THE MASS AND AGE OF VERY LOW MASS MEMBERS OF THE OPEN CLUSTER α PERSEI

GIBOR BASRI AND EDUARDO L. MARTÍN
Astronomy Department, University of California, Berkeley, Berkeley, CA 94720; basri@soe confessed.berkeley.edu, ege@popsicle.berkeley.edu
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ABSTRACT

We present spectroscopic optical and photometric infrared observations of 12 faint candidate members of the young open cluster α Persei found by Prosser in 1994. Keck HIRES echelle spectra provide radial and rotational velocity measurements for five objects, two of which are clearly nonmembers based on the radial velocities. These kinematic nonmembers also do not fit well in the (V − J) versus (I − J) cluster sequence. One additional faint object is likely a nonmember based on a low-resolution spectrum. Using HIRES, we have searched for the Li i resonance line. Combining the absence/presence of lithium and photometry of the faint α Persei targets with confirmed membership constrains their ages and masses. The lack of lithium in AP J0323 +4853 implies that its age is greater than about 65 Myr, which is older than the cluster classical upper main-sequence turnoff age of 50 Myr. A similar age discrepancy is found in the Pleiades. We detect lithium in the faintest of our program stars, AP 270, which implies a mass for it just at the substellar mass limit, given our adopted age and its luminosity. The membership of AP 281 is in question because of its high radial velocity compared with the cluster mean. On the other hand, AP 281 lies on the photometric cluster sequence and has a very high rotation velocity and Hα emission, indicating youth. If it is a member, its lack of lithium would push the minimum age of the cluster to 75 Myr, in agreement with a very recent upper main-sequence determination. In that case, AP 270 would not be a brown dwarf.

Subject headings: open clusters and associations: individual (α Persei) — stars: evolution — stars: fundamental parameters — stars: low-mass, brown dwarfs

1. INTRODUCTION

Young open clusters have become a fertile hunting ground for very low-mass (VLM) star and brown dwarf (BD) surveys. They offer the advantage that the VLM members are relatively bright and share the distance and metallicity derived from higher mass stars. The successful identification of BDs in the Pleiades (Basri, Marcy, & Graham 1996, hereafter BMG; Rebolo et al. 1996) is a good example of how this advantage can be exploited. The open cluster α Persei (Melotte 20) is one of the youngest open clusters within a radius of 200 pc from the Sun. It is listed with an age of 50 Myr and a true distance modulus of $m − M = 6.36$ in the catalog of Lynga (1987). Recently, the trigonometric parallax observations of the Hipparcos satellite have yielded a true distance modulus of $6.33 ± 0.09$ (Mermilliod et al. 1997), which is consistent with previous estimates. Being younger than the Pleiades and only a little more distant, α Per offers the opportunity of studying VLM objects at an earlier evolutionary stage.

The "lithium test" for substellarity was first proposed and applied to a BD candidate found in α Persei (Rebolo, Martín, & Magazzù 1992; Magazzù, Martín, & Rebolo 1993). Since then, it has been applied to BD suspects in the Pleiades and in the field (Basri 1998a) and has been used for constraining their ages and masses (BMG). In this work, we search for lithium in several of the faintest candidate members of α Per taken from Rebolo et al. (1992) and Prosser (1994). We find that the faintest of these objects (AP 270 in Prosser’s list) is indeed a “bona fide” cluster member and has a detectable lithium line. We discuss the age and mass of this object using recent evolutionary models and the methodology of “lithium dating” developed by BMG (see also Basri 1998b). That work has shown that the Pleiades is substantially older than thought based on classical analysis of the upper main-sequence turnoff (UMST) stars. Because lithium dating can provide a means of calibrating the convective overshoot in UMST stars (which affects their ages), it is important to confirm that this effect is generally seen in young clusters. By studying enough such clusters, the value of the overshoot parameter as a function of stellar mass could in principle be determined.

2. OBSERVATIONS

High-resolution spectroscopic observations of five of the faintest candidate members of α Persei from the list of Prosser (1994) were obtained at the Keck I telescope, using the HIRES echelle spectrometer (Vogt et al. 1994). The instrumental configuration and data reduction procedure were the same as in BMG. With a dispersion of about 0.01 nm pixel$^{-1}$ (binned), the resolving power obtained was $R \sim 33,000$. The targets observed are listed in Table 1; the typical exposure time for the AP stars was about 1 hr.

