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DETERMINATION OF BASIC PHYSICAL PROPERTIES OF BINARY STARS WITH HOT COMPONENTS

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DETERMINATION OF BASIC PHYSICAL PROPERTIES OF BINARY STARS WITH HOT COMPONENTS

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1 Importance of hot binaries

One can hardly overestimate the importance of understanding the binaries with hot components. A good knowledge of the basic physical properties of hot stars is crucial for further development of the theory of stellar structure and evolution since just for hot stars one observes the phenomena which await a fully self-consistent modelling, like rapid rotation, convection or overshooting. Thanks to their high luminosity, hot stars can also serve to distance estimates: it is clear that once one can adopt the results of their light and radial-velocity (RV hereafter) solutions with confidence, there is no other comparably accurate method to derive the distances to foreign galaxies, for instance.

In this paper, I attempted to summarize briefly the current situation in the research of hot binaries and the level of agreement between theory and observations.

2 Normal well-detached binaries

Thanks to patient effort of many binary-star observers, accurate RV and light curves are now available for several tens of binaries with hot components which are well-detached from their Roche lobes and can be considered to be normal, little evolved main-sequence objects. Summaries of these studies were published by several authors, for example by Popper (1980), Harmanec (1988) and Andersen (1991).

Harmanec (1988) used the absolute elements of all main-sequence objects to derive an empirical functional (polynomial) dependence of stellar masses, radii and bolometric magnitudes on effective temperature. Later, Schaller et al. (1992) calculated a grid of evolutionary models for new OPAL opacities (see Rogers and Iglesias 1992).

In Fig. 1, Harmanec's empirical calibration is compared with fully independent interior modelling. One can see a good agreement, both in radii and masses, the only larger discrepancy being for the most massive objects where Harmanec's calibration depends on only a few observed binaries. Actually, the line showing the empirical dependence runs parallel to, and below the line drawn for the models corresponding to the evolutionary ages about a half way between the zero-age and terminal-age main sequence. Considering Harmanec's empirical selection of main-sequence objects as luminosity class V objects with log $g > 3.9$ [CGS], this is what one would expect.

Schönberner and Harmanec (1995) derived a new M_V calibration for zero-age main sequence and also claimed a very good agreement between empirical and evolutionary masses.

Andersen (1991) and Pols et al. (1997) investigated isochrones for individual well-observed detached systems, calculating stellar evolutionary models specifically for them. They also found a good agreement in the majority of cases. In particular, Pols et al. found a good fit to both stars at a single age and metallicity for 80 % of 49 systems with reliable masses and radii.

However, as pointed out earlier during this meeting by Dr. Yilmaz, the agreement is sometimes achieved only at the cost of either a very large amount

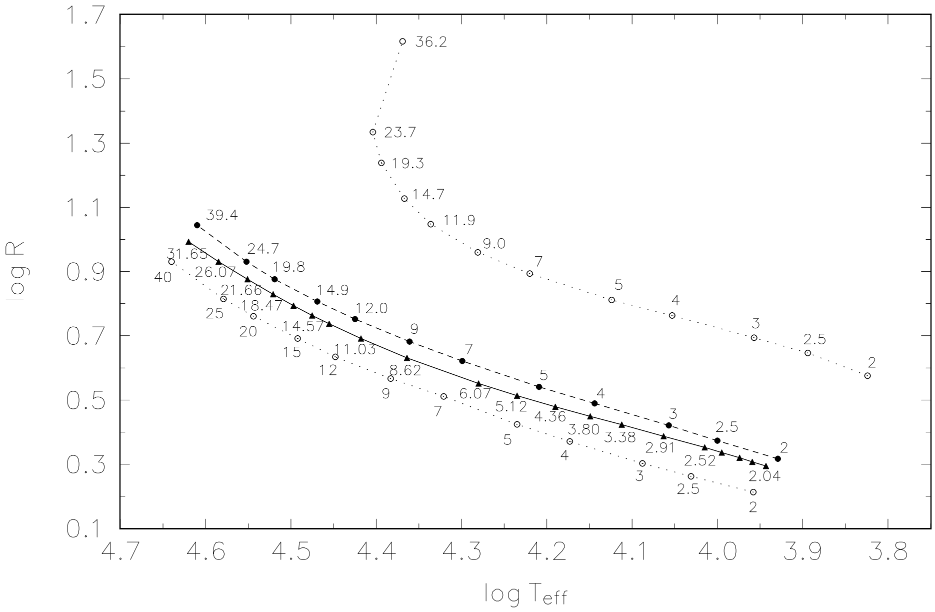

Figure 1: A comparison of stellar radii based on Harmanec's (1988) empirical calibration (triangles connected by a continuous line) and on Schaller's et al. (1992) stellar evolutionary models. Open circles and dotted lines denote the zero-age (models Nos. 1 of Schaller's et al. tables) and terminal-age (models Nos. 11) main sequence while the filled circles and a dashed line denote theoretical models coresponding to about one half of the main-sequence lifetime (models Nos. 4). Masses corresponding to either the empirical calibration or the models are indicated near the corresponding symbols (with only a few omitted in the crowded parts of the diagram). Note that Schaller et al. considered the mass loss via stellar wind which explains the decrease of mass with time for their models of the most massive stars.

of overshooting or for hardly credible chemical compositions.

