1986A&A...156..223L

Astron. Astrophys. 156, 223–233 (1986)

ASTRONOMY
AND
ASTROPHYSICS

A study of visual double stars with early-type primaries

V. Post-T Tauri secondaries*

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Received February 15, accepted June 19, 1985

Summary. In the previous articles of this series about 100 secondaries were found to be physical companions to O and B type primaries. The majority of the secondaries are of spectral type F, G or K and in the present work their properties are investigated in relation to their evolutionary status.

The ages of the systems have been determined from *uvbyβ* photometry of the primaries and it is found that all are younger than 150 million years and that half of them are less than 30 million years old. 37 secondaries have ages less than the expected contraction time to the zero-age-main sequence (ZAMS). The youth of the secondaries is also supported by their distribution in the HR diagram, where they fall on or slightly above the ZAMS on the radiative part of the evolutionary tracks of contracting models with masses between 0.5 and $2 M_{\odot}$. By comparing the ages of the secondaries with the isochrones calculated from these models it is found that the agreement in most cases is good but some stars are up to 30 million years older than predicted by the models.

More than 50% of the F, G and K secondaries exhibit spectroscopic features (Ca II H, K and Hα emission and strong lithium absorption) typical of young stars and reminiscent of T Tauri stars although not as conspicuous. Also, in contrast to the T Tauri stars they do not possess any significant infrared or ultraviolet excess emission and they only show a small degree of variability. These properties and the fact that they are older and lie closer to the ZAMS make it appropriate to classify them as post-T Tauri stars. Compared to some X-ray detected pre-main-sequence-stars suggested to be post-T Tauri stars the secondaries studied here appear to be older and more evolved.

The lifetime of some features characteristic of early stellar evolution is discussed and it appears that light variability, infrared and ultraviolet excess emission diminish drastically within the first 30 million years and that Hα emission becomes very weak before the age of 50 million years. Ca II H, K emission and strong lithium absorption remain more than another 100 million years. It is also clear that the strength of these features are different for stars of equal age and that the details of the early evolution is different for each star.

Key words: double stars – stellar evolution – post-T Tauri stars

1. Introduction

Young stars are usually found and searched for in or in the vicinity of nebulae and dark clouds such as the Orion nebula or the Taurus-Auriga complex. Typical observational characteristics for such stars are time variability and the presence of emission lines in their spectra. These stars are often referred to as stars of the Orion population of which the T Tauri stars represent stars with masses around one solar mass. In addition to these active young stars it is also known that there exist young stars both in clusters and in the general starfield which do not show much activity and which consequently are difficult to detect and identify as young stars. Such stars, and particularly the so called post-T Tauri stars, i.e. stars intermediate between T Tauri stars and the main-sequence, are the subject of this investigation.

The evolutionary phases for stars found in one and the same region of star formation range from the very earliest epochs when the stars are still embedded in dense dust clouds to the times when the contraction is stopped and the stars appear as normal stars on the zero-age main-sequence (ZAMS). From this spread in age it is evident that star formation in a given cloud complex is a continuous process spread out over several million years. This is also seen in the HR diagrams of such aggregates in which the spread of the stars above the ZAMS can be understood only if star formation has been going on for some millions to a few 10^7 yr (Iben and Talbot, 1966; Cohen and Kuhi, 1979). Because of this noncoeval star formation it is difficult to determine the age for individual young stars with any accuracy or to test the time scales of the theoretical calculations of early stellar evolution. The age of a particular star can only be estimated by comparing its location in the HR diagram (which is quite uncertain) to the evolutionary tracks and isochrones predicted by models of contracting stars. In this investigation these difficulties have been circumvented by using pre-main-sequence (PMS) stars which are secondary components in visual double stars for which the age can be derived from the primary. From the models calculated by Iben (1965, 1967) for the evolution to and from the ZAMS it is seen that two stars formed at the same time cannot simultaneously be on the main-sequence if the masses differ by a factor of seven or more. In the case of double stars with O or B type primaries this means that secondaries of about one solar mass must still be contracting or have just reached the ZAMS. The contraction time for such secondaries is longer or a large fraction of the entire time spent at the main-sequence by early type stars. By studying visual double stars with primaries of spectral type O or B and fainter secondaries which are likely to

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* Based on observations collected at the European Southern Observatory, La Silla, Chile

be of spectral type F, G or K it is therefore possible to detect young low mass stars which are likely to be in the PMS phase of their evolution. By selecting wide pairs the evolution of the components is guaranteed to be independent. The age of both components is undoubtedly the same since capture is unlikely (Lippincott, 1967). It can be derived from the primary's location in the HR diagram by comparison with the isochrones calculated for the evolution from the ZAMS. The masses of the components could in principle be determined from orbital motion, but presently this is not possible because of the large separations of the systems being studied here. However, the mass of the primary can be estimated by comparison with theoretical evolutionary tracks.

To detect double stars having the properties described above more than 250 double or multiple systems with O or B type primaries were surveyed spectroscopically and photometrically in *uvbyβ* in this investigation. The primaries are generally brighter than $V = 7^{\mathrm{m}}.5$ and the secondaries are typically 2 to 7 mag fainter than the primaries. The separations between the components range from 2″ to 60″ with some exceptions for wider pairs. Details about the selection of pairs were given in Paper I (Gahm et al., 1983) in which the spectroscopic data also were discussed. The results of the photometric observations were presented in Paper II (Lindroos, 1983). Paper III (Gahm, 1982) contains a table of radial velocities. In Paper IV (Lindroos, 1985) astrophysical parameters such as colour excess, distance, effective temperature and age were derived from calibrations of the *uvbyβ* indices. These data together with the spectroscopic results were used to decide which systems are optical and which are likely to be physical. Almost 100 secondaries, of which 60% are F, G or K type stars, were evaluated as likely physical companions. All the secondaries are younger than 150 million years and half of them are less than 30 million years old. By comparing their ages with the theoretically calculated contraction times it was found that several are contracting towards the ZAMS.