Low-resolution spectroscopy of AP 270, AP 275, and AP 276 was obtained on 1997 December 12 using the Kast double-arm spectrograph at the Shane 3 m telescope of the Lick Observatory. We removed the dichroic and employed the red arm only with grating number 6 (300 lines mm$^{-1}$). The objects observed with Kast are listed in Table 2. The spectral resolution (FWHM) and wavelength coverage provided by this instrumental setup were 0.88 and 472.6–1023.2 nm, respectively. Standard reduction and calibration procedures were accomplished with IRAF routines. We cor-

1 Available at http://cdsweb.u-strasbg.fr/htbin/mypcat3?VII/92A.

2 The original name was AP J0323 +4853 (Rebolo, Martín, & Magazzù 1992; Zapatero Osorio et al. 1996).
directed for the instrumental response using the flux standard HD 84937 (Stone 1996).

Near-infrared observations of 12 candidate members from Prosser (1994) were carried out on 1997 September 10 and 12 at the Lick 1 m telescope with the LIRC 2 camera (Gilmore, Rank, & Temi 1994). The detector is a NICMOS-3 256\(^2\) pixel array with a field of view of 7.2 arcmin\(^2\). We used the standard J and K' filter set. Total exposure times ranged from 60 to 300 s in each filter. We dithered the telescope, making a square of 30\(^\circ\) on the side. The IRAF DAOPHOT package was applied to reduce the frames and extract the photometry. Instrumental aperture magnitudes were corrected for atmospheric extinction and transformed into the United Kingdom Infrared Telescope (UKIRT) system (Leggett 1992) using observations of the stars in the field of the Pleiades BD Calar 3 as standards (Zapatero Osorio, Martin, & Rebolo 1997). We found that our K' photometry was useless because the background was too high and variable. Thus, we give only the J-band photometry in Table 3. The 1 \(\sigma\) error is less than 0.1 mag.

2.1. Spectroscopic Analysis

We measured heliocentric radial velocities for the five \(\alpha\) Persei candidate members observed with HIERES by cross-correlating the spectra of three echelle orders with our spectrum of the M6 V template Gl 406 obtained during the same run (on December 7). The spectral orders chosen cover the wavelength ranges 786.4–797.5, 804.2–815.6, and 822.9–834.6 nm, which contain hundreds of sharp molecular lines (mainly TiO and VO). They are not contaminated by strong telluric lines. The errors were estimated from the dispersion among radial velocities obtained from the different echelle orders and are always less than 1 pixel. We adopt a radial velocity for Gl 406 of \(v_{\text{rad}} = 19.2 \pm 0.15 \text{ km s}^{-1}\) from X. Delfosse (1998, private communication). It supersedes his published value with a new determination.

### Table 1

**HIRES Data**

| AP      | UT Date (1997) | RJD (2,450 +) | \(v_{\text{rad}}\) (km s\(^{-1}\)) | \(v \sin i\) (km s\(^{-1}\)) | EW (Li i) (\(\AA\)) | EW (Hα) (\(\AA\)) |
|---------|----------------|---------------|-------------------------------------|-----------------------------|---------------------|-------------------|
| 270...... | Dec 2          | 784.85        | 7                                   | \(-2.0 \pm 1.8\)            | 24 \pm 4            | 0.62 \pm 0.06     | -5.3 \pm 0.5      |
| 270...... | Dec 7          | 789.80        | 9                                   | \(-0.4 \pm 1.5\)            | ...                 | 0.70 \pm 0.08     | -4.5 \pm 0.5      |
| 273...... | Dec 3          | 785.90        | 2                                   | 26.2 \pm 2.1               | 7 \pm 3             | <0.33             | -3.8 \pm 0.6      |
| 273...... | Dec 7          | 789.85        | 4.5                                 | 25.3 \pm 0.8               | ...                 | <0.27             | -5.9 \pm 0.3      |
| 275...... | Dec 1          | 783.85        | 4.5                                 | \(-2.0 \pm 1.3\)            | 33 \pm 6            | <0.25             | -8.1 \pm 0.3      |
| 279...... | Dec 2          | 784.85        | 10                                  | 33.0 \pm 1.8               | 20 \pm 6            | <0.26             | -2.2 \pm 0.4      |
| 281...... | Dec 7          | 789.75        | 12                                  | 9.4 \pm 1.2                | 51 \pm 5            | <0.14             | -3.5 \pm 0.3      |

**Note.**—The approximate signal-to-noise ratio is given for the order centered at 849 nm. It decreases to shorter wavelengths.

