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LITHIUM IN VERY LOW-MASS STARS IN THE PLEIADES

B. R. OPPENHEIMER
Palomar Observatory, 105-24, California Institute of Technology, Pasadena, California 91125
Electronic mail: bro@astro.caltech.edu

G. BASRI
Department of Astronomy, University of California, Berkeley, California 94720

T. NAKAJIMA AND S. R. KULKARNI
Palomar Observatory, 105-24, California Institute of Technology, Pasadena, California 91125

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ABSTRACT

High-resolution, Keck Telescope echelle observations from 630 nm to 850 nm of seven Pleiads with spectral types from M5 to M6.5 reveal rather rapid rotation, with an average $v\sin i{\sim}52$ km s^{-1}, and chromospheric activity in Hα emission. The activity in these stars is not any stronger than that of other Pleiades low-mass stars, despite the expected high contrast of Hα with their cool photospheres and their rapid rotation. This shows that the "levelling off" of Hα equivalent widths previously noted in low-mass stars in young clusters is not related to the conventional rotation-activity connection. None of the stars previously categorized as brown dwarf candidates have lithium signatures in their spectra. They are, therefore, very low-mass stars and not brown dwarfs. However, two stars, HHJ 339 and HHJ 430, 1 and 2 magnitudes above the Pleiades zero-age main sequence, do show absorption due to Li I at 670.8 nm and in the subordinate feature at 812.6 nm. These two stars are also rotating very rapidly. These facts strongly suggest that these stars are rather young. Their proper motions and radial velocities agree with those measured for the Pleiades as a whole. We discuss various explanations for these stars, none of which is completely satisfactory. In one scenario they represent very late star formation in the Pleiades cluster (implying a huge range in the ages of Pleiads). This seems unpalatable given the lack of matter dense enough to form stars in the Pleiades at present. Another possibility is that these stars formed in a nearby, more recent star formation site and drifted into the Pleiades. Although the cluster recently passed through a clump of young Taurus stars, we do not see how it could "accrete" two of them. In our most feasible explanation, we posit that a cloud which was a member of the "Pleiades Supercluster" recently formed stars, which are now scattered between us and the Pleiades. HHJ 339 and HHJ 430 could be members of this group whose motion has now brought them near the older open star cluster. © *1997 American Astronomical Society.* [S0004-6256(97)03701-1]

1. INTRODUCTION

The Pleiades star cluster in Taurus is relatively nearby (~125 pc) (Stauffer *et al.* 1994) and seems to be rather young (~100 Myr) (Patenaude 1978; Stauffer *et al.* 1989; Basri *et al.* 1996). Because of these characteristics, it is an ideal hunting ground for brown dwarfs, which are thought to be brighter and thus easier to detect when young. Also because of its youth and proximity, it provides an excellent opportunity to study faint, very low-mass stars. As a result some investigators have identified faint point sources in the Pleiades as very low-mass stars and brown dwarf candidates (Hambly *et al.* 1993, hereafter HHJ). These stars are usually identified as Pleiades members by examination of their space motion, and their proper placement in an HR diagram (implying roughly the right distance). The stars in the Pleiades have fairly narrow distributions of proper motions and radial velocities. Therefore, stars in the direction of the Pleiades with space motions in agreement with these distributions are believed to be cluster members. This membership assertion is bolstered if the stars are chromospherically active (indicating youth), but the assertion remains statistical in nature.

Most researchers agree that the Pleiades cluster is between 70 and 130 Myr old. Though various papers have suggested that the stars might actually have a wide distribution of ages, (Herbig 1962; Stauffer 1982; 1984; HHJ), most of these claims have been adequately explained with inaccurate photometry and luminosity inflation due to unresolved companions of some of the stars (Stauffer *et al.* 1995). Some of the remaining spread of the main sequence could be due to cluster depth effects. At present, the general consensus is that the stars in the Pleiades are approximately coeval. The range of ages above primarily reflects controversy about the overall age of the cluster and not an age spread (Basri *et al.* 1996).

Studies (Steele *et al.* 1995; Steele & Jameson 1995; Stauffer *et al.* 1995; Basri *et al.* 1996; Basri & Marcy 1995) of some of the faintest low-mass Pleiades members, identified by HHJ as having the proper motion of the cluster, have

TABLE 1. Observed stars and derived parameters.

Star	Sp. Type	t_{int} (s)	N_{exp}	Hα W_λ	Ca I W_λ	K I W_λ	Rb I W_λ	Ti I W_λ	Li I W_λ[a]	Li I W_λ[b]	$v\sin i$ (km s^{-1})	v_{rad} (km s^{-1})
HHJ 6	M6.5	11300	3	-7.2	⋯	4.0	0.5	0.6	⋯	⋯	50±10	4.4
HHJ 10	M6	3000	1	-6.3	⋯	4.2	⋯	⋯	⋯	⋯	52±5	9.3
HHJ 11	M5.5	5000	2	-6.9	⋯	3.6	0.5[e]	0.4	⋯	⋯	45±5	5.1
HHJ 16	M5.5	3000	1	-8.9	⋯	3.6	0.7	0.6	⋯	⋯	45±5	6.3
HHJ 18	M5.5	3000	1	-6.0	⋯	2.3	0.6[e]	0.7	⋯	⋯	60±10	7.3
HHJ 19	M5.5	3000	1	-5.4	⋯	3.5	0.4[e]	0.7	⋯	⋯	55±5	9.3
HHJ 36	M5	3000	1	-6.9	0.3	2.5	0.4	0.5	⋯	⋯	37±5	5.2[c]
HHJ 339	M5	600	1	-10.4	0.4	2.1	⋯[d]	0.4	0.9	⋯[d]	58±5	9.4
HHJ 430	M5	1000	1	-10.0	0.3	2.1	0.4[e]	0.3	0.7	0.2	65±5	9.1

Notes to TABLE 1

[a] Li I 670.78 nm
[b] Li I 812.64 nm
[c] This measurement is from Stauffer *et al.* (1995).
[d] Not within the detector format
[e] Possible chromospheric emission core