In the present article the properties of the young secondaries will be investigated and compared to other PMS stars, particularly the so called post-T Tauri stars (or PTTS). The problems and properties of these stars were addressed by Herbig (1978) and more recently by Haro (1983). Thousands of T Tauri stars with ages not more than a few million years are known, but what happens after the T Tauri phase? The contraction time to the ZAMS is of the order of 50 million years so there must be many stars which have lost their T Tauri characteristics but have still not reached the ZAMS. They are difficult to detect, however, and only a few have been recognized. The ages of the contracting secondaries are generally larger than that of the T Tauri stars and many of them are PTTS candidates.

Reports on PMS stars in young double stars have been presented by Murphy (1969), Catchpole (1971), Andrews and Thackeray (1973), Eggen (1983a) and in somewhat older systems by Wallerstein (1966) and Wilson (1965). Several PMS stars have been reported to be close binaries: Gahm (1976), Rydgren et al. (1976), Herbig (1977), Cohen and Kuhi (1979 and Mundt et al. (1983). Recently T Tauri itself has been detected to be a triple system Dyck et al. (1982) and Nisenson et al. (1985).

2. Data for the physical systems

In Paper IV it was shown that 34% of the investigated secondaries are likely to be members in physical systems with O or B type primaries. For some of these systems the physical relation of the components is somewhat uncertain (physical?) and they have been omitted in the present paper. The remaining 78 systems contain 84 secondaries which are listed in Table 1 together with some relevant astrophysical data taken from Papers I and IV.

Description of Table 1.

Column 1: HD number.
Column 2: MK class for the primary. A parenthesis indicates that the classification is based on the photometric data.
Column 3: Component designation for physical secondaries.
Column 4: MK class for the secondary.
Column 5: Reddening, A_V.
Column 6: Logarithm of the luminosity in solar units.
Column 7: Logarithm of the effective temperature.
Column 8: Age in million of years.
Column 9: Distance in parsecs.
Column 10: Projected separation in AU between secondary and primary.
Column 11: Notes. Secondaries younger than the contraction time are indicated by "*C*". Diffuse lines are indicated by "Diff" and Emission lines are noted by "*E*(spectral lines)". The spectral lines Hα, Hβ, Hγ and Hδ are indicated by *a*, *b*, *g* and *d* and the Ca II H, K lines by H and K. Strong/weak lithium absorption at λ6707 Å is indicated by Li : S/W. The criterion for the lithium line to be strong is that it is comparable to or stronger than the Ca I line at λ6572 Å (see Paper I).

3. The secondaries in the HR-diagram

The physical secondaries are plotted in the HR diagram in Fig. 1. Also inserted in the figure are the evolutionary tracks for contracting models calculated by Iben (1965) for $X = 0.708$, $Z = 0.02$ and the corresponding ZAMS together with the observed ZAMS which have been used in this study, (Crawford 1975, 1978, 1979 and Schmidt-Kaler, 1982). The observed ZAMS lies entirely above Iben's and for temperatures below $\log(T_e) = 4.0$ the difference is about $0^{\mathrm{m}}.5$. However, the zero-age-line calculated by Hejlesen (1980) for $X = 0.70$, $Z = 0.03$ agrees quite well with the observed one for $\log(T_e) < 4.0$, (see Paper IV).

It is evident that the majority of the late type secondaries fall above the ZAMS and that they are approaching the ZAMS along the radiative parts of the model tracks for masses between 0.5 and $2\,M_\odot$. Very few stars fall on the convective tracks since these early phases of stellar evolution are of such short duration that only companions to very early type primaries can be expected to be found in this part of the diagram. Because of the youth of such stars, they are found in regions of star formation such as the Taurus-Auriga cloud complex. An extensive investigation of young stars in such regions has been presented by Cohen and Kuhi (1979). The location in the HR diagram of the T Tauri type stars included in their study is shown in Fig. 2 together with the secondaries of this investigation and theoretical isochrones for contracting stars. It is seen that the T Tauri stars occupy parts of the HR diagram corresponding to ages less than 20 million years for stars with masses less than $1\,M_\odot$ and to ages less than 6 million years for the more massive ones. Between the ZAMS and the T Tauri stars there is a gap which is filled in by the secondaries. The latter thus represent a somewhat older and more evolved population of

