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HD 98800: A UNIQUE STELLAR SYSTEM OF POST–T TAURI STARS[1,2,3]

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ABSTRACT

HD 98800 is a system of four stars, and it has a large infrared excess that is thought to be due to a dust disk within the system. In this paper we present new astrometric observations made with *Hipparcos*, as well as photometry from *Hubble Space Telescope* WFPC2 images. Combining these observations and reanalyzing previous work allow us to estimate the age and masses of the stars in the system. Uncertainty in these ages and masses results from uncertainty in the temperatures of the stars and any reddening they may have. We find that HD 98800 is most probably about 10 Myr old, although it may be as young as 5 Myr or as old as 20 Myr. The stars in HD 98800 appear to have metallicities that are about solar. An age of 10 Myr means that HD 98800 is a member of the post–T Tauri class of objects, and we argue that the stars in HD 98800 can help us understand why post–T Tauris have been so elusive. HD 98800 may have formed in the Centaurus star-forming region, but it is extraordinary in being so young and yet so far from where it was born.

Subject headings: binaries: visual — circumstellar matter — stars: evolution — stars: individual (HD 98800) — stars: pre–main-sequence

1. HD 98800 AS A STELLAR SYSTEM

Zuckerman & Becklin (1993) have noted that "In many ways, HD 98800 is the most unusual source in the *IRAS* catalogs." We concur, and, as we will discuss here, HD 98800 may also be exemplary and instructive as an example of a pre–main-sequence (PMS) star found far from any region of star formation. As we will show, the HD 98800 system is probably about 10 Myr old, meaning that it falls into the category of post–T Tauri stars (PTTs; see Herbig 1978). The dearth of PTTs remains a fundamental problem in stellar evolution, and we will argue that the stars in the HD 98800 system demonstrate why PTTs may have been so difficult to find.

First some nomenclature: what we call "HD 98800" consists of two visible objects, designated HD 98800A and HD 98800B, which are presently separated by about 0$''$.8. Both visible components are spectroscopic binaries, and we will label these four stars hierarchically as Aa, Ab, Ba, and Bb. The orbital and spectroscopic properties of these stars were discussed in Torres et al. (1995) and Soderblom et al. (1996; hereafter Paper I), respectively. To summarize, the Aa + Ab pair has an orbit with a period of 262 days and an eccentricity of 0.484, while the Ba + Bb pair has a period of 315 days and an eccentricity of 0.781 (Torres et al. 1995). The visual pair's orbit is estimated to have a period of at least 10^5 yr with an eccentricity of about 0.993; in other words, the visual pair is marginally bound and we are seeing it near periastron. Three of the stars appear in a Keck HIRES spectrum, and the presence of abundant lithium in all three (Paper I) argues that they are physically related objects, not a chance superposition on the sky. All three stars rotate slowly and show modest levels of chromospheric activity (Paper I).

HD 98800 stands out among K stars because of its large infrared excess. Sylvester et al. (1996) determined a fractional excess IR luminosity (i.e., the IR excess divided by the stellar bolometric flux) of 0.084, but the actual value may be twice that or more if the dust giving rise to this excess is around one star or the other, not both. HD 98800 is now well observed, with photometric data available from the

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[1] Based on observations obtained with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Aeronautics and Space Administration.

[2] Based on data from the ESA *Hipparcos* astrometry satellite.

[3] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology.

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optical (Gregorio-Hetem et al. 1992), infrared (Garcia-Lario et al. 1990; Zuckerman & Becklin 1993), and millimeter-wave regimes (Sylvester et al. 1996). All these observations do not resolve HD 98800 into its components and instead treat it as a single object.

In an analysis of these data, Sylvester & Skinner (1996) applied models to determine that HD 98800 has large (∼1 mm) dust grains (needed to reproduce the millimeter-wave flux). The nominal outer radius of the dust disk determined from their best-fitting model is very large, but they can accommodate an outer radius for the dust disk of as little as 25 AU, which means the dust can fit within the distance of closest approach determined by Torres et al. (1995). The estimated disk mass of Sylvester & Skinner (1996) is $4 \times 10^{-7} M_\odot$.

These analyses account for some of the observations of this system, but they leave more fundamental questions unanswered: How old are the stars in HD 98800? If they are main-sequence stars, as their luminosity classification would suggest, how is it that a dust disk has survived for so long when we anticipate that a typical disk lifetime is only $\sim 10^7$ yr (Skrutskie et al. 1990)? Around which spectroscopic binary (A or B) is the dust disk, or do both pairs have disks? If HD 98800 is a PMS system, how did it get so far from a star-forming region in such a short time? Where was it born? Are there other young stars associated with it? What else can we learn from this system?

We cannot answer all of these questions, but we address them in this paper. Our essential datum is the parallax for the system, which is critical for determining the luminosities of these stars and hence their age. The parallax places HD 98800 at about 47 pc, unambiguously indicating that HD 98800 is a system of pre–main-sequence objects. We have also obtained other observations, including images with *Hubble Space Telescope* (*HST*). As we noted, HD 98800 appears to be a post–T Tauri system, with some implications for that class of objects, but we cannot identify conclusively the origin of this extraordinary system.

2. NEW OBSERVATIONS

2.1. *Hipparcos*

The recently released *Hipparcos* catalog (European Space Agency 1997) provides details on the measurements made with that satellite and the construction of the catalog. The *Hipparcos* results for HD 98800 are listed in Table 1. The $(B-V)$ and $(V-I)$ (Cousins) colors in Table 1 are also from that catalog. *Hipparcos* resolved Aa + Ab from Ba + Bb, as shown by the parameters listed in Table 1.

TABLE 1

Hipparcos RESULTS FOR HD 98800 (HIP 55505)

Parameter	Value
R.A. (J1991.25)	11 22 05.34
Decl. (J1991.25)	−24 46 39.5
m_V	8.89
π (mas)	21.43 ± 2.86
μ_α (mas yr^{-1})	−85.45 ± 1.89
μ_δ (mas yr^{-1})	−33.37 ± 2.12
BT (mag)	10.597 ± 0.038
VT (mag)	9.236 ± 0.021
$(B-V)$ (Tycho)	1.150 ± 0.035
$(V-I)$ (Cousins)	1.11 ± 0.03
Hp	9.0217 ± 0.0030
Position angle (deg)	3
ρ (arcsec)	0.775 ± 0.004

The *Hipparcos* observed magnitude versus time is shown in Figure 1. HD 98800 is flagged as a variable object in the output catalog because of the range of magnitudes seen. No clear periodicity is seen in the variations. The *Hipparcos* parallax of 21.43 mas leads directly to a distance of 47 pc. We will determine luminosities and ages below, but this distance implies that the stars in HD 98800 are too luminous to be main-sequence stars.

