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LITHIUM IN BROWN DWARF CANDIDATES: THE MASS AND AGE OF THE FAINTEST PLEIADES STARS[1]

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ABSTRACT

We present high-resolution optical spectroscopy and infrared photometry of one of the lowest luminosity Pleiades stars, PPL 15. Its cluster membership is strengthened by both its measured radial velocity and Hα strength. Its reported mass is 0.06 $M_{\odot}$, based on its *I*-band luminosity and the Pleiades age of 75 Myr as reported by Stauffer, Hamilton, & Probst in 1994. We confirm its luminosity with *JHK* photometry. Such a low mass for PPL 15 implies that it should currently retain lithium, unlike all low-mass Pleiades stars tested so far. Our Keck HIRES spectrum of PPL 15 indeed exhibits the lithium absorption feature with an equivalent width of 0.5 Å. We estimate the likelihood this detection is spurious to be less than 1%. Thus, PPL 15 passes the lithium test for brown dwarf status.

Calculations of the luminosity as a function of mass and age for very low mass stars, along with the history of lithium depletion, have been provided by Nelson, Rappaport, & Chiang in 1993. Lithium *is* depleted in HHJ 3, which is only a little brighter than PPL 15. The self-consistent interpretation with both observations and theory is that the age of the Pleiades is ~115 Myr. If so, the derived mass for PPL 15 increases to ~0.078 $M_{\odot}$. The canonical 75 Myr age was derived from the upper main-sequence turnoff, but it substantially increases if core convective overshoot is included. Such mixing could bring the two methods of age determination into agreement. It is therefore possible that the ages of young clusters have generally been underestimated. The luminosity of brown dwarfs in these clusters would thus have been overestimated.

Subject headings: open clusters and associations: individual (Pleiades) — stars: abundances — stars: evolution — stars: low-mass, brown dwarfs

1. INTRODUCTION

The lowest luminosity stellar objects in young stellar clusters provide valuable information on star formation and early stellar evolution, and they constitute the best brown dwarf candidates (Stauffer et al. 1994b, hereafter S94). Young brown dwarfs are intrinsically brighter than their older counterparts in part because of significant ongoing gravitational contraction and in part because of the fact that they have simply been cooling for less time. Several young brown dwarf candidates have been identified in the Pleiades using direct imaging in optical or IR wavelength bands (Hambly, Hawkins, & Jameson 1991; S94). To date, no object either in a cluster or in the field has been certified as a brown dwarf, nor are any of the candidates absolutely convincing (Burrows & Liebert 1993). GD 165B, as the coolest known stellar object, stands out as a very likely brown dwarf (Becklin & Zuckerman 1988; Jones et al. 1995), but independent determination of its mass or age is difficult.

The ironclad certification of a brown dwarf requires a demonstration that nuclear burning of hydrogen does not occur, at a mass and age for which that is expected. A robust verification that there are some nuclear reactions in cool stars derives from the observed depletion of lithium, which occurs prior to arrival on the main sequence for stars having $M < 1\ M_{\odot}$ (Soderblom et al. 1993; Garcia-Lopez, Rebolo, & Martín 1994). Lithium burns at 2.5×10^6 K, lower than the ignition temperature for hydrogen. Thus, the retention of lithium in a fully convective star (which is well mixed) signifies the lack of hydrogen burning. Indeed, in the final analysis, this is the *only* test we know that can absolutely confirm the lack of hydrogen burning in an old, very cool object.

By observing a young cluster in which the lower main sequence is known to have depleted lithium, one can then look for the boundary at faint luminosities below which lithium has not yet been depleted (Rebolo, Martín, & Magazzù 1992). Such a boundary will occur above the theoretical upper mass limit for brown dwarfs if the cluster is young enough, but even then it serves as observational confirmation of the predicted low central temperatures of the objects. On the other hand, the highest mass brown dwarfs are expected to burn lithium eventually (without ever reaching equilibrium hydrogen burning). Objects which are old enough cannot be rejected as brown dwarfs simply because they do not show lithium. Nonetheless, extensive searches for lithium in very low mass stars, both in clusters and in the field, have thus far failed to find a single example of the reappearance of lithium at the bottom of the main sequence (Martín, Rebolo, & Magazzù 1994; Marcy, Basri, & Graham 1994, hereafter Paper I).

Another value of this lithium test is that the lithium boundary constitutes a new nuclear test of cluster ages. This joins the traditional diagnostics: the position of the upper main-sequence turnoff and, in sufficiently young clusters, the lower main-sequence turn-on. In the Pleiades, for example, there has been a quiet but long-standing conundrum about its age. The canonical age of 75 Myr is derived from standard calculations of the upper main-sequence turnoff. Herbig (1962), however, pointed out that the failure to detect a lower main-sequence

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turn-on implies a substantially older age. Stauffer (1984) argued for an age in excess of 100 Myr. There has also been a lengthy controversy about a possible age spread in the Pleiades; recent discussion of it can be found in Steele, Jameson, & Hambly (1993) and Stauffer, Liebert, & Giampapa (1995, hereafter S95). Furthermore, the age derived from the upper main sequence itself has been questioned by Mazzei & Pigatto (1989), who propose doubling it to 150 Myr. They also point out that the combination of theoretical and observational uncertainties make an age spread rather difficult to establish firmly. The predicted luminosity of stars at the lithium boundary is a function of age, providing an independent means of testing the age of the low-mass stars.

In this paper, we examine the brown dwarf candidate in the Pleiades with the lowest currently known luminosity, PPL 15, discovered by Stauffer, Hamilton, & Probst (1994a, hereafter SHP). Having a V magnitude of 22.46, its I magnitude is 0.3 mag fainter than HHJ 3, the previously faintest known member. Spectra of HHJ 3 (Paper I) demonstrated that it has burned lithium and negated its brown dwarf status. This is quite surprising, given the predicted mass for a 75 Myr old object of its luminosity of around 0.07 $M_{\odot}$; such an object should certainly have retained lithium. Until a brown dwarf is actually found, we cannot be sure of the theory behind such predictions or even that such objects can really form. It is possible, for example, that the star formation process is unable to halt accretion until a main-sequence mass is reached (Shu, Adams, & Lizano 1987).

The properties of an actual brown dwarf will test the theory of stellar interiors in a regime of unusual opacities and equations of state, as well as the important but difficult atmospheric opacities that also govern its appearance and evolution. From a practical standpoint, the establishment of a luminosity threshold below which lithium has failed to burn at a given age will permit confident detection of further brown dwarfs by purely photometric techniques. This in turn would allow deep K-band imaging to determine the number density of brown dwarfs, thus yielding their mass contribution relative to the H-burning stars. Brown dwarfs remain plausible contributors to the baryonic dark matter. In any case, there is now a gap of two orders of magnitude between the lowest mass stars and the highest mass planets known. We would like to know if this gap is due to physical causes or observational difficulties.

