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BINARY MASSES AS A TEST FOR PRE–MAIN-SEQUENCE TRACKS

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ABSTRACT

Observations of binaries have traditionally provided the means for ascertaining stellar masses. Here we use the published data on eight pre–main-sequence pairs to gauge the accuracy of our own, recently calculated, evolutionary tracks. We consider both eclipsing, double-lined spectroscopic binaries, which provide the mass of each star separately, and noneclipsing, double-lined systems, which yield only the ratio. We also analyze the visual, quadruple system GG Tau, for which the sum of the two component masses follows from observations of the circumbinary disk. In almost all cases, our theoretically derived masses or mass ratios are in good agreement with the empirical values. For two binaries (NTTS 162814−2427 and P1540), the observational results are still too uncertain for a proper comparison. We also find that the derived contraction ages within each pre–main-sequence pair are nearly equal. This result extends earlier findings regarding visual pairs and indicates that the components of all binaries form in proximity, perhaps within the same dense cloud core. Finally, our study reveals that the Trapezium star BM Ori is very young since both the star itself and its companion have contraction ages less than 10^5 yr.

Subject headings: binaries: general — stars: evolution — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Pre–main-sequence stars derive their luminosity from the gravitational contraction they experience prior to hydrogen ignition. Within the Hertzsprung-Russell (HR) diagram, they descend evolutionary tracks that start from the birth line and end at the zero-age main sequence (ZAMS). Although these objects emit vigorous winds and undergo disk accretion, especially at earlier times, the net change in mass during the contraction phase appears to be relatively small (e.g., Hartmann et al. 1998). Thus, it is still appropriate to consider the ensemble of tracks parametrized by the stellar mass.

The masses and ages derived by placing stars on the tracks are fundamental data, not only for characterizing individual objects but for assessing the mass distribution and history of formation activity within clusters and associations. Following the initial calculations of the 1960s, Cohen & Kuhi (1979) compiled a set of tracks that were used for many years. Swenson et al. (1994) and D'Antona & Mazzitelli (1994) then offered new sets that utilized different phenomenological theories of convection. These later results not only differed substantially from each other but also led to problematic distributions of stellar masses and ages (e.g., Green & Meyer 1995; Hillenbrand 1997). A number of authors have reinvestigated the problem, in part to resolve these differences (Martín & Claret 1996; Chabrier & Baraffe 1997; Baraffe et al. 1998; D'Antona & Mazzitelli 1998; Siess, Forestini, & Bertout 1999). Our own recent calculation (Palla & Stahler 1999) utilized standard mixing-length theory for convection, along with modern determinations of the equation of state and low-temperature opacities.

How are we to gauge the accuracy of pre–main-sequence tracks? One test is the position of the birth line, i.e., the upper envelope to the distribution of pre–main-sequence stars. Stahler (1983) first predicted this locus theoretically by combining a protostellar mass-radius relationship with the Cohen & Kuhi tracks. Palla & Stahler (1990) then extended the curve into the regime of intermediate-mass objects. Thus far, the predicted birth line does seem to match the observed envelopes in both T associations and groups containing Herbig Ae/Be stars (e.g., Chen et al. 1997; van den Ancker, de Winter, & Tjin A Djie 1998; Luhman 1999). This result attests to the essential validity of both protostar theory (leading to the mass-radius relation) and the pre–main-sequence tracks themselves.

For a more precise check, one should compare the stellar masses obtained using the tracks with those that can be derived empirically. On the observational side, there has been some attempt to derive masses from spectroscopically determined surface gravities (McNamara 1975, 1976), but the precision of the latter is rather poor. Bonnell et al. (1998) suggested using the infall speed of circumstellar matter, as gauged from the redshifted absorption of selected emission lines. The presumption here is that the detected motion occurs along magnetic flux tubes linking the inner edge of a disk to the stellar surface. Quantitatively, however, one faces not only the problem of geometric projection along field lines of unknown topology but also the complication that the physical velocities may not be truly free-fall. The most reliable technique is to use *rotational* speeds. Here one may employ the radial velocities of spectroscopic binaries (e.g., Lee 1992) or else molecular-line observations of disks around binaries (White et al. 1999) or single stars (Simon, Dutrey, & Guilloteau 2000).

In this paper we employ both spectroscopic binaries and circumbinary disks to gauge the accuracy of our own pre–main-sequence tracks. We begin in § 2 by verifying the endpoints of these tracks through observations of main-sequence systems. We then consider in § 3 a number of younger pairs. We focus initially on eclipsing, spectroscopic binaries, for which individual masses can be obtained with high accuracy. We analyze several systems that contain at least one pre–main-sequence member. Mass ratios, as opposed to individual values, are available for double-lined

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spectroscopic binaries from the relative amplitudes of the individual velocity curves. This ratio may be compared with pre–main-sequence theory, provided one can also assess the luminosities and effective temperatures of the binary components. We finally consider the special case of GG Tau, where combined stellar masses can be derived from the rotational velocity of the circumbinary disk.

Our conclusion, as presented in § 4, is that the pre–main-sequence tracks in question are indeed reliable, in the sense that they generally predict masses or mass ratios in excellent agreement with empirical values. Moreover, we find that the derived ages within a pair are usually very similar. Close binaries thus appear to be coeval, a tendency already adduced for wider systems (Hartigan, Strom, & Strom 1994; Brandner & Zinnecker 1997). We find two anomalous systems, NTTS 162814−2427 and P1540, for which both the mass ratios and ages seem discrepant. The fault, we suggest, lies in the determination of the surface temperatures and luminosities, a conclusion reinforced by other observations.