Table 1. Data for physical double stars

Primary		Secondary								
HD	MK	Comp	MK	A_V	Log L	Log T	Age	Dist	Sep	Notes
560	B9 V	B	G5 V E	0.00	-0.28	3.73	<50	81	624	C,E(a,H,K),Li:S
1438	B8 V	B	F3 V	0.04	0.32	3.84	95	171	1060	
3369	B5 V	B	A6 V	0.00	0.90	3.91	56	163	5851	
8803	B9 V	B	F6 V P	0.12	0.53	3.82	148	164	984	Diff,Li:W
17543	B6 IV	C	F8 V	0.21	0.12	3.78	62	157	3925	
23793	B3 V	B	F3 V P	0.08	0.41	3.83	<28	131	1179	C,Diff,Li:W
27638	B9 V	B	G2 V	0.00	0.37	3.75	123	79	1533	Li:S
33802	B8 V	B	G8 V E	0.01	-0.22	3.72	40	75	952	C,E(a,H,K),Li:S
34798	B4 V	B	B6 V	0.02	2.46	4.15	<18	216	8510	
35007	B3 V	C	(G3 V)	0.16	-0.01	3.74	23	236	8873	C
35173	(B5 V)	B	(B7 V)	0.57	2.31	4.15	44	331	8606	
36013	B2 V	B	(F9 V)	0.04	0.39	3.77	40	535	13375	C,Li:S
36151	B5 V	B	(G1 V)	0.08	0.44	3.76	<18	227	11032	C
		X	(G7 V)	0.08	-0.09	3.74	<18	227	10200	C
36779	B2.5 V	B	(K5 IV)	0.10	1.11	3.59	8	413	11357	C,Li:W
36960	B0.5 V	B	B1 V	0.00	4.03	4.38	4	528	18849	
38622	B2 V	C	(G2 V)	0.04	0.12	3.75	37	302	7519	C
40494	B3 IV	B	(G8 V)	0.00	-0.15	3.73	33	300	10139	C
43286	(B5 IV)	B	(G3 V)	0.06	0.42	3.74	64	498	9113	
47247	B5 V	B	A2 V	0.02	0.93	3.93	14	230	2091	C
48383	B4 V	B	(A8 V)	0.00	0.94	3.91	35	270	4157	
48425	(B3 V)	C	(G5 V)	0.00	-0.08	3.74	<25	355	12389	C
48857	B4 V	B	B9 V	0.08	1.96	4.07	39	531	22461	
53191	A0 V	B	(G3 V)	0.05	0.03	3.74	85	240	4080	
53755	B0.5 IV	B	F5 III	0.65	1.52	3.83	<10	1371	8500	C
56504	B9 IV	B	(G6 III)	0.07	2.00	3.70	112	932	28985	Li:W
60102	B9.5 V	B	(G8 V)	0.22	-0.10	3.73	107	198	3247	
60575	B4 V	B	(B8 V)	0.42	2.30	4.11	40	806	12412	E(a),Li:W

(Continued)

Table 1 (continued)

Primary		Secondary								
HD	MK	Comp	MK	A_V	Log L	Log T	Age	Dist	Sep	Notes
61555	B3 V	B	B7 V	0.00	2.67	4.14	12	127	1257	
63065	(B9.5 V)	B	(A2 V)	0.14	1.21	3.95	110	293	5128	
63465	B2.5 III	B	(F2 V)	0.25	0.87	3.84	26	441	4806	C
66005	B2 V	B	B2 V	0.15	3.49	4.31	<14	424	6953	
70309	B3 IV	B	(K2 IV)	0.12	0.59	3.66	19	304	12920	C
71510	B3 V	C	G3 V	0.01	0.42	3.75	32	244	8515	C
74067	B9 V	B	A2 V	0.00	1.0	3.96	63	69	269	
74146	B5 V	B	F0 IV	0.03	0.68	3.86	10	130	2158	C
76323	B5 V	B	A1 V	0.06	1.56	4.01	54	634	11095	
76566	B3 V	B	(G4 V)	0.00	0.06	3.74	39	383	13405	C
77002	B2.5 IV	B	B9.5 V	0.03	2.36	4.16	22	228	9211	
77484	(B9.5 V)	B	G5 V	0.09	0.00	3.75		555	2440	Li:S?
86388	B9 V	B	F5 V	0.02	0.40	3.81	65	170	1563	Li:W
87901	B8 V	B	K0 V E	0.00	-0.39	3.70	135	28	4956	E(H,K),Li:W
90972	B9.5 V	B	F9 V E	0.03	0.10	3.78	120	99	1089	E(H,K),Li:S
91590	AP	B	AP	0.01	0.74	3.88	38	259	7355	
99803	B9 V p	B	A3 V	0.04	0.82	3.93	126	100	1310	
100359	B7 IV	B	A1 V	1.25	2.87	3.97	44	301	6321	
104901	B9 II	B	F0 II E	1.11	3.31	3.86	46	1052	24196	E(a,b,g,d),Li:W
108767	B9.5 V	B	K2 V E	0.00	-0.62	3.70	<112	23	556	C,E(H,K),Li:S
112092	B2 V	B	B5 V E	0.06	2.78	4.21	15	143	4990	E(b),Diff
112244	09 Iab	B	K0 III	0.90	2.45	3.68	<5	2489	72430	C
112413	A0 III P	B	F0 V	0.00	0.61	3.85	<28	29	568	C
113703	B4 V	B	K0 V E	0.00	-0.38	3.68	<35	90	1026	C,E(a,b,H,K),Li:S
114911	B8 V	B	Ap	0.04	0.92	3.93	<20	90	5400	
120641	B8 V	B	F0 V P	0.00	0.78	3.89	<71	87	1566	Diff
120991	B2 II E	B	B8 V	0.50	1.94	4.06	13	1219	18163	

(Continued)

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Table 1 (continued)

