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HD 34700 is a T Tauri Multiple System

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Abstract. We have imaged the young double-lined spectroscopic binary HD 34700 in the near-infrared and find evidence for two faint, visual, stellar components at 5″.2 and 9″.2 distance. High-resolution echelle spectroscopy of both stars shows strong Li I 6708Å absorption and Hα emission. The spectral types of the companions are estimated from the spectra and photometry as M1-M2 and M2-M3. Their radial velocities are similar to the center-of-mass velocity of the central SB2, hence all four stars are most probably physically bound and constitute a young quadruple stellar system with an inner short-period binary. We provide a list of pre-main sequence spectroscopic binaries with additional components of which HD 34700 is yet another example. The available statistics strengthens the suspicion that dynamical effects in multiple systems play a key role in the formation of very close binaries early in their evolution.

Key words. spectroscopic binaries - stars: formation - T Tauri stars

1. Introduction

The star HD 34700 (HIP 24855) has recently been identified as a new double-lined spectroscopic binary system by Arellano Ferro & Giridhar (AFG, 2003). Their analysis shows that both components of the SB2 have strong Li I 6708Å absorption, and variable Hα emission lines, thus justifying a classification as a pair of T Tauri stars. Both components have an approximate spectral type of G0 IVe (Mora et al., 2001), and associated strong infrared excess is known since *IRAS* (Oudmaijer et al., 1992). The spectral energy distribution can be interpreted by a disk model (Sylvester & Skinner, 1996), and the presence of circumstellar material is further supported by the detection of ^{12}CO and ^{13}CO emission (Zuckerman, Forveille & Kastner 1995). The star is also a strong X-ray source, and given its location in the general direction towards Orion, its relative youth is undisputed. However, a more quanititative age determination is difficult, mainly because its parallax is rather uncertain in *HIPPARCOS* (π_{HIP} = 0.86 ± 1.84mas).

The number of known double-lined pre-main-sequence (PMS) spectroscopic binaries is still small (Melo et al., 2001). Motivated by the general interest to study them in depth, Torres (2004) presents a series of high-resolution spectra of HD 34700. He confirms its youth, solves an accurate orbit with a period of 23.4877 days, and an eccentricity of 0.2501 and finds that the stars are not tidally synchronized, because the projected rotational velocities measured are much larger.

Our own interest to study this stellar system was raised when looking at the *2MASS* images of HD 34700. The explanation given in AFG (their Fig.5) is somewhat ambiguous and mentions asymmetric emission, either caused by dust, or by an unresolved star. However, different cuts used to display the *2MASS* JHK images already start to resolve the system into three components. In fact, all three are listed in the *2MASS* point-source catalog (Cutri et al. 2003).

The goal of our work was to unambiguously resolve the individual stars, and to look for a potential physical relation of the wide components with the central SB2. We present new near-infrared (NIR) images and optical high-resolution spectroscopy of all stars which allow to derive radial velocities, spectral types, and the Li I strength as youth indicator. We show that our data are consistent with the notion that HD 34700 is in fact a young quadruple system, consisting of an inner SB2 and two late-type companions in wide orbits.

We compare the properties of this new system of T Tauri stars with the growing list of multiple, low-mass, pre-main sequence stars in (mostly) hierarchical configurations. HD 34700 might be another example of a stellar system, in which the inner, close binary is a result of dynamical interactions in multiple systems early in their evolution.

2. Imaging

HD 34700 was imaged on January 30, 2004, using the Infrared Side-Port Imager (ISPI) mounted at the CTIO 4m-Blanco telescope (Probst et al. 2003). JHK and narrow-band Br-γ images were secured under photometric conditions. A pixel scale of 0″.306 and sub-arc second image quality ensure that three vi-