All equivalent widths are given in units of Å and have measurement errors of about 10%. The radial velocities are in the heliocentric reference frame and all have an error of ±5 km s^{-1}. The Ca I line is at 657.280 nm. The K I line is at 769.898 nm. The Rb I line is at 794.760 nm. The Ti I line is at 842.650 nm. HHJ 339 also has a Ti I line at 843.498 nm with an equivalent width of 1.3Å. The spectral types come from Steele & Jameson (1995), except for HHJ 10, HHJ 11, and HHJ 339, which are our own and are based on careful comparison of these stars's spectra with those of the others in the sample.

revealed that many of these dim objects are, in fact, low-mass stars and not brown dwarfs. The so-called "lithium test" (Magazzù *et al.* 1991; Rebolo *et al.* 1992) has been the primary method by which these brown dwarf candidates have been reclassified as low-mass stars. The essence of the lithium test is to search for absorption due to lithium in the spectrum of the candidate at issue. The presence of lithium in dim, very low-mass objects is an indicator either of extreme youth (as in the case of weak-line T Tauri stars (wTTS)) or of a mass below the minimum mass required for sustained hydrogen fusion in the object's core, or both. A nuclear reaction destroys the primordial lithium abundance in the least massive stars in ~100 Myr, and much faster in more massive stars. After several years of searching, Basri *et al.* (1996) finally found one faint object in the Pleiades with detectable amounts of lithium. This object, PPL 15, was identified by Stauffer *et al.* (1994). It is most likely a brown dwarf just below the mass necessary for sustained hydrogen fusion. Subsequently lithium has been confirmed in two Pleiades stars, Teide 1 and Calar 3, which are fainter than PPL 15 (Rebolo *et al.* 1996). These are certainly brown dwarfs.

Measurements of the chromospheric activity and the rotation velocities of low-mass Pleiades and Hyades stars (Stauffer *et al.* 1994; Stauffer *et al.* 1995; Basri & Marcy 1995) have shown that the empirical age-activity and age-rotation relations (Giampapa & Liebert 1986; Soderblom *et al.* 1993b) may not hold for stars later than M5. However, the paucity of observations has made it difficult to make definitive statements concerning these matters. These studies and others (Liebert 1995) conclude that the low-mass stars maintain rapid rotation for longer times than their more massive counterparts. The immediate explanation for this has been that these very low-mass stars have diminished magnetic braking (Barnes & Sofia 1996). It is not yet clear whether this is due to a reduction in magnetic flux, or a reconfiguration of the flux into smaller structures that are less efficient at braking. These issues are discussed in more detail by Basri & Marcy (1995).

2. DATA ACQUISITION AND REDUCTION

We observed the stars listed in Table 1 on the nights of 1994 October 12, 13 and 15 at the W. M. Keck 10 m Telescope with the HIRES instrument (Vogt 1992). The only exception is that HHJ 339 was observed on the night of 1994 November 23. The total integration time for each star is listed in Table 1, along with the number of exposures represented by the integration time. We used the HIRES echelle spectrometer to capture fifteen orders of spectral data covering the range 630.0 to 850.0 nm. Gaps of approximately 4.5 to 5 nm, where no data were taken because of the limited size of the CCD chip, separate the orders. The Tektronix CCD chip measures 2048 pixels on a side. For every observation, we used a slit with a sky-projected width of $0.861''$ and a height of $14''$. This results in a resolution of $\lambda/\Delta\lambda=45000$, or a $\Delta\lambda=0.014$ nm at 630.0 nm and a $\Delta\lambda=0.019$ nm at 850.0 nm. This resolution element corresponds to approximately 3 pixels. On each night the seeing was about $1''$ and fairly stable, and the weather conditions were clear.

Data reduction involved the following steps, using software kindly supplied by Jim McCarthy and Austin Tomaney. First, we subtracted bias frames from the spectral images. The bias frames exhibit two dimensional structure, so we felt that simple subtraction of a median value of the bias frame would be insufficient to remove the CCD bias. The spectral images were then divided by a "flat field" image which was created with a 3 second exposure using a quartz lamp illuminating the telescope's dome. From these "flattened" and bias-subtracted images, we then removed cosmic rays using a standard routine that searches for sharp spikes in the image and interpolates over these spikes. The automatic routine did not always remove all of the cosmic rays apparent to the eye, so in a few frames some additional interpolation was done manually. The curved spectral orders were traced out on exposures of the brighter stars. These tracings were assumed correct for the fainter stars, which would not have been

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traced well by the routine due to the lack of signal. The tracing routine fits a gaussian profile to the star light in the spatial dimension of each order along a third-order polynomial in the dispersion direction. This accounts for the curvature of the orders.

Using this tracing, we then took a representative order for each star whose spectrum was to be extracted. In this order we summed about 200 columns. This allowed us to determine where in the order the actual signal from the star was and where the sky signal was. We assigned two ranges of pixels (about 15 pixels total) on either side of the star light in the representative order to be treated as sky light. Using these ranges, we were able to determine the contribution due to the sky background and to remove it. In this process, the signal in these two ''sky apertures'' was summed in the spatial direction. This sum was weighted according to the intensity of the signal. From this weighted average of all the sums across the slit, the sky profile over the entire slit was determined with a third-order polynomial fit. Further, the night sky continuum was calculated by evaluating the median in the dispersion direction over 11 pixel increments. This median was then used to scale the sky profile previously determined. In the case where a night sky line was present (when the weighted sum across the sky regions of the slit was 5σ above the sky continuum), the profile was scaled according to the weighted sum across the slit. In this way a two dimensional sky was calculated, and subtracted from, each order in the frame.

