the second fastest known; Gl 890 is the fastest at 70 km s⁻¹, with 2 Å of emission on top of an M1.5 photosphere (Pettersen et al. 1987).

One worries that there is something intrinsic to very cool stars which influences Hα formation (even though chromospheres should always be 6000–10 000 K when coronae are present above them). However, an extremely cool star with very strong emission has been found (PC 0025+0447, hereafter PC 0025; Schneider et al. 1991). The two coolest classified single stars currently are PC 0025 and BRI 0021; Kirkpatrick et al. (1994) classify them as M9.5 and M9.5+, respectively. The Hα emission line in the former has an equivalent width of 275 Å, while the latter has no Hα feature whatsoever! It appears that just being extremely cool does not preclude BRI 0021 from having Hα emission. Recently, Mould et al. (1994) have also shown that the entire Balmer series is in emission in PC 0025. More importantly, they calculate that its ratio of Hα luminosity to bolometric luminosity is about 3 time greater than for M3–5 stars in the Hyades. If the Hα luminosity of the latest stars was comparable to those of Hyades stars, it would be well above the values for Hα luminosity appropriate to the bottom of the main sequence in Fig. 6(b), raising the equivalent widths in Fig. 6(a) from single to triple digits. Thus, the extreme equivalent width in PC 0025 would be due primarily to the contrast effect we alluded to earlier if chromospheres remained saturated at the maximal value.

Actually, PC 0025 would have to be supersaturated, because a value above the inferred saturation boundary is required to generate the actual observed equivalent width. One wonders whether there is another body in the system that is somehow responsible for this great emission. It would have to be very faint. Another possibility which is gaining credence is that this is not a dwarf. Dahn (1994) reports that preliminary USNO parallax work indicates its distance is inconsistent with dwarf status. Tinney (1994) finds that preliminary proper motion limits would require a tangential velocity of less than 4 km s⁻¹ if it were a dwarf. It could possibly be a pre-main sequence object, or pathological in some other way that makes comparison with BRI 0021 actually inappropriate. Its initially presumed distance of 63 pc (Schneider et al. 1991) would make it likely that it is a rare kind of object, since such objects would easily be uncovered in searches for emission line objects like QSOs, and so far it is unique. BRI 0021, on the other hand, is known to have such a low absolute magnitude that it is not surprising more stars like it have not yet been found.

With a typical value for sin i, the true rotation speed of BRI 0021 is about 50 km s⁻¹ (still well below the breakup velocity of nearly 400 km s⁻¹). The radius of this faint dwarf is likely to be around 0.1R⊙ (Dorman et al. 1989). This means its period is about 2.5 h. The Hα emission is about a thousand times stronger in PC 0025 than our limit for BRI 0021, but its rotation cannot be even 10 times higher. If there is a threshold rotation speed which triggers strong Hα, it has to be in excess of 50 km s⁻¹ by the end of the main sequence. Of course, this reasoning depends on PC 0025 being a comparable dwarf. If it is not, there may be no trigger velocity and stellar activity may have died out at the bottom of the main sequence. The rapid rotation of BRI 0021 means that during our 1.5 h of exposure we sampled most of the stellar surface. It would be very interesting to monitor this star for rotational modulation (if any were seen it would be evidence for spots and magnetic fields without Hα emission). It would also be nice to check that Hα doesn’t appear at some later time.

To avoid the complexities of Hα line formation, we can look to more straightforward (hotter, optically thin) diagnostics of nonradiative heating. It is very fortunate that two highly relevant surveys of hot emission from very cool stars have recently been published. Wood et al. (1994) have studied the stars within 10 pc using the ROSAT WFC, which is sensitive to transition region and coronal radiation in the extreme ultraviolet. They have found four firm and one marginal detections of the seven stars M5 or later within 4 pc, and none further away than that (of nine additional possibilities). All their detections are M6 or earlier. In studying their overall sample (including IPC data for many other stars) they conclude that late M stars suffer a “saturation” effect in their coronae; once the surface area of the star is covered by emission, one cannot increase its coronal luminosity by spinning it yet faster. In practical terms, this means that maximal coronal luminosities decrease as one considers later M stars, because their radii are decreasing. Wood et al. don’t find evi-
dence, however, that the maximal “surface flux” of the corona decreases with effective temperature, as earlier x-ray studies had hinted. Unfortunately, this study does not bear strongly on coronae at M8–10.