2. MAIN-SEQUENCE BINARIES

Binary stars have traditionally been the main source of accurate stellar masses and radii and are employed to calibrate the mass dependence of the main sequence (Andersen 1991). Most useful in this regard are the detached, double-lined, eclipsing systems. Here one exploits both the radial velocity and light curves to obtain not only the masses of the individual components but also their luminosities and effective temperatures.

Figure 1 shows a portion of our pre–main-sequence tracks in the HR diagram, with masses from 0.1 to 1.2 $M_\odot$. Toward the upper end we have placed the components of two eclipsing systems with primaries of roughly solar mass, EW Ori and HS Aur. It is evident that the measured luminosities and effective temperatures indeed place all four stars close to the end of our tracks. From Table 1 of Andersen (1991), the masses of the EW Ori components are 1.19 and 1.16 $M_\odot$. For comparison, the interpolation from our tracks yields values of 1.14 and 1.11 $M_\odot$, respectively. For HS Aur, the measured masses are 0.90 and 0.88 $M_\odot$, while our tracks give corresponding values of 0.94 and 0.90 $M_\odot$, respectively.

The number of known systems with lower mass components diminishes rapidly. Until recently, there were only two observed eclipsing binaries with subsolar primaries, YY Gem and CM Dra. The latter has a metallicity from a third to half of solar (Leggett et al. 2000) and thus cannot be studied using our tracks. (For the effect of reduced metallicity on evolutionary tracks of low-mass stars, see, e.g., D'Antona & Mazzitelli 1998; Siess et al. 1999). Delfosse et al. (1999) have discovered a third system, GJ 2609, a quadruple whose more massive component is itself an eclipsing binary. No estimates for effective temperature are yet available.

The measured masses of YY Gem are 0.60 and 0.59 $M_\odot$ (Leung & Schneider 1978; Ségransan et al. 2000). We display the positions of both components in Figure 1. Note the large uncertainties in effective temperature, a well-recognized problem at these masses (Allard et al. 1997). Our adopted $T_{\rm eff}$-values for YY Gem (3806 and 3742 K) come from Chabrier & Baraffe (1995). These nominal values, together with the measured luminosities, again place the stars close to, but not precisely at, the ends of our tracks. Our inferred masses 0.57 and 0.49 $M_\odot$ for YY Gem are also more discrepant than for solar-mass systems, although the error is still under 20%. Such declining accuracy at the lowest masses is expected, as our models lack the refined equation of state and atmosphere calculations needed for accurate treatment in this regime (e.g., Chabrier & Baraffe 1995).

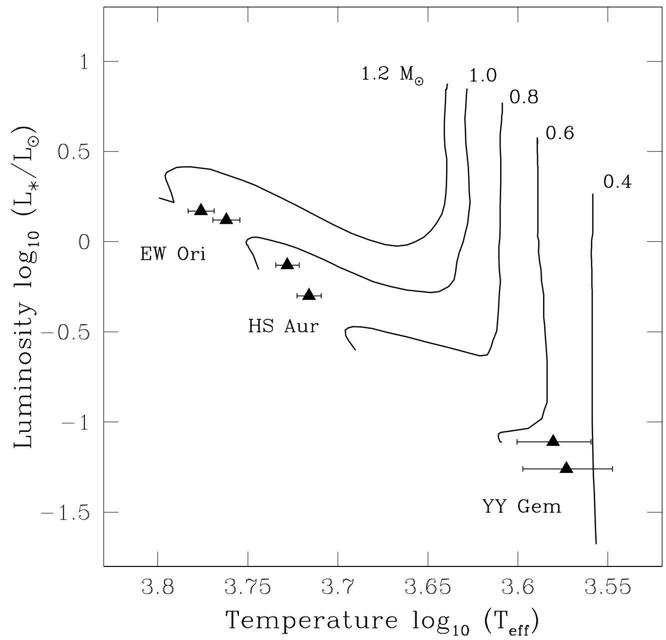

FIG. 1.—HR diagram of main-sequence binary systems. Only stars with mass smaller than 1.2 $M_\odot$ are included. Each evolutionary tracks is labeled by the corresponding mass in solar units.

3. YOUNGER SYSTEMS

3.1. *RS Cha*

This eclipsing, double-lined spectroscopic binary belongs to the recently discovered open cluster η Cha. The group itself contains about 50 members and lies at a distance of just 97 pc (Mamajek, Lawson, & Feigelson 1999). Strong X-ray emission from these stars identifies them as pre–main-sequence (Mamajek et al. 2000). For the RS Cha system, which has a period of 1.7 days, the spectroscopic and photometric analysis of Andersen (1991) yielded primary and secondary masses of 1.86 and 1.82 $M_\odot$, respectively, with an associated mass ratio of $M_1/M_2 \equiv q = 1.02$. Although this value is very close to unity, we have included the system in our sample because its eclipses allow accurate determination of individual masses.

Jordi et al. (1997) obtained effective temperatures of 7810 and 7295 K for the two components. Mamajek et al. (2000) used these results, along with the stellar radii determined by Clausen & Nordström (1980), to find corresponding luminosities of 15.2 and 13.9 $L_\odot$. We show the two stars within the HR diagram in Figure 2*a*. Our derived masses of 1.88 and 1.80 $M_\odot$ agree well with the empirical ones. Our theoretical q-value is 1.04. Finally, the derived ages for the primary and secondary are 5.0×10^6 and 4.3×10^6 yr, respectively.

