EMISSION-LINE STARS AS INTERACTING BINARIES
(Review Paper)

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A general binary hypothesis of the emission-line phenomenon in early-type stars was published eleven years ago (Kříž & Harmanec 1975, Harmanec & Kříž 1976; for a reformulation see Harmanec 1982). Since then, new observational techniques and theoretical concepts have led to a number of exciting findings which have made the emission-line phenomenon even more puzzling and challenging than before. It is therefore of interest to ask whether the binary hypothesis can withstand all these developments or not.

Let me begin with a general consideration: if one asks about the basic cause of the formation of an envelope around a star, one must ask about the *evolutionary* phase which may lead to it. Any models which deal with the stellar interior as a static structure and do not take into account the evolutionary trends at given phases will give us incorrect answers. In particular, a rotational instability of a single star can only develop in phases of evolutionary contraction of the star. As a single star gradually increases its radius during its main-sequence (MS) stage, there is no good reason why it should become rotationally unstable (unless it is rotating rigidly as a whole). That is why various authors have tried to associate the formation of Be stars with the phase of overall contraction at the end of MS stage (see *e.g.*, Kippenhahn *et al*. 1970). A recent detailed study of Be stars in open clusters (Slettebak 1985) suggests, however, that Be stars are found in various evolutionary stages, including the essentially unevolved ones. A point in favour of the binary hypothesis is that it offers a natural mechanism for the formation of envelopes around otherwise normal MS stars, namely accretion of matter in-flowing from the secondary components which themselves are in the stages of evolutionary *expansion* leading to the mass transfer between both stars.

It is clear, however, that the evolutionary contraction of a single star may also lead to the formation of an envelope. The contraction after the ignition of helium in the stellar core is particularly promising in this respect - see Harmanec 1985 and references therein. Thus, the existence of Be stars, which are not members of *mass-exchange* binaries must also be considered, even within the framework of the binary hypothesis.

I wish to stress, however, that the existence of truly single stars in the Universe remains an unproved hypothesis. New binaries are still being discovered even among bright stars. Moreover, binaries with low mass ratios are usually below our present detection threshold, yet they may be quite numerous. The X-ray binaries teach us that even low-mass satellites can have observable effects on their primaries. A possibility exists, therefore, that duplicity can be behind the time variations observed even in those emission-line stars (ELS), which have not formed their envelopes by mass accretion. I thus cannot agree with the recent tendency characterized, for instance, by the following statement borrowed from Baade (1985): "At any rate, this paper does not concern Be stars that are members of binaries." Apart from the fact that one may define an empty set by postulating this, there are numerous examples of a very complicated time behaviour of particular ELS, which later turned out to be connected with the duplicity of the objects in question. CX Dra (Koubský et al. 1986) or KX And (Štefl 1986) may serve as good examples. It is virtually impossible to establish their underlying orbital periods from, say, one year of observations by the standard period-searching techniques - in spite of the fact that the periods are not particularly long (6.696^d, and 38.9^d, respectively). Only rather recently both stars were found to be double-line spectroscopic binaries. (Further such examples are discussed in detail by Harmanec 1983.) The a priori exclusion of binaries from a general discussion of Be stars appears therefore unjustified and technically impossible at the present stage of our knowledge.

Following is a brief outline of the binary model:
The binary model (BM) assumes that the formation of the Be envelope is a result of evolutionary processes and interactions in a binary system. In most cases, the Be envelope is simply an accretion disk/envelope structure around the mass-gaining components of interacting systems (gainers). Computer modelling of mass transfer in binaries has demonstrated that most systems should be observed in later phases of mass transfer when the gainer is already much more massive, and usually also more luminous in the optical region, than its counterpart.

Figure 1 shows a possible configuration for a particular case of a binary consisting of (supposedly MS) B2 primary, which is 10 times more massive than its counterpart, and a Roche-lobe filling giant secondary, orbiting with a period of 130 days. An emission envelope with a radius of more than 27 stellar radii can exist within the Roche lobe of the primary. If the same binary were to have a shorter period, there would be less space for the formation of an envelope inside the lobe. This situation is typical for many Algol eclipsing binaries. For a number of then, the H I emission is only observable during the eclipses. On the contrary, increasing the orbital period, one increases not only the volume around the primary, but also the absolute radius of the (Roche-lobe filling) secondary. Such secondaries thus become observable in the optical spectrum, and one observes a symbiotic or a VV Cep star. (The reader is referred to the papers mentioned above for a more detailed discussion.)

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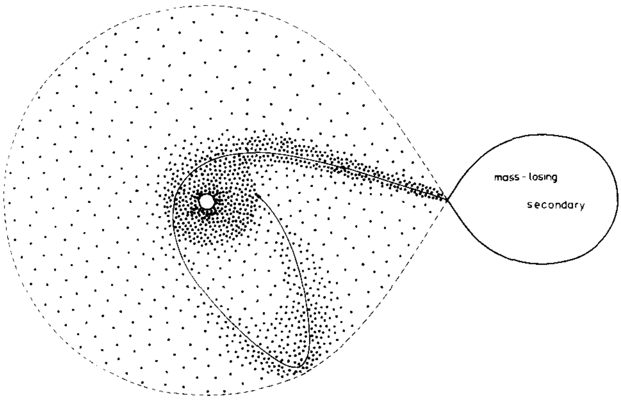
Fig. 1 A possible appearance of an interacting binary with the emission-line star



The transition between the individual categories thus appears continuous, given only by changes of several basic parameters (the evolutionary stage of the binary, its total mass, mass ratio, orbital period and initial chemical composition), and a large variety of different physical situations seems possible.

The rest of this review is devoted to the discussion of some characteristic properties of the ELS in the context of the BM with a special emphasis on discussing the most frequent objections to the BM. Numerous examples are known that the circumstellar envelopes are able to mimic later spectral subclasses and/or higher-luminosity objects in particular stars (see, for instance, Plavec et al. 1982, Harmanec 1982, 1983). I thus prefer to study the ELS without a strict restriction to the spectral class B only. This viewpoint appears natural within the framework of the BM but may not be accepted generally. That is why I make a clear distinction between the terms ELS and Be stars in the following discussion.

Considering the working character of this conference, and the number of unsettled problems related to Be stars, I made this review deliberately speculative and provocative at several places. I apologize to those readers who would prefer a more conservative approach to the problem.