### Table 2

**Kast Data**

| AP      | Signal-to-Noise Ratio | PC1 | PC2 | PC3 | PC4 | Spectral Type |
|---------|-----------------------|-----|-----|-----|-----|---------------|
| 270...... | 20                    | 1.55| 2.49| 1.49| 1.70| M6.7 \pm 0.8  |
| 275...... | 17                    | 1.79| 2.24| 1.30| 1.91| M6.2 \pm 0.6  |
| 276...... | 13                    | 1.81| 1.67| 1.17| 1.86| M5.1 \pm 0.6  |

**Note.**—Signal-to-noise ratio is for wavelengths around 810 nm.

### Table 3

**Photometric Data**

| AP      | \(V\) | \((V-I)_0\) | \(J_{\text{uk}}\) | \((I-J)_0\) | \(M_{I_s}\) | log \((L_{bol})\) | Membership |
|---------|-------|-------------|------------------|-------------|------------|------------------|------------|
| 268...... | 20.50 | 3.43        | 14.98            | 1.77        | 10.44      | -2.35            | Y:         |
| 270...... | 21.87 | 3.84        | 15.56            | 2.15        | 11.40      | -2.66            | Y:         |
| 272...... | 20.42 | 3.58        | 14.71            | 1.81        | 10.21      | -2.27            | Y:         |
| 273...... | 21.71 | 3.76        | 15.33            | 2.30        | 11.32      | -2.64            | N:         |
| 275...... | 21.10 | 3.81        | 14.95            | 2.09        | 10.64      | -2.45            | Y:         |
| 276...... | 21.60 | 3.69        | ...              | ...         | 11.28      | -2.63            | N:         |
| 279...... | 21.10 | 3.66        | 15.73            | 1.39        | 10.81      | -2.48            | N:         |
| 281...... | 21.41 | 3.70        | 15.45            | 1.94        | 11.08      | -2.56            | ?:         |
| 282...... | 18.48 | 2.90        | 13.75            | 1.51        | 8.95       | -1.82            | Y:         |
| 284...... | 19.44 | 3.23        | 14.33            | 1.56        | 9.38       | -2.05            | Y:         |
| 290...... | 19.20 | 3.23        | 14.04            | 1.61        | 9.34       | -1.96            | Y:         |
| 297...... | 17.63 | 2.71        | 13.16            | 1.44        | 8.29       | -1.57            | Y:         |

**Note.**—The \(V\) photometry is from Prosser 1994. The \(V-I\) color is also from Prosser, transformed from the Kron to the Cousins system using the cubic equation given in Leggett 1992. For AP 275 (=AP 30323+4853), we adopted the average NOT \(I\)-band photometry provided by Martin & Zapatero Osorio (1997). The colors and \(M_{I_s}\) values have been corrected for reddening. Luminosities are in solar units, estimated using \(M_{I_s}\).
based on four more observations and a better template. We also derived our own independent absolute radial velocity for Gl 406 using several atomic lines, obtaining $18.4 \pm 1$ km s$^{-1}$. Our radial velocity determinations for the program stars are given in Table 1.

Our HIRES spectra are also useful for measuring the rotational broadening ($v \sin i$). We used the same echelle orders as for the radial velocity measurements described above. For calibration, we convolved the spectrum of Gl 406 ($v \sin i < 2.9$ km s$^{-1}$; Delfosse et al. 1998) with successive values of $v \sin i$ in intervals of 10 km s$^{-1}$ and cross-correlated these convolved spectra with the original spectrum. The resulting correlation functions were compared with each of the correlation functions between a program star and the spectrum of Gl 406 to find the best rotational velocity. In particular, a Gaussian was fitted to the core of each correlation function and the Gaussian width used to make the comparison. This procedure is similar to that employed by Basri & Marcy (1995). The $v \sin i$ values obtained for the program stars are given in Table 1. The errors reflect the dispersion in values obtained from the different orders, while the value itself is found by first averaging all of the correlation functions for a given star.