One can, therefore, conclude, that the agreement between the observations and theory for the detached binaries is very good in the statistical sense but that the detailed comparisons for individual systems indicate that there are a few serious discrepancies which should be taken as a warning that our knowledge may still be incomplete, even for normal, well-behaved binaries.

3 Binaries with circumstellar matter present in the system

Real complications begin when one has to deal with binaries which show clear evidence of circumstellar matter. Their light and RV curves are distorted in several complementary ways and if these distortions are not identified and properly dealt with, one can arrive at grossly incorrect basic physical elements for the binaries in question.

Let us discuss a few most typical cases of such effects:

3.1 False eccentricity of RV curves

Specific structures of the circumstellar matter in a binary system can cause various phase-locked distortions of the observed RVs, thus distorting the shape of the observed RV curve. Let us assume for simplicity that the binary in question has a circular orbit (which indeed is often the case for interacting binaries). Figure 2 shows the RV curves of a binary moving in an eccentric orbit for four values of the longitude of periastron ω. One can see that the RV curves for ω of $0°$ and $180°$ have a sharp peak near the maximum or minimum RV, respectively. In contrast to it, the RV curves for ω of $90°$ and $270°$ have one steep and one slowly rising or declining branch and are characterized by the fact that their segments above and below the systemic velocity γ are mirror images of each other. These facts are useful to realize before one tries to understand different types of the distortions observed.

3.1.1 The Barr effect

The best known of various distortions is the Barr (1908) effect, caused by additional line absorption near the RV maximum, which leads to false ec-

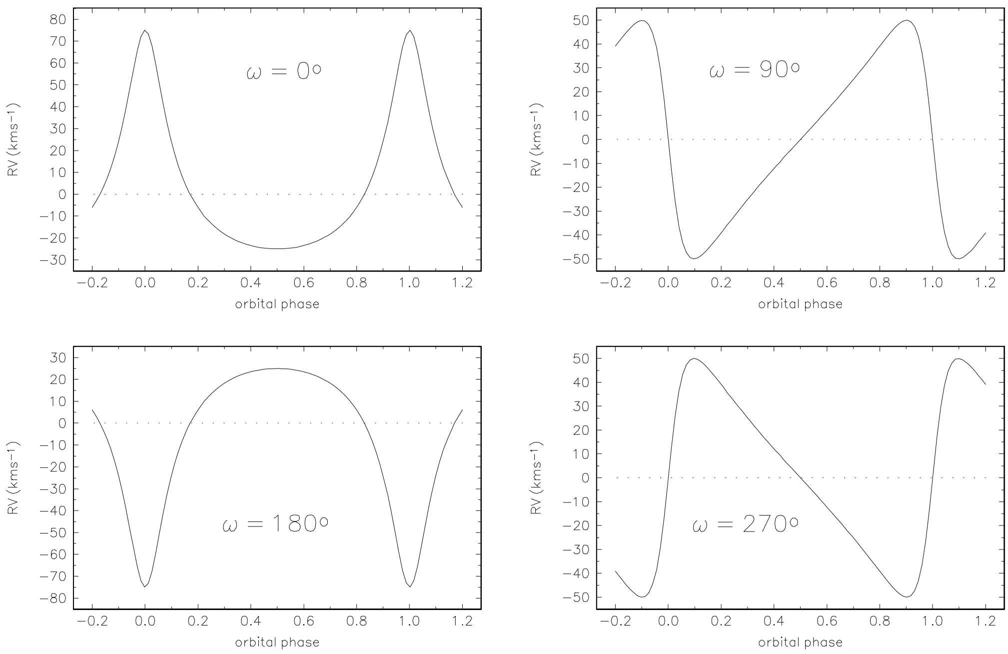

Figure 2: Radial-velocity curves of an eccentric-orbit binary (e=0.5, γ=0) corresponding to four distinct values of the longitude of periastron ω.

centricities with ω values close to 0°. A widely accepted interpretation of this effect was offered by Struve (1944): additional line absorption originates from a gas stream flowing from one star to another which is seen projected against the disk of mass gaining star at a certain interval of orbital phases. As illustrated by Fig. 3, the projection must be observed somewhere between the elongation with the mass-gaining star receding from us, and the conjunction (direction A in the diagram). Since the gas moves away from the observer at this interval of phases, its RV is increasing the observed RV of the mass-gaining star and the result is a RV curve with a sharp peak near or after the RV maximum which is formally reminiscent of a RV curve of a star in eccentric orbit with ω near to 0°. It is clear that the phase where the maximum absorption, and the maximum RV occurs, depends also on the orbital inclination; for non-eclipsing systems one expects the largest effect exactly at elongation when the mass-gaining star is receding from us.

While Struve's explanation is almost certainly the correct one for mass-exchanging eclipsing binaries like U Cep, one cannot be so sure for some other systems where the amplitude of the distortion amounts to only a few