2.2. *HST Fine Guidance Sensors*

We used the fine guidance sensors (FGSs) on *Hubble Space Telescope* during cycles 5 and 6 to measure the parallaxes and proper motions of the Aa + Ab and Ba + Bb components separately. The parallax series, obtained with FGS 3, occurred at three epochs, with two orbits of observations at each epoch and with each epoch separated from the next by 6 months. This strategy has been used successfully on other targets to achieve parallaxes with precision of 1–2 mas (Benedict et al. 1995).

However, in this case the complexity and multiplicity of the targets and the angular sensitivity of FGS 3 render the data set insufficient. Both the POS and TRANS mode observations appear to be perturbed by the duplicity of both HD 98800A and HD 98800B. The expected orbital period of each system is near 1 yr, which is nearly ideal for contaminating parallax measurements that are taken $\sim \frac{1}{2}$ yr apart. As a result, the FGS parallaxes for HD 98800 A and B are in agreement with the *Hipparcos* value and show that both stars are at the same distance, but the *Hipparcos* parallax is used here for determining the luminosities.

2.3. *HST WFPC2*

We undertook imaging observations with *HST*'s WFPC2 camera in order to be able to determine separate colors for A and B, and in the hopes of detecting evidence of the dust disk around one star or the other. These observations are listed in Table 2. Stellar fluxes were measured using the standard digiphot-apphot IRAF photometry package. An aperture of 7 pixels was used, and the background was calculated inside an annulus located between 35 and 40 pixels from the star center, well outside both A and B components. We corrected for flux outside the aperture using the Holtzman et al. (1995) correction and

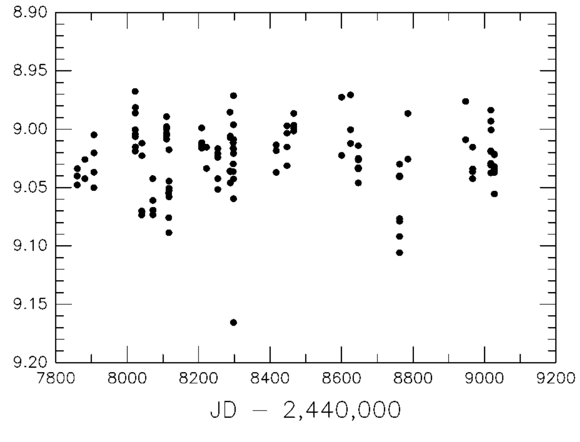

FIG. 1.—*Hipparcos Hp* magnitude vs. day number. The range exceeds that for nonvariable stars, which is approximately 0.01 mag. The points are shown without error bars to reduce confusion, but the median and average uncertainty of a single observation are both 0.017 mag for these 123 measurements.

TABLE 2

WFPC2 OBSERVATIONS

Date	Filter	Exposure Time (s)	Johnson Magnitude
Aa + Ab			
1996 Mar 3......	F439W	2.00	10.532 (*B*)
1996 Mar 3......	F555W	0.11	9.411 (*V*)
1996 Mar 3......	F953N	1.60	8.103 (*I*)
1996 Jan 5.......	F439W	2.00	10.593 (*B*)
1996 Jan 5.......	F555W	0.11	9.466 (*V*)
1996 Jan 5.......	F953N	1.60	8.219 (*I*)
Ba + Bb			
1996 Mar 3......	F439W	2.00	11.358 (*B*)
1996 Mar 3......	F555W	0.11	9.941 (*V*)
1996 Mar 3......	F953N	1.60	8.165 (*I*)
1996 Jan 5.......	F439W	2.00	11.352 (*B*)
1996 Jan 5.......	F555W	0.11	9.944 (*V*)
1996 Jan 5.......	F953N	1.60	8.166 (*I*)

obtained resulting magnitudes in the STMAG system. Small corrections are needed to convert the measured magnitudes from the F439W and F555W filters to the Johnson *B* and *V* bands; These were performed using the IRAF synphot task calcphot. We selected a K4V stellar spectrum from the Bruzual-Persson-Gunn-Stryker spectrum atlas (see Bushouse 1995), determined the correction (Johnson B = F439W + 0.5005 mag; Johnson V = F555W − 0.0072 mag), and finally obtained the Johnson *B* and *V* magnitudes for both components. The images obtained in 1996 January are compromised photometrically because the stars fell near a charge trap; in 1996 March the stars fell on a good portion of the CCD, and so the summary data are based on the 1996 March observations. The combined *V* magnitude we derive for A + B is 8.89, exactly that measured on the ground (Gregorio-Hetem et al. 1992). The combined *B* magnitude is 10.10, again consistent with the ground-based combined magnitude of 10.14. Our longest wavelength observations, in the narrowband F953N filter, require a large correction (Johnson I = F953N − 1.4735 mag) to be compared to ground-based *I* magnitudes and should therefore be viewed with caution, but the magnitude seen in that band is consistent with the $(V-I)$ color listed with the *Hipparcos* observations.

We could see no evidence in the images for non–point-source emission (Fig. 2). We confirmed this by determining a normalized and azimuthally averaged radial profile for star Aa + Ab and then comparing that to the model point-spread function (PSF) computed with the software package TinyTim (Krist 1993). This comparison is shown in Figure 2*b*. Profiles for Ba + Bb are not shown, but they had the same point-source PSF.