The HIRES spectra were also used for measuring the strength of selected atomic lines. Several interesting optical lines present in late M-type stars were included in our spectral range. We focus on three features: Hz, Li I at 670.8 nm, and K I at 769.9 nm because they are indicators of chromospheric activity, nuclear burning in the interior, and surface gravity, respectively. All of our program stars showed Hz in emission with single-peaked profiles. The equivalent widths are given in Table 1, along with upper limits for the equivalent width of the Li I in the stars where we do not detect it. These were measured by making estimates of the pseudocontinuum by eye and taking a reasonable range of possibilities to estimate the errors. The spectra are noisy, and many features are not real, so the error estimate may be liberal. Only in AP 270 is there a detection of lithium, as shown in Figure 1. The apparent absorption features on either side of the line are not real, and its asymmetry should not be taken seriously. We note that our upper limits to the Li I equivalent width are substantially lower than those obtained by Zapatero Osorio et al. (1996) from lower resolution spectra of AP 275 and AP 279. In Figure 2 we present the K I region. Much of the blue wing of the K I feature lies outside the recorded spectral domain. Nevertheless, we can clearly see that the K I line in AP 270 is narrower than in the M6 dwarf Gl 406. This difference is due to the lower gravity in the young $\alpha$ Per object compared to the older main-sequence star.

We used our KAST spectra to measure pseudocontinuum ratios that are known to be good spectral type indicators for M-type stars (Martín et al. 1996). We used the published values of the PC2, PC3, and PC4 indices for field dwarfs of known spectral type. The PC1 and PC5 indices are within our spectral range, but our spectra are too noisy at those wavelengths. The mean spectral subclass and 1 $\sigma$ dispersion obtained from the PC2, PC3, and PC4 indices are shown in Table 2. For AP 275, our spectral type is consistent with that of Zapatero Osorio et al. (1996).

3. DISCUSSION

3.1. Cluster Membership

According to Prosser (1992, 1994), the mean heliocentric radial velocity of $\alpha$ Persei members is $-2$ km s$^{-1}$. The radial velocities of AP 270 and AP 275 are close to the cluster mean, supporting membership. On the other hand, AP 273 and AP 279 have radial velocities that are much too high, indicating nonmembership. No radial velocity change larger than the measurement uncertainty was detected between the two spectra of AP 273 (or those of AP 270) taken on different nights. Thus, it is unlikely that the high radial velocity of AP 273 is due to a close companion. The radial velocity of AP 281 is higher than any of the high-confidence $\alpha$ Per members. Nevertheless, we consider this star a possible member because of its very high rotation velocity and good agreement with the cluster photometric sequence (see below). It is conceivable that the radial velocity is variable due to an unresolved companion. We do not find any trace of the companion in our spectrum, so it
would have to be much fainter than the primary (possibly a BD). More high-resolution spectra are needed in order to test this hypothesis.

A color-color diagram displaying the locus of kinematically young disk field dwarfs (Leggett 1992) is presented in Figure 3 together with the AP stars that we have measured at the Lick 1 m telescope. We have dereddened the AP stars by the mean color excess of \( E(V-I) = 0.16 \) (Prosser 1994). Most of the AP stars are located around the young disk star locus. It is interesting to note that the two most deviant stars are AP 273 and AP 279, which are nonmembers according to their radial velocities. These examples show that color-color diagrams can provide a very useful diagnostic of cluster membership, particularly in a cluster of low Galactic latitude like \( \alpha \) Per (b = -5.9\dgr) in which there can be a significant amount of contamination from Galactic disk stars.

We deem AP 276 to be a nonmember of \( \alpha \) Per because it has too early a spectral type for its \((V-I)\) color. Our final judgments concerning the membership of the AP stars studied in this paper are provided in Table 3. Stars for which we believe there is a high confidence of membership are indicated with a Y, while those with less confidence are flagged with “Y,” usually because of lack of kinematic information. AP 281 is kinematically a nonmember unless its radial velocity is variable.

3.2. Activity and Rotation

Our results further confirm that \( \alpha \) Per VLM members have \( \mathrm{H}\alpha \) in emission as expected for their young age. This diagnostic in young clusters has been discussed by, e.g., Prosser, Stauffer, & Kraft (1991) and for \( \alpha \) Per in particular by Prosser (1992). However, we note that the nonmembers AP 273 and AP 279 also have \( \mathrm{H}\alpha \) in emission. Hence, \( \mathrm{H}\alpha \) does not seem to be a powerful criterion for cluster membership. Zapatero Osorio et al. (1996) found that the maximum \( \mathrm{H}\alpha \) emission equivalent widths among \( \alpha \) Persei stars occur around spectral type M4 and does not rise or even declines toward cooler members. Our \( \mathrm{H}\alpha \) measurements are consistent with this. A similar behavior has also been observed among VLM members of the Pleiades cluster (Hodgkin, Jameson, & Steele 1995; Stauffer, Liebert, & Giampapa 1995). The decrease in \( \mathrm{H}\alpha \) emission could be due to a reduction of the efficiency of the turbulent dynamo in generating chromospheric activity. In field stars, the decline of \( \mathrm{H}\alpha \) emission has also been observed, although at cooler temperatures (spectral type M7 or later; Basri et al. 1996).

