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# AN AGE ESTIMATE FOR THE $\beta$ PICTORIS ANALOG HR 4796A

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## ABSTRACT

We have obtained a high-resolution, moderate signal-to-noise spectrum for the M dwarf companion to HR 4796A, an A0 star with a $\beta$ Pictoris–type IR excess. The spectrum of the M star shows an extraordinarily strong lithium 6708 Å absorption line with an equivalent width of $\sim 550$ mÅ. Age estimates derived from the lithium strength and from pre–main-sequence isochrone fitting indicate an age of about $8 \pm 2$ Myr for HR 4796B. Assuming this age is also applicable to HR 4796A, we conclude that HR 4796A is a relatively normal A star seen at an unusual time (i.e., when it is very young) rather than an A star of "average" age which has somehow managed to retain or acquire a dense, circumstellar disk, in rough agreement with conclusions reached previously by Jura et al.

*Subject headings:* binaries: visual — circumstellar matter — stars: evolution — stars: individual (HR 4796)

## 1. INTRODUCTION

Data from the *IRAS* satellite have been used to show that a small number of early-type stars have IR excesses resulting from circumstellar disks (Aumann et al. 1984; Gillett 1986). The prototype object for this class, $\beta$ Pic, has been studied extensively at optical, infrared, and submillimeter wavelengths (Lagrange-Henri et al. 1989; Telesco et al. 1988; Becklin & Zuckerman 1990) and is the only member of the class for which it has been possible to obtain an optical image of the disk (Paresce & Burrows 1987). Recently, Jura (1991) has suggested that the A0 star HR 4796A is another member of the $\beta$ Pic class. In fact, according to Jura, the *IRAS* data for HR 4796A indicate that its dust disk has twice the optical depth of the disk surrounding $\beta$ Pic. In a subsequent paper, Jura et al. (1993) obtained infrared photometry and low-resolution spectra of an M dwarf companion to HR 4796A, from which they derived an age estimate of 3 Myr for the system. This age is much less than the ages usually quoted for other well-known members of the $\beta$ Pic class: 100 Myr for $\beta$ Pic (Paresce 1991), 200 Myr for Fomalhaut, and 400 Myr for Vega (Backman & Paresce 1993). However, these age estimates are quite uncertain, and a definite pre–main-sequence age for HR 4796B might suggest that the dusty $\beta$ Pic disks could be common features of young A stars rather than rare features of older main-sequence A stars.

Because the interpretation of HR 4796A depends on being able to assign an accurate age, and because HR 4796A is the only $\beta$ Pic star for which an accurate age estimate is currently possible, it is important to attempt to verify the 3 Myr age estimate. This is particularly true because the optical spectrum for HR 4796B shown in Jura et al. (1993) appears to have significant contamination from the A star primary at least near 4000 Å, and their age estimate depends on colors derived from this spectrum. For this reason, we have obtained a high-resolution spectrum of HR 4796B and have used that spectrum to derive two independent age estimates for this star. We also provide accurate radial and rotational velocities and quantitative measures of the chromospheric activity for HR 4796B.

## 2. OBSERVATIONS AND DATA REDUCTION

Our spectrum of HR 4796B was obtained with the echelle spectrograph on the Cerro Tololo Inter-American Observatory 4 m telescope during 1995 January. We used the red, long camera with a 31.6 lines mm$^{-1}$ grating blazed in the red, and a 120 $\mu$m slit width (0".8 on the sky) providing a 2 pixel resolution of about 0.15 Å at H$\alpha$. The detector was a Tektronix 2048 × 2048 CCD, read out with four amplifiers using the new ARCON controller, allowing a spectral coverage of roughly 5800–8200 Å. Our relatively long, 13", slit and seeing consistently of order 1" allowed us to do sky subtraction of the spectra when necessary. The two-dimensional images were reduced and the echelle spectra extracted using standard and nonstandard (i.e., the QUAD package, developed to reduce data from the ARCON controller) packages within IRAF.

The only unusual facet of the reduction of the HR 4796B spectrum was the need to eliminate scattered light from HR 4796A, since the primary star is 7 mag brighter than the secondary and only 7".7 away (Jura et al. 1993). For the observation of HR 4796B, the slit was oriented east-west; given the approximate 225° position angle of the secondary relative to the primary, this placed HR 4796A about 5" from the slit and "above" B. The 1" seeing at the time of the observation made the scattered light signal from the primary $<5\%$ of the signal from B, and sky subtraction appears to have reduced any contamination by the primary to negligible levels (based on, for example, comparison of the detailed shape of the continuum distribution of HR 4796B vs. other stars of the same TiO band structure). Figure 1 shows two sections of our spectrum: one centered near H$\alpha$ and a second centered near the TiO band-