1.1. *Semantics*

Before proceeding, it is important to define exactly what we mean by the object classifications we are using. The definition of "brown dwarf," for example, has had a variety of subtly different incarnations. Even in Kafatos, Harrington, & Maran (1986), where the term came to be generally accepted, different authors meant slightly different things. The most common criterion seems to be the physical source of the luminosity of the object—"brown dwarfs" will never derive 100% of their luminosity from nuclear burning. Some authors use the term "transitional object" to describe objects that will at some time derive only slightly less than 100% from nuclear burning; the lower mass boundary for such objects is not precise. We propose a more graphical (but functionally similar) definition here: a brown dwarf is an object the luminosity of which never achieves a positive time derivative. This is a more precise statement, in the spirit of what Saumon, Burrows, & Hubbard (1995) implicitly use. As always, one neglects the deuterium-burning phase (if one occurs). This definition has the advantage that the criterion can be quickly assessed from a diagram showing luminosity, age, and mass, or even from evolutionary tracks in an H-R diagram. All definitions of brown dwarfs are based on stellar models, so even if one had an object whose mass was known to be very low because it was in a binary system, one could not be sure it is not burning hydrogen unless it passes the lithium test.

We suggested in Paper I that objects in young clusters that are supposed to lie in the mass range of brown dwarfs and that still show lithium while the slightly brighter cluster members do not be dubbed "lithium brown dwarfs." Because it is no less theoretical to talk about "lithium brown dwarfs" than simply "brown dwarfs," we here propose instead to define "lithium dwarfs" as fully convective objects beyond the deuterium-burning phase that have a measurable lithium resonance line at 670.8 nm. This is a clean and purely observational classification. In such objects there is a direct observational indication that hydrogen burning has not occurred. Thus, if GD 165B turns out to be a lithium dwarf, then it is incontrovertibly a brown dwarf. If it does not exhibit lithium, it could still be a high-mass brown dwarf that is sufficiently old. The lithium test for brown dwarf status is therefore cleanest for stars of known age, namely cluster members. In sufficiently young clusters, however, one will also find lithium dwarfs that will eventually be on the main sequence and are therefore not brown dwarfs.

The upper mass limit for brown dwarfs is unambiguous in each theoretical calculation, but unfortunate uncertainties in the opacities, treatment of atmospheric boundary conditions, and equations of state cause different calculations to derive different limits. In this paper, we refer to a consistent set of calculations to find the behavior of luminosity and lithium depletion as a function of age and mass. Our brown dwarf mass limit is therefore also taken from these for consistency. The particular values of all these quantities is likely to change as the theory is updated.

2. OBSERVATIONS

A finding chart and coordinates for PPL 15 are given in Figure 1. Spectra of PPL 15 were obtained at the Keck Observatory during two runs, on 1994 November 23 and 1995 March 13 during which a total of five and four 1 hr integrations were obtained, respectively. At no time were observing conditions ideal. The November run was plagued by cirrus of varying thickness, and the gibbous Moon was about 60° away. March was clear, but the gibbous Moon was only 30° from the Pleiades. In November, the star was only between 5% and 10% as bright as the sky; in March it was between 2% and 5% as bright, with worse seeing. The HIRES echelle spectrometer (Vogt et al. 1994) was set to obtain the wavelength region from 640 to 870 nm in 15 spectral orders, with gaps of $\sim$5 nm missing between orders. The Tektronix 2048 $\times$ 2048 CCD was binned on chip to 2 $\times$ 2 pixels to yield final pixels that span 4.5 km s^{-1} per pixel. The slit of 1."1 yielded an instrumental profile width of 2 pixels, corresponding to a resolution $\lambda/\Delta\lambda = 30{,}000$. At 670 nm this corresponds to 0.2 Å.

The reduction of the raw CCD images was first done in a "standard" fashion. Each frame had the median value of a bias frame subtracted. We removed cosmic rays from the entire image by means of an algorithm that searched for spikes that reached above thresholds in sharpness and amplitude. The 15 spectral orders were located in an exposure on a bright star. A cubic polynomial traced the "ridge" of the spectral orders to within 0.1 pixel. These nominal order locations were uniformly

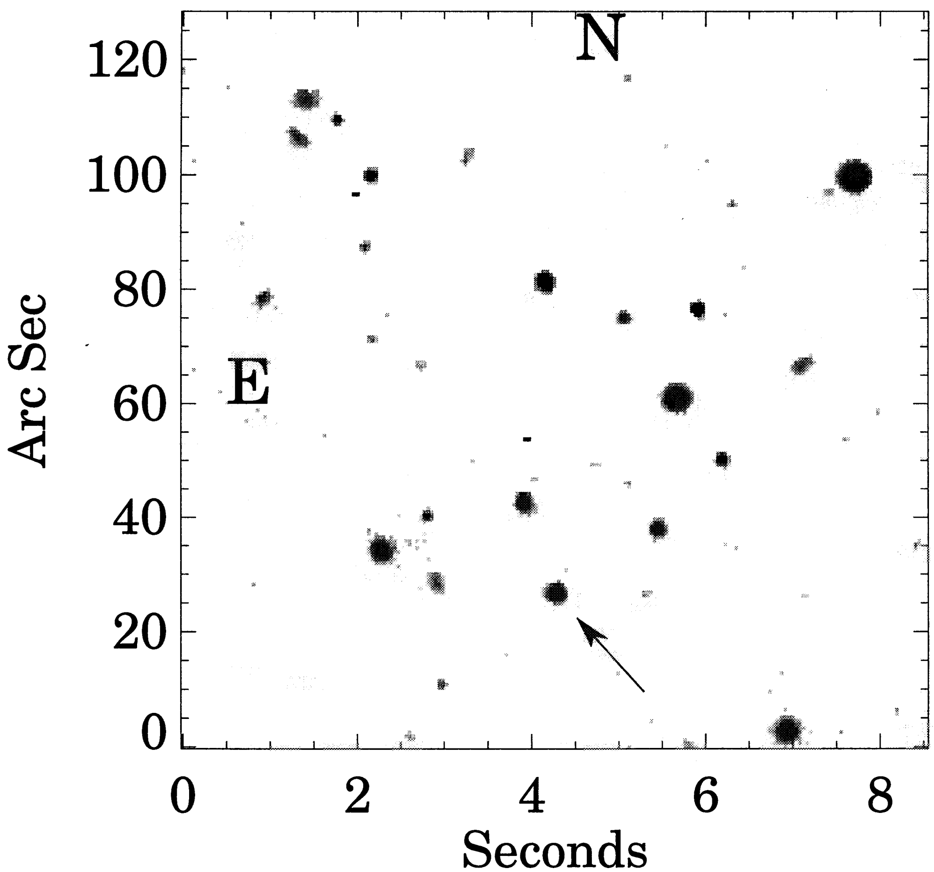

FIG. 1.—Finding chart. A portion of the 1989 discovery *I*-band frame for PPL 15, courtesy of John Stauffer (CfA). The object is at $3^h45^m06^s.4$, $+23°30'22''$ (1950). Shown is a 200 pixel square portion of the chip, with a scale of $0''.64$ pixel^{-1}. PPL 15 is marked with an arrow.

shifted by trial amounts perpendicular to the dispersion to "peak-up" on the orders in the faint exposure to be reduced. This technique ensures that the curvatures of faint echelle spectral orders are predetermined and that their zero-point location is based on neighboring brighter orders. The "sky" contribution was determined from the average of the median sky values on either side (10 pixels used) of the stellar spectrum. This approach achieves subtraction of OH sky lines to a few percent of their strength. The final stellar spectral orders were extracted by simply adding all remaining counts within a swath of 6 pixels centered on the order. The five best spectra of nine were combined by taking the median value at each pixel. This median carries one conservative advantage over a weighted average of the five spectra, in that extreme values will have no effect on the final spectrum.