2.4. *Discussion and Summary of the Observations*

Because HD 98800 is a multiple system, the *Hipparcos* proper motion is a measure of the mean photocentric

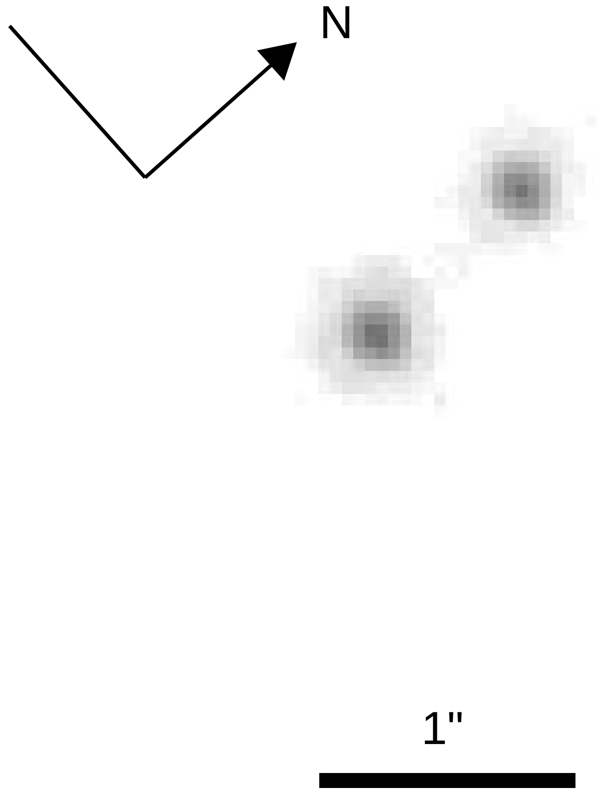

FIG. 2*a*

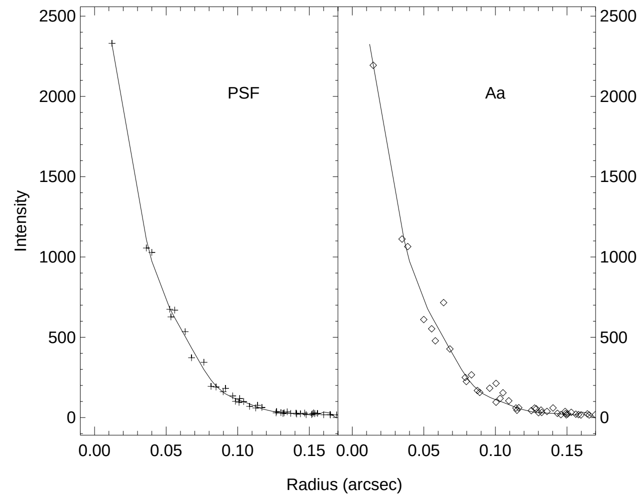

FIG. 2*b*

FIG. 2.—(*a*) WFPC2 F555W image of the HD 98800 system, presented with a logarithmic stretch. (*b*) Radial profile of a PSF computed using the TinyTim software package (*crosses*, *left panel*). A jitter of 15 mas was assumed in the computation. The solid curve is a cubic-spline fit to the plotted points. In the right panel the observed points from the image obtained in 1996 March (F439W, *diamonds*) are shown as a function of radius from the center of the image. The position of the center was determined with the IRAF imcenter task. The same cubic spline from the left panel is shown again, multiplied by a constant scale factor. The excellent agreement between the computed and observed PSFs for the Aa + Ab pair indicates that they are unresolved. A similar analysis for the other filters and for the Ba + Bb pair also shows no evidence for extended structure.

TABLE 3

SUMMARY OF OBSERVATIONS OF HD 98800

Parameter	Value
π (mas)	21.43 ± 2.86
Distance (pc)	46.7 ± 6.2
μ_α (mas yr^{-1})	-89 ± 3.1
μ_δ (mas yr^{-1})	-23 ± 2.9
Radial velocity (km s^{-1})	$+12.75 \pm 0.1$
U (km s^{-1})	-13.2 ± 2.1
V (km s^{-1})	-19.7 ± 1.3
W (km s^{-1})	-3.5 ± 1.5
$V_{\rm Aa+Ab}$ (mag)	9.41
$V_{\rm Ba+Bb}$ (mag)	9.94
$(B-V)_{\rm Aa+Ab}$ (mag)	1.11
$(B-V)_{\rm Ba+Bb}$ (mag)	1.40

motion over the interval of the mission, and that may be unrepresentative of the long-term motion of the system's center of mass (because of the mission's short time baseline and the orbital motion of the stars). Therefore we use the PPM (Bastian & Röser 1993) proper motions here. We adopt the systemic radial velocity of Torres et al. (1995), and use the procedure in Johnson & Soderblom (1987) to calculate the components of the space velocity vector for the J2000 reference frame; these are listed in Table 3.

For the present, we take the WFPC2 photometry to represent the true magnitudes and colors of HD 98800 A and B. There may be circumstellar reddening present, but Sylvester et al. (1996) argue that the dust grains in the HD 98800 system must be large ($\gtrsim 1$ mm) in order to account for the observed millimeter-wave fluxes, and such particles will produce gray extinction.

3. THE EVOLUTIONARY STATUS OF HD 98800

3.1. *Location of the Stars in the H-R Diagram*

The ages of these stars are determined by their temperatures and luminosities, both of which are inferred from the photometry. At a distance of only 47 pc, HD 98800 is unlikely to exhibit significant interstellar reddening, but its infrared excess suggests that circumstellar reddening may be present.

First, we consider the simplest case (case A), for which the temperatures are derived taking the WFPC2 photometry at face value and using Bessell's (1979) color-temperature relation. We also assume that no reddening or extinction are present. The $T_{\rm eff}$ value for component Aa, assumed to be negligibly contaminated by its companion, follows directly from the photometry; its absolute magnitude follows directly from the photometry and parallax. The relative $T_{\rm eff}$ values for the Ba and Bb components with respect to the Aa component were assumed to be identical to those employed in Paper I. The (relatively age-independent) differences in M_V for the Ba and Bb $T_{\rm eff}$ values were estimated from our stellar models (Siess, Forestini, & Dougados 1997), and used to deconvolve the single WFPC2 V magnitude for the B component into individual values for Ba and Bb.

