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THE AGE OF AB DORADUS[1]

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ABSTRACT

We have derived a new age estimate for the nearby young star AB Dor and have investigated the resulting implications for testing theoretical evolutionary models with the data reported by Close and coworkers for the low-mass companion AB Dor C. Using color-magnitude diagrams, we find that the AB Dor moving group is roughly coeval with the Pleiades ($\tau = 100$–125 Myr) and is clearly older than IC 2391 ($\tau = 35$–50 Myr). In fact, based on a comparison of the kinematics of AB Dor and the Pleiades, we suggest that the stars identified by Zuckerman and coworkers as members of a moving group with AB Dor are remnants of the large-scale star-formation event that formed the Pleiades. Using the age of $\tau = 50^{+50}_{-20}$ Myr adopted by Close, the luminosity predicted by the models of Chabrier and Baraffe for AB Dor C is larger than the value reported by Close but is still within the quoted uncertainties. Meanwhile, the agreement is good when our age estimate for AB Dor C is adopted. Thus, we find no evidence in the data presented by Close for AB Dor C to suggest that previous studies using the models of Chabrier and Baraffe and bolometric luminosity as the mass indicator have significantly underestimated the masses of young low-mass stars and brown dwarfs.

Subject headings: infrared: stars — stars: formation — open clusters and associations: individual (IC 2391, Pleiades) — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

Surveys of young open clusters and star-forming regions have identified hundreds of very faint members that appear to be brown dwarfs (Basri 2000). However, the mass estimates for these objects are dependent on the validity of theoretical evolutionary models (e.g., D'Antona & Mazzitelli 1997; Baraffe et al. 1998; Chabrier et al. 2000). Close et al. (2005, hereafter C05) recently tested the accuracy of the masses derived from these models with observations of a low-mass companion to the young nearby star AB Dor. By combining their adaptive optics images of AB Dor C and the astrometry of the primary from Guirado et al. (1997), they measured a mass of $M = 0.09 \pm 0.005\ M_{\odot}$. C05 found that the theoretical evolutionary models of Chabrier et al. (2000) overestimated the near-infrared (IR) fluxes of AB Dor C by roughly 1 mag. They concluded that the use of these models to interpret photometry of young low-mass objects leads to masses that are underestimated by a factor of 2 and that many of the objects previously identified as brown dwarfs in star-forming regions and open clusters are instead low-mass stars. The age for AB Dor is important in this context because the comparison of the observed luminosity of AB Dor C to theoretical models requires an assumed age. For instance, if AB Dor had an age of 100 Myr instead of 50 Myr as assumed by C05, much of the discrepancy between model and observations would disappear. Therefore, in this Letter we reexamine the age of AB Dor.

2. ANALYSIS

In adopting an age for the AB Dor system, C05 considered the apparent displacement of AB Dor above the main sequence, AB Dor's rapid rotation and high lithium abundance, and, in particular, its membership in a moving group (Zuckerman et al. 2004). The age for this moving group was derived by Zuckerman et al. (2004) from a comparison of its Hα emission strengths to those of the Tucana group and from a comparison of its three M-type members to isochrones for 10 Myr and the zero-age main sequence (ZAMS) in a diagram of M_V versus $V - K_s$, which indicated that the AB Dor group is older than Tucana ($\tau > 30$ Myr) and younger than the ZAMS for M stars. Based on this analysis, Zuckerman et al. (2004) reported an age of 50 Myr for the AB Dor group. C05 subsequently adopted this age and assigned an uncertainty of $+50/-20$ Myr.

In the following analysis, we reexamine the isochronal age of the AB Dor moving group by including the M-type companion AB Dor B (Rossiter 137B), which was not considered by Zuckerman et al. (2004) and C05, and by comparing the AB Dor group to the Pleiades and IC 2391 open clusters. We then use modern astrometric data to investigate the previously proposed notion that AB Dor shares a common origin with the Pleiades supercluster (e.g., Innis et al. 1986).