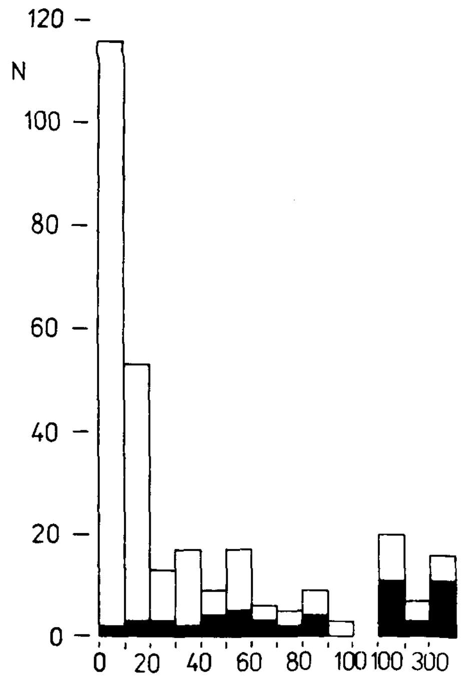
1 A lack of known ELS binaries?

The long orbital periods, broad spectral lines and low semi-amplitudes of the radial velocity (RV) curves expected for typical Be binaries must substantially reduce the chance of discovering such systems as spectroscopic binaries (SB's). Note that in spite of a concentrated effort, no really good RV curves have so far been obtained for Be III-V stars, which are the optical components of X-ray binaries. Without a priori knowledge of the orbital period from photometry or X-ray data, they would hardly be obtained at all!

The following simple statistics may serve as a basis for more quantitative considerations. Fifty four out of 295 ELS which I was able to identify among the stars with HR numbers are known binaries. Figure 2 shows the distribution of these objects according to the number of available RV observations (compiled from Abt and Biggs 1972 and a large number of more recent papers). It is apparent that a full one half of all bright ELS have less than 20 observations! Most of objects with many RV's are known binaries, and the rest are long-term RV variables and some frequently studied supergiants. Systematic analysis of the existing data would certainly reveal new SB's; I have found some, in fact, during the course of this study. It thus appears that the duplicity of the majority of even bright ELS remains untested by the RV data.

One of the strongest objections against the duplicity of all ELS has been raised by Plavec (1976), who pointed out that if all ELS are interacting binaries with Roche-lobe filling secondaries, one should observe a high percentage of eclipsing binaries (EB's). He showed that the probability that such a system will be observed as an EB is roughly given by the relative radius of the Roche lobe around the secondary, r_2, where r_2 is a function of the mass ratio only. For a typical mass ratio of 0.1, one should observe 58 EB's among the HR objects; 20 are observed in fact. Given the long orbital periods and the fact that new bright EB's are still being discovered, this discrepancy does not seem too significant. Moreover, if a large fraction of ELS have low-mass companions in short-period orbits and common outer envelopes, the situation would be quite different. If both stars fill their Roche lobes, the primary eclipse must be shallower than 0.14^m, and 0.02^m for a mass ratio of 0.1, and 0.01, respectively.

Fig. 2 The distribution of the ELS from the HR catalogue according to the number of available RV observations.



2 Is there some evidence of an interaction between the components of known binaries containing ELS?

It is sometimes argued that the observed duplicity of some Be stars has nothing to do with the formation and the time variations of their envelopes. To investigate what are the basic properties of known Be and other emission-line binaries, I have compiled a catalog of 154 such objects. No restrictions concerning spectral or luminosity classes have been applied, and the only objects deliberately excluded from the catalog at this stage were low-mass cataclysmic and X-ray binaries. The catalog will be published in detail elsewhere.

A simple statistical investigation of the catalog reveals several

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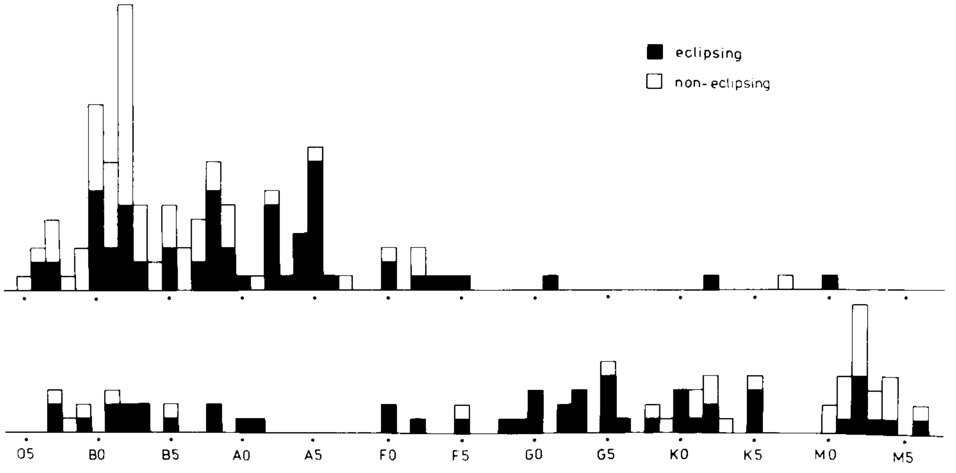
interesting facts:

a) Figure 3 is the distribution of the spectral types of the

Fig. 3 A histogram of spectral types of the ELS (upper diagram) and secondary components (lower diagram) in known binary systems with emission-line components.



primary (emission-line), and secondary components. Two facts are notable:

i. The distribution of the spectral types of secondaries is rather uniform except that A-type secondaries are apparently lacking.

ii. The whole sample is strongly biased towards EB's due to selection effects, yet, it appears that most ELS of spectral type later than B9 are found in EB's. One possible explanation of this fact (Harmanec 1982) is that the dense parts of the accretion disks seen equator-on screen the primary (presumably OB) stars and simulate later spectral classes. OB primaries hidden in dense disks would also provide the necessary source of excitation of the H I emission in these objects. Such an interpretation (based on the UV spectrograms) has been put forward for SX Cas by Plavec et al. (1982).

b) The histogram which shows the distribution of the longitude of periastron ω from the orbital solutions of the RV curves (see Fig. 4) is of primary importance. It corroborates the earlier suspicions (Barr 1908, Struve, 1944, Kříž and Harmanec 1975, Harmanec 1985) that virtually all of the orbital eccentricities derived from the RV curves of ELS are spurious and caused only by the non-uniform distribution of the circumstellar matter and by gas streams! Note that the classical Barr effect (clustering near 0°), and the opposite effect of mass outflow (clustering near 210°, first noted by Kříž and Harmanec 1975) are almost exclusively observed for the ELS, and for the other components, respectively. This is a strong argument in favour of the existence of gas streams flowing from secondaries to primaries, exactly as demanded by the binary hypothesis.