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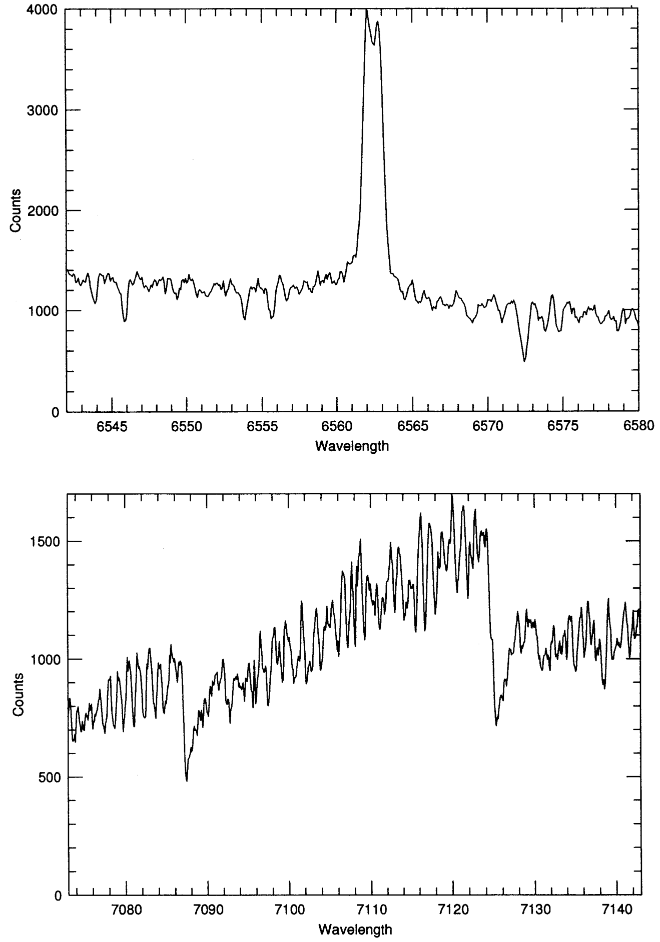

FIG. 1.—Portions of two orders from our echelle spectrum of HR 4796B. The top spectrum shows the strong H$\alpha$ emission line present in this star, while the bottom spectrum shows the TiO bandhead structure near 7100 Å.

head at 7050 Å. The H$\alpha$ strength and profile is quite typical for a dMe star.

### 2.1. *Estimated Color and Spectral Type*

The wavelength region covered by our spectra include several prominent TiO bands, and the strength of these bands provides the best means to determine the intrinsic color of early M dwarfs. During this same observing run, we also obtained spectra for about a dozen late K and early M dwarfs in the young open clusters IC 2391 and IC 2602 for which Cousins system $(V-I)$ colors have been published (Randich et al. 1995; Patten 1995). From these stars we can derive a calibration of the apparent depth of the TiO bands as a function of $(V-I)_c$ color. Figure 2 shows one such plot in which the filled circles are late-type members of the two open clusters and the cross is the point for HR 4796B (the vertical axis value is what we measure, and the location of HR 4796B on the horizontal axis is where it should fall given a least-squares fit to the relation provided by the open cluster stars). We have constructed six such TiO indices, yielding an estimate of $(V-I)_c = 2.37 \pm 0.07$. Correcting for the slight color excesses $E(V-I)_c \sim 0.06$ common to both clusters (Becker & Fenkart 1971), the intrinsic color for HR 4796B is $(V-I)_{c,0} = 2.31 \pm 0.07$. Using the calibration provided by Bessell (1991), this indicates a spectral type of about M2.5. Using the model atmosphere temperature scale of Kirkpatrick et al. (1993), the effective temperature corresponding to this color is ~ 3650 K.

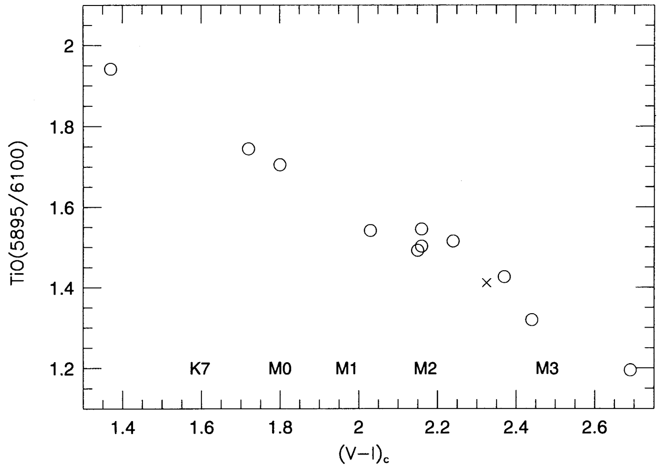

FIG. 2.—TiO band index (the ratio of the continuum height at 6100 Å vs. that found near 5895 Å) vs. $(V-I)_c$ for a sample of stars in IC 2391 and IC 2602. See text for details.

### 2.2. *Lithium Equivalent Width and Abundance*

Figure 3 shows the portion of our spectrum which includes the 6708 Å lithium doublet; the lithium feature is obviously extremely strong. A value of EW(Li) = 550 ± 28 mÅ was obtained by fitting a single Gaussian curve to the Li I + Fe I feature. Since the equivalent width of the Fe I $\lambda$6707.4 line is negligible compared with the equivalent width of the lithium line, we did not try to eliminate this contribution [according to Soderblom et al. 1993, EW (Fe I $\lambda$6707.4) = $20(B-V) - 3$ mÅ, which would be less than the error of our measurement for the M2+ spectral type of HR 4796B].

We have estimated the lithium abundance for HR 4796B using the Pavlenko et al. (1995) curves of growth, which were calculated in non-LTE conditions. For the observed lithium equivalent width, the effective temperature derived above, and a surface gravity of $\log g \simeq 4.3$ (see § 3.1), we derive $\log N$ (Li) = 2.4. For this temperature and equivalent width, the difference between LTE and non-LTE lithium abundances are small (Martín et al. 1994).