A second independent reduction was done in which we extracted the raw image along arcs parallel to the order locations, after bias subtraction and removal by hand of cosmic rays. This yields an array in which the sky and star rows are straight, although the pixel values have undergone a trapezoidal interpolation (which is guaranteed to yield the correct sum over a few pixels). We evaluated the sky above and below the rows chosen to be "star" rows by virtue of being more than 7% of the relative brightness of the best star row compared to the median sky value and being contiguous with each other. The two sky median spectra (over 10 pixels each) were compared to eliminate any clearly aberrant pixels. The final sky spectrum was then subtracted from each star row. The measurement of signal-to-noise ratio (S/N) in spectra of late M stars is difficult from appearances alone; the intrinsic spectrum is very "noisy" because of the numerous and sometimes overlapping molecular lines. Rather than trying to measure the noise in continuum regions (of which there are none), we evaluated the S/N by using the counts in the spectrum and sky rows to estimate the Poisson noise, along with an estimate of the read noise. The signal was considered to be the median of a sky-subtracted star row. Given these estimates, we used a simplified "optimal extraction" in which we weighted individual rows by their S/N. After obtaining the summed individual spectra, we also used the ratio of star to sky counts to weight them in making a final sum.

2.1. *Lithium*

The final spectra of the lithium region at 670.8 nm are shown in Figure 2. All spectra shown in Figure 2 have been subjected to smoothing as described in the legend. Also shown in Figure 2*a* is a purely theoretical LTE spectrum kindly provided us by Hauschildt, Allard, & Schweitzer (1995). It contains lithium at the solar photospheric abundance of [Li/H] = 1.16. Their NLTE spectrum with lithium at the full primordial abundance

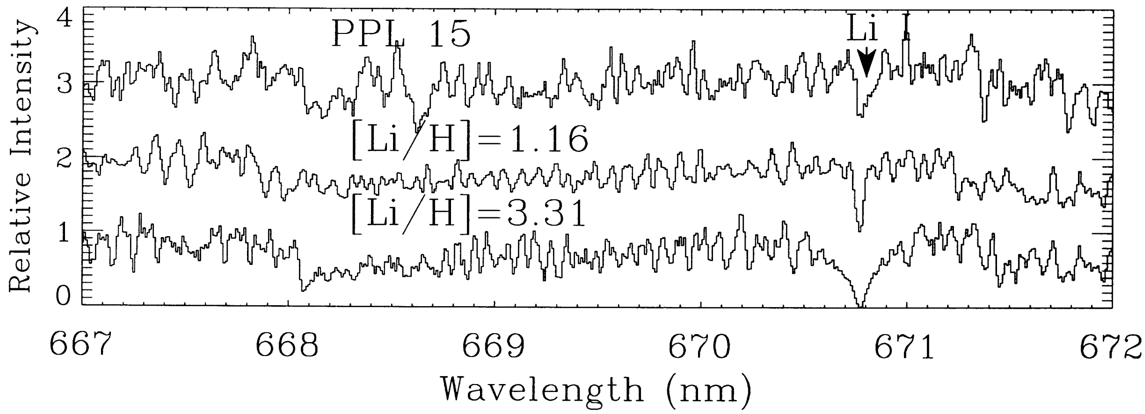

FIG. 2*a*

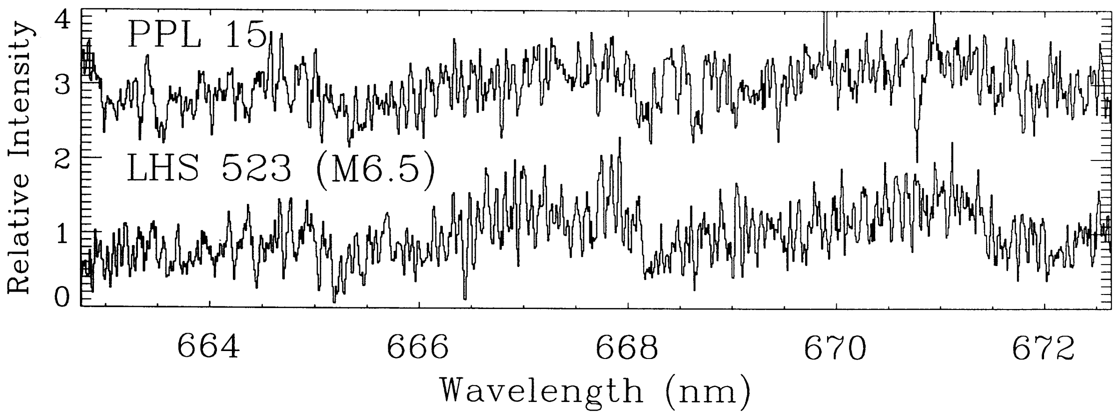

FIG. 2*b*

FIG. 2.—The lithium region of PPL 15. (*a*) The optimal reduction is shown in the upper trace, offset by 2 continuum units. A model spectrum offset by 1 continuum unit is the middle trace. The model (Hauschildt et al. 1995) is for 2600 K, log (*g*) = 5.0, and in LTE. Lithium has been given the same abundance as the solar photosphere (a little less than 1% of meteoritic). The bottom trace is a 2700 K model calculated in NLTE, with the full primordial abundance of lithium. (*b*) The full lithium order is shown with a spectrum taken during the same run of LHS 523 (M6.5 V). In both panels all spectra have been subjected to a boxcar smoothing of 4 (*upper*) and 2 (*lower*) pixels; the model spectra were first interpolated onto the observational pixels.

of [Li/H] = 3.31 is shown in the lowest trace. These are calculated from the model grid described by Allard & Hauschildt (1995) for a star with an effective temperature of 2600 K, log (*g*) of 5.0. We also show the full spectrum along with a spectrum of a field M6.5 star (LHS 523) observed with the same instrumental configuration in Figure 2*b*, for comparison. These two spectra show the same general shape because of the molecular bands, indicating that there really is a stellar signal from PPL 15 despite the relatively low S/N. The bands have depths similar to that of the expected lithium line, suggesting that it should be visible, too. We confirm that molecular features are also visible in our spectra in the adjacent orders, which have similar S/N.

The S/N in the summed observed spectra is clearly adequate to detect features that reach down to 20% of the mean and cover a few pixels. *A deep feature with an equivalent width of* 0.5 Å *appears at exactly* 670.8 nm, *the wavelength of the lithium resonance line.* We determine the wavelengths from ThAr spectra but also cross-check with T Tauri spectra taken on the same night and find that the lithium line has its expected location in those spectra. We have only shown the spectra from the optimal extraction, as they are less noisy, but the lithium line is equally visible in both reductions. Taken at face value, Figure 2 appears to be a clear detection of lithium in PPL 15, making it the first confirmed "lithium dwarf."