Primary		Secondary								
HD	MK	Comp	MK	A_V	Log L	Log T	Age	Dist	Sep	Notes
123445	B9 V	B	K2 V	0.12	-0.81	3.66	<20	107	3060	C,E(H,K)?
127304	A0 V	B	K1 V	0.04	-0.61	3.71	<79	91	2349	C
127971	B7 V	B	K0 V	0.08	-0.30	3.68	<18	112	3012	C
129791	B9.5 V	B	K5 V E	0.26	-0.75	3.65	39	123	4341	C,E(a,H,K),Li:S
135591	08 V	C	(A8 III)	0.59	1.49	3.90	5	1036	46102	C
137387	B3 IV E	B	K5 IV	0.47	1.6	3.57	<20	524	1470	C,Li:W
138800	B8 IV	X	K0 V	0.22	-0.60	3.71	102	168	2520	
143118	B2 V	B	A5 V P	0.02	1.17	3.92	3	157	2351	C,Diff
143939	B9 III	B	K3 V E	0.00	-0.28	3.74	<32	153	1316	C,E(H,K)
144217	B0.5 V	C	B2 V	0.53	3.44	4.30	10	174	2366	
145483	B9 V	B	F3 V	0.25	0.78	3.84	<71	81	373	
157246	B1 III	B	A7 V	0.42	1.77	3.89	11	760	13604	C
159176	07V+07 V	B	B9 V	0.99	2.96	4.15		1297	7003	
		C	B8 V	0.99	2.64	4.15		1297	17250	
		X	(B5 V)	0.99	2.75	4.18		1297	32425	
159574	B8 Ib	B	B7 V	1.06	2.37	4.16	46	938	11912	
162082	B7 V	B	F2 V	0.63	0.76	3.85	<14	314	3359	C
165530	B7 V	B	B9 III P	0.49	2.36	4.12	48	480	6384	
166937	B8 Ia E	B	B9 III	1.03	2.78	4.26		920	15500	
		D	(B2 V)	1.03	3.22	4.31		920	44600	
		E	B2 V	1.03	3.39	4.32		920	46000	
167263	09 III	B	A3 V	0.92	1.18	3.94	5	1227	7362	C
167647	B3 V+A	B	(A1 V)	0.23	1.26	3.98	39	339	13187	
170580	B2 V	B	A7 V P	0.86	1.00	3.90	30	431	8663	Diff
170740	B2 V	B	A0 V	1.39	1.71	4.08	19	225	2767	
174585	B2.5 V	B	(K2 IV)	0.17	0.83	3.68	26	338	11762	C
		C	G0 V	0.17	0.81	3.78	26	338	19841	C
177817	B8 IV	B	A0 V	0.21	1.28	3.99	100	224	1434	
180183	B3 V	B	K0 V	0.10	0.94	3.69	14	523	10146	C,Li:W

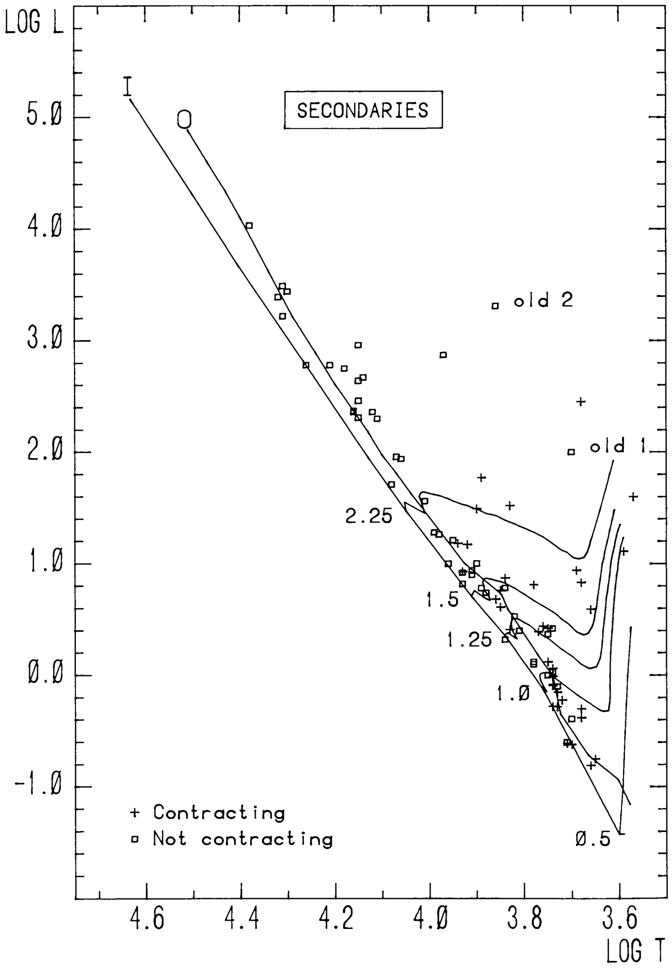

Fig. 1. The physical secondaries in the HR diagram together with the observed ZAMS ("O") by Crawford (1975, 1978, 1979) and Schmidt-Kaler (1982) and theoretical evolutionary tracks and ZAMS ("I") by Iben (1965). The stars indicated as "old 1" and "old 2" are the evolved stars HD 56504 B and HD 104901 B, which are discussed in the text

