Hot emission-line stars after 134 years of study

A personal view of current problems

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A brief review of current problems in the research of hot emission-line stars is presented. Special attention is paid to problems of reliable determination of basic physical properties of underlying stars and to possible role of duplicity in the whole phenomenon. A preliminary catalogue of OBA emission-line stars in binaries is also included.

Keywords: hot emission-line (OBAe) stars – binaries – spectral and light changes

1 Introduction

Similarly as many other types of stars, emission-line stars has been defined phenomenologically. Their defining property is the presence of Balmer emission, observed at least once during their documented history. The first distinct group of hot emission-line stars were Be stars, i.e. emission-line stars of spectral class B. In more recent literature, one can also find the term *classical Be stars* which is reserved for Be stars of luminosity classes III to V only. Since a reliable determination of the luminosity class for such objects is all but easy, I personally tend to avoid this restrictive definition.

The Balmer emission has also been observed for some cooler and hotter stars than those of spectral class B. Nowadays, a number of Oe and Ae stars is known – see, e.g., Frost & Conti (1976) and Andrillat et al. (1983).

The story of Be stars began when Secchi (1867a, 1867b) published his 1866 observations of stellar spectra with a visual spectroscope and reported the discovery of the Hβ emission for the first two B stars, β Lyr and γ Cas. Wavelength-calibrated photographic spectra became available in the last decade of the nineteenth century and soon led to discoveries of several distinct types of spectral variables. Now, at the end of twentieth century, we believe we know the principal causes of the variability of almost all known types of variables. We distinguish several types of pulsating stars, oblique rotators which vary due to uneven brightness and/or chemical composition on their surfaces, eclipsing and ellipsoidal variables and eruptive variables, among others. However, the very nature of the Be phenomenon and at least some of the observed variations of Be stars still remain a puzzle.

This short review has no ambition to provide a complete and exhausting summary of the current knowledge of amazing and complex Be phenomenon but rather to offer a few thoughts and personal reflections of the problem. The readers interested to obtain a deeper insight into the subject and its various aspects are referred to proceedings from three most recent large international conferences – see Smith et al. (2000), Balona et al. (1994) and Slettebak & Snow (1987).

2 Current knowledge and open problems

2.1 Well established facts

The whole phenomenon of occasional presence of emission lines in the spectra of O, B and A stars is clearly a very complex one and one could certainly write a very thick book to describe the existing knowledge properly. Here, I took the risk to summarize the knowledge about hot emission-line stars into only a few principal items:

- Students of Be stars agree that most of the observed emission originates in extended envelopes, which are probably flattened towards the stellar equator and at least an order of magnitude larger than the underlying stars. There is growing evidence that a part of the emission may be related to the stellar wind for O and early B stars and to other parts of circumstellar environment for the OBAe stars in binaries.
- A characteristic property of OBAe stars is their

spectral, light and polarimetric variability, often unpredictable, which occurs on several distinct timescales - see, e.g., Harmanec (1983) for an early review. Especially pronounced are the long-term B $\Longrightarrow$Be $\Longrightarrow$Be shell a vice versa transitions. Emission lines, present not only in the Balmer but also in helium and many metallic lines, can disappear completely and the Be star is then indistinguishable from a normal B star. These long-term variations are also seen in photometry and polarimetry. There are variations on a time scale of weeks to months which are either scaled down events similar to long-term changes or events related to the binary nature of particular OBAe stars. Finally, there are rapid variations which occur on a time scale roughly comparable to the expected stellar rotation period.

- It seems that several observed characteristics of OBAe stars are related to their rotation and to the aspect effect under which one observes the star in question. Majority of underlying stars are rapid rotators and there are reasons to believe that those for which a low v sin i is observed are also rapid rotators but seen nearly pole-on. Two distinct types of correlation between the long-term spectral, light and colour changes, a positive correlation and an inverse correlation, have also been interpreted as due to aspect effect of a flattened inner and optically thick part of the envelope, a *pseudophotosphere*, by Harmanec (1983, 1994, 2000). According to him, the inverse correlation corresponds to stars observed roughly equator-on. Interpretation in terms of a pseudophotosphere has also been used successfully by Koubský et al. (1997) to the interpretation of the observed spectral changes of the B7e star V839 Her = 4 Her. It also agrees with the finding by Hubert & Floquet (1998) who found from the Hipparcos light curves that the inverse correlation is preferentially observed for stars with higher v sin i. Also the long-term variations observed for Be stars in binaries for which one has some idea about the orbital inclination fit into this scheme. Finally, the geometrical interpretation of the two types of correlation is also supported by the fact that any given Be star shows always the same type of long-term behaviour – either brightenings or fadings. Another aspect effect has also first been noted by Harmanec (1983) and later confirmed on a larger sample by Grady et al. (1987), namely that the narrow absorption components of satellite UV resonance lines are only seen for Be stars with v sin i > 150 km s^{-1}.

2.2 Principal unsolved problems

In spite of all effort, there is no generally accepted solution to the following open problems:

- What physical mechanism is responsible for a rather frequent formation and dispersal of Be envelopes? The original model of the envelope formation via rotational instability near the equator by Struve (1931) does not explain the time variability. Besides, several authors argued that the rotation of Be stars is below break-up – see Porter (1996) for the most recent study on this issue. The interpretation of Be envelopes as accretion disks is probably the correct one for Be stars in interacting binaries but it cannot be accepted universally, as discussed below. Also the promising compressed-wind model of the formation of Be-star disks by Bjorkman & Cassinelli (1993) seems to have serious problems to create dense enough disks and to explain the variability patterns observed – cf., e.g., Bjorkman (2000).

