Detached and Interacting OB-Star Binaries

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Abstract. We present an analysis of detached and interacting OB-star binaries. Values of masses, radii, and internal-structure constants from stars in detached systems are in excellent agreement with the latest stellar models. Some revisions to the effective temperature scale for O stars would seem to be required. The mass-exchanging, or interacting, OB binaries discussed in this sample seem to require case-A models to explain their properties, rather than the published case-B models.

1. The Detached O+O-Star Binaries

Eclipsing-binary stars with well-defined light-curves at more than one pass-band, and accurate radial-velocity curves for both components, provide us with definitive empirical masses, radii, temperatures, and luminosities. The compilation by Andersen (1991) of such data for unevolved, detached binaries covered the main sequence from $0.6M_{\odot}$ to $23M_{\odot}$, with only two binaries (EM Car, V478 Cyg) making a precise contribution to our empirical knowledge of O stars. Schönberner & Harmanec (1995) used these data to derive a new empirical brightness calibration for stars with effective temperatures in the range 6700–30 000 K. They showed that this calibration was in excellent agreement with the stellar models by Schaller et al. (1992), and that, over the entire mass range of $1.3M_{\odot}$ to $25M_{\odot}$, there were no systematic differences between the observed and evolutionary masses. They also demonstrated that their M_V–$T_{\rm eff}$ relationship disagreed with all other then-used calibrations for early-type stars.

During the current decade, new observational data on detached O+O-star binaries have been acquired by several investigators, and the resulting astrophysical parameters are given in Table 1. Of the 8 systems listed, 7 are eclipsing binaries, and the data on all of them have been analysed with the best available spectroscopic techniques of cross-correlation, tomography, and disentangling, and with light-curve synthesis such as the Wilson-Devinney (WD) code (Wilson & Devinney 1971; Wilson 1979) or LIGHT2 (Hill 1979; Hill & Rucinski 1993). We have compared these new data with the predictions of the stellar models of Schaller et al. (1992) to see whether or not the successes found by Schönberner & Harmanec (1995) for stars of lower masses are sensibly extended into the O-star region. These comparisons are displayed in Fig. 1 in the mass–$\log g$ plane and the $\log T_{\rm eff}$–$\log g$ plane. To within errors of observation, typically 2–5%, the two components of each binary system are to be found on the same isochrone, from ~ 1.5 Myr to ~ 6 Myr, in the mass–$\log g$ plane, thereby confirming and extend-

Table 1. Fundamental parameters of detached OB-star binary systems.

Object	Sp. Type	M ($M_\odot$)	$T_{\rm eff}$ (K)	R ($R_\odot$)	$\log g$ (dex cgs)
DH Cep[1]	O5.5 V	32.7 ± 1.7	$41\,000 \pm 2000$	8.7 ± 0.3	4.07 ± 0.04
	O6.5 V	29.8 ± 1.6	$39\,550 \pm 2000$	8.6 ± 0.3	4.05 ± 0.04
V3903 Sgr[2]	O7	27.3 ± 0.6	$38\,000 \pm 1900$	8.1 ± 0.1	4.06 ± 0.02
	O9	19.0 ± 0.4	$34\,100 \pm 1700$	6.1 ± 0.1	4.14 ± 0.01
EM Car[3]	O8 V	22.9 ± 0.3	$34\,000 \pm 2000$	9.4 ± 0.2	3.86 ± 0.02
	O8 V	21.4 ± 0.3	$34\,000 \pm 2000$	8.4 ± 0.2	3.92 ± 0.02
SZ Cam[4]	O9.5	18.5 ± 0.7	$29\,725 \pm 500$	8.5 ± 0.3	3.85 ± 0.03
	B0	16.1 ± 0.6	$27\,180 \pm 520$	7.9 ± 0.3	3.85 ± 0.04
Y Cyg[5]	O9.3	17.5 ± 0.4	$31\,000 \pm 2000$	6.0 ± 0.3	4.12 ± 0.04
	O9.4	17.3 ± 0.3	$31\,570 \pm 2000$	5.7 ± 0.3	4.17 ± 0.04
V478 Cyg[6]	O9.5 V	16.6 ± 0.9	$30\,500 \pm 1000$	7.4 ± 0.1	3.92 ± 0.03
	O9.5 V	16.3 ± 0.9	$30\,500 \pm 1000$	7.4 ± 0.1	3.91 ± 0.03
AH Cep[7]	B0.5 V	15.4 ± 0.2	$29\,900 \pm 500$	6.1 ± 0.1	4.02 ± 0.04
	B0.5 V	13.6 ± 0.2	$28\,600 \pm 1000$	5.9 ± 0.1	4.04 ± 0.05
CW Cep[8,9]	B0.5 V	11.8 ± 0.1	$27\,430 \pm 1000$	5.5 ± 0.1	4.03 ± 0.02
	B0.5 V	11.1 ± 0.1	$26\,430 \pm 1000$	5.0 ± 0.1	4.09 ± 0.02