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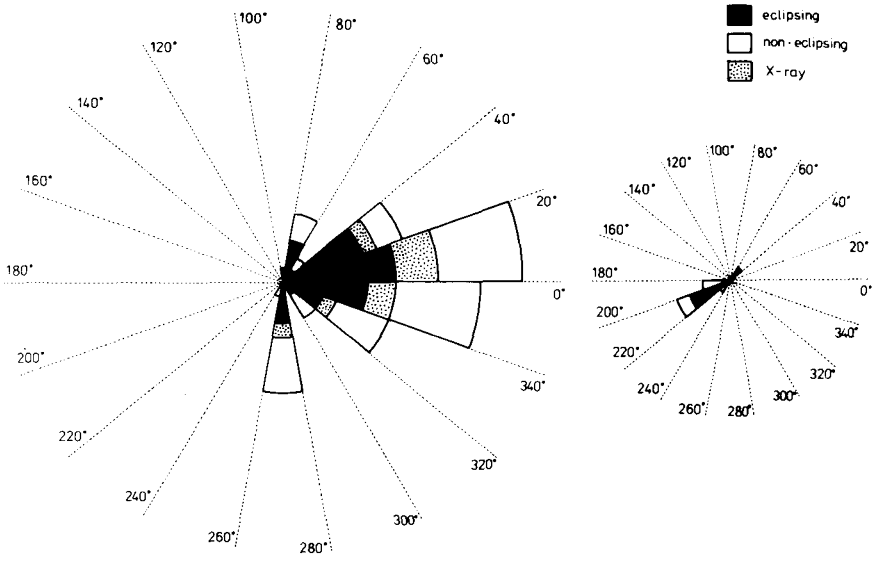
Several additional comments are relevant:
i. As Fig. 1 illustrates, only a small part of the stream velocity is projected into the direction towards the primary in elongation (with the primary receding), the only time when the stream can be projected against

Fig. 4 The distribution of the longitude of periastron as obtained from the orbital solutions for the ELS and for secondaries (the left and right diagram, respectively).



the primary's disk in non-eclipsing systems. Perhaps this explains why relatively mild effects are observed in some RV curves.
ii. There are two notable sidelobes of the distribution of ω for the ELS, a strong one at 270° and a less pronounced one near 70°. Sterne (1941) has shown that false eccentricities with the values of ω near 270° or 90° are to be expected for strongly tidally distorted stars. Harmanec (1984a) found a value of ω near 270° in periods of inactivity, and a value near 0° in phases of long-term variations for ζ Tau. Given the fact that the RV curves of ζ Tau, 88 Her and other stars with $\omega \sim 270°$ are based on the shell lines, it is reasonable to speculate that the peak near 270° identifies the objects in which the shell envelope fills (or nearly fills) the whole Roche lobe around the ELS.
iii. The statistics presented here are consistent with my recent proposal (Harmanec 1985) that the optical components of massive X-ray binaries are in fact mass-gaining, not mass-losing stars, as their ω values cluster near 0° (see Fig. 4). It is necessary to stress, however, that Bolton (1986, priv. comm.) suggests that a similar distortion of the RV curves can also be obtained if the line profiles are in fact influenced by the line emission arising in the focused stellar wind flowing from the optical to the X-ray star. It is not clear to me, however, how the sinusoidal RV curve of the He II (and probably also H I) emission (which lags for about 0.63^{P} in phase behind the RV curve

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of the optical primary) observed, e.g., by Gies and Bolton (1986) for Cyg X-1 could increase the observed RV of the absorption lines near their velocity maximum without decreasing similarly their RV near their velocity minimum, which is not observed. (Note that the He II emission is strong in phases of its maximum RV in Cyg X-1.) Clearly, a detailed modelling of the absorption-line RV curves for several well observed X-ray binaries (such as carried out, e.g., by Moulding 1977 for Cyg X-1) based on both alternative interpretations would be desirable to resolve the ambiguity.

iv. Even were the above - very plausible - interpretation of the non-uniform distribution of the values of ω incorrect, it appears quite evident now that the models of particular objects, which accept the observed orbital eccentricities as the real ones (as, e.g., for V1507 Cyg, AZ Cas, BY Dra, CH Cyg, or some X-ray binaries) may be incorrect and should be re-investigated. I do not see any good reason why all such binaries should have one particular orientation of their orbits with respect to the Sun. The masses derived on the assumption of reality of these orbital eccentricities must be equally incorrect.

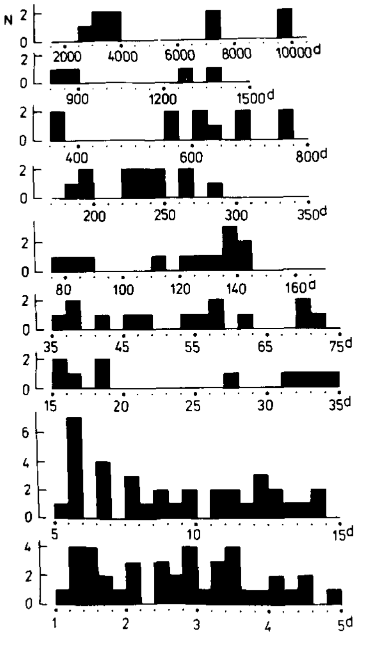
v. The orbits of many of these stars in fact may be eccentric but we have practically no information about their true eccentricities at present, with the exception of a few systems with well-established apsidal motions.

c) The distribution of orbital periods, displayed in Fig. 5, is also of great interest.

i. It shows that, if the list of known ELS in binaries is compiled without prejudice, the conclusion of Abt and Cardona (1984) about the near-absence of Be binaries with periods less than 10^{-1} yr is untenable. CX Dra ($P=6.7^d$), β Lyr (12.9^d), U Cep ($P=2.49^d$), FY Vel (33.7^d) V716 Cen ($P=1.49^d$), U CrB (3.45^d), RY Sct (11.1^d), RZ Sct (15.2^d), HR8153 (5.41^d) - all Be stars - may serve as counter-examples.

ii. A detailed inspection of Fig. 5 reveals a notable preference for certain values of the orbital periods and a near-absence of other values. One is strongly tempted to spectulate about the presence of various types of "spin-orbital" or even "orbital-orbital" resonances, reminiscent of puzzling resonances seen in the solar system. A careful investigation of this possibility seems quite promising (see below).