The difference in the spectral type at which \( \mathrm{H}\alpha \) emission becomes very weak between the young open clusters and the field VLM stars indicates that this phenomenon may be time dependent.

The rotation velocities of the faintest \( \alpha \) Per members observed by us are moderately high, which is not surprising because the stars are young. The rotation velocity of AP 279 is lower than the equatorial rotation velocity derived from the photometric period (Martin & Zapatero Osorio 1997), indicating that the star is viewed at a moderate inclination.

What is surprising is that the radial velocity nonmembers AP 279 and especially AP 281 have rather high \( v \sin i \). Rotational velocities \( \geq 20 \text{ km s}^{-1} \) are unusual among M5–M6 dwarfs in the solar neighborhood (Delfosse et al. 1998).

Since AP 279 and AP 281 were discovered in a photometric survey, which is unbiased with respect to rotation or chromospheric activity, there is no reason that they should be young if they do not belong to the cluster. As noted above, AP 281 might be cluster member if it is a spectroscopic binary. But this possibility is unlikely for AP 279 because it fails to match the cluster sequence in the color-color plot (Fig. 3). We do not have a firm explanation for why these stars are rotating so fast if they are not members of \( \alpha \) Per. The Hyades (\( \sim 600 \text{ Myr} \)) contains some M5 members with \( v \sin i \) in the range 20–40 km s\(^{-1}\) (Jones, Fischer, & Stauffer 1996). Even higher velocities appear to be the norm at the age of the Pleiades (Oppenheimer et al. 1997). The latter paper discusses stars that satisfy almost all cluster membership criteria, yet are very unlikely to be members. We can speculate (as did Oppenheimer et al. 1997) that there is an enhancement in the number of relatively young field stars in the general direction of these northern winter clusters.

3.3. The Age of the Cluster

3.3.1. Isochrone Fitting

The location of our program stars in a color-magnitude diagram is shown in Figure 4. We have also plotted the positions of Pleiades stars from the proper-motion study of Hambly, Hawkins, & Jameson (1993) with IR photometry provided by Steele, Jameson, & Hambly (1993). Also shown are Pleiades BDs with lithium detections (Rebolo et al. 1996; Martin et al. 1998) including IR photometry from Zapatero Osorio et al. (1997). If we disregard the kinematic nonmembers AP 273 and AP 279, the rest of the AP objects define a relatively narrow sequence in this diagram, including the uncertain member AP 281. On the other hand, the Pleiades stars occupy a much wider region. The \( J \)-band photometry for many of these stars comes from photo-
graphic plates and could be inaccurate (Steele & Jameson 1995). It is also possible that there are contaminating field stars in the Pleiades sample, even though it has been selected from a proper-motion study. For instance, Martin et al. (1996) recently found that HHJ7 is a nonmember on the basis of low-resolution spectroscopy, and several other HHJ stars are suspected nonmembers because they lie below the main sequence. Furthermore, Steele & Jameson (1995) have shown that part of the spread is due to unresolved binaries.

The α Persei stars overlap with the brighter half of their Pleiades counterparts, suggesting that it is on the average a younger sample. However, the scatter seen in the Pleiades prevents a more detailed comparison. Theoretical isochrones for 30, 50, 70, and 100 Myr (Baraffe et al. 1998) computed using NextGen model atmospheres (Allard et al. 1998) are superposed on the data in Figure 4. The isochrones are parallel to the general observed sequence. All of the α Per members lie above the 70 Myr isochrone, and most are even above the 50 Myr one. However, we do not think that α Per stars are younger than 50 Myr because it would not be consistent with any other age estimates, as discussed below. We note that there could be problems with the isochrones of Baraffe et al. (1998) mainly due to the water absorption line list, which affects the IR colors (Allard et al. 1994, 1998).