- There is also no universal agreement on the nature of some of the types of variations observed:

  i. The long-term cyclic V/R variations of the relative intensity of the violet and red peaks of the emission lines were first interpreted by Struve (1931) as due to a slow revolution of an elongated envelope. Kříž & Harmanec (1975) and Harmanec & Kříž (1976) suggested that the formation of such an envelope and its subsequent revolution can be caused by the presence of a mass-losing secondary in a binary system. They demonstrated a good quantitative agreement for the Be binary ζ Tau. However, searches for a Roche-lobe filling secondary to ζ Tau ended with negative results so one would have to seek another mechanism of mass trasfer to defend their interpretation. Kato (1983) and Okazaki (1991) developed a model of one-armed oscillation to explain the V/R changes and their model is quoted and adopted in several recent studies. I have always had some problems to understand the geometrical difference between their model and the elongated disk model. Actually, Okazaki himself writes: *"Note that the elongated disk model ... is regarded as being a geometrical version of the hydrodynamical one-armed oscillation model."* Whatever model will finally be adopted as the correct one, it is encouraging to note that gradual changes of spatial orientation of elongated Be envelopes have become observable (so far for ζ Tau and γ Cas) thanks to the systematic effort of the GI2T group in France – see Vakili et al. (1998) and Berio et al. (1999).

ii. For some time after the discovery of additional variable absorptions in the UV resonance lines (often called narrow absorption components, already mentioned above), their investigators interpreted them as blobs of material outflowing from the stars via inhomogeneous stellar wind – see, e.g., Henrichs et al. (1983) or Howarth & Prinja (1989). Bates & Halliwell (1986), Prinja (1988) and Harmanec (1987a, 1989) suggested that they could also be created via local outflow from the stellar equator of rotating stars or from the L_2 Lagrangian point in revolving binaries and this idea has later been developed by, e.g., Harmanec (1991), Owocki et al. (1995) and Cranmer & Owocki (1996). However, the pattern of variations is quite complicated in some well observed stars and a clear rotational modulation is hard to demonstrate convincincly – see, e.g. Prinja (1994).

iii. For more than two decades since the first discoveries of rapid line-profile and light changes of OBe stars – see Baade (1979, 1982), Walker et al. (1979, 1981), Bolton (1982), Vogt & Penrod (1983) and Percy (1983) – there has been a heated debate and struggle to find out their true physical cause. It seems now that only the model of corotating *surface* structures – first suggested by Walker et al. (1979) – is out of the game. Many investigators prefer the model of non-radial pulsations (nrp hereafter), originally suggested by Smith (1977), Baade (1979, 1982), Walker et al. (1981), Bolton (1982), Vogt & Penrod (1983) and Percy (1983). On the other hand, there is also a continuing support for the model of corotating structures *slightly above* the photosphere, first promoted by Walker et al. (1981), Vogt & Penrod (1983), Harmanec (1989) and Harmanec & Tarasov (1990). For the most recent defenses of the nrp model and model of corotating structures see Baade (2000) and Balona (2000), respectively, and references therein.

3 Possible ways to resolve the open problems

I suspect that we might have followed several dead ends in the research of Be stars:

1. For a long time, the observers of Be stars were attracted by their spectacular long-term spectral variations and paid much less attention to the quiet stages when the respective stars were without emission.
2. As mentioned above, there has been a tough competition to find *the correct* explanation of rapid (multi)periodic line-profile and light changes and less attention has been paid to other important types of variations in the more recent period of spectroscopy with electronic detectors.
3. One can note the tendency to model one specific property or variability pattern of OBAe stars, without taking into account other existing facts and the huge complexity of the phenomenon.

Here, I suggest a few lines of research which – in my view – may turn out fruitful in our joint effort to reveal the remaining secrets of hot emission-line stars.

3.1 Need for reliable basic physical properties of underlying stars

I am convinced we badly need to derive truly reliable basic physical properties of particular underlying OBA stars, like their mass, radius, luminosity or effective temperature, *by direct methods*. Note that there are almost no such determinations available at present. This is closely related to the need for model atmospheres of rotating stars but also for models of structures which I call *pseudophotospheres*. I am more and more convinced that the emission-line envelopes – whatever their origin and their geometry is – are not detached from the stellar photospheres. The inner parts of such envelopes may become optically thick *also in continuum* during some phases of the formation of the envelopes and simulate stellar photospheres, probably somewhat cooler than the underlying stars. At the same time, their rotational flattenings and limb and gravity darkenings could be quite different from those of a rapidly rotating star, depending on the way of their formation. One can even ask whether in the quiet phases without emission lines one observes a true photosphere or a residual pseudophotosphere. The problem is in a way similar to a problem in the modelling of late-type emission-line stars like RS CVn stars which are currently interpreted as spotted oblique rotators. To model the light curve of a spotted star, one needs to know the stellar luminosity of the star from a period without *any* spots. Is there such a phase? There is a similar problem with the hot emission-line stars. One could argue that the basic physical properties could be derived from the observations at phases without emission lines. I have adopted such an approach to derive the radii of a number of OBe stars – see Harmanec (2000) – but the problem is that one cannot be quite sure that the phases without the emission correspond indeed to the properties of the underlying stellar object. Note, for instance, that the V magnitude of X Per, recorded during several different periods when the star was *apparently* without emission, is different – though constant – during each such period; see Piccioni et al. (2000) and Roche et al. (2000).

Pending this warning, the result of my above-mentioned study was that there is no clear distinction between luminosity III-V and I-II objects for the OBe stars with the best available radii. This may indicate that one should not discriminate between emission-line stars of apparently lower or higher luminosity, at least until the whole phenomenon is well understood.

From a more general point of view, I would like to warn that almost all our knowledge of accurate stellar masses and radii rests on observations of *eclipsing binaries* which, especially for hot and often rapidly rotating stars, may represent a rather strong selection effect. The problem is really accute for emission-line stars since in the eclipsing binaries, the circumstellar matter often simulates a much cooler spectral type than what would correspond to the star inside the envelope – as mentioned already by Harmanec (1982).

3.2 The true importance of rapid changes

The Be-star community has intensively investigated the tiny rapid line-profile and light changes for more than 20 years. Yet, there is no clear answer regarding their physical cause. It is fair to say that I am not a neutral person in this game. I have been defending the model of corotating structures all the time since I entered the debate – see Harmanec (1983, 1984, 1989) and Harmanec & Tarasov (1990), i.e. already in the period when the majority voice was for the nrp model. Yet, I am prepared to admit I have not been right or – which seems as another possibility – to accept the fact that both, nrp and corotating structures are observed simultaneously in particular stars.

