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The age-mass relation for chromospherically active binaries

I. The evolutionary status

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Abstract. In this paper we present a study of the evolutionary status of a sample of chromospherically active binary systems for which accurate determinations of their stellar parameters are available. Stellar ages have been obtained by using evolutionary tracks. The agreement between the estimates of ages for the two components of a given system is very good, which proves the reliability of our method.

It has been possible to separate the chromospherically active binaries in three groups, according to the mass of the primary component: evolved stars with masses in the range 2.5-5 $M_\odot$, evolved stars (subgiants) with $M \simeq 1.4\ M_\odot$ and main–sequence stars with $M \simeq 1.1\ M_\odot$.

We have found a relationship between stellar masses and ages of the form $\mathrm{Log\,Age} = 9.883(\pm0.022) - 2.965(\pm0.122)\ \mathrm{Log\,(Mass/M_\odot)}$. This relationship is very close to that for stars on the TAMS. The relation can be understood, in the framework of the evolution of the components and orbital elements of binary systems, as an effect of the increase of the stellar radius as the components evolve off the main sequence, and the decrease of the rotation period due to tidal effects which leads to enhanced chromospheric emission levels, several times higher than that of the Sun.

The relationship has a dependence on rotation, due to the fact that for a given range of masses, younger stars rotate faster. We have also found that the more evolved stars are the more active, for a given interval of rotation periods.

Key words: stars: activity – stars: binaries: close – stars: evolution – stars: late type

1. Introduction

This is the first paper of a series devoted to the study of the evolutionary status, Lithium abundance and evolution of orbital elements of chromospherically active (CA) binaries.

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Stellar clusters and binary systems provide some of the best laboratories for checking the stellar evolution and stellar interiors. In particular, different phenomena, such as rotational synchronization, orbital circularization, apsidal motion and mixing mechanisms in the stellar interior, which occur in binary systems, are extremely sensitive to the stellar structure. Some of these effects become very conspicuous in close binaries. CA binaries are also very suitable objects to check how the dynamo-generated magnetic activity behaves, how the internal and surface rotation are in comparison with the solar ones and what their role in the dynamo theory is. The eclipsing binaries also allow to model starspots, mapping the surface, etc. (Guinan & Giménez 1993).

Active binary systems like RS Canum Venaticorum (RS CVn) and stars like BY Draconis (BY Dra) show high chromospheric, transition region and coronal activity levels and, in the case of binarity, the rotation periods are, in general, synchronized with the orbital periods. The RS CVn systems have, at least, a cool evolved component. The BY Dra stars are main sequence stars, which have strong Ca II H and K emission lines (Fekel et al. 1986). Both single and binary systems are contained in the BY Dra class, the high activity levels being due either to youth, or tidal effects in binaries. Both type of CA binaries (RS CVn and BY Dra) have very similar kinematical properties (Eker 1992). These stars exhibit activity levels at least one order of magnitude larger than that of the Sun (Fernández-Figueroa et al. 1986; Strassmeier et al. 1990). Their enhanced activity is thought to be due to a very efficient generation of magnetic fields tightly linked to the fast rotation reached as synchronization occurs. It is well known that activity in late-type stars increases as the rotation period, P_{rot}, and/or the Rossby number R_o decrease (Noyes et al. 1984). R_o is defined as the ratio between the rotation period and the turnover time for a large convective cell.

In addition to these properties, an important fraction of the orbits of CA binaries has a zero or nearly–zero eccentricity, e. It is assumed that the original eccentricity, namely e_o, of an orbit goes to zero with time by tidal effects (Zahn 1977) or equivalent mechanisms, like hydrodynamical spin–down (Tassoul 1988).

In previous works the evolutionary status of CA binaries have been studied. In particular, Popper & Ulrich (1977) claimed that RS CVn are postmain–sequence objects, which are crossing the Hertzsprung gap. From a kinematical criterion, they assigned an age of $\sim 3 \times 10^9$ years for these systems. Montesinos et al. (1988), from a sample of 22 RS CVn systems showing total or partial eclipses, found that these binaries can be separated in three different groups, namely, normal main–sequence stars, systems containing apparently normal evolved stars, and systems which have undergone an 'abnormal' evolution, in the sense that either the more massive stars have the smallest radii or components with similar masses show a large difference between their radii. They pointed out that all systems fitted in tracks with metal contents equal to or larger than the solar one. Demircan (1990) also examined a sample of RS CVn binaries. He concluded that most of the components have effective temperatures cooler than those obtained from the classical Mass–Luminosity relationship. By discussing the evolution on the k–q plane (where k and q are the radius and mass ratios, respectively), he concluded that most of these systems have undergone normal evolution.

The understanding of the evolutionary status of active close binaries is very important to clarify the role of rotation on the chromospheric activity and its relation with other related phenomena, such as the rate of Lithium depletion (Pallavicini et al. 1992; Fernández–Figueroa et al. 1993; Barrado et al. 1994).

Since the properties of CA binaries (enhanced activity in RS CVn, fast rotation of BY Dra) seem to be strongly correlated to their binary nature, this work attempts to connect these peculiarities with the evolution of these systems. For this purpose, we have calculated the ages of these binaries by using evolutionary tracks. In Section 2, we give details of the sample of stars selected. In Section 3, we discuss the evolutionary status of CA binaries as a group and the estimates of their ages. In Section 4, we present and discuss the Age–Mass relationship for CA binaries. In Section 5, the role of rotation is discussed, along with its relation with the chromospheric activity.

2. The data

We have studied in this paper a sample of CA binaries which includes two different sets. Both of them have been selected from the Catalog of CA binaries by Strassmeier et al. (hereafter CABS, 1993). The first one contains 50 systems (36 of them are eclipsing binaries) which have accurate determinations of masses and radii. The original and also the most recent references have been checked in order to obtain the uncertainties in masses and radii. The second set contains binaries for which *only* determinations of masses are available. The first set is included into the second one.

Table 1 shows the first set of stars and some relevant stellar parameters (name, HD or BD number, spectral type, radius, mass for primary and secondary components, P_{phot}, if the binary is eclipsing, and the original sources).