As an aside, we note that the stellar parameters of the two components place them near the regime of pulsational instability determined by Marconi & Palla (1998). Figure 4

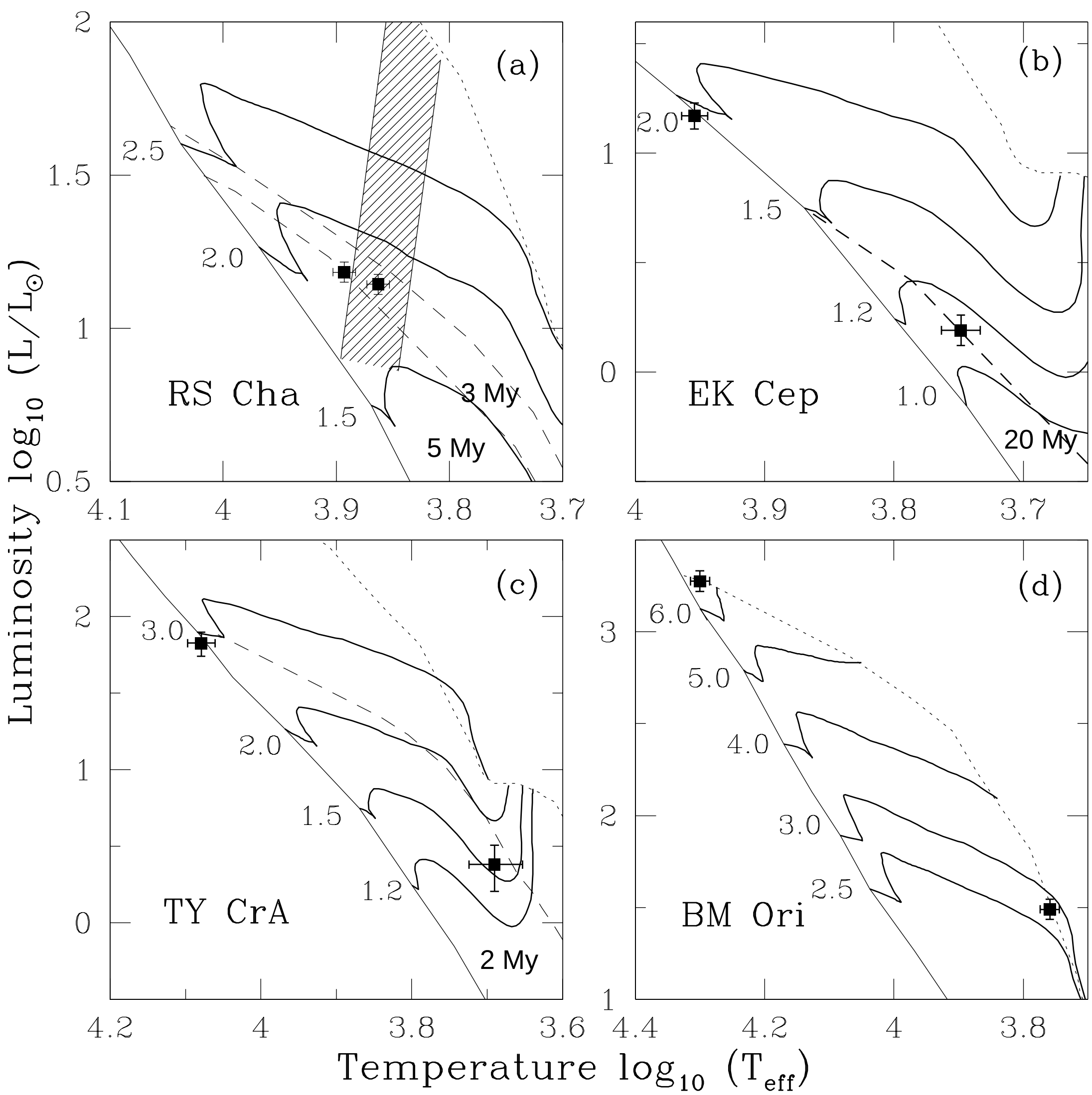

FIG. 2.—Location of the four eclipsing, pre–main-sequence systems in the HR diagram. In each panel the evolutionary tracks are shown by the solid lines, labeled by the appropriate mass (in solar units). Dashed lines are isochrones, given in units of 10^6 yr. The dotted line is the birth line computed with an accretion rate $\dot{M} = 10^{-5}\ M_\odot\ yr^{-1}$. In the case of RS Cha, the shaded area represents the instability strip for young stars.

shows that the secondary falls securely within the theoretical instability strip, indicated by the two parallel lines. This object should therefore be pulsating in the fundamental or first overtone. Any pulsation of the primary, however, would be of higher order. Andersen (1975) observed, in fact, a periodic variation (of the δ Scuti type) in the composite light curve. Further comparison between theory and observation should prove instructive.

3.2. *EK Cep*

This system lies at a distance of 150 pc and does not appear to be associated with other young stars (Popper 1987). Ebbighausen (1966) showed it to be an eclipsing, double-lined binary of low eccentricity ($e = 0.09$) and relatively short period (4.4 days). From the radial velocity curves, the mass ratio is 1.81. Tomkin (1983) derived an orbital inclination i of 89° and thereby found primary and secondary masses of 2.03 and 1.12 $M_\odot$, respectively.

The primary is a ZAMS star of spectral type A1 and effective temperature 9000 K (Hill & Ebbighausen 1984; Popper 1987). Its luminosity, as determined photometrically, is 15 $L_\odot$. Martín & Rebolo (1993) detected lithium absorption in the secondary, establishing its pre–main-sequence nature. The effective temperature for this component is 5700 K and its luminosity 1.5 $L_\odot$ (Popper 1987).