The reason why I have not been convinced by the defenders of nrp model as yet can best be illustrated on a particular example: Rivinius et al. (1998a, 1998b) suggested that the line profiles of the B2e star μ Cen vary regularly with as many as six different periods, four of them being close to 0.5 day. However – as Figs. 2 and 3 in Rivinius et al. (1998b) show – the subsequent removal of individual detected frequencies *does not lead* to any really significant reduction of the scatter along the phase curves which should be the case for a real multiperiodic variation. Besides, I still find a bit dangerous to search for periods close to $0\overset{d}{.}5$ from data which – for their large part – were obtained with a frequency of one spectrum per night only. I also do not find the correlation between the constructive interference of the detected periods and the emission episodes so convincing as claimed by the authors – cf., e.g., Fig. 1 in Rivinius et al. (1998a).

It is fair to say, however, that the proponents of the nrp interpretation achieved remarkably good results in the modelling of the observed line-profile changes using the best available theoretical model profiles based on the assumption of non-radial pulsations in the atmospheres of rotating stars – see Maintz et al. (2000) and Rivinius (2000).

From a more general point of view it is clear that if one could make a really convincing case for one of the competing interpretations, there is some promise to obtain a new technique of the determination of some basic properties of Be stars. If the rapid line-profile changes are due to nrp, there is a prospect for asteroseismology, though the way to self-consistent theoretical models of oscillations in rapidly rotating stars will still be quite long, I suspect. On the other hand, if the rapid changes are due to corotation, one would obtain a new method how to derive true rotational periods of Be stars or their disks. One should be aware, however, of another, less favourable solution to the problem: It is conceivable that we have been intensively observing something like the clouds in the summer sky or the waves in a rocky river and our observations of rapid changes would not bring us any closer to the true mysteries of Be stars...

4 What is the role of duplicity in the Be phenomenon?

It is important to realize that duplicity can have two principal roles:

1. It can be somehow responsible for the formation of the Be envelopes.

2. It can be responsible for several particular types of variations which are observed for the majority of Be stars.

Let us consider some aspects of the problem in turn.

4.1 Possible role of duplicity in the formation of Be envelopes

It is well established now that the duplicity is causally linked to the OBAe phenomenon for hot components of binaries which are accreting mass from their secondaries via the Roche-lobe overflow. For all such binaries, from Algols over W Ser class to symbiotics and VV Cep, the Balmer emission clearly originates in a complex of circumstellar matter around the mass-accreting star (gas stream+accretion disk+halo+jets) formed during the process of mass transfer.

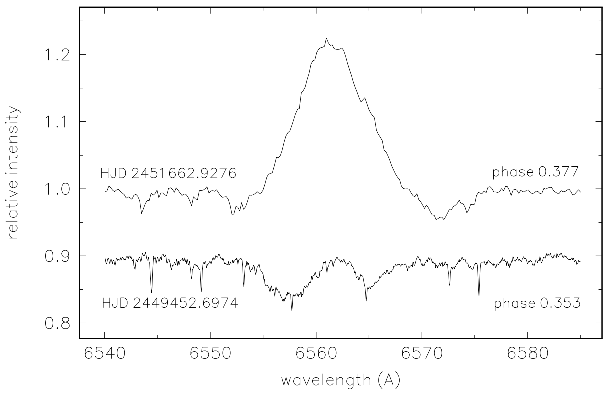

Fig. 1: Hα spectra of V1007 Sco showing a recent appearance of a strong emission. Note that both spectra correspond to almost the same orbital phase and that the older spectrum was shifted for 0.1 of the continuum level to allow a better comparison of both profiles

Another mechanism which may led to the formation of emission lines in binaries composed of two hot stars is a violent collision of their stellar winds. I suspect, however, that this mechanism is sometimes called for even in cases where some mass exchange via gas streams does in fact occur. This could be the case of V1007 Sco for which a preliminary study was published by Mayer et al. (2001) and for which we are now preparing a more detailed paper. In Fig. 1, two Hα spectra, taken a few years apart at almost the same orbital phase, are compared. They show a huge change in the profile, typical for long-term changes of Be stars. It is not clear how such a change could result from the stellar-wind interaction only.

It is necessary to say that the Roche-lobe overflow cannot serve as a universal explanation of the Be phenomenon as tentatively suggested by Kříž & Harmanec (1975) and Harmanec & Kříž (1976). Already Plavec (1976) pointed out that one does not observe enough eclipsing binaries among the known Be stars. The binary models of the Be phenomenon were also critically examined and refuted by Baade (1992). Detailed studies of several spectroscopic binaries with Be-star primaries excluded the presence of Roche-lobe filling secondaries – cf., e.g., a recent study of V839 Her by Koubský et al. (1997).

Another obvious objection against the universal validity of the binary model of Be stars which is based on the assumption of a mass transfer from the secondary towards the Be primary is the existence of binaries with a Be primary and a compact, X-ray emitting secondary. The canonical interpretation of the excitation of X-rays is a mass flow from the optical component towards the compact star, i.e. in the opposite direction than what would be needed to form an accretion disk around the OBe star.

In defense of the role of duplicity, Kříž (1978, 1982) and Harmanec (1985) argued that there could be another, *post case-B* mass transfer due to rotational instability of secondaries contracting towards the helium main sequence after the ignition of the helium in their cores at the end of mass transfer process. The hot secondary in the known Be binary φ Per was suggested to be in such a phase. There is, however, a problem with this interpretation. While the limit of the dynamical stability indeed shrinks for rapidly rotating stars and may allow some mass loss at the equator or even a formation of an outflowing disk, it is not so easy to start a new phase of *mass transfer* between the binary components since the gas loosing the small hot star needs to achieve the escape velocity of about 1.4 $\times$ the Keplerian velocity. This probably cannot be achieved via the Maxwell velocity distribution unless the secondary has a surface temperature of the order of 100 000 K. It is worth of a more detailed study to see whether a strong stellar wind could facilitate mass transfer in similar cases. One should also investigate whether some other mechanisms of mass inflow or outflow, related to the presence of a companion to the Be star, could be found.

To cimcumwent the above-mentioned problem of Be+X binaries, Harmanec (1985) argued that there is no direct observational evidence of the mass flow *from the Be stars towards X-ray components* for such systems and presented some indirect evidence that the material is in fact flowing in the opposite direction. However, unless someone finds a mechanism able to excite X-rays from the compact objects other than the mass accretion, his proposal remains a pure speculation. It is notable, however, that there is no clear difference between the properties of "normal" Be stars and Be stars in the Be+X binaries – cf., e.g., Harmanec (1985, 1987a) and Zamarov et al. (2001).