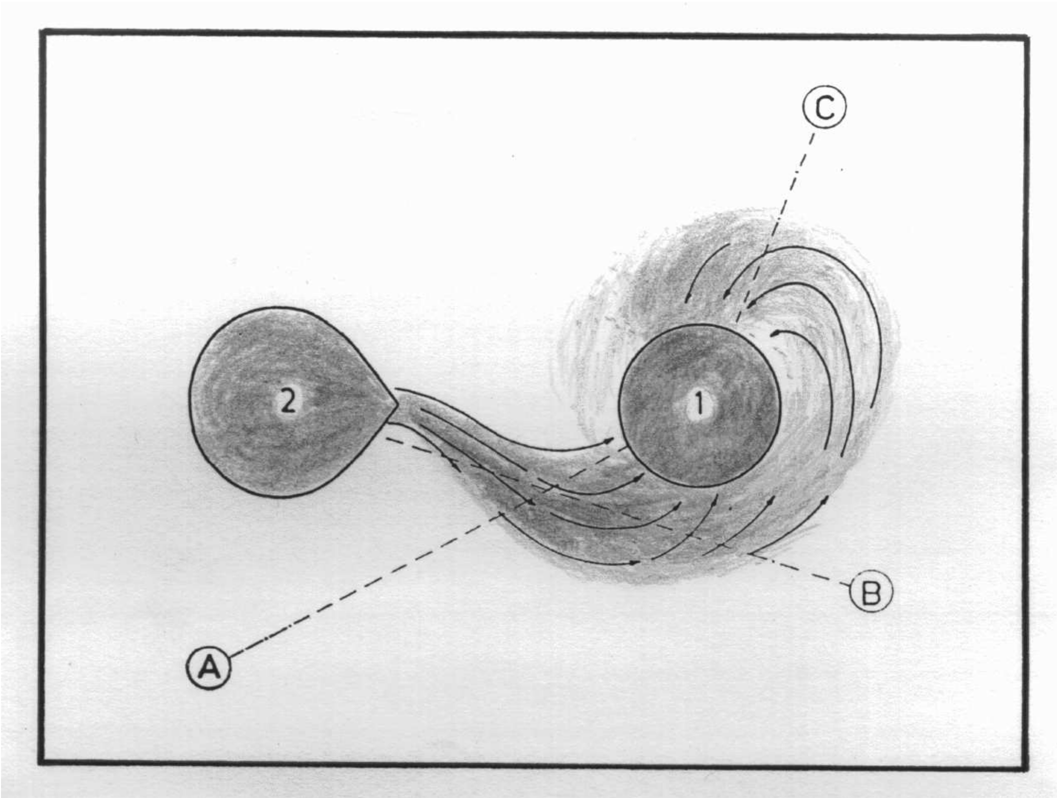

Figure 3: A schematic diagram of a binary with gas streams and an envelope.

$\mathrm{km\,s^{-1}}$. Why if the typical gas stream velocities are of the order of several hundreds of $\mathrm{km\,s^{-1}}$?

Kříž and Harmanec (1975) pointed out that there is often an additional hump in the velocity curves affected by the Barr effect, visible near minimum RV. They interperted it as a projection of the same stream as it encircles the mass-gaining star and slows down, therefore attaining higher densities - see Fig. 3, direction C.

3.1.2 An effect complementary to the Barr effect

Kříž and Harmanec (1975) also suggested that in mass-exchanging binaries in which the *mass-losing* component is the brighter of the two, one should observe a projection of the gas stream against the disk of the mass-losing star – see Fig. 3, direction B. They claimed this should lead to RV curves with false eccentricities having ω of 180° - 220°. I carried out a numerical simulation of such distortions to find out that it actually leads to RV curves with ω of about 140°.

3.1.3 Effects of tidal distortion

It was pointed out already by Sterne (1941) that the difference between the optical and mass centre of gravity for tidally distorted stars must lead to a deformation of the RV curve which manifest itself by a false eccentricity with values of ω close to either 90° or 270°.

Harmanec (2001) pointed out that *any disturbance* of the RV curve which is *symmetric with respect to the line joining the binary components*, must produce such false eccentricities with ω close to either 90° or 270°. This is so due to the characteristic shape of RV curves with ω of 90° or 270°, as discussed above. A good example of physical effect leading to this kind of RV-curve disturbance is focused stellar wind of early-type stars that are close to filling their Roche lobes.

3.2 Incorrect semi-amplitude of the RV curve

Another possible consequence of circumstellar matter within the binary system is that one obtains an incorrect value of the semi-amplitude of the RV curve of the component embedded in gaseous structures. This can again be caused by several effects.

3.2.1 Effects of gas-stream projection

One obvious cause is related to the Barr effect and similar effects discussed above which usually tend to increase the true semi-amplitude of RV curves. If correctly recognized, such a problem can, in principle, be overcome, e.g. by using spectra with a good resolution and setting on line wings. Another simple solution is to derive the RV amplitude from a part of RV data, omitting velocities from the phase interval where the gas projection against the disk of the respective star occurs. This technique was successfully aplied by, e.g., Hill et al. (1997).

In cases when the distortion of a RV curve by gaseous structures is so large that reliable RV measurements are not possible, one can use another method for semi-detached binaries. It can be assumed that the rotation of the Roche-lobe filling star is synchronised with orbital revolution. If so, one can use the observed rotational velocity and the binary orbital period to the determination of the radius of the Roche-lobe filling star in any absolute units. The RV curve of the Roche-lobe filling secondary is usually a well-defined one and one can derive the mass function from it. Adopting some trial value of the mass of the Roche-lobe filling star, one derives the mass ratio, therefore the mass of the other star, from the mass function. The binary separation then follows from the third Kepler law. The relative radius of the Roche lobe in units of binary separation is a function of the mass ratio only. One can compare the absolute radius with the radius of the Roche lobe and if they differ for more than the accuracy of the observations, a new trial value of the mass of the Roche-lobe filling star is chosen and the whole iterative process is repeated.