After locating both stars in the HR diagram (Fig. 2*b*), we confirm that the primary lies on the ZAMS and find a mass of 2.0 $M_\odot$. For the secondary, we derive $M_* = 1.1\ M_\odot$ so that our q-value is 1.7. The isochrone passing through the secondary's position gives it an age of 2×10^7 yr. This figure exceeds the contraction time of 8×10^6 yr for a 2 $M_\odot$ star to reach the ZAMS. Thus, the stars could have formed at the same time, 2×10^7 yr in the past.

3.3. *TY CrA*

The Herbig Be star TY CrA is the brightest member of a young, embedded cluster in the Corona Australis dark cloud complex, at a distance of 130 pc (Marraco & Rydgren 1981). Photometric and spectroscopic observations reveal an eclipsing, double-lined spectroscopic system (Kardopolov, Sahanionok, & Philipjev 1981; Corporon, Lagrange, &

Beust 1994; Casey et al. 1995). Analysis of the radial velocity curves gives a period of 2.89 days and shows the orbit to be nearly circular ($e = 0.02$). From the relative amplitudes of the velocities, the mass ratio q is 1.93. The system also contains a third component at a distance of about 1 AU from the close binary (Casey et al. 1995; Corporon, Lagrange, & Beust 1996).

Casey et al. (1998) have conducted a detailed investigation of the stellar properties of the binary components. (For earlier work, see Beust et al. 1997.) They assign the primary an effective temperature of 1.2×10^4 K, consistent with the estimated spectral type of B8 (Lagrange, Corporon, & Bouvier 1993). For the secondary, they find $T_{\rm eff} = 4900$ K. Gauging the luminosities is more difficult, because of both the third star and the presence of reflection nebulosity. Casey et al. find primary and secondary luminosities of 67 and 2.4 $L_\odot$, respectively. Both the temperature and luminosity estimates utilize an estimated A_V of 3.1 mag.

Figure 2*c* shows the location of both components in the HR diagram. The primary evidently falls close to the ZAMS and has a theoretically derived mass of 2.9 $M_\odot$. For the secondary, we infer a mass of 1.6 $M_\odot$. These figures may be compared with the masses of 3.16 and 1.64 $M_\odot$ obtained by Casey et al. (1998) from the known orbital inclination of $i = 83°$. Our theoretical mass ratio, $q = 1.8$, differs by less than 10% from the empirical value.

Since the primary may already have settled onto the main sequence, a contraction age may not be appropriate. A star of 3 $M_\odot$ reaches the ZAMS in 2×10^6 yr, according to our tracks. As seen in Figure 2*c*, the corresponding isochrone passes close to the secondary, indicating near-coevality. However, the nominal contraction age that best fits the secondary's position in the diagram is 3.9×10^6 yr. The location of the primary in the diagram is, of course, also consistent with this latter age.

3.4. *BM Ori*

The faintest member of the Trapezium is θ^1 Ori B, also known as BM Ori. It has long been recognized as the primary of an eclipsing binary, with a period of 6.5 days and a circular orbit (Hartvig 1920; Popper & Plavec 1976). More recently, near-infared studies have demonstrated that this spectroscopic binary is actually part of a hierarchical, pentuple system. There is a wide binary whose components lie 0ʺ.94 and 1ʺ.02 from the brightest star (Petr et al. 1998; Weigelt et al. 1999) and a single star at a displacement of 0ʺ.9 (Simon, Close, & Beck 1999).

Within the spectroscopic binary, the primary appears to be a normal B3-type star lying close to the ZAMS (Popper 1980; Hillenbrand 1997). The secondary, however, shows a large infrared excess, and its spectral classification has been uncertain for a long time (e.g., Popper & Plavec 1976). Vitrichenko & Plachinda (2000) employed CCD spectrophotometry during the primary minimum and recovered a G2-type spectrum for the secondary. Antokhina, Ismailov, & Cherepashchuk (1989) had earlier obtained a luminosity of 31 $L_\odot$ for this component.

Figure 2*d* displays the two stars within the HR diagram. The primary, as expected, lies close to the ZAMS and has an inferred mass of 6.2 $M_\odot$. The secondary lies very close to the birth line, shown by the dashed curve. We derive a secondary mass of 2.7 $M_\odot$ and a q-value of 2.3, the highest of any system we have analyzed. Since the primary also lies close to the birth line, the binary components are coeval, with nominal ages less than about 10^5 yr.

Obtaining the masses from the light curve is not straightforward because of the peculiar nature of the system. Even during primary minimum, the B star continues to be visible (Hall & Garrison 1969; Doremus 1970). The current interpretation is that the eclipse in this phase is produced by a disk surrounding the secondary (Vitricenko 1996). The disk is also presumed responsible for the infrared excess. In any case, a more conventional light-curve analysis yields masses of 6.3 and 2.5 $M_\odot$, respectively, for the primary and secondary, and a q-value of 2.5. A refined study, accounting for the disk geometry, could alter these numbers.

3.5. *V773 Tau*

We next consider noneclipsing, spectroscopic binaries. Our first system is located in the B209 (L1495W) dark cloud at an astrometric distance of 148 pc (Lestrade et al. 1999). The primary is a weak-lined T Tauri star that exhibits strong X-ray activity (Feigelson et al. 1994). It is also the most luminous radio source in Taurus-Auriga (O'Neal et al. 1990), with giant loops of nonthermal emission (Feigelson et al. 1994).