2.1. *The Isochronal Age of the AB Dor Moving Group*

The evidence for a physical association between AB Dor A and B is quite compelling. First, the trigonometric parallax of AB Dor from the Very Long Baseline Interferometer places it within 25 pc of the Sun, and the spectroscopic parallax for AB Dor B suggests it is also within about 25 pc of the Sun if it has an age $\gtrsim$50 Myr. Based on the number density of stars in the solar neighborhood (Reid et al. 2002), the probability of finding two stars within 10″ of each other and closer to the Sun than 25 pc that are not physically associated with each other is $\sim 4 \times 10^{-6}$. Second, the proper motion of AB Dor is fairly large ($\sim$0″.1 yr^{-1}), but the separation and position angle between AB Dor A and B have remained sensibly constant for

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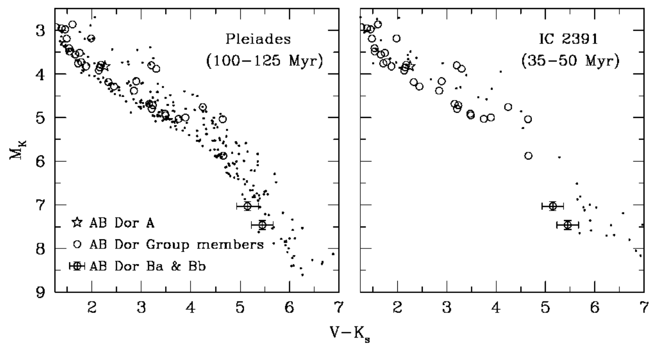

FIG. 1.—M_K vs. $V - K_s$ for the nearby star AB Dor (*star*), its companions Ba and Bb (*circles with error bars*), and the members of the AB Dor moving group (*circles*; Zuckerman et al. 2004). The sequence formed by these stars coincides with the sequence for the Pleiades (*left*; $\tau = 100$–125 Myr; Meynet et al. 1993; Stauffer et al. 1998a) and falls well below the sequence for IC 2391 (*right*; $\tau = 35$–50 Myr; Mermilliod 1981; Barrado y Navascués et al. 1999, 2004). The vertical dispersions of the open cluster sequences are primarily due to the presence of binaries, with observational error being a very minor contributor.

80 years. The radial velocities of the two stars also agree to within the measurement errors of a few kilometers per second (Innis et al. 1986). Third, both stars are demonstrably very young, based on their spectroscopic, radio, and X-ray characteristics (Lim 1993). Taken together, the likelihood that these two stars are unrelated is extremely small. Therefore, nominally one should be able to obtain a better isochronal age estimate for the AB Dor system from AB Dor B than from AB Dor itself, because the displacement above the ZAMS is larger at lower masses for a given pre–main-sequence age.

The most direct, least model-dependent way to infer an isochronal age for the members of the AB Dor moving group is via a comparison to empirical isochrones defined by well-observed open clusters. For this comparison, we select the Pleiades and IC 2391, which have ages of 125 and 50 Myr, respectively, according to analysis of their Li depletion boundaries (Stauffer et al. 1998a; Barrado y Navascués et al. 1999, 2004). Somewhat younger ages of 100 and 35 Myr have been derived from their upper main sequence turnoffs (Meynet et al. 1993; Mermilliod 1981). We compiled a list of members of the Pleiades from Stauffer & Hartmann (1987) and Stauffer et al. (1998b) and a list of members of IC 2391 from Stauffer et al. (1989, 1997) and Barrado y Navascués et al. (2004). For these members, we adopt the V measurements from those studies and data at K_s from the Two Micron All Sky Survey (2MASS). The well-documented error in the *Hipparcos* distance to the Pleiades indicates that for clusters beyond 100 pc, accurate main-sequence distances are preferred over *Hipparcos* measurements (Pinsonneault et al. 1998, 2004; Soderblom et al. 2005). Thus, we adopt distances of 133 and 154 pc and extinctions of $A_V = 0.12$ and 0.03 for the Pleiades and IC 2391, respectively (Soderblom et al. 2005; Forbes et al. 2001).

For the AB Dor moving group, we consider the members identified by Zuckerman et al. (2004) as well as the components of the AB Dor multiple system. We adopt the distances for these stars from Perryman et al. (1997), except for the two stars that lack *Hipparcos* measurements, which are excluded. We use the Johnson V data compiled by Perryman et al. (1997) for all stars except AB Dor A and B, for which we take V from Cameron & Foing (1997). Measurements at K_s are adopted from 2MASS for all stars. Using the internal 2MASS database, D. Kirkpatrick kindly checked the accuracy of the 2MASS data for AB Dor A and B, which are separated by 9″. He found that the two stars are well resolved in the short "Read 1" exposures and that the photometric measurements from two separate observations agree within a few percent for both stars. AB Dor B itself is a close binary (C05). We have estimated the individual V and K_s magnitudes of the components by combining the measured flux ratio at K_s (C05), the unresolved photometry, an assumption of coevality, and the relation between ΔV and ΔK_s implied by the empirical isochrone in the form of the Pleiades sequence. The uncertainties in the distance, combined photometry, and flux ratio for AB Dor Ba and Bb produce 1 σ errors of ± 0.22 and ± 0.1 mag in their individual values of $V - K_s$ and K_s, respectively.