3. The evolutionary status

3.1. The position of CA binaries in the radius–T_{eff} diagram

Figure 1 shows radii plotted against T_{eff} for the sample and, overimposed, the evolutionary tracks by Schaller et al. (1992) and Schaerer et al. (1993a) for metallicities Z=0.020 (solid lines) and Z=0.008 (dashed lines). It is possible to separate the stars in three different groups, according to the mass of the primary component, which is the more massive:

- Main sequence (MS) stars with $M \simeq 1.1\ M_{\odot}$.- These stars are evolving off the MS, as can be seen by comparing their radii with those corresponding to Zero Age Main–sequence (ZAMS) stars.
- Evolved stars with $M \approx 1.4\ M_{\odot}$.- Stars belonging to this group can be classified in three different subgroups: Subgiants evolving off the MS, subgiants starting to climb up the Red Giant Branch (RGB) and giants in the RGB.
- Evolved stars with masses in the range 2.5–5 $M_{\odot}$.- All these stars but HR6469 are giants. HR6469 is the third component of a triple system and shows a very weak Ca II H & K emission (Fernández–Figueroa et al. 1994).

In Fig. 1, different luminosity classes are shown with different symbols (triangles for giants, squares for subgiants and stars for main–sequence stars). Primary components are shown as solid symbols and secondary components as open symbols. Despite the facts that the classification in luminosity class is essentially spectroscopic and that most of the radii were obtained by using data from eclipses and/or from luminosities, there is a very clear separation between the groups. Note that some CA binaries have not clear luminosity class classification. For these cases, we have chosen the luminosity classes in agreement with their radii.

3.2. The age calculation

In order to determine the age of each system we have used the theoretical evolutionary tracks by Schaller et al. (1993), Schaerer et al. (1993a) and Schaerer et al. (1993b), which were calculated with the new opacities by Roger & Iglesias (1991). A value of $\alpha_p = 1.6$ for the ratio between pressure scale height and mixing length was used, and mass loss was included in the computations of the tracks.

The method for estimating ages consists of an interpolation with radii and then, with masses, because both stellar parameters are well known for most of the stars in our sample. This method allows us to obtain ages accurate enough for our purposes. By using the tracks we have also obtained simultaneously values for the effective temperature. The comparison between the latter quantity, T(Z), and the effective temperatures calculated from Johnson photometry –(B–V) index– or, when this index was not available, from assignations according to the spectral type (Schmidt–Kaler, 1982), allows us to choose among the fits obtained with four different sets of evolutionary tracks (Z = 0.040, 0.020, 0.008 and 0.001). For most of the stars the difference between both determinations is less than 250 K, which is the average uncertainty in the T_{eff} calibration of Böhm-Vitense (1981),

Table 1. Relevant stellar parameters for CA binaries.

Name	HD/BD	Primary component			Secondary component			P_{phot} (days)	Eclip.	Sources
		Sp. type	Radius ($R_\odot$)	Mass ($M_\odot$)	Sp. type	Radius ($R_\odot$)	Mass ($M_\odot$)			
ζ And[1]	4502	K1III	13.4	2.70	–	≈0.7	0.78	–	yes	1,22
CF Tuc	5303	K4IV	3.32	1.205	G0V	1.67	1.057	2.798	no	1,9
AY Cet	7672	G5III	15	2.09	WD	0.012	0.55	77.22	no	1,23,24
UV Psc	7700	G4-6V	1.21	1.22	K0-2V	0.91	0.87	–	yes	1,6
LX Per		K0IV	3.05	1.32	G0IV	1.64	1.24	7.905	yes	1,3
V711 Tau	22468	K1IV	3.9	1.4	G5IV	1.3	1.1	2.841	no	1,5
RZ Eri	30050	Am	2.83	1.69	K0IV	7.0	1.63	31.4	yes	1,3
α Aur	34029	G1III	12.6	2.56	K0III[3]	8.7	2.49	8	no	1,10
CQ Aur	250810	K1IV	8.7	2.00	F5	1.9	1.63	10.56	yes	1,4
SV Cam	44982	G2-3V	1.11	0.93	K4V	0.74	0.67	0.593071[2]	yes	1,11
VV Mon	–05 1939	K0IV	6.0	1.50	G2IV	1.75	1.42	6.05056[2]	yes	1,3,17
SS Cam[1]	–	K0IV-III	6.4	1.83	F5V-IV	2.2	1.75	4.823	yes	1,4
AR Mon[1]	57364	G8III	10.8	2.7	K2-3III	14.2	0.8	–	yes	1,25
54 Cam	65626	F9IV	3.14	1.64	G5IV	2.64	1.61	10.163	no	1
GK Hya[1]	+02 1993	G8IV	3.39	1.34	F8	1.51	1.25	3.587033[2]	yes	1,4
RU Cnc	+24 1959	K1IV	4.9	1.47	F5IV	1.9	1.46	10.135	yes	1,4
RZ Cnc[1]	73343	K1III	10.2	3.20	K3-4III	12.2	0.54	21.64303[2]	yes	1,25
TY Pyx	77137	G5IV	1.59	1.22	G5IV	1.68	1.20	3.32	yes	1,27
WY Cnc	+27 1706	G5V	1	0.93	≈[M2]	0.66	0.53	0.8293712[2]	yes	1,18,19
XY UMa[1]	+55 1317	G3V	0.98	0.95	[K4-5V]	0.73	0.70	0.4789944[2]	yes	1,20
DH Leo	86590	K0V	0.97	0.83	K7V	0.67	0.58	1.0665	no	1,30
DH Leo	86590	K5V	–	–	–	–	–	–	no	1,35
RW UMa	+52 1579	F8IV	2.31	1.56	K0IV	4.24	1.49	7.328223[2]	yes	1,4
IL Com	108102	F8V	[1.1]	0.85	F8V	[1.1]	0.82	0.82	no	1,28
UX Com	+29 2355	K1[IV]	2.5:	1.20	G2	1.0:	1.02	3.642386[2]	yes	1,4,37
RS CVn	114519	G9IV	4.00	1.44	F4IV	1.99	1.41	4.7912	yes	1,2,3
BH Dra[1]	118216	F2IV	3.10	1.5	K2IV	2.85	0.8	–	no	1,29
BH Vir	121909	F8V-IV	1.10	1.04	G2V	1.20	1.02	0.816871[2]	yes	1,12
SS Boo	+39 2849	G0V	1.30	0.97	K0IV	3.30	0.97	7.606133[2]	yes	1,4
RT CrB	139588	G5-8IV	3.0	1.42	G2	2.6	1.4	5.117159[2]	yes	1,4
σ^2 CrB	146361	G0V	1.21	1.14	F6V	1.22	1.12	1.1687	no	1,30
WW Dra	150708	G2IV	2.12	1.36	K0IV	3.9:	1.34	4.629617[2]	yes	1,3
ϵ UMi	153751	G5III	12	2.8	A8-F0V	1.7	1.3	–	yes	1,31
V792 Her	155638	K0III	12.28	1.47	F2IV	2.58	1.41	27.07	yes	1,13,14
HR 6469	157482	G5IV	12.2	2.05	–	–	–	81.9	yes	1,32,33
HR 6469	157482	F2V	≥1	1.65	[G0V]	–	1.15	–	yes	1,32,33
Z Her	163930	F4V-IV	1.85	1.61	K0IV	2.73	1.31	3.962	yes	1,2,3
MM Her	341475	K0IV	2.85	1.28	G2	1.60	1.22	7.936	yes	1,3
V772 Her	165590	G0V	1.0:	1.04	[M1V]	–	0.59	0.878	yes	1,16
V772 Her	165590	G5V	0.6:	0.88	–	–	–	–	yes	1,16
PW Her	–	K0IV	3.8	1.50	F8-G2	1.4	1.17	2.881002[2]	yes	1,4
AW Her	348635	G8IV	3.2	1.33	G2	2.4:	1.25	–	yes	1,4
HR 7428	184398	K2III-II	62	4.83	A2V	–	2.90	108.854[2]	no	1,35
V1764 Cyg	185151	K1III:	25	1.5	F	–	[1.3]	39.878	no	1,33,35
HR 7578	188088	K2-3V	≥ 0.8	≥0.85	K2-3V	≥ 0.8	≥0.85	16.5	yes	1,38
ER Vul	200391	G0V	1.07	1.10	G5V	1.07	1.05	0.6942	yes	1,15
HR 8170	203454	F8V	1.11	1.17	≈K5V	0.74	0.66	–	no	1,10
FF Aqr	–03 5357	G8IV-III	6.12	2.00	sdO-B	0.1	0.5	9.207755[2]	yes	1,21
RT Lac[1]	209318	G9IV	3.4	1.66	G5:	4.2	0.78	5.074015[2]	yes	1,26
AR Lac	210334	K0IV	2.72	1.27	G2IV	1.52	1.230	1.983222[2]	yes	1,4
RT And	+52 3383A	F8V	1.17	1.50	K0V	0.84	0.99	0.6289298[2]	yes	1,7,8
SZ Psc	219113	K1IV	5.1	1.62	F8IV	1.50	1.28	3.955	yes	1,3
KT Peg	222317	G5V	0.93	0.93	K6V	0.72	0.62	6.092	no	1,34