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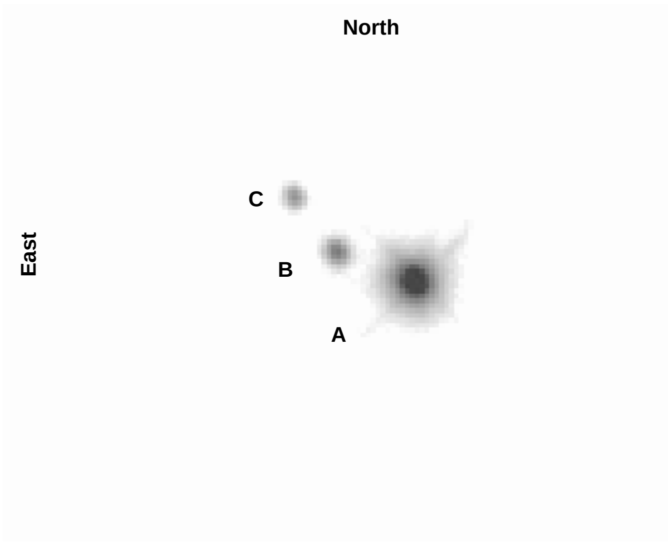

Fig. 1. K-band image of HD 34700 observed with ISPI. North is up, and east is to the left. Separations, postion angles, and photometry are given in table 1.

Table 1. Results of IR imaging for HD 34700.

	sep. [″]	PA [°]	J	H	K	Brγ^{a}
A	-	-	-	-	7.7^{b}	0.0
B	5.18	69.1	12.29	11.52	11.03	3.3
C	9.17	54.9	12.78	12.14	11.91	4.2

[a] instrumental magnitudes
[b] extrapolated from the relative Brγ magnitudes of A, B, and C

sual components, called hereafter A, B, and C, are well resolved (Fig. 1).

We derive the relative astrometry and photometry from PSF fitting, using 6 nearby stars from the *2MASS* point-source catalog (Cutri et al. 2003) as standards. Unfortunately, the component A is slightly saturated in the broadband images, compromizing its photometry. We estimate the errors of the photometry of the components B and C in the JHK images to be less than 0.03^{m}, the errors in the Brγ band are higher because of the faintness of the sources. Nevertheless, the Brγ relative magnitudes between A, B and C are a useful approximation for the broad-band K magnitudes, and we derive a K$\approx 7.7 \pm 0.1$ for component A. This value is also consistent with the 2MASS combined K-band magnitude of 7.48 for the system. Results of the astrometry and photometry are summarized in table 1. The consistency of the relative astrometry between several images is about 0.″01.

We note that the NIR colors of the component C match those of a dwarf with a spectral type between M2 and M3. The H−K$\approx$ 0.5 color of the component B indicates its substantial reddening. We tentatively conclude that this component is likely affected by circumstellar dust absorption. This interpretation is fully consistent with the broad and variable H_{α} profiles observed (see below).

Interestingly, HD 34700 was observed with NICMOS in coronographic mode onboard HST already on September 17, 1998. Two short (0.826s) acquisition images in the filter F165M easily resolve the system into three point sources. The astrometry based on the calibrated frames accessible via the public archive yields a separation of 5.″23 and PA=69.3° between components A and B, and a separation of 9.″25 and PA=55.1° between A and C. These values are thus fully consistent with our 2004 epoch observations. The relative stability of the ABC configuration over 6 years would be an additional argument that the system is physically bound if the proper motion were significant. However, the proper motion of HD 34700 is only ~1 mas/yr and does not allow the conclusion that this is a common proper motion system.

3. Spectroscopy

Guided by the accurate astrometry of the ISPI image, we performed spectroscopy of each of the three visual components of HD 34700 on March 4, 2004 under photometric conditions. We used the Fibre-fed Extended Range Optical Spectrograph (FEROS) attached to the ESO 2.2m telescope in LaSilla, offering a spectral resolution of 48000, and a coverage between ~3500Å and ~9200Å distributed over 32 echelle orders (Kaufer et al. 1999). Centering of components B and C was achieved by issuing relative offsets with respect to the primary SB2. Although all three components were fully resolved in the acquisition camera under seeing conditions of 0.″9, the central SB2 saturates the images, and telescope co-guiding on an anonymous field star was performed instead. The fiber of FEROS has a diameter of 2.″0, and component B is located about 5.″0 from the central source. Assuming a Gaussian profile of 1.″0 width for the central source, we estimate the flux contamination at the location of component B to be negligible. Some low-level contamination, however, is found after cross-correlation (see below). For reference, the spectrum of the bright central SB2 was recorded, too. The integration time was 10 minutes for the SB2, and 20 minutes for each of the components B and C. The data reduction was performed in a standard way using the FEROS pipeline (bias, background correction, flat-fielding, optimal extraction and wavelength calibration). Whereas the spectrum of A exhibits a very high S/N of ~150 at 5600Å (as expected for an object of V=9.15), the spectra of B and C are noisy, with S/N of ~7 and ~3, respectively.

