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ASTRONOMY AND ASTROPHYSICS

The strongly constrained interacting binary BY Crucis*

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Abstract. We discuss spectroscopic and photometric observations (UV to IR) of BY Crucis, a new bright member of the interacting binaries of the W Serpentis class. The orbital period is 106.4 days, and the mass function amounts to 5.92 $M_\odot$. The primary is an early-F supergiant which fills its Roche lobe; the massive secondary is hidden inside a thick accretion disk, which is probably the dominant light source in the ultraviolet. The observed variations in the photometric lightcurves are caused mainly by ellipsoidal variations. It is unlikely that an eclipse occurs.

A particularly interesting circumstance is that BY Cru is a probable member of a visual multiple system which contains another evolved star. This circumstance enables us to estimate with some accuracy the age of the interacting binary and the initial mass of the primary. The history of this binary is then much more constrained than for the other W Serpentis stars. Also taking into account the fact that the binary has avoided Case C Roche lobe overflow, we determine upper and lower bounds for the initial and present masses of both components, and conclude that mass transfer has only been moderately non-conservative.

Key words: binaries: close – circumstellar matter – stars: evolution – stars: individual: BY Cru

1. Introduction

The star BY Crucis (also known as HD 104901 B, CD-61°3326, SAO 251722) is the second-brightest component of a visual triple system. The A-component of the system is a 7.4-magnitude star that has been classified as a B8/9Iab/b supergiant by Houk and Cowley (1975); the C-component is a 10.1-magnitude early-B main-sequence star. Houk and Cowley assigned a spectral type F0Ib/III to the 7.8-magnitude component B, but noted that the spectrum was mixed up with that of the A-component. Other reported classifications for component B are F0Ib/II (Stephenson and Sanduleak 1973) and F0IIp (Gahm et al. 1983). The three stars form an oblique triangle in the sky, with the angular separation between components A and B being about 23.0 arcseconds, that between B and C about 45.0 arcseconds, and between components A and C about 25.5 arcseconds.

It is exceptional that two components of a triple system are supergiants. The simultaneity of the first crossing of the Hertzsprung gap requires almost equal initial masses, if the association is physical. One would then also expect that both stars have the same luminosity. The difference in bolometric correction would imply that the F-type component is the brighter one by some 0.3 mag in the visual band; in fact, it is 0.4 mag fainter than the B-type primary. Nevertheless, we will see below that it is likely that the association is physical indeed, and that the F-type component is underluminous.

It happens that this F-type component is a remarkable object. As a Hα-emission object it has been catalogued as star 747 in Henize's (1976) compilation of southern emission-line objects. It is also known to display an infrared excess due to circumstellar dust (Tapia 1982). Tapia, not being aware of the binary nature of the star, ascribes the IR excess to mass loss due to a strong stellar wind; he situates BY Cru and HD 104901 A at an equal distance, in the range between 3.1 and 4.0 kpc. Third, it is a photometric variable: Eggen (1983) observed light variations with an amplitude of 0.35 magnitude and determined a period of 106.6 days; he interpreted the variability as due to ellipsoidal effects in a close binary system.

Our interest in BY Cru arose because of its being a F-type supergiant with circumstellar dust: as such, it was a candidate for being an object evolving from the AGB toward the planetary-nebula phase (Trams et al. 1991). From the observations of various kinds we obtained, it is now clear that BY Cru is not a low-mass post-AGB star, but a rather massive interacting binary. The incorrectness of our first ideas about this object was no reason for abandoning its study; instead, it appears that this star is of extreme interest as an interacting binary. Not only is the mass function rather high, also the occurrence of this binary in

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Table 1. *CORAVEL* radial-velocity observations.

Heliocentric Julian Date	phase	V_{rad}	error	observer
8289.852	0.066	14.71	1.15	MAYOR
8312.777	0.281	65.99	1.19	MAYOR
8317.689	0.328	56.50	1.21	MAYOR
8320.671	0.356	50.92	0.93	MAYOR
8324.668	0.393	37.89	1.08	MAYOR
8400.637	0.107	33.44	1.50	DUQUENNOY
8452.508	0.595	-61.50	1.48	MERMILLIOD
8460.487	0.670	-84.64	1.13	MERMILLIOD
8461.482	0.679	-86.07	1.38	MERMILLIOD
8462.490	0.689	-91.32	1.43	MERMILLIOD
8641.886	0.375	42.97	1.15	DUQUENNOY
8648.881	0.441	13.40	1.56	DUQUENNOY
8686.866	0.798	-89.55	1.33	ANDERSEN
8690.700	0.834	-82.94	0.94	ANDERSEN
8694.734	0.872	-75.80	1.17	ANDERSEN
8698.771	0.910	-61.75	0.67	LINDGREN
8703.867	0.958	-36.08	0.82	LINDGREN
8705.747	0.975	-26.71	0.77	LINDGREN
8706.754	0.985	-19.85	0.57	JORISSEN
8783.600	0.707	-89.51	1.21	ANDERSEN
9054.784	0.256	69.08	1.01	JORISSEN
9169.477	0.334	60.15	1.32	DUQUENNOY
9172.506	0.363	51.98	1.48	DUQUENNOY
9175.515	0.391	37.97	1.02	DUQUENNOY
9404.842	0.546	-38.81	0.75	WAELKENS
9405.815	0.556	-43.73	0.70	WAELKENS
9406.820	0.566	-47.71	0.81	WAELKENS
9407.819	0.575	-52.41	0.74	WAELKENS
9408.801	0.584	-55.82	0.72	WAELKENS
9409.813	0.594	-58.91	0.69	WAELKENS
9522.560	0.654	-76.33	0.98	NORTH
9526.647	0.692	-86.53	1.24	NORTH

a visual multiple with another evolved component provides us with a remarkable opportunity of dating the binary and of estimating the initial mass of the mass-transferring component, and thus with stringent constraints on possible evolution scenarios.