4.2 Role of duplicity in the various types of variability observed

4.2.1 Long-term RV and V/R changes

As already mentioned above, Kříž & Harmanec (1975) and Harmanec & Kříž (1976) suggested that an orbiting companion could be responsible for the slow revolution of the elongated envelope and demonstrated a good quantitative agreement for ζ Tau. Since then, the number of binaries among the Be V/R variables has been growing steadily and the following systems are known: V923 Aql = HD 183656; Koubský et al. (1989), V832 Cyg = HD 200120; Tarasov & Tuominen (1987) and Rivinius & Štefl (2000) and the most recent one, γ Cas = HD 5394; Harmanec et al. (2000).

4.2.2 Phase-locked V/R and other variations

Phase-locked V/R variations are well known for stars like φ Per = HD 10516; Lockyer (1926), Božić et al. (1995) and Gies et al. (1998), V696 Mon = HR 2142: Peters (1972), V839 Her = 4 Her: Harmanec et al. (1976), V744 Her = 88 Her: Doazan et al. (1982) or κ Dra = HD 109387: Juza et al. (1991).

Very interesting and so far unexplained phase-locked absorption features have been discovered in the Hα emission wings of V839 Her by Koubský et al. (1997). Strongly blue-shifted (RV of -700 km s^{-1}) phase-locked absorption lines, observed at a narrow interval of orbital phases, were discovered by Koubský et al. (1987) in the IUE spectra of CX Dra. The puzzle is that CX Dra is not an eclipsing binary and is observed under an intermediate inclination angle.

Recurrent shell phases of φ Per, AX Mon or V696 Mon were all found to be phase-locked phenomena in these binary systems – see Hynek (1944), Cowley (1964) and Peters (1971, 1972). Harmanec (1982) suggested that also the recurrent shell phases in Be stars like BU Tau or V832 Cyg = 59 Cyg could be scaled-up versions of similar, phase-dependent phenomena in very long-periodic binaries. Both, V832 Cyg and BU Tau were later found to have visual companions (by McAlister et al. 1984 and Gies et al. 1990, respectively) but the connection of their shell phases to their orbits has not been demonstrated.

One can also mention other related phenomena: An increase of the X-ray emission every periastron passage has been reported for several Be+X binaries. Actually, the orbital period was derived first from the X-ray light curve for some of them – cf., e.g., the 111-d period of V725 Tau = HDE 245770: Nagase et al. (1982) and Priedhorsky & Terrell (1983). This behaviour is usually accompanied by a strengthening of the Balmer emission and it is interpreted as a release of a new Be envelope during the periastron passage. One can at least speculate about similar scenarios also for Be binaries without measurable X-ray flux. Appearances of strong emission-line phases have been reported for β Cep and δ Sco during the periastron passage of their long orbits – see Mathias et al. (1991) and Fabregat et al. (2000). Note that the real physical mechanism responsible for the release of a new Be envelope is not obvious, however, since the stars do not come too close to each other even at periastron. Maybe, it is the steep gradient of the change of the gravitational pull from the companion, not the pull itself, which somehow initiates the release of the envelope.

Recently, two very good reviews on the possible role of duplicity in the Be phenomenon have been published by Gies (2000, 2001).

Since there is no representative enough catalogue of emission-line OBA stars in binaries, I decided to include at least a preliminary version of such a catalogue into this review. I made no restriction concerning the luminosity class or magnitude of the objects. I apologize that the limited extent of this review did not allow inclusion of at least most relevant references. This can be circumwent in my opinion by the use of the electronically available CDS bibliographical service. Besides my own records, I consulted searches for the presence of emission in Algol binaries carried out by Plavec & Polidan (1976), Peters (1980), Kaitchuck & Honeycutt (1982) and Kaitchuck et al. (1985), a similar search for O supergiants by Ebbets (1982), for O binaries by Thaller (1997) and also a recent list of Be binaries published by Gies (2000). A few comments on the content of the catalogue are appropriate. In cases when such evidence is available, I commented on the presence of a cooler shell and indicated the correct spectral type. In all other cases I quoted the spectral class given in available sources. For eclipsing binaries, the spectral classes quoted for the hot primaries may, therefore, be in many cases much later than their true spectral classes. Note, for instance, that the spectral class of the primary of SX Cas, based on medium-resolution spectrograms, was usually given as A5III. Note also that gas streams and other parts of the circumstellar matter could lead to the distortion of the RV curves and to the determination of false eccentricities for some systems which in fact move in a circular orbit. The Barr effect, related to the apparent increase of RV near the velocity maximum due to the projection of gas stream which moves away from the observer in the appropriate orbital phases, is well known and leads to false eccentricities with values of ω close to zero. Less widely known are other types of distortion. Note that any distortion which

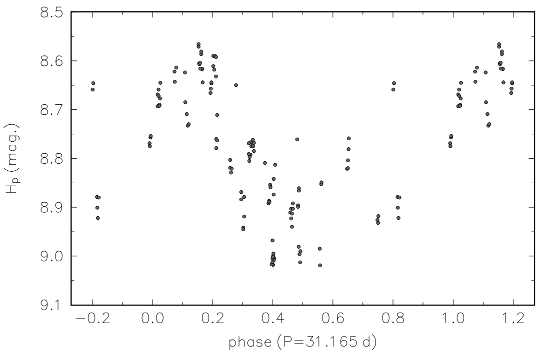

Fig. 2: The light curve of GG Car based on good (label 0 and 1) Hipparcos H_p photometry, for the best-fit period in the neighbourhood of the 31-d period reported earlier. It is seen that there are many deviating points, casting doubts on the reality of the 31.1-d period

is symmetric with respect to the line joining the two stars must lead to false eccentricities with the ω values close to 90° or 270°. Consequently, eccentric orbits with the values of the periastron passage close to all the above-mentioned values should be taken with some reservation unless there is evidence that the eccentricity is a real one. For binaries with a well proven presence of the apsidal motion, I give the symbol AM instead of the value of the periastron passage in column "ω." In column "Type", usual abbreviations EB, SB1, SB2 and EL are used for the eclipsing, single-line and double-line spectroscopic binaries and ellipsoidal variables, respectively. Symbol "LT" denotes that the duplicity of the star was discovered from the light-time effect of the rotational period of its X-ray companion.