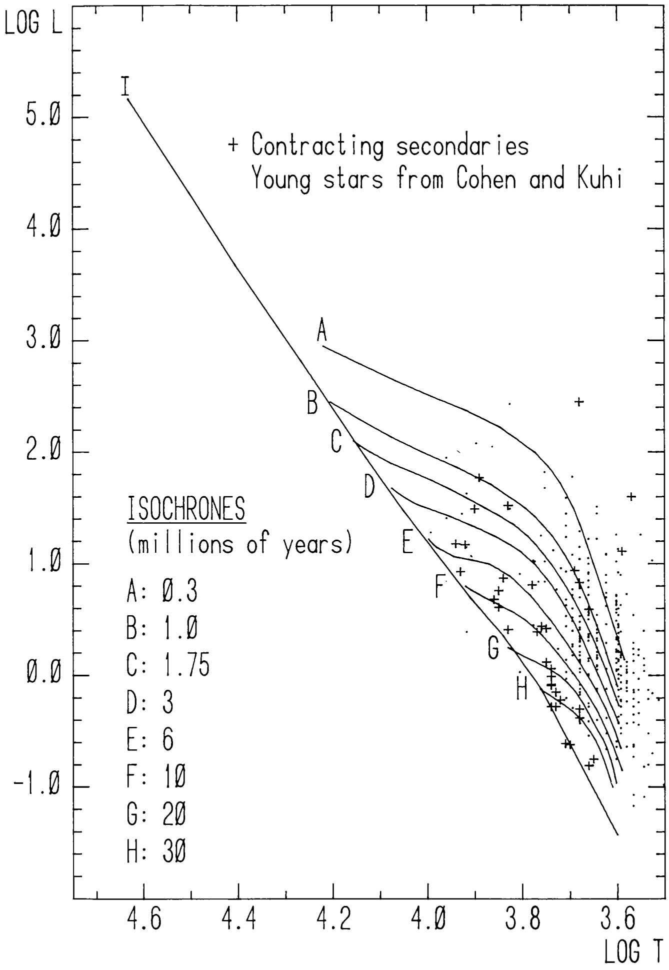

Fig. 2. HR diagram with isochrones from Iben and Talbot (1966) for contracting stars. Young late type stars found in star forming regions studied by Cohen and Kuhi (1979) and the contracting secondaries are shown with different symbols. It is seen that many of the secondaries fall in the gap between the ZAMS and the T Tauri type stars

stars than the T Tauri stars, but which are still in early phases of their evolution. Their location in the HR diagram, coincides with the radiative evolutionary tracks of low and intermediate mass stars and is in agreement with the prediction by Herbig (1978) for the PTTS. As mentioned in the introduction such stars should be abundant but so far have eluded detection. Herbig (1978) discussed a few candidates and some stars have been suspected to be PTTS by Mundt et al. (1983). However, their stars fall higher above the ZAMS than the secondaries and it is unclear if they really are older than the T Tauri stars although they, like the secondaries, show less of the activity typical of PMS stars. The later type secondaries in this investigation constitute the first large sample of PTTS which will enable us to study properties of stars in their final approach to the ZAMS and early phase of main-sequence evolution.

4. Comparison of ages and isochrones

The ages of the secondaries are assumed to be equal to that of the primaries and were determined by comparing the positions of the primaries in the HR diagram with the isochrones calculated by Hejlesen (1980) for the evolution from the ZAMS (see Paper IV). With two exceptions all the secondaries are in early phases of their evolution and half of them are less than 30 million years old. By comparing their ages and spectral types with the theoretically calculated contraction times (Iben, 1965) it is found that 37 secondaries are still contracting. These stars are noted by a "*C*" in column 11 of Table 1. It should be noticed that some of these stars actually do not fall above the ZAMS. The reason for this is most likely due to the absolute magnitude determination of the primary which affects both the age and the height above the ZAMS, see further Paper IV.

For the contracting secondaries it is possible to compare the derived ages with the isochrones calculated by Iben and Talbot (1966) for models of contracting stars. The result is presented in Table 2 where the difference between the age found for the primary and the isochrone on which the secondary falls in the HR diagram is calculated for each star. It is seen that in many cases the agreement is very good or at least not contradicting. If one considers the uncertainty in the age determination it appears that in almost all cases the value of the isochrone is

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Table 2. Comparison of ages and isochrones (numbers are in millions of years)

HD		Age	Isochrone	Diff
33802	B	40	30	10
35007	C	22	25	-3
36013	B	39	10	29
36151	B	<18	8	?
	X	<18	25	-7
36779	B	9	<1	8
38622	C	35	18	17
40494	B	33	27	6
47247	B	15	8	7
48425	C	<25	25	?
63465	B	26	7	19
70309	B	19	1	18
71510	C	32	8	24
74146	B	10	6	4
76566	B	38	20	18
112244	B	<5	<1	?
113703	B	30	<35	?
123445	B	<20	>30	<-10
127971	B	<18	23	?
129791	B	45	>30	?
135591	C	5	2	3
137387	B	<20	<1	?
143118	B	3	4	-1
143939	B	<32	20	?
157246	B	12	1	11
162082	D	<14	9	?
167263	B	5	5	0
174585	B	26	1	25
	C	26	5	21
180183	B	14	1	13

contained within these errors. However, it is interesting to note that the differences in general are positive, i.e. the stars are older than the isochrones. The opposite is rare and the differences also much smaller. Even if the errors are large it is unexpected that the difference systematically should be positive. To reduce the errors in the ages the comparison was limited to a few small areas in the HR diagram in which the secondaries form small groups for which a mean value of the age could be calculated (Lindroos, 1981). The result was similar to the one above and it is therefore not evident that the discrepancy is caused by the errors. In the same work it was also investigated if the ages of the primaries could be systematically overestimated but this was found to be unlikely, on the contrary, the discussion in Sect. 3e of Paper IV indicates that the ages might be underestimated by 5 to 10 million years. The question as to whether the luminosity of the secondaries is too high was also investigated but the required systematic error in the absolute magnitudes of the primaries was too high to have been unnoticed.

