6. Be STARS: CIRCUMSTELLAR ENVIRONMENT

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VARIABILITY IN THE CIRCUMSTELLAR ENVELOPE OF Be STARS

A.M. HUBERT
Observatoire de Paris, section d'Astrophysique de Meudon
URA 335 du CNRS, F-92195 Meudon Cedex, France

Abstract. A progress report will be given on recent studies of circumstellar variability of Be stars, their implications on the formation process, the dynamics, the structure and the morphology of the envelope. The following points are discussed: recurrence of outbursts, simultaneous infall and outflow events, variability in hot regions versus variability in the cool envelope, the establishment and vanishing of Be and Be-shell phases, periodic medium-term and quasi-periodic long-term phenomena, and constraints on models.

1. Introduction

The main difficulty in establishing envelope models for Be stars lies in the complexity of the observed phenomena, in their wide time-scale variability (days, months, years), and in the fact that they are superimposed on short-term variations of the central star. Rapid variability can be generated by shocks, local density enhancements and discrete mass-loss events. Long-term variations are a sign of global change in the circumstellar envelope, but their connection with the properties of the central star is still very difficult to establish. Intensive observations of a few stars over several months or years and using various techniques, have improved our understanding about the nature and time scale of circumstellar variability.

In view of the great number of publications in the field and of the length allowed for this review, it is of course incomplete and I apologize in advance for omission of any important points.

2. Outbursts - Simultaneous Infall and Outflow

In the star μ Cen the birth of the envelope is not the result of a continuous process, but of separate individual events or outbursts (Hanuschik *et al.* 1993 and references therein). The stronger the Hα emission, the longer the Be phase (Peters 1984, Baade *et al.* 1988). C II line profile changes, as well as dramatic V/R variations, are present during the rising phase of outburst, but disappear at maximum and thereafter. Hanuschik *et al.* (1993) analyzed the development of major and minor outbursts over a 200-d interval in 1987 and proposed a decretion-accretion model with magnetic activity producing the ejection process.

The geometry and the kinematics of the circumstellar material in λ Eri during the outbursts of 1987–1988 have been investigated by Smith *et al.*

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(1991). High-velocity emission and absorption features in the He I λ 6678 line have been interpreted as the signature of vertical motions of ejected blobs returning to the star. The variation of the separation of the Hα emission line peaks was explained by the slow expansion of a detached, thin, quasi-Keplerian disk. The complex structure of the Hα emission line profile during minor outbursts could be interpreted as the result of a "continuous" rain onto the star of low-angular momentum material from an unstable ring in low orbit.

Recurring shell-infall events in FY CMa were detected in the UV by Grady *et al.* (1988) between 1979 and 1988. Peters (1988) has noted the coexistence of red-shifted circumstellar lines of low- and moderately-ionized species and narrow violet-shifted components in the N V lines. Similar observations have been made for the Be-binary systems HR 2142 and ϕ Per. A possible explanation for these simultaneous violet- and red-shifted components could be a rapidly decelerated gas colliding with the stellar wind. The resulting shock produces a high-temperature region where the N V resonance lines and the He I emission component could be formed.

Short-lived outbursts are usually detected in early-type Be stars, but they can also be present in late-type Be stars. Indeed, Ghosh *et al.* (1989) reported a short-lived outburst in Hα and in the C II λ 6578 emission lines for the B9e star HR 4123. They estimated that the Lyman continuum radiation has to be enhanced by a factor of 10^4 to explain the strong temporary Hα emission, though they did not include ionization from the second level of hydrogen.

3. Hot Regions—Cool Circumstellar Envelope

From a multi-technique analysis of the ω Ori outburst during 1982–1983, Sonneborn *et al.* (1988) at first explained the lack of correlation between the highly-ionized UV lines, the polarized continuum and the visual flux by a spatial separation between the wind acceleration and the inner part of the disc. However, Brown & Henrichs (1987) made a more quantitative analysis of the same data, and argued that two types of mass loss could be present: an isotropic density enhancement effect, and an episodic highly-flattened mass ejection.

Coordinated far-UV and optical observations of 59 Cyg from 1978–1987 allowed Doazan *et al.* (1989) to describe the formation and evolution of a new, cool, Hα emitting envelope and to discuss modelling implications. They concluded from their data that the mass outflow is highly time-dependent and interacts strongly with the cool envelope.