References: 1, Hilditch, Harries & Bell (1996); 2, Vaz et al. (1997); 3, Andersen & Clausen (1989); 4, Harries, Hilditch & Hill (1997b); 5, Hill & Holmgren (1995); 6, Popper & Hill (1991); 7, Holmgren et al. (1990); 8, Clausen & Giménez (1991); and 9, Schönberner & Harmanec (1995).

ing the excellent agreement found for lower-mass stars between the empirical masses and radii and the model predictions. As we have shown earlier (Hilditch et al. 1996), the temperatures for these O stars, estimated from spectral types, colour indices, and equivalent-width ratios, show some discrepancies with those expected from the models at the masses and radii derived empirically for each star. These different temperatures are listed in Table 2, together with the M_V values for each star based upon the empirical radii and the temperatures from the stellar models.

In the M_V–$\log T_{\rm eff}$ plane (Fig. 2) we may compare the locations of these binary components with the isochrones from the stellar models, and with the empirical relationship between absolute visual magnitude and effective temperature used by Massey et al. (1995a, 1995b) in their important investigations of the initial mass function for massive stars. This empirical relationship is based upon the spectral-type vs. M_V relationship from Conti et al. (1983), and the spectral-type vs. $T_{\rm eff}$ relationship from Chlebowski & Garmany (1991). We see from Fig. 2 that, whilst the empirical calibration does indeed follow the general trend of the unevolved main sequence, it is not accurate enough to be used as a means to establish a precise value of M_V at a given temperature, or vice versa. Better agreement is achieved by using the Böhm-Vitense (1981) $T_{\rm eff}$–spectral-type calibration, although this is still systematically too hot. The Howarth &