After the sky subtraction, a profile in the spatial direction was fitted to the remaining star signal in each order. The profile was a third-, fourth-, or fifth-order polynomial in the spatial direction for each column along each order fitted to a sum of between five and forty columns of data, depending on the strength of the signal. For weaker signals more columns of data were summed and lower order polynomials were fitted. For the brighter stars, such as HHJ 430, though, only five columns were needed to determine a profile accurately. Finally, using this profile, the data in each column of each order were summed in the spatial direction and weighted according to the profile. This provides a so-called ''optimal extraction.''

There are several advantages to using such a complicated data extraction scheme. First, the tracing of orders takes into account the curvature of the orders. Other data extraction methods involve straightening the orders by resampling the data. This can introduce resampling noise if not done very carefully, which can degrade the signal-to-noise ratio of the final spectrum, significantly in the case of very faint stars. Second, the weighting of the sum in the spatial direction by a profile gives more weight to the brighter pixels. This also yields an improvement in signal-to-noise ratios compared with the simpler method of a straight, unweighted sum.

3. OBSERVATIONS

Measurements of each star's heliocentric radial velocity, as listed in Table 1, were made using the standard cross correlation technique using several regions of the spectra, including the area around the Hα emission feature and the order centered on 712.0 nm, in which lie some strong TiO absorption bands. These radial velocities are all relative to HHJ 36, which Stauffer *et al.* (1995) determined to be 5.2 km s^{-1} with an accuracy of ± 5 km s^{-1}. Based on the various measurements of each star's radial velocity, the error in the radial velocities is ± 5 km s^{-1}.

Steele & Jameson (1995) reported that HHJ 18 has excess opacity in the 800-900 nm region of its spectrum, unlike that of a normal M5.5 star. In the 50 nm of our spectrum in the blue half of this region, we cannot confirm this excess opacity. In fact, the spectrum appears almost identical to that of HHJ 16 (another M5.5 star) in this region.

3.1 Rotation and Chromospheric Activity

Measurements of each star's Hα equivalent width are also included in Table 1. There is no obvious correlation of these widths with any of the other derived parameters in the table.

We have measured the rotational velocities of the stars in our sample using methods similar to those expounded in Basri & Marcy (1995). The star we use as a slowly rotating template is LHS 292. Because the stars here are such rapid rotators, we found that several of the spectral regions used by Basri & Marcy (1995) were not as useful. We therefore concentrated on the CaH bands between 694 nm and 700 nm. Other orders were used primarily as confirmations of the values found there. Again we compared cross correlation functions against the slow rotator with the observations and with model spectra at different rotations. Very low signal-to noise ratios compromised our accuracy in a couple of cases. Our measurements of $v\sin\ i$ are listed in Table 1, along with their accuracies. All of the stars are rotating at least as rapidly as 35 km s^{-1}, and they have an average rotational velocity of 52 km s^{-1}.

It is perhaps not surprising that all these stars are such rapid rotators. They are the low-mass extension of the rapidly rotating K dwarfs in the Pleiades (Stauffer & Hartmann 1987; Soderblom *et al.* 1993a). These M dwarfs are rapidly rotating in part because of ''spin up'' as they shrink toward the main sequence, and perhaps because they are fully convective. The ''spin down'' of higher mass stars may be initially confined to their convective envelopes. In contrast, the late M dwarfs must lose angular momentum throughout their structures. On the other hand, one might expect the observational effect of random inclination angles to produce a few apparently slow rotators, which are not present in our sample. It must be the case, therefore, that they are all rotating *very* rapidly. Low-mass stars show little evolution in Hα strengths from the Pleiades age to that of the Hyades (Stauffer *et al.* 1995), so it will be very interesting to pursue the rotational behavior of the very low-mass Hyades stars.

3.2 Atomic Features

The depletion of lithium in a very low-mass star provides an excellent constraint on both its mass and its age. For a given mass, the lithium is predicted to be depleted at a well defined age (D'Antona & Mazzitelli 1994). Conversely, the minimum mass at which lithium is still detectable in a cluster provides an age for the cluster. Finally, when the cluster age

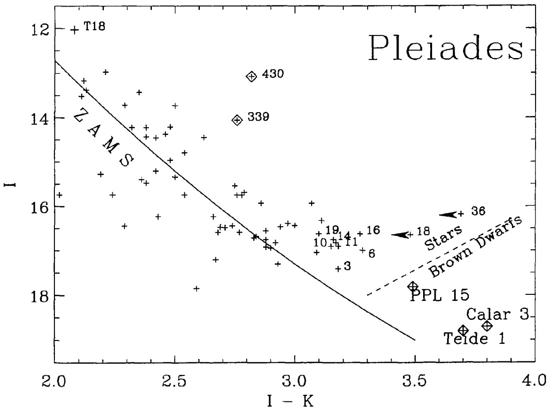


FIG. 1. Color-magnitude diagram of the Pleiades showing all the stars (labelled with their HHJ numbers) observed in various searches for lithium and the recently discovered lithium brown dwarfs. Stars with detected lithium have diamonds around them.

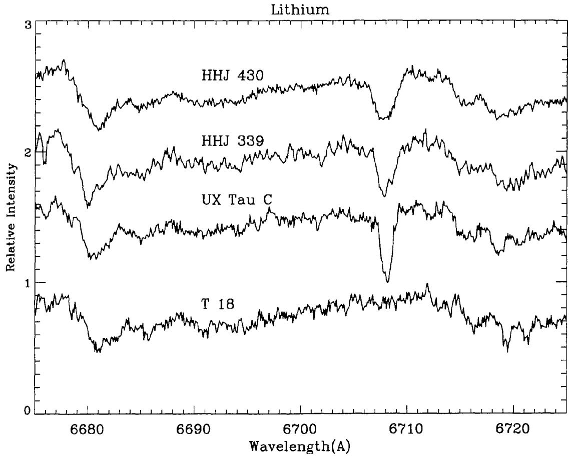


FIG. 2. The 670.8 nm Lithium resonance line in HHJ 339, HHJ 430, and UX Tau C, a well studied T Tauri star. For comparison, the same region of T 18's spectrum is also shown courtesy of J. R. Stauffer.

is sufficiently large, the presence of lithium at the bottom of the main sequence signals detection of brown dwarfs. Basri *et al.* (1996) have already discussed the age of the Pleiades as found by the lithium test. Here, we have observed stars brighter than those considered by them. Such stars should all be depleted of lithium unless there were a substantial age spread in the cluster.