2. The binary nature of BY Cru

2.1. Velocity variations and orbit

Since February 1, 1991, we have obtained 32 radial velocity observations of BY Cru, using the *CORAVEL* spectrograph attached at the 1.54m Danish Telescope at the European Southern Observatory in Chile. These data are listed in Table 1: given are the heliocentric Julian Date of each observation, the orbital phase, the velocity, the estimated uncertainty of the individual measurements, and the name of the observer. The estimate of the error takes into account the photon and scintillation noise (Baranne et al. 1979).

The large amplitude of the velocity variations does not leave any doubt that BY Cru is a spectroscopic binary. The orbital period that represents best the velocity data is 106.4 days. We show in Fig. 1 the phase diagram and a synthetic velocity curve computed with the amplitude K_1 = 81.3 $\pm$ 0.6 km/s. According to Lucy and Sweeney's (1971) test, the eccentricity does not significantly differ from zero, so that we have adopted a circular orbit. An epoch of phase 0.0, corresponding to the moment that the visible supergiant is in front of its companion, is HJD 2448495.60 $\pm$ 0.15. The standard deviation with respect to the adopted solution is 2.0 km/s, and thus exceeds the observational scatter slightly but significantly. This is not unusual for stars with correlation dips that are significantly broadened by rotation, and suggests that our error estimate is somewhat optimistic. Another possibility is that the correlation dips are slightly affected by gas streams in the system.

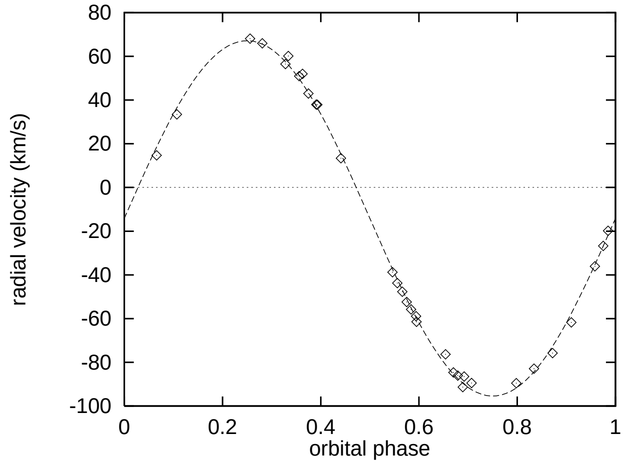

Fig. 1. The phase diagram of the radial-velocity variations of BY Cru

The resultant mass function is 5.92 $\pm$ 0.17 solar masses. The mass of the primary in this single-lined system must then be less than that of the unseen secondary, unless both stars are more massive than 23.7 solar masses. Finally, we note that a byproduct of the *CORAVEL* observations is the projected rotational velocity $v\ sin\, i$. Its mean value amounts to 19.8 $\pm$ 1.1 km/s.

2.2. Photometric variations

We have obtained 152 observations of BY Cru in the Geneva seven-color system, with the Geneva Photometer attached to the 0.70m Swiss Telescope at La Silla Observatory, Chile. These observations confirm the photometric variability first detected by Eggen (1983), although the variability is somewhat larger in our set of data. Eggen's and our observations are consistent with the 106.4-day period. We show the phase diagrams for the visual magnitude and the [B-V] and [U-B] color indices on Fig. 2; the phases are the same as for the velocity curve. The scatter in the data points is due to the fact that the lightcurve varies intrinsically from one epoch to another, indicating that the binary is presently very active.

The color variation shows that the observed temperature is highest during the maxima, suggesting that the photometric variability in these filters is mostly due to gravity darkening. A most unusual circumstance, already pointed out by Eggen (1983), is