Table 1 contains objects which are certain or very probable binaries, Table 2 lists possible binaries which need verification with additional data and Table 3 lists objects which were reported as binaries in some studies but for which the detected variability may be due to other causes. *There is no guarantee of the completeness of these lists.* I have included only brighter and best studied cases of binaries combining emission-line primaries with X-ray secondaries. I have also included symbiotic binaries for which orbital period is known. Note that the most recent and probably also the most complete catalogues of X-ray binaries and symbiotic stars have been published by Liu et al. (2000), and by Belczyński et al. (2000), respectively. Since most of the symbiotic binaries are relatively faint objects, I identify them also by their numbers from the Belczyński et al. (2000) catalogue (BMMIF numbers in column "Other name").

5 Desiderata

In my view, the most important things to do for the progress in our understanding the OBAe stars are:

1. To construct self-consistent model line profiles not only for rotating stellar atmospheres but also for various conceivable forms of Be envelopes: a nearly spherical outflow, wind-focused outflow, or accretion disk, for instance. In particular, I would like to point out the need for models of accretion disks around hot stars which would also include the effect of the central star on the temperature and other properties of the disk, as suggested by Linnell (these Proceedings). It is clear that a self-consistent solution of this problem would give us a powerful tool to the determination of masses and radii for observationally complicated binaries with thick disks.

2. To derive, by direct methods, accurate masses, radii and effective temperatures of a statistically significant number of particular Be stars. The determination of masses is particularly uneasy: it is usually more or less uncertain for OBAe stars in eclipsing binaries because of complications due to circumstellar structures. Very promising appear studies of Be stars in visual binaries with reasonably short periods ($10^0 - 10^1$ yrs.) via spectroscopy and speckle interferometry: right now, the most promising candidate is δ Sco (orbital period 10 yrs.) which may be passing through periastron these months. However, to keep its secrets as long as possible and to complicate reliable determination of its radial-velocity curve, it developed a strong emission spectrum at the same time, as already mentioned above.

3. To continue patient systematic monitoring of brighter Be stars with high-S/N echelle spectroscopy, calibrated photometry in several passbands, polarimetry and interferometry.

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Table 1: A preliminary catalogue of binary systems with OBAe stars. Values of ω for pulsar secondaries refer to these secondaries

Variable star name	Other name	HD number	P_{orb} (days)	e	ω (°)	Type	Spectral class	Note
KN Cas	–	–	?	?	?	EB	M1Ib+B2e	
SX Cas	BD+54 7	232121	36.561	0.0	–	EB	B4e+K3III	P decreasing
V742 Cas	BD+57 28	698	55.9233	0.0	–	SB1	B5II-IIIe	
AO Cas	HR 65	1337	3.5235	0.0	–	EL	O9.5III+O8Ve	
EG And	BMMIF003	4174	482.57	0.0	–	EB	M3III+e	
BM Cas	BD+63 110	–	197.2800	0.0	–	EB	A7Iae	shell
γ Cas	27 Cas	5394	203.59	0.260	48	SB1	B0.5e+X??	
U Cep		5679	2.4930	0.0	–	EB	B7Ve+G8III-IV	
SMC X-1	Sk 160	–	3.8922	0.0	–	EL	B0Ie+X	
V662 Cas	LSI+65 010	–	11.588	0.16	11		B0.5e+X	
AZ Cas	BD+60 310	–	3403.6	0.55	4	EB	M0Ib+B0Ve	
AX Per	BMMIF008	–	679.9	0.0	–	EB	M6III+Oe	
φ Per		10516	126.6731	0.0	–	SB2	B0.5IVe+sdO	
RY Per		17034	6.863569	0.0	–	EB	B4:e+F7:II-III	
RX Cas	BD+67 244	–	32.3301	0.0	–	EB	B3e+K1III	P increasing
β Per	Algol	19356	2.8673	0.02	AM	EB	B8Ve+G2	tertiary A7Vm
BD Cam	BMMIF011	22649	596.21	0.09	322	SB1	M3+OBe	
X Per	4U 0352+30	24534	250.3	0.111	288	LT	O9.5e+X	
RW Tau		25487	2.7688	0.0	–	EB	B8Ve+K0IV	
RW Per		276247	13.1989	0.0	–	EB	A5IIIe+gG0	shell
TZ Eri	BD-06 880	–	2.606132	0.0	–	EB	A5Ve+K0III	
V1080 Tau	BD+24 676	283817	17.690348	0.0	–	EL	A3e+G0:	
KS Per		30353	362.8	0.30	277	SB1	A5Iae+sdO	shell
RS Cep		–	12.4199	0.0	–	EB	B9.7Ve+G8III	
	103 Tau	32990	58.31	0.19	274	SB1	B2Ve	occultation double
SX Aur		33357	1.2101	0.0	–	EB	B2Ve+B3V	
V1261 Ori	BMMIF017	35155	642.	0.07	214	EB	S4+e	
	HR 1803	35588	2.8884	0.12	199	SB1	B3Ve	
LY Aur	BD+35 1137	35921	4.0252	0.0	–	EB	O9.5IIIe+B0.5III	triple
χ Aur	25 Aur	36371	676.85	0.116	182	SB1	B4Iabe	
V1046 Ori		37017	18.65612	0.468	118	SB2	B2e+B7::	magnetic primary
ζ Tau	123 Tau	37202	132.9735	0.0	–	SB1	B1e	
NSV 16617		37453	66.57	0.0	–	EB	F5II+Be	
V434 Aur		37657	3.3994	0.0	–	SB1	B3Ve	
V725 Tau	A0535+26	245770	110.3	0.47	130	LT	O9.7e+X	
DN Ori	BD+10 967	40632	12.966467	0.0	–	EB	A2e+F5III	
BG Gem	–	–	91.645	0.0	–	EB	K0I+Be	
V696 Mon	HR 2142	41335	80.860	0.0	–	SB1	B2e	
SS Lep	17 Lep	41511	260.34	0.024	204	SB1	B9e+M4III	
WY Gem	BD+23 1243	42474	23550.	0.61	57	SB1	M2Ia+B2e	
V395 Aur		43246	23.1755	0.016	270	SB	F8III+B8Ve	
ν Gem	18 Gem	45542	4748.	0.923	99	VB	B6IIIe	
ν Gem	18 Gem	45542	40.198??	0.0	–	SB1	B6IIIe	uncertain
AX Mon	BD+05 1267	45910	232.499	0.0	–	SB2	B2e+K2II	
V640 Mon	Plaskett's	47129	14.3961	0.0	–	SB	O7Ie+O6I	
V505 Mon		48914	53.78	0.0	–	EB	B5e	
RX Gem		49521	12.209	0.0	–	EB	A4e+K1	
HZ CMa	HR 2545	50123	28.601	0.0	–	EL,SB1	B6e+(K0III::)	
AU Mon		50846	11.113	0.0	–	EB	B5e+F0	
V644 Mon		51480	120.6??	?	?	SB?	B1V+K0I-II	
UW CMa	29 CMa	57060	4.3934	0.118	45	EB	O7Iaef+O7	
BX Mon	BMMIF023	–	1259.	0.444	12	EB	M5III+Oe	
RY Gem	BD+15 1573	58713	9.300567	0.0	–	EB	A2e+K2	
–		59771	89.9	?	?		F4II+Be	
PW Pup	CD-30 5135	–	158.0	?	?		F2Iabe+Be	