None of the stars we observed at the bottom of the main sequence shows lithium. This is consistent with the age suggested by Basri *et al.* (1996) and a minimal age spread. The luminosities of all our targets, along with the age from Basri *et al.* (1996), demand that they are very low-mass stars and not brown dwarfs. For ages less than the Basri *et al.* (1996) value of ~ 120 Myr, the lack of lithium in these stars places an even stronger contraint that they are stars and not brown dwarfs. Figure 1 is a color-magnitude diagram for the Pleiades very low-mass stars, with all the stars that have been tested for lithium labelled. Based on TiO band strengths estimated from moderate resolution spectra, Stauffer *et al.* (1995) argue that the true colors of HHJ 18 and HHJ 36 are considerably bluer than the published values. This is indicated by the arrows in Fig. 1. Stars in which lithium has been found are indicated with a diamond. The two stars which are not on the Pleiades main sequence do show lithium and are discussed in Sec. 4.

We have examined the behavior of a few atomic features as listed in Table 1. Because of the rapid rotation of the stars combined with a large number of blended molecular lines, we do not feel the line strengths can be measured with accuracies better than about 10%. While HHJ 339 and 430 clearly have weaker lines than the others (and are the hottest), we do not see diagnostics at high resolution which clearly distinguish between M5 and M6. The best ordered behavior is found for K I: cooler stars using low resolution classification show a stronger line. We also checked the width of the K I features in HHJ 339 and 430, to see whether they are narrower than in other stars of the same spectral type that are closer to the main sequence (such as HHJ 36). There is a hint that this is so, but we are reluctant to make a strong statement because small differences in temperature can cause comparable effects. Basri *et al.* (1996) suggested that Rb I might serve a similar function, but our spectra are complicated by the possible presence of chromospheric emission cores in the Rb I line in some stars.

4. TWO ENIGMATIC DETECTIONS OF LITHIUM

One of the most intriguing results of this investigation emerges from the observations of two brighter members of the HHJ sample, HHJ 339, and HHJ 430. These stars appear in pre-main sequence locations on the Pleiades HR diagram (see Fig. 1), which is curious in itself and is why we observed them. It could have meant that they are simply foreground stars with the same proper motion as the Pleiades. They have Hα strengths at the upper end of the equivalent widths seen for very low-mass Pleiads; the implied surface fluxes are even higher since the underlying continuum is brighter.

The unexpected result in our spectra, however, is the strong presence of lithium in both HHJ 339 and HHJ 430 (Fig. 2). Not only is the resonance line at 670.8 nm quite visible, but the subordinate line at 812.6 nm is also easily seen in HHJ 430. (In HHJ 339, the subordinate line sits in one of the dataless gaps between the spectral orders.) In both cases, the lithium strengths are similar to those found in wTTS. None of the published X-ray studies of the Pleiades have HHJ 430 in the field of view. However, HHJ 339 is in the recent *ROSAT* pointed observation of the Pleiades undertaken by Micela *et al.* (1996). They are only able to assign an upper limit to its X-ray luminosity of $\log L_X < 29.30$ erg s^{-1} beacuse it lies $48'.1$ away from the center of the field. This upper limit is not inconsistent with the typical X-ray luminosity of wTTS, which is $\log L_X \approx 28-30$ erg s^{-1}. In conclusion, these stars have essentially all the usual characteristics of wTTS.

4.1 Are HHJ 339 and HHJ 430 Pleiads?

Although their proper motions are near the median for cluster members according to HHJ, it is concievable that they could simply be foreground wTTS with the same proper motion. However, they could not be very much closer since they already sit in the proper place in the HR diagram to be on the pre-main sequence at the distance of the Pleiades. We argue below (Sec. *4.2*) that these stars must be in their pre-main sequence phase in order to have retained lithium.

As an additional check, we carefully measured their radial velocities, since the Pleiades is not very different in radial velocity from field stars in that direction. Velocities found by us for our whole sample have a mean of 7.2 km s^{-1} and a standard deviation of 2.1 km s^{-1}. This is just as expected and in agreement with Basri *et al.* (1996) and Stauffer *et al.* (1995). The stars HHJ 339 and HHJ 430 lie about one sigma above the mean velocity (with HHJ 11 similarly high).

Thus, the three traditional membership criteria—proper motion, radial velocity, and Hα strength—provide reasonable evidence that they are cluster members. As already mentioned, their luminosities and temperatures do not place them on the Pleiades main sequence, but are consistent with a pre-main sequence location. It is unlikely that binarity could cause them to occur as far from the main sequence as they do (in the absence of strange spectroscopic anomalies). Only a parallax measurement could make the membership assertion more certain.

We note that these two stars were first posited to be members of the Pleiades because they were seen to flare by Haro *et al.* (1982) who called them HCG 332 and HCG 509, instead of HHJ 339 and HHJ 430.

4.2 How old are HHJ 339 and HHJ 430?

We have taken three independent approaches to placing constraints on their mass and age. The first and third methods give upper limits to the masses and ages, while the second attempts to estimate these physical parameters directly.