Fig. 5 The distribution of orbital period of known binaries with the ELS



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3 Long-term emission-line variations

The BM explains this characteristic property of ELS as a consequence of the variations in the rate of mass transfer from the secondary. Such variability is well-established for various interacting binaries - the cataclysmic variables being the extreme examples. It is probably more than a coincidence that the long-term spectroscopic and photometric variations of a number of Be stars are reminiscent of mild novae or some symbiotic stars. The exact physical mechanisms leading to these variations in cataclysmic or symbiotic binaries will certainly be quite complex. They may include cyclic angular momentum exchange between rotation and revolution (Biermann & Hall 1973), or disk instabilities (Duschl 1985). A correlation between the intensity of outburst and the time elapsed between two subsequent events has been established for cataclysmic variables (Bath and Paradijs 1983). This may naturally explain why cyclic but not strictly periodic variations are observed. It would therefore be of interest to look for a similar correlation also among Be stars.

4 Long-term V/R and RV variations

These are two of the most difficult to explain properties of Be stars. They have been quantitatively well explained by the BM on the assumption of a temporarily elongated envelope which is formed by a discontinuous mass-transfer burst and which revolves gradually in space due to the attractive force of the secondary (Kříž and Harmanec 1975, Kříž 1979). Recently, this model has been successfully applied to the explanation of superhumps in the light curves of cataclysmic variables (Vogt 1983). In spite of its apparent success, the model has not been generally accepted for the ELS because of doubts about the dynamical stability of the elongated revolving envelope. Hensler (1985) has modelled the process with numerical hydrodynamic calculations and found that the elliptical gas envelope in a binary system is able to survive for more than 20 orbital periods without being circularized due to tidal disruptions if the kinematic viscosity is reduced by a factor of 5-10 from the standard value. The BM is thus potentially able to explain the formation, amplitude, line-profile variations and cycle length of the long-term RV and V/R variations.

Baade (1985) has raised two other objections against it: i. The phase lag between the V/R curves of individual Balmer lines observed for some stars, and ii. the problem of "starting phases" of the variations. A more systematic observational study of the first point is needed. Baade quotes Slettebak's (1982) observations of 7 Be stars but an inspection of the original paper reveals that what was actually observed (on one or a few spectrograms per star only) was the presence of asymmetry in the H I emission and its absence in the Fe II emission or *vice versa*. This, of course, need not be evidence of a phase lag but only evidence that, say, the outer parts of the envelope are more elongated than the inner ones. The evidence for real phase lags in EW Lac and β^1Mon, quoted by Baade, is limited to only the initial, or final phases of the long-term variations, respectively. Such behaviour need not contradict the elongated-disk model, especially if one considers that large permanent envelopes were already present in both stars before the development of the V/R variations.

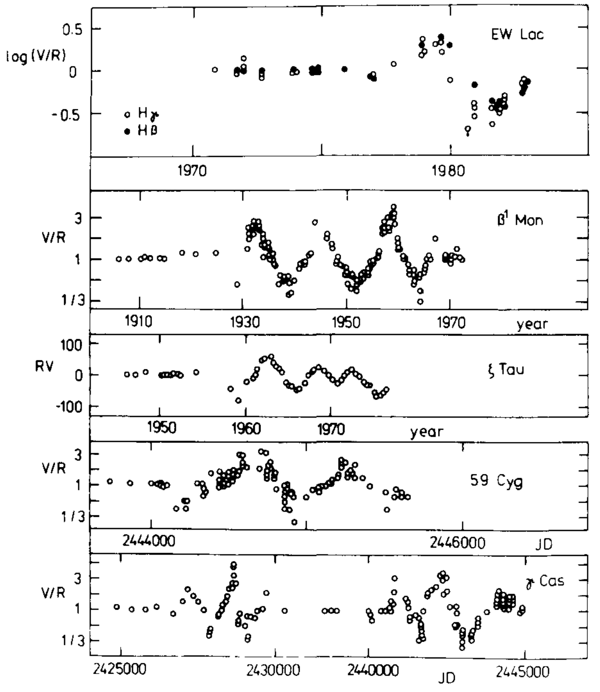

Fig. 6 Several examples of the initial phases of the long-term V/R or RV variation. The data were adapted from Kogure (1984), Cowley and Gugula (1973), Harmanec (1984a), Doazan et al. (1985) and Doazan et al. (1983)

As to the second objection raised by Baade, I find it rather artificial and non-existing in fact. Baade (1985) argues: "I could not find any case in which V/R or RV variations had started with a phase angle clearly different from 0 or 180 degrees." I ask: What else can happen when the V/R or RV variation starts than that the corresponding quantity begins to rise or decrease with respect to the previous steady value until it reaches its first local extremum? Figure 6 shows several examples of the starting phases of the long-term variations which illustrate that the objection raised by Baade is not serious. In conclusion, the search for a correct and detailed model for the long-term V/R and RV variations remains very difficult, but the BM has clearly achieved the highest degree of consistency on the way to its solution and appears worthy of further study.

5 Rapid line-profile and photometric variability

Rapid changes of ELS have been extensively studied in recent years. The spectroscopic research was inspired by the work of Smith (1977, 1978), Walker et al. (1979, 1981), Baade (1979, 1982a,b), and Bolton (1982) and carried on primarily by Vogt and Penrod (1983), Baade (1984), and Penrod (1986). The interest in rapid photometric variability was initiated by Percy and his collaborators (Percy 1979, Percy and Lane 1977, Percy et al. 1981) and by subsequent studies by Harmanec (1983, 1984b,c, 1986), Spear et al. (1981), Stagg et al. (1985), Balona and Engelbrecht (1986), and others. Thanks to this concentrated effort, the true periods of rapid variations have been established in several cases.

