HIGH-RESOLUTION SPECTROSCOPY OF ULTRACOOL M DWARFS

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ABSTRACT

We present high-resolution echelle spectroscopy of 39 dwarfs with spectral types between M6.5 and L0.5. With one exception, those dwarfs were selected from the Two Micron All Sky Survey database using photometric criteria, \((J-K_s) \geq 1.1\) and \(K_s \leq 12.0\), and therefore should provide a sample free of the kinematic biases that can affect proper-motion–selected samples. Two of the stars, 2MASSI J0253202+271333 and 2MASSW J0952219–192431, are double-lined spectroscopic binaries. We have used our observations to search for Li \(\lambda 6708\) Å absorption, characteristic of substellar mass; estimate the level of chromospheric activity through measurement of H\(\alpha\) emission fluxes; measure rotational velocities via line broadening; and determine radial velocities and Galactic space motions. Two dwarfs have strong lithium absorption, the previously known brown dwarf LP 944-20 and 2MASSI J0335020+234235, which we identify as a probable \(0.06\) \(M_\odot\) brown dwarf with an age of \(\sim 1\) Gyr. We have investigated the prospect of using the observed frequency of lithium absorption among ultracool M dwarfs (M7 to M9.5) as a probe of the initial mass function, comparing the observed frequency against predictions based on recent theoretical models of low-mass dwarfs and an assumed star formation history. Our results show that the conclusions drawn are vulnerable both to systematic differences between the available models and to incomplete local sampling of the most recent star formation events (ages less than \(10^8\) yr). The latter consideration stems from the mass–dependent rate of evolution of brown dwarfs. Even given those caveats, however, the available observations are difficult to reconcile with Salpeter-like power-law mass functions (\(\alpha \geq 2\)) for masses below \(0.1\) \(M_\odot\). A comparison between the rotational velocities and H\(\alpha\) fluxes shows no evidence for significant correlation. The mean activity level of the ultracool dwarfs lies almost a factor of 10 below that of early- and mid-type M dwarfs. The relative number of dwarfs with \(v \sin i < 20\) km \(s^{-1}\) with respect to greater than \(20\) km \(s^{-1}\) is independent of spectral type. Finally, velocity dispersions derived for our photometrically selected sample of ultracool dwarfs are significantly lower than those measured for nearby M dwarfs but show remarkable similarity to results for earlier type emission-line (dMe) dwarfs. The latter are generally assigned ages of less than \(\sim 3\) Gyr.

Key words: Galaxy: stellar content — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

On-line material: color figures

1. INTRODUCTION

The pioneering Two Micron Sky Survey (TMSS) undertaken by Neugebauer & Leighton (1969) provided the first large-scale celestial survey at near-infrared wavelengths. Extending only to \(K \sim 3\) mag and covering 75% of the sky (Neugebauer, Martz, & Leighton 1965), the TMSS revolutionized our understanding of the nature of cool, luminous objects, such as Mira variables (Ulrich et al. 1966), red supergiants (for example, VY CMa, Hyland et al. 1969), and dust-enshrouded asymptotic giant branch stars (e.g., IRC 10216; Becklin et al. 1969). The current generation of surveys, the Deep Near-Infrared Survey (Epchtein et al. 1994) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997), reach flux levels more than 10,000 times fainter than the TMSS and provide the first census of the near-infrared sky at moderately faint magnitudes. As such, they offer the prospect of a similar revolution in our understanding of cool, low-luminosity objects. Initial analyses have concentrated primarily on the coolest dwarfs discovered in those surveys, sources whose atmospheric properties and consequent emergent energy distributions have necessitated the creation of new spectral classes: type L (Kirkpatrick et al. 1999; Martin et al. 1999) and, more recently, type T, for Gl 229B–like dwarfs (Strauss et al. 1999; Burgasser et al. 1999). The new surveys, however, also have the potential to revolutionize studies of late-type M dwarfs. Even if those objects are now a shade passé, analy-
ses of enlarged samples can probe such fundamental parameters as the stellar mass function, $\Psi(M)$, kinematics, and the origin and range of magnetic activity close to the hydrogen-burning limit.

Photometric and spectroscopic data for nearby late-type M dwarfs are summarized in a series of papers by Kirkpatrick, Henry, & Simons (1995), Kirkpatrick, Henry, & Irwin (1997), Henry, Kirkpatrick, & Simons (1994), and Henry et al. (1997). That sample includes 26 dwarfs with spectral types between M7 and M9.5, which, following Kirkpatrick et al. (1995), we designate ultracool M dwarfs. A minority of those sources were identified in deep photometric surveys by Reid & Gilmore (1981), Kirkpatrick et al. (1994), Tinney, Mould, & Reid (1993), and Kirkpatrick et al. (1997). The majority, however, were discovered through spectroscopic follow-up observations of faint red stars from proper-motion surveys, primarily Lytten’s Palomar catalogs. As a result, a statistical analysis runs the risk of bias due to preferential inclusion of higher velocity stars, which are more likely to be drawn from the older stars in the Galactic disk, while young, low space-motion objects, such as M-type brown dwarfs, lie undetected. The availability of near-infrared survey data provides the first opportunity for the construction of a substantial sample of ultracool M dwarfs using purely photometric criteria.

This paper presents high-resolution spectroscopic observations of 38 bright, ultracool M dwarfs and one L dwarf drawn from the 2MASS database. Our analysis has three main goals: first, an estimate of the fraction of ultracool dwarfs that exhibit detectable lithium absorption; second, the derivation of improved statistics on the distribution of rotational velocities; and, finally, a determination of the kinematics of these low-luminosity dwarfs. We have also used the echelle spectra to study the range of chromospheric activity at these spectral types. The paper is structured as follows: § 2 describes the sample selection and spectroscopic observations, § 3 summarizes the results of our search for lithium absorption, § 4 discusses our measurements of rotational velocities and comments on correlations with the level of chromospheric activity, § 5 considers the space velocity distribution, and § 6 presents our conclusions.

2. SAMPLE SELECTION AND SPECTROSCOPIC OBSERVATIONS

2.1. Sample Selection

Achieving the scientific goals outlined in the introduction requires high signal-to-noise observations at high spectral resolution of late-type M dwarfs. To that end, we have selected our targets from the 2MASS database using both color and apparent magnitude criteria. 2MASS provides photometry in three passbands: $J$ (1.25 $\mu$m), $H$ (1.6 $\mu$m), and $K_s$ (2.2 $\mu$m), where the subscript “s” denotes that the passband is truncated at the long wavelength (thermal) limit as compared with the standard $K$ passband (see Persson et al. 1998).

Our selection criteria are derived from the $(M_J, J-K_s)$ color-magnitude diagram described by nearby stars and brown dwarfs with accurate $(\sigma_{\alpha}/\alpha < 15\%)$ trigonometric parallax measurements (Fig. 1). The photometric data plotted in this figure are from Leggett (1992), the 2MASS database, and Dahn et al. (2000). M dwarfs outline an almost-vertical main sequence with $0.8 < (J-K_s) < 0.9$ to $M_J \sim 10.5$, corresponding to spectral types earlier than $M_6$. At lower luminosities, the main sequence moves redward: GJ 1111 (spectral type M6.5) has $(J-K_s) = 1.04$, VB 8 (M7) has $(J-K_s) = 1.05$, VB 10 (M8) has $(J-K_s) = 1.10$, and LHS 2924 (M9) has $(J-K_s) = 1.17$ mag. $J-K_s$ continues to increase to a maximum value of $\sim 2.1 \pm 0.1$ mag for the latest type L dwarfs, such as Gl 584C (L8, Kirkpatrick et al. 2000).

Our observations are aimed at ultracool M dwarfs with spectral types between M7 and M9.5. Following Figure 1, the majority of our targets are chosen to have near-infrared colors in the range $1.3 \leq (J-K_s) \leq 1.1$ and $K_s \leq 12.0$ mag. Table 1 lists positions, $IJKHKS$ photometry, and spectral types for our sample. The 2MASS $K_s$ magnitudes have typical accuracies of $\pm 0.01$–$0.02$ mag, and the near-infrared colors have typical uncertainties of $\pm 0.03$ mag. Most of the Cousins $I$-band magnitudes have been synthesized from flux-calibrated, low-resolution spectra obtained at either the Keck Observatory or at Las Campanas Observatory (see Gizis et al. 2000b, for details). Comparing these measurements against broadband data for stars with conventional photometry indicates uncertainties of $\pm 0.2$ mag.

Four dwarfs listed in Table 1 require comment: 2MASS J1242464+292619, or 2M 1242+29 (we use this abbreviated form hereafter), 2M 0339–35, 2M 0149+29, and 2M 2234+23. The last two are M9.5 dwarfs that have $(J-K_s) > 1.3$; both were identified as candidate L dwarfs. The object 2M 1242+29 was identified in 2MASS Proper-CAM $JHK$ data (Kirkpatrick et al. 1997) and is significantly fainter than our formal magnitude limit, with $K_s = 13.23$. While we tabulate our observations of this star, we have not included it in any of the statistical analyses discussed further below. Finally, 2M 0339–35 (LP 944-20) meets our selection criteria and was observed with HIRES, but inclement
the last is the brightest L dwarf currently known, 2M 1242+29, of the remaining four dwarfs have spectral types M6/M6.5; the 39 dwarfs include 14 with spectral types M7 or M7.5, 14 of type M8/M8.5, and seven of M9/M9.5. Three of the remaining four dwarfs have spectral types M6/M6.5; the last is the brightest L dwarf currently known, 2M 0746+20 (L0.5), recently resolved as a near equal-mass binary through HST observations (Reid et al. 2001).