It thus appears that the ages of the models by Iben for contracting stars in some cases are underestimated by up to 30 million years. In Fig. 1 it is seen that the ZAMS by Iben and the observed one are displaced in $\log(T_e)$ by about 0.04. However, shifting the isochrones in $\log(T_e)$ so that the zero-age lines coincide has only a very small effect on the ages of the stars and does not remove the discrepancy. The chemical composition is different for Iben's models ($Z = 0.02$) and the main sequence models by Hejlesen (1980) used here ($Z = 0.03$) but this affects the age by only a few million years. Bhattacharjee and Williams (1980) investigated the effects of mass accretion on PMS evolution and found that the age is dependent on the previous evolution and cannot be derived from models calculated with constant mass. The early PMS evolution is also sensitive to the initial conditions in the cloud as discussed by Appenzeller (1983) and it appears that during the convective phase the age and mass is not unique at a given place in the HR diagram. However, tracks calculated using different initial values converge just before radiative equilibrium is reached and since the convective phase is short the spread in age close to the ZAMS cannot be as large as found here. A more plausible explanation is that the contracting models are non-rotating while PMS stars generally are believed to be fast rotators. Intuitively one expects that rotation should slow down the contraction and this is also confirmed by model calculations. The most complete calculations are presented by Bodenheimer and Ostriker (1970) but only models more massive than $3\,M_\odot$ are included in their work. Their results show that by including rotation the contraction time for a given mass more than doubles but the time to reach a given place on the ZAMS is only slightly changed. For stars of lower mass Bisnovatyi-Kogan (1980) presents models for which the evolution time to the main sequence almost doubled when rotation was included. More observations are required for a further study of this problem. It would be particularly interesting to investigate if the secondaries for which the ages differ also rotate faster.

5. Evolved secondaries

As mentioned earlier all the secondaries are younger than 150 million years and with the exception of two stars they are either contracting or have just settled on the main-sequence. The two exceptions, specially marked in Fig. 1, are the giants HD 56504 B and HD 104901 B, which are too old to be PMS stars. They can be physically related to their primaries provided that they originally were more massive and have been subject to mass loss. From their locations in the HR diagram relative to the post-main-sequence evolutionary tracks it is found that the mass of the expelled matter must be about $1\,M_\odot$, which is acceptable with mass loss rates normally observed. Since these stars do not represent early stellar evolution they are not included in the discussions of PMS stars. HD 104901 B is also known as CPD $-61°$ 2233 and CoD $-61°$ 3326 and has number 747 in the catalogue of Hα emission line stars by Henize (1976).

In Paper I it was reported that the hydrogen lines were in emission with a violet displaced absorption feature (P Cygni profile) indicating mass loss. This star has been investigated in more detail by Eggen (1983b) and Tapia (1982). Eggen studied the light variability and found a variation of 0.35 mag. in *V* and suggested that the star is an eclipsing binary with a period of 53.3 days. The variability is also noted in the results presented below. Eggen derives a distance of 0.72 pc for *A* which is slightly smaller than the number given here but he also supports that *A* and *B* are at the same distance. Tapia investigated the infrared properties of the two components. His J, H and K magnitudes agree well with those reported in Paper II, but his *L* magnitude for *B* is 0.2 magnitudes larger. The data presented here in Table 3 indicate a strong infrared excess emission also noted by Tapia. He finds that this can be explained by the presence of a circumstellar dust shell with a temperature of 800 K. He also suggests that *A* and *B* are at the same distance from the sun but the value he derives for this distance is somewhat large: 3.1–4.0 pc.

Table 3. Infrared properties of selected secondaries

HD	MK	Normal (V-K)	Observed (V-K)	Diff
33802 B	G8 V	1.60	1.79	-0.17
35007 C	G3 V	1.49	1.32	0.17
36013 B	F9 V	1.16	1.31	-0.15
36151 B	G1 V	1.30	1.23	0.07
X	G7 V	1.57	1.44	0.13
36779 B	K5 IV	3.48	3.02	0.46
38622 C	G2 V	1.40	1.57	-0.17
40494 B	G8 V	1.60	1.60	0.00
48425 C	G5 V	1.54	1.77	-0.23
53191 B	G3 V	1.49	0.99	0.50
56504 B	G6 III	2.12	2.05	0.07
70309 B	K2 IV	2.42	2.53	-0.11
71510 C	G3 V	1.52	1.51	0.01
74146 B	F0 IV	0.79	0.61	0.18
76566 B	G4 V	1.52	1.78	-0.26
87901 B	K0 V	2.00	2.19	-0.19
90972 B	F9 V	1.17	1.47	-0.30
91590 B	Ap V	0.45	0.44	0.01
104901 B	F0 II	0.6	1.37	-0.8
108767 B	K2 V	2.00	2.18	-0.18
112244 B	K0 III	2.26	2.27	-0.01
123445 B	K2 V	2.99	2.44	0.55
127971 B	K0 V	2.68	2.57	0.11
129791 B	K5 V	3.30	3.00	0.30
135591 C	A8 III	0.6	0.78	-0.2
137387 B	K5 IV	3.40	3.23	0.17
138800 X	K0 V	2.00	2.32	-0.32
143118 B	A5 V	0.4	0.25	0.15
170580 B	A7 V	0.56	0.89	-0.33
180183 B	K0 V	2.24	2.01	0.23

6. Properties of the post-T Tauri stars

Typical properties of contracting stars are light variability, infrared excess emission and spectroscopic peculiarities such as the presence of emissions lines. For instance Hα is almost always present in emission. These features are weak or absent among normal main-sequence stars and it is generally believed that they decline and eventually disappear as the stars evolve towards the ZAMS. Since the PTTS are older and closer to the ZAMS it is expected that these features are less pronounced or even have disappeared (Herbig, 1978). To study this question the presence of PMS signatures among the secondaries have been investigated and the results are presented below.

6.1. Spectroscopic peculiarities

The whole survey includes 38 secondaries noted to have emission lines (Ca II H, K and Hα) diffuse lines or a strong absorption line from lithium at λ6707 Å. Of these 20 (or 53%) are classified as likely physical and they are specially indicated in Table 1. Unfortunately, spectroscopic data is completely lacking for about 30% of the physical secondaries and for 70% the red spectral region has not been investigated. This means that the number of stars with spectroscopic peculiarities probably is substantially higher than detected. Among the stars with emission 60% are physical and for stars with strong lithium absorption the fraction is as high as 80%. The large fraction of physical secondaries with these spectral features which are characteristic of T Tauri stars and early stellar evolution (Herbig, 1962) provides a strong support that they are physical companions and young stars.