4.2.1 Luminosity and lithium depletion

Our first method is to estimate the luminosity of the stars assuming they are in the cluster, and then to find the lowest mass and largest age at which lithium could still be undepleted at that luminosity. The bolometric luminosity can be estimated from colors, using bolometric corrections. We adopt a distance modulus for the Pleiades of 5.60. Stauffer *et al.* (1994) give a formula for estimating luminosity from the I magnitude. Applying this to HHJ 339 and HHJ 430 yields luminosities, $\log(L/L_\odot)$, of -1.69 and -1.36 respectively. Alternatively, one can use the K magnitude and bolometric correction from Tinney *et al.* (1995). For $I-K$ colors of 2.88 and 2.94, the bolometric corrections are about $BC_K \sim 2.95$. This yields luminosities of -1.56 and -1.14, respectively. This offset in the methods was also seen by Basri *et al.* (1996). Taking the geometric mean of them, we adopt $\log(L/L_\odot)$ of -1.63 and -1.25 for HHJ 339 and HHJ 430, respectively. We use the calculations of D'Antona & Mazzitelli (1994) to find at what mass and age lithium is beginning its depletion. Adopting the set of models that seems to match observed lithium depletions best (their Table 6), we find that HHJ 339 is likely to have a mass between 0.15–0.20 $M_\odot$ with an age between 10 and 30 Myr. For HHJ 430 the age is at most 20 to 30 Myr, with a mass of between 0.30–0.35 $M_\odot$. These estimates are upper limits on the ages and masses; so the stars could also be less massive and younger. The third method, described below, takes this analysis further.

For completeness, we consider whether these two stars could be foreground stars on the main sequence. In that case, they would have to be about one and two magnitudes closer which would lower their intrinsic luminosities so that, for both stars, $\log(L/L_\odot) \approx -2.0$. Referring once again to the tables in D'Antona & Mazzitelli (1994), this would imply, because of the strong presence of lithium, that HHJ 339 and HHJ 430 are about 0.1 $M_\odot$ and must be younger than 25 Myr. Such young stars, however, must sit above the main sequence, contrary to the original supposition. This provides an additional, though less stringent, argument for cluster membership, since they are in fact in the pre-main sequence if at the distance of the cluster.

4.2.2 Theoretical isochrones

The second method to determine the ages and masses of these stars is to try to place the stars directly onto evolutionary tracks and see what mass and age is implied. These have to be compatible with the observation of lithium. Here, the difficulty is in assigning an effective temperature based on colors (made more difficult by the stars's not being on the main sequence). A lot of work has recently gone into this problem.

For example, Kirkpatrick *et al.* (1993) fit synthetic spectra of stellar atmospheres with observed spectra to determine a temperature scale for M dwarfs. Using this scale, we assign a temperature of 3250 ± 125 K to HHJ 430 and 339. Refering once again to the tables of D'Antona & Mazzitelli (1994), and the bolometric luminosities found above, we find that HHJ 339 can be between 0.05 and 0.15 $M_\odot$ with corresponding ages between two and ten million years. HHJ 430 can fall within the same mass range, but the age is constrained to be within 0.1 and 3 Myr.

These estimates are consistent with the upper limits derived above. [In addition, it was this sort of work which led Steele *et al.* (1993) to conclude that there was an age spread in the Pleiades, but the corrections in Steele & Jameson (1995) reversed those conclusions. No discussion of either HHJ 339 or HHJ 430 appears in either paper.]

These models assume that the evolving stars have solar metallicity, a reasonable assumption for the Pleiades.

4.2.3 Lithium line curves of growth

Recently, a number of researchers have investigated the curves of growth of several lithium lines in very low-mass, pre-main sequence stars (Pavlenko *et al.* 1995 and references therein). This work greatly facilitates the assignment of abundances to line widths observed in stars. For the two stars at issue, the model atmosphere calculations of Pavlenko *et al.* (1995) give lithium abundances of $\log N(\mathrm{Li}) = 3.0 \pm 0.2$ for HHJ 339 and $\log N(\mathrm{Li}) = 2.6 \pm 0.3$ for HHJ

430. (Here, log N(H) is 12, and the cosmic abundance of lithium is assumed to be $\log N(\mathrm{Li}) = 3.2$.) These estimates assume that the stars have effective temperatures of between 3000 and 3500 K and the error estimates arise from allowing that the lithium can be in LTE or NLTE and that the stars may have chromospheres strong enough to affect the line widths. The theoretical equivalent widths are relative to a "true" continuum, while ours are observational, which likely makes them systematically smaller. Thus, these abundances should be taken as lower limits.

From these derived lithium abundances, one can determine the ages of the stars based on the lithium depletion models used in the first attempt at constraining this parameter above. Using Table 6 of D'Antona & Mazzitelli (1994), and assuming that HHJ 339 and HHJ 430 have masses of between 0.1 and 0.3 $M_\odot$, our abundances, which are clearly not far below the assumed cosmic abundances, result in ages of 20 ± 10 Myr for both HHJ 339 and HHJ 430. Because lithium depletion happens rapidly, these ages are upper limits.

The conclusion of all three arguments is that these two stars are no older than 30 Myr, but could be as young as a few Myr.

4.3 How Can Young Stars Exist in a 100 Myr Cluster?

The rather startling implication of this analysis is that these two stars, which appear to satisfy cluster membership criteria, are as much as 100 Myr younger than the stars on the Pleiades main sequence. Taken at face value, this would imply that star formation has been going on for a very long time in this cluster, so that there exists a huge age spread in its members. Interestingly, Steele *et al.* (1993) had reached a similar conclusion (that stars existed from the upper main sequence turnoff age of the cluster down to less than 10 Myr). They did not discuss how star formation could persist in a cluster over such a long period of time. Furthermore, such lengthy periods of star formation are not compatible with the current consensus on the star formation process and the lifetimes of star-forming clouds (Leisawitz *et al.* 1989). Stauffer *et al.* (1995) and Steele & Jameson (1995) agree that this inferred age spread was due in part to an incorrect color conversion. However, the corrected photometry in Steele & Jameson (1995) does not remove the full spread in the MS observed in the Pleiades color-magnitude diagram (see their Fig. 10), nor does it remove the age spread implied by the theoretical isochrones.