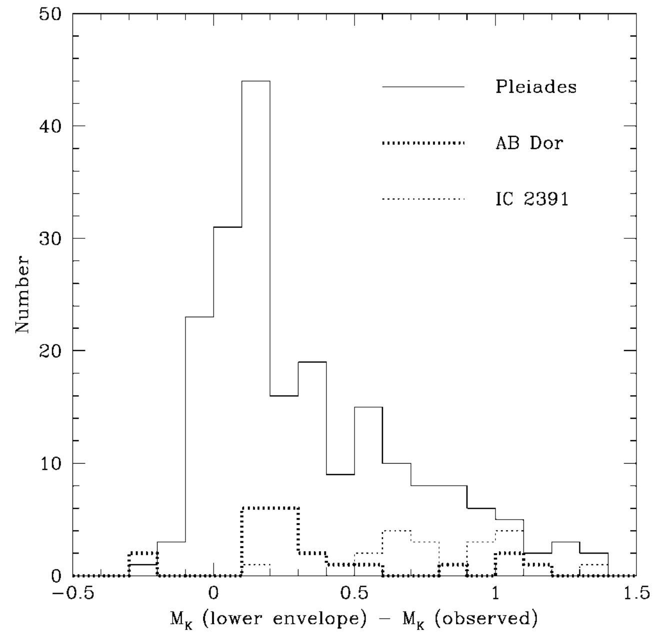

FIG. 2.—Histograms of M_K offsets in Fig. 1 between the lower envelope of the Pleiades sequence and the observed positions of stars in the Pleiades (*solid line*), the AB Dor moving group (*thick dotted line*), and IC 2391 (*thin dotted line*). The mean offsets are $\langle \Delta M_K \rangle = 0.34$, 0.35, and 0.83 mag, respectively.

The data for the Pleiades and IC 2391 open clusters and the AB Dor moving group are plotted together in a diagram of M_K versus $V - K_s$ in Figure 1. We find that the K- and M-type members of the AB Dor group on average fall well below the sequence of IC 2391. These data clearly demonstrate that the AB Dor moving group is older than IC 2391 ($\tau = 35$–50 Myr). Meanwhile, the sequence for the AB Dor group closely matches that of the Pleiades. To quantitatively compare these sequences, we have measured the offset in M_K between the observed position of each star and a fit to the lower envelope of the Pleiades sequence and have generated a histogram of these offsets for each population. We consider only stars at $V - K_s = 2$–5.5, because bluer stars have very small displacements above the ZAMS for the ages in question, and redder stars are not present in the known membership of the AB Dor group. A visual comparison of these histograms in Figure 2 indicates an offset of 0–0.1 mag between the AB Dor group and the Pleiades, which suggests that AB Dor is coeval with the Pleiades or is slightly younger. An offset of 0.1 mag for the AB Dor group would correspond to an age of 90–100 Myr if we use an age of 100–125 Myr for the Pleiades and the differential luminosities predicted by Baraffe et al. (1998). However, the mean offsets of the Pleiades and AB Dor sequences are indistinguishable, with $\langle \Delta M_K \rangle = 0.34$ and 0.35 mag, respectively. In addition, AB Dor Ba and Bb are clearly not younger than the Pleiades, and these stars should be given the greatest weighting in this exercise, given that they are much more directly and unambiguously associated with AB Dor than the moving group members and that they are better age indicators on a color-magnitude diagram than earlier type stars. The use of photometry in other bands and colors, such as V and $V - I$, produces the same position of AB Dor Ba and Bb relative to the Pleiades. Note that C05 reported that AB Dor C is overluminous relative to the Pleiades; this apparent discrepancy is resolved by a forthcoming analysis of the spectral classification of AB Dor C (K. L. Luhman et al. 2005, in preparation).

As for AB Dor itself, previous studies appear to rule out binarity as an explanation for its overluminous nature relative to the Pleiades, but its extremely rapid rotation is a plausible cause. Such effects on the H-R diagram have been predicted from evolutionary models of solar-type stars (Sills et al. 2000), although they have not been obvious in observations to date (Stauffer & Hartmann 1987). We also note that at least one solar-type member of the Pleiades, HZ 102, is like AB Dor A in that its overluminous position on the color-magnitude diagram appears not to be due to binarity. Thus, strictly from an empirical point of view, AB Dor appears to be consistent with the Pleiades on a color-magnitude diagram.