We measure approximate flux ratios of $f_{B/A} = 0.0017$ and $f_{B/A} = 0.0010$ in the continuum. This means that B and C are roughly 6.9 and 7.5 magnitudes fainter than the primary, respectively. Assuming the visual apparent magnitude of the A component to be $V_A = 9.15$, we estimate $V_B \sim 16$ and $V_C \sim 16.5$.

3.1. Spectral types

Due to the low signal-to-noise, spectral types for B and C components can only be determined roughly. A coarse estimate can be obtained by comparing the absolute visual magnitudes with those predicted by evolutionary models. Following Torres (2004), we may assume that HD 34700 is actually located in Orion (i.e. at a distance of $d = 450$pc, corresponding to a dis-

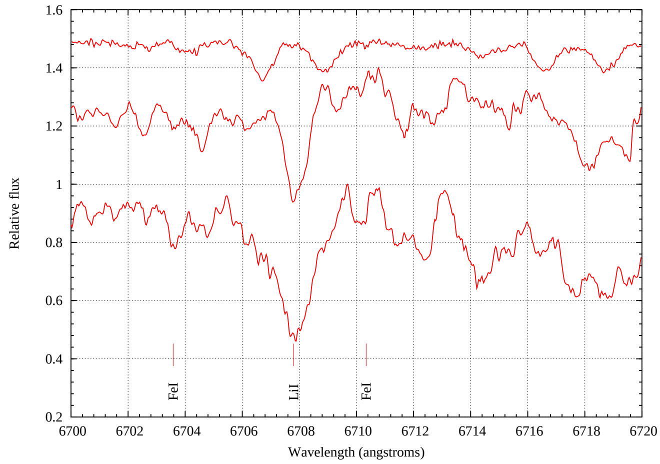

Fig. 2. High-resolution spectra of all components of HD 34700 in the Lithium region (top to bottom: A, B, C).

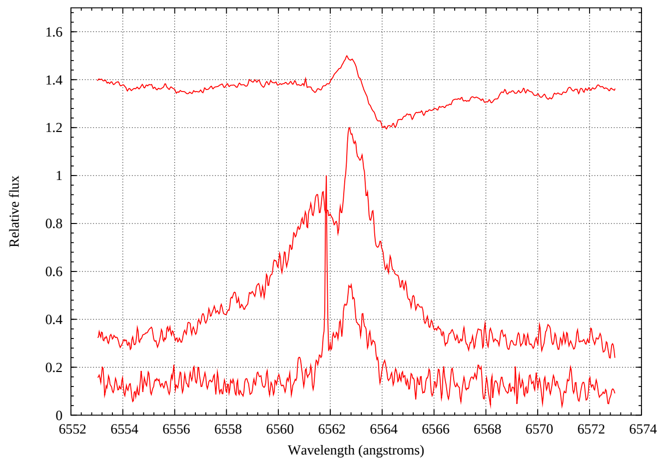

Fig. 3. High-resolution spectra of all components of HD 34700 in the Hα region (top to bottom: A, B, C).