Fleming et al. (1993) directly study the behavior of coronae right down to the end of the main sequence. They use the soft x-ray (IPC) survey by ROSAT supplemented by pointed observations. This is less affected by ISM absorption. There is also evidence that M stars have higher temperature coronal components than K stars, which means this passband may detect more of the coronal continuum. They detect three of our field dMe stars, whose x-ray luminosities vary between 27.2 and 26.7 (log erg s⁻¹). PC 0025 has an upper limit of 27.5. Of the coolest stars, LHS 2924 (M9e) and VB10 (M8e) yield upper limits of 25.7 and 25.5, respectively. The latest spectral type with a positive x-ray detection is VB8 (M7e), at a level of 26.9. There is no published limit for BRI 0021 itself. Fleming et al. also conclude that there is strong evidence for coronal saturation, and that down to M8 anyway, there is no real evidence that maximal coronal efficiencies (Lₓ/Lₜₚ) diminish with effective temperature. Actually, their plot of this ratio against Ṁ for their actual detections contains a strong resemblance to the decline seen in Fig. 6(b). As noted by Fleming et al., their x-ray upper limits for stars M8 and later fall well below the positive detection at M7. Combined with the Hα results (which do not suffer from the problem of upper limits), we think there is good preliminary evidence that there is some decline in stellar activity at the latest spectral types. Our result for BRI 0021 can be construed as a strong further push in that direction.

The current understanding of the stellar magnetic dynamo mechanism is too poor to provide clear guidance on its behavior at the faint end of the main sequence. It is currently thought that stars become fully convective below about 0.3 M☉ (Dorman et al. 1989). There is some support for the notion that dynamos at higher mass might be driven primarily in a shell (overshoot layer) at the bottom of the convection zone. Rosner (1980) discusses the relative merits of a shell dynamo vs the distributed model that is probably required once a star is fully convective. From a theoretical point of view there are stability problems with a distributed dynamo (Fisher et al. 1991, and references therein). Observational support comes from helioseismology results (Goode 1991) which indicate that the solar convection zone rotates more or less rigidly along radii throughout it. Most dynamos rely on some sort of differential shear to operate.

The Hα and x-ray results discussed above seem to indicate that the dynamo does not turn off as stars become fully convective—the possible falloff at M8 occurs at a much lower mass. Not only do some of the latest stars manage to show Hα emission, but fully convective stars on the pre-main sequence have no trouble at all generating very strong fields (Basri et al. 1992). Indeed, the ratio of coronal to bolometric luminosities is maximum somewhere near the fully convective boundary. All of this could be taken as evidence in favor of distributed dynamos (perhaps of varying efficiency). Of course, it is possible that both shell and distributed dynamos exist, and that their relative importance shifts from shell to distributed as one moves cooler through the fully convective boundary. Regarding the behavior at the end of the main sequence, one might appeal to a change in either convective velocities, surface turbulence, or the conversion of magnetic energy to heating (followed by radiative cooling) in the upper atmosphere. On this latter point, Mullan (1984) has proposed one mechanism to reduce heating in the late M stars. Fleming et al. (1993) argue that Mullan’s mechanism is incompatible with the x-ray data in its current form.

It has been suggested by Spruit & van Ballegooijen (1982) that the nature of the dynamo should change if the base of the convection zone retreats below some threshold radius. Durney & Robinson (1982) discuss the efficiency of distributed αω dynamos as the convection zone deepens. They predict increasing magnetic flux production towards cooler stars, and suggest that M stars with periods as slow as the Sun’s should become saturated with surface fields by M5. The Zeeman measurements in Saar (1990) tend to bear this out. Durney & Robinson do not explicitly discuss what should happen later than M5, but leave the impression that field production should remain efficient.

A later paper by Durney et al. (1993) takes the more current view that the main dynamo responsible for the rotation–activity connection is a shell dynamo, which produces cycli cal large scale magnetic structures. They posit another, distributed, dynamo which operates by generation of a small scale turbulent magnetic field throughout the convection zone. This field would be less sensitive to rotation, and would be less effective at providing a mechanism for stars to lose angular momentum, because they argue it would produce bipolar regions of smaller scale (despite actually containing more total magnetic energy). The authors suggest that the reduced magnetic wind is why the very cool Hyades stars remain as rapidly rotating as in the Pleiades. The turbulent field could be one source of “basal” chromospheric fluxes in most cool stars, and would be the only source of field for the fully convective stars. The problems with this theory are that there does not seem to be much of a change in activity at the fully convective boundary, nor does activity decrease from the hot side of that boundary as one might expect if the shell dynamo were being increasingly constricted (on the contrary, Lₓ/Lₜₚ is maximal near this boundary). One must also explain why, once stars are fully convective, there is a further decrease in activity. It is unclear that Hα surface fluxes should decrease, even if the efficiency of angular momentum loss is decreasing. Finally, observations show that flares from late M dwarfs are actually larger (of order the stellar radius) in scale, somewhat contrary to the supposed reduction of scale for magnetic regions proposed for fully convective stars. Whatever the nature of the dynamo, however, its effects are severely weakened in BRI 0021.