Figure 2 plots the JHK two-color diagram for the sample, where we identify the different spectral types. The $J-K_s$ selection limit is apparent from the distribution. We use data for the parallax sample plotted in Figure 1 to outline the characteristic tilted $S$ shape of the main sequence. The turnover in $J-H$ at $(H-K_s) \sim 0.2$ stems from a combination of two factors: the wavelength dependence of H$^{-}$ opacity, which peaks at $\sim 1.6 \mu m$, and a shallower temperature gradient as convection becomes more important at spectral types later than M1/M2 (Mould 1976). The higher opacity places the photosphere at shallower depths and lower temperatures, reducing the total flux emitted in the $H$ passband. The blueward trend reverses at spectral type $\sim$M5, as H$^{-}$ becomes a less important opacity source at lower temperatures, and $J-H$ increases rapidly at later spectral types. Kirkpatrick et al. (2000) discuss the near-infrared colors of

### Table 1

| Source | Other Name | $I$ | Ref.* | $J-H$ | $H-K_s$ | $K_s$ | Sp. Type | Sourceb | Epoch |
|--------|------------|-----|-------|-------|---------|-------|----------|---------|-------|
| 2MASSI J0051068+282753 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J010324+294925 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0104006+270150 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0109089+295613 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSI J0152392+271333 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0230597+185423 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0330050+240528 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J033520+234325 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0339352-325344 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0339528+245726 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0350573+181806 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0429028+133759 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0746425+200032 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0810586+140203 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0818580+233352 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0853361-032931 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0925348+170441 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J0947127+402649 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1016347+275150 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1047127+305122 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1047127+402649 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1047138+304108 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1200329+204851 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1201088+030035 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1221222–122835 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1242464+292619 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1246517+314811 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1253124+403040 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J130219+233035 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1336504+475133 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1340322+300755 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1501081+225001 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1540162–235556 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1542248+292535 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1527194+413047 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1550382+304108 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J1714523+301941 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J2206228–204705 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J2233478+354747 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J2234138+235956 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 2MASSW J2235490+184029 .......... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

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*a* References for photometry: (A) Tinney 1996; (B) Flux-calibrated spectroscopy; (C) Dahn et al. 2000; (D) Leggett 1992.

*b* Spectral type source: (1) Reid & Gilmore 1981; (2) Kirkpatrick et al. 1995; (3) Gizis et al. 2000b; (4) Tinney 1998; (5) Kirkpatrick et al. 1997; (6) Leggett, Harris, & Dahn 1994; (7) Reid et al. 2000; (8) Gizis et al. 2000a; (9) Tinney et al. 1993.
2.3. Chromospheric Emission

All of the dwarfs observed possess emission lines indicative of chromospheric activity, although for LHS 2632 the emission lies at the threshold of detection even with HIRES. The most prominent features are the He i lines, although many dwarfs also exhibit emission in the cores of the K i 7665/7699 doublet, while approximately 25% of the sample show noticeable He i 6678 Å emission. Weak He i emission (EW < 0.3 Å) may be masked in other dwarfs by the complex TiO absorption in that part of the spectrum.

Table 2 lists the equivalent widths measured for the hydrogen and helium lines, and Figures 3–6 plot our spectra in the vicinity of the Hα line. We also list the activity level, $F_{bol}$/$F_{bol,i}$, discussed further in § 4. Two dwarfs stand out: 2M 0320+18 (LP 412-31), with an Hα equivalent width of 83 Å, and 2M 0350+18, where Hα reaches an equivalent width of almost 40 Å. As with the rest of the sample, these two dwarfs have previous spectroscopic measurements at these wavelengths, albeit at lower resolution. Gizis et al. (2000b) measure an Hα equivalent width of 29 Å in the former case but failed to detect any emission from 2M 0350+18. Evidently, both of the current observations were made while these two stars were undergoing strong flares.

Conversely, three dwarfs have significantly lower levels of activity in our spectra than measured in previous observations. Observations of 2M 0149+29 during a substantial outburst are described by Liebert et al. (1999), while both LHS 2243 and LP 475-855 were significantly more active at the time of the low-resolution observations described in G00. These variations and the overall distribution of activity are discussed in more detail in § 5.

2.4. Radial Velocities

We have employed two methods to determine radial velocities for the dwarfs in the present sample. First, we measure the central wavelength of Hα emission and correct the apparent radial velocity for heliocentric motion using the IRAF routine VHELIO. Those measurements are listed in column (5) of Table 2 as $V_{hel}$. In most cases, we estimate measurement uncertainties of ±2–3 km s$^{-1}$; the exceptions are dwarfs with weak emission or broad Hα profiles, such as LHS 2632, 2M 1047+40A, and TVLM 513-46546.

We have also determined radial velocities using standard cross-correlation routines. Given the seasonal variation in observing runs and slight variations in the instrumental setup, we were unable to use the same radial velocity standard for all of the targets. Our observations are tied to three reference stars: LHS 2065 (M8) in 1999 March, Gl 412B (M5) in 1999 June, and Gl 83.1 (M4.5) in 1999 December. Marcy & Benitz (1989) measure a heliocentric radial velocity of $-28.6$ km s$^{-1}$ for the last star, while Delfosse et al. (1998) cite $V_{hel} = 68$ km s$^{-1}$ for both components of Gl 412. Finally, Tinney & Reid (1998) measure $V_{hel} = 8.7 \pm 1.5$ km s$^{-1}$ for LHS 2065.

Both Gl 83.1 and Gl 412B have earlier spectral types than the dwarfs in our sample. However, the cross-correlation peaks generally exceed 0.5 in height in orders dominated by TiO absorption rather than by strong atomic absorption or emission lines. The velocities listed in column (6) of Table 2 ($V_{CCF}$) are averaged from measurements of six to nine echelle orders, with the uncertainty reflecting the rms dispersion about the mean.
In general, there is good agreement between the radial velocities derived using the two methods. However, several dwarfs exhibit anomalies. Two are clearly binary: as Figure 7 shows, the cross-correlation spectra for both 2M 0253+27 and 2M 0952-19 exhibit two distinct peaks, characteristic of double-lined spectroscopic binaries. In the former case, the cross-correlation peaks have heights in the ratio 4:1 at 8000 Å, with the blueshifted component being the stronger of the two; in the latter, the flux ratio is 2:1, again in favor of the component with the more negative velocity. We list CCF velocities for both components of these dwarfs in Table 2. Neither shows evidence for separable Hα emission (Figs. 3 and 4), so $V_r$ presumably reflects a weighted average of the centroids of the individual emission lines. We note that 2M 1550+30 shows an asymmetric cross-correlation peak (Fig. 7), suggestive of an SB2 binary with a secondary close to the detection limit (as in Figs. 5 and 6, Reid & Mahoney 2000, hereafter RM00).

Four other dwarfs require comment: 2M 0350+18, 2M 1047+40B, 2M 1336+47, and 2M 2206-20. In each case, $V_r$ and $V_{CCF}$ differ by more than 5 km s$^{-1}$. The last three dwarfs are all fast rotators with broad cross-correlation peaks and asymmetric Hα profiles (Figs. 3-6). The observed discrepancies probably arise in our estimation of the centroid of the Hα line and hence of $V_r$. The object 2M 0350+18, in contrast, is a slow rotator, but has an unusual Hα profile, with a narrow spike superposed on a broad pedestal. This is reminiscent of one observation of the Hyades SB2 binary, RHy 42 (RM00). In that case, the unusual morphology arises from the superposition of two normal Hα profiles at a veloc-
ity separation of $\Delta V \sim 50$ km s$^{-1}$. Our present data, however, show no evidence for binarity on the part of 2M 0350+18. The H$\alpha$ profile of this star is discussed further below. In subsequent sections, we adopt $V_{\text{CCF}}$ as the reference radial velocity for all the dwarfs in our sample.

As noted above, the repeatability of the thorium-argon calibration spectra indicate that our velocity calibration should be accurate to $\pm 1$ km s$^{-1}$; this is generally supported by analysis of the night-sky emission spectra extracted from our data (as discussed in more detail by RM00). We have a limited number of external tests of our measurements. Two late-type M dwarfs in the present sample were also observed by Tinney & Reid (1998): they measured radial velocities of $V_{\text{hel}} = -0.6 \pm 2$ km s$^{-1}$ for BRI 1222 and $V_{\text{hel}} = 8.1 \pm 3$ km s$^{-1}$ for TVLM 513-46546; we measure velocities of $-5.6 \pm 0.4$ and $5 \pm 6$ km s$^{-1}$, respectively. TVLM 513-46546 is one of the most rapidly rotating dwarfs in the present sample, as discussed further below, accounting for the large uncertainty in $V_{\text{CCF}}$. The 5 km s$^{-1}$ offset for BRI 1222 exceeds the combined formal uncertainties of both measurements. Further observations are required to settle the discrepancy; we apply no adjustment to our measured velocities.