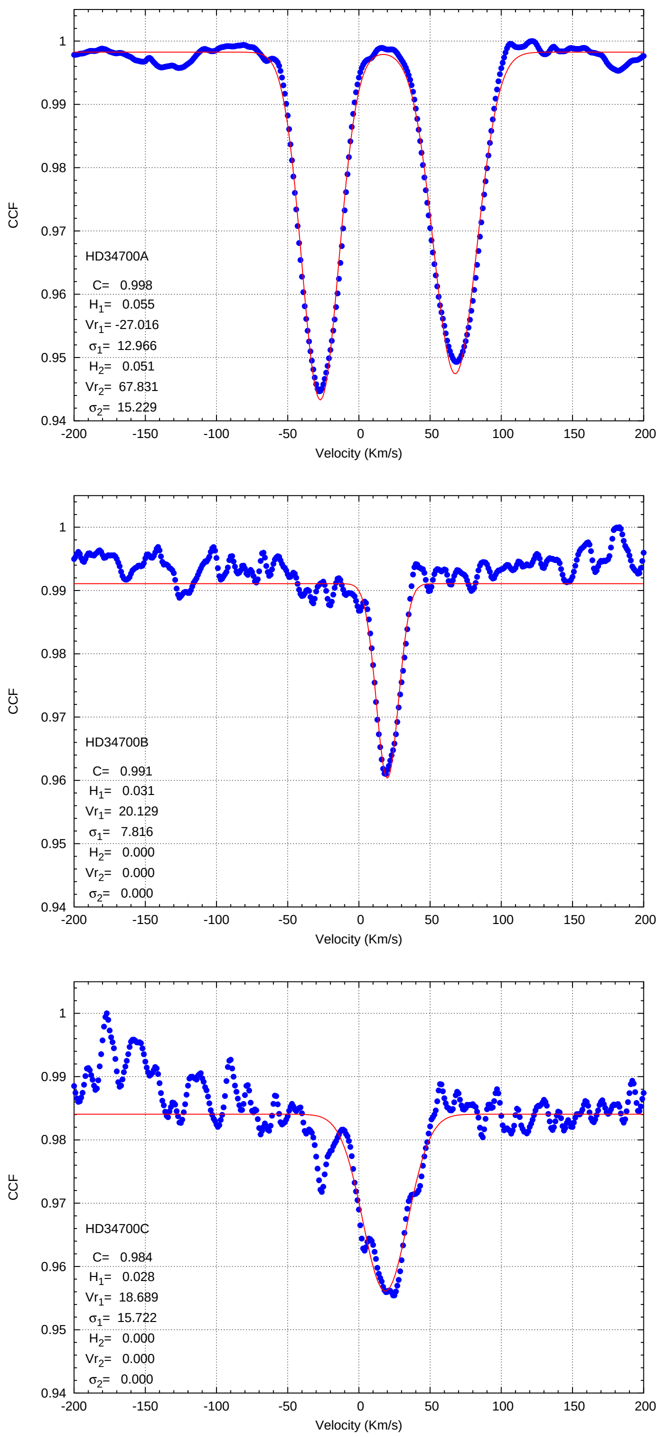

Fig. 4. Cross-correlation functions (top to bottom: A, B, C).

tance modulus of 8.2 mag) with an age of 3Myrs. Referring to Baraffe et al. (1998), we translate the visual magnitudes into a mass of $\sim 0.6 M_{\odot}$ and $T_{eff} \sim 3600$ for B, $\sim 0.5 M_{\odot}$ and $T_{eff} \sim 3500$ for C. Using the effective temperature–spectral type relation given for class IV stars, B and C should then have spectral types around M2 and M3, respectively.[1]

Visual comparisons of the spectra for the B and C components with the spectral library of Montes et al. (1997) fully agree with this estimate, and give spectral types between M1-2 and M3-4.

3.2. Youth indicators

Since Li is strongly depleted in the interior of late-type fully-convective stars already during the pre-main sequence phase, the presence a strong Li I absorption in the atmosphere of these low-mass stars is a strong youth indicator.

AFG and Torres (2004) tried to assess the age of the SB2 with Li I, too. However, due to the G0 spectral types, the Li criterion does not pose strong youth constraints. In Fig.2, we show a close-up of the spectral region around the Li I 6708 Å for all three components. The A component is shifted to the rest frame using the systemic velocity given by Torres (2004) whereas, for the B and C components, we use the radial velocities computed from our cross-correlation functions (see Table 2). Although the spectra of components B and C are much noisier than A,

[1] Torres (2004) alternatively estimates a distance of 250pc and age of about 9Myr for the SB2. Temperatures and spectral types for B and C are still consistent with the values given above.

they still allow to determine key quantities of the stars. Strong Li I absorption is clearly evident for all objects. For each component of A we measure a lithium equivalent width of 0.15Å, compatible with the 0.17Å reported by Torres (2004). The Li I absorption lines for B and C fall nicely in between the well-separated components of the SB2. This already indicates that the radial velocities of B and C are close to the center-of-mass velocity of the SB2 system. The Li I equivalent widths of B and C are much higher, we measure 0.5Å and 0.7Å but assign somewhat larger error bars (0.2Å) due to the noise in the line and continuum.