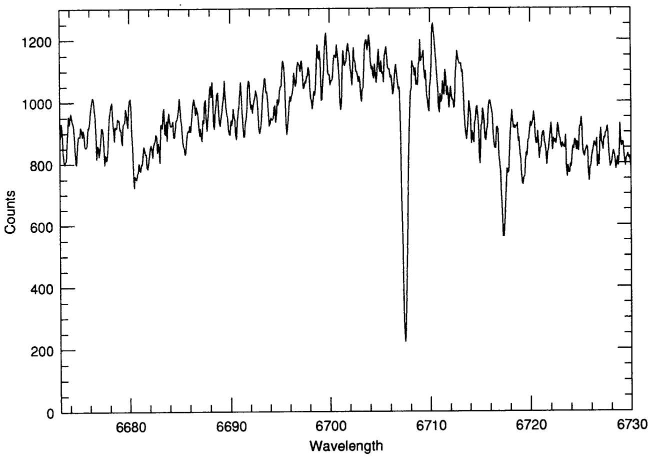

FIG. 3.—A portion of the echelle order containing the lithium 6708 Å absorption line for HR 4796B.

We checked our spectrum for the subordinate line of lithium at 6104 Å, and it is definitely present but blended with a stronger feature. Without a detailed model atmosphere, we do not believe a useful abundance estimate could be made from this feature.

### 2.3. *Radial and Rotational Velocity; Chromospheric Activity*

Radial and rotational velocities for HR 4796B and for the other M dwarfs we observed were obtained by cross-correlation of the program star spectra versus the spectrum of the relatively bright, nearby M dwarf Gl 105B. For this purpose, we chose two orders in the red, where these stars are brightest; these two orders are dominated by TiO bands but do not include a strong bandhead, where the TiO bands become blended. Specifically, the two wavelength regions used for the cross-correlation analysis were 6640–6750 and 7770–7870 Å. To correct for thermal or flexure-induced drifts in the zero point of the wavelength scale, we also cross-correlated a spectral region dominated by terrestrial absorption bands ($\lambda\lambda$7160–7280) and demanded that the Earth's atmosphere be stationary, which is accurate enough for our purposes. Finally, we used spectra of three M dwarfs for which Marcy & Benitz (1989) provide accurate radial velocities (Gl 205, 273, and 447) to set our radial velocity zero point. Our resultant heliocentric radial velocity for HR 4796B is $9.0 \pm 1$ km s$^{-1}$, in reasonably good agreement with the radial velocity of 6 km s$^{-1}$ listed in the Bright Star Catalog for HR 4796A.

By convolving the standard star spectra with rotational broadening functions, it is possible to calibrate the width of the cross-correlation profile as a function of the projected stellar rotational velocity (see Hartmann et al. 1986). After doing this, we derive $v \sin i = 12.0 \pm 1$ km s$^{-1}$ for HR 4796B.

The equivalent width for the H$\alpha$ emission line for HR 4796B is $3.5 \pm 0.5$ Å, where the error is largely dependent on how one places the continuum. The H$\alpha$ profile is slightly broadened, and the central reversal is slightly filled in relative to a more slowly rotating dMe star, as is illustrated in Figure 4, where we overplot the H$\alpha$ profile for a Hyades dMe star (VA 54) that has a similar equivalent width to HR 4796B but whose rotational velocity is $<6.0$ km s$^{-1}$. The other emission features present in our spectrum for HR 4796B are He I $\lambda$5876, which is marginally detected with an equivalent width of $\sim$0.4 Å, and weak emission cores to the Na I D doublet.

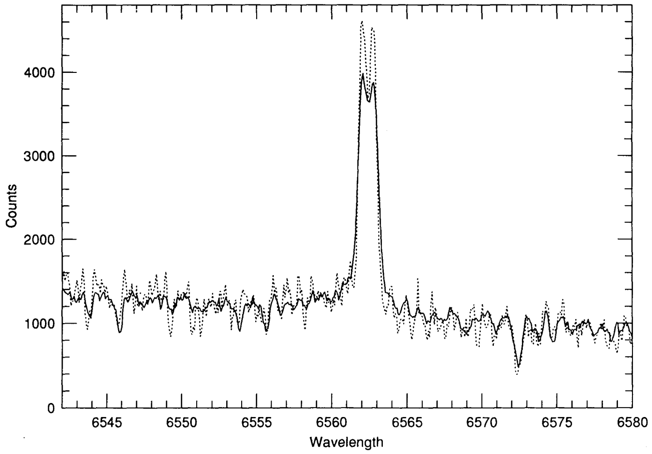

FIG. 4.—Comparison of the H$\alpha$ profile for HR 4796B (*solid line*) and VA 54 (*dashed line*), a Hyades M dwarf. The two stars have approximately the same H$\alpha$ equivalent width, but HR 4796B has a moderate rotational velocity ($v \sin i \sim 12$ km s$^{-1}$), whereas VA 54 is a slow rotator with $v \sin i < 6$ km s$^{-1}$.

## 3. DISCUSSION

### 3.1. *Is HR 4796B a Physical Companion to HR 4796A?*

We believe that the answer to this question is almost certainly yes. The two stars have very similar proper motions (Jura et al. 1993) and their radial velocities are the same to within the errors of measurement. HR 4796B is a very unusual field M dwarf. Only about 5% of the field M dwarfs have rotational velocities $>10$ km s$^{-1}$ (Stauffer & Hartmann 1986). To our knowledge, none of the M dwarfs in the Gliese catalog with spectral types later than or equal to M1 have a detectable lithium 6708 Å absorption feature. The probability of finding such an unusual M dwarf within 8″ of such an unusual A star, particularly since in both cases their unusual nature can be explained by their being very young, seems too remote to warrant further consideration. We consider the two stars to be a physical pair and assume that they have the same age.