Figure 3 shows the locations in an H-R diagram of stars Aa, Ba, and Bb for the three cases we describe here. (Note that the position of star Bb is shown using the temperature estimated in several ways, but that the luminosity follows from assuming that Bb is the same age as Aa and Ba, and so is not an independent point.) Pre–main-sequence tracks are from Siess et al. (1997), as is the conversion table between luminosity and magnitude. The evolutionary paths are computed for a solar metallicity ($Z = 0.02$,) with relative abundances from Anders & Grevesse (1989). These stars are located near the bottom of the Hayashi track, a radiative core has already developed, and Li is now burning in their convective envelopes. The stellar gravity is very similar for all components: $\log g \approx 4.25$. From the position of the stars in the H-R diagram, we estimate an age for the system of about 7 Myr. The masses of the three components are between 0.8 and 1.0 $M_\odot$ for Aa, 0.75 and 0.85 $M_\odot$ for Ba and 0.45 and 0.6 $M_\odot$ for Bb (Table 4).

As a second scenario (case B), we use the $T_{\rm eff}$ values of Paper I, which were estimated from the Keck HIRES spectrum, together with the same absolute magnitudes of case A (Fig. 3*a*); these same magnitudes are justified for the Ba and Bb components because, while the $T_{\rm eff}$ values are slightly different, the relative values are the same and they predict the same M_V difference used to deconvolve the photometry of the B component. Note that in this case the derived ages of Aa and Ba agree with each other, but at 12 Myr they are somewhat older than for case A. If the case B $T_{\rm eff}$ values are correct and the color-temperature relation is correct, then the observed colors would suggest some reddening: about 0.06 mag in $B-V$ for Aa and 0.08 mag for Ba.

Another possibility, case C, was motivated by investigation of the Li lines described in the next section. An extensive series of syntheses in the 6708 Å Li I spectrum region lead us to believe that the relative fluxes of the Aa, Ba, and Bb components in this regime are near 50%, 40%, and 10%; these are close to the values of Paper I. With initial guesses at the $T_{\rm eff}$ values (essentially those of case A), we solved for the relative radii of the components. These then yielded predicted fluxes at V, which were compared to our WFPC2 photometry. Since initial differences are found, we then determined what extinction of the Ba and Bb components would be necessary to explain the difference in the Li-based predicted fluxes and the observed fluxes. At the same time, the predicted fluxes allowed us to deconvolve the combined WFPC2 V magnitudes of Ba and Bb (with model calculations as described above) and to refine the initial $T_{\rm eff}$ guesses. The procedure is then iterated. We found that an extinction of $A_V \approx 0.44$ mag for Ba and Bb could explain the predicted Li-based and observed *HST*-based V flux differences.

TABLE 4

EVOLUTIONARY PARAMETERS OF HD 98800

Component	$T_{\rm eff}$ (K)	M_V	Age (Myr)	$M/M_\odot$	$\log N$(Li)
Case A $T_{\rm eff}$ from WFPC2 Photometry					
Aa	4350	6.06	7	0.95	3.1
Ba	4100	6.79	7	0.75	2.0
Bb	3550	8.5:	...	0.45	3:
Case B $T_{\rm eff}$ from Paper I, No Reddening Correction					
Aa	4500	6.06	12	1.00	3.1
Ba	4250	6.79	12	0.85	2.2
Bb	3700	8.5:	...	0.6	1.8
Case C $T_{\rm eff}$ from Paper I, Ba + Bb Reddening Corrected					
Aa	4350	6.06	7	0.95	3.1
Ba	4250	6.36	7	0.85	2.3
Bb	3700	8.1:	...	0.5	3:

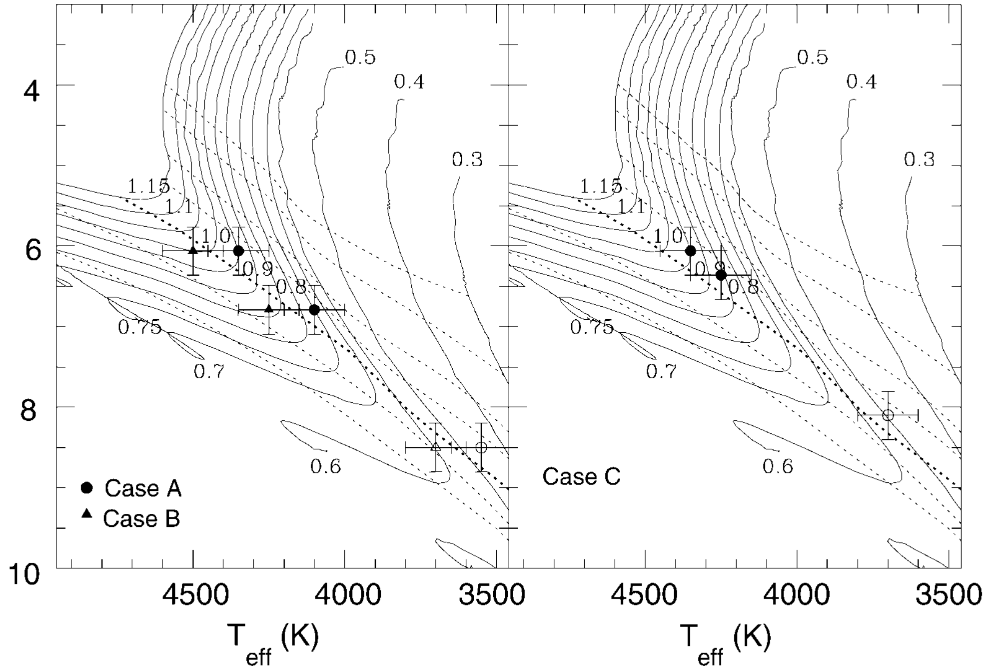

FIG. 3.—H-R diagram and location of the different components of HD 98800. Each mass track (*solid lines*) is labeled in solar units. From top to bottom, the isochrones (*dotted lines*) correspond to ages of 1, 1.5, 3, 5, 10 (*heavy dotted line*), 20, and 40 Myr. Uncertainties are approximately 100 K in T_{eff} and 0.3 mag in M_V. *Left panel*: Cases A (*circles*) and B (*triangles*). *Right panel*: Case C. The points for HD 98800Bb are shown as open points because their position is inferred from the temperature for a particular case assuming Bb has the same age as Aa or Ba. For any one case the stars are in the order Aa, Ba, and Bb from hottest to coolest.