Near-infrared imaging by Leinert et al. (1993) and Ghez, Neugebauer, & Matthews (1993) revealed a wide companion. These two groups found the separation to be 19 and 29 AU, respectively, while Ghez, White, & Simon (1997) lowered the figure to 12 AU. In any case, Martín et al. (1994) and Welty (1995) demonstrated that the system is actually a triple since the brightest source is a spectroscopic binary. The analysis of the velocity curves by Welty shows the orbit to be eccentric ($e = 0.267$) and yields a mass ratio of $M_1/M_2 \equiv q = 1.32$. Welty then fit the composite optical spectrum with K2 and K5 photospheres, weighted to match the observed flux ratio at 0.65 μm. He finally determined luminosities for the two components by requiring that their spectral energy distributions sum to the empirical one, within the optical and near-infrared regime. His derived luminosities, scaled to the recent, astrometric distance, are $L_1 = 3.01\, L_\odot$ and $L_2 = 1.90\, L_\odot$.

These values for luminosity and temperature, in combination with our pre–main-sequence tracks, yield primary and secondary masses of 1.73 and 1.26 $M_\odot$, respectively. Their ratio is 1.37, in good agreement with the dynamical value. In contrast, Welty used the tracks of D'Antona & Mazzitelli (1994) and found a theoretical ratio of 1.78.

Welty's derivation of the luminosities neglected any contribution to the optical or near-infrared fluxes from the wide companion. This assumption, however, may not be justified. Ghez et al. (1997) studied the companion photometrically and assigned it a spectral type of K3 and a luminosity of 1.33 $L_\odot$. They then subtracted its spectral energy distribution from the total, assuming the remainder stems from the spectroscopic binary, at least for optical and near-infrared wavelengths. Adopting Welty's spectral types and near-infrared flux ratio for the binary components, they derived new luminosities of $L_1 = 2.31\, L_\odot$ and $L_2 = 1.39\, L_\odot$.

Figure 3*a* shows the two components of the spectroscopic binary in the HR diagram, using the stellar parameters of Ghez et al. (1997). Also shown are portions of our pre–main-sequence tracks and isochrones. Our derived masses are now 1.53 and 1.19 $M_\odot$, yielding a mass ratio of 1.29. The ages are 4.1×10^6 yr and 2.8×10^6 yr for the primary and secondary, respectively.

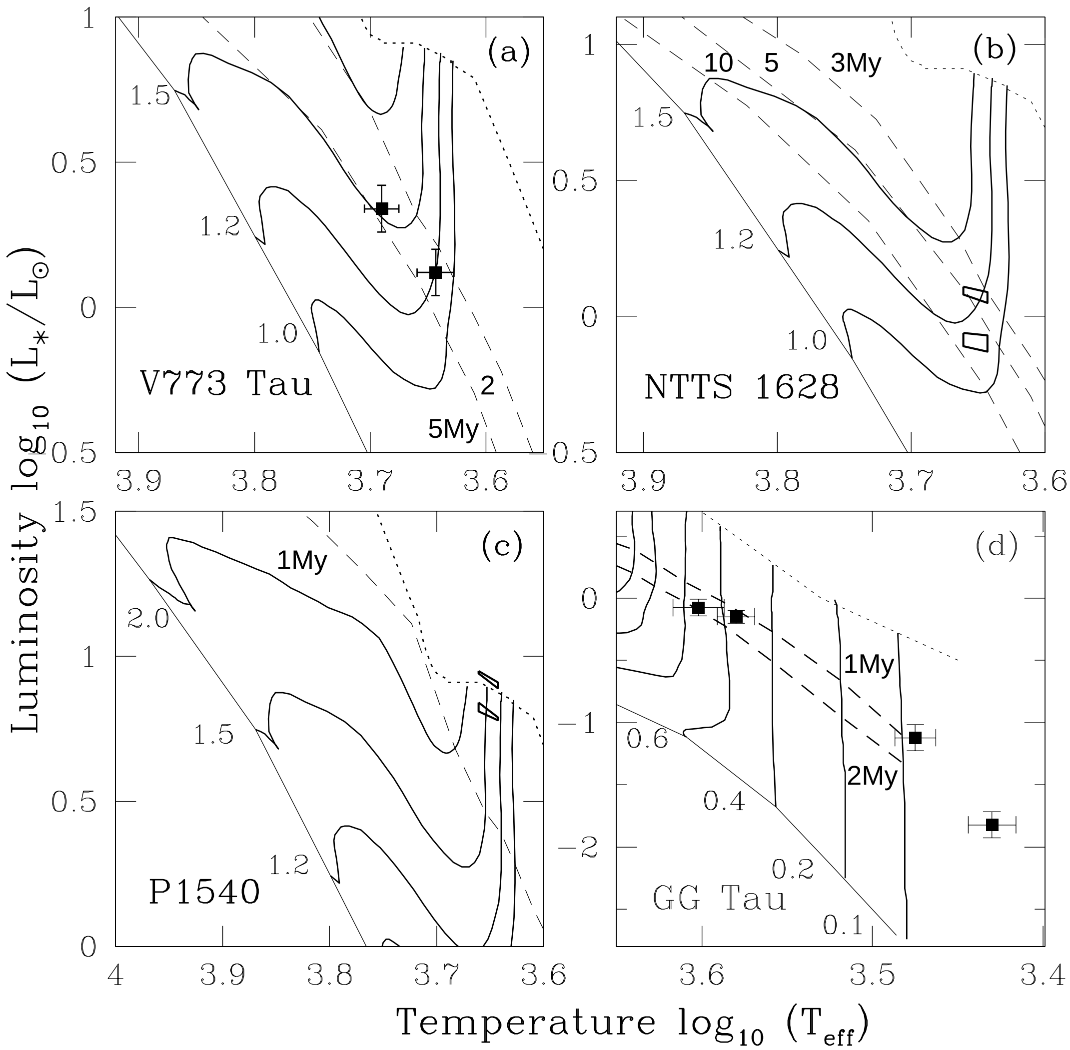

FIG. 3.—Position of the noneclipsing, spectroscopic binaries in the HR diagram. The curves have the same meaning as in Fig. 2. For the GG Tau quadruple system, the faintest component lies below our minimum mass track of 0.1 $M_\odot$.