### 3.2. *The Age of HR 4796B As Derived from Isochrone Fitting*

Jura et al. (1993) used their photometry and an inferred spectral type of M2–M5 to derive a luminosity of 0.15 $L_\odot$ and an effective temperature of 3500–3100 K for HR 4796B. From comparison to the pre–main-sequence isochrones of Nelson, Rappaport, & Joss (1993, hereafter NRJ), they converted this temperature range to a mass estimate of 0.3–0.15 $M_\odot$. For this mass range, both the NRJ models and the Burrows et al. (1993, hereafter BHSL) models indicate an age $\leq 3$ Myr for luminosities greater than 0.1 $L_\odot$. Their adopted age was thus $\sim 3$ Myr.

We disagree in only a minor way with Jura et al. in terms of these observations: our $(V-I)_c$ color corresponds to a spectral type of M2.5 and thus is at the blue end of their possible spectral type range but still overlaps with the range that they cite, and our derived luminosity for HR 4796B is 0.12–0.15 $L_\odot$, depending on how we determine the bolometric conversion. We do disagree, however, with the procedure used to convert these observations into an age estimate, which involves both the selection of a temperature scale to use for M dwarfs and how one combines this temperature scale with theoretical isochrones. Jura et al. implicitly adopt what can be referred to as a blackbody temperature scale by assigning a temperature of 3500 K at spectral type M2 (see Bessell 1979, 1991). When used in combination with the NRJ and BHSL theoretical models, such temperature scales lead to implausible results for low-mass stars: the models are too blue compared to the observations (BHSL; Monet et al. 1992). If one nevertheless assumes that the models are correct and the temperature scale is valid, when applied to real M dwarfs the inevitable result is that one derives ages that are too young and masses that are too low.

We illustrate the range of possible results one can obtain by adopting differing M dwarf temperature scales for a given single theoretical model in Figure 5, where we compare photometry for low-mass stars in the Pleiades (age = 70 Myr) to theoretical isochrones from D'Antona & Mazzitelli (1994). Figure 5*a* shows the result using a blackbody temperature scale (Bessell 1979). Instead of following the empirical isochrone, the theoretical isochrones cross through the lower envelope of the Pleiades stars, suggesting that the early Pleiades M dwarfs have ages of order 50 Myr but the latest M dwarfs shown have ages less than 10 Myr. Also shown in