Assuming a standard *interstellar* reddening law of $A_V = 3.1E_{(B-V)}$ (which may be questionable despite the possibility that gray extinction may be present; Sylvester & Skinner 1996), we arrive at final T_{eff} estimates for case C of 4350, 4250, and 3700 K for the Aa, Ba, and Bb components, respectively. The final deconvolved V magnitudes and *Hipparcos* parallax then resulted in $M_V = 6.06$, 6.36, and 8.1 for Aa, Ba, and Bb, respectively. This procedure yields consistent age estimates of 7 Myr for both the Aa and Ba components.

No one of these three cases is a perfect match, but case C is our best guess for the state of the HD 98800 system.

3.2. *Age and Lithium Abundance*

In Paper I it was noted that the large Li abundances of the HD 98800 components were consistent with youth, but that an exact age could not be estimated because of the difficulty of understanding Li depletion in solar-type stars. These large abundances are a robust conclusion that can be affirmed from simple visual comparison of Li λ6708 to the nearby Ca 6717 Å line. Figure 4 of Paper I shows that the Li lines exceed the Ca lines in depth (at least for the Aa and Ba components). In our experience of observing Li in a number of Population I F, G, and K dwarfs, this is a rare circumstance, except in young, Li-rich stars such as some found in the Pleiades. We also compared the relative Li/Ca line strengths to those of cool Pleiades dwarfs, as shown in the Keck HIRES spectra in Figure 1 of Jones et al. (1996), confirming that the Li abundances in the stars of HD 98800 are larger than similar Pleiades stars.

As noted above, we also examined whether these features could yield additional information on the relative flux contributions of the HD 98800 components. One might think that seeking to constrain the abundances and relative fluxes for all three components from just three features is fruitless, but this is not exactly true. In particular, in the regime of large Li abundances we are dealing with here, the intrinsic (undiluted) features are very strong—of near-zero continuum depth. Thus if one errs by underestimating the flux contribution of a given component, one cannot simply increase the Li abundance to reproduce the observed line depth. Instead, such alterations tend to have substantial effects on the line wings, and not the line depths. So while there is some degeneracy, the observed Li line depths tend to be sensitive to the relative flux contributions, while the line profile shape away from line center provides valuable constraints on the Li abundances.

Spectrum synthesis of the 6708 Å region was conducted with an updated version of the LTE analysis package MOOG (Sneden 1973), using the model atmosphere grids of Kurucz (1992, private communication). The line list was taken from the recent work of King et al. (1997). Many combinations of trial T_{eff} values for the three stars were utilized. These included the favored values from Paper I, values adjusted from Paper I given the new *HST* photometry, and a range of a few hundred degrees in these relative T_{eff} values of the three components visible in the spectrum (this could account for extinction of one or more of the components, for example). Arbitrarily varying the Li abundances for all these different T_{eff} values, we sought to improve the synthetic fit shown in Figure 4 of Paper I. In particular, we desired to fit better the maximum flux seen in the red (blue) edge of the Ba (Aa) component without destroying agreement in the line core or making the line wings too broad. This led to a slightly increased flux contribution for Ba at 6707 Å, compared to that used in Paper I.

As a result, it then became challenging to fit the core and red wing of the Aa component.

We found consistently that the relative flux contributions in the 6708 Å region were within a few percent of 50%, 40%, and 10% for the Aa, Ba, and Bb components, respectively. These are close to the values of 50%, 35%, and 15% from Paper I, and they produced good agreement between the observed and synthetic Li profiles. The Li results are summarized in Table 4. These abundances have each been lowered by approximately 0.1 dex to correct for non-LTE effects (the actual corrections are −0.02 dex for star Ba in cases B and C, −0.07 dex for Ba in case A, −0.08 dex for Bb in case A, −0.09 dex for star Aa in all cases and Bb in case C, and −0.16 dex for Bb in case B). The LTE abundances for case B were taken from Paper I. Those for cases A and C are those derived here using the above flux ratios. Unfortunately, none of the several satisfactory flux contribution/parameter combinations we found (including case C above) resulted in very good simultaneous agreement with the photometric flux ratios, relative model radii, and the Bb/Ba mass ratio (0.834) from the orbital solution of Torres et al. (1995).

The main results from this are as follows. First, the plausible combinations we explored did suggest larger Li abundances in Aa than in Ba. Abundances for the former component ranged from 2.7 to 3.3 [on the scale of log $N(\mathrm{H}) = 12$], while abundances for the latter component ranged from 2.1 to 2.8. Second, the case C scenario indicated that the Li abundance of the cooler Bb could be larger than that of the hotter Ba component. While open cluster and field star observations have repeatedly shown a pattern of declining Li abundance with declining T_{eff} (decreasing mass), this behavior of Li increasing for cooler stars, as we see here for HD 98800, is not unexpected. Cooler stars have deeper convection zones, but at some T_{eff} dependent on (at least) age and metallicity, the temperatures and densities at the base of the convection zones are simply too low to deplete as much Li in as much time as a slightly hotter star with a shallower convection zone. This behavior is analogous to that which makes the presence of Li useful in confirming the brown dwarf status of exceedingly cool (but presumably significantly older than HD 98800) objects in the field and young clusters. Indeed, standard evolutionary models we constructed predict this upturn in Li abundance over the range 4200–3900 K for ages of 5–12.5 Myr.

A comparison of our abundances to stellar models is presented in Figure 4, which shows surface Li abundance as a function of T_{eff} for various ages. In our computations, the initial Li content is taken to be $\log N(\mathrm{Li})_0 = 3.31$, the meteoritic value (Anders & Grevesse 1989). As we can see, for a given case the age of the system is strongly constrained. For case B, for example, we derive an age between 10 and 12 Myr. This constraint arises from the component Bb, less massive and still burning its Li efficiently at the bottom of its deep convective envelope. For more massive stars (Aa and Ba), the temperature at the base of the convective envelope is lower, and consequently Li surface abundance is depleted more slowly.