(1) Semidetached or contact binary.
(2) $P_{phot} \approx P_{orb}$.
(3) P_{phot} = 80 days

References.-
1.- CABS (second edition), 2.- Popper (1988a), 3.- Popper (1988b), 4.- Popper (1990), 5.- Popper (1991a), 6.- Popper (1991b), 7.- Dean (1974), 8.- Zeilik et al. (1989), 9.- Coates et al. (1983), 10.- Batten et al. (1991), 11.- Budding et al. (1987), 12.- Zeilik et al. (1990), 13.- Fekel (1991), 14.- Nelson et al. (1991), 15.- Hill et al. (1990), 16.- Batten et al. (1979), 17.- Imbert (1978), 18.- Awadalla & Budding (1979), 19.- Budding et al. (1982), 20.- Geyer (1977), 21.- Dworetsky et al. (1977), 22.- Gratton (1950), 23.- Simon et al. (1985), 24.- Fekel & Eitrer (1989), 25.- Popper (1976), 26.- Huenemoerder & Barder (1986), 27.- Andersen et al. (1981), 28.- Huisong & Xuefu (1987), 29.- Eker & Doherty (1987), 30.- Barden (1985), 31.- Hinderer (1957), 32.- Strassmeier & Fekel (1990), 33.- Fekel et al. (1986), 34.- Stockton & Fekel (1992), 35.- Hall (1990), 36.- Fekel (1991), 37.- Popper & Ulrich (1977), 38.- Fekel & Beavers (1983)