3.6. *NTTS 162814−2427*

The primary of this system was discovered as an X-ray source in the Scorpius-Ophiuchus region (Montmerle et al. 1983) and later classified as a naked T Tauri star (Walter et al. 1988). Mathieu, Walter, & Myers (1989) demonstrated that the star is actually a double-lined spectroscopic binary, with a period of 36.0 days and a mass ratio q of 1.09. Its measured eccentricity of 0.48 is one of the highest values known among pre–main-sequence binaries.

Although the ultraviolet and infrared excesses in the composite spectrum are relatively small, they foiled the attempt by Mathieu et al. to deconvolve the component stars. This problem was alleviated by Lee, Martín, & Mathiu (1994), who used high-dispersion spectroscopy both to gauge the stars' relative brightness and to assign a plausible range of spectral types (see also Lee 1992). For each pair of spectral types, Lee et al. reconstructed the stellar luminosities by applying a bolometric correction to the dereddened I-band fluxes. Here they utilized a visual extinction A_V of 1.9.

The closed areas in Figure 3*b* represent the four pairs of luminosity and effective temperature offered by Lee et al. (1994). The effective temperatures derived by these authors correspond to spectral types of K4 and K5 after using the conversion scale of Cohen & Kuhi (1979). Comparison with our pre–main-sequence tracks shows that both masses are slightly above 1 $M_\odot$ and that the theoretical q-values range from 1.04 to 1.18. These figures neatly bracket the empirical one of 1.09. Figure 3*b* also includes three selected isochrones. Although none of these intersects both rectangular areas, the data are consistent with a common age near 5×10^6 yr.

3.7. *P1540*

This double-lined, spectroscopic binary is located 10′ west of the Trapezium, just outside the Orion Nebula cluster (Hillenbrand 1997). Marschall & Mathieu (1988) analyzed the radial velocities and found the system to have a relatively long period (34 days) and high eccentricity ($e = 0.12$). The derived mass ratio, $q = 1.32$, matches that of V773 Tau. As in that case, the components are both weak-lined T Tauri stars and exhibit enhanced X-ray emission. The system is notable for its high space motion. While the center-of-mass radial velocity of 26 km s^{-1} is consistent with membership in the Orion Id association, the measured proper motion is much too great (Jones & Walker 1988). Marschall & Mathieu conclude that the system is a runaway, possibly ejected through dynamical interaction within the Trapezium region.

Observational determination of the component luminosities and effective temperatures is still incomplete. Lee et al. (1994) have suggested four pairs of values, in which the spectral types lie in the range from K4 to K5 and the luminosities are between 6.0 and 11.5 $L_{\odot}$. The analysis was similar to that of NTTS 162814−2427. That is, a high-resolution spectrum was compared to combinations of standard templates in order to assess both the individual spectral types and the flux ratio here in the *I* band. After using photometric observations of color excess to correct for extinction, Lee et al. applied a main-sequence bolometric correction to obtain the stellar luminosities.

The quadrangles in Figure 3*c* show the regions demarcated by these four solution pairs in the HR diagram. It is evident that the system is extremely young, with the stellar parameters placing both components close to the birth line. The derived mass ratios range from 1.0 to 1.37 and thus are ostensibly compatible with the observational value. However, it is evident from the figure that none of the pairs are even roughly coeval. This peculiarity was emphasized by Marschall & Mathieu (1988), who based their analysis on the Cohen & Kuhi (1979) tracks.

Both components of P1540 exhibit strong lithium absorption, another indication of youth. Lee et al. (1994) employed stellar atmosphere models to determine the actual lithium abundances of five pre–main-sequence binaries, including this one. In general, the derived abundance in a star is sensitive to both the effective temperature and surface gravity and hence the stellar luminosity. For all four luminosity-temperature pairs, P1540 had lithium abundances for both components higher by a factor of 3–7 than the canonical interstellar value. Moreover, this was the only system to exhibit such an anomaly. Lee et al. suggested that the result stemmed from incorrect stellar parameters. In particular, a lowering of both spectral types by several subclasses appears to be compatible with the spectroscopic data (E. Martín 2000, private communication). Lowering the spectral types would also decrease the masses, in concordance with the relatively high lithium abundances. A detailed reexamination of this interesting system is clearly warranted.

3.8. *GG Tau*

The GG Tau system is a hierarchical quadruple, consisting of two binary stars (Leinert et al. 1993). The tighter pair, designated GG Tau A, has a projected separation of 0″.25, or 35 AU at the Taurus distance. This system is 10″.1 north of a wider binary (GG Tau B), with a separation of 1″.48 (207 AU). Thus, neither pair is a spectroscopic binary. However, the system is of interest for testing pre–main-sequence models because of the presence of a large, low-mass disk around GG Tau A. This structure has been imaged in both millimeter lines and continuum and in near-infrared scattered light (Dutrey, Guilloteau, & Simon 1994; Roddier et al. 1996). Following the initial study by Dutrey et al. (1994), Guilloteau, Dutrey, & Simon (1999) have fit the disk's velocity profile to a Keplerian rotation low, thus finding the *total* mass of GG Tau A to be 1.28 $M_{\odot}$.