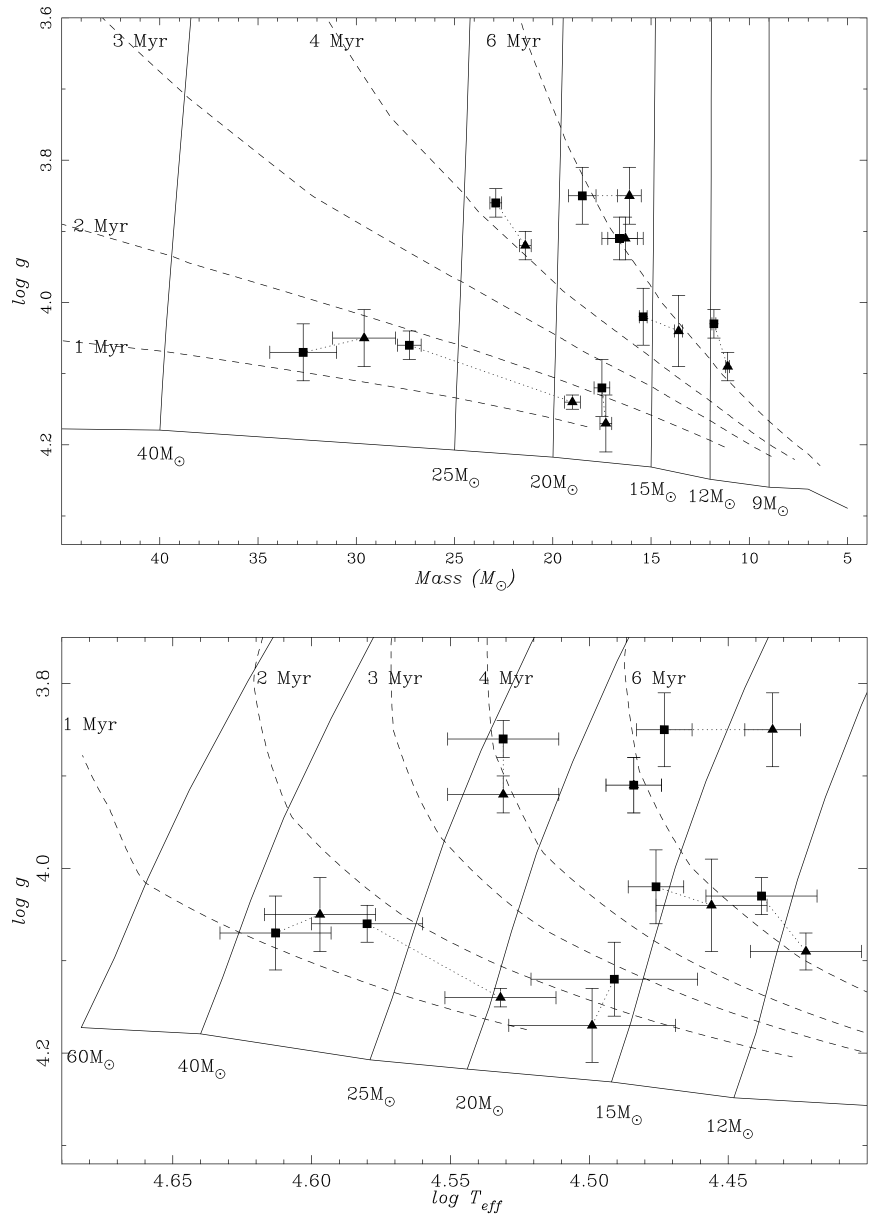

Figure 1. The positions of the primary (squares) and secondary (triangles) components (joined by a dotted line) of the detached binaries in the mass–$\log g$ plane (upper panel) and the $T_{\rm eff}$–$\log g$ plane (lower panel). The solid lines are the evolutionary tracks by Schaller et al. (1992) for different ZAMS masses. The dashed lines are isochrones for 1, 2, 3, 4, and 6 Myr.

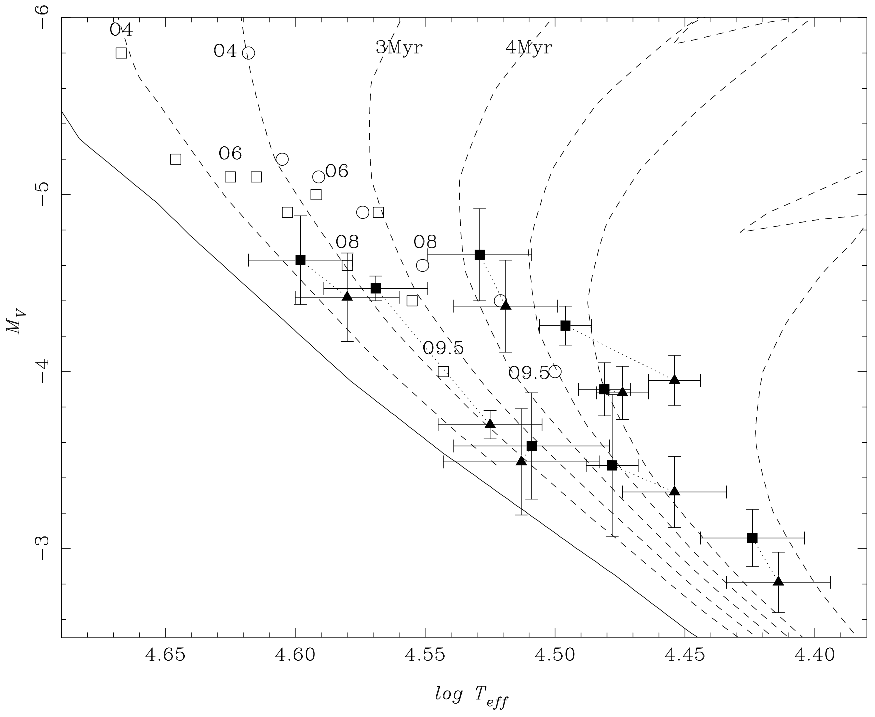

Figure 2. The positions of the primary (squares) and secondary (triangles) components of the detached binaries in the $T_{\rm eff}$–M_V plane. The solid line represents the ZAMS, while the dashed lines are isochrones at 1, 2, 3, 4, 5, and 6 Myr taken from the models by Schaller et al. (1992). The open squares (labelled with spectral types) describe the empirical relation used by Massey et al. (1995a, b), while the open circles (also labelled with spectral types) denote the empirical temperature calibration of Böhm-Vitense (1981) combined with the M_V–$T_{\rm eff}$ calibration of Conti et al. (1983). Dotted lines join the primary and secondary components of each binary.