2.5. Rotation

Tonry & Davis (1979) demonstrated that the width of the peak of a cross-correlation function (CCF) is dependent on the line profiles present in the template and program object. In the case of stars, the dominant contributor to line width is usually rotational broadening, allowing measurement of the projected rotational velocity. The measured full width at
half-maximum of the CCF peak is calibrated against $v \sin i$ by applying artificial broadening for a range of velocities to the spectrum of a slowly rotating star. We have adopted the line profile prescription given by Gray (1982) and use this technique to estimate $v \sin i$ for the dwarfs in the present sample.

Our analysis generally follows the procedures described by RM00. We have limited analysis to spectral orders spanning the wavelength range 7360–7460 Å and 7840–7960 Å, both covering regions that lack TiO band heads, strong atomic lines, and significant terrestrial absorption. The resulting measurements, using Gl 83.1, Gl 412B, and LHS 2632 as templates, are given in Table 2. The intrinsic resolution of the HIRES data corresponds to a rotational velocity of $v \sin i \sim 2.5$ km s$^{-1}$; however, both Gl 83.1 and Gl 412B are known to have higher rotational velocities (Table 2), and, as a result, our detection limits are effectively $v \sin i \sim 4$ km s$^{-1}$ (1999 December data) and $v \sin i \sim 6$ km s$^{-1}$ (1999 June), respectively. Those limits are still sufficient to distinguish rapid rotators from more conventional late-type M dwarfs. Our third radial velocity standard, LHS 2065, has a modest rotational velocity (Basri 2001), so we have used the slow rotator LHS 2632 as the rotational reference for the 1999 March observations. We estimate velocity uncertainties of $\pm 2$ km s$^{-1}$ at low $v \sin i$ and $\sim 5$ km s$^{-1}$ for the fast rotators.

Basri (2001) has recently published rotational velocity measurements for more than 70 dwarfs with spectral types later than M5. The majority of these measurements are based on Keck HIRES data and therefore have similar resolution to our data set. There are nine dwarfs in common with our sample, and Table 3 compares the two sets of values.
results. In general, the agreement is within the expected uncertainties. The exception is 2M 1224-12 (=BRI 1222), for which our measurement indicates modest rotation of 8 km s\(^{-1}\) as compared with only 2.0 km s\(^{-1}\) detected by Basri. Table 3 also shows that the star was significantly more active at the time of our observation. These results are discussed in more detail in § 4.

3. LITHIUM IN ULTRACOOL M DWARFS

A major goal of this project is determining the fraction of late-type M dwarfs in the solar neighborhood that exhibit lithium absorption. As originally discussed by Rebolo, Martin, & Magazzu (1992), lithium fusion (\(^7\)Li + p \rightarrow \(^4\)He + \(^4\)He) requires a temperature of \(T_{\text{Li}} \sim 2 \times 10^6\) K. Since hydrogen fusion occurs at \(T > 3.5 \times 10^6\) K, primordial lithium is destroyed rapidly in fully convective low-mass stars and higher mass brown dwarfs. Objects with masses below a specific mass limit, \(M_{\text{Li}}\), are predicted to have central temperatures lower than the critical threshold, \(T_{\text{Li}}\), even when evolving through the M dwarf regime, and these objects preserve lithium at its primordial abundance. The exact mass limit is model dependent, with current estimates of \(M_{\text{Li}}\) ranging from 0.06 to 0.065 \(M_\odot\) (Chabrier & Baraffe 1997; Ushomirsky et al. 1998); in any case, detection of Li 6708 Å absorption in an L dwarf is a clear indication of substellar mass.

At higher masses, \(M > 0.065 M_\odot\), the rate of lithium depletion increases with increasing mass. This correlation permits the use of lithium detection as a mass discriminant in open clusters and the general field. Figure 8 plots theoretical tracks for low-mass stars and brown dwarfs, drawn from
both the Burrows et al. (1997, the Arizona models) and the Baraffe et al. (1998, the Lyon models) sequences. The two sets of model calculations show good agreement for $M < 0.06 \, M_\odot$, but differ at higher masses. In particular, the Lyon models place the hydrogen-burning limit at $\sim 0.072 \, M_\odot$, while a $0.075 \, M_\odot$ dwarf is a transition object in the Arizona calculations. The implications of these differences for the present analysis are discussed further below. For both sets of models, Figure 8 outlines the lithium depletion locus, defined where the lithium abundance is predicted to drop to 1% of the primordial value. The critical effective temperature ranges from 3200 K for a 0.1 $M_\odot$ star to $\sim$2600 K for a 0.065 $M_\odot$ brown dwarf.

Spectral type is correlated primarily with effective temperature. Thus, Figure 8 can be used to predict the spectral type where lithium should become detectable in young and intermediate-age star clusters; alternatively, the observed spectral type (or luminosity) at the threshold for lithium detection can be used to infer the age of the cluster. Stauffer, Schultz, & Kirkpatrick (1998) use the latter approach to estimate an age of 120 Myr for the Pleiades, while Stauffer et al. (1999) derive an age of 90 Myr for the $\alpha$ Persei cluster. M dwarfs in the field span a wide range of ages. However, both sets of models plotted in Figure 8 indicate that the lithium depletion line meets the $M = M_{\text{Li}}$ evolutionary track at a temperature of $\sim$2600 K and an age of $\tau \sim 400$ Myr; that is, all dwarfs that deplete lithium have completed the depletion cycle by this age and temperature. As a corollary, any dwarf with an inferred effective temperature lower than 2600 K and detectable lithium absorption is predicted to be a brown dwarf with a mass less than 0.065 $M_\odot$.

This characteristic behavior allows us to probe the stellar mass function. The relative number of ultracool dwarfs with and without lithium absorption in our sample, $F_{\text{Li}}$, depends

Fig. 6.—Same as Fig. 3
on the relative number of dwarfs with masses $M < 0.065 M_\odot$ with respect to $M > 0.065 M_\odot$. Thus, if the immediate solar neighborhood provides a fair sampling of the disk population, if our sample is an unbiased subset of local dwarfs, and if the stellar birthrate, $B(t)$, is well behaved, then $F_{Li}$ depends on the shape of the mass function, $\Psi(M)$; the steeper $\Psi(M)$, the more low-mass dwarfs and the higher $F_{Li}$.

As discussed further below, circumstances may prevent us from satisfying all the requisite conditional statements.

### 3.1. Lithium Detections in the Present Sample

Our observations were designed specifically to include coverage of the Li 6708 Å doublet, the strongest feature due to that species. Figures 9–12 plot our data for that region of the spectrum, marking with the expected location of the Li i doublet, adjusted for the apparent velocity at the time of observation. Table 2 lists the results: of the 39 ultracool

| NAME                  | $v \sin i$ (km s$^{-1}$) | $H_\alpha$ (Å) | $v \sin i$ (km s$^{-1}$) | $H_\alpha$ (Å) |
|-----------------------|--------------------------|----------------|--------------------------|----------------|
| LP 412-31             | 9.0                      | 18.4           | 8                        | 82.8           |
| LHS 2632              | <3                       | <4             | <4                       | 0.6            |
| LHS 2645              | 6.5                      | 4.9            | 6                        | 6.1            |
| RG 0050.5             | <5                       | 2.9            | <4                       | 1.2            |
| LHS 2243              | <5                       | 15.8           | <4                       | 19.5           |
| 2M 1242+29            | 5.0                      | 8.1            | <4                       | 15.8           |
| TVLM 513-46546        | 60                       | 1.8            | >40                      | 3.5            |
| LHS 2065              | 9                        | 8.4            | 11                       | 12.6           |
| BRI 1222              | 2.0                      | 9.7            | 8                        | 21.3           |

#### Fig. 7.
Representative cross-correlation spectra for 2M 0253+27, 2M 0952+17, and 2M 1550+30. The first two dwarfs show bimodal distributions, characteristics of double-lined spectroscopic binaries, while the last has an asymmetric profile, suggestive of a high flux ratio SB2.

#### Fig. 8.
Lithium depletion for low-mass stars and brown dwarfs. The top panel plots evolutionary tracks from the Burrows et al. (1997) models for masses of 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.075, 0.08, 0.09, and 0.1 $M_\odot$; the bottom panel tracks plots for masses of 0.02, 0.025, 0.04, 0.05, 0.06, 0.07, 0.075, 0.08, 0.09, 0.10, and 0.11 $M_\odot$ from the Baraffe et al. (1998) calculations. Note that the stellar/brown dwarf transition occurs at $\sim 0.075 M_\odot$ in the former models and at $\sim 0.072 M_\odot$ in the latter. In both cases, we delineate the approximate boundaries of the M dwarf, L dwarf, and T dwarf regimes; the shaded region marks the appropriate temperature limits for spectral types M8–M9.5 (see text for discussion). The heavy solid lines outline the $R_{Li} = 1\%$ boundary; lithium should not be detected in dwarfs that have evolved beyond this limit. [See the electronic edition of the Journal for a color version of this figure.]