Instead, Steele & Jameson (1995) suggest, using quantitative arguments, that most of the spread can be explained by a binary main sequence situated about 0.75 mag above the MS, and of the same age. However, this cannot fully explain the distance from the MS at which a few of the stars lie, including HHJ 36 and HHJ 16 and especially HHJ 18. Steele & Jameson (1995) find an anomalous spectrum for HHJ 18, whereas Stauffer *et al.* (1995) and ourselves do not. These stars lie on younger isochrones, but do not show lithium as HHJ 339 and HHJ 430 do. As mentioned above, we suspect that HHJ 18 and HHJ 36 are really bluer than indicated, and belong with the other main-sequence stars. It may also be the case that HHJ 36 is not a Pleiades star at all: Tinney *et al.* (1995) suggest that it does not have the correct proper motion, although HHJ claim it does. We conclude there is no good evidence for an "intermediate age" population which would be expected if the age spread was large.

It is interesting to note that the stars which Steele & Jameson (1995) identify as single lie predominantly blueward of their 70 Myr isochrone, suggesting an older age. Basri *et al.* (1996) point out that there is a discrepancy in the ages implied by the low-mass stars and by the high-mass stars in the cluster, in the sense that the low-mass stars seem generally older. They provide important, new support for the older, 100 Myr age, and note that convective overshoot in the cores of the massive stars could bring them into agreement with this older age. If one does not accept that argument, then there is still good evidence for a large age spread. In order that there be no evidence for an age spread greater than 10 Myr, one must accept their argument, and revised photometry or distances for the outlying stars mentioned above must bring them closer to the main sequence.

As another, secondary argument against an age spread in the Pleiades, Stauffer *et al.* (1995) plot Hα equivalent widths versus an ad hoc age indicator, the number of magnitudes a given star sits above the main sequence. They argue that because the stars with the youngest ages do not have the largest Hα equivalent widths, the age indicator is not correct and there is no evidence for an age spread. This argument is weak, however, because it is well-known that stars at such late spectral types have huge spreads in their Hα equivalent widths at various ages, from that of the Pleiades to that of the Hyades (600 Myr, see Stauffer *et al.* 1991).

In any case, the proposition that the Pleiades contains stars which formed both 120 Myr and 20 Myr ago from the same ISM cloud is not one which is easily accepted (but would be very important if true). The stars in our sample imply that this is a possibility. In this context, however, it is surprising that there are no obviously intermediate-aged stars.

It seems rather unlikely that stars were born inside the Pleiades only a few to ten million years ago because there is no interstellar material in the Pleiades that is dense enough to form stars. The cluster is colliding with a cloud right now (White & Bally 1993; Herbig 1996) which is the source of the reflection nebulosity the cluster is famous for, but it does not contain dense material. The knot discussed by Herbig (1996) is dense, but does not contain much mass. It is unclear whether it is capable of forming a star; even if it did, the star would not remain in the cluster because it has a different space motion. In both cases, these clouds are near the Pleiades now but were not a few million years ago. White & Bally (1993) and Herbig (1996) disagree about the motion of the interstellar material, but do not disagree that the Pleiades is moving through it. The Pleiades could have collided with a dense cloud 20 Myr ago, but it must have been essentially following the cluster in order to produce two stars with the cluster's space motion and location. In that case, it would probably be considered part of the original cluster material.

If one assumes, instead, that our two lithium stars did not form in a very late bout of star formation within the Pleiades, how is it possible for such young stars to be apparent cluster members? The Pleiades sits in the midst of a rather complicated grouping of giant molecular clouds, those belonging to Gould's Belt and Taurus. For studies of the kinematics of this interstellar material, refer to, for example, White & Bally (1993) and Herbig (1996). Because of this, many clumps of star-forming clouds exist in rather close proximity to the Pleiades cluster. At the distance of 127 pc, a cloud 5° away could be as close as tens of parsecs. Furthermore, huge numbers of X-ray bright and lithium bearing stars (indicating ages of a few tens of Myr) have recently been discovered in this part of the sky distributed over tens of degrees (Neuhäuser *et al.* 1995a), some with radial velocities consistent with that of the Taurus clouds (Neuhäuser *et al.* 1995b).

To investigate this further, we consider the relative motions of the Pleiades and the Taurus clouds over the past 30 million years, the upper limit on the ages of HHJ 339 and HHJ 430. The Taurus clouds have been shown by Herbig (1996) to be moving with a relative radial velocity of about 10.5 ± 1 km s^{-1} and a relative proper motion of $2\overset{''}{.}0\pm0\overset{''}{.}4$ per century at a P. A. of $325°\pm30°$ relative to the Pleiades. This is determined by the radial velocity of the CO emission and the proper motions of various clumps of wTTS in the clouds. Furthermore, the Taurus clouds now lie at a distance of 150 ± 10 pc (Herbig 1996). This means that about 2 million years ago the Pleiades may well have passed directly through a star forming clump in the Taurus cloud [see Fig. 3(b)].

Considering the interaction cross-sections, it is essentially impossible that the Pleiades could have ''captured'' one, let alone two, of the young stars in this cloud. However, recent models of few-body systems by Sterzik & Durisen (1995) show that typical configurations of young stellar objects in star forming regions may eject stars from these regions, with 60% acquiring velocities greater than 3 km s^{-1}. Furthermore, their simulations also demonstrate that these stars can be ejected on timescales much less than the evolution timescale of the newborn stars. Feigelson (1996) also promotes such a scheme, in which many star forming regions disperse some of their stars outside of their traditionally accepted boundaries and suggests that it can explain the apparent deficit of wTTS older than a few million years in star forming regions. So perhaps HHJ 339 and HHJ 430 are examples of these ''runaway'' wTTS. For this to work, the stars must be ejected from the star forming clump at the same time that the Pleiades was passing through it. Furthermore, the stars have to be ejected with the same space motion as the Pleiades. This would be a remarkable coincidence if there were only one of these stars; it seems highly implausible that two would behave this way.