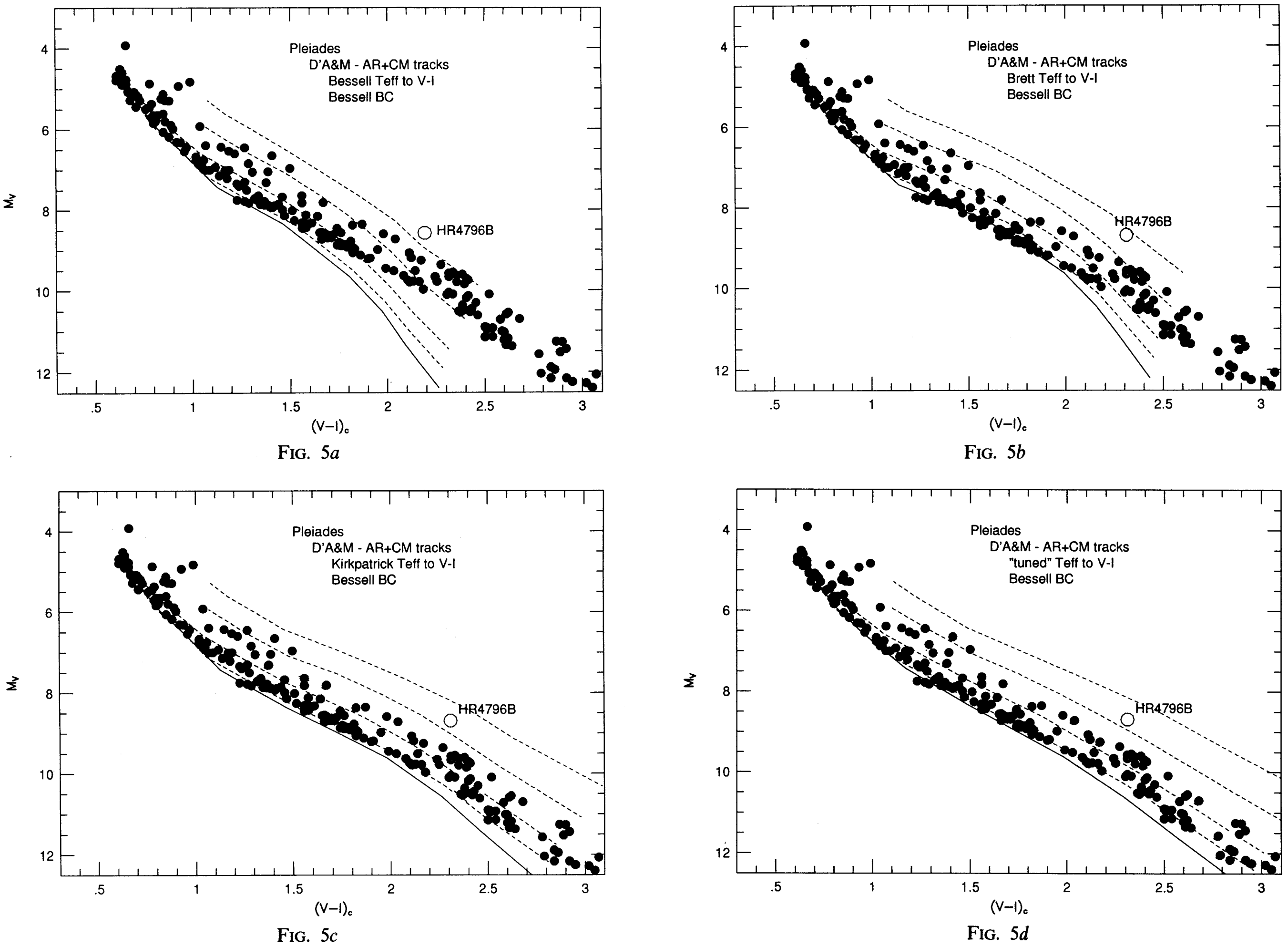

FIG. 5a

FIG. 5b

FIG. 5c

FIG. 5d

FIG. 5.—(*a*) $M_V$ vs. $(V-I)_c$ diagram for low-mass members of the Pleiades (age $\simeq$ 70 Myr). The theoretical tracks are from D'Antona & Mazzitelli (1994); specifically, the tracks are for the Alexander + Rogers opacities and Canuto-Mazzitelli (CM) treatment of convection. Bolometric corrections from Schmidt-Kaler (1982) were used for $T_{\rm eff} > 4000$ K and from Bessell (1991) for $T_{\rm eff} < 4000$ K. A conversion from effective temperature to $(V-I)_c$ from Bessell (1979) was adopted. Tracks are shown for 3 Myr, 10 Myr, 35 Myr, 70 Myr, and a ZAMS. Also shown is the location of HR 4796B. (*b*) Same as (*a*), except that for $T_{\rm eff} < 4000$ K, we have adopted the model atmosphere temperature scale from Brett (1995). (*c*) Same as (*a*), except that for $T_{\rm eff} < 4000$ K, we have adopted the model atmosphere temperature scale from Kirkpatrick et al. (1993). (*d*) Same as (*a*), except that for $T_{\rm eff} \leq 4500$ K, we have adopted a temperature scale tuned to force a match between the 70 Myr theoretical isochrone and the lower envelope to the Pleiades stars. See text and Table 1 for details.

Figure 5*a* is the location of HR 4796B using our data, from which one would infer an age of order 2–3 Myr (and a mass of order 0.3 $M_\odot$), in apparent agreement with Jura et al. Because of the behavior of the Pleiades stars, however, we argue that for M dwarfs it is inappropriate to use this theoretical model and this temperature scale together, and that any age so derived is invalid. Instead, one must link the choice of theoretical model to the choice of the M dwarf temperature scale and require that the chosen combination reproduce the empirical zero-age main sequence (ZAMS) or empirical isochrones for young clusters. With that validation, it is then possible to use the theoretical model isochrones to estimate the age of individual stars such as HR 4796B.

Figures 5*b*–5*d* provide the results of using three other temperature scales with the D'Antona & Mazzitelli model isochrones. The four temperature scales used in Figure 5 are summarized in Table 1. In all cases, the temperature scale for G and K dwarfs ($T > 4500$ K) is from Bessell (1979). Figure 5*b* uses a new model atmosphere temperature scale for M dwarfs from Brett (1995); this provides a better fit to the Pleiades stars than the blackbody temperature scale, but the lower envelope of the Pleiades stars (the single-star isochrone) still ranges in apparent age from $>100$ Myr (at $V-I \sim 1.5$) to $<30$ Myr (at $V-I > 2.4$). Figure 5*c* uses a model atmosphere–based M dwarf temperature scale from Kirkpatrick et al. (1993). This clearly does a much better job in providing a match between the theoretical 70 Myr isochrone and the Pleiades single-star sequence for the entire color range. There is a slight tendency even here for the K and early M dwarfs ($1.5 < V-I < 2.0$) to fall slightly below the 70 Myr isochrone, while the later M dwarfs fall slightly above the 70 Myr isochrone. By making minor, but ad hoc, changes to the temperature scale used in this figure, we can create a new temperature scale (the "tuned" temperature scale in col. [5] of Table 1) which aligns the theoretical 70 Myr isochrone to the empirical isochrone, as shown in Figure 5*d*. We do not advocate the use of the "tuned" temperature scale for other purposes. However, this temperature scale, or one very similar to it, is what must be used in order to apply these D'Antona & Mazzitelli low-mass isochrones to age date other stars or clusters in a consistent

TABLE 1

TEMPERATURE TO COLOR CONVERSIONS

| $T_{\rm eff}$ (1) | $V-I$ (Be 79)[a] (2) | $V-I$ (Br 95)[b] (3) | $V-I$ (Kirk 93)[c] (4) | $V-I$ ("tuned")[d] (5) |
|---|---|---|---|---|
| 6000.0...... | 0.625 | 0.625 | 0.625 | 0.625 |
| 5500.0...... | 0.760 | 0.760 | 0.760 | 0.760 |
| 5000.0...... | 0.93 | 0.93 | 0.93 | 0.93 |
| 4500.0...... | 1.11 | 1.11 | 1.11 | 1.15 |
| 4000.0...... | 1.57 | 1.76 | 1.57 | 1.60 |
| 3750.0...... | ... | ... | ... | 2.10 |
| 3500.0...... | 2.19 | 2.38 | 2.65 | 2.80 |
| 3000.0...... | 3.03 | 3.18 | 4.05 | 4.20 |
| 2875.0...... | ... | ... | 4.59 | 4.70 |
| 2800.0...... | ... | 3.70 | ... | ... |
| 2750.0...... | 3.58 | ... | ... | ... |

[a] Conversion from Bessell 1979.