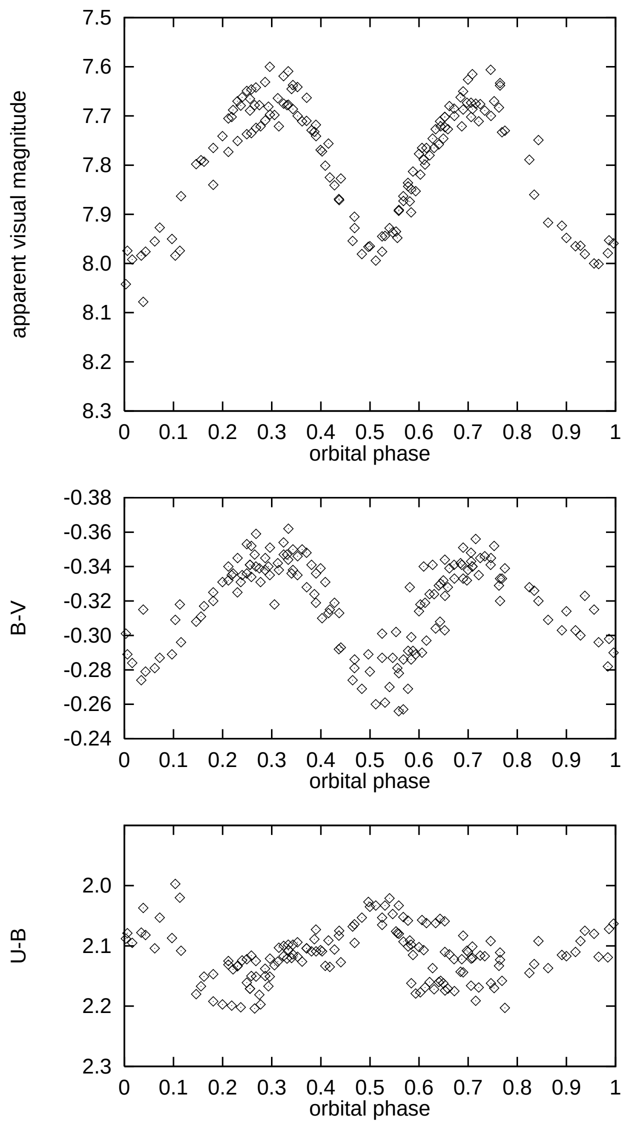

Fig. 2. The phase diagram for the photometric variations of BY Cru

that the width of the minima is not the same, despite the circular orbit. The broad minimum occurs when the F-supergiant is in front of the companion. The minima are of almost equal depth, although at some epochs the minimum at phase 0.0 is somewhat deeper. More observations during this orbital phase are needed in order to understand the long term variability. The fact that both minima are of almost equal depth suggests that we are not observing a real eclipse, but rather ellipsoidal variations. The photometric amplitude is fairly large for ellipsoidal variations, the depths of the minima being about 0.40 - 0.45.

3. The visual triple system HD 104901 ABC

3.1. Multiwavelength observations

In order to determine the reddening and the energy distribution for the three components of the visual multiple system, we have obtained observations in various bands of the spectrum. UV fluxes have been obtained from low-resolution spectra measured with *IUE* on May 19, 1992; April 11, 1994 and May 7 and 8, 1994: for components A and B both short- and long-wavelength spectra were obtained, and for component C only a long-wavelength spectrum. The spectra of BY Cru were taken at the orbital phases 0.49, 0.06 and 0.31 respectively. Optical photometry was obtained with the Swiss Telescope at La Silla at various epochs since 1989; no significant variability was observed for components A and C. Finally, we obtained JHKLM photometry for component B in February 1989, and January 1992, with the IR photometers attached to the 1m and 2.2m telescopes at the European Southern Observatory.

Table 2. Observed fluxes and dereddened energy values, normalised to the energy in the visual band, for BY Cru. The calibrations of the observations and the dereddening procedure are described in the text.

wavelength (nm)	flux (10^{-12} $erg/s\ nm\ cm^2$)	$\lambda F_\lambda / \lambda_V F_V$
125.0	0.80	0.051
139.0	1.00	0.048
149.0	1.60	0.074
160.0	1.40	0.069
170.0	1.40	0.068
180.0	2.30	0.113
190.0	2.20	0.124
200.0	1.80	0.131
210.0	1.70	0.164
219.0	1.40	0.157
230.0	1.00	0.091
240.0	1.70	0.121
250.0	2.20	0.130
274.0	2.70	0.122
295.0	4.00	0.172
309.0	4.70	0.194
347.1	8.68	0.323
424.6	32.43	1.189
550.4	30.34	1.000
1240.0	7.87	0.284
1630.0	4.67	0.207
2190.0	3.12	0.169
3790.0	1.81	0.157
4640.0	1.30	0.137
12000.0	4.67	0.207
25000.0	3.12	0.169
60000.0	1.81	0.157
100000.0	1.30	0.137

We list in Table 2 the fluxes at various wavelengths for BY Cru. The UV fluxes are averages over 10 Å intervals around the indicated wavelength. The optical and near-IR fluxes were derived from the magnitudes using the flux calibrations by Rufener and Nicolet (1988) and Le Bertre (1988), respectively. Finally, the far-IR fluxes for component B were taken from the IRAS Point-Source Catalog.

3.2. Reddening and Energy Distributions

Cramer (1982) has worked out a method for determining the reddening of B-type stars: the reddening-free parameters X and Y are constructed from the observed indices in the Geneva system, and then the intrinsic colors $[U-B]_0$ and $[B-V]_0$ are estimated from X and Y. The estimates of the intrinsic colors from X and Y are most reliable for non-supergiants stars. Applying the method to component C ($X = 0.442; Y = 0.001$) yields a value of 0.38 for the color excess E[B-V], corresponding to E(B-V) = 0.34 in the Johnson system.

For the supergiant components A and B, the reddening can be estimated less precisely from optical photometry. Meylan et al. (1980) list for the color index $B_2 - V_1$ intrinsic values of -0.168, -0.146, and 0.068 for Ib supergiants of type B8, B9, and F2, respectively. The first two values lead to color excesses $E(B_2 - V_1)$ in the range 0.23 - 0.25 for component A, corresponding to an E[B-V] between 0.30 and 0.33, and the third value leads to E[B-V] = 0.38 for component B; if the luminosity class of component B were lowered to class III, an E[B-V] of only 0.26 would result.

That the interstellar reddening toward all three stars is about the same, is confirmed by the equal depths of their 220 nm absorption dips. Assuming a Savage and Mathis (1979) extinction law, we find that the depth of these dips is well matched for a color excess E[B-V] = 0.38 for all three components, i.e. the value derived from photometry for the component for which it could be estimated most precisely. We then conclude that the extinction is the same for all three stars. The likelihood of a physical link is strengthened by this argument.