#### Fig. 9.
Lithium in ultracool dwarfs; all of the spectra have been adjusted to align any potential Li i absorption with the dotted line. This figure plots data for (from top to bottom) Gi 83.1 (M4.5); Gi 412B (M5); 2M 2233+35 (M6); 2M 1047+40A and 2M 1714+30 (M6.5); 2M 0330+24, 2M 0429+13, 2M 0818+23, 2M 0925+17, and 2M 0952-19 (M7).
dwarfs in the sample, two show unequivocal absorption at that wavelength, with one other possible detection. The object 2M 0339-35 (LP 944-20) was known as an M-type brown dwarf prior to our observations (Tinney 1998). As Figure 9 shows, 2M 0335+23 stands out from the other dwarfs in the present sample, with a broad, distinct feature at the appropriate wavelength. This dwarf is strikingly similar to 2M 0339-35, with comparable spectral type (M8.5 vs. M9), nearly identical rotational velocity ($v \sin i = 30$ vs. 28 km s$^{-1}$), and lithium absorption of comparable strength. Our data suggest that 2M 0335+23 is chromospherically more active, although the difference is within the range of variation for individual dwarfs (see §4). Given those characteristics, we identify 2M 0335+23 as a brown dwarf, with a likely age of $\sim 1$ Gyr and a mass of $0.06 M_{ \odot }$.

The possible lithium detection is for the M8 dwarf, 2M 1242+29. As noted above, this is fainter than the magnitude limit of our photometric sample, and the HIRES spectrum is correspondingly noisy. Nonetheless, there appears to be a relatively broad absorption feature at the appropriate wavelength for Li i 6708. This dwarf was discovered from observations undertaken with the prototype 2MASS camera (Kirkpatrick, Beichman, & Skrutskie, 1997), and the Palomar spectrum obtained at that time does not have sufficient resolution or signal-to-noise ratio to detect this relatively weak feature. If confirmed by further observations, the measured equivalent width suggests little lithium depletion and indicates a mass just below 0.065 $M_{ \odot }$, for 2M 1242+29.

Considering the sample as a whole, our observations indicate that 36 of the 39 ultracool dwarfs have masses above the lithium depletion limit. The objects 2M 0335+23, 2M 1242+29, and possibly 2M 1242+29 are identified as brown dwarfs with masses below 0.065 $M_{ \odot }$. Of these three dwarfs, only 2M 0335+23 and 2M 0339-35 are included in the photometrically selected sample.

3.2. Modeling the Lithium Fraction

Deriving $F_{ Li }$ is a straightforward observational process. Subdiving our sample by spectral type, $F_{ Li } = 6\% \pm 4\%$ for spectral types M7–M9.5 (two of 35 dwarfs), and $F_{ Li } = 10\% \pm 7\%$ for spectral types M8–M9.5 (two of 20).
Interpreting those measurements in terms of the shape of the mass function, $\Psi(M)$, is more complicated and requires use of the models plotted in Figure 8.

First, we require a relation between spectral type and effective temperature. As discussed elsewhere (Reid et al. 1999b, hereafter R99; Kirkpatrick et al. 2000), this calibration remains uncertain, largely because of the complex nature of atmospheres at these cool temperatures. Leggett et al.’s (1996) multiwavelength analysis sets a benchmark of $T_{\text{eff}} = 2700$ K at spectral type M6.5 (GJ 1111), while current consensus places the boundary between the M and L spectral types at $T_{\text{eff}} = 2050 \pm 50$ K (Kirkpatrick et al. 2000; Schweizer et al. 2001, 2002). Given those results, we adopt the following temperature-spectral type relations:

- M7–M9.5, $2700 \geq T_{\text{eff}} > 2050$;
- M8–M9.5, $2500 \geq T_{\text{eff}} > 2050$.

Our goal is to compare predicted and observed values of $F_{\text{Li}}$ for a range of assumed mass functions. We follow the techniques outlined by R99: Monte Carlo simulations are used to generate a sample of “dwarfs” with known distance, $d$, and age, $\tau$; masses are drawn from a power-law mass function, $\Psi(M) \propto M^{-\alpha}$; we assume a uniform birthrate, $B(t)$, with $10^{10} > t > 10^{7}$ yr, where $t$ is look-back time (i.e., $t = 0$ at the present epoch). Given $M$, $\tau$, and $d$, we compute $m_{\text{bol}}$ and $T_{\text{eff}}$ from the theoretical tracks, and, using the appropriate bolometric corrections (R99), calculate $J$, $H$, and $K_s$ magnitudes. Based on those data, we identify dwarfs with $K_s \leq 12.0$ and temperatures in the relevant range and compute the fraction predicted to have undepleted lithium.

The most significant complication in interpreting these model predictions is illustrated by Figures 13 and 14, which show simulated mass vs. $T_{\text{eff}}$ and mass vs. age distributions.

![Fig. 13. — Mass vs. $T_{\text{eff}}$ and mass vs. age distributions predicted for low-mass dwarfs with $K_s \leq 12$, drawn for a mass function $\Psi(M) \propto M^{-1}$ based on the Arizona theoretical tracks. In the uppermost diagram, the filled squares identify dwarfs in the temperature range $2700 > T_{\text{eff}} > 2050$ K; the solid line marks the approximate location of the lithium depletion boundary. The histograms plot the number distribution for the full $K_s < 12$ simulation as a function of temperature and mass; the dotted histogram marks the contribution from lithium-rich dwarfs, and the histograms are scaled to match the corresponding distributions in Fig. 14. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
of ultracool dwarfs with $K_s < 12$ drawn from a power-law mass function with $\alpha = 1$. With no internal energy source, brown dwarfs “cool like a rock” (Burrows & Liebert 1993), with the rate of cooling increasing with decreasing mass. Selecting a sample based on a fixed range in spectral type (temperature) is therefore equivalent to selecting dwarfs within a particular range of ages for a given mass. In particular, low-mass brown dwarfs (LMBDs; $M < 0.03 M_\odot$) cool so rapidly that most enter the L dwarf regime by $\tau \sim 10^8$ yr (Fig. 8); that is, LMBDs are only eligible for inclusion in an ultracool M dwarf sample for less than $10^8$ yr. As a result, our conclusions are vulnerable to systematic bias introduced either by the assumed stellar birthrate or by age-specific inhomogeneities in the solar neighborhood disk population.

Considering the stellar birthrate, we adopt the simplest assumption of a uniform star formation over the history of the disk. We considered this issue in our analysis of the substellar mass function (R99), since the observed numbers of field L and T dwarfs are also dependent on the recent star formation history. We concluded that the available data, based primarily on the distribution of Ca ii activity among G dwarfs (e.g., Soderblom, Duncan, & Johnson 1991), were consistent with a uniform birthrate. More recently, Gizis et al. (2002, or PMSU3) have reexamined this issue and have found that the distribution of chromospheric activity among nearby M dwarfs is also consistent with a relatively uniform age distribution. These results are in contrast to studies of the global star formation history, which tend to favor star formation rates that increase by an order of magnitude between the present epoch and redshift $\sim 1.5$ (Madau, Pozzetti, & Dickinson 1998). We note that if such a history were appropriate to the Galactic disk, then we would expect a higher proportion of long-lived, bona fide stars among our ultracool sample.

Spatial inhomogeneities are a potential problem, since young stars are not a well-mixed population, but tend to lie in or near star-forming regions. Such regions are absent...
from the immediate solar neighborhood, suggesting that a local sample, such as that discussed here, might be deficient in such youthful objects relative to a global average over the disk. That deficiency manifests itself as fewer lithium-strong brown dwarfs, which, in turn, could lead to our underestimating \( \alpha \), the power-law index of \( \Psi(M) \). On the other hand, there are some extremely young stars in the solar neighborhood, notably the TW Hydrae association, \( \tau \sim 2 \times 10^7 \) yr (Kastner et al. 1997). Moreover, approximately \( 1\% \) of the G dwarfs in Henry et al.’s (1996) Ca survey have activity levels consistent with ages of less than \( 10^8 \) yr (Soderblom, King, & Henry 1998). With distances of less than 50 pc, these stars are drawn from the same volume as our ultracool dwarf sample, although one should also note that, with a total sample of \( \sim 800 \) stars, subdividing on such a fine timescale leads to correspondingly high statistical uncertainties. In any case, we allow for possible age bias in the ultracool sample by applying several lower age limits, \( \tau_{\text{min}} \), in the model calculations.

3.3. Results: Constraints on \( \Psi(M) \)

Table 4 summarizes the results of our simulations. As noted above, we consider two observational samples: spectral types M7–M9.5, with \( F_{\text{Li}} = 6\% \pm 4\% \); and spectral types M8–M9.5, with \( F_{\text{Li}} = 10\% \pm 7\% \). The table lists predictions based on both the Arizona and Lyon theoretical tracks and for mass function indices \( 0 \leq \alpha \leq 2 \). We adopt the age and mass lithium depletion limits outlined in Figure 8—0.065 \( M_{\odot} \) for the Arizona models and 0.07–0.06 \( M_{\odot} \) for the Lyon data set. Relatively few brown dwarfs lie in this mass range, so changing those limits by \( \pm 0.005 \) \( M_{\odot} \) has little effect on the results. The predicted percentage of dwarfs with detectable lithium are listed for lower age limits of \( 10^7 \), \( 5 \times 10^7 \), and \( 10^8 \) yr.