[b] Conversion from Bessell 1979 for $T_{\rm eff} \leq 4500$ and from Brett 1995 for lower temperatures.

[c] Conversion from Bessell 1979 for $T_{\rm eff} \leq 4500$ and from Kirkpatrick et al. 1993 for lower temperatures.

[d] Conversion from Bessell 1979 for $T_{\rm eff} \leq 5000$, and as derived here (see text) at lower temperatures.

manner. Plots like those shown in Figures 5*a*–5*d* for low-mass stars in the 35 Myr old clusters IC 2391 and IC 2602 lead to the same conclusions as we have deduced from the Pleiades stars (Stauffer et al. 1995).

We have also made similar tests using theoretical evolutionary tracks provided to us as private communications by Vandenberg (1987) and Swenson (1994). We made plots using each of the three published temperature scales in Table 1 for each of the theoretical models; in Figure 6, we show the best fits for each of the models, where "best" is defined to be where the theoretical isochrones do not cross the empirical Pleiades isochrone. For the Vandenberg tracks, the best fit to the open cluster data is also produced using the Kirkpatrick et al. (1993) temperature scale for M dwarfs; for the Swenson tracks, the best fit is produced using the Bessell (1979) temperature scale for M dwarfs. In neither case, however, is the fit of the 70 Myr theoretical isochrone to the empirical Pleiades isochrone as good as that using the D'Antona & Mazzitelli isochrones. One interpretation of this could be that the Pleiades is actually somewhat older than 70 Myr; using the Vandenberg tracks, a best-fit age would be of order 100–150 Myr, whereas the Swenson tracks (with the Bessell temperature scale) suggest an age >150 Myr for the Pleiades. More likely, we believe, this indicates the need for a different temperature scale or that there are modifications needed in the evolutionary models.

There is a common thread to all of the best-fitting models, and that thread allows us to derive a relatively firm conclusion as to the age of HR 4796B. For each of the models, when one uses a temperature scale which provides as close a fit as possible between the theoretical isochrones and the open cluster isochrones near $(V-I)_c = 2.3$, the age inferred for HR 4796B (as shown in Figures 5*c*, 6*a*, and 6*b*) is 8–10 Myr. The mass we infer for HR 4796B from the best of the fits (Fig. 5c) is 0.48 $M_\odot$. It is our opinion that the age estimate for HR 4796B is robust in the sense that any evolutionary model/temperature scale combination which has been tuned to agree with the empirical open cluster isochrones should give a similar age.

A possibly significant external error to the above age estimate could arise from our adopted $I$ magnitude, which was used in combination with the $(V-I)_c$ color to derive $M_V$. We have taken the $I$ magnitude from Jura et al. (1993); since their $I$ magnitude was estimated from a slit spectrum, it could be in error by a few tenths of a magnitude. Even if it was error free, late-type pre–main-sequence stars can have photometric variability of several tenths of a magnitude from starspots, and so an $I$ magnitude simultaneous with our $(V-I)_c$ color might be preferable. We have derived an independent estimate of the $I$ magnitude for HR 4796B from our slit spectrum. By comparing the count rate at 8000 Å for HR 4796B to several other M dwarfs observed that night at similar air masses, we estimate that the $I$ magnitude for HR 4796B when we observed it was $I_c$(est) = 10.57 ± 0.06 mag, where the 1 $\sigma$ error bar was derived from the scatter of the difference between the estimated magnitudes (derived from the count rates) and the true magnitudes for the other M dwarfs. The formal error bar on our $I$ magnitude is almost certainly fortuitously low, and the true 1 $\sigma$ error is more likely 0.1–0.2 mag. Our $I$ magnitude is about 0.2 mag brighter than that given by Jura et al., and thus if we had used it in Figures 5 and 6 we would have inferred a slightly younger age for HR 4796B, about 6–8 Myr. With our $I$ magnitude and a $K$ magnitude from Jura et al. (1993), we derive $(I-K) = 2.21$