Correcting the observed fluxes for the reddening, assuming a Savage and Mathis (1979) law, enables us then to construct the energy distributions that are shown on Fig. 3 and to fit them with Kurucz (1979) models. For component A, the best fit is found for $T_{eff} = 11000$ K and $log\, g = 2$, consistent with a B7Ib spectral type, and so with the observed optical colors and E[B-V] = 0.38. For component C, the best fit is for $T_{eff} = 20000$ K and $log\, g = 4.5$, which is consistent with a B2V spectral type. Given the spectral type of component B, the effective temperature should be about 6700 K; in Fig. 3b we see indeed that the near-UV and optical fluxes are well represented with a ($T_{eff} \simeq 6700$ K, $log\, g = 2$) model atmosphere.

Both in the far-UV and in the IR, excess radiation is observed for BY Cru. The UV excess represents a source which is hotter but much less luminous than the primary. It is likely that this source is located inside the Roche lobe surrounding the secondary; we will elaborate on the nature of this source in the next section. The IR excess can be due to dust surrounding the whole system, though a contribution of the circumstellar accretion disk may be possible. If one assumes that the IR excess is due to a circumbinary disk and that the primary star is the only significant heat source for the dust shell, modelling the IR excess with an optically-thin-dust model (Waters et al. 1989) leads to an extension from 17 to about 4000 stellar radii.

3.3. Luminosities, Distance, Masses, and Age

According to Cramer and Maeder (1979) the absolute magnitudes of non-supergiant B stars with X larger than 0.4 can be derived from the reddening-free parameters X and Y. For component C, this exercise yields values for M_v and M_{bol} of -2.0 and -4.1, respectively. The distance modulus of this star then amounts to $m_v - M_v = 11.1$ (distance 1.6 kpc).

Before adopting the same distance modulus for the two supergiant components, in order to estimate their luminosities, it is necessary to critically assess whether the system is a genuine multiple system. The close association of the three stars in the sky suggests a positive answer: the mutual distances are less than an arcminute, while no other star brighter than the faintest component occurs within more than 10 arcminutes in the sky. We have mentioned already that the reddening towards all three components is the same. On the other hand, while the velocities of components A and C, which amount to -23.6 ± 1.1 km/s and -22.4 ± 1.6 km/s respectively, again confirm that the association is physical, these velocities do differ significantly from the systemic velocity of component B, which amounts to -14.1 ± 0.5 km/s.

A distance of 1.6 kpc for component A yields an absolute visual magnitude of -4.7 and an absolute bolometric magnitude of -5.2, i.e. values which are fully consistent with the spectral type of this component. An independent constraint on the luminosity of component B can be obtained from the effective temperature and from the radius, which we estimate from the projected rotational velocity. Assuming corotation, we find a mean projected radius for the F-supergiant of $R_1\, sin\, i = 41.6\, R_\odot$. A reasonable lower limit for $sin\, i$ is 0.9 (see Sect. 4.2), so R_1 can at most be some ten percent higher than $R_1\, sin\, i$. We also have to take into account that the effects of gravity darkening slightly sharpen the spectral lines. From all these considerations, the real radius of the supergiant probably is of the order of some 50 $R_\odot$.

Interestingly, this radius is consistent with the value we find by also adopting a value of 1.6 kpc for the distance of component B. If we assume that the visual magnitude of the supergiant corresponds to the maxima of the light curve, we then find that the absolute visual and bolometric magnitudes are -4.5 and -4.7, respectively. At an effective temperature of 6700 K, this corresponds to a mean radius of 52.7 $R_\odot$. If we consider the average observed magnitude as representative for the luminosity, a radius of 47.5 $R_\odot$ is found. We infer that the radius must fall somewhere in the range between 42 $R_\odot$ and 53 $R_\odot$, but probably nearer to the larger value than to the lower one.

We then conclude that the distance to component B is also of the order of 1.6 kpc, and therefore that it is likely that component B is physically associated with components A and C. We conjecture that the deviant system velocity is the result of mass loss from the system. This mass loss must have occurred recently, since a velocity difference of 9 km/s would have led to an appreciable separation if it had occurred during the whole lifetime of the star. Some support from this conjecture comes from the observed IR excess, which might originate in a cir-