The dispersion of the data points in Figure 4 might suggest that there could be a spread in ages among α Persei members of greater than 20 Myr. However, this cannot be taken at face value because there are several factors producing uncertainties in estimating the ages of individual objects from a color-magnitude or an H-R diagram. In addition to the sources of dispersion already cited above for the Pleiades (photometric errors and contamination from field stars), there could easily be some unresolved binaries. It is also the case that these young stars are intrinsically variable. Martin & Zapatero Osorio (1997) have shown that the VLM α Per members can have brightness changes of order 0.1–0.2 mag in the R and I filters. For AP 275, they found average magnitudes of $I_c = 17.13$ in their 1994 data and $I_c = 17.03$ in their 1995 data, while Prosser (1994) obtained $I_c = 17.22$ in his 1991 data. We have adopted the value of $I_c = 17.13$ because it is intermediate between the other two and has a lower formal error.

3.3.2. Lithium Dating

A more precise method of dating VLM cluster members is by lithium dating (BMG; Bildsten et al. 1997; Basri 1998b). This exploits the fact that the luminosity at which lithium is efficiently depleted in fully convective objects is a steep function of time and fairly model independent. Using analytical calculations, Ushomirsky et al. (1998) have obtained an equation that gives a lower limit on the age of a nondegenerate fully convective star that has depleted lithium, solely as a function of its luminosity and metallicity. They applied their results to the α Persei stars with lithium nondetections from Zapatero Osorio et al. (1996) and inferred a minimum age of $61 \pm 7$ Myr for the cluster (if coeval) from AP 279. Unfortunately, we have found AP 279 to have a radial velocity that is inconsistent with cluster membership. The next faintest α Per star with a radial velocity that is consistent with membership and a lithium nondetection is AP 275. Using Figure 4 of Ushomirsky et al. (1998) and the range in luminosities estimated by Zapatero Osorio et al. (1996), we find a minimum age of $58 \pm 8$ Myr. This age estimate is also quite insensitive to the actual lithium abundance, as demonstrated in equation (40) of Ushomirsky et al. (1998). It does depend on the effective temperature calibration for these pre-main-sequence objects, which is still subject to some uncertainty, and on the assumption of evolution at constant effective temperature needed for the analytic analysis.

Here we perform the analysis with detailed models and current observations. We have primarily used the evolutionary models of Baraffe et al. (1998), kindly supplied to us in advance of publication by I. Baraffe (see Chabrier & Baraffe 1997). It is reasonable to use these models because they provide a good fit to the photometric cluster sequence of α Persei members. A further advantage is that the authors directly provide the theoretical absolute magnitudes in several passbands because they use model atmospheres that provide reasonable good fits to the observed spectra of VLM stars and BDs (Allard et al. 1998). In Figure 5 we present the lithium depletion predictions in the $I_c$ and $J$ filters. For the latter filter, we have transformed the calculations of Baraffe et al. (1998) from the Carnegie image-tube system to the UKIRT system using the relationship provided by Leggett (1992) derived from US Naval Observatory data. We adjust the observed $I_c$ and $I_c - J$ magnitudes for reddening with corrections of $-0.14$ and $-0.16$ mag, respectively.

The following values of true distance modulus for α Per were found in the literature: 6.36 (Lynga 1987), 6.4 (Prosser 1994), 6.24 (Dzervitis, Paupers, & Vansevicius 1994), and 6.33 (Mermilliod et al. 1997). These have been corrected with the values of reddening adopted by each author. The mean value is $m - M = 6.33$, which coincides with the Hipparcos-based result of Mermilliod et al. (1997). The Hip-
The dotted abundance, the dotted are the locus of objects that have preserved 90% of their initial lithium abundance, the dotted—short-dashed line represents 50% preservation, the dotted—long-dashed lines are for 10%, long-dashed—short-dashed lines are for 1%, and short-dashed lines are for 0.1%. The dotted lines show the absolute magnitudes of AP 275 and AP 270. The vertical dashed line is at our adopted age for the cluster of 65 Myr. The other (which we adopt) is to use the bolometric correction derived from main-sequence stars with an error of 0.1 mag. Moving the isochrones about 0.1 mag redward in the J band lists (Allard et al. 1994, 1998). This could be the source of the offset of the isochrones in Figure 4 discussed earlier. Moving the isochrones about 0.1 mag redward in the Ic—J would make the age inferred from them in closer agreement to the lithium age and at the same time make the lithium age inferred from J (Fig. 5b) agree better with that from Ic (Fig. 5a) or bolometric luminosity (Fig. 6).