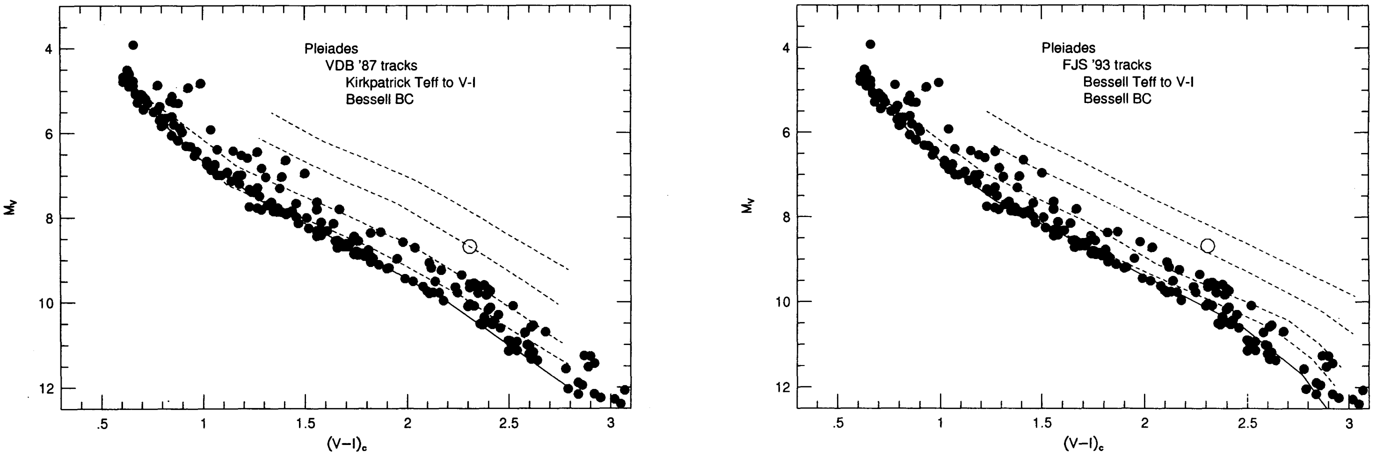

FIG. 6.—Comparison of two other sets of theoretical isochrones to the Pleiades observations. The temperature scale adopted was chosen to provide the closest match between the theoretical isochrones and the Pleiades single-star sequence. The location of HR 4796B is again shown as a large open circle.

1995ApJ...454..910S

for HR 4796B, which is consistent with our $(V-I)_c$ estimate given the possible errors and the nonsimultaneity of the photometry.

### 3.3. *The Age of HR 4796B As Derived from Lithium*

We measure an equivalent width of 550 mÅ for the lithium 6708 Å line in HR 4796B. According to theory, lithium is burned very quickly in stars of this mass; therefore, it is clear from just this datum that HR 4796B is quite young. The lithium equivalent width we observe for HR 4796B is essentially the same as that for LkCa 5 and V710 Tauri B, stars of spectral type M2–M3 and age of order 1 Myr (Martín et al. 1994), and thus HR 4796B could be as young as $\sim 1$ Myr based solely on the lithium equivalent width. It is easy for us to place an empirical upper limit on the age for HR 4796B based on lithium, since none of the eight M dwarfs we have observed in IC 2391 and IC 2602 have detectable lithium. Therefore, we confidently place an upper limit of $< 35$ Myr for HR 4796B.

It is possible to use theoretical models to make this constraint tighter. For example, using Swenson's (1994) models, for a 0.4 $M_\odot$ star, 90% of the initial lithium is still present at an age of 7.5 Myr, while only 10% remains at an age of 10 Myr (and the rest is burned quite soon thereafter). At 0.5 $M_\odot$, 90% of the initial lithium is still present at 5.6 Myr, and only 10% remains by 8.2 Myr (again, with the rest burned very quickly). Based on these models, we place an upper limit to the age of HR 4796B of about 10 Myr. Similar age limits can be derived using the predicted lithium burning timescales obtained by D'Antona & Mazzitelli (1994).

Given the peculiar, and to some extent theoretically unexplained, lithium depletion characteristics for G and K dwarfs in young clusters (Pinsonneault, Deliyannis, & Demarque 1992), it is worth asking whether one should take a lithium age derived in the above manner seriously. We believe that in this case the age limit should be relatively secure. The difficulty with predicting lithium depletion for higher mass stars is that these stars develop radiative cores at about the same time they get hot enough at their centers to burn lithium. The amount of pre–main-sequence lithium burning which is predicted then becomes a very sensitive function of the evolutionary details of the core/envelope boundary. For a star of the mass we infer for HR 4796B (0.4–0.5 $M_\odot$), the models predict that the star is almost fully convective until an age $> 10$ Myr and that the central temperature becomes hot enough to burn lithium prior to 10 Myr. Thus, all the lithium depletion occurs while the star is still fully convective (and, from a modeling standpoint, while its structure is uncomplicated), and the timescale for lithium depletion should be relatively trustworthy.

### 3.4. *The Age of HR 4796B As Estimated from Its Rotational Velocity and Chromospheric Activity*

Rotation and chromospheric/coronal activity decline with age for low-mass stars. Is it possible to use measures of these properties to derive useful, quantitative constraints on the age of HR 4796B? Unfortunately, the answer is most probably not.

Figure 7 compares the chromospheric activity (using Hα as the proxy) for HR 4796B to that for our 35 Myr cluster stars and to low-mass stars in the Hyades (age $\sim 600$ Myr). The figure suggests that HR 4796B is probably younger than the Hyades, though even that conclusion is not absolute since the error bars associated with the HR 4796B point and the points defining the upper envelope for the Hyades distribution probably overlap. The most active stars in our 35 Myr clusters (IC 2391 and IC 2602) do have activity levels as great as that observed in HR 4796B, indicating that based solely on chromospheric activity, HR 4796B could have an age older than 35 Myr. HR 4796 has also been detected as an X-ray source by *EXOSAT* (Giommi et al. 1991). If the X-rays are all from HR 4796B, as is plausible, then $\log(L_X/L_{\rm Bol}) \simeq 10^{-3}$, the "saturation" value for low-mass stars. This is the typical level of coronal activity for Pleiades age and younger M dwarfs (see Stauffer et al. 1994) and thus provides only a loose constraint on the age of HR 4796B.