Three alternative interpretations of rapid variations have been considered so far: non-radial pulsations (NRP) (first proposed by Baade 1979), effects of rotation coupled with non-uniformly bright structures in the ELS atmospheres and/or envelopes (first considered by Walker 1953 and Walker et al. 1981), and the effects of orbital motion in a short-period binary (for detailed historical references see, e.g., Harmanec 1983, 1984b). There is still no really strong reason to prefer one of the above interpretations. The range of the reasonably well established periods (0.5 to more than 3 days) does not permit discrimination among the competing models.

As Vogt and Penrod (1983) showed, the line-profile variations can be accurately modelled either as rotating density spokes in the circumstellar disk or as high-order NRP. Vogt and Penrod estimated (for ζ Oph) that the eclipse of the stellar disk by each spoke should be about 0.05^m deep and used the lack of such a large photometric variability during 3.5 hours of differential V photometry, obtained simultaneously with the Reticon spectrograms, as a cogent argument against the spoke model. However, the geometry of their spoke model is such that the stellar disk must be eclipsed by 2-3 spokes simultaneously at any time! This reduces any photometric variations below about 0.02^m and changes their phase dependence with respect to that expected by Vogt and Penrod, thus invalidating their main (and only) argument against the density-spoke model for ζ Oph.

Harmanec (1983, 1984b,c, 1986) has called attention to the existence of double-wave light curves for several Be stars that are rapid photometric variables. Double-wave light curves have subsequently been found for practically all of the Be variables with well established periods (see Balona & Engelbrecht 1986 and references therein, and Balona, priv. comm.). They seem to be more easily understandable in terms of rotation or binary motion. Here, I want to demonstrate that whatever the immediate cause of rapid variations will turn out to be, it may have its origin in the duplicity of the ELS in question.

a) NRP:

The main current problem of the hypothesis of NRP is to find the excitation mechanism of pulsations in rapidly rotating stars. I have objected to this hypothesis intuitively (Harmanec 1983, p. 374) because the combined effects of rapid rotation, conservation of angular momentum and viscosity will probably work against pulsations in rapidly rotating stars. Osaki (1986) has discussed the possible mechanisms of excitation of NRP in massive stars, and he concluded that the rotation profile of a rapidly rotating, non-radial pulsator will tend to change quickly in such a way as to suppress the pulsational instability. However, Osaki mentions another plausible mechanism of excitation of NRP: a resonant generation of waves in binary systems with noncircular orbits or with non-synchronously rotating components. The predominant mode of such pulsations is the travelling mode with $l=\pm m$, in accordance with the current interpretation of line-profile variations of Be stars! Notably, Smith (1985), in his detailed study of NRP in Spica, found all of the safely identified modes to be resonantly coupled (or otherwise connected) with the orbital period. Considering the non-uniform distribution of the orbital periods of binaries with the ELS demonstrated above, this seems to indicate the possibility of obtaining a natural and powerful excitation mechanism of NRP within the framework of the binary model. Additionally, the spin-orbital resonances and the induced pulsations could possibly combine in their effect on the rate of mass transfer between the components. The proposals of Matese and Whitmire (1983) or van't Veer (1984) concerning mass motions in stellar

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interiors should also be mentioned in this connection.

b) Rotation

The interpretation of rapid variations in terms of rotation would imply that rapidly variable ELS are spotted stars and/or that localized density enhancements can exist in their circumstellar disks during some epochs. The density spokes considered by Vogt and Penrod may look curious but the solar streamers or density spokes in Saturn's rings are indisputable observational facts which document the existence of such structures in the Universe. Similarly, the Red Spot on Jupiter can be mentioned as an example of a large permanent "spot". As to indirect evidence, a recent model of σ Ori E by Bolton et al. (1986) should certainly be mentioned.

Clarke & McGale (1986) have recently proposed an interesting modification of the oblique rotator model for Be stars. They have argued that even a single enhancement in the number of free electrons in an extended rotating atmosphere may produce a double-wave light curve which is remarkably similar to the light curves observed for some Be stars. It is the form of the scattering function of the free electron that produces the double periodicity. Variations in the number of free electrons can also naturally account for the observed variations in the amplitudes and shapes of such curves.

The interpretation of Be stars as "spotted" stars seems to be strengthened by the striking similarity of the Be-star light curves to those of RS CVn binaries (Balona and Engelbrecht 1986, Harmanec et al. 1987 - in preparation). RS CVn's are now generally considered to be spotted stars (see, e.g., Hall 1981). As a matter of fact, this analogy may go far beyond the similarity of the shape of the light curves. For instance, the correlation between the long-term variations of the strength of the H I (and other) emission and amplitude and shape of the periodic light curves are remarkably similar for both groups. Detailed studies of RS CVn binaries indicated that virtually all these binaries exhibit some Hα emission, though it is often very weak and variable (Bopp 1983). Also, the discovery of gas streams in one RS CVn system has recently been reported (Huenemorder 1985). One may thus speculate that the RS CVn circumstellar envelopes are not so dissimilar to the Be envelopes and vice versa. Detailed studies including light-curve and line-profile modelling will be needed but the possibility that duplicity is a key element in producing the phenomena observed in both kinds of stars cannot be ignored at present.

c) Duplicity:

The combined effects of ellipticity, reflection and geometrical eclipses (in particular cases) have also been invoked in the interpretation of the periodic light curves of some Be stars. In several cases this interpretation was later abandoned because of either the lack of accompanying RV variations, and/or the variability of the light curves and the absence of light changes at some epochs.

The lack of eclipsing systems with deep eclipses is an additional objection against this model as a general model of rapid variations of

ELS. I am now inclined to believe that these objections can be overcome and that this model also deserves further study. The following comments can be made in favour of a possible binary interpretation of the rapid variations observed.

First, it is interesting to note that the distribution of the orbital periods of known B-type binaries has a sharp peak between 1 and 3 days (Harmanec 1981), which rather favourably compares with the observed periods of rapid Be variables. In fact, the periods longer than, say, 1.5 days are more easily understandable as binary periods than as rotation periods (no restriction on the range of NRP periods being apparent at present).