According to Martin (1997), stars with spectral types later than K7 that have Li I absorption lines with equivalent widths larger than 0.55Å are genuine T-Tauri stars. We conclude that the two late-type companions are therefore bona-fide TTS. Due to the high uncertainties in the equivalent width, and the spectral types we do not attempt to estimate their Li abundances more quantitatively. But we note that in the diagram of Li equivalent width versus temperature both stars are indistinguishable from the pre-main sequence TTS population identified in Orion (Alcalá et al., 2000) and Taurus-Auriga (Wichmann et al., 2000) having ages in the range from 1 to 10 Myrs.

Another common youth indicator for TTS is the H_α line which appears in emission as a result of chromospheric activity and/or accretion of circumstellar material. A close-up around the H_α region is shown in Figure 3. In the SB2 (top), Hα has a complicated and broad profile, as already noted by AFG and Torres (2004). Instead, both components B and C show a broad and strong H_α in emission with equivalent widths of 25Å and 6Å, respectively. B is formally classified as classical TTS and C as weak-line TTS, but given the complexity of their profiles, we suspect that in both stars a part of the emission is caused by accretion.

3.3. Radial velocities and $V \sin i$

Radial velocities have been derived by cross-correlating the observed spectra with a numerical mask, resulting in a cross-correlation function (CCF). Details of the cross-correlation procedure are given in Melo, Pasquini & deMedeiros (2001). Cross-correlation has been performed using 4 different numerical spectral templates, namely, M4, K0, G2, F0. In the case of the A component, the intensity of the cross-correlation increased towards masks of earlier spectral types reaching its maximum for the G2 and decreasing again for the F0 mask which is in agreement with the spectral types derived by AFG and Torres (2004). As an additional check, our radial velocities for both components of the SB2 can be compared to the radial velocities predicted by the ephemeris computed based on the orbital elements given by Torres (2004). For the time of our observations, JD=2453069.522 (i.e., $\phi = 0.0217$), the predicted values are 68.79 km/s for the primary and −27.34 km/s for the secondary, in full agreement with the values given in Table 2. For the B and C components, only the M4 mask produces meaningful cross-correlation peaks which confirms the late-type spectral estimate above. The CCF computed with the K-F masks indicates a signal corresponding to the radial velocity of the SB2, and therefore some contamination. The CCF for all three components are shown in Figure 4. For the A component (top) only the CCF produced with the G2 mask is shown, whereas for the B and C components an M4 mask was used. Since no simultaneous calibration lamp was used, radial velocity errors are dominated by the spectrograph shifts due to changes in ambient conditions (i.e., temperature and pressure). These shifts are typically about 100-200m/s per night (see, e.g. Melo et al. 2001).

Table 2. Spectroscopic results for HD 34700: equivalent widths, radial velocities V_r, and rotation $V \sin i$. Observations are performed on JD = 2453069.522.

Source	Li I(6708) Å	Hα(6562) Å	V_r km s^{-1}	$V \sin i$ km s^{-1}
Aa	0.15	-	68.036	26.3
Ab	0.15	-	−27.98	21.7
B	0.5	25	20.129	11.5
C	0.7	6	18.689	27.5

Projected rotational velocities $V \sin i$ were computed using the $\sigma(CCF) - V \sin i$ calibration for FEROS described in Melo et al. (2001). Our value for the A component is in very good agreement with those from Torres (2004). Unfortunately, no FEROS calibration exists for the M4 mask, where the CCF for the B and C components has been computed. We have therefore utilized calibrations derived by Delfosse et al. (1998) for the ELODIE spectrograph with a similar resolving power (42000).Thus, we believe that the $V \sin i$ given for the B and C components are reasonable estimates, with an error of 1-2 km/s.