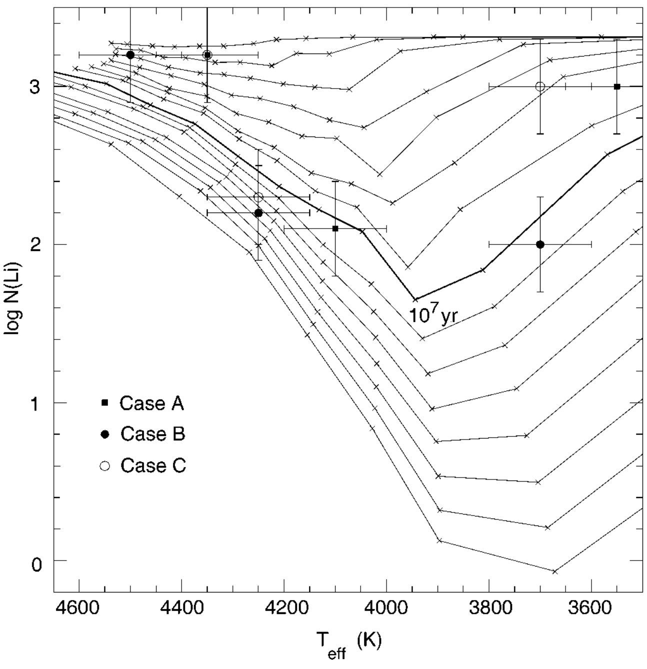

FIG. 4.—Evolution of the surface Li abundance as a function of T_{eff}. Isochrones are equally spaced in time by 1 Myr, starting with 3 Myr at the top to 17 Myr at the bottom. The heavy line corresponds to 10 Myr. Uncertainties are approximately 0.3 dex in the Li abundance and 100 K in T_{eff}. The squares correspond to case A, the solid circles to case B, and the open circles to case C.

3.3. *Conclusions about Age*

The location of the stars of the HD 98800 system in the H-R diagram unambiguously indicates that they are pre–main-sequence stars, and that they are at the bottom of their Hayashi tracks. A comparison of Li abundances to stellar evolution models constrains the age of HD 98800 to ∼10 Myr old, with an uncertainty due to modeling of about 3 Myr. Thus from its evolutionary status HD 98800 presents the characteristics of post–T Tauri stars, ending their fully convective phase and joining a radiative path toward the main sequence.

4. METAL ABUNDANCES

We reanalyzed the Keck HIRES spectrum of the HD 98800 system described in Paper I in an attempt to derive detailed abundances of several metallic elements. In the end we were unable to derive satisfactory abundances. This is due not to complications such as the choppy continuum, frequent severe blending, and the necessity of correcting for the effects of flux dilution; we believe these were handled reliably. Rather, we encountered a wavelength dependence, described below, in the relative line strengths of neutral metal features over only 1000 Å. We realized later that this effect is probably purely observational and arises from atmospheric refraction but that it may compromise our analysis to some extent.

Abundances were determined from measured line strengths using the MOOG package. Lines were checked for "cleanliness" by direct inspection, inspection of the Kurucz et al. (1984) solar flux atlas, and by inspection of synthetic spectra including features within several angstroms of the line in question using the Kurucz CD-ROM line lists. The same lines retained for analysis were measured in our high signal-to-noise HIRES solar proxy spectrum of the daytime sky and analyzed in the same fashion so that detailed accuracy of the absolute *gf* values is not very important and so that assumed solar abundances need not be adopted. Identifications and atomic data came from the list of Thévenin (1990).

The resulting line-by-line abundance differences between Aa and Ba show a marked trend with wavelength; this is approximately 0.20 dex at 6500 Å, and increases to about 0.30 dex near 7700 Å. Further investigation showed that this resulted from a curious trend in the Aa component alone. We thus conducted similar analyses of two cool single Pleiades dwarfs using the HIRES spectra discussed in Jones et al. (1996). These Pleiades dwarfs are of similar temperature to the stars in HD 98800, and their spectra were obtained at the same time with the same equipment as the HD 98800 spectrum. No such trends are seen in the Pleiades dwarfs, indicating there is no fundamental flaw in the analysis procedure or the software.

Instead, the cause apparently can be traced directly to the relative line strengths. Inspection of features of the same species having similar excitation potential in the blue and red ends of our spectra show differences; as suspected, the Aa component's features appear shallower relative to Ba in the red. In hindsight, this effect might be deduced from Figure 3 of Paper I. The top panel there shows the Ni I $\lambda7522$ and $\lambda7524$ lines. It can be seen that the Ba component exhibits deeper lines than the Aa component. On the other hand, from much bluer spectra at 5180 Å, Torres et al. (1995) identify Aa as the primary component. Such a conclusion from Figure 3 of Paper I is not at all obvious. The two works are, however, using the same nomenclature. This was verified by noting that the Ba and Bb components in Paper I showed the radial velocity shift predicted by the orbital solution of Torres et al. (1995).

Relative line depth ratios of features of the same species having nearly identical excitation potential were measured for the Aa and Ba components. These were then compared to the ratios demonstrated by the same features in the HIRES spectra of cool Pleiades dwarfs. This exercise again indicated that the Aa component was the source of the discrepancy. This was further verified by comparing the relative line depth ratios to ones synthesized with a range of parameters and flux ratios.

However, we note that our composite spectrum of HD 98800 was obtained at a large zenith distance, and that two stars separated by about 0″.8 were being observed with an aperture 0″.86 wide. Guiding errors could lead to a systematic offset in the ratio of the light from Ba relative to Aa, but atmospheric refraction could account for a differential effect with wavelength. We suspect that this is the origin of this apparent discrepancy in the abundances in Aa relative to Ba. Thus we cannot yet present reliable detailed abundances. At present, though, experimentation with a wide variety of parameter combinations suggests to us that the abundance of all elements considered is within 0.2 dex of the solar values, which is typical for most stars of the solar neighborhood. However, we believe that we are not far amiss for two reasons. First, the guiding was done with a red filter, so that the center of light of the A + B pair should have been well centered on the aperture. This means that the infrared wavelengths may yield unreliable abundances but that the shorter wavelengths should be all right. Second, as we noted above the strength of the Li doublet allows an analysis to be made that is nearly independent of knowledge of the relative fluxes. We remain confident in our conclusions about Li and the roughly solar estimate for [Fe/H].