The summed spectrum consists of nine individual spectra, taken in a variety of chip positions. The four spectra with the highest S/N individually show the feature; it is 5–8 pixels wide in each of them. These best spectra are all from 1994 November. Lithium is not readily apparent in the remaining spectra, which are too noisy to show even the molecular features. We assess the S/N in the spectra by comparing them directly with each other. From each November spectrum, we subtract the median of the other four spectra. The median of the differences is adopted as the "noise" in the spectrum. We use this median rather than the standard deviation to reduce the effect of cosmic rays. The "signal" is taken as the median of the spectrum. The S/N in the lithium order measured this way lies between 0.6 and 1 for the individual spectra. Assuming the noise adds in quadrature, the S/N in an (unweighted) summed spectrum will be about 2 in the lithium order. Smoothing by 4 pixels can improve this to a S/N of 4, which is relevant to the displayed spectra. The lithium line, with its ~ 8 pixel FWHM, contains two independent "binned pixels," each having noise of 0.25 of the "continuum." We may determine the reality of the "dip" at the lithium line by noting that each of two binned pixels resides below 0.5 of the continuum; they deviate from the continuum by $\sim 2\ \sigma$. The random probability of two consecutive such low pixels is about 0.0025. We are comfortable stating that the chance that our summed detected lithium feature is spurious is less than 1%. Nonetheless, there is no substitute for a confirmation at higher S/N. A few clear Moonless hours on HIRES would allow a firmer detection. It is also possible to conduct a confirmation at substantially lower resolution ($R > 4000$) given S/N higher than 10.

The conversion of lithium equivalent width to lithium abundance must be made by spectral synthesis, using models of the appropriate temperature. Fortunately, there have been a number of recent calculations for lithium in the literature. The most relevant to this work is that by Pavlenko et al. (1995, hereafter P95), who provide curves of growth for the lithium resonance line for atmospheres of 2500 K and 3000 K at $\log(g) = 5.0$. According to them, the lithium line grows in strength as the temperature decreases through this range, with primordial lithium producing a line in excess of 1 Å equivalent width (as in the lowest spectrum in Fig. 2*a*). It remains above 1 Å until lithium drops to well below one-tenth of cosmic abundance. At our observed strength of 0.5 Å, P95 would predict the lithium is depleted below 1% of its original value. Judging from the middle spectrum in Figure 2*a*, Hauschildt et al. (1995) might assign a value a little above 1%. Certainly, the exact lithium abundance implied by our spectrum is rather uncertain at the moment. The calculations are subject to a number of uncertainties, such as molecule formation, NLTE effects, and effects of a chromosphere. It may be that PPL 15 is just in the process of depleting its lithium, which will be gone in a few million years. This is not as coincidental as it may first seem, given that we have taken only a small step fainter than the last star observed, which had lithium depleted. What is qualitatively important is that a lithium feature with 0.5 Å equivalent width was not present in Pleiades stars as faint as HHJ 3 but appears at the luminosity of PPL 15. Thus, we believe that PPL 15 locates the lithium depletion boundary for the Pleiades.

2.2. *The Radial Velocity and Spectral Type of PPL 15*

One crucial property of PPL 15 required to validate the lithium test is its actual membership in the Pleiades. PPL 15 was not found through a proper motion survey; instead, SHP conducted a deep CCD survey for objects of the proper color and magnitude in the region of the Pleiades. S95 confirmed that several of their candidates had the expected Hα emission, and radial velocities consistent with membership, but did not observe PPL 15. Our spectra easily confirm both these membership criteria for it. Indeed, the confirmation is obvious in the raw images since there is a faint Hα line in the sky (from the cluster) that bisects the stellar Hα line (see Fig. 3*a*). We have seen this in all our Pleiades observations. It is not telluric emission, which can also be seen in the figure (we display a March observation, at which time the telluric and cosmic lines are well separated). The broad emission is consistent with the 21 cm emission 4 km s^{-1} redward of the cluster velocity (White

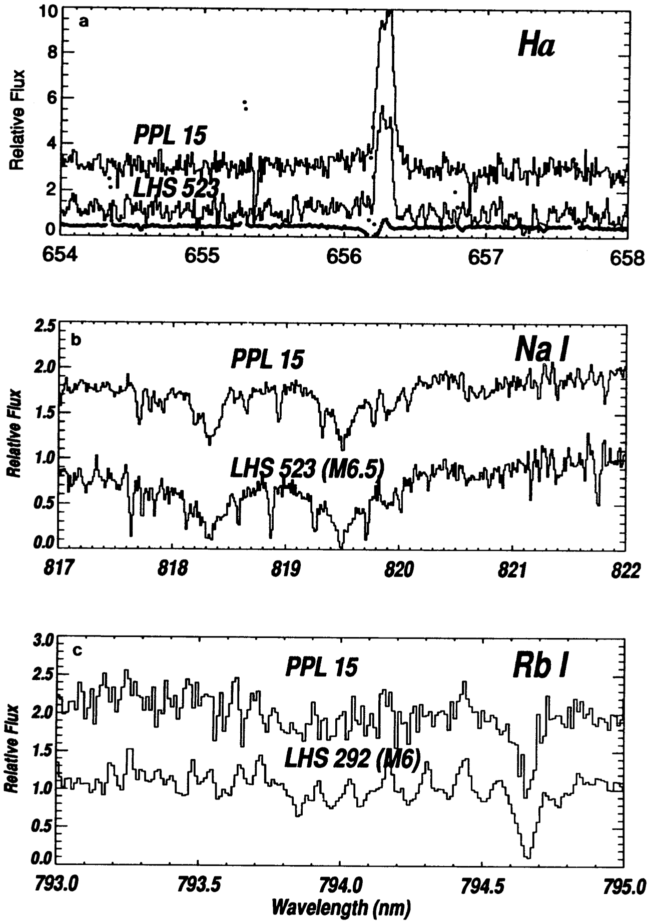

FIG. 3.—Atomic lines in PPL 15. (*a*) The Hα line in PPL 15 (offset by 1 unit) and LHS 523 (M6.5). The lowest (*dotted*) trace is an arbitrarily scaled spectrum of the sky during a March PPL 15 exposure. The broad Hα emission feature visible in it is from the cluster; the narrow blueward feature is telluric, and the absorption feature is from moonlight. (*b*) The region of the Na I infrared lines around 819 nm. Most of the narrow features are telluric; they appear shifted because the spectra are in the stellar rest frame. (*c*) The region of the temperature-sensitive Rb I resonance line at 794.7 nm in PPL 15 and LHS 292 (M6).

& Bally 1993). The equivalent width of the stellar Hα line, 5.5 Å, is quite consistent with expectations from S95 and Hodgkin, Steele, & Jameson (1995). It would be desirable in the future to confirm that PPL 15 is a proper motion cluster member as well.

The radial velocity of PPL 15 was measured with a variety of approaches. On two nights, 1994 November 23 and 1995 March 12, a solar spectrum was obtained from the sky at twilight. The Doppler shift of the PPL 15 Hα emission line was measured relative to the solar absorption Hα line. The derived heliocentric velocities of PPL 15 were $+8.0$ km s^{-1} and $+5.6$ km s^{-1} on the two nights, respectively, with an error judged to be 4.3 km s^{-1} (1 pixel). Apparently the radial velocity of PPL 15 did not change significantly during the 4 months separating these two measurements. Corrections for Earth's orbital and rotational motion were accomplished using a routine written by J. A. Valenti, based on the algorithm of Stumpff (1980). We also measured the velocity of PPL 15 relative to the Sun by using the sodium lines at 818.3 and 819.4 nm (Fig. 3*b*). We checked the zero point of the wavelength scale by using neighboring telluric lines and found scale shifts to be less than 4 km s^{-1}. The sodium lines yield a heliocentric Doppler shift of $+5.7$ km s^{-1} for PPL 15 in 1994 November, in agreement with the Hα measurement.