The intensity of the emission is not as high as seen in the classical T Tauri stars but is reminiscent of that in T Tauri stars of the weaker emission classes (Herbig, 1962). This result fits well with the conception that the secondaries are older and more evolved PMS stars.

In Paper I it was shown that Li abundances of the stars noted with strong lithium absorption may be close to the primordial abundance. Since the depletion of lithium at the surface is very rapid for late type stars there is a strong indication that these secondaries are young.

Although the spectroscopic data is incomplete, some statistics and relations between the presence of the various peculiarities and the evolutionary phase can be studied. In the following only stars later than F0 are considered.

1. At least 50% of the secondaries show some spectral peculiarity and, according to their age, 60% of these are contracting.
2. 30% show Ca II H, K in emission and of these 60% also have Hα in emission, 90% have strong lithium absorption and 80% are contracting.
3. 45% have strong lithium absorption and of these 70% have Ca II H, K in emission, 60% have Hα in emission and

70% are contracting. All stars detected with strong lithium absorption are later than F9 and for such stars the frequency of this feature is 60%.

4. 25% have Hα in emission and all of these have Ca II H, K in emission and strong lithium absorption and are contracting.

5. Several secondaries have diffuse lines, but many are classified as optical. Of the 6 physical ones 3 have spectral types B or A and 3 are F type stars. No correlation with age, contraction or any of the other peculiar features is evident.

6. 37 secondaries are contracting (Paper IV) and 33 of them have spectral types later than F0. From the ones for which data is available the following is derived: 80% have at least one of the peculiar features, 40% have Ca II H, K in emission, 40% have Hα in emission while 50% have a strong lithium absorption. Of these with Ca II H, K in emission, which have been observed in the red, a large fraction (90%) also have a strong lithium absorption and 60% have Hα in emission. All three of these features are present in 40% of the contracting stars.

6.2. *Infrared colours*

A typical property of T Tauri stars is the strong excess emission longwards of 1μ. The emission at these wavelengths is normally much larger than anticipated from the spectral type or effective temperature and it is probably caused by emission of circumstellar dust, heated by the stellar radiation. Main-sequence stars normally do not have any infrared excess and since the secondaries lie between the T Tauri stars and the ZAMS it is possible to study how the excess decays as the stars evolves. To investigate this some 40 secondaries were selected for observations in the *JHKL* bands with the ESO 1 m reflector and an InSb detector in March 1981. The magnitudes measured for the stars are presented in Paper II.

To detect possible excess emission the observed values of the V-K index (corrected for extinction) was compared to the value expected for normal stars of the same MK class. The latter were taken from Wing (1983) for dwarfs later than K3 and from Koornneef (1983) for other stars. Correction for reddening was made by taking $A_K/A_V = 0.1$. The result is presented in Table 3 which shows the expected value, the observed value and their difference. The average value of the differences is 0.01 ± 0.30. Half of the secondaries have negative differences indicating excess emission. However, these differences are small and not larger than the positive ones. Furthermore, there is no correlation between age, luminosity class or height above the ZAMS and the possible excess. The conclusion is therefore that these stars do not have any significant infrared emission but appear as normal stars of the same MK class. The evolved star, HD 104901 B, has a $V-K$ index which is $0^{m}8$ larger than expected, indicating excess mission.

6.3. *Light variability*

From the photometric data presented in Paper II it is difficult to draw any definite conclusions about possible variability. In most cases the observations of a given star have been collected over a short period of time (one or two days) and a variable star might have been constant in brightness. Some stars do show rather large errors in the meanvalues of the indices but it is difficult to distinguish variability from errors in the measurements because the stars are rather faint for the instruments used. However, the brightness of the secondaries often differ significantly (one magnitude) from the values listed in the catalogue by Jeffers et al. (1963) from which they are selected. The magnitudes in this catalogue are mostly visual estimates and the large differences compared to the photoelectric values in most cases only reflect how crude the former are.

In order to investigate if the secondaries are variable at visual wavelengths 10 stars with different properties (MK class, height above the ZAMS, emission lines) were selected for observations in the *uvby* bands on several nights over a 10 day period in March 1983 with the ESO 50 cm and 1 m telescopes. Unfortunately, due to poor weather, 3 nights in the middle of the run were lost and 3 of the stars could only be observed once or twice. In Table 4 the maximum differences in the observed magnitudes in the filters *u*, *v*, *b* and *V* are given for each star. Differences larger than 0.05 (0.10 for *u*) are considered as real indications of variability. It is seen that several of the stars appear to be variable, although the amplitude of the variation in most cases is small. However, because of the limited number of observations of each star the maximum amplitude can be larger. In any case, the degree of variability is less among these stars than among the classical T Tauri stars. Like for the T Tauri stars the amplitude increases towards the shorter wavelengths. It is interesting to find that the youngest star (HD 36779 B), which also is far above the ZAMS has the largest degree of variability. With this exception it is difficult to find any clear relation between variability, age and height above the ZAMS or the strength of emission lines. Instead it appears that stars of similar age and in the same phase of evolution have quite different properties in this respect, indicating that the detailed PMS evolution is different for individual stars.

7. Discussion

None of the PTTS secondaries show any large degree of light variability, infrared or ultraviolet excesses and consequently it appears that these properties disappear on a short time scale.