Such a technique was applied by Andersen et al. (1988, 1989) to the determination of basic physical properties of SX Cas and RX Cas or by Harmanec (1990) to the estimate of the correct mass ratio of β Lyr. In the appendix to Harmanec's paper, the above procedure of a fast iterative solution is described in detail.

3.2.2 Incorrect RV amplitude due to the V/R variations of emission lines from a circumstellar disk

It has been well established that in binaries with an emission-line component one observes a phase-locked V/R variations of the violet and red peaks of double-peaked Balmer (and other) emission lines. These variations are practically in phase with the respective RV curves of emission-line binary components – see, e.g. Peters (1972), Harmanec et al. (1976), Doazan et al. (1982) or Harmanec et al. (2002).

As recently pointed out by Harmanec et al. (2002), the presence of a weak and barely visible emission in the He I absorption lines, combined with the phase-locked V/R variations mentioned above, can actually lead to *overestimation* of the true orbital velocity amplitude if the RV curve is derived for such lines. The effect is visualized in Fig. 4: At RV maximum, the V/R ratio is larger than 1, therefore the blue wing of the seemingly absorption line is partly filled by emission and its position is shifted to the red. Setting on the wings of the absorption line thus gives a RV which is *more positive* than what would correspond to the true orbital RV. Just the opposite effect occurs a half of period later.

A possible solution to this problem was suggested and tentatively applied by Božić et al. (1995) in the case of φ Per = HD 10516, and by Harmanec et

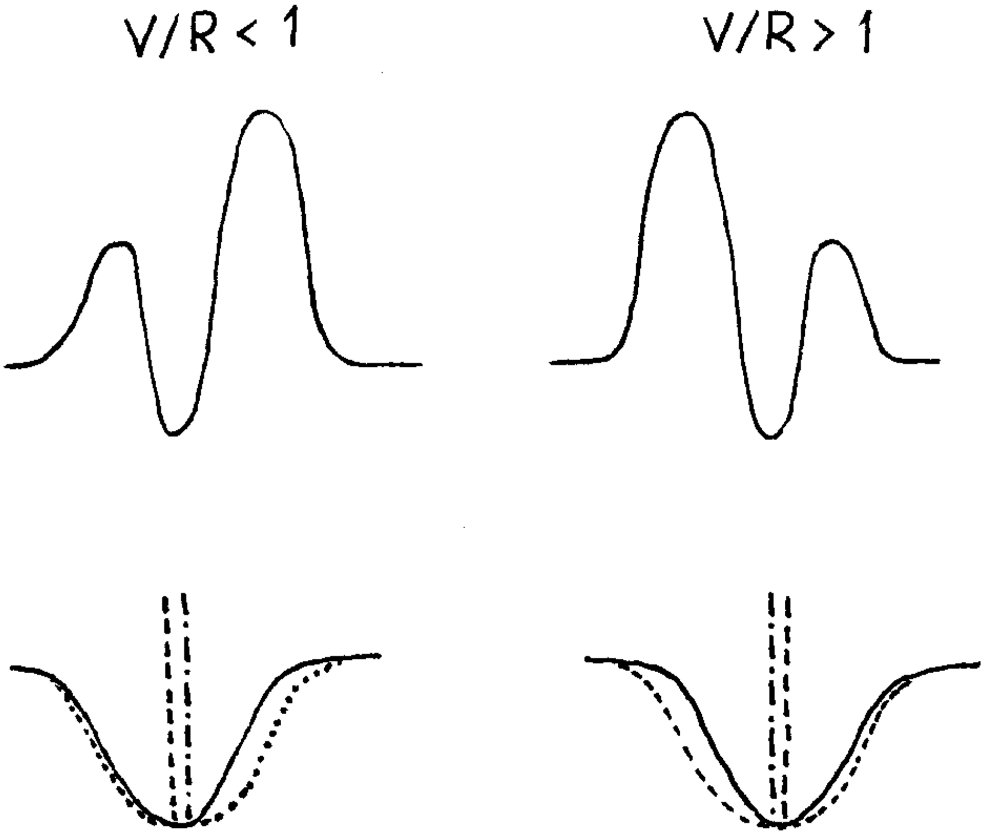

Figure 4: An illustration of the effect of phase-locked V/R changes on the measured RV of He I absorption lines: Upper panels show a Balmer emission profile at two elongations of the binary while the bottom panels show a He I absorption profile, only weakly filled by emission in the outer wings. Since the phase-locked V/R and RV variations occur essentially in phase with each other, the red wing of the He I absorption is more filled by emission than the blue one when $V/R < 1$ and vice versa. The observed He I profile (full line), still appearing as an absoprtion line, is therefore shifted to the blue when $V/R < 1$, and to the red when $V/R > 1$, with respect to the actual position of the true He I absorption profile (dashed line). This increases the observed amplitude of the RV curve with respect to the orbital one.

Table 1: A comparison of the semi-amplitudes of RV curves of several Be binaries, measured on the outer wings of the Balmer emission lines, and on the wings of He I absorption lines.