We propose that magnetic activity is increasingly quenched in M7–10 stars, allowing them to retain their angular momentum for much longer than early M stars. Such quenching implies that the spindown time increases dramatically in late M stars, not only because their pre-main sequence spinup (due to contraction) lasts longer because of the increasing time scale for this evolution, but because the magnetic braking becomes increasingly inefficient. This is
not just due to a change in the magnetic geometry, but a decrease in the total field itself. Furthermore, the fundamental relation between rotation and magnetic activity is altered. Prior to obtaining more rotational data, it is hard to say where this sets in; Fig. 6(b) suggests it could be as early as M5.5. It may be that the latest M stars are all relatively rapid rotators, and their spindown time is the age of the galaxy. The decrease in the ability of the dynamo to convert rotation into stellar activity is even more striking if angular velocity is what counts (as dynamo theory prefers); angular velocity increases as radius decreases down the main sequence for a given (fixed) equatorial velocity. The equatorial velocity of BRI 0021 is ~25 times solar, but its angular velocity is ~250 times greater. The suggestions of Durley et al. (1993) may provide a theoretical path to these changes in the dynamo that is worth pursuing, despite our specific complaints above.

If our conjecture is true, stars like LHS 2924 should be moderately rapid rotators, despite their low Ha and coronal emission, even if they are relatively old. The trigger velocity for very strong emission must also go up, or possibly even disappear, so that 40 km s\(^{-1}\) at M9.5+ is insufficient to produce much of a chromosphere. This might serve as the explanation for the limiting equivalent widths found for faint stars in young clusters by Stauffer et al. (1994). The implication is that BRI 0021 is not anomalous. This hypothesis has the virtue that it is easily tested: we will shortly obtain \(v\sin i\) for several more of the coolest stars. If PC 0025 turns out to be a dwarf, we predict it should be a very rapid rotator and this would constrain the trigger velocity for production of chromospheres. If our conjecture proves incorrect, one still has to explain the puzzle of BRI 0021.

There is other evidence that something may be going on in the very late spectral types. There is a suggestion of a kink in the color–magnitude relation at M7–8 (Tinney 1993) interpreted to suggest that the lowest luminosity stars may actually be substellar. Kirkpatrick & McCarthy (1994) study stars whose masses can be derived dynamically because they are in binaries. Even those which come out at the hydrogen burning limit (0.08\(\odot\)) have apparent spectral types of \(\sim\)M6.5. This suggests directly that the later spectral types could be brown dwarfs, whose magnetic activity is a complete mystery. The possible substellar nature of M7–10 dwarfs also receives support from the behavior of the stellar luminosity function (upturn at faint magnitudes), the galactic distribution of late M dwarfs (concentrated to the galactic mid-plane), and kinematics which may be indicative of the young disk population (Bessell & Stringfellow 1993; Kirkpatrick 1994; Reid et al. 1994). Note that BRI 0021 itself satisfies several of these criteria. Of course, the sample of such stars is still woefully small. If M7–10 stars are really brown dwarfs, one expects a strong selection effect for youth among them, since they will cool to extremely faint magnitudes after the first Gyr. This argument is strengthened by the longevity of the lowest mass hydrogen burning stars; all such stars formed since the galaxy began are still shining (Bessell & Stringfellow 1993).

It is important to look for signs of youth in the latest M dwarfs. One obvious diagnostic is lithium, but it only establishes extreme youth among stars more massive than 0.07\(\odot\) (although any detection of lithium in a late M field star is already a strong presumption for brown dwarf status). As mentioned earlier, our nondetection of lithium in BRI 0021 only implies that it is older than 0.2 Gyr and more massive than 0.065\(\odot\) (Nelson et al. 1993). Another obvious diagnostic of youth in M stars (until now) has been rapid rotation, and BRI 0021 certainly has that. Without the Ha anomaly, one would cite its rotation as strong evidence in favor of the brown dwarf status of M8–10 stars. If our hypothesis about spindown times is correct, however, then even if most of the very cool stars show measurable rotations, this will unfortunately not constitute additional evidence of their youth.

Regardless of whether BRI 0021 is really a brown dwarf, it stands by itself as highly enigmatic. The single star with the coolest current spectral classification, it is rotating extremely rapidly without displaying either the lithium diagnostic of extreme youth or the Ha emission which usually accompanies rapid rotation. It is important to resolve whether PC 0025 is a dwarf which stands in stark contrast to it, or whether PC 0025 is instead not a comparable object. In any case, BRI 0021 is a new class of star in the rotation–activity arena. The detailed study of stars at the bottom of the main sequence has become even more imperative than it already was.

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