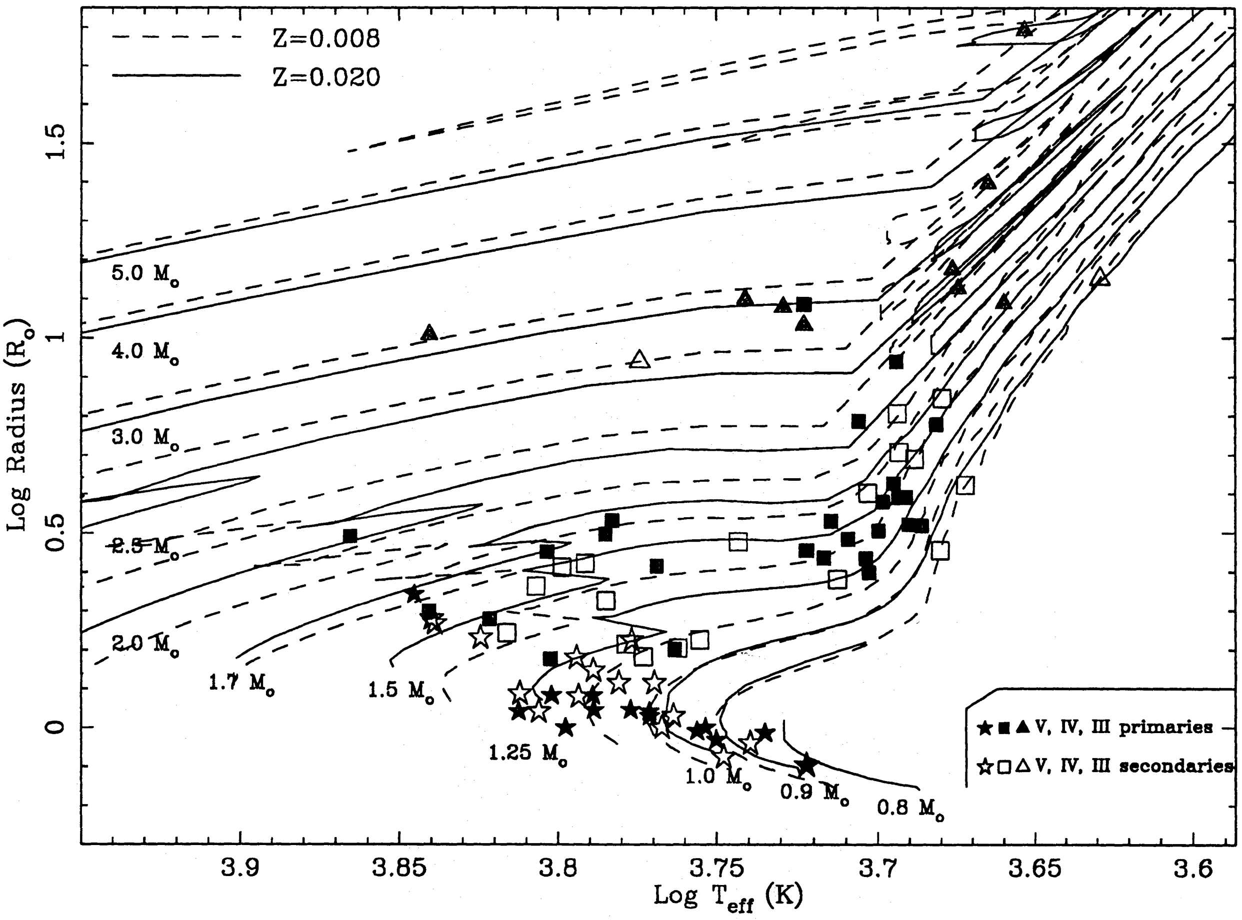


Fig. 1. Radii plotted against T_{eff} for the CA binaries. We also show the evolutionary tracks by Schaller et al. (1992) and Schaerer et al. (1993a) for metallicities Z=0.020 (solid lines) and Z=0.008 (dashed lines)

which has been used by us throughout. For a few stars, evolutionary tracks with higher metallicities are required, given the lack of an acceptable agreement between both temperatures. In these cases T(Z) is much larger than the effective temperature. The fits for these stars are not accurate enough. Some of them are systems which have undergone an 'abnormal' evolution. In this context Giménez et al. (1991) showed that the determination of some parameters of CA binaries from standard photometric calibrations should be taken with caution since there can be real differences between the atmospheres of this kind of stars and normal non-active objects.

The uncertainties in radii and masses have been used to obtain uncertainties in the ages: The maximum/minimum and minimum/maximum possible values of the radius and mass for a given star, respectively, give the maximum/minimum age when the star is placed on a given set of evolutionary tracks. We have not included the intrinsic uncertainties introduced by the tracks, either due to the computational algorithm or the metallicities. We have checked the determination of ages by comparing the ages obtained for both components of double–lined binary systems (SB2). The agreement is very good, even when the luminosity classes of the components are III and V, which is the most extreme case. Figure 2 shows the comparison between the

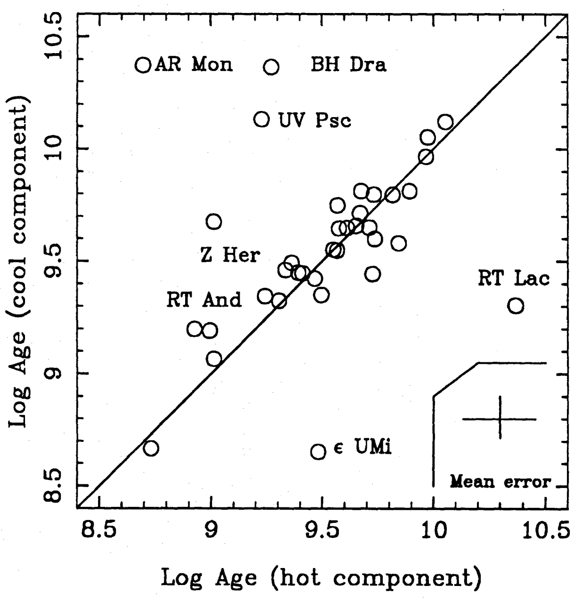


Fig. 2. Comparison between the ages of the primary and secondary components of SB2 systems obtained with the evolutionary tracks. The agreement between both ages are excellent except for those systems which have undergone an 'abnormal' evolution

ages of the primary and secondary components of SB2 systems, including average error bars. Given the excellent agreement between both ages we have assigned to each component of a given binary the individual age given by its location on the corresponding isochrone.

The exceptions to this agreement are those systems which have undergone an 'abnormal' evolution, with very quick processes of mass transfer between the stars, such as UV Psc (HD 7700), AR Mon (HD 57364), BH Dra (HD 118216), ϵ UMi (HD 153751), Z Her (HD 163930) and RT Lac (HD 209318). In particular, AR Mon (Hall 1989), BH Dra (CABS 1993) and RT Lac (Milone & Naftilan 1980) are semidetached binaries or one of the components is very close to fill the Roche lobe and AR Mon and RZ Cnc were also classified as Algol–type systems by Giuricin at al. (1983). We have assumed that they have been at this stage for a long time and that the current value of the masses are appreciably different from the original ones. For this reason the calculated ages for each component are in disagreement. Moreover, each component of the system Z Her, which is a member of the Hyades open cluster, has also different age than that of the cluster.

On the other hand, ζ And, RZ Cnc (HD 73343), FF Aqr and AY Cet can also be classified as 'anomalous', given the ratios between masses and radii of the components. The first two systems have secondary components which fill the Roche lobe. Another system candidate to have an 'anomalous' evolution is HD 108102 which could be reaching the contact configuration or be close to it. In fact, HD 108102 has very similar components, and for this reason the calculated ages are quite close to each other ($\sim 10^{10}$ years). However this system is known to be a member of the Coma cluster (age $\sim 8 \times 10^8$ years, Gilroy 1989). Probably, it had a very short orbital period (around 1 day) and a mass ratio q between the components different from 1. The angular momentum lose has led to a decrease of the orbital period and the components would have reached contact not a long time ago, transferring mass from the more massive component.

Five of the systems with 'abnormal' evolution were studied by Montesinos et al. (1988). They also pointed out the anomalous evolution of AR Mon, Z Her, RZ Cnc and RT Lac, based on the comparison between the radius and mass ratios. However, they classified UV Psc as a system with normal evolution, in disagreement with us given the new measurements of its stellar parameters.

In the sample of CA binaries with accurate determinations of masses and radii, some systems are possibly contact binaries or semidetached binaries (SS Cam, CABS 1993; GK Hya and XY UMa, Kholopov 1985). Despite of the mass transfer process which should be taking place between both components, the agreement between the calculated ages for the primary and the secondary components of these systems is excellent. Therefore, we can assume that these systems have very recently filled up their Roche lobe and that the mass transferred has been negligible compared with the total mass.