It is true that the statistical studies of the distribution of the mass ratios of known binaries (e.g., Lucy & Ricco 1979) indicate a strong tendency toward equal mass binaries. However just these systems are usually most easily recognized as binaries. One has to expect unequal mass ratios for interacting systems, and many of them may have remained unrecognized as binaries. The low-mass companions would cause neither observable RV variations nor deep eclipses of their primaries, but they would affect the shape of the primaries, which would produce measurable light variations with the orbital period. (Some short-period massive X-ray binaries may serve as examples of such systems.) The amplitude of the light variations will depend strongly on how much circumstellar gas is present in the system at the time of observation, i.e. how large is the filling factor of the Roche lobe around the primary. In cases of either strong mass transfer between the components or in cases when the close binary itself accretes mass from a more distant third star, an envelope can form around the whole system. Hutchings and Hill (1971) and recently Pustylnik and Einasto (1984) modelled the effects of such a circumstellar envelope and showed it can indeed produce a double-wave light curve reminiscent of ellipsoidal variables. On the empirical side, I recall that the optical light curve of the Ae + X-ray binary HZ Her varies from approximately single-wave curve in active phases to a double-wave curve with two nearly identical minima and maxima during inactive phases (Hudec & Wenzel 1976). This is closely reminiscent of the variations of the light curves of the "normal" ELS. Anyway, the observed correlation between the presence of circumstellar matter and the amplitude of the light variations seems understandable if the light variations are indeed produced as indicated above.

Kříž and Harmanec (1975) have pointed out that if the observed absorption lines arise in an envelope around the whole binary, their RV's will still reflect the motion of the brighter component but their amplitude will be reduced by the 1.5 power of the distance of the envelope from the system's centre of gravity. A possibility, which should be investigated quantitatively, exists that this effect could be used to construct an acceptable binary model for ELS like 28 CMa. Baade (1984) has shown that the narrow absorption lines in the optical spectrum of 28 CMa, which change their RV with a period of 1.37 days, cannot be identified with the spectral lines of a secondary component, as I suggested some time ago (Harmanec 1981, 1982, 1983). They might however, be understood as shell lines originating in an outer envelope around the whole binary. It seems to me that such a model might have also the potential to explain the observed (single-wave) variations of the width of the He I lines, the different RV amplitudes of different lines (a phenomenon observed in many interacting binaries) and the disappearance of the periodic light variations in the phase of the overall weakening of the H I emission.

If orbital motion is accepted as the clock directly responsible for the rapid variations observed, the present classification of time scales would have to be changed. Rapid variations would become a part of the orbital variations in general. In fact, the light curves of CX Dra ($P=6.696^d$), RX Cas (32.3^d), KX And (38.9^d), AX Mon (232^d), and other known ELS binaries (see Harmanec 1983 for the original references), and their time variations bear a close resemblance to those of some short-period variables.

6 Superionized regions?

The discovery of the strong resonant absorption lines of C IV, Si IV, or N V in the UV spectra of the ELS (for a review see, e.g., Marlborough 1982) led to various considerations about the coexistence of cool and hot circumstellar regions and about the presence of chromospheres and coronas around the ELS (c.f. Doazan and Thomas 1982). Hubený *et al.* 1985, 1986 have called attention to the heavy line blending in the UV spectra of hot stars. They warned that the evidence of the presence of superionized regions in the majority of the ELS may be less strong than usually believed. The strongest evidence rests on the X-ray observations, but only a few ELS have been detected as X-ray sources apart from known X-ray binaries and RS CVn's. The UV resonant emission lines reported by Plavec and Koch (1978) for some ELS binaries may be another piece of evidence for superionized regions, but they have been interpreted as evidence for hot accretion regions caused by matter infalling from secondaries.

If the existence of chromospheres could be firmly established for the ELS, the similarity of the early-type ELS to the RS CVn binaries (for which the presence of active and variable chromospheres is normally considered) would be strengthened.

Anyhow, the UV spectral phenomena observed for the ELS do not appear conflicting with the BM, although no clear causal connection is apparent at present.

7 Narrow blue-shifted absorption components of the strong spectral lines

The interest in the blue-shifted, and sometimes multiple narrow absorption lines has revived, thanks to UV spectroscopy. However, as I pointed out recently (Harmanec 1983), the same phenomenon has also been observed in the Balmer lines, though notably only for stars of spectral type B2 or earlier. For most stars, the data are scarce and do not permit detailed studies of possible regularities in the time behaviour (although this statement may become invalid during this meeting). Therefore, the relation to the BM is unclear.

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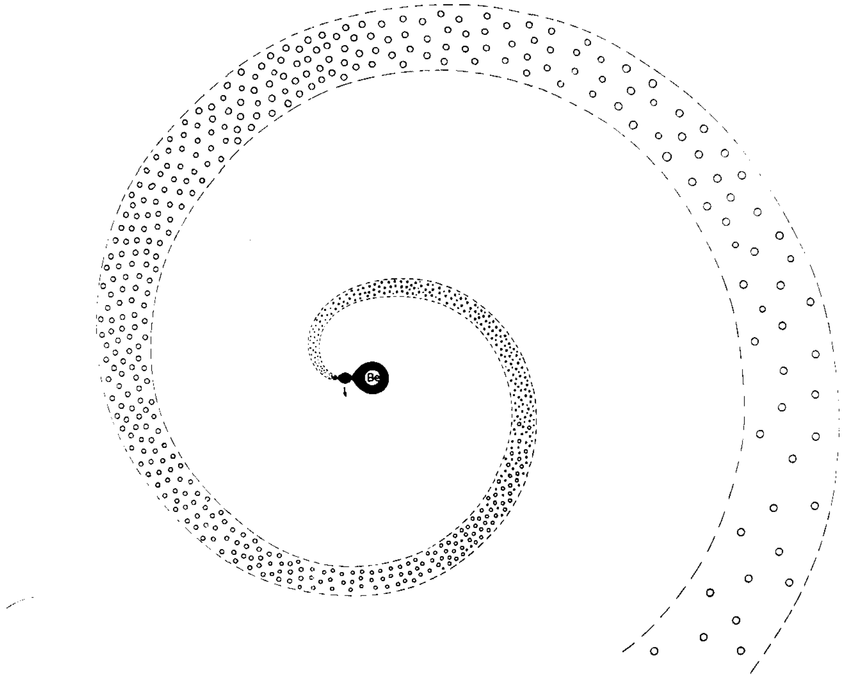
Following is my speculation how the occurrence of the blue-shifted multiple lines could be connected with the duplicity. Schuerman (1972) investigated the effect of radiation pressure of one binary component on Roche equipotential surfaces. His results show, among other things, that the mass-losing star may more easily lose mass through the outer Lagrangian point L_2 with the increasing effect of radiation pressure and that the material escaping from the binary has access to large distances from the orbital plane. The probable geometry of the outflow is depicted in Fig. 7. It is clear that "separate multiple shells" of material can be formed in this way, provided the outflowing material is accelerated

Fig. 7. A binary with an outflowing outer envelope which can potentially simulate separate expanding shells of material.



radially and the mass outflow is dense enough so that the identity of several spirals is maintained before their dispersal. Thanks to the (potentially) large spread of material out of the orbital plane, this configuration may produce the shell absorption lines even when viewed at inclination angles significantly different from the equator-on configuration. Even mild variations in the rate of mass transfer and outflow could speed up or delay the appearance of each "new shell" in projection against the stellar disk, thus causing the release of shells to appear cyclic rather than strictly periodic.