Prinja (1989) temperature calibration lies between the Chlebowski & Garmany and Böhm-Vitense scales.

The most massive system in the sample of O+O binaries is DH Cep, in NGC 7380, which is an 'ellipsoidal' variable. Because of the lack of eclipses, we cannot be so certain about the stellar radii, though the minimum masses $m \sin^3 i$ are accurately determined. The solution of the B and V light-curves of DH Cep by Hilditch et al. (1996) has recently been criticized by Penny et al. (1997) on the grounds that a wide range of possible radii and orbital inclinations can provide an acceptable match to the light-curves, and that the values of M_V determined by Hilditch et al. (1996) differ by $0.5^{\rm m}$ from the absolute magnitudes inferred from cluster membership. We agree that a wide range of radii and orbital inclinations can indeed match the light-curves, but a proper investigation of the

Table 2. Effective temperatures of the detached O-star binaries taken from the literature ($T_{\rm o}$), and obtained by interpolating in the Schaller et al. (1992) models ($T_{\rm m}$). Also listed is the temperature difference, and the absolute visual magnitude computed using $T_{\rm m}$. References are as in Table 1.

Object	$T_{\rm o}$ (K)	$T_{\rm m}$ (K)	$T_{\rm m} - T_{\rm o}$ (K)	M_V
DH Cep[1]	41 000	39 700	−1300	-4.63 ± 0.25
	39 550	38 020	−1530	-4.42 ± 0.25
V3903 Sgr[2]	38 000	37 100	−900	-4.47 ± 0.07
	34 100	33 543	−557	-3.70 ± 0.08
EM Car[3]	34 000	33 057	−943	-4.37 ± 0.26
	34 000	33 814	−186	-4.66 ± 0.26
SZ Cam[4]	29 725	31 387	+1662	-4.26 ± 0.11
	27 180	28 471	+1291	-3.95 ± 0.14
Y Cyg[5]	31 000	32 320	+1320	-3.58 ± 0.30
	31 570	32 613	+1043	-3.49 ± 0.30
V478 Cyg[6]	30 500	30 283	−217	-3.90 ± 0.15
	30 500	29 847	−653	-3.88 ± 0.15
AH Cep[7]	29 900	30 047	+147	-3.47 ± 0.40
	28 600	28 455	−145	-3.32 ± 0.20
CW Cep[8,9]	27 430	26 529	−901	-3.06 ± 0.16
	26 430	25 970	−460	-2.81 ± 0.17

$\overline{\chi^2}$ hypersurface shows that the minimum value of $\overline{\chi^2} = 1.026$ is attained at an orbital inclination of $i = 47°$. The 67.5% $(1 - \sigma)$ confidence interval for $\overline{\chi^2}$ is $i \sim 39° - 52°$, but the formal solution from LIGHT2 gives $i = 47 \pm 2°$ (mistakenly reported in Hilditch et al. (1996) as $47 \pm 1°$). These results for the radii of the components of DH Cep are consistent with those derived from the *eclipsing* O+O binaries, where there is negligible uncertainty about the radii and the orbital inclinations. The empirical M_V calibration given by Massey et al. is not sufficiently precise to provide a radius for a star at an adopted temperature.

We should note also that the systems Y Cyg and CW Cep display well-established apsidal motion with periods of $U = 47.8 \pm 0.2$ yr (Holmgren et al. 1995) and $U = 45.6 \pm 0.4$ yr (Clausen & Giménez 1991). These results, together with the astrophysical parameters determined from the light- and radial-velocity curves, provide determinations of the mean internal-structure constants that are in excellent agreement (Claret & Giménez 1993) with the theoretical values from the models of Claret & Giménez (1992). These results are additional confirmation of the validity of these stellar models. It suggests that we may use the models to provide us with the temperatures for stars at determined masses and radii, and hence their absolute magnitudes.