The models allow us to quantify some issues raised in the introduction to this section. First, brown dwarfs with \( M > M_{\text{Li}} \) make little contribution to \( F_{\text{Li}} \) in either set of calculations. Even for the flattest mass function, \( \alpha = 0 \), higher mass, partially lithium-depleted brown dwarfs make up less than \( 0.5\% \) of the total, and the contribution of those objects becomes negligible for \( \alpha \geq 1 \). Thus, absent other considerations, the lithium fraction provides a clean estimate of the slope of the underlying mass function.

Second, the quantitative results confirm the strong dependence of \( F_{\text{Li}} \) on the effective lower age limit, \( \tau_{\text{min}} \), of the local sample. The systematic bias increases as the underlying mass function steepens, and the relative number of young LMBDs increases.

It is also clear that the two sets of models make significantly different predictions of \( F_{\text{Li}} \) for a given value of \( \alpha \): the Lyon models predict lithium fractions that are lower by almost a factor of 2 than those predicted by the Arizona models. As noted above, this reflects differences in modeling the stellar, rather than brown dwarf, régime. Figure 8 shows that the Lyon 0.075 and 0.09 \( M_{\odot} \) models essentially bracket the M7–M9 temperature range for \( \tau > 2 \times 10^9 \) yr. In contrast, that region of the \( (T_{\text{eff}}, \tau) \)-plane is populated by a more restricted range of masses, \( \sim 0.078 \) to \( \sim 0.088 \) \( M_{\odot} \), in the Arizona models. As the histograms in Figures 13 and 14 illustrate, the result is that the latter simulations predict fewer stellar mass M7–M9 dwarfs and a correspondingly higher fraction of lithium-rich ultracool M dwarfs.

The correlation with \( \tau_{\text{min}} \) and the systematic disagreement between the two sets of models complicate the interpretation of the observed value of \( F_{\text{Li}} \) as a constraint on \( \Psi(M) \). Moreover, quantifying the comparison between the models and observation is difficult, not least because all of the relevant observational parameters (our estimates of \( F_{\text{Li}} \) and the young G dwarf fraction) have significant associated uncertainties. As a first cut, we assume a moderate bias against very young objects locally (\( \tau_{\text{min}} = 0.05 \) Gyr) and consider the constraints set if we require the predicted value of the lithium fraction fall within 1 \( \sigma \) of the observations.

Under those criteria, the Lyon models suggest that a power-law mass function is consistent only for \( \alpha < 1.5 \), while predictions based on the Arizona models require a significantly flatter mass function, \( \alpha \leq 0.5 \). The different indices reflect the relative contribution of stars and brown dwarfs to the ultracool sample; as discussed above, the Arizona models predict larger numbers of substellar mass objects and, as a result, require a flatter index to match the

| Temperatures | \( \tau_{\text{min}} \) (Gyr) | Arizona | Lyon |
|--------------|-----------------|--------|------|
|              | \( \alpha = 0 \) | \( \alpha = 0.5 \) | \( \alpha = 1.0 \) | \( \alpha = 1.5 \) | \( \alpha = 2.0 \) | \( \alpha = 0 \) | \( \alpha = 0.5 \) | \( \alpha = 1.0 \) | \( \alpha = 1.5 \) | \( \alpha = 2.0 \) |
| 2050–2700……… | 0.01 | 14 | 19 | 25 | 33 | 45 | M9.5–M7 | 6 ± 4 |
|              | 0.05 | 11 | 13 | 16 | 20 | 25 | M9.5–M8 | 10 ± 7 |
|              | 0.1 | 9 | 10.5 | 11 | 15 | 17 | M9.5–M8 | 10 ± 7 |
| 2050–2500……… | 0.01 | 18 | 23 | 30 | 40 | 51 | M9.5–M8 | 10 ± 7 |
|              | 0.05 | 15 | 18 | 22 | 28 | 35 | M9.5–M8 | 10 ± 7 |
|              | 0.1 | 14 | 16 | 18 | 24 | 26 | M9.5–M8 | 10 ± 7 |

| Sp. Types | \( F_{0.085} \) |
|-----------|-----------------|
| M9.5–M7   | 6 ± 4 |
| M9.5–M8   | 10 ± 7 |
low lithium fraction in the observed sample. The derived indices are generally consistent with previous analyses, both based on the surface densities of L and T dwarfs in the field ($\alpha \sim 1.3$; R99) and based on surveys of young clusters (Luhman et al. 2000; Luhman 2000; Barrado y Navascués et al. 2001). In general, the open cluster analyses, where age is less of an uncertainty, favor flatter mass functions, with $0.5 < \alpha < 1$.

What do these estimates imply for the local density of brown dwarfs? Modeling the stellar mass function as a power law, $\alpha = 1$, for $1.0 > M/M_\odot > 0.075$, brown dwarfs are predicted to outnumber stars by $\sim 5:1$ for $\alpha = 1.5$ between the hydrogen-burning limit and $0.01 M_\odot$. The ratio is $\sim 2:1$, in the same sense, for $\alpha = 1.3$ at low masses (R99). However, if $\alpha = 1.0$, then subsolar mass stars outnumber brown dwarfs by $\sim 5:4$, while the ratio rises to $\sim 7:1$ for $\alpha = 0.5$. Converting to mass density, brown dwarfs add $40\%$, $20\%$, $7\%$, and $1\%$ to the local stellar mass density for $\alpha = 1.5$, 1.3, 1.0, and 0.5, respectively.

Statistically, the most significant result from the present analysis is that the only means of matching a steep, Salpeter-like ($\alpha \geq 2$) mass function to the present observations is by depletion of the immediate solar neighborhood of all brown dwarfs younger than $10^8$ yr. As we noted above, the presence of active, less than $10^8$ yr old G dwarfs within that same volume argues against this extreme hypothesis. Thus, all current observational analyses indicate that it is extremely unlikely that brown dwarfs contribute substantially to the local mass density.

4. ROTATION AND ACTIVITY

Chromospheric activity in solar-type stars has long been known to be well correlated with the stellar rotational velocity. That correlation is due to the presence of a magnetic $\alpha \Omega$ (shell) dynamo, generated by a toroidal field located at the boundary between the radiative core and the convective envelope. Traditionally, this paradigm has been extended to M dwarfs, even though those stars are known to become fully convective at spectral type $\approx$M4. Hawley, Reid, & Gizis (2000) outline an alternative model, in which activity in mid- and late-type M dwarfs is driven largely by a turbulent dynamo (Durney, DeYoung, & Roxburgh 1993) within the convection zone. The overall level of activity decreases significantly in dwarfs later than M9, with only a small number of L dwarfs showing detectable H$_\alpha$ emission (G00). This might reflect either decreased efficiency of the turbulent dynamo or the formation of radiative zones, which inhibit the emergence of magnetic flux, or increased resistivity in the predominantly neutral atmospheres (Mohanty & Basri 2002).

If magnetic activity in late-type M dwarfs is powered by turbulence, one expects little direct correlation between the level of activity and rotation. Hawley et al. (2000) analyzed the relatively scarce data available at that time and found no evidence for a significant correlation among late-type M dwarfs. This conclusion is generally confirmed by Basri (2001) for a sample that includes 26 ultracool M dwarfs, 10 of which are in the present sample. The additional dwarfs observed here more than double the number of ultracool M dwarfs with known rotational velocities, allowing us to revisit this issue.

Chromospheric activity in late-type dwarfs is generally gauged by measuring the strength of H$_\alpha$ emission. Table 2 lists equivalent width measurements for all of the dwarfs in the present sample. However, those data should not be used directly to characterize activity: the equivalent width of an emission line depends on the contrast with respect to the local continuum, rather than the absolute line flux. As one moves down the M dwarf sequence, the continuum flux emitted at 6560 A decreases, both in absolute terms and as a fraction of the bolometric flux. Thus, a 5 A equivalent width H$_\alpha$ line in an M3 dwarf represents significantly more chromospheric flux than 5 A emission in an ultracool M9. Reid, Hawley, & Mateo (1995b, hereafter RHM95) originally suggested that the appropriate method of dealing with this issue is, following X-ray astronomy, computation of the normalized flux ratio, $F_{\alpha}/F_{\text{bol}} \equiv L_{\alpha}/L_{\text{bol}}$, the fraction of the luminosity emitted in H$_\alpha$ emission.

In studying this issue, we have combined data from our own observations and Basri’s (2001) analysis, adopting our measurements for objects in common. All of the dwarfs in our sample have low-resolution spectroscopy, allowing direct determination of the continuum flux at 6560 A, $F_C$, and hence conversion of H$_\alpha$ equivalent widths to flux measurements. Similar data exist for approximately half of the Basri sample; the remaining stars have either direct R-band photometry or $V-I$ and/or $I-J$ color measurements, from which we can estimate $R-I$ and hence $R$. Given $F_R$, we estimate $F_C$ using the empirical relation derived by RHM95, $F_C = 1.45F_R$.