Binary	HD	$P_{\rm orb.}$ (d)	$K_{\rm emis.}$ ($\rm km\,s^{-1}$)	$K_{\rm abs.}$ ($\rm km\,s^{-1}$)	Source
γ Cas	5394	$203\fd6$	4.7	7.0	Harmanec et al. (2000)
φ Per	10516	$126\fd7$	10.4	21.0	Božić et al. (1995)
κ Dra	109387	$61\fd6$	2.3	6.8	Juza et al. (1991)
V839 Her	142926	$46\fd2$	4.8	8.0	Koubský et al. (1997)
V832 Cyg	200120	$28\fd2$	13.0	27.2	Rivinius and Štefl (2000), Harmanec et al. (2002)
V1931 Cyg	200310	$146\fd6$	10.8	8.4$\pm$5.3	Koubský et al. (2000)

al. (2000, 2002) who studied γ Cas = HD 5394 and V832 Cyg = HD 200120, respectively. The idea is the following: Is seems very probable that the rotational velocity of any real circumstellar disk is decreasing with the increasing distance from the central star. One can also assume that due to the properties of equipotential surfaces of the Roche model, the inner parts of such disks will be nearly axially symmetric and will reflect the true orbital motion of the cetral star quite well. Due to the above-mentioned distribution of the rotational velocity within the disk, it is clear that the possible asymmetries of the outer parts of the disk will mainly affect the central parts of the emission-line profiles (including the observed V/R changes) while the more symmetric inner parts of the disk will mainly contribute to the outer wings of the emission lines. Božić et al. (1995) and Harmanec et al. (2000, 2002) indeed found that RV curve based on the outer wings of the double Balmer emission lines is well-defined and gives an amplitude smaller than that of the absorption lines.

I attempted to collect data for all cases of emission-line binaries for which similar RV measurements are available. They are summarized in Table 1.

One can see that (with the exception of an uncertain case of V1931 Cyg), the amplitudes of the RV curves, based on the emission-line wings, are al-ways smaller than the amplitudes of the corresponding RV curves derived from absorption lines. This seems to confirm the presence of the effect in real emission-line binaries, whatever the true cause of the phase-locked V/R variations is.

3.2.3 Incorrect RV amplitudes due to low resolution and/or line blending

The problems of low resolution for fainter objects, and of severe line blending in binaries with similar spectral types and with fast rotating components, are in fact common to all hot binaries, no matter whether a significant amount of circumstellar matter is present within the system or not.

The need for a good spectral resolution to derive reliable binary masses has often been reminded by Popper – cf., e.g., Popper (1967, 1971, 1980). For a long time, students of binaries have also been aware of the fact that RVs of Balmer lines are not suitable to the determination of accurate masses for hot stars in binaries - cf., e.g., Andersen (1991).

There are many early-type binaries with two components of very similar spectral types (although not necessarily of identical v sin i) and the line blending for some of them can indeed be severe, even preventing the discovery of the binary nature from spectroscopy in some cases. Perhaps the most extreme known case is V436 Per = 1 Per which was considered to be a physical variable for a long time until it was idetified as a $25\overset{\mathrm{d}}{.}9$ binary in an eccentric orbit. Figure 5 is a comparison of the RV curve, measured from the spectra of V436 Per in a classical way, with the true RV curves derived via KOREL spectral disentangling (Hadrava 1995) and via cross-correlation (Hill 1993, Hill and Holmgren 1995) by Harmanec et al. (1997). One can see that the classical RV measurement leads to a RV amplitude of some 10 $\mathrm{km\,s^{-1}}$ only (and, therefore, to an unbelievable mass function) while the true semi-amplitudes of both heavily blended binary components are close to 100 $\mathrm{km\,s^{-1}}$, an order of magnitude higher, and lead to normal binary masses.

3.2.4 Incorrect RV amplitudes due to a circumbinary envelope

In cases when there is an envelope around the whole system, it is possible that the shell absorption lines from such an envelope, projected against the disk of one of the stars, will also exhibit phase-dependent RV variations.