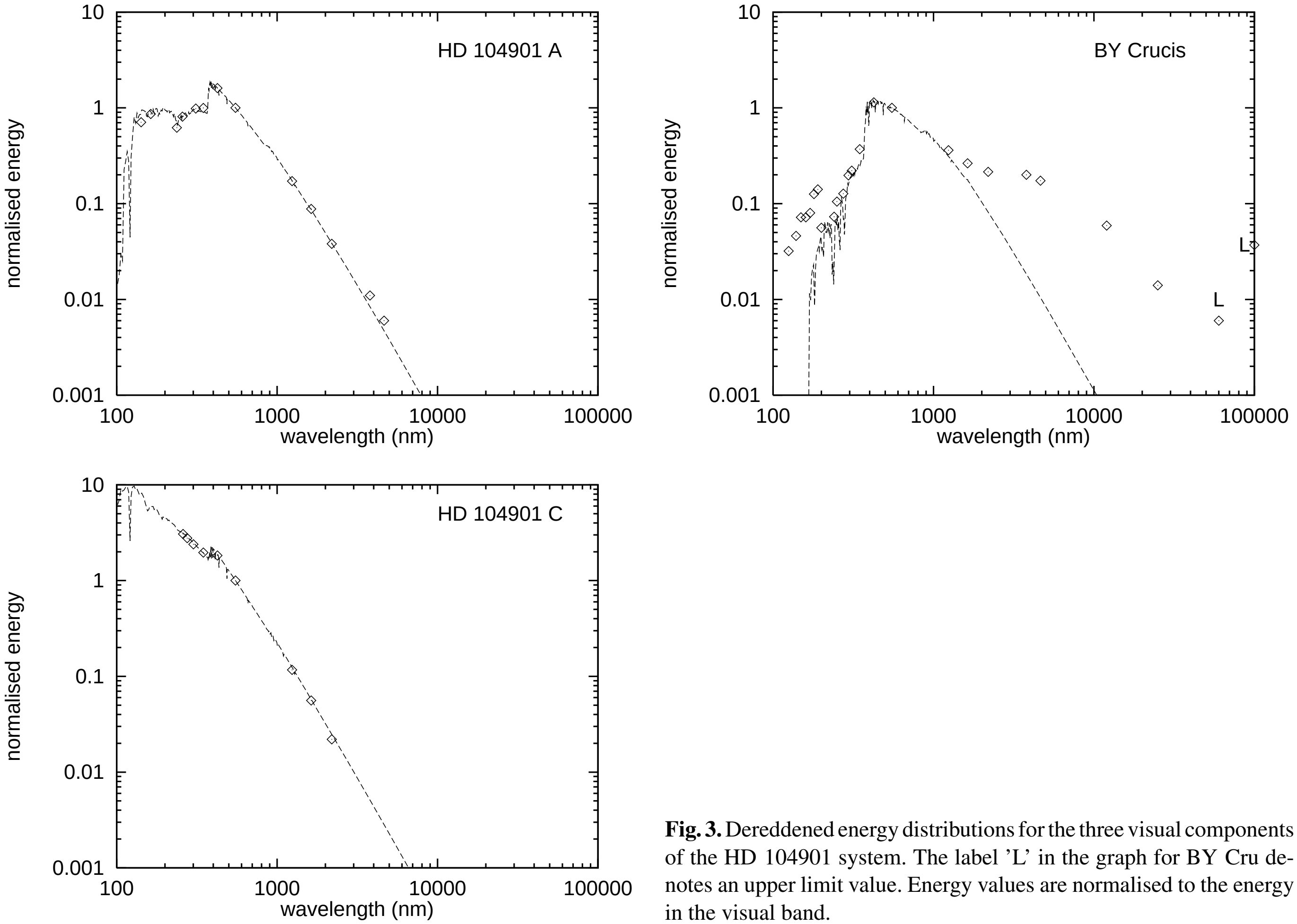

Fig. 3. Dereddened energy distributions for the three visual components of the HD 104901 system. The label 'L' in the graph for BY Cru denotes an upper limit value. Energy values are normalised to the energy in the visual band.

cumbinary disk. On the other hand, we will see in Sect. 5 that it is not very likely that much mass has been lost from the system.

The velocity of stars in the direction of HD 104901 and at a distance of 1.6 kpc, implied by galactic rotation, is about -11 km/s. This is in good agreement with the observed radial velocity of component B, but less with components A and C, although a deviation from galactic rotation of about 10 km/s is acceptable, due to peculiar stellar velocities.

Interpolating between the evolutionary models by Maeder and Meynet (1991) for the present parameters for component C ($log\, T_{eff} = 4.30, log\, L/L_{\odot} = 3.54$) yields a mass of $7.5\, M_{\odot}$ and an age of $30\, 10^6$ years for this star. For component A ($log\, T_{eff} = 4.04, log\, L/L_{\odot} = 3.99$), the mass which is derived then amounts to $8.5\, M_{\odot}$, and the age is also $30\, 10^6$ years. An error of 20% on the luminosity would be reflected in an error of less than 10% on both masses.

The initial mass of the most evolved component of BY Cru must have been only slightly larger than the present mass of component A, i.e. 8.5 solar masses. The initial mass of the secondary must have been lower, but the mass function implies that the secondary is presently much more massive than the primary.

4. The present nature of BY Cru

4.1. The nature of the companion

One of the more remarkable aspects of BY Cru is the elusive character of the companion, which in all reasonable cases must be much more massive than the primary. The absence of recorded X-ray emission from the system suggests that the companion is not a compact object, but rather a main-sequence star hidden inside circumstellar matter. As we will elaborate on in Sect. 6, BY Cru should be classified among the so-called *W Serpentis stars*, which are massive binaries in a phase of rapid mass transfer (Plavec 1980).

The probable presence of an accretion disk around the secondary is attested by the excess of UV radiation. This UV excess peaks at 200 nm and has a total flux of some 10 % of that of the F-supergiant component. Both the UV color temperature and the UV luminosity are much less than what would be expected from a $9\, M_{\odot}$ star. One possibility could be that the optical radiation from this star toward us is severely lowered by an extremely high rotation and the associated gravity darkening. However, it seems unlikely that such an effect would lower the brightness of the star by up to five magnitudes: indeed, the companion is probably more massive than the A-component of the triple system! Moreover, the IUE spectra reveal several emission lines of

HeII, CII and CIV, NV, SiII and SiIV, in addition to the continuum, and thus show that a circumstellar disk of hot plasma is present.