Table 4. Variability of selected secondaries

HD	$\overline{V}$	ΔV	Δb	Δv	Δu	NN
27638 B	8.41	0.07	0.04	0.06	0.19	4
33802 B	9.94	0.06	0.07	0.11	0.26	3
36013 B	12.52	0.17	0.18	0.23	0.29	4
36779 B	11.20	0.13	0.26	0.56	1.29	8
87901 B	8.09	0.02	0.07	0.13	0.21	8
90972 B	9.59	0.20	0.23	0.52	0.76	8
104901 B	7.71	0.30	0.28	0.36	0.43	8
108767 B	8.45	0.06	0.14	0.31	0.44	8
113703 B	10.90	0.13	0.20	0.16		3
129791 B	12.91	0.07	0.16	0.30		4

Since all stars are older than 30 million years these properties decay significantly before that age is reached. The stars showing Hα emission are all younger than 50 million years while those with Ca II emission or strong lithium absorption are up to 135 million years old. Since few older stars are included in the investigation it is not possible to draw any conclusions about the decay time of Ca II emission relative to that of lithium absorption. It should be pointed out that not all stars younger than these limits have the respective property. Some stars younger than 50 million years do not have Ca II emission or strong lithium absorption.

From these results the following scenario for PTTS is obtained. The T Tauri phase ends at an age less than 20 million years and the stars loose their prominent PMS features. At an age of 30 million the PTTS have these observable properties: Ca II H, K and Hα emission, strong lithium absorption but little or no infrared or ultraviolet excesses and only minor light variability. As they evolve they will first loose the Hα emission before the ZAMS is reached but many will still show Ca II emission and strong lithium absorption. However, it is likely that many PTTS do not possess these features or that they are too weak to be noticed.

The observed properties of the PTTS almost perfectly confirms what Herbig (1978) predicted for them, i.e. that they should have strong Ca II emission but weak or absent Hα emission, a strong Li λ6707 Å line and minor infrared excess. He also proposed an order by which the PMS properties would decay which is only slightly modified by the result above, which indicates that variability and excess emission disappear before Hα emission.

Recently some X-ray detected stars in the Taurus-Auriga star formation region have been suggested to be PTTS by Mundt et al. (1983). These five stars all have weak Hα emission, strong Li λ6707 Å absorption, ultraviolet excess, strong X-ray emission ($L_X \sim 10^{30}\,\mathrm{erg\,s^{-1}}$) and they are of spectral types K7 – M0 IV–V. 3 of them also have Ca II H, K in emission and at least some of them have no infrared excess and four are constant in brightness within 0.5 mag. In the HR diagram they all lie above the main-sequence, in the lower part of the area occupied by the T Tauri stars. These properties are quite similar to those found for the secondaries, the differences are mainly that the secondaries are of somewhat earlier spectral types and lie closer to the ZAMS.

The basic reason for Mundt et al. to suggest the X-ray stars to be PTTS seem to be their low activity. However, since their location in the HR diagram coincide with that of normal T Tauri stars, it cannot be decided that they are older than these. The authors propose that it could e.g. be that they only presently are in a phase of low activity and later again will develop strong T Tauri features. However, there are indications, theoretical and observational (see e.g. Appenzeller, 1983) that, at least for the T Tauri phase, there is no unique relation between a PMS star's position in the HR diagram and its age, and if so the X-ray detected stars could be older than the T Tauri stars. Even if the question of their age is uncertain it appears likely, since they fall higher above ZAMS and have larger variability, that they are younger and less evolved than the stars investigated here. The X-ray properties of the PTTS secondaries have not been investigated and it would be interesting to see if they, like the low activity PMS stars, have a stronger X-ray emission than the classical T Tauri stars or if it has decayed to a level normal for main-sequence stars. Such an investigation is presently planned.

8. Conclusions

In this investigation of young double stars and early stellar evolution the following results have been obtained:

1. 84 secondaries have been found likely to be physical members in double star systems with O or B type primaries. 60% of the secondaries have spectral types later than F0.
2. The location of the late type secondaries in the HR diagram is just above the ZAMS and coincides with the radiative part of the evolutionary tracks calculated for contracting stars of masses 0.5 to 2 $M_\odot$.
3. The ages of the stars are less than 150 million years and half of them are younger than 30 million years. Comparison of the ages and the theoretical contraction times shows that 37 secondaries are contracting towards the ZAMS. The agreement of the isochrones from contracting models and the ages of the secondaries (determined for the primary) is in most cases satisfactory. However, some stars are more than 20 million years older than indicated by the isochrones. It is suggested that this could be caused by rapid rotation of the stars.
4. 50% of the secondaries later than F0 exhibit spectroscopic features (emission lines and strong lithium absorption) reminiscent of T Tauri stars which support that they are young.
5. The degree of light variability, infrared and ultraviolet excess emission is strongly reduced (or absent) compared to normal T Tauri stars. This together with their location in the HR diagram between the T Tauri stars and the ZAMS and their higher age make it appropriate to call them post-T Tauri stars.
6. The evolution after the T Tauri phase can be characterized as follows: light variability, infrared and ultraviolet excesses decay first and are almost absent when the stars are 30 million years old. Hα emission disappears before the age of 50 million years while Ca II H, K emission and strong lithium absorption at λ6707 Å still are evident in stars older than 135 million years. However, the evolution of stars is individual and a large variation in the strengths of these properties is observed for stars of similar age and mass.
7. Compared to some X-ray detected PMS stars suggested to be post-T Tauri stars the secondaries are older and more evolved and lie closer to the ZAMS.

Acknowledgement. It is a pleasure to thank Dr. G Gahm for his assistance during the progress of this research.

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Note added in proof: Two of the secondaries have been observed with the EXOSAT satellite. The preliminary results indicate that HD 108767 B is a weak X-ray source while HD 129791 B is not detected. The latter star and HD 113703 B were observed with the IUE satellite. None of these two stars show any detectable ultraviolet emission.

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