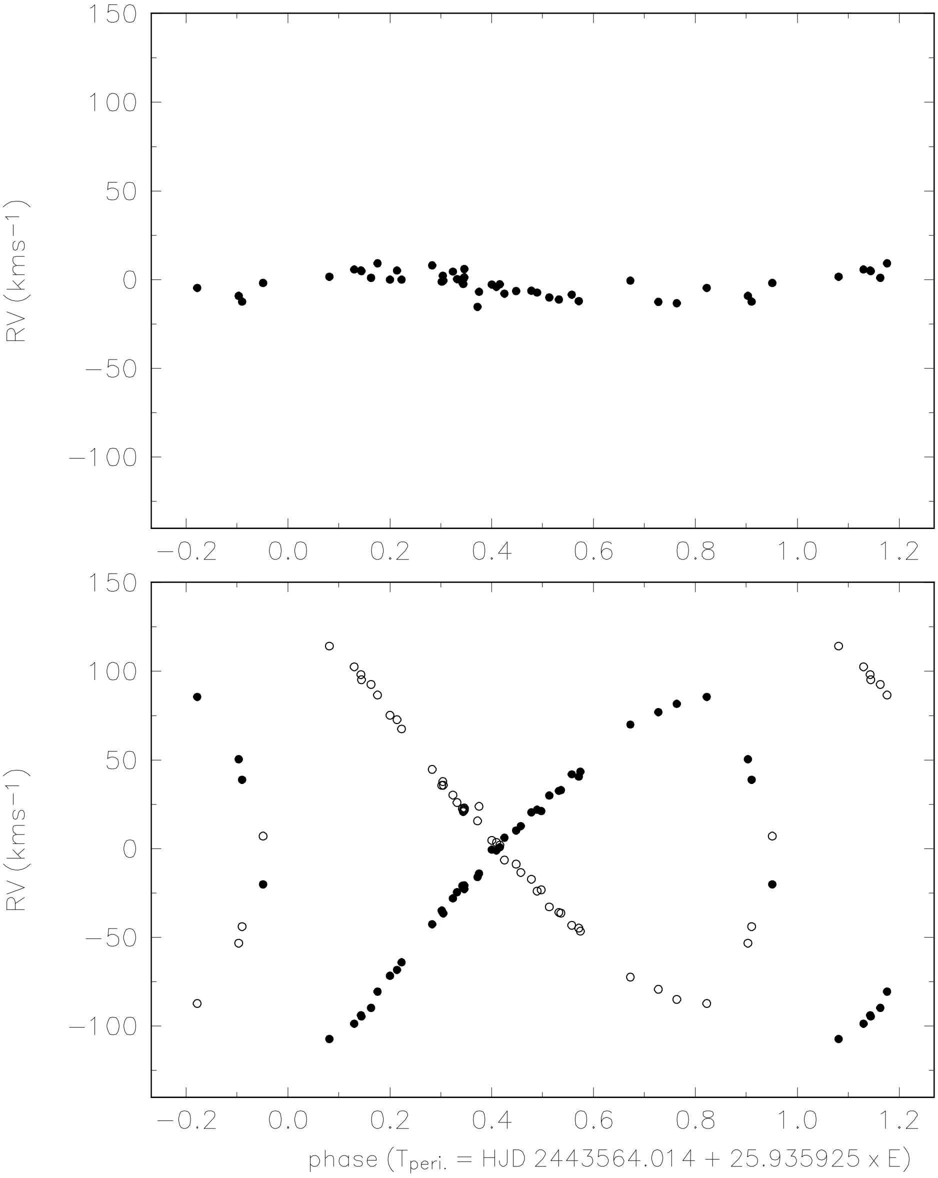

Figure 5: A comparison of the RV curve of the eclipsing binary V436 Per based on the classical RV measurement (upper panel) and on KOREL disentangling (bottom panel; the primary is shown by filled, and the secondary by open circles).

However, their amplitude will be strongly reduced with respect to the true orbital RV curve of the respective star. A quantitative discussion of this effect can be found in Kříž and Harmanec (1975).

3.3 Effects of the disk on the observed light curves

It is clear that in cases of eclipsing binaries with large and opaque disks around one of the components, the shape of the light curve must be strongly affected by the presence of the disk and that a standard solution of the light curve cannot give correct radii of the stars. This problem was first realized for the famous intracting binary β Lyr (see Harmanec 2002 for the most recent review of 200 years of investigation of β Lyr and for details of the whole story).

The first quantitative model of β Lyr light curve in which the disk was modelled as a rotationally flattened body was published by Wilson (1974). He clearly demonstrated how the radiation from the hot star inside the disk is redistributed away from the orbital plane and pointed out the need to distinguish properly between the observed flux at given direction and the stellar luminosity. Later, Zola (1991, 1995) modified the standard Wilson-Devinney program (Wilson and Devinney 1971) to include modelling of a disk.

Perhaps the best currently available set of programs for modelling the light curves *and continuum energy distribution* of binaries with opaque disks is the BINSYN suite by Linnell and Hubeny (1996). The modelling is based on Roche geometry and the 1996 version of BINSYN includes a self-consistent model of *an accretion* disk, the radiation of which is fully powered by the accretion. This last fact would somewhat limit the applicability of the model to hot binaries with opaque disks, however. It is very probable that such disks acquire a significant part of their radiation by reprocessing the radiation of the stars inside the disks. Unfortunately, the very complicated problem of the radiative transfer in such disks has not yet been solved. That is why Linnel (2000) added another option to a more recent version of BINSYN which allows to assign the values of effective temperature of the disk face empirically, by an external table of values.

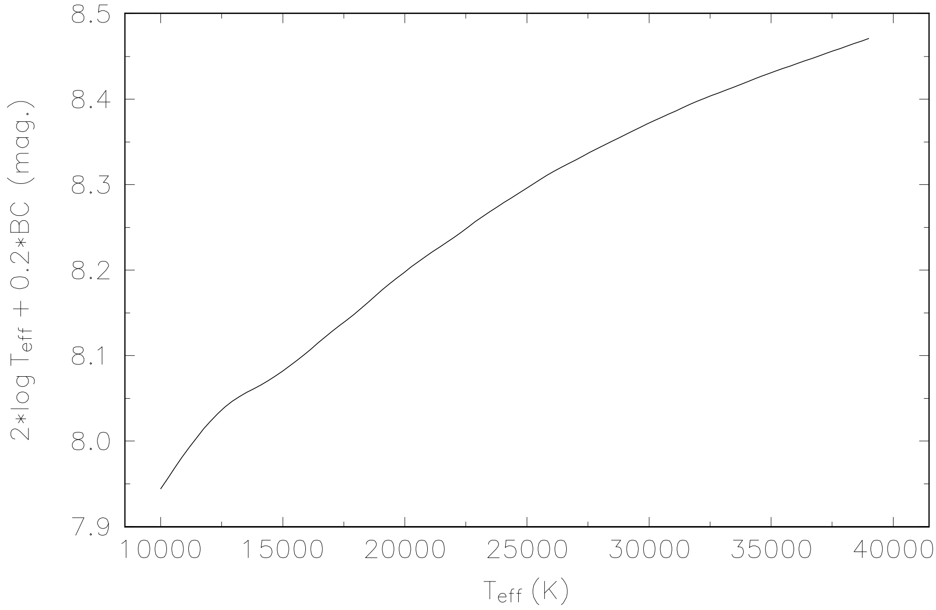

Figure 6: A plot of the function $2 \log T_{\rm eff} + 0.2BC$ vs. effective temperature $T_{\rm eff}$ for hot stars. The bolometric corrections were obtained by a linear interpolation in $\log T_{\rm eff}$ in the table of empirical bolometric corrections published by Code et al. (1976).