So far, continuum radiation from the disk has only been clearly observed in the UV, but it may in fact also contribute significantly to the optical flux. In fact, the unequal length of the photometric minima probably indicates that the disk contributes substantially to the total optical flux. It is important to note that, as is the case with the optical lightcurves, no eclipses are observed in the UV continuum radiation; the UV continuum in the short-wavelength spectra remains almost constant during the observed phases, while the long-wavelength UV continuum changes at most some 15%, due to the variable contribution of the supergiant.

4.2. A model for BY Cru

The present masses of both components are rather well constrained by the mass function and the massive nature of the system. The fact that the secondary must be massive implies that it is extremely unlikely that the primary evolved from a low-mass star and would be presently a post-AGB-star with, say, some 0.6 solar masses.

The core of a massive F-supergiant is expected to contain not less than between 1.5 and 2 solar masses. If we adopt a present mass of 2.0 $M_\odot$ for the primary, a lower limit of 8.9 $M_\odot$ for the secondary is found from the mass function. If $sin\, i$ is unity, the mass ratio, $q = 0.22$, implies then that the Roche lobe of the mass losing star has a mean radius of about 54 $R_\odot$; for other inclinations in the permitted range (see below), the Roche lobe radius is about the same. These values are thus larger than the upper limit we derived for the radius of the supergiant. In order to achieve agreement, the mass of the primary has to be lowered to about 1.8 $M_\odot$, which means that the mass of the secondary is about 8.7 $M_\odot$, if $sin\, i$ is close to 1. The mean Roche lobe radius of the primary is then 52.5 $R_\odot$.

The important ellipsoidal variations and the fact that the secondary is hidden inside the accretion disk, suggest that the inclination is rather high, though not 90°, because no real eclipses are observed. Another constraint on the inclination angle is set by the projected rotational velocity, $v\, sin\, i = 19.8$ km/s. Assuming corotation for the mass-losing supergiant, the projected rotational velocity yields a mean projected radius of about $R_1\, sin\, i \geq 41.6\, R_\odot$. From the luminosity and the effective temperature, we find $R_1 \leq 52.7\, R_\odot$. Both values then imply a lower limit of 0.79 for $sin\, i$. If we then also take into account that gravity darkening effects probably imply that the radius determined from $v\, sin\, i$ is an underestimate and that 52.7 $R_\odot$ is an upper limit for the radius of the supergiant, we feel that a value of 0.90 ($i \simeq 64°$) is a realistic observational lower bound for $sin\, i$.

5. Evolutionary history of the system

The IR excess, if caused by matter orbiting the system, shows that the mass transfer has been non-conservative. However, the assumption that the primary evolved from a 9 solar mass star implies that the non-conservativeness of the mass transfer must have been moderate, and probably recent. If too much mass had escaped from the system, it would probably not have avoided Case C mass transfer, which would have led to mass transfer on a dynamical timescale, not to the wide system we observe today. The main reason is that in a non-conservative scenario the system must have been appreciably larger in the past than it is now, so that Roche lobe overflow would have started later, and in fact after the primary had developed a convective envelope. Below we work out quantitatively the possible history for different initial conditions. Our conclusion will be that BY Cru is a Case B mass transfer product, and that not more than some 10% of the total initial binary mass can have escaped from the system.

Let us first consider a conservative mass transfer model. Given the range in possible inclination of the binary and the present radius for the loser, possible values for the parameters of the binary system, initial and present, can be estimated. In Sect. 3 a lower and upper limit radius of the primary was presented, being resp. 42 $R_\odot$ and 53 $R_\odot$. In the following discussion this range is expanded to 40 $R_\odot$ - 55 $R_\odot$, and possible evolutionary scenarios are examined. The inclination is, for the moment, left a free parameter.

The assumptions in the present calculations are 1) the mass transfer between the components is conservative; 2) HD 104901 is a genuine triple system, so that the age of the interacting binary is about 30 Myr.; 3) transition between a radiative and a convective envelope occurs at about spectral type G0 for supergiants; 4) the present mass of the primary star is close to its core mass (= remnant mass), the mass of the envelope being only a small fraction of the total star mass, and 5) the primary presently still fills its Roche lobe. Under these conditions possible evolutionary scenarios can be traced.

For mass ratios, $q = \frac{M_1}{M_2}$, in the range 0.1 - 0.8, one obtains the mean radius of the Roche lobe of the primary, and hence its mean stellar radius since the star still fills its lobe, by the simple expression due to Paczyński

$$\frac{R_{L_1}}{a} = 0.462 \left(\frac{M_1}{M_1 + M_2} \right)^{\frac{1}{3}},$$

where a stands for the separation between the centers of the two stars. When all parameters, that are presently known to us, are inserted, a relation $M_1 \;\alpha\; R_1^3$ is found. This relation is, within the given range of q, independent of R_2. The mass function, $f(M)$ can then be used to calculate a corresponding M_2. Unlike M_1, M_2 does depend on the inclination of the system.

Iben and Tutukov (1985) give an approximate relation between the total mass of an intermediate mass star and its non-electron-degenerate, compact helium core at the end of the main sequence, $M_{He} \sim 0.08\; M^{1.4}$. Assuming that the present mass of the loser is close to this core mass, we obtain a value for the initial mass of the donor star. Since we assumed a conservative mass transfer model, the initial mass of the gainer can now also be determined, the result depending again on the inclination of the binary. All remaining initial parameters of the binary

Table 3. The obtained binary parameters for BY Cru for orbital inclination 76°, assuming conservative mass transfer. Solutions with a higher inclination yield results that are in conflict with the observations.