The combination of the absolute Ic and J magnitudes and luminosities of AP 270, AP 275, and AP 281 with the theoretical predictions for lithium depletion yields the following results:

1. For an age of 50 Myr, which is the canonical cluster age based on the UMST stars (Mermilliod 1981), AP 270 is expected to have preserved more than 90% of its initial lithium content, consistent with our lithium detection in it. However, AP 275 is expected to have preserved 50% (Fig. 5a, J band) or 10% (Fig. 5b, J band) of its initial lithium. This is not consistent with our upper limit to the lithium equivalent width, which implies a lithium depletion of more than 2 orders of magnitude according to the calculations of Pavlenko et al. (1995) and Pavlenko (1997). The initial lithium abundance of α Per members is the standard ISM value in the stars hotter than about 5500 K (Randich et al. 1998). If AP 281 is a member, then its lack of lithium is also inconsistent with an age of 50 Myr.

2. For an age of 65 Myr, AP 270 is expected to have preserved about 90% (Fig. 5a) or 50% (Fig. 5b) of its initial lithium content, and AP 275 should have preserved less than 1%. Both expectations are consistent with our lithium observations. The age at which AP 275 depletes lithium is a little older (5 Myr) than the estimate based on the analytical calculations of Ushomirsky et al. (1998). If, however, AP 281 is a member, then it would be expected to still have 50% (10%) of its lithium, and we should still see a strong lithium line in it. Thus, the minimum cluster age is 65 Myr based on AP 275 but must be older if AP 281 is a member.

3. For an age of 75 Myr, AP 270 is still expected to preserve 50% (Fig. 5a) or 10% (Fig. 5b) of its initial lithium abundance. Our measured lithium equivalent width implies a surface lithium abundance of more than 10% of the original according to the “pseudoequivalent” width calculations of Pavlenko (1997). Hence, AP 270 is still reasonably consistent with such an age. Both AP 275 and AP 281 would have depleted lithium at this age, but this is about how long it takes a star with the brightness of AP 275 to do it. Thus, the minimum cluster age if AP 281 is a member is roughly 75 Myr, or about 50% older than the age given by the classical UMST stars. These conclusions are all fully consistent with what is found if luminosities instead of Ic and J magnitudes are used, as can be seen in Figure 6.

While the lithium nondetection in AP 275 (or AP 281) sets a minimum age for the cluster, the lithium detection in AP 270 sets a maximum age. This is illustrated in Figure 6, in which the 1% lithium line can be taken as essentially the dividing line between spectroscopic detection or nondenotation of lithium. The choice of 1% does not matter much, since the entire process of lithium depletion takes place in a few Myr. The point at which this line is intersected by the luminosity of a given star defines the minimum/maximum age of the star depending on whether lithium is a...
nondetection/detection. For AP 270, the lines intersect a little below 90 Myr, so that is the maximum allowed age of the cluster based on these data. It would be surprising if it were that old, of course. Error bars on the luminosity based on the uncertain distance modulus are also shown in Figure 6. These translate into age uncertainties by affecting the point at which the luminosity intersects the depletion line. It can be seen from the figure that the uncertainty in age from this source is about \( \pm 5 \) Myr.

We have tried to assess what the uncertainties due to the models are. In addition to using the Ushomirsky et al. (1998) formula and the Baraffe et al. (1998) models, we have been kindly provided models by A. Burrows (1998, private communication; see Burrows et al. 1997). We compared the luminosity evolution of objects of different mass between these and those from Baraffe and the ages at which lithium disappears in the two models. The Burrows calculations tend to be a little brighter and hotter for a given mass and age; apparently their atmospheric treatment lacks flux a little more slowly than the Baraffe treatment. This leads to later times for lithium depletion in the Burrows models by about 10 Myr in the relevant range of mass and age. We do not wish to speculate on which set is more correct, preferring to note that for our purposes the Baraffe models yield more conservative conclusions.

The discussion above leads us to adopt an age for the \( \alpha \) Persei cluster of 65 Myr as consistent with our lithium dating. The age is unlikely to be lower than 60 Myr and could be as high as 75 Myr or more if AP 281 is a member (or if other stars of similar brightness and better pedigree are found not to have lithium). In the Pleiades cluster, lithium dating has led to an age estimate for the members around the substellar limit of \( 115 \pm 10 \) Myr (BMG; Martin et al. 1998), which is about 1.5 times older than the canonical age (Mermilliod 1981). This is roughly the same effect that we are finding for \( \alpha \) Per. As discussed by BMG and Basri (1998b), this discrepancy can be solved with convective core overshooting in evolutionary models of UMST stars. Meynet, Mermilliod, & Maeder (1993) computed models with moderate overshooting and obtained older ages for the Galactic open clusters. In particular, they found 100 Myr for the Pleiades and 52 Myr for \( \alpha \) Persei. These ages are more in agreement with the ages inferred from lithium in VLM members than the previous ones obtained without overshooting.