As an alternative approach, the velocity of PPL 15 was measured relative to GL 273 and GL 285 (YZ CMi), for which velocities are known with an accuracy of 0.3 km s^{-1} (Marcy & Benitz 1989). Doppler measurements of PPL 15 were made in spectral regions of Hα and sodium, as above. The sodium region between 817.0 and 821.0 nm provides particularly secure Doppler precision because the sodium lines have sharp cores, the photon flux is high (in late-M stars), and the telluric lines serve as an incontrovertible wavelength metric. The PPL 15 velocities derived by visual alignment were $+3.4$ km s^{-1} (using GL 285) and $+0.5$ km s^{-1} (using GL 273), with an accuracy of about 1 pixel. These velocities are approximately 5 km s^{-1} below those obtained when using the twilight spectrum as template. One problem is that the sodium lines are very weak in the solar spectrum, and our twilight spectrum is far more heavily contaminated by telluric water than the stellar spectrum. Nonetheless, we average all velocity measurements to yield a final velocity of $+4.6 \pm 4$ km s^{-1} for PPL 15 relative to the solar system barycenter.

The bulk radial velocity and kinematics of the Pleiades cluster may be established from several sources. Rosvick, Mermilliod, & Mayor (1992) find a radial velocity of 5.9 km s^{-1}. We independently measured the radial velocities of two extremely low mass Pleiades members, HH J3 and HH J14, finding 7.7 and 8.4 km s^{-1}, respectively (Paper I). S95 measured 16 low-mass Pleiades members, finding an average velocity, $v_r = 7.1$ km s^{-1}. Since S95 adopted a velocity for their standard star based on the Rosvick et al. measurements, the two sets of measurements share a common zero point. The Stauffer et al. velocities affirm that the lowest mass stars share the cluster mean velocity. We therefore adopt the Pleiades cluster velocity of 5.9 km s^{-1}. S95 find a 1 σ velocity dispersion of 5.6 km s^{-1}, nearly equal to their quoted errors of 5 km s^{-1}. The actual velocity dispersion of the Pleiades is likely to be less. The measured velocity of PPL 15, 4.6 km s^{-1}, lies near the cluster mean of 5.9 km s^{-1} and so is clearly consistent with membership in the Pleiades. Furthermore, the velocity dispersion of field M dwarfs is about 40 km s^{-1}, which makes it highly improbable that PPL 15 is a member of the general field.

In Figure 3 we also compare atomic lines from PPL 15 with field M dwarfs of nearly the same spectral type. The sodium line region in Figure 3*b* contains numerous telluric lines, which are all shifted blueward in LHS 523 (M6.5) relative to the PPL 15 spectrum (the spectra are on a stellar rest frame). Not only do the sodium lines themselves appear to be similar, but other stellar features are also reproduced (such as the broader feature at 820.7 nm). In Figure 3*c* we show the spectral region of the Rb I line at 794.8 nm. In Basri & Marcy (1995) we found that the strength of this line seems to be fairly sensitive to the temperature of the star. The line in PPL 15 has no measurable difference in equivalent width (0.7 Å) from that in LHS 292 (M6). This implies that their spectral types are similar. Note, however, that the spectra are not identical and that some molecular features in one star are not present in the other. These spectra have substantially higher S/N than at the lithium order and seem to indicate that we should not expect a field star to provide a perfect model of the true spectrum of PPL 15. This may in part be due to its higher gravity. We are able to derive a limit on $v \sin i$ only by cross-correlation between the spectra of <10 km s^{-1}. This is low in comparison to the other HHJ stars we have examined (Paper I).

2.3. *Infrared Photometry and the Luminosity of PPL 15*

SHP estimate that the bolometric luminosity of PPL 15 is $\log L/L_{\odot} = -2.92$, using a method based on its I magnitude. Using a similar method, J. Stauffer (private communication) estimates the luminosity of HHJ 3 to be $\log L/L_{\odot} = -2.76$. Since most of the flux from the star is in the infrared, it is desirable to check these with infrared photometry. We observed PPL 15 at the Lick 3 m Shane telescope on 1995 February 2 using the facility infrared camera which is equipped with a NICMOS-III detector array. The standard J, H, and K' infrared filter set was used. Flux calibration was done relative to the UKIRT faint standards FS 7 and FS 11 (Casali & Hawarden 1992). The UKIRT photometry does not include measurements with the K' filter. Therefore, we calculated the K' magnitudes for the standards using the transformation $K' - K = 0.19(H - K)$ (Wainscoat & Cowie 1992). The correction is small because FS 7 and FS 11 are blue. The resultant photometry for PPL 15 on the UKIRT system is $J = 15.34$, $H = 14.65$, and $K = 14.32$. The uncertainty is 0.05 mag at each wavelength. The night seemed clear during these observations, but fog rapidly shut down the mountain shortly thereafter.

Figure 4 shows the I, $I - K$ color magnitude diagram for PPL 15 and the faintest members of the Pleiades. This plot shows that PPL 15 is not an unusual object but, rather, lies on the extrapolated main sequence defined by brighter stars. The faint end of the Pleiades main sequence is well defined in Figure 4 and represents the continuation of the higher mass sequence of Stauffer (1984). Our analysis of the lithium would be invalid if PPL 15 were anomalously young or a T Tauri star. Steele et al. (1993) argue from the scatter in $I - K$ colors that the faintest Pleiades stars exhibit a large age spread (3–70 Myr). If so, the age of PPL 15 would be a serious concern. S95,

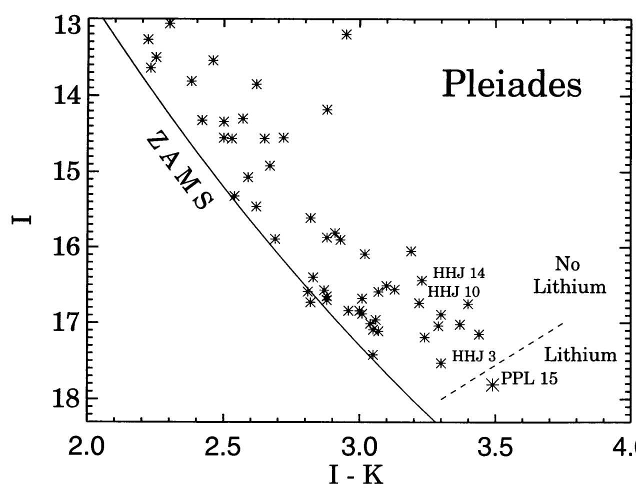

FIG. 4.—A color-magnitude diagram showing the faint Pleiades stars. The stars plotted are all proper-motion members from Hambly et al. (1991) except PPL 15. The infrared photometry is taken from Steele et al. (1993) except for PPL 15. HHJ 36 and 18 have not been plotted because of suspected photometric errors (Stauffer et al. 1995). The solid line is the young-disk ZAMS, shifted to the distance modulus and reddening of the Pleiades (Leggett 1992). Labeled stars have been tested for lithium; only PPL 15 has shown it as indicated by the dashed line.

on the basis of new spectroscopic data and a reanalysis of the photometry, reject this conclusion. Evolutionary tracks are approximately vertical in the color-magnitude diagram. PPL 15 does not lie above the extension of the general locus of stars at higher luminosity to fainter levels (Fig. 4), so there is no evidence that the age of PPL 15 is significantly younger than the more luminous cluster members. The presence of a T Tauri accretion disk would lead to an infrared excess in $I-K$. PPL 15 shows no such excess. Therefore, we conclude that mass is the only factor that distinguishes PPL 15 from the brighter Pleiades stars.