The Li equivalent width and $v \sin i$ of AB Dor are similar to the values observed for rapidly rotating K dwarfs in the Pleiades (Soderblom et al. 1993; as well as in IC 2391, Stauffer et al. 1989; Randich et al. 2001). In addition, the Hα emission strengths for the M-type members of the AB Dor group (Vilhu et al. 1991; Zuckerman et al. 2004) are indistinguishable from measurements in the Pleiades (Soderblom et al. 1993; Jones et al. 1996; Terndrup et al. 2000; Oppenheimer et al. 1997; Stauffer & Hartmann 1987), as illustrated in Figure 3. Thus, these age diagnostics are consistent with the coevality of the AB Dor group and the Pleiades that is suggested by the color-magnitude diagram. Based on the above considerations, a conservative age range for the AB Dor multiple system and moving group is 75–150 Myr.

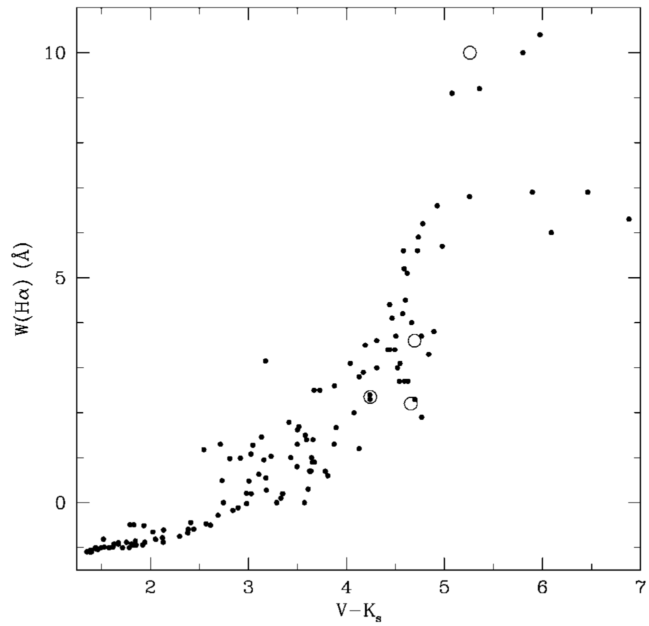

FIG. 3.—Equivalent widths of Hα vs. $V - K_s$ for AB Dor B (*top circle*), the three additional M-type members of the AB Dor moving group (*bottom circles*), and members of the Pleiades (*points*). Positive equivalent widths represent emission.

2.2. *The Kinematic Origin of the AB Dor Moving Group*

To calculate the Galactic space motion of AB Dor, we use the equations from Johnson & Soderblom (1987), the weighted mean radial velocity from studies that measured the quantity multiple times (+28.5 ± 0.6; Collier Cameron 1982; Vilhu et al. 1987; Balona 1987; Innis et al. 1988; Donati et al. 1997; Nordström et al. 2004), the long-baseline proper motion from the Tycho-2 catalog (Høg et al. 2000), and the weighted mean of the *Hipparcos* and Tycho-1 trigonometric parallaxes (Perryman et al. 1997). We derive a heliocentric Galactic space motion vector for AB Dor of $U = -7.7 \pm 0.4$ km s^{-1}, $V = -26.0 \pm 0.4$ km s^{-1}, and $W = -13.6 \pm 0.3$ km s^{-1}. For comparison, we calculated a velocity vector for the Pleiades using the new distance estimate from Soderblom et al. (2005) and the proper motion, radial velocity, and mean cluster position from Robichon et al. (1999), arriving at $U = -6.6 \pm 0.4$ km s^{-1}, $V = -27.6 \pm 0.3$ km s^{-1}, and $W = -14.5 \pm 0.3$ km s^{-1}. An immediate result of this analysis is that AB Dor is only ~2 km s^{-1} from the Pleiades in velocity space. But how close is AB Dor to the Pleiades space motion compared to stars in the field? For a field sample, we use the 13,222 stars with calculated *UVW* velocity vectors from the magnitude-limited sample of F/G-type stars from Nordström et al. (2004). AB Dor is the fourth closest star to the Pleiades in terms of velocity, using the vector from Nordström et al. (2004; it is present in the sample despite its K spectral type), while it is the eighth closest star, according to our revised vector. Many of the AB Dor group stars from Zuckerman et al. (2004) are in the sample from Nordström et al. (2004) and are among the ~40 closest stars to the Pleiades mean motion. These stars include HD 45270, HD 19183, PW And, and UY Pic. Out of the 40 stars closest to the Pleiades vector from the Nordstrom catalog, 13 are listed as members of the AB Dor moving group by Zuckerman et al. (2004). Hence, AB Dor and its moving group members are in rather exclusive company among the ~0.3% of stars in the Nordstrom catalog that are nearest the Pleiades velocity vector.