Consideration of rotational velocities leads to much the same conclusions. To our knowledge, no Hyades star with $2.0 < (V-I)_c < 2.4$ has $v \sin i > 10$ km s$^{-1}$, and thus HR 4796B must at least be younger than 600 Myr. However, M stars with rotational velocities both less than and greater than 10 km s$^{-1}$ exist in clusters with ages from 1 Myr to at least 70 Myr, indicating that the spread in initial angular momentum is too large and spin-down timescales too long for $\sim 0.5$

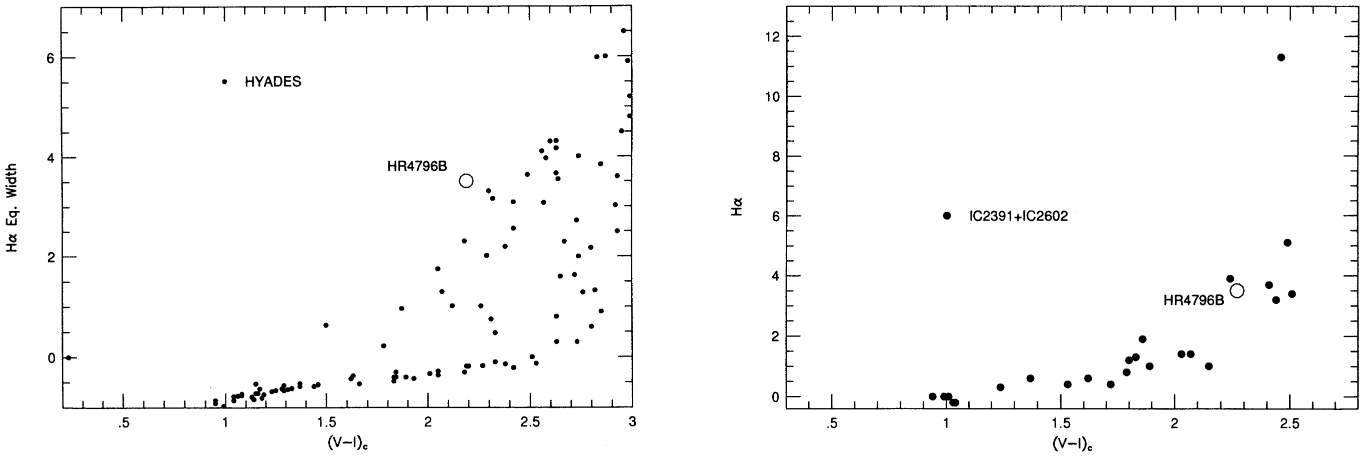

FIG. 7*a* FIG. 7*b*

FIG. 7.—Hα vs. $(V-I)_c$ diagram for (*a*) the Hyades and (*b*) IC 2391 + IC 2602, with a point for HR 4796B marked in both plots. The figure suggests that HR 4796B is probably younger than the Hyades but could be as old (or older) than IC 2391 and IC 2602.

$M_\odot$ stars for rotation to be useful as a means to age date HR 4796B.

## 4. SUMMARY

We have shown that it is possible to place strong, quantitative constraints on the age of the M dwarf companion to HR 4796A based on both the location of HR 4796B in an observational H-R diagram and the strength of its 6708 Å absorption line. The age estimates from both methods give similar results, with a best estimate age from synthesizing the results of the two methods of order $8 \pm 2$ Myr. The rotational velocity and chromospheric activity of HR 4796B also indicates that the system is relatively young, but these properties provide much weaker quantitative age limits. Our age estimate is somewhat older than the 3 Myr age advocated by Jura et al., though we agree with their primary qualitative conclusion that HR 4796 is quite young compared to the ages normally quoted for other $\beta$ Pic stars. The lack of an obvious molecular cloud "cradle" or other nearby high-mass stars of similar age is puzzling if one adopts the 3 Myr age for HR 4796B, particularly so because the wide binary nature of HR 4796 precludes its having been ejected at high velocity from its star-forming region by a two- or three-body interaction with one of its siblings. With an age of 8 Myr, however, it could now be much further from its birth site, and it is more likely that the molecular cloud from which it formed will have dissipated (see Leisawitz, Bash, & Thaddeus 1989). Our age estimate for HR 4796B adds support to the identification of HR 4796 as an outlying member of the Upper Centaurus Lupus association, as suggested by Jura et al. (1993), given the average age of 12–15 Myr for that group (de Geus, de Zeeuw, & Lub 1989).

It is tempting to consider whether the quite young age for HR 4796 should be taken as a sign that the other $\beta$ Pic stars are also quite young. That question is beyond the scope of the current paper, though we note that at least Vega and Fomalhaut are likely to have ages $> 100$ Myr and thus are considerably older than HR 4796B. In addition, $\beta$ Pic could be quite young (Paresce 1991), which might suggest an evolutionary trend from large dust optical depths at young ages to much lower dust optical depths for the "old" $\beta$ Pic stars. Data to be obtained by the *Infrared Space Observatory* may answer this question, since observations have been proposed to search for $\beta$ Pictoris–type disks around A stars in a number of open clusters spanning a range in age from 1 Myr to ~200 Myr.

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