White et al. (1999) have obtained optical spectra for all members of the quadruple. They confirm that the components are T Tauri stars or brown dwarfs with spectral

TABLE 1

Parameters of Young Binary Systems

System (K)	d (pc)	$T_{\rm eff}$ ($L_{\odot}$)	L ($M_{\odot}$)	$M_{\rm dyn}$ ($M_{\odot}$)	$M_{\rm PS}$ ($M_{\odot}$)	$(M_A/M_B)_{\rm dyn}$ ($M_{\odot}$)	$(M_A/M_B)_{\rm PS}$ (10^6 yr)	$t_{\rm PS}$
RS Cha	97							
A		7810 ± 180	15.2 ± 1.2	1.858 ± 0.016	1.88	1.02 ± 0.02	1.04 ± 0.06	5.0 ± 0.3
B		7295 ± 170	13.9 ± 1.2	1.821 ± 0.018	1.80	...	...	$4.3^{+0.8}_{-0.6}$
EK Cep	150							
A		9000 ± 200	14.8 ± 1.4	2.03 ± 0.01	1.97	1.82 ± 0.02	$1.73^{+0.15}_{-0.05}$	20
B		5700 ± 200	1.55 ± 0.3	1.12 ± 0.01	1.14	...	...	20 ± 4
TY CrA	130							
A		12,000 ± 500	67 ± 12	3.16 ± 0.02	2.91	1.93 ± 0.02	$1.82^{+0.11}_{-0.04}$	...
B		4900 ± 400	2.4 ± 0.8	1.64 ± 0.01	1.60	...	...	$3.9^{+3.6}_{-2.4}$
BM Ori	460							
A		19,950 ± 200	1890 ± 250	6.3 ± 0.3	6.21	2.52 ± 0.15	2.32 ± 0.15	<0.1
B		5740 ± 200	31 ± 4	2.5 ± 0.1	2.68	...	...	<0.1
V773 Tau	148							
A		4900 ± 180	2.31 ± 0.43	...	1.53	1.32 ± 0.06	$1.29^{+0.35}_{-0.23}$	4.1 ± 0.9
B		4400 ± 180	1.39 ± 0.43	...	1.19	...	...	$2.8^{+1.6}_{-1.0}$
NTTS 162814	125							
A		4390	1.20	...	1.26	1.09 ± 0.07	1.11 ± 0.07	$5.1^{+0.2}_{-2.1}$
B		4083	0.85	...	1.08	...	...	$5.3^{+2.5}_{-0.1}$
P1540	470							
A		5010	11.5	...	1.71	1.32 ± 0.03	1.19 ± 0.18	<0.1
B		4680	7.9	...	1.25	...	...	0.2 ± 0.1
GG Tau	140							
Aa		4000 ± 150	0.84 ± 0.13	1.28 ± 0.07	0.78	...	...	2.3 ± 0.3
Ab		3760 ± 120	0.71 ± 0.09	(total)	0.54	...	...	$1.5^{+0.2}_{-0.5}$
Ba		2985 ± 180	0.08 ± 0.02	...	<0.1	...	...	...
Bb		2690 ± 190	0.015 ± 0.004	...	≪ 0.1	...	...	...

types ranging from K7 to GG Tau Aa to M7 for GG Tau Bb. They further derive effective temperatures for all the stars and estimate their luminosities by applying a bolometric correction to the *I*-band fluxes. Figure 3*d* places the components in the HR diagram. The two most luminous stars belong to GG Tau A, and our derived masses are 0.78 $M_\odot$ for the primary and 0.54 $M_\odot$ for the secondary. The total is 1.32 $M_\odot$, in close agreement with the dynamical value. Both components of GG Tau B lie below our tracks, and we can only place upper limits of 0.1 $M_\odot$ on their masses. Note finally that all four stars appear to be approximately coeval. Our derived ages for GG Tau Aa and GG Tau Ab are, respectively, 2.3 and 1.5 × 10^6 yr.

4. DISCUSSION

Table 1 conveniently summarizes essential properties of all the systems covered in this paper. We first list empirical values for the effective temperature and luminosity of each component, including uncertainties given in the literature. We next give the observationally determined mass ($M_{\rm dyn}$) for all eclipsing systems, as well as the total value for GG Tau A. In the fifth column, we tabulate our own masses ($M_{\rm PS}$), as obtained by comparison with the pre–main-sequence tracks. The next two columns list the mass ratios, both the observational ones [$(M_A/M_B)_{\rm dyn}$] and our derived values [$(M_A/M_B)_{\rm PS}$]. The final column presents our derived ages, again including uncertainties, for each component that appears to be pre–main-sequence.