All of the dwarfs in our sample and most of the Basri dwarfs have $JHK/K_b$ photometry. As discussed above, there is little variation in the $J$-band bolometric corrections for dwarfs with spectral types between $\approx$M6 and L5; thus, for dwarfs with near-infrared data, we adopt $m_{\text{bol}} = J + 2.1$.

The remaining dwarfs have $I$-band photometry. $I$-band bolometric corrections are small (less than 0.5 mag) for ultracool dwarfs, and we estimate $B_{I}$ from the relations given in Reid & Hawley (2000).

The derived flux ratios are listed in Table 2 with the equivalent width measurements. Figure 15a plots these results as a function of $v \sin i$, differentiating among the different spectral types. There is no evidence for a significant correlation either within a given spectral type or for the sample as a whole. Nor is there evidence for a strong correlation between spectral type and rotation among the ultracool M dwarfs in our sample (Fig. 15b). If we define fast rotators as dwarfs with $v \sin i > 20$ km s$^{-1}$, the relative number of fast and slow rotators is statistically identical at M7 (three of 12), M8 (four of 13), and M9 (one of seven). There is marginal evidence that the lower envelope in $v \sin i$ increases to later spectral types: three of the seven M9/M9.5 dwarfs (43%) have $v \sin i < 10$ km s$^{-1}$ as compared with 11 of 15 (74%) of the M7/M7.5 dwarfs. As discussed by Basri (2001), all L dwarfs that have been observed at sufficient spectroscopic resolution to detect rotation have $v \sin i \geq 10$ km s$^{-1}$.

Turning to chromospheric activity in the present sample, we can consider three issues: the mean level of activity, the dispersion in activity, and the prevalence of substantial flares. All three issues are discussed extensively by G00, based on lower resolution spectroscopy of 60 late M and L dwarfs. Our echelle observations resolve weaker H$_\alpha$ emission than was possible in that analysis and therefore extend...
coverage to lower activity levels, but the overall conclusions are unchanged.

Figure 15c plots activity, log \( (L_{\alpha}/L_{\text{bol}}) \), as a function of spectral type for ultracool dwarfs from both the present sample and dwarfs from Basri (2001). The mean level of activity among earlier-type M dwarfs in the field. In both cases, the filled circles are from this paper and the open circles from Basri’s observations, and, for clarity, we offset the spectral types by +0.1 for the latter sample. [See the electronic edition of the Journal for a color version of this figure.]

5. DISTANCES AND KINEMATICS

The primary aim in compiling a photometrically selected sample of ultracool dwarfs is to avoid bias toward high-velocity, old M dwarfs. As a corollary, the current sample should provide reliable statistics on the solar motion and velocity dispersions of these late-type dwarfs. Those data, in turn, offer a means of probing the likely age distribution of the sample. Several previous analyses have suggested that ultracool dwarfs are younger, on average, than earlier type M dwarfs (Hawkins & Bessell 1988; Kirkpatrick et al. 1994; Reid, Tinney, & Mould 1994). The most extensive previous kinematic study by Tinney & Reid (1998) found no statistical evidence that ultracool dwarfs were drawn from a different velocity distribution, but that analysis includes only 13 photometrically selected dwarfs. We can reexamine this issue with our larger sample.

5.1. Distance Determination

Our spectra provide direct measurement of radial velocities, and proper motions are available from the literature for most of the sample. All of the remaining targets in the photometrically selected sample are easily visible on UKST and/or POSS II photographic sky survey plates; indeed, most are clearly detected on the POSS I E plates. As discussed by G00, those data, combined with 2MASS astrometry, provide sufficient baseline for proper-motion
measurements. All of the proper-motion measurements are

\[ M_K = 7.593 + 2.25(J-K_s), \quad \sigma_{\text{rms}} = 0.36 \text{ mag}. \]

However, there is a potential complication in that the current sample was color-selected with the requirement \((J-K_s) > 0.95\). This opens the possibility for bias, since the dispersion in the \((M_J, J-K)\) main sequence at higher luminosities is sufficient to allow redder, higher luminosity stars to scatter into the sample (Fig. 1). This is highlighted by the location of the M6 dwarfs in Figure 2.

Fortunately, most of the dwarfs in the photometrically defined sample also have \(I\)-band photometry either based on direct measurements or synthesized from our low-resolution spectroscopy. We can use those colors to estimate distances based on the photometric parallax calibration derived by Reid & Cruz (2002),

\[ M_I = 16.491 - 16.499(I-J) + 14.003(I-J)^2 - 4.717(I-J)^3 + 0.697(I-J)^4 - 0.0330(I-J)^5, \]

\[ 1.65 \leq (I-J) < 4.0, \quad \sigma = 0.31 \text{ mag}, \quad 37 \text{ stars}. \]
Figure 16.—Comparison of parallax determinations for ultracool dwarfs. The top panel compares trigonometric and photometric distance modulus estimates for dwarfs in the current sample with astrometric measurements, where \[ (m - M) \text{ _phot} = (m - M) \text{ _astrom} - (m - M) \text{ _parallax} \] solid squares plot the comparison with \( (m - M) \text{ _phot} \). The bottom panel compares distance moduli derived from the photometric parallaxes, where \[ (m - M) \text{ _phot} = (m - M) \text{ _astrom} - (m - M) \text{ _parallax} \] [See the electronic edition of the Journal for a color version of this figure.]

Figure 17.—Space motions of ultracool dwarfs: the symbols are coded by spectral type as in Figs. 2 and 10, and the two most extreme outliers are identified. [See the electronic edition of the Journal for a color version of this figure.]

Figure 16 compares distance moduli derived from the limited trigonometric parallax data and from the \( J - K_s \) and \( I - J \) color indices. The top panel shows that there is no evidence for a systematic difference between the trigonometric and photometric indicators, which is not surprising, since several of these dwarfs were included in calibrating the latter. One star deserves special comment: the \( I - J \) and \( J - K_s \) photometric parallaxes for RG 0050.5 are in excellent agreement, indicating a distance of 30.5 pc, while trigonometric measurements give 22.2 pc. Thus, this star is bluer than expected and lies \( \sim 0.7 \) mag below the mean relation for M8 dwarfs.

There is, however, a clear systematic trend when we compare the photometric distance indicators with the \( J - K_s \) calibration tending to derive lower distances (by \( \sim 20\% \) and fainter absolute magnitudes. We find

\[
\delta (m - M) = (m - M) \text{ _phot} - (m - M) \text{ _parallax} = 0.35 \pm 0.11, \text{ 29 stars.}
\]

Given this comparison, we use \( I - J \) in preference to \( J - K_s \) in computing the distances listed in Table 5. The uncertainties therein are based on the dispersions in the calibrating color-magnitude relations.

5.2. Kinematics of Ultracool Dwarfs

We have used our distances estimates for each dwarf to derive \( V_r \) and \( V_b \) from the proper-motion measurements and combined those data with the radial velocity to derive the Galactic space motions listed in Table 5. The velocity distribution is shown in Figure 17. Following the convention of the Catalogue of Nearby Stars (Gliese 1969), the \( (U, V, W) \) motions are defined as a right-handed system (\( U \) positive toward the Galactic center).

If we consider the sample as a whole (including all 37 systems that meet the apparent magnitude selection criteria), the mean motions and dispersions are

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-23.9, -14.6, 9.5; 31.1, 16.2, 16.6) \text{ km s}^{-1}.
\]  

Excluding 2M 0746+20 and the two M6/M6.5 dwarfs results in minimal changes,

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-23.7, -14.2, -9.3; 32.1, 17.1, 16.9) \text{ km s}^{-1}.
\]

The two most extreme outliers in the velocity distribution are 2M 0109+29 (M9.5) and 2M 1403+30 (M8.5). Both are identified in Figure 17, and in both cases the significant uncertainties reflect the extent to which the velocity estimates rest on the transverse motions. Excluding those two dwarfs from the analysis gives

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-18.5, -12.1, -9.8; 26.7, 15.9, 15.9) \text{ km s}^{-1},
\]

based on data for 31 ultracool dwarfs (M7–M9.5).

We have used different symbols in Figure 17 to identify dwarfs of different spectral type. Inspection of those diagrams shows limited evidence for significant variation in kinematics, and that conclusion is broadly confirmed by statistical analysis. Given the small sample size, we can only subdivide to a limited extent. However, we have computed mean motions for the 14 M7/M7.5 dwarfs, finding

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-20, -13, -10; 32, 21, 14) \text{ km s}^{-1},
\]
and for the 14 M8/M8.5 dwarfs,

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-18, -16, -7; 27, 17, 15) \text{ km s}^{-1}. \tag{5}
\]

These two sets of results are statistically indistinguishable. We therefore take the kinematics listed in equation (2), derived from 34 M7–M9.5 dwarfs, as characteristic of the ultracool dwarf sample.