4. Discussion

We find that the radial velocities of components B and C are, within the errors, consistent with the center-of-mass velocity of the central SB2. But these radial velocities are also consistent with radial velocities of TTS in the general direction of Orion. Alcalá et al. (2000) identified about 100 TTS scattered all around Orion. The most adjacent TTS to HD 34700 is RXJ0519.9+0552, a K7 wTTS at a projected distance of $\sim 30'$. Its radial velocity is, however, discrepant from HD 34700. No prominent past or present-day star forming clouds lie in the vicinity of these stars. The space density of TTS in this region being low, a chance projection of a physically unrelated TTS within an annulus of $10''$ around a given TTS is highly improbable (but not impossible). To find two chance projections in the same annulus appears even more implausible.

Considering the similar evolutionary state of all components, we tentatively conclude that HD 34700 forms a multiple TTS system consisting of an inner SB2 and two outer physical companions. We cannot make conclusive statements on the long-term dynamical stability of HD34700. The projected configuration of this quadruple appears non-hierarchical. However, at a distance of 450pc the observed separations of B and C imply a crossing time of the order of 10^5yrs, hence even a

Table 3. Multiple TTSs with SBs having a known orbit. The periods of spectroscopic binary P_{in} (in days) and the angular distances to visual companion(s) d_{out} (in arcseconds if not otherwise stated) are listed.

Source	P_{in}	d_{out}	Remark
HD155555	1.7	33″	
V1154 Sco	2.4	0.″288	
RW Aur	2.77	0.″12 + 1.″39	Quad.
RXJ0529.4+0041	3.03	1.″3	eclips.
RXJ0541.4-0324	4.98		SB3
RXJ1301.1-7654	13	1.″44	
UZ Tau	19.1	0.″368 + 3.″54	Quad.
HD 34700	23.5	5″+ 10″	Quad.
ROXs 42C	36	0.″157	
RXJ0532.1-0732	46.9		SB3
V773	51.1	0.″2 + 0.″2	Trap.
Crux-3	58.3	4.6yrs	SB3
ROXs 43A	89.1	6″	
HD98800	262 + 315	0.″8	Quad.
Haro 1-14	591	12.″9	

non-hierarchical multiple system could survive during several Myrs.

Interestingly, similar configurations are encountered quite frequently in TTS systems. In order to be able to make statistically meaningful comparisons, we restrict the following discussion to low-mass TTS systems where the spectroscopic orbit has been solved sufficiently accurately, and in which all components have spectral types later than F5. A rather complete compilation of periods and eccentricities is given by Melo et al. (2001), and 37 PMS SBs follow our selection criterion. Together with two orbits of weak-line TTS SBs (RXJ0528.0+1046 and RXJ0529.3+1210) from Torres, Neuhäuser & Günther (2002), and the classical TTS system RW Aur (Gahm et al., 1999) the number of currently known TTS systems that contain (at least) one SB with a solved orbit is 40. Twelve of them have inner periods $P_{in} < 10d$.

In order to derive the fraction of multiple systems ($N > 2$), we have searched the literature and the Multiple Star Catalog (MSC, Tokovinin 1997) in order to retrieve all known TTS SBs with *at least one additional component*. We are not aware of any particular survey that has attempted to reveal visual companions specifically around TTS SBs, and the list of companions associated to a SB in Table 3 is likely to be incomplete.

Table 3 lists 15 systems that have at least one additional companion. Three of those are components inferred from high-resolution spectroscopy, i.e. are SB3. Seven are visual components from a hierarchical tertiary configuration (with separations ranging from 0.″16 to 33″), and the remaining 5 systems are quadruple. In our well-defined sample of PMS-SBs, we thus determine the fraction of multiple systems (i.e. systems which are at least triple) to be $15/40 = 0.38 \pm 0.10$. Triple systems have a fraction of $10/40 = 0.25 \pm 0.08$, and the fraction of quadruples with respect to triples is $5/10 = 0.5 \pm 0.22$. If we restrict the sample to SB with inner periods $P_{in} < 10d$, we find 4 triples and 1 quadruple, i.e. a higher-order multiplicity fraction of $5/12 = 0.42 \pm 0.19$.