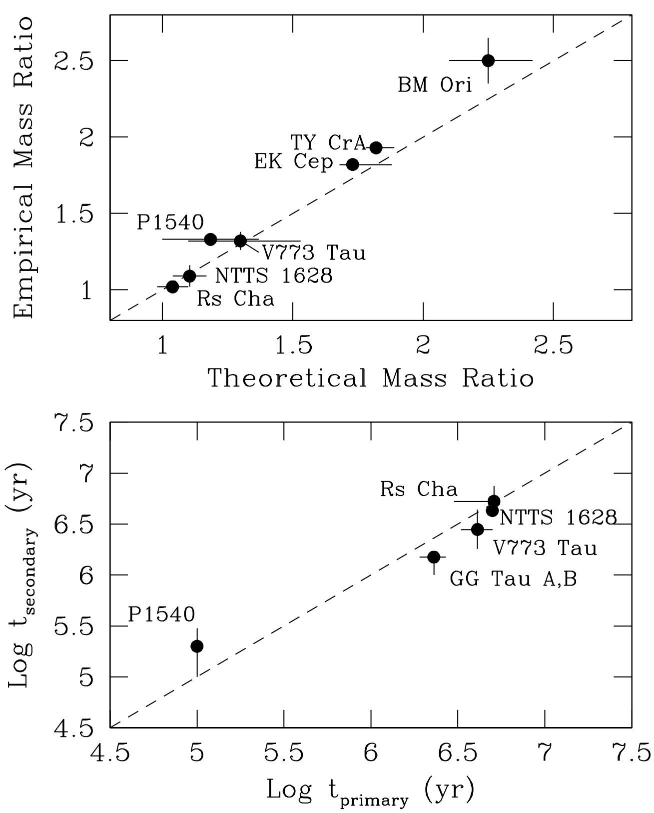

FIG. 4.—Comparison between theoretical and empirical mass and age estimates. The upper panel shows the mass ratios. Here all binaries are included except GG Tau, for which mass ratios cannot be obtained observationally. The error bars are as indicated in Table 1. The lower panel displays primary and secondary ages. We have omitted such systems as EK Cep, whose primary is located on the ZAMS and thus has no assigned contraction age.

A more graphic presentation of the same results is given in Figure 4. The upper panel compares the mass ratios, as derived both empirically (*vertical axis*) and from our tracks (*horizontal axis*). For both values, we include the uncertainties listed in Table 1. While the empirical mass ratios are known quite accurately, we note the relatively large uncertainties in the theoretical values, especially for P1540 and V773 Tau. Both systems lie in regions of the HR diagram where the tracks are especially crowded so that modest changes in effective temperature translate into large mass shifts. The overall agreement between theoretical and empirical ratios is good, but there is a systematic drift from unity for higher mass systems. We attribute this trend to the difficulty in determining the secondary properties when the primary is a luminous, massive star. On the other hand, we have not considered the effect of convective overshooting, which could be an important physical process to include in more realistic models of higher mass stars (e.g., Ribas, Jordi, & Gimènez 2000).

We have also obtained absolute mass values for the sample of stars recently investigated by Simon et al. (2000). These authors used interferometric, molecular-line observations of disks around nine stars in Taurus-Auriga. Assuming the disks to be in Keplerian motion, they were able to ascertain the masses of the central objects. We have placed all these objects in the HR diagram and find masses that agree with those of Simon et al. to within 8%. Two exceptions, where we find substantially lower mass values, are the single star BP Tau and the binary UZ Tau. In both cases, the molecular-line observations are problematic, as discussed in detail by Simon et al.

An interesting dividend from our study is the determination of contraction ages for each object above the ZAMS. As seen in the lower panel of Figure 4, there is a remarkably close match between the ages of the primary and secondary star within each binary. We stress that there is no reason a priori to expect such agreement, and there is no generally accepted theory of binary formation that predicts coevality. Nevertheless, our finding extends the important, earlier investigations by Hartigan et al. (1994) and Brandner & Zinnecker (1997), which demonstrated a similar trend in visual binaries. The implication of all these studies is that the individual components of binaries are born in situ at the same time, regardless of their eventual configuration. Now the widest pre–main-sequence binaries have separations of order 10^4 AU (e.g., Mathieu 1994), a distance comparable to the sizes of dense cloud cores (Myers & Benson 1983). It is an attractive hypothesis, therefore, that both components form through protostellar collapse within the same cloud fragment. A question of key importance for theory is how the structure and evolution of these molecular structures promotes simultaneous density buildup in at least two internal locations.

Returning to the stellar mass determinations, the tally of double-lined spectroscopic binaries is richer than that studied here. We have omitted a number of systems with mass ratios very close to unity since they do not provide stringent tests on the accuracy of our tracks. These binaries include DQ Tau ($q = 1.03$; Mathieu et al. 1997), W134 ($q = 1.04$; Padgett & Stapelfeldt 1994), and V826 Tau ($q = 1.02$; Lee et al. 1994). Adopting the quoted luminosities and temperatures for each star, we concur that the component masses all match to within 10%. We have also omitted the equal-mass, eclipsing binary GG Ori in the Orion OB1 association. Our mass estimate of 2.36 $M_\odot$ for each component is very close to the value of 2.34 $M_\odot$ found by Torres et al. (2000). Finally, we have not analyzed RX J0529.4+0041, an eclipsing binary in the Orion OB1a subgroup (Covino et al. 2000). The measured masses are 1.30 and 0.95 $M_\odot$, but the luminosity and temperature of the secondary are not yet firmly established. Our own value for the primary mass is 1.26 $M_\odot$, in close agreement with the observational finding.

Our study by no means represents a thorough empirical test of pre–main-sequence tracks. Future investigations would do well to concentrate on lower mass stars and on systems with larger mass ratios than those considered here. As we have discussed, the largest uncertainties in modeling are for objects near the brown dwarf limit. Traditional studies of spectroscopic binaries have also emphasized nearly equal mass systems, simply because of the practical difficulty in detecting a relatively dim companion. This purely observational bias has misled theorists considering the question of binary origin (e.g., Boss 1988, 1993). Recently, Mazeh et al. (2000) have stressed the utility of near-infrared observations for ascertaining the properties of lower mass secondaries. With a wider range of binary systems in hand, we may look forward to a more complete assessment of current pre–main-sequence tracks, and to the eventual refinement of the underlying theory.

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