Infrared photometry can be converted to bolometric luminosity using the calibration of Tinney, Mould, & Reid (1993). Their calibration is based on infrared spectrophotometry of a number of nearby cool stars whose parallaxes are known. They give bolometric corrections for $K_{\rm CIT}$ magnitudes, which is the same as the UKIRT scale. With our $I-K$ color for PPL 15 of 3.48, we estimate the bolometric correction to be 3.08 mag. For a distance modulus of 5.53 for the Pleiades with no reddening correction (S95) we find that $M_{\rm bol}$ is 11.87 and $\log L/L_{\odot} = -2.85$, a little brighter than the estimate from the I magnitude of SHP. We can make the same calculation for HHJ 3 using the photometry of Steele et al. (1993). We estimate its bolometric correction to be 3.04, with a resulting $M_{\rm bol}$ of 11.74 and $\log L/L_{\odot}$ of -2.80. This is fainter than Stauffer's estimate, and so we find the two stars to be more similar in bolometric luminosity than he estimates. The back–front effect in the cluster is less than 0.1 mag, so PPL 15 is likely to be intrinsically fainter than HHJ 3 even with our numbers. It would be very valuable to redo infrared photometry of the faintest Pleiades stars with the same instrument on the same night to refine their differential magnitudes. We choose final values for the luminosity intermediate between our K- and Stauffer's I-based determinations. Our adopted bolometric luminosities are $\log L/L_{\odot} = -2.78$ for HHJ 3 and -2.88 for PPL 15.

3. DISCUSSION

The study of lithium in ever fainter Pleiades objects provides a test of (the so far untested) theories of brown dwarf evolution. As S94 point out, bolometric luminosity, rather than color, is the preferred quantity to compare with theoretical brown dwarfs. Without relying on the uncertain atmospheric models for these objects, or the somewhat uncertain conversion of infrared colors to surface temperatures, one can constrain their mass and age. The two fundamental quantities used in the following analysis are the bolometric luminosity and lithium depletion. While it is true that these are not completely directly observable, there is a minimum of uncertain steps between the actual observables (I and K magnitudes, lithium equivalent width) and the quantities of interest. Our determinations of these have been discussed above. Spectral synthesis implies the lithium limit on HHJ 3 means it is depleted below 0.1% of the primordial value, while the 0.5 Å equivalent width in PPL 15 is consistent with lithium abundances 10 times or more as great. The exact lithium abundances must be considered uncertain; it is the qualitative difference in the spectra which is important.

3.1. *The Luminosity-based Mass of PPL 15*

Nelson et al. (1993, hereafter NRC) and D'Antona & Mazzitelli (1994) have calculated the history of lithium depletion and luminosity as a function of mass in very low mass stars. NRC have kindly provided us with the digital results of their work; these contain the relations between luminosity and age shown as solid curves in Figure 5. The luminosity of very low mass stars with ages around 100 Myr derives almost exclusively from gravitational contraction and should be one of the least controversial calculated quantities. Burrows et al. (1993) and D'Antona & Mazzitelli (1994) have also made extensive calculations for very low mass stars and brown dwarfs, giving their luminosity as a function of mass and age. The luminosity history in the two calculations is reasonably consistent, especially in the mass range relevant to this paper. There is somewhat more disagreement at the lower masses for brown dwarfs. Saumon et al. (1995) provide a review of the latest models. We choose the NRC calculations for our analysis because they also give the lithium depletion rates with small time and mass intervals; they agree with the results of D'Antona & Mazzitelli (1994).

To convert observed bolometric magnitudes to absolute luminosity, one must know the distance. SHP quote a distance of 125 pc corresponding to a true distance modulus of 5.48, and S95 use a value for the true distance modulus of 5.53 (which corresponds to an apparent distance modulus of 5.65 with their assumed A_V of 0.12 mag). These are based on photometric ZAMS fitting, tied to the Hyades distance scale (which is itself still slightly uncertain). On the other hand, ZAMS fitting tied to models has produced a distance modulus of 5.60 (Vandenberg & Poll 1989). This would imply a true distance modulus of 5.48 given the extinction in S95. Vandenberg & Poll believe that the extinction is patchy enough that 5.60 is already the true modulus. Two recent papers (using less traditional or certain methods) support 5.60 (O'Dell, Hendry, & Cameron 1994; Giannuzzi 1995). The release of *HIPPARCOS* parallaxes should soon settle this issue. For now, however, the inferred mass for PPL 15 depends directly on what value is adopted. The larger the distance modulus, the larger the inferred mass of PPL 15.

We adopt a true distance modulus to the Pleiades of 5.53 and values for $\log L/L_{\odot}$ for HHJ 3 and PPL 15 of -2.78 and -2.88, respectively. For now, we assume their age is 75 Myr. From Figure 5 it is clear that their implied masses are then 0.070 and 0.061 $M_{\odot}$, respectively. Note that these mass estimates do not depend on assumed colors or color-temperature conversions, nor do they require any lithium data. Given a set of models and an age, the mass of an object of known luminosity is set. If the true distance modulus is 5.60, then the masses of HHJ 3 and PPL 15 would increase by about 0.003 $M_{\odot}$, while if the modulus is 5.48, the masses decrease by about 0.002 $M_{\odot}$. We have indicated the range of luminosities we consider reasonable in Figure 5. Given these and the assumed 75 Myr age, both objects are excellent brown dwarf candidates, and both are predicted to definitely retain their lithium.

3.2. *Lithium Testing of PPL 15*

To apply the lithium test, we need to know at what luminosity a star of a given mass becomes depleted in lithium (to a point where the observed spectral line is substantially decreased in equivalent width). We have used the depletion histories from NRC to place the "lithium boundaries" in Figure 5. The burning rates of lithium are well understood, and other calculations of lithium depletion are in general agreement with NRC. The subtleties of lithium depletion due to depths and rates of mixing that make this such a fascinating subject higher up on the main sequence are not important in these fully convective objects. The mixing to the core occurs on