However, most of the RS CVn and BY Dra do not fill the Roche lobe and their evolution can be considered as normal (Montesinos et al. 1988; Dempsey et al. 1993), in the sense that each component has evolved as if it were a single star. We have assumed that systems with very similar components but inverted ratios between radii and masses (the less massive star has the largest radius) are not 'abnormal', given the uncertainties in masses and radii. As can be seen in Fig. 2, there is no bias towards any direction: cool components are not older, on average, than hot components and viceversa.

The estimates for the ages, their errors, the determinations of T(Z) and effective temperatures are given in Table 2. Also the assigned metallicities from the best fits to the grid of evolutionary track are indicated. Note the different set of evolutionary tracks used for each component in some binary systems.

It is possible to compare the ages obtained by us with those by Eker (1992) using a 'kinematical' criterion, which is a rough approximation. He classified the CA binaries in five groups, namely, giants with high and low velocity dispersions, subgiants, and dwarfs with high and low velocity dispersions. He assigned to them the following ages –in logarithm– ≥ 9.7, $\sim$9, 9.3–9.5, $\geq$9.7 and $\sim$9, respectively. We have obtained the following average ages for those stars which belong to our and Eker's sample, these are 8.73$\pm$0.99, 8.70$\pm$0.05, 9.52$\pm$0.22, 9.77$\pm$0.15 and 9.57$\pm$0.47, respectively. The agreement between the different groups is acceptable, except for giants having high velocity dispersions. We think that these velocities are no representative, since these stars are quite massive, and the required age to evolve off the main–sequence is as long as Eker's estimation.

4. The age-mass relationship

4.1. Age versus mass

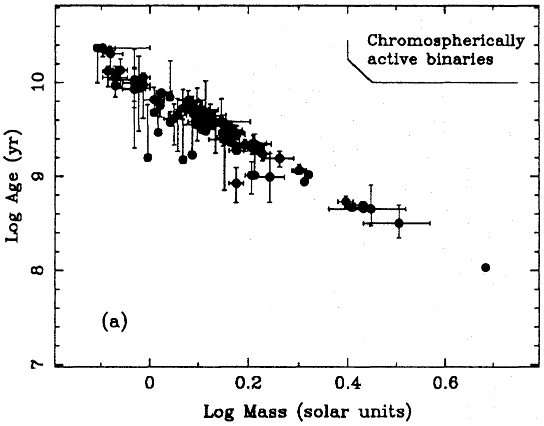
Figure 3a shows the Age plotted against Mass for the first set of CA binaries. Despite the uncertainties for some stars, the relationship between age and mass for chromospherically active binary systems seems to be very clear.

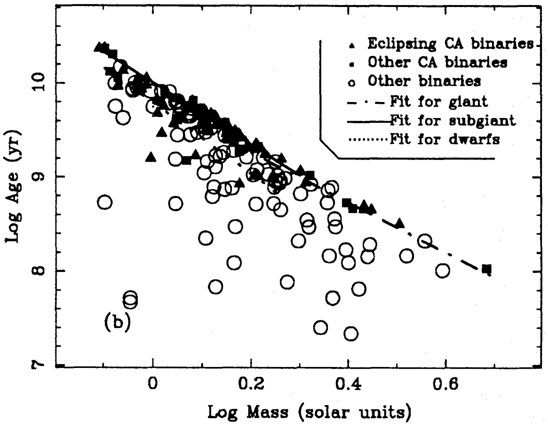
In Fig. 3b we have compared our sample of CA binaries with visual and non–active spectroscopic binaries. We have plotted non–eclipsing and eclipsing systems with different symbols (squares and triangles respectively). We attribute some of the deviations to 'abnormal' evolution or to bad fits with the available tracks (see above or Montesinos et al. 1988 and Demircan 1990). In some cases, there are additional effects (e.g. rotation) which are discussed below.

Ages for visual and spectroscopic binaries (Popper 1980 and others), most of them having much longer orbital periods, P_{orb}, were obtained by us following the same method. For these systems the rotation periods normally are not synchronized with the orbital period, the rotation of each component has slowed-down following the Skumanich's law (Skumanich 1972; Soderblom et al. 1993) and the activity is not enhanced. These stars are shown as open circles in Figure 3b.