Kinematic analysis of the *Hipparcos* catalog (Perryman et al. 1997) has shown that many young BAF-type stars have motions clustered near that of the Pleiades cluster (e.g., Chereul et al. 1998, 1999; Asiain et al. 1999), which has been referred to as the Local Association or the "Pleiades supercluster" (Eggen 1970, 1975). Innis et al. (1986) suggested that AB Dor might belong to the Pleiades supercluster, while more recently, Zuckerman et al. (2004) has proposed the existence of a moving group with AB Dor. Zuckerman et al. (2004) reasoned that the more negative V (~−27 km s^{-1}) and W (~−14 km s^{-1}) velocity component of the AB Dor group makes it distinctive from other recently discovered young stellar groups within 100 pc of the Sun, but AB Dor's velocity is directly coincident with the Pleiades, as we have shown. Very young open clusters are often found to be surrounded by unbound OB associations (Garmany 1994), a situation observed today with the α Persei cluster (de Zeeuw et al. 1999). We suggest that the systems identified by Zuckerman et al. (2004) as members of a moving group with AB Dor are probably the remnants of unbound OB and T associations connected with the star-formation event that formed the bound Pleiades open cluster.

3. DISCUSSION

We now use our new estimate of the age of AB Dor in testing the theoretical evolutionary models of Chabrier et al. (2000). C05 tested these models by comparing the observed and predicted values of M_J, M_H, M_K, and $T_{\rm eff}$ for AB Dor C. However, the predicted near-IR magnitudes are subject to known deficiencies in the opacities used in the synthetic spectra. Indeed, discrepancies between observed and synthetic colors and magnitudes at near-IR wavelengths have been noted in previous studies (e.g., Chabrier et al. 2000; Leggett et al. 2001). Instead, the most fundamental and robust parameter predicted by any set of models is the bolometric luminosity. In addition, the masses of young low-mass objects are typically inferred from the predicted luminosities rather than near-IR magnitudes. Therefore, we consider this parameter in the following discussion.

To test the predicted luminosity for AB Dor C, we use the diagrams of luminosity versus age in Figure 4. We show the luminosity of $0.0018 \pm 0.0005\ L_\odot$ derived by C05 with the estimates of age for AB Dor C from C05 and from this work. Although C05 reported a significant difference between the observed and predicted near-IR fluxes for AB Dor C (primarily *J* and *H*), Figure 4 demonstrates that the predicted bolometric luminosity is actually consistent with their measured value within the uncertainties. Meanwhile, using our estimate of the age of AB Dor C, the data and model predictions agree reasonably well. The claim by C05 that the masses of young low-mass stars and brown dwarfs are significantly underestimated using the models of Chabrier et al. (2000) hinged on the assumed age for AB Dor C (as well as its other stellar properties). Because our best estimate for the age of the AB Dor system is twice as old as they assumed, we find no significant discrepancy with the model predictions when using bolometric luminosity as the mass indicator.

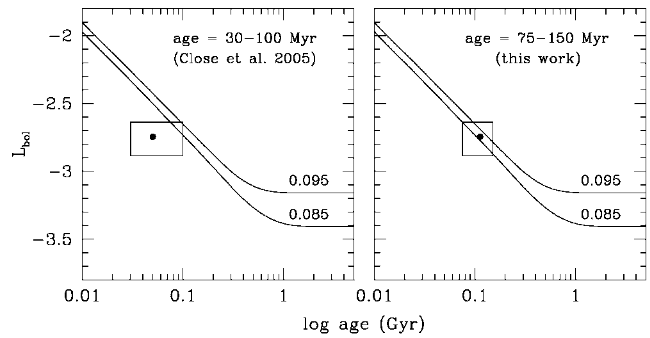

FIG. 4.—Comparison of the luminosity of AB Dor C reported by C05 to the values predicted by the evolutionary models of Chabrier et al. (2000) for masses bracketing its dynamical mass of $0.09 \pm 0.005\ M_\odot$ (C05). *Left*: Using the age adopted by C05, the models appear to overestimate the luminosity of AB Dor C, although the observed and predicted values overlap within the measurement uncertainties (*rectangles*). *Right*: The agreement is better with our age estimate.

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