5. DISCUSSION

5.1. *The Kinematic Origin of HD 98800*

The HD 98800 system is very young, yet it appears far from any obvious region of star formation. Where was it born? Using the proper motion, parallax, and radial velocity of HD 98800, we calculated the space motion (see Table 3). After correcting for a basic solar motion of $(U, V, W) = (-9, +11, +6)$ km s^{-1}, we determined that the position of HD 98800 was at $(X, Y, Z) = (-30, +59, +15)$ pc relative to the Sun 10 Myr ago, in a coordinate system in which the x-axis points in the Galactic anticenter direction, the y-axis is in the direction of Galactic rotation, and the z-axis toward the north Galactic pole. For this calculation, we have assumed rectilinear motion, which is probably a fair assumption for the X and Y positions but may not be for Z. Given the low velocity dispersion of young objects, we looked at regions currently within 400 pc of this position and with measured proper motions and radial velocities and asked where they were 10 to 20 Myr ago. The only region that appears to be a likely point of origin for HD 98800 is the Scorpio-Centaurus (Sco OB2) complex, which consists of upper Scorpius, Upper Centaurus-Lupus, and Lower Centaurus-Crux.

Sco-Cen is a large, complex region of star formation that is part of the Gould Belt. It stretches across ∼70° of sky, corresponding to a breadth of ∼200 pc and a thickness of 60 pc at its distance of ∼165 pc. Proper motions and radial velocities from Bertiau (1958) were used to project three centers within the complex backward in time. The results of this projection are shown in Figure 5; the points of the arrows show the current locations of HD 98800 and parts of the Sco-Cen complex. The plus sign at the center is the current location of the Sun. The bases of the arrows show the locations 20 Myr ago (with respect to the LSR), and the large dots show the positions 10 Myr ago.

Given the large size of Sco-Cen, Figure 5 shows that in the past HD 98800 was within or close to parts of the complex. But when was HD 98800 closest to these regions, and how far apart were the regions and HD 98800 at that time? Looking only at the distances projected on the Galactic plane, the closet approach to upper Scorpius was 22 Myr ago at a distance of 19 pc, and to upper Centaurus-Lupus 15 Myr ago at a distance of 30 pc. Given the size of the complex and the uncertainty of the calculation, we conclude that it is reasonable that HD 98800 was within the complex between 10 and 30 Myr ago. It also appears more likely that HD 98800 is associated with one of the Centaurus regions than it is with upper Sco.

The expansion age for various parts of the Sco-Cen complex is ∼20 Myr, and the evolutionary age for upper Cen-Lupus and lower Cen-Crux is ∼10 Myr (Blaauw 1964; de Geus, de Zeeuw, & Lub 1989). Thus the time of closest approach is consistent with the age of parts of the complex. If this is indeed the origin of HD 98800, then it puts a constraint on the age to be less than ∼20 Myr and makes an age of 10 Myr more likely than 7 Myr, although upper Sco may be as young as 5 Myr (de Geus et al. 1989).

HD 98800 is qualitatively similar to some G and K stars that may belong to Sco-Cen. Park & Finley (1996) reported on some objects in Crux found with *ROSAT*. Feigelson & Lawson (1997) obtained low-resolution optical spectra of them, and they have Hα emission strengths very similar to HD 98800, although their Li lines appear somewhat

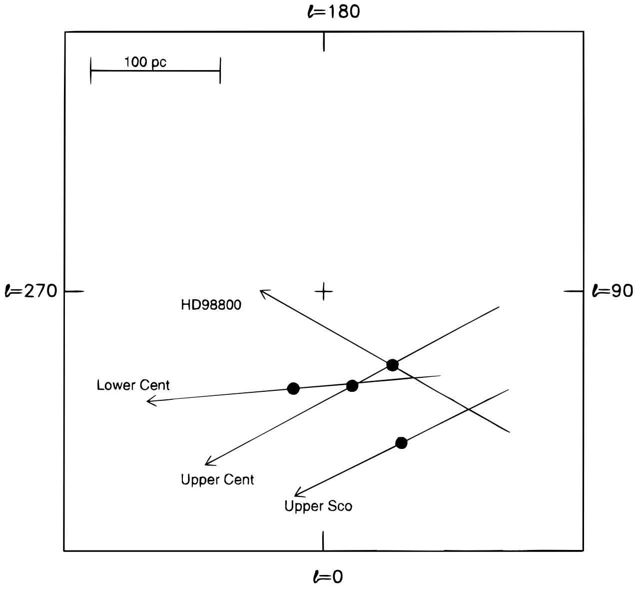

FIG. 5.—Locations of HD 98800 and the Sco-Cen complex now and in the past with respect to the LSR. The heads of the arrows show the current locations, the bases of the arrows show the locations 20 Myr ago, and the large dots show the positions 10 Myr ago. The plus sign is the current position of the Sun.

weaker. HD 98800 is also similar in Hα emission strength and Li abundance to some stars studied by Walter et al. (1994) in upper Scorpius.

5.2. *Where's the Dust?*

We see no evidence in our WFPC2 images for a β Pictoris-like dust disk, so we cannot yet pinpoint where the infrared excess is being produced. The unusual orbit of the visual pair suggests that the extraordinary IR excess of the HD 98800 system is related to the fact that the Ba + Bb pair is near periastron relative to Aa + Ab. Perhaps the disk is being warped by the proximity of the other more massive star, leading to more absorption of the central star's light. Another possibility, mentioned in Paper I, is that one of the stars, say Aa, illuminates a disk that is in the Ba + Bb system. The solid angle the disk subtends, as seen from the companion star, is very large, allowing much of the companion's light to heat the disk. This gets around the usual problems of geometry when a star illuminates material around itself, but if the optical depth of a disk is very low in the direction parallel to its symmetry axis (because of a low filling factor), then this scenario may not work. Models of this type could be calculated to see whether this possibility is reasonable.

We suspect that the dust disk may be around the Ba + Bb pair because those stars look redder than we expected, based on estimates of temperature from the composite spectrum, but that is only a hunch (and conflicts with large grains giving rise to gray extinction). near-infrared camera and multiobject spectrometer (NICMOS) observations of this system should resolve this question.

5.3. *HD 98800 as a System of Post–T Tauri Stars*

Their locations in the H-R diagram and their likely relationship to Sco-Cen argues for the HD 98800 system being close to 10 Myr old. There are other stars known to be about this age, but nearly all of them are in or near star-forming regions, if only because that is where searches have been made. Star-forming regions typically contain T Tauri stars that are about 1 to 3 Myr old.