Table 2. Results for the sample of CA binaries

Name	HD/BD	Teff (K)	T(Z) (K)	Log Age -1σ	Log Age (yr)	Log Age +1σ	Z (10^{-3})
ζ And	4502	4524	4726	0.021	8.659	0.020	8
		–	4308	–	≥10.373	–	8
CF Tuc	5303	4295	4902	0.010	9.812	0.009	20
		6030	5981	0.082	9.892	0.035	8
AY Cet	7672	5020	4746	–	9.017	–	20
		–	–	–	–	–	–
UV Psc	7700	5516	6340	–	9.228	0.445	20
		5500	5489	0.177	10.132	0.121	20
LX Per		5000	5122	0.031	9.657	0.028	20
		5940	6006	0.070	9.651	0.085	20
V711 Tau	22468	4840	4938	0.218	9.580	0.246	20
		5460	5885	–	9.842	0.391	40
RZ Eri	30050	6645	6361	0.076	9.242	0.077	20
		4996	4781	0.106	9.344	0.107	20
α Aur	34029	5090	5508	0.030	8.667	0.037	1
		5910	5945	0.035	8.731	0.061	8
CQ Aur	250810	4750	4944	0.031	9.065	0.059	20
		5450	6916	–	9.012	0.319	40
SV Cam	44982	5850	5986	0.198	9.996	0.149	8
		–	–	–	–	–	–
VV Mon	–05 1939	6360	6548	0.542	9.392	0.218	20
		4790	4803	0.046	9.448	0.090	20
SS Cam	–	4700	4942	0.093	9.191	0.077	20
		6400	7003	0.269	8.993	0.252	40
AR Mon	57364	4900	5283	0.044	8.696	0.039	20
		4310	4258	0.016	10.373	0.001	8
54 Cam	65626	6060	6097	0.051	9.324	0.046	20
		6060	6185	0.070	9.305	0.057	40
GK Hya	+02 1993	5308	5185	0.054	9.552	0.047	8
		6226	6225	0.171	9.550	0.235	20
RU Cnc	+24 1959	4800	4879	0.077	9.492	0.094	20
		6490	6632	–	9.361	0.210	20
RZ Cnc	73343	4600	6927	0.154	8.500	0.195	20
		–	–	–	–	–	–
WY Cnc	+27 1706	5770	5669	0.298	10.030	0.330	20
		–	–	–	–	–	–
TY Pyx	77137	5500	5798	0.068	9.730	0.055	40
		5420	5693	0.046	9.796	0.038	40
XY UMa	+55 1317	5830	5704	0.457	9.937	0.347	20
		–	–	–	–	–	–
DH Leo	86590	5250	5431	0.200	10.306	0.086	20
		–	–	–	–	–	–
DH Leo		–	–	–	–	–	–
RW UMa	+52 1579	6310	6410	0.069	9.333	0.061	20
		4620	4955	0.053	9.460	0.085	20
IL Com	108102	6200	6493	0.209	10.054	0.122	1
		6200	6399	0.169	10.121	0.055	1
UX Com	+29 2355	4700	5046	0.130	9.812	0.101	20
		5870	5852	–	9.674	–	20
RS CVn	114519	5030	5049	0.040	9.446	0.037	8
		6700	6930	0.089	9.410	0.064	8
BH Dra	118216	6880	7336	0.032	9.272	0.063	1
		5000	4789	0.088	10.365	0.001	8
BH Vir	121909	5860	5906	0.116	9.795	0.043	20
		6200	6216	0.114	9.815	0.132	8
SS Boo	+39 2849	5948	6038	0.357	9.974	0.115	8
		4800	4855	0.065	10.053	0.056	8
RT CrB	139588	4600	5536	0.029	9.547	0.028	20
		5850	5874	0.072	9.567	0.057	20
σ^2 CrB	146361	6030	6153	0.382	9.648	0.180	20
		6360	6487	0.278	9.611	0.156	8
WW Dra	150708	5910	6093	0.326	9.575	0.113	20
		4880	4910	0.068	9.646	0.060	20
ϵ UMi	153751	5150	5360	0.179	8.652	0.258	20
		7200	6675	–	9.482	0.539	8
V792 Her	155638	4640	4571	0.045	9.422	0.040	8
		6540	6291	0.040	9.466	0.034	8
HR 6469	157482	5608	5283	–	8.939	–	1
HR 6469		–	–	–	–	–	–
		–	–	–	–	–	–
Z Her	163930	6590	6901	0.201	9.012	0.144	40
		5000	5210	0.033	9.675	0.031	40
MM Her	341475	5235	5275	0.057	9.599	0.090	8
		5655	5783	0.181	9.735	0.115	40
V772 Her	165590	6142	6275	–	9.465	0.439	8
		–	–	–	–	–	–
V772 Her		–	–	–	–	–	–
PW Her		4898	4994	0.048	9.443	0.089	20
		6046	6150	–	9.725	0.203	20
AW Her	348635	4804	5010	0.119	9.650	0.118	20
		5100	5160	0.192	9.710	0.230	20
HR 7428	184398	4420	4502	0.009	8.029	0.036	8
		–	–	–	–	–	–
V1764 Cyg	185151	4600	4624	–	9.296	–	1
		–	–	–	–	–	–
HR 7578	188088	4800	5275	–	9.966	0.377	20
		4800	5275	–	9.966	0.377	20
ER Vul	200391	6030	5904	–	9.569	0.119	40
		5770	5803	0.116	9.748	0.079	40
HR 8170	203454	6200	6149	–	9.176	0.427	20
		–	–	–	–	–	–
FF Aqr	–03 5357	5000	5082	0.022	9.059	0.044	20
		–	–	–	–	–	–
RT Lac	209318	4840	6066	0.071	9.305	0.052	20
		5117	4701	–	≥10.368	–	8
AR Lac	210334	5000	5057	0.051	9.714	0.077	40
		5655	5932	0.143	9.669	0.130	40
RT And	+52 3383A	6200	9707	0.205	8.925	0.171	1
		5770	5595	–	9.198	0.564	20
SZ Psc	219113	4840	4936	0.091	9.350	0.082	20
		6175	6345	–	9.496	0.316	20
KT Peg	222317	5770	5625	0.623	9.926	0.240	20
		–	–	–	–	–	–





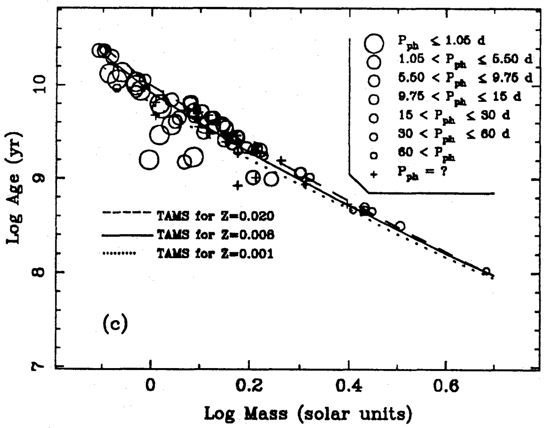


Fig. 3a–c. Age plotted against Mass: **a** plot for the first set of CA binaries. **b** here non–eclipsing and eclipsing systems are shown with different symbols (squares and triangles respectively). Visual and inactive spectroscopic binaries are shown as open circles. We also show the fits for giants, subgiants and dwarfs. **c** the components of binary systems with Ca II emission are shown as open circles, the size of the symbol is inversely proportional to the rotation period: the faster the rotation, the larger the radius of the circle symbol (see key). The components with no Ca II emission detected are shown as crosses. The TAMS calculated with metallicities Z = 0.020, 0.008 and 0.001 are shown as dashed, solid and dotted lines, respectively)

4.2. Fitting the data

4.2.1. Weighted power law fits

We have carried out several fits of the type Age = C M$^{\alpha}$ where C is a constant. Taking into account the errors in ages and masses the results are:

$$\text{Log Age} = 9.940 - 2.882 \text{ Log } (\frac{M}{M_\odot}) \quad \text{(yr)} \tag{1}$$

$$\text{Log Age} = 9.915 - 2.758 \text{ Log } (\frac{M}{M_\odot}) \quad \text{(yr)} \tag{2}$$

Equation (1) was obtained including only the eclipsing binaries (53 points) of the sample (which have better determinations of the stellar parameters) whereas Eq. (2) includes also non–eclipsing CA binaries (70 points). The residuals obtained with expressions (1) and (2) are less than $\sim$ 0.1 dex for most of the stars ($< \sigma > = 0.065$ and $< \sigma > = 0.064$, respectively). It can be said that there is no difference between the result for eclipsing binaries and the fit for the whole set.