The empirical calibrations of temperatures and absolute magnitudes for these very hot stars are no longer sufficiently precise. But the implications

Table 3. Fundamental parameters of semi-detached OB-star binary systems.

Object	Sp. Type	M ($M_\odot$)	$T_{\rm eff}$ (K)	R ($R_\odot$)	$\log g$ (dex cgs)	$\log(L/L_\odot)$
V448 Cyg[1]	O9.5 V	25.2 ± 0.7	$30\,000 \pm 500$	6.7 ± 0.2	4.19 ± 0.03	4.54 ± 0.04
	B1 II–Ib	14.0 ± 0.7	$20\,460 \pm 645$	16.3 ± 0.3	3.16 ± 0.03	4.66 ± 0.06
AB Cru[2]	O8	19.8 ± 1.0	$35\,800 \pm 500$	10.5 ± 0.3	3.69 ± 0.05	5.21 ± 0.03
	B0.5	7.0 ± 0.7	$27\,200 \pm 500$	8.9 ± 0.3	3.39 ± 0.05	4.58 ± 0.03
XZ Cep[3]	O9.5 V	15.8 ± 0.4	$30\,000 \pm 500$	7.0 ± 0.2	3.95 ± 0.02	4.58 ± 0.04
	B1 III	6.4 ± 0.3	$23\,120 \pm 420$	10.5 ± 0.2	3.20 ± 0.02	4.48 ± 0.03
LZ Cep[4]	O8.5 III	15.3 ± 0.5	$32\,000 \pm 500$	9.0 ± 0.2	3.72 ± 0.02	4.91 ± 0.03
	O9.5	6.3 ± 0.2	$30\,000 \pm 500$	7.5 ± 0.1	3.48 ± 0.02	4.64 ± 0.03
IU Aur[5]	B0.5	14.5 ± 0.7	$29\,825 \pm 500$	6.2 ± 0.1	4.01 ± 0.03	4.36 ± 0.04
	B0.5	7.3 ± 0.5	$26\,830 \pm 100$	5.7 ± 0.1	3.79 ± 0.04	4.21 ± 0.02

References: 1, 3, Harries, Hilditch & Hill (1997a); 2, Lorenz, Mayer & Drechsel (1994); and 4, 5, Harries, Hilditch & Hill (1997b).

of these results for determining distances to clusters and associations are not clearcut. The Böhm-Vitense (1981) effective-temperature calibration is close to agreement with the stellar models at O5, systematically too hot by 2500 K at O8–O9, and approaching agreement again by B0. That from Chlebowski & Garmany (1991) seems to be systematically too hot, but again not by a constant amount at all spectral subtypes. The mean values of M_V given by Conti et al. (1983) as a function of spectral type each have standard errors $\sim 0.6^{\rm m}$, so we are asking for small-scale systematic shifts of these values of $\sim 1\sigma$ to bring the empirical calibrations of M_V into agreement with the stellar models and the empirical results from eclipsing binaries composed of O+O stars.

2. The Interacting Binaries

Vanbeveren (1995) concludes that *all* massive close binaries (MCBs) will evolve via Roche-lobe overflow (RLOF), assuming that the mass loss in the red-supergiant phase is insufficient to prevent the stellar radius growing during hydrogen-shell burning. According to case-B mass-transfer (when mass exchange occurs post core-hydrogen burning) the initially more massive star (the mass loser) will expand to fill its Roche lobe soon after core-hydrogen exhaustion, and a phase of rapid mass-transfer will ensue, leading to mass-ratio reversal and the mass loser filling its Roche lobe and transferring mass more slowly to the mass gainer. The stripping process that occurs during the rapid mass-transfer phase is thought to result in a low-mass ($\sim 10 M_\odot$) WN star, while the mass gainer is rejuvenated by the additional material and will appear as a main-sequence O star. It is possible that the most massive stars in MCBs ($> 50 M_\odot$) will shed stellar-wind mass during the red-supergiant phase to underfill their Roche lobes throughout evolution to a WR star. In this case the lack of rejuvenation of the mass gainer will mean that it will appear as an evolved object, and the orbit may not have circularized (Vanbeveren 1995).