These numbers can be compared with the general fraction of triple systems. In the sample of nearby field G-dwarfs studied by Duquennoy & Mayor (1991) only some 10% have $N > 2$ components, but this result is affected by incompleteness. More recently, Tokovinin (2004) derived the fraction of systems which are at least triple to be around 0.2 – 0.25 in an (almost) complete, nearby ($< 10pc$) sample. Thus, the proportion of triple systems in our sample of PMS SBs is high compared to all stars in the field.

Now we compare the incidence of additional companions to SBs only, as opposed to all stars. In young star clusters the ratio of triples to binaries is consistently found to be around 10%, and has been determined in the Pleiades (Mermilliod et al., 1992) and in Praesepe (Mermilliod & Mayor, 1999). Mayor & Mazeh (1987) estimate that some 25% of SBs are triple. The fraction of triples increases when we restrict the discussion to close SBs only. All 5 systems with $P_{in} < 10d$ in Duquennoy & Mayor (1991) are triple, and at least 43% of the nearby, low-mass SBs with $P_{in} < 10d$ cataloged by Batten, Fletcher & MacCarthy (1989) have known physical tertiaries. The higher-order multiplicity fraction (42%) in our PMS sample restricted to $P_{in} < 10d$ is therefore compatible with these numbers, if not lower.

We conclude that the frequencies of triples and quadruples in our entire sample of PMS SBs may be higher than among field and young clusters stars. For the sub-sample restricted to close SBs, however, we find a similar multiplicity fraction.

Two effects might explain this apparent over-abundance of higher-order systems. It is known that the binary fraction of TTS is – at least in some star forming regions – significantly higher than in the field (Leinert et al. 1997, Ghez et al. 1997). The trend for a higher multiplicity fraction in our sample may therefore simply reflect the general behavior of observing higher multiplicities in earlier evolutionary phases, although the stars of our sample are well mixed throughout the sky, and should not be dominated by regional selection biases.

In general, the fraction of SBs in components of visual multiple stars is higher than in stars without any companion. Melo (2003) finds an excess of 2–3 in the rate of PMS-SBs that have one or more visual companions, compared to those without companion. A similar conclusion is reached in an analysis of the frequency of spectroscopic sub-systems among the components of visual binaries in the field (Tokovinin & Smekhov 2002).

The statistics presented above therefore corroborates Melo's (2003) results and suggests that the multiplicity fraction of PMS-SBs is genuinely enhanced. A possible explanation is that the formation of a close binary is linked to the presence of a more remote companion. The distant companion can assist in the removal of the angular momentum from the close binary and eventual shrinkage of its orbit by several different mechanisms, e.g. by Kozai cycles in combination with tidal dissipation (Kiseleva, Eggleton & Mikkola 1998). We might therefore also understand the relative *underabundance* of multiples with *small* P_{in} in our PMS sample compared to the field in the sense that secular processes are still acting to evolve the systems into more hierarchical and stable configurations.

We also note that the decay of young multiple systems formed in few-body clusters is yet another possible scenario compatible with this notion (Sterzik & Tokovinin 2001; Sterzik, Durisen & Zinnecker 2003).

5. Summary

We have resolved HD 34700, a T Tauri double-lined spectroscopic binary system, by NIR imaging and found two additional faint, visual, stellar components at 5.″2 and 9.″2 distance from the primary system. Both stars are late-type, and show strong Li I absorption indicative for the PMS nature. Their radial velocities are consistent with the center-of-mass velocity of the primary, and we conclude that HD 34700 is actually a physically bound multiple TTS system consisting of an inner SB2 and two late-type companions in wide orbits.

The statistics of TTS with known spectroscopic orbits reveals that the fraction of multiple TTS that contain one close (SB) sub-system is enhanced as compared to the field. This strengthens the notion that the formation of close binaries is linked to the presence of a third stellar component and to dynamical interactions in multiple systems early in their evolution.

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