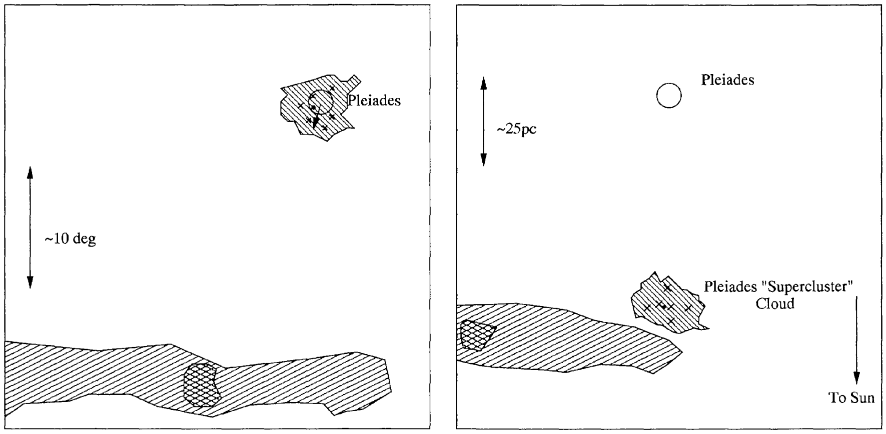
On the other hand, there *is* a set of pre-main sequence stars which have almost the same the space motion as the Pleiades. These are part of the ''Pleiades supercluster,'' most recently discussed by Eggen (1995). Some of these objects are clearly above the main sequence, and many have strong stellar activity and show strong lithium lines. There is every reason to believe that they are much younger than the stars in the Pleiades cluster itself. In that sense, the supercluster does have a very large age spread. The only star discussed by Eggen (1995) which is similar to our lithium stars is the early M binary T 18. This is actually a member of the Pleiades cluster. Stauffer (private communication) has provided us with his spectrum of one component of T18 (Fig. 2); it clearly has depleted lithium to, at most, a small fraction of the abundance in our two HHJ stars and is quite consistent with complete depletion. While it is slightly hotter (making the equivalent width of lithium for a given abundance smaller), this star does not present the same quandary as our stars in terms of being obviously very young. However, if it is at the distance of the cluster, it lies above the main sequence even after accounting for its binary nature (Fig. 1), unless it is really quadruple. Eggen (1995) points out that it is similar to a non–cluster member of the supercluster, HD155555C. The other (more massive) members of that triple system show lithium (Martin & Bradner 1995) but the M star does not (consistent with an age of 30 Myr).

It is interesting that Yuan & Waxman (1977) claim that the motion of the supercluster as a whole may suggest an age of about 150 Myr, another indication for the larger-than-classical age proposed by Basri *et al.* (1996). Yuan & Waxman (1977) show that the actual motion of the cluster over its lifetime is complicated; it oscillates above and below the galactic disk plane. Determining through which clouds it may have passed is very difficult (particularly since they may not still be around).

The young supercluster stars are not particularly puzzling, however, since they are not actually in the Pleiades cluster, but are merely streaming by us with a similar space motion (that of the supercluster). This space motion is not very different from the general solar neighborhood, so use of the supercluster concept is not crucial to our argument. One can imagine that there was a wide complex of vaguely related clouds which shared a general motion but formed stars at different times. This suggests our best hypothesis for what HHJ 339 and HHJ 430 might really be. Suppose a cloud in the supercluster complex (or simply with space motion sufficiently similar to that of the Pleiades) formed stars 20 to 30 Myr ago [Fig. 3(a)]. Its motion would be similar to the Pleiades. We suppose that its center of expansion now is in the direction of the cluster and roughly halfway between us and the Pleiades cluster. Suppose further that this cloud became unbound (as is usual) when it formed stars, and that they left with a velocity dispersion of 2–3 km s^{-1}.

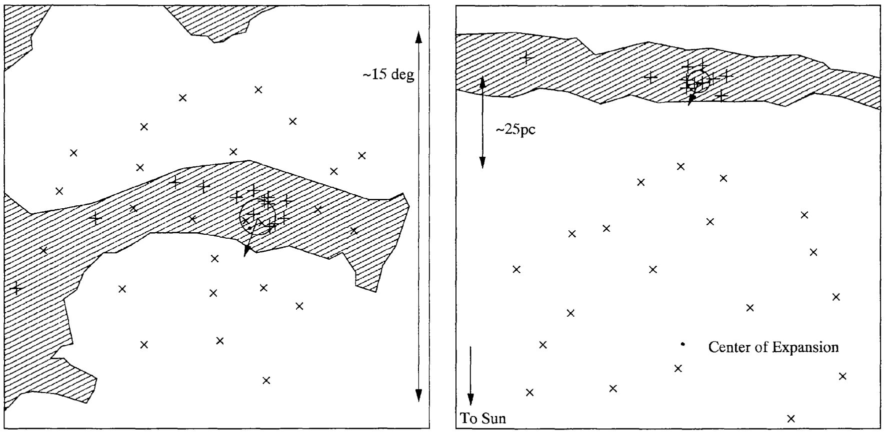
The front edge of the expanding cloud of young stars would now be fairly close to us, explaining several of the nearby, young stars in Eggen (1995). These can be found as bright X-ray sources, with the correct space motion. The back side of the expanding cloud of young stars would now be approaching the Pleiades cluster, with radial velocities slightly higher than it (as our two stars display; Fig. 3.) Presumably these stars have maintained this motion over their lifetimes, while bound cluster members with similar velocities are in orbits within the cluster. Members of this group would be harder to pick out of the field, unless a proper motion survey like that of HHJ were performed. Thus, we would predict that there are many other stars like HHJ 339