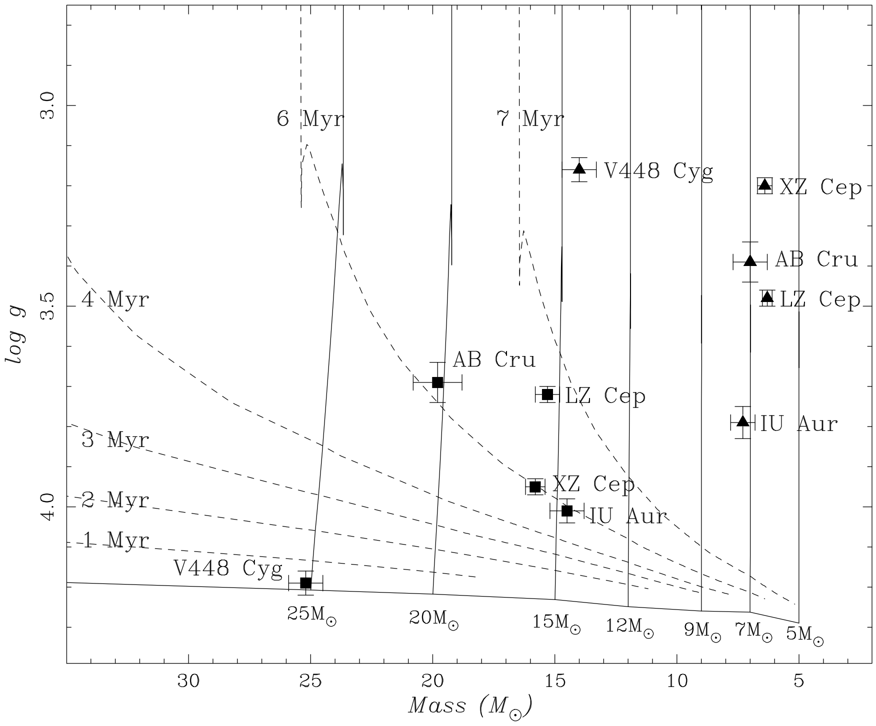

Figure 3. The positions of the primary (squares) and secondary (triangles) components of the semi-detached binaries plotted in the mass–log g plane. The solid lines are the evolutionary tracks from Schaller et al. (1992), while the dashed lines represent isochrones for the same models.

In this section we examine the parameters of semi-detached OB binary stars, and compare them with models of MCB evolution (De Loore & Vanbeveren 1994, hereinafter DLV94). The fundamental parameters of 5 semi-detached systems are listed in Table 3 and are plotted in the mass–log g plane in Fig. 3, along with the single-star evolutionary models by Schaller et al. (1992).

2.1. The Mass Losers

Examining Fig. 3 we see that the mass losers appear as evolved stars, over-luminous for their mass, as expected for Roche-lobe-filling stars. They appear as early-B types, with masses around $7M_{\odot}$, with the exception of the massive system V448 Cyg, which has a secondary of $14M_{\odot}$. The mass gainers (generally late-O spectral type) are closer to the ZAMS, although they lie near the 6–7 Myr isochrones of the Schaller et al. models. (Once again V448 Cyg is exceptional, with the primary lying on the Schaller et al. ZAMS.)

Assuming the observed masses of the secondary stars (the mass losers) are the masses at the end of RLOF we may estimate the initial masses from the

Table 4. The observed masses of the mass loser (M_l) and the mass gainer (M_g), along with the initial mass of the loser (M_{il}) and the gainer (M_{ig}) assuming a mass ratio (q) of 0.6 and 0.9. The mass-conservation parameter, $\beta = \Delta M_g/\Delta M_l$, is also listed for the two values of q. All masses are in solar units.

Object	M_l	M_g	M_{il}	M_{ig}	β	M_{ig}	β
				$q = 0.6$		$q = 0.9$	
V448 Cyg	14.0	25.2	29.2	17.5	0.51	26.3	−0.07
AB Cru	7.0	19.8	15.5	9.3	1.24	14.0	0.68
IU Aur	7.3	14.5	16.1	9.7	0.66	14.5	0.00
XZ Cep	6.4	15.8	14.1	8.5	0.95	12.7	0.40
LZ Cep	6.3	15.3	13.9	8.3	0.92	12.5	0.37

best-fit relation of DLV94:

$$M_f = 1.069 + 0.317M_i + 0.00432M_i^2 \tag{1}$$

where M_f is the observed mass and M_i is the initial mass. We can then assume an initial mass-ratio (0.6 or 0.9 for consistency with the models) and compute the initial mass of gainer and the mass-transfer conservation parameters, β. If we assume the canonical value $\beta = 0.5$, then $q \simeq 0.6$ for V448 Cyg and IU Aur, while $q \sim 0.9$ for AB Cru, XZ Cep, and LZ Cep.