We can compare these results against similar analyses of higher mass M dwarfs. Hawley et al. (PMSU2) have calculated space motions for a volume-complete sample of early- and mid-type M dwarfs in the solar neighborhood, making an explicit division between stars with and without Hα emission. Combining data for all M dwarfs, they derive

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-10, -21, -8; 38, 26, 21) \text{ km s}^{-1}. \tag{6}
\]

For non–emission-line dM dwarfs, they derive

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-9, -23, -8; 41, 27, 21) \text{ km s}^{-1}. \tag{7}
\]

The velocity dispersions are significantly higher than our measurements for ultracool dwarfs. In contrast, for the emission-line dwarfs, they find

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-12, -13, -8; 27, 20, 15) \text{ km s}^{-1}, \tag{8}
\]

values much closer to the analysis of the ultracool sample.

Dahn et al. (2002) have recently undertaken a similar comparison using tangential velocities for a sample of 28 ultracool dwarfs, including eight with spectral type M8–M9.5, 17 L dwarfs, and three T dwarfs. There are only two stars in common with the present sample. However, they also find that the kinematics of this L dwarf–dominated sample are very similar to those of the PMSU dMe stars.

Velocity dispersions provide only a one-dimensional parameterization of the velocity distribution; in particular, they provide no indication of how well the overall distribution matches a Gaussian. Probability plots (Lutz & Upgren 1980) serve that function: a Gaussian distribution gives a straight line if one plots the cumulative distribution in units of the measured standard deviation, σ. Figure 18 plots such data for the U, V, and W distributions defined by the 34 systems in our ultracool dwarf sample (M7–M9.5), 73 dMe systems, and 355 dM systems. The latter are volume-limited samples with δ > 30″ and absolute magnitudes in the range 7.0 ≤ \(M_V\) ≤ 15.0 (M0–M6; see Reid, Hawley, & Gizis 1995a, or PMSU1). There is clearly much closer agreement between the distributions outlined by the ultracool dwarfs and the dMe dwarfs.

We can compare these distributions quantitatively using the Kolmogorov-Smirnov test. That comparison shows that there is a probability of more than 10% that the ultracool dwarfs, and dMe stars are drawn from the same kinematic population: the two data sets are statistically indistinguishable. However, while the same holds for a comparison between the W velocity dispersion of the ultracool dwarfs and the dM sample, there is a probability of less than 5% that the U and V distributions are drawn from the same parent population. Comparing the ultracool dwarf sample against the complete PMSU1 data set (dM + dMe) reveals inconsistencies at the same level, as one might expect given the predominance of the non–emission-line M dwarfs.

Can the relatively low space motions of the ultracool dwarfs be attributed to a systematic error in our distance scale? The present sample was identified using photometric criteria (location in the \([K_s, J-K_s]\)-plane), and most have distance estimates derived from photometric parallax. Our use of I–J rather than \(J–K_s\) should compensate, to a large extent, for stars introduced into the sample through scatter in color (as illustrated in Fig. 16). However, the dispersion in absolute magnitude about the mean main sequence can also lead to higher luminosity, more distant stars and a statistical underestimation of both the average distances and tangential velocities.

We can estimate the likely extent of this effect using classical Malmquist bias: if we select stars from a uniform density distribution, the mean absolute magnitude of the sample, \(\bar{M}\), is given by

\[
\bar{M} = M_0 - 1.38\sigma^2, \tag{9}\]

where \(M_0\) is the mean absolute magnitude of a volume-limited sample, and \(\sigma\) the rms uncertainty associated with the absolute magnitude calibration. The \((M_V, I–J)\) relation has a dispersion of 0.31 mag; the \((M_K_s, J–K_s)\) calibration given by G00 has a dispersion of 0.36 mag. Adopting the latter value gives a statistical offset of 0.18 mag in equation (9) or an average underestimate of \(~9\)% in distance. We have recalculated the kinematics for the 34 M7–M9.5 dwarfs, increasing all of the distances (including trigonometric parallax measurements) by 10%. The resultant kinematics are

\[
(U, V, W; \sigma_U, \sigma_V, \sigma_W) = (-24.7, -15.4, -9.7; 34.2, 18.6, 17.5) \text{ km s}^{-1}. \tag{10}\]
These still fall short of the M dwarf kinematics given in equation (6).

Our conclusion is that the ultracool dwarfs in the present sample have kinematics that are statistically very similar to those of solar neighborhood dMe dwarfs. The velocity dispersions are significantly lower than those of the non–emission-line M dwarfs in the local old disk population but intriguingly similar to the mean kinematics of the L dwarf–dominated sample analyzed by Dahn et al. (2002).

5.3. Discussion

An obvious candidate for the observed discrepancy between the kinematics of ultracool M dwarfs and the average kinematics of earlier type M dwarfs is a difference in mean age between the two samples. $H_\alpha$ emission declines with age (at a mass-dependent rate), so the dMe sample has a younger mean age than the dM sample and, as a consequence, cooler kinematics. If we assume a constant star formation rate over the history of the disk, the relative numbers in the dM and dMe samples suggest that the latter stars are drawn from the most recent 15%/–20% of disk star formation, or ages up to 2 Gyr for a canonical 10 Gyr disk. Matching the velocity dispersions of the dMe sample against Jahreiss & Wielen’s (1983) calibration gives a slightly older age, $\tau = 3 \pm 1$ Gyr. The similar kinematics shown by the ultracool dwarfs suggest that they also have ages of $\tau < 2$–3 Gyr.

Is an age difference a physically reasonable explanation for the different kinematics of dM and ultracool dwarfs? In the case of the Dahn et al. analysis, that hypothesis is not unreasonable, since a significant fraction of the L and T dwarfs in their sample are likely to be substellar-mass brown dwarfs. Given the apparent similarity in motions, it is tempting to ascribe the results of our current analysis to the same underlying cause.

However, as Figures 8, 13, and 14 show, we expect M-type ultracool dwarfs to include a mixture of very low-mass stars and brown dwarfs, with the former dominating the sample. All M dwarfs have main-sequence lifetimes well in excess of a Hubble time, so both the ultracool dwarfs and the PMSU1 dM + dMe sample should include representation from the oldest stars in the Galactic disk. Our simulations predict an average age of $\sim4.5$ Gyr for $\tau_{\text{max}} = 10$ Gyr and a uniform birthrate. Given a near-exponential birthrate, such as that favored by cosmological studies (Madau et al. 1998), the average age rises to $\sim7$ Gyr. In either case, the observed velocity dispersions of the ultracool dwarfs are significantly lower than expected for a sample dominated by hydrogen-burning dwarfs.

If we accept that kinematics are reliably correlated with age and that our observations provide a fair sample of the ultracool dwarf population, then there appear to be two possible explanations for these observational results:

1. The solar neighborhood is deficient in very low mass ($M < 0.09 \, M_\odot$) dwarfs older than $\sim4$ Gyr. This might reflect sampling of the local disk population or a significant increase in star formation within the last 5 Gyr (that is, opposite to the cosmological trend favored by Madau et al. 1998). Such a change seems unlikely, although most age indicators, such as chromospheric activity, become less reliable at ages exceeding $\sim2$ Gyr. In any event, this conclusion implies a steepening in the inferred mass function at low masses, since analyses assume that the observed numbers of low-mass stars reflect formation throughout the entire lifetime of the disk.

2. Low-mass dwarfs have lifetimes of less than 4 Gyr as M7–M9.5 dwarfs. This effectively requires that the majority of ultracool dwarfs are high-mass brown dwarfs or transition objects (the return of M dwarfs as brown dwarfs in masquerade). That hypothesis, in turn, requires that either the spectral type/temperature scale adopted here is incorrect, in the sense that late-type dwarfs lie at cooler temperatures (i.e., an adjustment in the opposite sense to that favored by Basri et al. 2001), or that both sets of evolutionary models plotted in Figure 8 are incorrect in their location of the hydrogen-burning limit.

If the latter option is correct and brown dwarfs dominate the ultracool sample, then we also require a flat or decreasing mass function ($\alpha < 0.5$) to accommodate the observed lithium fraction.

The referee has suggested that significant revision in the evolutionary models is unlikely given the good agreement between those models and observations of the binary brown dwarf, Gl 569Bab (Lane et al. 2001). We note, however, that the agreement hinges on the age of 300 Myr associated with the system. That age estimate derives partly from the observed levels of chromospheric and coronal activity of the primary, Gl 569A, which Lane et al. argue are consistent with an age between 0.2 and 1 Gyr, and partly from an hypothesized association with the Ursa Major moving group (Kenworthy et al. 2001). Analyzing data for higher mass ($M_f < 7$) members, Soderblom & Mayor (1993) use isochrone fitting to derive an age of 300–400 Myr for the latter moving group.