(a) 30 Myr ago



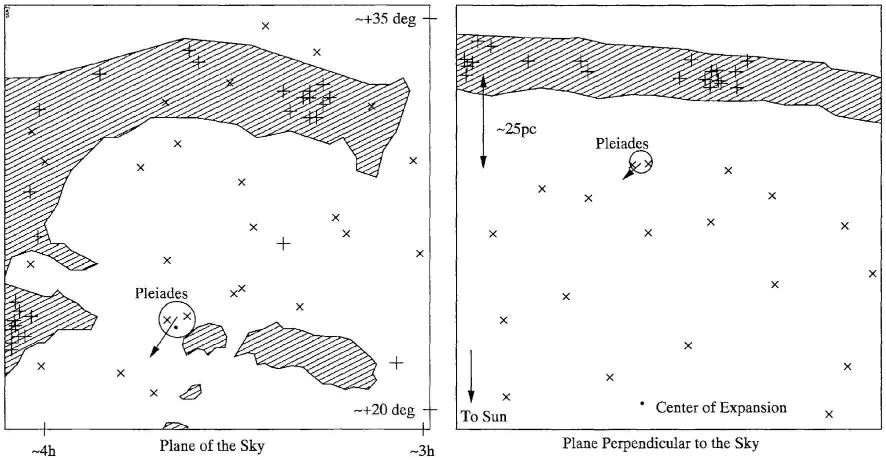
Plane of the Sky | Plane Perpendicular to the Sky

(b) 2 Myr ago



Plane of the Sky | Plane Perpendicular to the Sky

(c) The Present



Plane of the Sky | Plane Perpendicular to the Sky

FIG. 3. Schematic views of the Pleiades and Taurus clouds in both the plane of the sky and projected into a plane perpendicular to the sky. In all six panels, the Pleiades cluster is represented by a small circle. The x markers represent stars in the Pleiades "supercluster." In this scheme, these stars will increase in number and the clump will expand about their center of expansion (marked with a dot) as discussed in Sec. 4. HHJ 339 and HHJ 430 might come from such a population. The large shaded region represents the Taurus molecular cloud. Approximate scales are indicated. The arrows indicate the motion of the Pleiades relative to the Taurus clouds. (a) shows the region as it might have appeared 30 Myr ago. The darker shaded region is where the wTTS present in (b) and (c) will form. The shaded region encapsulating the x markers is meant to show that 30 Myr ago these stars were forming and a lot of gas must have been present. (b) shows the same region but at an epoch only 2 Myr ago, when the Pleiades passed through a region of star formation in the Taurus clouds. Plusses indicate wTTS which are known to exist in the present. (c) shows the present epoch. Plusses again indicate approximate locations of known wTTS. In this set of panels, the Taurus clouds have the approximate shape that Ungerechts & Thaddeus (1987) found in CO emission. This figure is meant to illustrate a working hypothesis that explains the presence of HHJ 339 and HHJ 430 in the Pleiades. By no means are the locations and motions represented precise.

and HHJ 430, which have space motions similar to the Pleiades. Most of these should not be in the exact direction of the Pleiades nor at nearly its distance, but a few could be. It would then not be outrageously coincidental that these two stars appear to be in the cluster. Instead, this is an observational selection effect. Indeed, Neuhäuser *et al.* (1995a) see a large population of X-ray bright late-type stars in the general direction of Gould's belt, most of which are far from any molecular clouds.

Our hypothesis can be tested two ways. First, if the kinematics of many of the cool, stellar X-ray sources in the general direction (up to tens of degrees away) of the cluster are studied, we would predict that a reasonable number of them would be considered part of the Pleiades supercluster. Second, if the detailed proper motion and parallax of HHJ 339 and 430 are studied (with HST, for example) we would not be surprised to find that they are really a little in front of the cluster and perhaps don't have exactly its space motion. Third, we would predict an excess of field stars closer than the Pleiades which show signs of youth (e.g., have lithium or rapid rotation) to be found in the general direction of Taurus and surrounding constellations, compared with other directions.

5. CONCLUSIONS

We have examined high resolution spectra of several of the faintest known stars in the Pleiades. None of them shows lithium, confirming that the lithium depletion limit and the region in the HR diagram inhabited by substellar objects occurs just faintward of them. The stars in our sample are very rapidly rotating and exhibit strong chromospheric activity, as evidenced by their Hα emission features. This chromospheric activity is not unusual for such stars. However, the fact that all of these stars are rapidly rotating shows that the previously noted (Stauffer *et al.* 1991) "levelling off" of Hα equivalent widths in young, very late-type stars is unrelated to a levelling off of rotational velocities. Given the current understanding of the rotational history of low mass stars, it is not surprising that these stars are all rapid rotators.

Two brighter stars, HHJ 339 and HHJ 430 exhibit lithium features and are clearly young. We argue that these stars belong to the Pleiades cluster because of radial velocities, proper motions, and HR diagram positions consistent with not only cluster membership, but also lithium depletion models. They were observed because they are apparently on the Pleiades pre-main sequence. The presence of lithium confirms that they are young. They must be some 50 to 100 Myr younger than most of the Pleiades stars. We discuss several explanations for this. One is that they represent very late star formation in the cluster, implying that stars have been forming in the Pleiades for a very long time. However, this explanation is problematic because the high density gas required for star formation is not present now, and stars of intermediate age are not obviously extant. As another explanation, the possibility that the cluster could have encountered a star-forming cloud recently enough to make these stars is also discussed; we argue that it would be difficult to arrange for the stars to have the right space motion unless the cloud had essentially always been related to the cluster.

We also consider the possibility that the stars formed in an unrelated cloud and then ended up as cluster members. Although it is conceivable that one such star might have escaped from a nearby star-forming cloud several million years ago, at the same time as the Pleiades passed by, and with the motion of the Pleiades, it is difficult to imagine two such stars being ejected in exactly the same direction and velocity at the same time.

On the other hand, there is a population of stars which are as young as our lithium stars and share the general space motion of the Pleiades. Our most plausible explanation of HHJ 339 and HHJ 430 is that they were born in this "supercluster." In this scheme, the star formation took place fairly recently at a location between the Sun and the Pleiades. Over the past few-to-tens of millions of years the nascent stars in this region became unbound and expanded such that these two stars, HHJ 339 and HHJ 430, can appear to be in the Pleiades. Since the "supercluster" exhibits the same space motion as the Pleiades, these two stars would appear to satisfy all the usual membership criteria, except that they are unusually young. We do not advance this idea as clearly correct; it is just the most conservative explanation we could think of for these enigmatic stars.

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