2.2. Models vs. Observations

How do the evolutionary models of DLV94 compare with these OB-binary systems? There are two DLV94 models which approximate to the observations. The first model assumes initial masses of $20M_\odot + 12M_\odot$ with a period of 6.9 d. At the end of RLOF the masses are $7.5M_\odot + 17.8M_\odot$, which is in satisfactory agreement with the masses of AB Cru. The mass gainer in AB Cru has a gravity of 3.69 ± 0.05, whereas the model predicts 3.94. The less massive star is the more luminous in both the model and the observations. A more stringent test of the models is provided by the massive system V448 Cyg, which is a member of the cluster NGC 6871 and has a well-defined age of 7 Myr. The DLV94 model with initial masses of $30M_\odot + 18M_\odot$ best matches this system. The end of RLOF occurs at 6.9 Myr, with final masses of $12M_\odot + 25M_\odot$, in good agreement with the observations (see Table 4). The gravity of the mass gainer in V448 Cyg (4.19 ± 0.03) is in approximate agreement with the model (4.06), although the model temperature (39 000K, corresponding to an O7 spectral type) is far higher than indicated by the spectrum (O9.5).

In both the MCB models discussed above, the mass loser is a Wolf-Rayet star, whereas we observe the stars to have early-B spectral characteristics. Presumably these systems have evolved according to case-A mass transfer, with the primary star filling its Roche lobe while it is still on the main sequence. It is interesting to note that WR+O binaries with similar masses and periods to V448 Cyg, such as WR 42 and WR 153 (Lamontagne et al. 1996), have taken very different evolutionary paths. Case-A computations, particularly a 'tailored' model for V448 Cyg, are urgently required in order to confirm that models of MCBs can produce mass losers with apparently normal spectral signatures.

Acknowledgments. This research was supported by a PPARC postdoctoral research grant.

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Discussion

Langer: It's very unlikely that you'll find any systems in case-B mass transfer, because that phase lasts only a few 10^4 years, while case-A mass transfer lasts for several *million* years.
Hilditch [to Langer]: Yes, but these are semi-detached *post* mass-transfer systems.
Langer: Semi-detached? That means one star fills its Roche lobe, doesn't it?
Hilditch: Yes; the lobe-filling star is the mass loser, and is overluminous for its mass.
Langer: But if it fills its Roche lobe at present then it's still losing mass?
Hilditch: Yes; what I meant was that these systems have already gone through the phase of *rapid* mass transfer.
Crowther: Just a comment on the calibrations you've used: in astronomy we know there's scatter everywhere, and at a given spectral type there's no such thing as a single value for temperature, or M_V, or whatever – you're probably looking at a spread of a few thousand in temperature, or several tenths in M_V, at any spectral type.
Conti: I was a little concerned about fiddling with the temperature scale, but, you know, it could be; but it depends fairly heavily on the spectral types that are assigned to DH Cep, for example. It could be that there's something off in the spectral types you take for a close binary. Does Nolan have anything to say on that? [Looks around.]
Howarth: He stepped out just a moment ago, but if he were here I'm sure he'd point out that there's no such thing as an 'O9.3' star [laughter].
Hilditch: People *say* that there are such things O9.3 stars; we're not spectral-type experts.
Kudritzki: I wouldn't be surprised if the effective-temperature scale had to be revised to slightly cooler values, because all the temperatures we've determined in the past have been from unblanketed non-LTE models. I think a shift by as much as 2000 K is very possible with metal-line blanketing, so if you find this empirically, I think that's okay.
Harries: Sure; and even if you take DH Cephei out of the equation I think the argument that you need to reduce the temperatures at early spectral types still remains valid.
Hubeny: Just a comment that the calibrations you use, of temperature versus spectral type, are based on non-LTE hydrogen/helium models. You can get very different results if you use Kurucz line-blanketed LTE, which give just the reverse effect, an *increase* in inferred temperatures, compared to line-blanketed non-LTE models, which imply *lower* temperatures. This is just the point you're making, of course – that there are differences between the calibrations.