Closer inspection of the data, however, suggest an older age. First, the observed radial velocity of $-6.9 \pm 1.0$ km s$^{-1}$ (Gizis et al. 2002) is significantly different from the predicted value of $-0.6$ km s$^{-1}$ (Madsen, Dravins, & Lindegren 2002). This peculiar velocity corresponds to a drift of $\sim6.5$ pc Myr$^{-1}$ relative to the centroid of the moving group, or more than 2 kpc, over its lifetime. This suggests that membership is unlikely. Second, the intrinsic properties of Gl 569A favor an older age: Gl 569A has a level of X-ray activity ($L_X/L_{bol}$) matching the average level of stars in the Hyades of similar luminosity and spectral type ($\sim600$ Myr), the chromospheric activity ($L_{\text{ch}}/L_{bol}$) is lower than most of dwarfs in the Hyades, and the star lies in the middle of the $(M_\star, V-I)$ main sequence defined by nearby field dwarfs. All of these properties are more consistent with an age between 0.6 and 1 Gyr than the $\sim300$ Myrs favored by Lane et al. Adopting the older ages leads to evolutionary masses of 0.07 to 0.09 $M_\odot$ for both components of Gl 569Bab and a predicted total mass 20%/–50% higher than the dynamical measurement of $0.123^{+0.027}_{-0.022} \, M_\odot$.

It remains possible that the sample of ultracool dwarfs discussed in this paper is biased in some respect. We are currently undertaking a large-scale survey that aims to identify all ultracool dwarfs within 20 pc of the Sun (Cruz, Reid, & Liebert 2002). High-resolution observations of those dwarfs, coupled with trigonometric parallax measurements, should help solidify our understanding of this issue.

6. CONCLUSIONS

We have presented high-resolution optical spectroscopy of 39 ultracool dwarfs. Our prime goal is the detection of
absorption due to Li at 6708 Å an unequivocal indicator of substellar mass at these cool temperatures. Two dwarfs exhibit significant absorption: LP 944-20, identified previously as a brown dwarf by Tinney (1998), and 2MASSW J03050204+234235. Both are included in a 33 dwarf photometrically selected subsample, spanning spectral types M9.5–M7. We have compared the observed fraction of lithium-rich dwarfs, \( F_{\text{Li}} \), against predictions from simulations based on theoretical tracks calculated for low-mass dwarfs by both Burrows et al. (1997) and Baraffe et al. (1998), employing a range of power-law mass functions and assuming a constant birthrate. Our models show that \( F_{\text{Li}} \) depends strongly on the proportion of young (\( t < 10^8 \) yr) dwarfs in the solar neighborhood, a result stemming from the correlation between mass and cooling time and reflecting the temperature range spanned by ultracool dwarfs. Moreover, the two sets of models predict lithium fractions that differ by over 50%. Nonetheless, it seems clear that the observed values of \( F_{\text{Li}} = 6\% \pm 4\% \) for M7–M9.5 dwarfs and 10\% \pm 7\% for M8–M9.5 dwarfs are only consistent with near-Salpeter mass functions (\( \alpha > 2 \)) if the solar neighborhood is completely deficient in brown dwarfs with ages \( t < 10^8 \) yr. This seems unlikely, given the observed distribution of chromospheric activity among G dwarfs in the same volume.

We have also considered the rotational properties of our sample of ultracool dwarfs and the correlation between rotation and chromospheric activity. Our observations confirm Hawley et al.’s (2000) conclusion that there is no significant correlation between the latter two parameters for late-type M dwarfs. The relative number of fast (\( v \sin i > 20 \) km s\(^{-1}\)) and slow rotators is invariant with spectral type, although there is marginal evidence that the average rotational velocity of M9/9.5 dwarfs is higher than among earlier types. The range of chromospheric activity exhibited in our observations is consistent with previous studies (G00; Basri 2001), with the typical H\( \alpha \) flux lying below the mean level for earlier type M dwarfs. Two of the 39 dwarfs have H\( \alpha \) fluxes significantly higher than previous measurements. The inferred duty cycle of 5\% for flare outbursts is consistent with previous estimates for late-type dwarfs.

Finally, we have combined our radial velocity measurements with proper-motion data and distance estimates to derive space motions for the ultracool dwarfs in our sample. The mean kinematics are almost identical to those derived by Hawley et al. (1996) for a volume-limited sample of M0 to M6 emission-line dwarfs. This result is surprising, given that the ultracool dwarf sample is expected to be dominated by long-lived, very low mass stars, with an average age of 4–5 Gyr (for a disk age of 10 Gyr). This discrepancy raises serious questions concerning both the existence of possible biases in the sampling of the Galactic disk stellar population and the reliability of evolutionary models for low-mass stars and brown dwarfs. Detailed analysis of high-resolution spectroscopic observations of a larger sample of ultracool dwarfs is required before those questions can be answered in a satisfactory manner.

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REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Barrado y Navascues, D., Stauffer, J. R., Bouvier, J., & Martin, E. L. 2001, ApJ, 546, 1006
Basri, G. 2001, in ASP Conf. Ser. 223, Cool Stars, Stellar Systems and the Sun: 11th Cambridge Workshop, ed. R. J. Garcia Lopez, R. Rebolo, & M. R. Zapatero Osorio (San Francisco: ASP), 261
Basri, G., Mohanty, S., Allard, F., Hauschildt, P. H., Delfosse, X., Martin, E. L., Forveille, T., & Goldman, B. 2000, ApJ, 538, 563
Becklin, E. E., Frogel, J. A., Hyland, A. R., Kristian, J., & Neugebauer, G. 1969, ApJ, 158, L133
Bessell, M. S. 1991, AJ, 101, 662
Burgasser, A., et al. 1999, ApJ, 522, L65
Burrows, A., & Liebert, J. 1993, Rev. Mod. Phys., 65, 301
Burrows, A., et al. 1997, ApJ, 491, 856
Chabrier, G., & Baraffe, I. 1997, A&A, 327, 1039
Cruz, K. L., Reid, I. N., & Liebert, J. 2002, in preparation
Dahn, C. C., et al. 2000, in ASP Conf. Ser. 212, From Giant Planets to Cool Stars, ed. C. A. Griffiths & M. S. Marley (San Francisco: ASP), 74
Epchtein, N., et al. 1994, Ap&SS, 217, 3
ESA. 1997, The Hipparcos Catalogue (ESA SP-1200) (Noordwijk: ESA)
Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., & Burgasser, A. H. 2000a, MNRAS, 311, 385
Gizis, J. E., Monet, D. G., Reid, I. N., Kirkpatrick, J. D., Liebert, J., & Williams, R. J. 2000b, AJ, 120, 1085 (G00)
Gizis, J. E., Reid, I. N., & Hawley, S. L. 2002, AJ, in press
Gliese, W. 1969, Zerfall, Astron. Rechen-Instit, Heidelberg, No. 22
Gray, D. F. 1982, The Observation and Analysis of Stellar Photospheres (Cambridge: Cambridge Univ. Press)
Hawley, S. L., & Reid, I. N. 1996, AJ, 112, 2799
Hawley, S. L., Reid, I. N., & Gizis, J. 2000, in ASP Conf. Ser. 212, From Giant Planets to Cool Stars, ed. C. A. Griffith & M. S. Marley (San Francisco: ASP), 252
Henry, T. J., Ianna, P. A., Kirkpatrick, J. D., & Jaureg, H. 1997, AJ, 114, 388
Henry, T. J., Kirkpatrick, J. D., & Simons, D. A. 1994, AJ, 108, 1437
Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439
Herbig, G. 1956, PASP, 68, 531
Hyland, A. R., Becklin, E. E., Neugebauer, G., & Wallerstein, G. 1969, ApJ, 158, 619
Jahreiss, H., & Wielen, R. 1983, in IAU Colloq. 76, The Nearby Stars and the Luminosity Function, ed. A. G. Davis Philip & A. R. Upgren (Schenectady: L. Davis), 277
Kastner, J. H., Zuckerman, B., Weintraub, D. A., & Forveille, T. 1997, Science, 277, 67
Kennworthy, M., et al. 2001, ApJ, 554, L67
Kirkpatrick, J. D., Beichman, C. A., & Skrutskie, M. F. 1997, ApJ, 476, 311
Kirkpatrick, J. D., Henry, T. J., & Irwin, M. J. 1997, AJ, 113, 1421
Kirkpatrick, J. D., Henry, T. J., & Simons, D. A. 1995, AJ, 109, 797
Kirkpatrick, J. D., McCraw, J. T., Hess, T. R., Liebert, J., & McCarthy, D. W. 1994, ApJS, 94, 749
Kirkpatrick, J. D., et al. 1999, ApJ, 519, 802
———. 2000, AJ, 120, 447
Lane, B. F., Zapatero Osorio, M. R., Britton, M. C., Martin, E. L., & Kulkarni, S. R. 2001, ApJ, 560, 390
Leggett, S. K. 1992, ApJS, 82, 351
Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., & Hauschildt, P. H. 1996, ApJS, 104, 117
Leggett, S. K., Harris, H. C., & Dahn, C. C. 1997, ApJ, 503, 107
Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., & Hauschildt, P. H. 1996, ApJS, 104, 117
Luhman, K. L. 2000, ApJ, 544, 1044
Luhman, K. L., Rieke, G. H., Young, E. T., Cottam, A. S., Chen, H., Rieke, M. J., Schneider, G., & Thompson, R. I. 2000, ApJ, 540, 1016

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