As first noted by Kolka (1983) and recently supported by van Gent and Lamers (1986), new expanding shells of P Cyg seem to be released at about 60-day intervals. The latter authors also found a possible pseudoperiod near 30 days in the photometric data. I tentatively propose to identify P Cyg with a strongly interacting binary of a low mass ratio in the phase of a rapid mass transfer and mass loss from the system. A plausible value of the orbital period would be about 60 days, which would imply a double-wave light curve. (Notably, the 62-day or 31-day orbital period has recently been suggested for GG Car, another very peculiar Be star with P Cyg profiles, by Gosset et al. 1984, 1985).

Conclusions

The available data are insufficient to test possible duplicity for the majority of even bright Be stars. The BM seems to offer a consistent interpretation of those ELS which have already been known as binaries but to what extent it can be considered as a general model of the emission-line phenomenon remains an open question.

I am personally still convinced (and I tried to collect and present some evidence) that the binarity may be the "fundamental" cause of the emission-line phenomenon and that the BM is capable of incorporating most of the existing models of particular phenomena observed in the emission-line stars.

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DISCUSSION FOLLOWING HARMANEC

Tarafdar:

In the binary model matter is ejected from one component and moves into the surrounding region of the other star. The matter starts with high angular momentum corresponding to the velocity of the component of origin. The matter has to lose angular momentum to fall near the other star. Can you explain how is the matter losing its angular momentum at the low density in the circumstellar region?

Harmanec:

According to available models of accretion disks it appears the matter is gradually spirally towards the star, and the accretion is not immediate. This could account for the high rotation velocities of Be stars, incidentally. Velocity effects - if important - will force the disk to solid-body rotation; therefore redistribution will cause the inner points of the disk to have lower than Keplerian rotation and spiral towards the star, and the outer parts to get to higher orbits, thus filling gradually the whole volume of the Roche lobe.

Smith, R.C.:

You showed a diagram with a mass transfer stream and concentration of mass both in a dish around the accreting star and near the edge of the Roche lobe. The concentration near one edge occurs only in the initial flow. If a disk is formed, it will do so as a result of viscous interactions, which will rapidly destroy the non-circular motions needed to maintain any mass concentration near the outside of the Roche lobe. So you cannot simultaneously have mass concentrations in a disk and near the edge of the lobe.

Harmanec:

These effects must depend on the absolute radius of the Roche lobe around the mass gaining star. I believe that in longer-periodic systems or in systems with a lower rate of mass transfer the identity of the density enhancement above the leading hemisphere can be maintained. Hydrodynamical calculations including the disk-stream interaction are certainly needed, but penetration of the disk by a stream has been discussed in connection with the symbiotic and cataclysmic binaries. Anyhow, the observational evidence is that the bumps in the lower parts of the R/V curves that I explain by the effect are highly variable from cycle to cycle.

Percy:

Regarding evolutionary events which might lead to the Be phenomenon: don't forget that the majority of early B stars are observed to develop pulsational instability (admittedly of the β Cephei type) towards the end of their core hydrogen burning evolution.

Harmanec:

Defending the binary hypothesis of the Be phenomenon, I do not deny the existence of physical processes in stars. In fact, I have had the impression that the early Be stars may indeed be "animals" different from the later-type Be stars, or at least that some additional effects influence the early B stars.

Peters:

The Balmer emission in HR 2142 appears to come almost entirely from the accretion disk. We do not see clear evidence of emission from the gas stream or any other regions of possible density enhancement. I do not see how your model can explain the temporal behavior of the narrow components in some Be stars. It appears that the pattern of the components (i.e. number, velocity, strengths, etc.) is unique for each star. Even if

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variations are confirmed, the new pattern appears to also be unique for the star. In one star, 66 Oph, the pattern and temporal trend repeat.

Harmanec:

The role of outflow via the L2 point must be very sensitive to the stochastic perturbations due to the interplay between the rate of mass outflow, variations of the angular momentum, thus variations of the orbital period, visibility of the components depending on the distance from the star, density and velocity. I do not think other hypotheses succeeded to solve all these problems, either. But, I stress again that a really quantitative model is necessary and, fortunately, perhaps possible in the case of the proposed model. At least the natural formation of *separate* shells due to *continuous* mass outflow appears to be a strong point of the model of the outflow via L_2, I think.

Buscombe:

The reasons observers determined radial velocities of B stars more than 100 times each were usually either (a) they were known β CMa pulsators or (b) by having sharp lines the particular stars were selected to test spectrographic instrumental adjustment, and in several cases e.g. τ Sco and HD 79447, were eventually found also to be β CMa pulsators!

Harmanec:

I would add interacting binaries, bright supergiants and long-term V/R variables; all of them are found among emission- line stars, with many available radial velocities.

Smith, M.A.:

Regarding your comment on "stellar spokes", the Vogt and Penrod example you chose, ζ Oph, is one in which the "spoke velocity" is comparable to the estimated rotational velocity of the star. Even here it is a bit high, in excess of 500 kms^{-1}, and it is already a bit problematical to see how the spokes could orbit at such a high, super-Keplerian velocity. A better case in point would be Spica, in fact, where the profile-feature velocity and the well-estimated rotational velocity match closely - but this would undermine your binary connection for that star!

However, the important point is that if one looks at the relevant timescales, the "superperiods", indicated by traveling spectral bumps in a variety of B stars, one finds that in some cases they are shorter than P(rot), and in other cases longer. One can play around with estimates of sini and stellar radii, but there are a number of stars for which one cannot juggle these numbers and get the superperiods and rotational periods to match. It is difficult to see in these cases how the spoke interpretation could be saved.