3.4 What can help us?

As I pointed out in a recent review of basic physical properties of emission-line stars (Harmanec 2000), one can now profit from the availability of accurate Hipparcos parallaxes for brighter stars (Perryman et al. 1997). In cases where it is possible to obtain a good estimate of visual brightness, one can use it and the parallax to an independent estimate of the stellar radius, both for single stars and binary components. Naturally, this technique is particularly suitable for objects in clusters where one can apply a more accurate mean parallax of the cluster.

Combining the definition of the effective temperature $T_{\rm eff}$

$$M_{\rm bol} = 42.368 - 5 \log(R/R_{\odot}) - 10 \log T_{\rm eff} \tag{1}$$

with the distance modulus and bolometric correction BC

$$V_0 - M_{\rm V} = -5 \log \pi - 5, \tag{2}$$

one gets a working equation

$$\log(R/R_{\odot}) = 7.474 - 2\log T_{\rm eff} - 0.2 \cdot (BC - V + A_{\rm V}) - \log \pi. \tag{3}$$

Note the fortunate circumstance that the function $2\log T_{\rm eff} + 0.2BC$ is varying quite slowly for the hot stars – see Fig. 6. This implies that even for an approximate estimate of $T_{\rm eff}$ one obtains a rather accurate value of the radius provided the visual magnitude V, reddening $A_{\rm V}$ and parallax π are known with a good accuracy.

For stars for which angular diameters θ, corrected for limb darkening, were derived with interferometers, one can obtain another estimate of stellar linear radii using the relation

$$(R/R_{\odot}) = 107.47\frac{\theta}{\pi}. \tag{4}$$

As I have demonstrated recently, the comparison of both methods leads to a very satisfactory agreement for emission-line stars – see Harmanec (2000).

According to Harmanec (1983, 1994, 2000), there are two distinct types of brightness and colour changes of emission-line stars, related to the changes in their emission-line strength: positive or inverse correlation. A proper choice of the V magnitude to be used in equation (3) is, therefore, a delicate task which requires some knowledge of the recorded observational history of the object in question. To obtain a correct value of the radius, one has to use the V magnitude and reddening $A_{\rm V}$ from a phase when the star was without emission.[1] These may not be easy to obtain in particular cases since, for instance, the well-known bright Be binary γ Cas, studied spectroscopically for about 150 years, was observed to be without emission for only a few months at the dawn of the World War II. Note that the problem is in a sense similar to modelling the star spots in RS CVn and similar stars where one needs to know the brightness of the star without the spots.

[1] As suggested by Harmanec (1983) and confirmed by consecutive studies, the existence of the two types of correlaton is essentially an aspect effect, the inverse correlation being observed only for stars seen roughly equator-on. This implies that most Be stars exhibit a positive correlation between the emission-line strength and brightness. This fact is the reason behind an often repeated incorrect statement that the Be stars are brighter than normal B stars of the same spectral subclass (cf., e.g., Bidelman 1947, Schmidt-Kaler 1964, or a recent paper by Wegner 2000).

Table 2: A comparison of masses and radii of emission-line components of two eclipsing binaries, obtained from the orbital and light-curve solutions, with the radii $R_1^{\rm Hip}$, derived from their Hipparcos parallax and V magnitude corrected for the contribution of the secondary (the range of possible values, given by the parallax uncertainty, is in brackets).

Binary	HD	$\log T_{\rm eff}$	M_1 ($M_\odot$)	R_1 ($R_\odot$)	$R_1^{\rm Hip}$ ($R_\odot$)
U Cep	5679	4.112	4.21	2.69	2.59 (2.33–2.91)
V360 Lac	216200	4.280	6.5	6.4–8.8	6.32(5.06–8.43)

Harmanec (2000) listed masses and radii for several known emission-line eclipsing binaries, reasonably well derived from the light-curve and orbital solutions. For two of these binaries I was also able to estimate the radii of their emission-line primaries using the above method of radius determination. The results are summarized in Table 2. One can see that the results agree within the limits of the quoted errors.

3.5 A test case: φ Per

Besides the applications already discussed above, it may be useful to investigate the above-mentioned effects for a well-observed binary system with circumstellar matter to see whether one can arrive at reliable basic physical properties for such complicated cases.