Initial		Present	
$M_{1,init}$	8.9 $M_{\odot}$	$M_{1,pres}$	1.7 $M_{\odot}$
$M_{2,init}$	1.9 $M_{\odot}$	$M_{2,pres}$	9.1 $M_{\odot}$
P_{init}	77 $days$	P_{pres}	106 $days$
$a_{1,init}$	30 $R_{\odot}$	$a_{1,pres}$	176 $R_{\odot}$
$a_{2,init}$	138 $R_{\odot}$	$a_{2,pres}$	33 $R_{\odot}$
$R_{L_1,init}$	86 $R_{\odot}$	$R_{L_1,pres}$	52 $R_{\odot}$
		$R_{1,pres}$	52 $R_{\odot}$

system can now be derived: orbital period, separation between the components and initial Roche lobe radii. Since nothing is known about the evolution of the eccentricity of the orbit, it is kept zero throughout all calculations. Using the tables of stellar evolution models (Maeder and Meynet, 1988), the age at which mass transfer started, the luminosity and temperature of the loser at the moment of onset of mass transfer can be found.

Since there is a range in the present radius of the loser, and the inclination is not known, a whole set of possible evolutionary scenarios is obtained. Evidently, not all solutions are realistic. Using the fact that the age of the system is about 30 Myr, meaning that mass transfer must have started before or about this age, and the fact that mass transfer started when the envelope of the loser was not yet deeply convective, since the system would have gone through a common envelope phase, most of the obtained solutions become impossible. As it turns out, there is no solution for i = 90°. The inclination at which the first solution appears for the conservative scenario is about 76°, which is probably not far from the real inclination of the binary. This evolutionary path yields a late Case B mass transfer, which started when the system was about 29.5 Myr old. The initial and present parameters of this solution are listed in Table 3. As mentioned above, the corresponding present radius of the donor lies close to the upper limit derived in Sect. 3.

Conservative mass transfer scenarios, corresponding to the observational lower limit for the inclination, i = 64° (Sect. 4), yield possible initial masses for the primary ranging from 8.9 $M_{\odot}$ to 9.6 $M_{\odot}$. If, on the other hand, no restriction is put on the lower limit of the inclination, the lowest value found is i = 55°, corresponding to an initial primary mass of 9.6 $M_{\odot}$. Scenarios with inclinations below 55° start with initial mass ratios to close to unity and/or the Roche lobe overflow starting later than at an age of about 30 Myr.

If a non-conservative mass transfer model is assumed, a new parameter is introduced: the total mass that escaped from the system during the mass transfer process, ΔM ($M_{\odot}$). During the calculations the mass loss rate is approximated by a constant value. Calculations, carried out with different values of ΔM, show that the number of solutions decreases with increasing total mass loss, unless ΔM takes a rather high value. According to these models it seems very unlikely, if not impossible, that more than about two solar masses have been lost

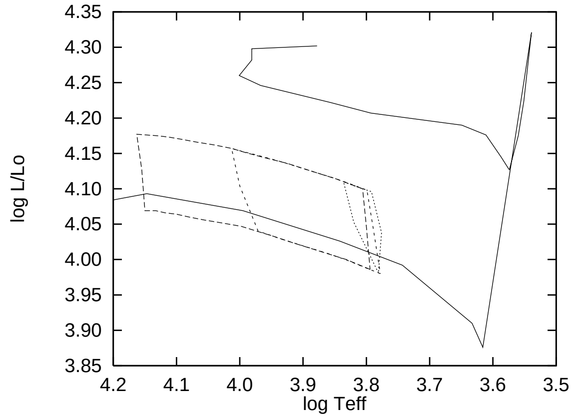

Fig. 4. Hertzsprung-Russell diagram with possible positions of the loser of BY Cru, at the beginning of Roche lobe overflow. Shown are the boundaries of the regions corresponding to conservative mass transfer (dashed), and the cases in which 1 $M_{\odot}$ (short dashed) and 2 $M_{\odot}$ (dotted) has escaped the binary. The full line is part of the evolutionary track of a 9 $M_{\odot}$ star.

from the binary. The reason why the number of solutions decreases with growing ΔM is mainly the corresponding growth of the absolute dimensions of the Roche lobe of the primary, even when this Roche lobe as a fraction of the orbital separation is smaller than in the conservative mass transfer model. Consequently, in the non-conservative scenarios, the primary will be more evolved before it fills its Roche lobe, developing a deep convective envelope when it approaches the giant branch. Most non-conservative scenarios become impossible because they go through common envelope phase, leaving two component stars that are tightly bound in orbit, not the wide system observed in BY Crucis.

In Fig. 4 the possible locations in the HR-diagram of the primary of BY Cru at the onset of mass transfer are shown for the conservative mass transfer scenarios, and for the cases in which 1 $M_{\odot}$ and 2 $M_{\odot}$ are lost from the system. As noted before, the number of solutions decreases with increasing ΔM. Within a region of solutions, the inclination increases from left to right (decreasing effective temperature), and the initial mass of the loser increases from bottom to top (increasing luminosity). Also shown in Fig. 4, for comparison, is part of the evolutionary track of a 9 solar mass star.