Harmanec:

My point was that nonradial pulsations for Be stars became a fashion on the basis of the evidence which is not as convincing as the authors declared. As you have seen, I am prepared to accept the existence of nonradial pulsations in rapidly rotating stars if I can see some powerful mechanism like the spin-orbital resonances I mentioned to be able to produce it. Otherwise, I think we should also confront the observations with other possible models.

Dachs:

By repeated measurements of Balmer emission line profiles within a couple of weeks or months, you can easily be able to pick out binary Be stars of the type of ϕ Per or Peters' star (HR 2142), from their V/R variations. According to our experience, there are no other binary candidates of this type in our sample of about 50 stars.

Harmanec:

Frankly speaking, I am aware only four Be binaries for which this phase-locked V/R variations have been established. Besides the objects you mention, 88 Her, 4 Her, and TT Hya come to my mind, unless you wish to include 28 CMa, HR 2370 or V 1339 Aql, which may or may not be binaries. The detectability of the phase-locked V/R variations must certainly depend on the relative dimensions of the emission-line envelope with respect to the corresponding Roche lobe or alternatively on the emissivity of the gas stream between the components. In any case, I agree with you that a period analysis of the V/R variations observed could potentially help us to recognize new Be binaries.

Henrichs:

It seems to me that ejected matter from L_2 will basically stay in the orbital plane, as all accelerating forces act radially away from that point. This makes it difficult to explain how such matter can cause discrete absorption components as these are very frequently observed, in more cases than one would expect from your model.

Harmanec:

Well, it is a kind of expansion into vacuum and Hadrava's preliminary hydrodynamic calculations show a substantial broadening of the stream perpendicularly to the orbital plane.

Baade:

In my opinion, you have put Jupiter's Great Red Spot (GRS) into the wrong category: Even though it is called a spot it actually is a velocity field which bears some resemblance to Rossby waves. As such the GRS is an example that velocity fields can be asymmetric and stable which is also required to explain double-wave light curves of Be stars in terms of nonradial pulsations.

It is remarkable that at least a very large subsample of the Be stars observed in Hα by Dachs and collaborators and in the far IR by *IRAS* seem to have disks with surprisingly homogeneous properties. These disks are therefore either all due to mass loss or all due to mass accretion from a companion. Is it alternatively possible to fit the *IRAS* data with accretion disk models?

Lamers:

Yes. The *IRAS* data provide information on the density and density structure of the disks, which we found to fit a $\rho \sim r^{-n}$ with $n \simeq 2.5 + 0.5$ relation. If accretion disks can have this density distribution, they can explain the IR excess too. The *IRAS* data do not give information on the velocity. So, in principle the disk could be due to accretion. The main argument for outflow rather than inflow comes from the profiles of lines seen in presumably edge-on shell stars which show violet asymmetries (Oegerle and Polidan, 1982).

Waters:

The *IRAS* observations of a large number of Be stars show that in the case of binaries with well-known late-type components the far-IR radiation is dominated by the late type companion, and are clearly different from the bulk of the Be stars. This shows that the companions of Be stars cannot be of late (G,K,M) spectral type and luminosity class I-III.

Harmanec:

I agree. This is why I have shown you the histograms showing the distribution of the spectral types of the secondaries of the ELS binaries. There is no preference for

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some spectral types, all spectral types are seen. It is probable that binaries with late-type secondaries are more easily detectable as binaries; perhaps just those with the early-type secondaries await to be discovered as binaries.

Peters (responding to comment by Waters):

I am skeptical about your claim that the presence of late type companions can easily be detected in *IRAS* data. I will definitely agree that the M or even K stars are revealed. But the IRAS data on the interacting binary Be star HR2142 do not show evidence of the mass-losing late type companion which we know must be present.

Waters:

If the late-type companion is subluminous, it may be difficult to detect it in the far-IR, especially in the presence of a dense circumstellar disc around the primary Be star.

Snow:

One of the most important observational results reported here this week is that there is a definite connection between the Be phenomenon and the presence of discrete absorption components observed in the ultraviolet. I think this presents difficulties for the binary hypothesis. In particular, your model needs to more fully address the following components: velocities as high as several hundred kms^{-1}; the time variability (sometimes in hours) of the components; and the fact that these components occur in most Be stars. It seems to me that the binary model requires fairly special conditions in order to produce the components, and has difficulty explaining both their velocity and variability.

Harmanec:

I would not be that skeptical at the moment. The model of the outflow via the outer Lagrangian point L2 seems quite promising to me to be investigated in detail. Even without the radiative pressure you obtain the outflow velocities of the order of -100 kms^{-1}. If you add the effect of the radiation pressure, you would probably increase the velocity of the shells to much higher values. No doubt, quantitative modelling is needed but we hope to work in this direction. Another plausible possibility is that the narrow components are due to some physical process intrinsic to Be stars but even then it is possible that this mechanism is triggered by the binary interaction. Many known Be binaries do show multiple narrow components and phase-dependence on the orbital width has been established in a few sufficiently well studied cases.

Underhill:

When discussing discrete components you indicated that it was a question of release from a point in the equipotential surfaces of two stars. Underhill and Fahey (1984) also emphasized that you must have releases from a point. In their case it was release from a point on the surface of the star. Underhill and Fahey discussed also the acceleration of the released material and what that did to its trajectory. To get a configuration which will give discrete components you must have release from a point.

Harmanec:

Thank you for the comments. My model indeed assumes a point-like origin of the outflow.

Grady:

Your suggestion that discrete components may be caused by mass loss from the L2 point in an interacting binary system has two difficulties. 1) Discrete components in 11

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Be stars are known to appear and disappear episodically. In two systems, 59 Cyg and 66 Oph, there is *no* suggestion of periodicity. 66 Oph was quasi-regular for 3 years (Grady *et al.* 1987) but is currently running late by 1 year. 2) Using γ Cas as an argument for binarity of all Be stars is shaky. This star is one of two hard x-ray sources known among Be stars, and differs dramatically in wind characteristics from essentially every other Be star observed by *IUE*.

Harmanec:

I can only repeat my replies to Henrichs and Peters. Quantitative modelling is needed.