Table 1: Continued

Variable star name	Other name	HD number	P_{orb} (days)	e	ω (°)	Type	Spectral class	Note
KQ Pup		60414	9752.	0.46	203	EB	M2Iabe+B2	
UX Mon	BD-07 2291	65607	5.904472	0.0	–	EB	A5IIIe+G2III	
	3 Pup	62623	161.3 or 138.5	0.0	–	SB1	A2Iabe	
V Pup		65818	1.4545	0.0	–	EB	B1Ve+B3	
UU Cnc	BD+15 1733	–	96.682	0.0	–	EL	K4II+ABe	
XY Pup	BD-11 2261	67862	13.77830	0.0	–	EB	A3e	shell
γ^2 Vel		68273	78.519	0.38	261	SB2	WC8+O7.5e	
	BMMIFs11	–	763.3	0.0	–	SB1	?	
FY Vel		72754	33.738	0.0	–	EL,SB	B8Ie	
GP Vel	Vela X-1	77581	8.9644	0.14	355	EB	B0.5Ibe+X	
S Vel	CD-44 5573	82829	5.9336663	0.0	–	EB	A5Ve+K5IIIe	
TX UMa		93033	3.0633292	0.0	–	EB	B8Ve+G0III	
QZ Car		93206	5.9991	0.0	–	EB	O9.7Ibe	quadruple
QZ Car		93206	20.73596	0.342	144	EB	O9.7Ibe	quadruple
–	CD-58 3545	93403	15.093	0.23	22	SB2	O5ef+O7.5	
TT Hya		97528	6.9534	0.0	–	EB	B9.5e+K0III	
V779 Cen	Cen X-3	–	2.0871	0.0?	–	EB	O7IIIe+X	
SY Mus	BMMIF033	100336	624.5	0.0	–	EB	M2III+Oe	
TX CVn	BMMIF036	–	199	0.16	33	SB1	M0III+A1Ve	circular?
BY Cru	ADS	104901	106.4	0.0	–	EL	F+Be	
W Cru		105998	198.53	0.05	74	EB	G2Iab+Be	
BP Cru	Wra 977	–	41.508	0.472	310	LT	B1.5Iae+X	
κ Dra	5 Dra	109387	61.5549	0.0	–	SB1	B5IIIe	
RW Hya	BMMIF045	117970	370.3	0.0	–	EB	M2III+Oe	
V716 Cen	HR 5311	124195	1.49009305	0.0	–	EB	B5Ve	
IV Vir	BMMIF051	–	281.6	0.0	–	SB1	K2+e	
HL Lib	BD-21 3917	127208	24.615	0.0	–	SB1	G6III+B8.5e	
U CrB		136175	3.4522	0.0	–	EB	B7Ve+G0III	
TW Dra		139319	2.8067	0.02	350	EB	A5e+K0III	
QV Nor	4U 1538-52	–	3.7299	0.174	64	EB,LT	B0Ie+X	
V748 Cen	BMMIFs13	–	566.5	?	?	EB	F2Ie+M4III	
V839 Her	4 Her	142926	46.1921	0.0	–	SB1	B7e	
T CrB	BMMIF057	143454	227.5687	0.0	–	EL,SB1	M4.5III+Be	
AG Dra	BMMIF058	–	554.	0.0	–	SB1	K2II+Oe	
V918 Sco	HR 6164	149404	9.81475	0.0	–	SB2	O7.5Ife+ON9.7I	
R Ara		149730	4.4251	0.43	15	EB	B9e(+X)	
NSV 8020		152218	5.603979	0.308	81	SB2	O9III+O9.8IIIe	
V1007 Sco		152248	5.8160	0.137	AM	EB	O7fe+O7fe	
CL Sco	BMMIF071	–	624.7	?	?	EL	M5II:+Be	
V861 Sco		152667	7.8482	0.04	0	EB	B0Iae+B2V:	
HZ Her		–	1.7002	0.0	–	EB	A9-Be+X	
V884 Sco		153919	3.4118	0.16	5	EB	O6.5fe+X	
XX Oph	BD-06 4638	161114	18.608??	0.40	350	SB?	B0IIIe+M6III	
V2315 Oph	IC4665*32	161261	2.1012	0.0	–	SB	B9e	
V2323 Oph	BD+06 3525	161660	10.793	0.22	189	SB1	B7Ve	
V393 Sco		161741	7.71415	0.38?	21?	EB	B9e	
RS Oph	BMMIF101	162214	455.72	0.0	–	SB1	K7I-II+OBe	rec.nova
V744 Her	88 Her	162732	86.7221	0.16	270	SB1	B6e	
V453 Sco		163181	12.006	0.08	36	EB	B0.5Iae+OBNe	
V441 Her		163506	285.8	0.13	338	SB1	F2Ibe	
W Ser		166126	14.157	0.37	31	EB	G1Iab+Be	
μ Sgr	13 Sgr	166937	180.55	0.42	77	EB	B8Iae+B1.5V	
FG Ser	BMMIF134	–	650.	0.0	–	EB	M5III+e	
MY Ser	BD-12 4980	167971	3.3213	0.0	–	EB	O8e	triple