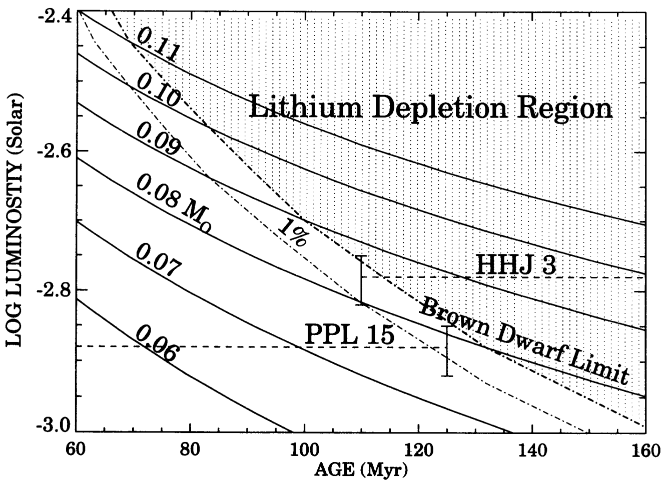

FIG. 5.—A lithium diagnostic diagram. The luminosity of objects for various masses near the brown dwarf limit are shown as a function of age (*solid curves*, labeled with the mass in solar masses). These are from Nelson, Rappaport, & Chiang (1993). The lithium depletion boundary from the same calculations is shown as the thick dash-dotted line; to the right of it (*shaded region*), lithium should be absent from the spectrum. The boundary at which lithium is depleted to the 1% level, when the resonance line should begin noticeably weakening, is shown as the thin labeled dash-dotted line. The adopted luminosities of the two objects on which we have conducted the lithium test, HHJ 3 and PPL 15, are the labeled horizontal lines, with uncertainties (systematic and observational) estimated by the error bars. The upper mass limit for brown dwarfs (*label*) is about 0.082 $M_\odot$ in these calculations.

a dynamical timescale—much shorter than the evolutionary timescale that sets the central temperature. The age sets the mass-luminosity relation relevant to all the cluster members (assuming they are coeval). In this section we shall again assume the canonical age for the Pleiades of 75 Myr.

There are still some concerns about the predicted appearance of the lithium line in objects as cool as these. One problem is the treatment of collisional damping in the wings of the line, as examined by P95. It will be resolved soon by high-resolution spectra of the coolest stars. The two main concerns are the extent to which lithium is bound up in molecules (especially LiCl) and the effect of NLTE ionization on neutral lithium, particularly in the presence of a chromosphere. Allard & Hauschildt (1995) and P95 have both done detailed examinations of the first question, using temperature structures for these spectral types derived from detailed ab initio calculations. They conclude that while there is substantial molecular formation, it is not sufficient to desaturate the lithium resonance line, which remains quite strong in such cool stars.

NLTE effects can further reduce the line, because it forms in the highly cooled (due to molecules) upper photosphere, where radiation from deeper layers can cause ionization and thus reduce the population of the neutral ground state. P95 find a reduction of about 0.1 dex. The lower curve in Figure 2*a* represents the latest and most sophisticated calculation (Hauschildt et al. 1995) and confirms that the line remains quite strong. The presence of a chromosphere, which both HHJ 3 and PPL 15 possess (given their Hα lines), causes further ionization. P95 have considered this question and conclude that the lithium resonance line remains strong after including all the above effects, although a hot, deep chromosphere can substantially weaken it. It will be useful to observe T Tauri stars cooler than 3000 K to confirm that atmospheric effects are not rendering the lithium test problematic.

The calculations of P95 imply that the observed lithium line is not weakened appreciably until the lithium abundance is reduced by nearly 2 orders of magnitude. The timescale over which the final depletion takes place (during which the lithium abundance drops from 1% to well below 0.1%) is less than 5 Myr according to NRC (note the steepness of the curves in their Fig. 3). This means that the luminosity and age of the lithium depletion boundary is fairly well defined and we need not quibble about just how much lithium must be burned before the line desaturates and then disappears. Shown in Figure 5 are the loci of stars in luminosity and age that experience depletion down to 1% of the primordial value and then full depletion (the "lithium depletion boundary"). Our conclusions do not depend very much on which of these boundaries we choose.

The application of the lithium test is then quite straightforward. Having chosen an age and measured a luminosity for each star, the observation of lithium determines whether it lies to the left or the right of the lithium depletion boundary. It is clear in Figure 5 that at 75 Myr, any star with a mass less than about 0.10 $M_\odot$ should show a strong lithium line. Certainly one would expect stars as faint as HHJ 3 and PPL 15 to do so. The observations tell us that PPL 15 passes this test (though perhaps not at the fully undepleted abundance we would expect), and HHJ 3 fails it quite decisively. The same failure arises with the depletion observation in HHJ 10 by Martín et al. (1994).

Since this test does not depend on color or temperature information, one must indict the lithium depletion rates, the dependence of luminosity on mass, or the chosen age. There would have to be serious errors in supposedly well-understood physics in order to resolve the glaring inconsistency posed by the observed lithium depletion in HHJ 3 via changes in the models. Among the possibilities for changing the age of the lithium depletion boundary are further refinements in the lithium-burning rates. These might lie in the nuclear cross sections (with implications for big bang cosmology as well), or they might arise from the fact that the lithium burns while only a high-energy tail of the populations makes it possible (because of the rapid mixing). An inhomogeneous medium could influence how this occurs. This is speculative, and it would be hard to achieve the full effect required. We therefore take a closer look at age determinations for the Pleiades.

3.3. *The Age of the Pleiades*

Let us now consider the luminosities of the objects to be known and adopt the models of NRC but leave the age to be determined. Consider the brightest very low mass star that retains lithium in a cluster. The point at which its observed luminosity crosses the lithium depletion boundary yields one good estimate for the age of the cluster. D'Antona & Mazzitelli (1994) also mention this possibility for dating clusters. From Figure 5 it is clear that we obtain rather tight constraints on both the mass and age of HHJ 3 and PPL 15. The mass is less sensitive than the age to luminosity errors, since the lithium boundary is almost parallel to the luminosity-age tracks in this mass-age range. Our adopted luminosities are given by the dashed lines in Figure 5. The observed lithium depletion in HHJ 3 forces its age to be above 110 Myr. The detection of lithium in PPL 15 implies that it is younger than about 125 Myr. Both observations, however, are consistent with an age of 115–120 Myr. *Unless the models are seriously in error, there is strong evidence for a Pleiades age well above 75 Myr.* Indeed, the lithium test provides a "nuclear" age that may be as powerful a diagnostic as the conventional nuclear age from the upper main-sequence turnoff (with perhaps less uncertain physics behind it, as discussed below).

The resulting upper limit on the mass of PPL 15 implied by the older age is between 0.076 and 0.079 $M_\odot$ (depending on its assumed luminosity). This puts it just below the upper mass limit for brown dwarfs as found by NRC of 0.082 $M_\odot$. The Burrows et al. (1993) estimate of the brown dwarf mass limit is lower—about 0.076 $M_\odot$. If one likes the term, PPL 15 is definitely a "transitional object," in which some hydrogen burning is taking place. This fusion will eventually cease again but not before having destroyed all lithium. The mass of HHJ 3 found using the older age becomes around 0.085 $M_\odot$, which makes it clearly not a brown dwarf. The slope of the lithium depletion boundary near the luminosities of these stars yields a difference of up to 15 Myr in the ages at which they lose lithium, given their different bolometric luminosities. This is why we can find them on opposite sides of the lithium boundary now.

The models do contain uncertainties, primarily because of the treatment of surface opacities. The gray opacities used by NRC were from Alexander (1986) and are now considered to be low by about a factor of 2 in the relevant temperature range (Alexander & Ferguson 1994). Higher surface opacities lower the central temperatures, so that a star will reach equilibrium at a lower luminosity for a given mass and age. It will therefore take the star longer to deplete its lithium. Nelson et al. (1995) have repeated their calculations with the new opacities, yielding no substantial changes relevant to this paper. They also confirm that very low mass stars are very well mixed on very short timescales (10^3 yr). The remaining improvement desirable in their treatment is use of a modern nongray atmosphere.