4.2.2. Unweighted power law fits

We have calculated different kind of regressions for the set of eclipsing binaries. The ordinary least square –OLS (Y/X), following the notation of Isobe et al. (1990)– of the dependent variable –Age– against the independent one –Mass– for the set of CA eclipsing binaries is:

$$\text{Log Age} \;=\; (9.853 \pm 0.027) - (2.711 \pm 0.115) \text{ Log } (\frac{M}{M_\odot}) \tag{3}$$

where the standard deviations in the intercept and slope are given.

An alternative to OLS (Y/X) is the bisector method, which treats the variables symmetrically. This approach is the most accurate for estimating the functional dependence of the variables. In this case the result is:

$$\text{Log Age} \;=\; (9.883 \pm 0.022) - (2.965 \pm 0.122) \text{ Log } (\frac{M}{M_\odot}) \tag{4}$$

Those systems which have undergone an 'abnormal' evolution have not been included in any of the above fits (see above and Montesinos et al. 1988, Demircan 1990). Note that the slopes of the fits are very close to 3 in all cases. Other fits are shown in Table 3 –OLS(Y/X)– , where only the primary components have been included. All the regressions have very small residuals, for instance, differences of 0.2 dex correspond to 2σ in Eq. (3).

These fits are shown in Fig. 3b, where we have overimposed the curves obtained by using the fits in Table 4 (solid, dotted–dashed and dotted lines represent the fits for giants, subgiants

Table 3. OLS(Y/X) fits for different luminosity classes: Log Age = (A ± SD(A)) – (B ± SD(B)) Log $(\frac{M}{M_\odot})$ (yr)

Subset	A ± SD(A)	B ± SD(B)	Fit	Number of data
Giants	9.807±0.044	2.643±0.095	(5)	5
Subgiants	10.002±0.020	3.253±0.102	(6)	38
Dwarfs	9.790±0.036	2.772±0.306	(7)	27

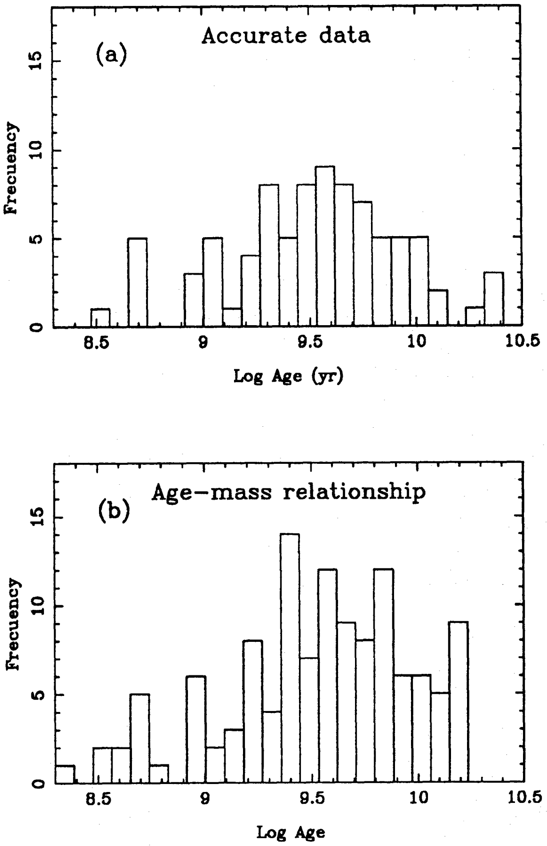


Fig. 4a and b. Histogram for ages calculated for CA binaries: **a** systems which have accurate values of mass and radius. **b** systems which have the mass determined. The ages were obtained by using Eq. (4)

and dwarfs, respectively). Note the good agreement between the three fits in the range of intermediate masses, around 1.8 $M_\odot$.

4.3. The TAMS and the CA binaries

Figure 3c shows, again, age plotted against mass. In this case, the components of binary systems with Ca II H & K emission are shown as open circles, the size of the symbol being inversely proportional to the rotation period: the faster the rotation, the larger the radius of the circle. The components with no Ca II emission detected are shown as crosses. We have overimposed the Terminal Age Main Sequence (TAMS) calculated for different metallicities (Z = 0.020, 0.008 and 0.001 are shown as dashed, solid and dotted lines, respectively). As it can be seen, the TAMS fits extremely well to the Age–Mass relationship. The dependence of age on mass for stars having Z=0.008 in the TAMS is:

$$\text{Log Age} = (9.926\pm0.030) - (2.927\pm0.090)\ \text{Log}\ (\frac{M}{M_\odot}) \quad (5)$$

This fit is very close to those obtained from the sample of CA binaries. In view of this, we have interpreted the Age–Mass relationship in the specific scenario of the natural evolution of stars. However, there could be other tentative explanations for this relation. If we assumed that the Age–Mass relationship is *not only* determined by evolutionary phenomena, such as changes in the stellar radii, orbital elements, rotation, etc, this relationship would lead to important consequences on the Star Formation Rate (SFR) for CA binaries. Figure 4a shows the age distribution. The ages cluster around Log Age = 8.7, 9.0, 9.6 and 10.0. This fact would indicate that there were remarkable bursts of binary system formation in the past, and these events gave birth to binaries with different but narrow ranges of masses (M = 0.9 $M_\odot$ for the old ones and M $\sim$ 3 $M_\odot$ for the young ones). Similar results could be inferred from Fig. 4b, which corresponds to CA binaries which have the mass determined. The ages were obtained by using Eq. (4). However, there is not any reason to expect large differences between the SFR for binaries and single stars and some authors (Twarog 1980; Carlberg et al. 1985) have pointed out that the SFR for the latter group is almost constant. For this reason, our interpretation goes in another direction, specified below. Then, the Age–Mass relationship can be understood within the context of the evolution of the stellar and orbital parameters due to the interaction between the components of binary systems.