Table 1: Continued

Variable star name	Other name	HD number	P_{orb} (days)	e	ω (°)	Type	Spectral class	Note
V2756 Sgr	BMMIF133	–	243.	?	?	EB?	OBe+M2III:	
AR Pav	BMMIF142	–	604.46	0.0	–	EB	Oe+M5III	
RY Sct		169515	11.125	0.0	–	EB	B0e	
RZ Sct		169753	15.190	0.0	–	EB	B2IIe+A0II	
V443 Her	BMMIF145	–	594.	0.0	–	SB1	M5.5III+e	
V447 Sct	BD-07 4689	173219	58.395	0.08	47	SB	B2Ibe+(Be??)	
RR Dra		–	2.8313	?	?	EB	A2e+K0	
RZ Oph	BD+07 3832	–	261.9277	0.0	–	EB	F3Ibe+K5II	shell
CX Dra		174237	6.696	0.0	–	EL,SB2	B3e+F5III	
AD Her		349425	9.7666	0.17	276	EB	A4Ve+K2	
β Lyr		174638	12.935	0.0	–	EB	B8II+B0e::	
V342 Aql		180639	3.3910	0.0	–	EB	A4IIe	
U Sge	HR 7326	181182	3.3805941	0.03	194	EB	B8.5e+G3III	circular orbit?
υ Sgr		181615	137.96	0.06	17	EB	B8e+O9V?	F2 shell
BF Cyg	BMMIF166	–	756.8	?	?	EB	Be+M7III	
CH Cyg	BMMIF167	182917	5700.?	?	?	EB	M7III+Be	
V923 Aql		183656	214.74	0.0	–	SB1	B6e	
δ Sge		187076	3720.	0.30	265	SB	M2II+B9e:	
V1507 Cyg		187399	27.971	0.39	211	SB1	B8III+Be	pec. l.c.
V1765 Cyg	HR 7551	187459	13.37383	0.335	AM	SB2	B0.5Ibe+B0V:	
V1339 Aql		187567	1.2722	0.0	–	SB1	B2.5IVe	
CI Cyg	BMMIF172	–	853.8	0.109	298	EB	M5.5II+Be	
	HR 7628	189178	70.22	0.39	310	SB1	B5V shell	
V1357 Cyg	Cyg X-1	226868	5.5997	0.02	279	SB	O9.7Iabe+X	
V1362 Cyg	BD+36 3841	190467	57. ?	?	?	SB1	B3-5e	
V448 Cyg	BD+34 3871	190967	6.5197162	0.0	–	EB	O9.5+B1II	
SW Cyg	BD+45 3062	191240	4.573068	0.0	–	EB	A2e+K3	probably B primary
KU Cyg	BD+46 2879	–	38.4393	0.0	–	EB	Fshell+K5III	B6e: primary
QS Vul	22 Vul	192713	249.115	0.0	–	EB	G3Ib+B9e	
VW Cyg		228545	8.4303	0.18	15	EB	A2e+G5	
		193576	4.0110	0.06	137	SB1	B1IVe	
PU Vul	BMMIF176	–	4900.	?	?	EB	M4III+Be	F shell
V729 Cyg	BD+40 4220	–	6.5978	0.0	–	EB	O7fe+O6fe	
W Del	BD+17 4367	352682	4.8060	0.0?	–	EB	A0e+G2	
V367 Cyg		198287	18.59773	0.0	–	EB	A5Iabe	hidden in a shell
S Equ		199454	3.4361	0.15	84	EB	B8Ve+F9III	
V1329 Cyg	BMMIF181	–	957.	0.1:	90	EB	M6III+e	
	HR 8023	199579	48.608	0.10	67	SB1	O6Ve	
DV Aqr		199603	1.5755	0.0	–	EB	A9Ve	
V832 Cyg	59 Cyg	200120	28.1702	0.20	271	SB1	B1.5e	
	BMMIF182	–	1448.	0.0?	–	SB1	K5III+e	
V1931 Cyg	60 Cyg	200310	146.6	0.0	–	SB1	B1e	
	HR 8153ab	203025	5.4136	0.11	–	SB1	B2IIIe	closer pair
	HR 8153abc	203025	225.44	0.23	17	SB1	B2IIIe	third star
V381 Cep	HR 8164	203338	75??		?		M1Ibe+B2e	
AQ Peg		–	5.5483	0.24	15	EB	A2e+G5	
ε Cap	39 Cap	205637	95.:	?	?	SB1	B2.5Ve	
V1914 Cyg		207739	140.782	0.027	49	EB	F8II+Be	
AG Peg	BMMIF185	207757	816.5	0.110	112	SB1	M3III+Be	
AW Peg		207956	10.622	0.0	–	EB	A4Ve+F2e	
VV Cep		208816	7430.5	0.35	59	EB	M2Ia+B8Ve	
V2174 Cyg	BD+53 2749	235679	225.33	0.0?	–	SB1	BN2.5Ibe	
π Aqr	52 Aqr	212571	84.273	0.0	–	SB1	B1Ve	
V360 Lac	14 Lac	216200	10.085408	0.0	–	SB2	B3e+F9IV	
KX And		218393	38.918	0.0	–	SB2	B05e+K1III	
Z And	BMMIF187	221650	758.8	0.0	–	EL,SB1	M2II+Oe	
V373 Cas	HR 9052	224151	13.41921	0.13	AM	EB	B0.5IIe+B4III	

Table 2: A preliminary catalogue of *possible OBAe binaries* for which the binary nature was reported or at least suspected in the past. Further dedicated studies are needed to prove or disprove their binary nature – see the notes to individual objects