The lithium results actually indicate that the cluster ages are somewhat older than the Meynet et al. (1993) scale, suggesting that stronger overshooting is necessary in their models. On the other hand, the overshooting employed by Mazzitelli & Pigatto (1989) was too strong because it yielded a Pleiades age of 150 Myr. Very recently, Ventura et al. (1998) have redone the convective overshoot calculations using the "full spectrum turbulence" treatment of Canuto, Goldman, & Mazzitelli (1996). With approximately the same amount of overshoot as Maeder et al., they find the same ages for the Pleiades and \( \alpha \) Per as we do (presuming that AP 281 is indeed a member). While such good agreement may be fortuitous, it does indicate that the lithium dating technique is robust and that the source of its disagreement with classical UMST ages almost certainly lies in the stellar evolution treatment of high-mass stars.

We conclude that the lithium observations of VLM cluster members can provide the best way of empirically calibrating the amount of convective overshooting in high-mass stars, as first suggested by BMG. Obviously we should continue trying to define the lithium boundary in open clusters of various ages to refine these conclusions, and in \( \alpha \) Per itself it is important to locate a number of other stars near the substellar boundary and test them for lithium.

### 3.4. Is AP 270 a Brown Dwarf?

The mass of any VLM cluster member can be estimated from its luminosity, once the cluster age is established (Fig. 6). With our adopted age of 65 Myr, the mass of AP 275 is a little over 0.1 \( M_\odot \), the mass of AP 270 is right at the substellar limit of 0.075 \( M_\odot \) (75 jupiters), and if AP 281 is a member, its mass would be around 0.087 \( M_\odot \). If the cluster is even older, then all three objects are stellar. On the other hand, if the age is any less than 65 Myr, then AP 270 moves more comfortably into the substellar domain. The boundary of lithium reappearance is not expected to coincide with the substellar boundary in this cluster; at the bottom right-hand corner of Figure 6, the depletion line crosses the substellar boundary at about 120 Myr (the age of the Pleiades). Thus, we would expect stars a little brighter than AP 270 to also show lithium. Alternatively, if the cluster is 75 Myr old, then AP 270 is itself a star that shows lithium. In any case, AP 270 is a benchmark object defining the reappearance of lithium in the \( \alpha \) Persei open cluster. Brown dwarf candidates fainter than AP 270 have not been identified yet. They should be well within the capabilities of present CCD imaging systems on 2 m–class telescopes, and we are conducting a program to find them.

The mass estimated from the presence of lithium in AP 270 allows us to test the predictions of theoretical evolutionary models at the substellar boundary. For an age of 65 Myr and a mass of 0.075 \( M_\odot \), the Baraffe models predict absolute magnitudes of \( M_V = 14.55 \), \( M_J = 11.50 \), and \( M_I = 9.37 \), which can be compared with \( M_V = 15.24 \), \( M_J = 11.40 \), and \( M_I = 9.25 \) for AP 270 obtained using a distance modulus of 6.33 and an interstellar reddening of \( A_V = 0.3, E(V-I) = 0.16 \). The predicted magnitudes are only 0.1 mag faint in \( I \), and \( J \), but for \( V \) the predicted magnitude is uncomfortably bright. The use of atmospheric opacities that include the effects of dust may help to reduce the discrepancy in \( V \). Increasing the brightness of the models in \( I \) and \( J \), and \( V \) would help in Figure 4 to reconcile the isochrone age with the lithium age. This would also help with the problem that the faintest two \( \alpha \) Per members appear to be substellar in Figure 4, while we have argued above that they are not so low in mass. The increase needed is 0.3 mag, however. The Burrows models are brighter, but we do not have the specific color predictions that would allow us to make the comparison with our photometry.

A fine analysis of our high-resolution spectra using spectral synthesis should be able to determine the surface lithium abundance of AP 270. The same kind of analysis should provide good estimates of the temperature and gravity of AP 270, which would be very useful for testing evolutionary models. It would also result in improved estimates of AP 270's age and mass. We are beginning a larger program of fine analysis for several of the currently known BDs, using models of Allard and Hauschildt that include the effects of dust.

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