As Herbig (1978) pointed out, if stars have been formed at a constant rate there should be an order of magnitude more post–T Tauris (PTTs) than there are T Tauris (TTs) because of the timescales for evolution on the Hayashi track relative to the remainder of the PMS evolution. Herbig tried several ways to search for PTTs, without success (with the possible exception of FK Ser; Herbig 1973), and subsequent attempts have turned up only a few. More recently, X-ray imaging has been used as a means to find PTTs. We know TTs are bright in X-rays, with $\log L_X/L_{\rm bol} \approx -3.8$, and that zero-age main sequence (ZAMS) stars are relatively bright too: $\log L_X/L_{\rm bol} \approx -4.2$ (Briceño et al. 1997). That suggests PTTs should be found at intermediate levels of X-ray emission, and those levels are well within the reach of, e.g., *ROSAT*.

ROSAT has been used to observe the environs of star-forming regions to find PTTs, and candidate objects have been found, but their interpretation is not clear. Neuhäuser et al. (1997) and Magazzù et al. (1997), for example, report *ROSAT* observations of the Taurus-Auriga region and the surrounding area, about 580 square degrees in all. They list about 110 new T Tauri and PTT stars. Briceño et al. (1997), however, note that foreground ZAMS stars can account for these detections both in number and flux level, which would indicate that few or no PTTs were in fact in the Tau-Aur region. Wichmann et al. (1997) have examined such stars in the Lupus region and find that their Li-rich stars fall within the Gould Belt, suggesting they are bona fide T Tauris, not ZAMS stars.

There are several resolutions to this problem. First, as noted by Palla & Galli (1997), perhaps the "problem" is nonexistent because stars with ages of ∼10 Myr are simply not present near the Sun due to the episodic, as opposed to steady, nature of star formation. A second solution would be that PTTs exist but that they are far from star-forming regions and so dispersed that they are difficult to find. A third possibility is that PTTs exist and are abundant, but they have remained invisible to us because our searches are inappropriate.

The first possibility is beyond the scope of this paper, of course. The third is partly plausible if we consider the optical spectrum of the HD 98800 system. As we noted in Paper I, all three stars have very low $v \sin i$ values and correspondingly low levels of chromospheric activity, as seen in the Ca II infrared triplet lines. This seems surprising for such young stars, and especially so for star Bb, since it is about half a solar mass. Other very young stars of similar mass produce strong activity, enough so that they would contribute significantly to an emission spike at Hα, even if their flux contribution to the system would be modest. Thus if these stars in HD 98800 are typical for an age of 10 Myr—and there is no reason to believe they are not typical—PTTs cannot be found through the methods that have been tried, such as objective prism surveys.

X-rays are another matter. Kastner et al. (1997) report *ROSAT* data for HD 98800, and the X-ray flux is more than enough to make this system detectable even if it were moved as far away as Tau-Aur. They report $\log L_X/L_{\rm bol} = -3.4$ for HD 98800, which is even brighter than most TTs. Thus the X-ray searches for PTTs should find them, at least if they are within the fields examined.

That brings us back to the second possibility, namely, that PTTs are really there but they're far removed from regions of star formation, making them difficult to find. The mere existence of a system like HD 98800 shows that this is possible. Moreover, the fact that the visual orbit has high eccentricity and a very long period means that Aa + Ab is only weakly bound to Ba + Bb. That means that HD 98800 cannot have found its way so far from where it was born through an unusual and energetic gravitational encounter that spit it out. Instead, HD 98800 had to leave its nursery through some gentle means, and that suggests it is more typical than not.

HD 98800 is about 150 pc from Sco-Cen (Fig. 5), so its velocity relative to Sco-Cen must be about 15 km s^{-1} for it to have gotten to where it is within 10 Myr. Feigelson (1996) suggests that dispersal of TTs takes place through two mechanisms. The first is just due to the thermal velocity within a molecular cloud. But that is typically only about 1 km s^{-1}, much too little to account for HD 98800. Feigelson's second mechanism is formation of stars in short-lived, rapidly moving cloudlets, which seems like a plausible origin for the HD 98800 system. Taurus-Auriga is not known to have clouds within it moving away as fast as 15 km s^{-1}. HD 98800 may be part of a group of very young stars (Kastner et al. 1997), another of which is TW Hya. *Hipparcos* measured a parallax for TW Hya that leads to a space motion consistent with that of HD 98800 if TW Hya's radial velocity is about +15 km s^{-1}. Sco-Cen is a significantly larger star-forming region than Tau-Aur, so perhaps HD 98800 and its cohort are on the high-velocity end of the distribution of a large population.

To identify other possible members of an HD 98800 cohort, we calculated space motions for the IR excess stars in Table 1 of Sylvester et al. (1996). Many of those stars do not have reported radial velocities, so we began by calculating U, V, and W for a range of radial velocities from −50 to +50 km s^{-1} to see whether these lines converged in velocity space. Several did, and follow-up checks showed that one star, HD 23680, has a reported radial velocity (+16.5 km s^{-1}, Barbier-Brossat & Petit 1990) that would give it a space motion indistinguishable from that of HD 98800. However, HD 23680 is nearly 200 pc away from the Sun (its *Hipparcos* parallax is 5.54 mas) in a very different direction from HD 98800, and so it seems unlikely to have had a common origin.

How many more stars or systems like HD 98800 might there be? Some significant number needs to be identified if we are to assess the prevalence of PTTs in the solar neighborhood. A few other examples of HD 98800–like objects may exist. First, there is FK Ser (BD −10°4662), Herbig's prototype PTT, which, curiously, is a visual binary. Unfortunately, its *Hipparcos* parallax is too imprecise (9.42 ± 6.17 mas) to allow its age to be determined from its luminosity. Also, FK Ser has Hα emission more like that of a traditional TT than the Hα seen in HD 98800. Jeffries et al. (1996) obtained optical spectra of a double system detected by *ROSAT*, 2RE J0241−525, and suggest that it too may be a PTT. It is again unfortunate, but this latter binary was not in the *Hipparcos Input Catalog* and so no parallax exists. But it is highly suggestive that binaries are common, not rare, among stars indicted as PTTs; whatever process puts such stars into the field is apparently not disruptive of their environs.

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