The difficulty in predicting how our analysis will change with improved models is that we must infer the mass and the age simultaneously from the luminosity at which lithium is last seen to be depleted. According to Baraffe et al. (1995), the latest nongray models yield a higher mass for a star of a given color and luminosity than calculations such as those of NRC. As argued above, the lithium boundary slides to the right with increasing opacities; a star of a given luminosity depletes its lithium later. One might guess that the next round of models will yield both a larger mass and age for PPL 15 than we find here. There is another effect of better treatment of the atmospheric boundary conditions—the upper mass limit for brown dwarfs becomes smaller because it is easier for stars to generate an equilibrium luminosity. All these effects make it possible that a determination of the mass of PPL 15 from new models will place it above a self-consistent brown dwarf mass limit.

Since Herbig (1962), there have been indications from the position of the low-mass stars in the H-R diagram that the ages of young clusters could be older than suggested by classical upper main-sequence turnoff ages. Iben & Talbot (1966) reinforced this conclusion. Stauffer (1984) obtained new photometry for the Pleiades and found that when the G and early-K stars are made to lie on the ZAMS (they were originally below it in Stauffer's paper), the late-K and M stars lay on pre–main-sequence locations, indicating an age of a little over 100 Myr using tracks from Vandenberg, Hartwick, & Dawson (1983). Alternate models considered by Stauffer yielded even older age estimates. Without the adjustment of the moderate-mass stars to the ZAMS, the implied age climbs to 200–300 Myr. He concluded that the low-mass stars by themselves indicate an age for the cluster of something over 100 Myr. The nuclear age of 75 Myr has continued to be used by Stauffer and others despite these indications of older age. It may seem that the lower mass tracks are less reliable than those for the upper main sequence because the former have complicated atmospheric opacities. In fact there are also substantial uncertainties in the interior physics for the higher mass stars.

There have been suggestions for some time that the B stars (the visible "sisters" in the cluster) are older than canonical estimates (D'Antona & Mazzitelli 1985; Mazzei & Pigatto 1989). The age uncertainty stems from the well-known problem with treating convection at the core boundary in hot stars. Not only is the amount of overshoot from the convective core unknown, but the stability of the region above it depends sensitively on the mixing of core material into it. When core material is mixed up, hydrogen can then be mixed down into the core, extending the main-sequence lifetime and resulting in lower inferred masses for a given turnoff luminosity. This in turn leads to a larger age estimate from a given turnoff compared with ages from standard evolution calculations. Mazzei & Pigatti (1989) point out that there are also a number of observational uncertainties. If the calculations of Bertelli et al. (1994) are correct, the implication is that a number of young clusters are substantially (up to 50%) older than their canonical ages. Meynet, Mermilliod, & Maeder (1993) have reexamined the ages of a number of clusters in light of what is now thought to be a modest amount of convective overshoot. Their derived age for the Pleiades is 100 Myr. Although they do not provide quantitative uncertainties, it seems clear that the age we suggest (115 Myr) is quite compatible with the modern estimate for the nuclear age of the Pleiades.

"Lithium dating" also offers the possibility that we can turn the problem around. If we use ages determined from the lithium boundary, it becomes possible to find which models of the upper main-sequence turnoff yield a consistent age. Consistency could be used to calibrate the appropriate amount of mixing outside the convective core in the high mass stars. Different masses could be calibrated with clusters of different ages. This would join the many tests for convective overshoot based on the upper main sequence, which indicate at best a modest amount of mixing according to Stothers (1991). Given an older age scale, it becomes more likely that both the high- and low-mass stars are of similar age, and evidence for an age spread in the Pleiades is weakened (Mazzei & Pigatto 1989). It will be essential to check the location of the lithium boundary in other young clusters, comparing the ages found that way with estimates based on various models for the upper main-sequence turnoff.

It is well to keep in mind that our age and mass estimates include several uncertainties. The predicted luminosity-age relations for the brown dwarfs are vulnerable to errors in the interior equation of state and both interior and atmospheric opacities. The theory of lithium depletion is also subject to these errors and is fairly untested at low mass. On the other hand, the fully convective nature of the stars makes the assumption of full mixing quite reasonable. In estimating the luminosity, the bolometric correction contains an error, as does the photometry. Another uncertainty is the distance to the cluster. Our current measurement of the line strength is not very precise. The conversion of lithium line strength to a lithium abundance is also somewhat uncertain, although a determination of qualitative depletion is less sensitive to this while the line is saturated. It is hard to judge the cumulative amount and direction of these (mostly systematic) errors.

4. CONCLUSION

We have now observed two of the faintest Pleiades stars and applied the lithium test for brown dwarf status to them. The targets, HHJ 3 and PPL 15, are not very different in luminosity. In Paper I, we showed that HHJ 3 has depleted its lithium. Here we find that PPL 15 has not depleted its lithium to the point of undetectability, although it may have partially depleted it. At the canonical age for the Pleiades of 75 Myr, current theory implies both objects have masses below 0.07 $M_{\odot}$. Theory also predicts that neither object should have depleted its lithium. Only PPL 15 is consistent with this prediction. We propose that the best explanation for the lithium difference is that the age of the Pleiades is substantially larger, in the neighborhood of 115 Myr. In that case HHJ 3 has a mass of 0.085 $M_{\odot}$, over the mass limit for brown dwarfs. PPL 15 then has a mass of 0.078 $M_{\odot}$ and is probably a brown dwarf (albeit one very close to the boundary between stars and brown dwarfs). In any case PPL 15 is the first example of a "lithium dwarf:" an extremely low mass object in which the lithium line appears while being absent in slightly more luminous cluster members (which also possess deep convection zones). Because we have now found such an object, the color and K magnitude of such objects are set for the Pleiades, and photometric searches for them can proceed with more confidence.

The lithium test is shown to be a good age indicator as well as a brown dwarf diagnostic. The age of the Pleiades has been hinted to be greater than 75 Myr by the lower main-sequence turn-on luminosities. In more direct conflict with the canonical age are stellar evolution models in which there is mixing in the region just above the convective cores of massive stars. These also suggest an older age, derived from the upper main-sequence turnoff. Our result can be taken as support for such models, which further suggests that the ages of young clusters may generally be up to 50% above what the standard models (without mixing) suggest. The physics behind lithium dating is actually better understood than that needed to treat mixing above convective cores. We note that the ages of clusters up to a few gigayears will be affected (by decreasing amounts as the age increases); older than that, the turnoff stars do not have convective cores and so are not subject to the same uncertainties. A new age scale has implications for all the stellar properties whose evolution has been inferred from young clusters. For example, the angular momentum and magnetic activity histories of convective stars will be modified. White dwarf cooling studies may provide an independent check of cluster ages.

Future efforts should include finding other Pleiades stars near the lithium boundary to confirm its location in bolometric luminosity for this cluster. We should confirm that Pleiades stars fainter than PPL 15 all show lithium; objects less than $\frac{2}{3}$ its luminosity should be brown dwarfs no matter what reasonable age is taken for the cluster. We should also locate the lithium boundary in other clusters and see whether their implied ages are also larger than the canonical values from the upper main-sequence turnoffs. The expected luminosity of all cluster brown dwarfs becomes lower as the ages become higher. With the discovery of the first lithium dwarf, a new page in the study of very low mass stars and substellar objects has been turned.

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