It is thus clear from the calculations of these simple models that, in order to avoid scenarios yielding parameters that are in conflict with the observations, at most some 10% to 15% of the initial binary mass can have escaped from the interacting binary; two solar masses is a reasonable upper limit for the total mass lost during the mass transfer proces.

In both the conservative and the non-conservative mass transfer models, the initial primary mass lies in the range 8.9 to 9.6 $M_{\odot}$. Depending on the total mass lost from the system, and the exact inclination of the binary, the initial mass of the secondary is found in the range 1.9 to 5.7 $M_{\odot}$, if the observational lower limit on the inclination of 64° is respected.

6. Observational similarities with other objects

The BY Cru system shows many similarities with the W Serpentis stars, a class of stars which has presented the astronomical community with many puzzles. Since the system presently under study appears so well constrained, it can be hoped that studies of BY Cru may shed new light on this class of peculiar stars as a whole.

The part of the electromagnetic spectrum where these interacting binaries present us with most unusual features, probably is the UV. We have undertaken a comparative study of the UV spectral features of BY Cru with those of several classes of peculiar objects, by correlating IUE spectra from the ULDA database (Wamsteker et al. 1989) with our spectra. The other objects chosen for this correlation were taken from the list by Kondo et al. (1987), who discussed many objects that may be considered as prototypes for several classes of stellar sources that show some activity in the UV. The correlation only covers the short-wavelength IUE spectra, since BY Cru is active mainly in this range. The following correlation product was defined

$$\int d\lambda\,(\lambda\,F_\lambda)_{BY\;Cru}\,[(\lambda\,+\,\Delta\lambda)\,F_{\lambda+\Delta\lambda}]_{other\,object}$$

which was then normalized to the correlation product of BY Cru itself. The $\Delta\lambda$ is introduced in the product to compensate for different systemic radial-velocities of the compared objects. The results of this exercise are presented in Table 4.

A correlation of 0.98 was found with one spectrum of the W Serpentis star RX Cas; from the eleven objects for which a correlation larger than 0.73 was found, ten were W Serpentis stars (RX Cas, W Cru, W Ser, β Lyrae and V367 Cyg) in different phases, and one (the ninth in order) was a spectrum of the symbiotic Z And. Clearly, then, BY Cru should be classified as a W Serpentis star.

The fact that the first non-W Ser objects in the list are symbiotics further strengthens our conclusion that the far-UV emission lines of BY Cru originate from an accretion disk rather than from a stellar continuum. Also the case of the classical Algol U Cep is revealing. The correlation with this object is poor as long as the system is observed out of eclipse, i.e. when the UV flux is dominated by the B7V component. However, the correlation improves significantly when the B7V component is eclipsed, and when the UV flux is dominated by its accretion disk.

Other objects (novae, WR stars, X-ray binaries, and stars with active chromospheres) showed notably poorer correlations. Interestingly, the IUE spectra of the F+B supergiants HD 37453, HD 59771 and HD 207739, the primaries of which are much alike BY Cru, are poorly correlated with that of BY Cru, confirming once more that the emission in the UV in our star originates from a disk rather than from the companion.

Table 4. Results of the correlation study between the IUE low-resolution spectra of BY Cru and a variety of objects. The correlation product is normalized so that the product is 1.000 for BY Cru itself. Orbital phases are given where these are known and relevant.

Nr	Name	Class	Orbital Phase	Correlation
1	RX Cas	Serpentid	0.20	0.980
2	RX Cas	Serpentid	0.99	0.951
3	W Cru	Serpentid	0.98	0.931
4	W Ser	Serpentid	0.51	0.909
5	W Ser	Serpentid	0.77	0.880
6	W Cru	Serpentid	0.36	0.857
7	β Lyr	Serpentid	0.08	0.813
8	W Ser	Serpentid	0.98	0.800
9	Z And	Symbiotic		0.754
10	V367 Cyg	Serpentid	0.50	0.735
11	β Lyr	Serpentid	0.47	0.731
12	U Cep	Algol	0.00	0.654
13	V1016 Cyg	Symbiotic		0.645
14	β Cet	Chromosphere		0.597
15	SX Cas	Serpentid		0.585
16	V367 Cyg	Serpentid	0.94	0.565
17	RW Aur	PMS star		0.539
18	V1668 Cyg	Nova		0.519
19	PW Vul	Nova		0.469
20	KX And	Serpentid pole-on		0.466
21	HD 192103	WR star		0.461
22	GW Ori	PMS star		0.452
23	HD207739	F+B binary		0.394
24	HD59771	F+B binary		0.379
25	RW Tri	Cataclismic Variable		0.372
26	U Cep	Algol	0.96	0.307
27	HZ Her	X-ray binary		0.297
28	HD37453	F+B binary		0.288
29	AT Mic	Chromosphere		0.222
30	AU Mic	Chromosphere		0.204
31	YZ CMi	Chromosphere		0.180
32	α Cet	Variable		0.157
33	U Cep	Algol	0.40	0.147

7. Remarks for future research

BY Cru presents us with rather exceptional opportunities to study mass transfer in massive binary systems. The next step in our investigation of this system will be a detailed study of the disk and the accretion process. This study involves the observation of absorption and emission lines at various orbital phases, both in the UV and the optical wavelength ranges. Monitoring of the absorption lines of the primary should enable us to determine to what extent the optical continuum is affected by the disk. Once these results are available, it will become possible to perform a quantitative analysis of the light and color variations.

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