One of the most systematically studied emission-line binaries is the bright star φ Per, a B0.5e + sdO system with an orbital period of $126\overset{\rm d}{.}7$. For a long time, only the RV curve of the primary was observed. It was Poeckert (1981) who discovered a weak He II 4686 emission line moving in antiphase to the lines of the B0.5 star. He also showed that narrower secondary absorptions in some He I lines follow the orbital motion of the secondary. Gies et al. (1993) reported the discovery of a faint double emission in the core of the He I 6678 absorption line which also showed RV variation in antiphase to the RV curve of the primary. They concluded that one emission component originates from a disk around the secondary while the other is from a gas stream flowing

Table 3: Observed semi-amplitudes of the orbital RV curves of the two binary components of φ Per as derived from various spectral lines. Unless otherwise stated the data come from the paper by Božić et al. (1995)

K_1 ($\mathrm{km\,s^{-1}}$)	line/source
21 ± 2	broad He I absorptions
15 ± 2	broad Balmer-line absorptions
12.1 ± 0.8	broad H8-H11 lines; Poeckert (1981)
10.4 ± 0.7	steep Balmer-line emission wings
9.8 ± 0.8	far-UV absorption lines of the B0.5e star; Gies et al. (1998)
K_2 ($\mathrm{km\,s^{-1}}$)	line/source
98.0 ± 2.4	He I absorptions
104.4 ± 7.0	He II 4686 emission; Poeckert (1981)
88.3 ± 1.7	He I 6678 emission; Gies et al. (1993)
100.8 ± 6.2	He I 6678 emission wings
81.3 ± 0.6	sharp Fe V, Cr V far-UV absorptions; Gies et al. (1998)

toward the primary. Božić et al. (1995) obtained new He I 6678 spectra and interpreted the He I 6678 emission as a double-peaked emission from the disk around the secondary and derived its RV curve, based on the outer wings of the emission line.

Gies et al. (1998) obtained a few observations of the binary with the high-resolution spectrograph on board of the Hubble Space Telescope and measured RVs of numerous narrow absorption lines of Fe V, Cr V and other high-ionization lines to derive the orbital RV curve of the secondary. They concluded from line-profile modelling that the secondary is a slowly rotating O VI star with an effective temperature of (53000 ± 5000) K. They also derived a new RV curve of the primary from these far-UV spectra.

The association of the He I 6678 emission with a disk around the subdwarf secondary was challenged by Hummel and Štefl (2001) who argued that this

Table 4: Various estimates of the masses of binary components of φ Per.

$M_1 \sin^3 i$ ($M_\odot$)	$M_2 \sin^3 i$ ($M_\odot$)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	Reference
14.3	7.8			Hendry (1976)
–	–	20	4	Suzuki (1979)
21.1	3.4	21 ± 5.6	3.4 ± 0.8	Poeckert (1981)
16.35	1.69	16.4–21.8	1.7–2.2	Božić et al. (1995)
8.91 ± 0.26	1.09 ± 0.09	9.3 ± 0.3	1.14 ± 0.04	Gies et al. (1998)

line is in fact originating from a segment of the disk around the Be primary, facing the secondary. They calculated line profiles for such a model and found a satisfactory agreement with the observed profiles. I note that there is another fact which seems to speak in favour of their interpretation: If the He I 6678 emission would be a double emission from the disk around the secondary, its phase-locked V/R variations should also be in anti-phase with respect to the V/R variations of the Balmer emission lines from the Be-star disk. In fact, the observed V/R variations of the He I 6678 line are *in phase* with those for the Balmer lines, confirming the origin of the He emission in the disk around the primary. The same behaviour was also found for another Be binary, V832 Cyg, by Harmanec et al. (2002).

Various determinations of the velocity amplitudes of both binary components are summarized in Table 3. To illustrate the effect of the proper choice of velocity amplitudes on the binary masses, I summarize in Table 4 a few independent determinations of the masses of binary components of φ Per. From what was said above, it seems appropriate to adopt $K_1 = 10.4\ \mathrm{km\,s^{-1}}$, based on the wings of the Balmer emission lines after Božić et al. (1995), and $K_2 = 81.3\ \mathrm{km\,s^{-1}}$, derived from the far-UV sharp absorption lines of the secondary by Gies et al. (1998), to the best estimate of the binary masses. One obtains

$$M_1 \sin^3 i = 8.6 M_\odot \quad (5)$$
$$M_2 \sin^3 i = 1.1 M_\odot. \quad (6)$$

Analyzing numerous UBV observations, Božić et al. (1995) arrived at

$E(B-V)$=0$^{\rm m}_{.}$14 which agrees well with an independent determination by Beeckmans and Delplace (1980), based on the UV iron bump and on the galactic position of the star, and at $T_{\rm eff}$ = 27000 K. In combination with the Hipparcos parallax, equation (3) implies

$$R_1 = 5.65(4.85 - 6.76)R_\odot.$$

A normal mass and radius of a star with $T_{\rm eff}$ = 27000 K after Harmanec (1988) are

$$M_1 = 11.68M_\odot \text{ and } R_1 = 5.08R_\odot.$$

Taking the most probable value of the radius from the Hipparcos parallax and these nominal values literally, one would conclude that the inclination of the rotational axis of the primary (assumed to be identical with the orbital inclination) is $i = 65°$ and the Be star is rotating at, or close to break-up velocity.

From the fact that no eclipses were observed and from the resolution of the Be-star disk via interferometry (Božić et al. 1995, Quirrenbach et al. 1997), one can conlude that

$$88° > i > 63°.$$

With the data at hand, this simple analysis therefore leads to an internally consistent picture but it is clear that the associated errors of all important input values still allow a rather large range of the basic physical properties.

4 Future prospects

It is my belief that we are all living in the exciting period when new observational possibilities, especially large optical interferometers, will soon help us to unravel many of the secrets of our beloved binaries. We have to be prepared, however. The experience shows that the correct interpretation of the new, and probably very exciting results, will only be posible if our collective patient effort (systematic spectral, photometric and polarimetric observations and careful analyses), continues with the same intensity as before.

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