Therefore, the justification of the Age–Mass relationship for CA binaries appears to be clear: as a star is close to the TAMS or it is evolving off the MS, the internal structure changes very rapidly. If the original spectral type of the star was earlier than mid–F, the star begins to develop a convective envelope. If the spectral type was later than mid–F, the external structure was convective from the beginning, but as the star approaches the TAMS the depth of the convection zone increases very quickly. The final consequence is that a deep convective envelope develops (Ruciński & Vandenberg 1986). For instance, a star with M = 1.5 $M_\odot$ and Z=0.020, arrives at the point where the relative maximum T_{eff} on the main sequence (the blueward hook) with an age of 2.69×10^9 years and starts the He combustion with an age of 2.77×10^9 years (Schaller et al. 1992). During this interval of only 80 millions of years, the fractional depth of the convective envelope goes from almost zero to be larger than 0.6. Since the rotation rate of the components has increased due to the transfer of orbital angular momentum to rotational angular momentum (Van't Veer & Maceroni 1992) and the possible dredge up of angular momentum from the core to the envelope (Pinsonneault et al 1989; Simon & Drake 1989), the binary fulfils both conditions in order to present enhanced chromospheric activity. This scenario explains the different degrees of activity for CA binaries.

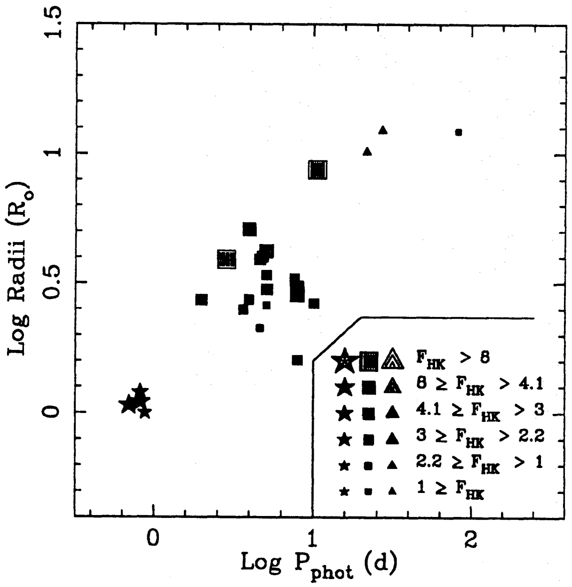


Fig. 5. Radii against rotation period (symbols are the same as in Fig. 1, but the sizes are proportional to the flux in Ca II H & K, see key). For a given rotation period, stars which have larger radii show higher chromospheric fluxes

It can be seen that there are no young close binaries with large levels of activity. Despite the fact that the rotation rate is very large –the components of the system can rotate very rapidly, due to the fact that synchronization between the orbital period and the rotation period is reached very soon (Tassoul & Tassoul 1992 and references therein)–, the dynamo effect should not be too efficient since there is no convective envelope or it is very shallow.

5. The role of rotation

Figure 3c helps to see the effect of rotation. For a range of masses, there are a few systems whose calculated ages are less than the average for CA binaries, therefore, these systems have not reached the TAMS. However, they are older than the comparison group (visual an non-active spectroscopic binaries). In addition, they have a very short rotation period; in fact, P_{phot} is less than 1 day in some cases, such as RT Lac, UV Psc and V772 Her, where both components are almost in contact. The ages of the first two binaries have been obtained assuming that their evolution has been anomalous (Sect. 3.2). Then, the reason why these ages are different from those calculated with the Age–Mass relationship might be a consequence of their anomalous evolution and/or very short orbital periods. Since, for close binaries, the rotation period is synchronized with the orbital period, the rotation is very rapid, and the dynamo mechanism becomes more effective than that for slower rotators at the same evolutionary stage. However, a certain degree of evolution is required in order to develop a deep convective envelope.

We have compared the fluxes in the Ca II H & K lines for those stars which are in common with the sample studied by Fernández–Figueroa et al. (1994). It is possible to see that most of the emitters are above the TAMS, and those ones which are below are very rapid rotators.

In order to clarify the relation with evolution, we have plotted stellar radii against rotation periods. We show the sample in Fig. 5 (symbols are the same as in Fig. 1, but their sizes are proportional to the flux in Ca II H & K). There is a trend between both parameters, but a large scatter is apparent since there is not a direct link between both quantities. In general, it is known that for a given rotation period, stars which have larger radii show higher chromospheric fluxes. Moreover, we attribute the fact that binaries have higher activity levels than single stars (Montesinos & Jordan 1988) to the evolutionary status; these binaries are more evolved than single stars. On the other hand, for a given radius, the activity increases as the rotation period decreases. Unfortunately there are not too many stars in common between both samples, and this relation can be only established for subgiants, but the same results arise if the X ray fluxes are used instead of the Ca II H & K fluxes. In this context, we confirm the conclusion of Dempsey et al. (1993), who obtained a similar result by using a larger sample of CA binaries. They observed a cut–off at $P_{phot} \simeq 3$ days, which they attributed to a leveling off of the X ray fluxes.

Therefore, the enhanced activity of CA binaries can be interpreted in the scenario of the evolution of the internal structure of low mass stars, taking into account the evolution of the orbital elements and rotation. Binary systems having very short orbital periods and low masses will evolve along the main sequence developing a deep convective envelope, decreasing their orbital period due to magnetic braking and synchronization between the orbital and the rotation period, and increasing their rotation rate due to the transfer of orbital angular momentum to rotational angular momentum (Duquennoy et al. 1992, Van't Veer & Macceroni 1992). Then, when these systems cross the TAMS, they fulfil the conditions to show an enhanced activity. After this stage is reached, it is possible to speculate about the next steps of the evolution of these systems. They would continue losing angular momentum and they would become contact systems with orbital periods of a few hours in time scales of 0.1-1.0×10^9 years, depending on the initial orbital period (Guinan & Bradstreet 1988). Afterwards, these binaries could coalesce into rapidly rotating single A–type stars, which would evolve to FK Com variables (Webbink 1976). In the case that the more massive component of the binary reaches its Roche lobe early in its evolution, the binary will probably evolve into an Algol-type system.

6. Conclusions

We have obtained the ages for those CA binaries with accurate determinations of their stellar parameters. We have found that there is a lack of young, low-mass stars in this sample. Therefore, we confirm the evolved status of CA binaries. We have found a tight relationship between Age and Mass for CA binaries.

The lack of young low mass stars could indicate that binaries become chromospherically active when they reach a certain age, which would depend on their mass. The role of rotation is also very important. Some systems are younger than the average and show enhanced activity, but this situation only appears in those systems having an extremely short rotation period.

In a future paper, we will study the role of the evolution of the internal structure on the CA binaries and on the Li depletion. The ages obtained for stars in our sample, and the ages calculated by using the Age–Mass relationship for other samples for which no accurate determinations of radii are available, will allow us a comparison between the lithium depletion in CA binaries and stars belonging to open clusters, such as the Hyades, M67 and NGC188.

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