Variable star name	Other name	HD number	P_{orb} (days)	e	ω (°)	Type	Spectral class	Note
NSV 15755	17 Tau	23302	100.46??			SB1	B6e	1
NSV 15775	η Tau	23630	4.1349	0.0	–	SB1	B7IIIe	2
BU Tau	28 Tau	23862	218.0	0.60	149	SB1	B8e	3
MX Per	48 Per	25940	16.59594	0.0	–	SB1	B3e	4
ω CMa	28 CMa	56139	34.675	0.7:	120	SB1	B2e	5
FW CMa	HR 2825	58343	31.9045	0.0	–	SB1	B2.5e	6
β CMi	HR 2845	58715	218.498	0.48	235	SB1	B8e	7
FY CMa	HR 2855	58978	92.7	0.0?	–	EL	B1IIe	8
NSV 04807	CD-54 3389	89249	?	?	?		B2e+K	9
GG Car	CPD-59 2855	94878	31.1	0.0	–	SB,EL	Be	10
χ Oph	7 Oph	148184	34.1211	0.262	0	SB1	B2e	11
V4372 Sgr	BD-15 5362	183133	48.08	0.0	–	EL	B2e	12
QZ Sge	9 Sge	188001	78.74	0.556	262	SB1	O8Ife	13
V421 Cep	HR 8153	203025	225.44	0.226	17	SB1	B2e	14
LQ And	HR 9070	224559	7.41324	0.3:	330:	SB1	B4e	15

Notes:

1... Reported as a spectroscopic and also occultation binary (cf. Abt 1984) but its orbital motion was not confirmed by later studies. Jarad et al. (1989) reported RV variations with possible periods of $3^{d}.83$ or $4^{d}.29$ but these probably reflect rapid line-profile changes rather than orbital motion. It is conceivable that the star is a binary but a firm proof is missing.

2... Jarad et al. (1989) reported periodic RV variations using their and published RVs and suggested tentatively that the star is a spectroscopic binary. However, inependent confirmation based on electronic spectra is clearly desirable.

3... The star was reported to be a spectroscopic binary by Katahira et al. (1996) but the RV curve they obtained shows a great deal of scatter and needs verification from electronic spectra.

4... The orbit was derived by Jarad et al. (1989) from their and published RVs and should be confirmed.

5... Harmanec's (1998) putative orbit needs verification from a homogeneous set of observations.

6... The period is based on RV measurements from two sources by Kodaira (1971) and needs verification.

7... The orbit was derived by Jarad et al. (1989) and needs verification with additional data.

8... Putative binary nature of the star is based on ellipsoidal-like variations discovered by Sterken et al. (1996) and needs verification from spectroscopy.

9... Stahl & Leitherer (1987) discovered a cool spectrum in addition to the Be spectrum of the star but no final evidence that the object is indeed a binary is available.

10... Gosset et al. (1984) found a $62^{d}.039$ period with double-wave curve from photometry while Gosset et al. (1985) derived twice shorter period from RV measurements. My analysis of Hipparcos photometry indicates that the $31^{d}.1$ period is still present but with large deviations from the mean curve – see Fig. 2. The binary nature of the object remains only putative in my view.

11... The orbital period was derived by Harmanec (1987b) from several published RV data sets and needs verification from a homogeneous set of data.

12... The binary nature of the star was suggested on the basis of periodic ellipsoidal-like light variations and Hα profile changes by Lawson et al. (1994) and needs confirmation via a RV curve.

13... The orbit, derived by Underhill & Matthews (1995) shows a great deal of scatter and certainly needs verification.

14... The orbit was derived by Sanford (1926) and needs independent verification. Sanford also reported secondary variation with a period of $5^{d}.41364$ in the RV residuals from the 225-d orbit. Hubert & Floquet (1998) derived two possible periods from Hipparcos photometry, $3^{d}.183$ or $1^{d}.365$ without giving details. My own unpublished analysis of Hipparcos photometry gives and double-wave curve with a period of $260^{d}.526$. Clearly, a new dedicated study of RV and light variations of this star is very desirable.

15... The orbit was derived by Matthews et al. (1991) and is based on data from a series of electronic spectra plus several heterogeneous sources. The putative orbital period is close to resonance with the well-known $0^{d}.619$ period of light changes and certainly needs verification via new dedicated series of spectroscopic observations.

Table 3: A preliminary catalogue of stars which *should not be considered* to be OBAe binaries although their binary nature was reported or at least suspected in the past. They include mostly cases for which the observed periodic variations are probably due to other physical causes, not due to orbital motion – see the notes to individual objects

Variable star name	Other name	HD number	P_{orb} (days)	e	ω (°)	Type	Spectral class	Note
π And		3369	143.6065	0.56	349	SB2	B5Ve+B5V	1
o Cas		4180	1033.	0.11		SB1	B5e	2
V777 Cas		11606	1.44362	0.0	–	SB1	B2Ve	3
NSV 16885	HR 2370	45995	5.286266	0.68	8	SB1	B2e	4
NSV 03271	HR 2577	50820	18.6121??	?	?	SB2?	B2e+K1II	5
GS Mus		105056	1.7403	0.08	322	EL	ON9.7Iae	6
V382 Cep	6 Cep	203467	2.4389	0.0	–	SB1	B3IVe	7

Notes:

1... This *is* a confirmed spectroscopic binary, with two spectra visible but the only report of the Balmer emission comes from low-dispersion study by Houziaux & Ringuelet-Kaswalder (1968). I suspect that the absorption lines of both B5 stars observed at an elongation were misinterpreted for a weak central emission since there is no other report of the presence of the emission for this, rather frequently observed binary.

2... Duplicity of the star was suggested on the basis of 20 RVs by Abt & Levy (1978) but Harmanec (1987b), using all existing RVs, showed that the variations are in all probability due to long-term changes in the Be envelope.

3... The period was found from RVs by Gies & Bolton 1986 who derived formal circular elements but pointed out that the variations may be due to line-profile variations in fact.

4... Harmanec (1987b), analyzing heterogeneous published data, tentatively suggested that the object is a spectroscopic binary but was unable to decide between the $5\overset{d}{.}29$ and $1\overset{d}{.}229$ periods. A new dedicated study is desirable.

5... Harmanec (1987b) analyzing all published RVs, hesitantly suggested the quoted period as a possible orbital period, but consecutive studies (Dempsey et al. 1988; Griffin 1990, priv. com., Coravel RVs) show a constant RV. The spectrum is composite so the object may be a binary but in a very wide orbit.

6... The period was derived from published RVs and photometry by Harmanec (1987b) and later confirmed by van Genderen et al. (1989) (who suspected also the presence of another period of $3\overset{d}{.}5$ in the residuals) but it is not clear whether the variations are due to orbital motion, atmosheric oscillations or corotation of some patches.

7... The RV curve of Krajčeva & Koubský (1983) shows a rather large scatter around the mean curve and in all probability reflects rapid line-profile changes rather than the orbital motion (Koubský, priv.com.)

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