A Be star atlas of far-UV and optical high-resolution spectra was published by Doazan *et al.* (1991). It contains selected spectral regions in the UV and visual wavelengths for 166 Be stars.

4. Establishment and Vanishing of Shell Phases

Changes in the mass-loss rate and in the radiative flux are thought to induce variability in the opacity, the size, and the geometry of the envelope and to give rise to an alternation between a quasi-normal B phase, and a Be or a Be-shell phase, as is commonly observed for many stars.

An alternation of Be and Be-shell phases in 27 CMa from 1985–1989 was reported by Ghosh (1990). P Cyg profiles in Hα appeared several months before a new shell phase, indicating a strong episodic mass loss.

Having been observed for more than one century, Pleione is well-known for its alternation of B, Be and Be-shell phases. The light variations associated with phase changes in its envelope has often been described in the literature. Radiative energy flux changes in the far UV through the Be-shell and the Be transitions were considered by Doazan *et al.* (1993). The apparent continuum level increases in the UV at the time when the strong shell phase is vanishing. A decrease of the UV flux during a shell phase was reported, for the first time, by Beeckmans (1976) for 59 Cyg. It was explained by the large number of absorption lines and enhanced continuum and line opacity (see also Slettebak & Carpenter 1983).

The last Be-shell phase of Pleione, observed from 1973–1986, has been extensively described in the visual range by many authors. Ballereau *et al.* (1988) have interpreted the increasing negative radial velocity of the shell lines associated with a decrease of the emission-line peak separation as being due to an expanding phase of the envelope. According to Doazan *et al.* (1988), the fading of the shell lines is accompanied by the appearance of C IV and Si IV resonance lines. Strong features in the Mg II resonance lines are present at the maximum of the shell phase. This is similar to the strong feature in the Ca II resonance lines discovered by Hirata & Kogure (1976) at the beginning of the same shell phase and interpreted as due to the ejection of a dense, rapidly-rotating ring.

According to Koubský *et al.* (1993), quasi-emission central bumps have been detected in the metallic shell lines of 4 Her: they are associated with the establishment of a new Be-shell phase. Up to now, such bumps have been observed only in the photospheric lines of B and Be stars (see e.g. Porri & Stalio 1988, Baade 1989). They were at first interpreted as an effect of equator-to-pole variations of photospheric parameters (Baade 1990), then of cool polar stellar caps (Jeffery 1991). Is there a physical connection between the quasi-emission central bumps in photospheric and shell lines?

A recent phase change in X Per has been reported by Norton *et al.* (1991): it has reverted to a "normal" O-B absorption-line star. A decrease in the IR flux by over 1 mag accompanied the disappearance of Hα emission, indicating that the same regions are responsible for these variations.

5. Medium-term Periodic Variations

In this section we consider only medium-term periodic variations observed in binary Be stars.

Periodicities in the variation of line profiles (V/R ratio, radial velocity), in light, and in the level of polarization—as well as the presence of additional absorptions due to gas streams at certain orbital phases—provide very interesting information on the interaction between the gas and the stellar components and on the geometry of the envelope in Be binary systems. However, in such binary systems the photospheric lines of the primary, and sometimes also of the secondary star, are strongly affected by the circumstellar features. Even if the spectral lines of the companion are detected, it is often difficult to determine accurately the true radial velocity and the mass function. The following examples are illustrative.

The radial velocity curve of 4 Her based on photospheric lines has lower amplitude and eccentricity than the curve derived from shell lines (Koubský *et al.*, these Proceedings). This difference can be interpreted as a consequence of a mass transfer effect.

The puzzle of KX And (Štefl *et al.* 1990) has to be recalled: the photospheric He I radial velocity of the presumed primary star is in phase with the radial velocity of the shell lines, but shifted by about -100 km s^{-1}!

In ϕ Per there is no evidence for the photospheric lines of the secondary, but only lines which originate from the circumstellar gas around this star have been detected (Poeckert 1981; Gies *et al.* 1993). Furthermore, there is an important circumstellar contamination of the photospheric lines of the primary. Depending on the lines selected and the method of measurement, a difference in the amplitude of the radial velocity of the primary and the secondary is obtained. Compare the values obtained by Gies *et al.* (1993), and on the other hand those determined by Harmanec *et al.* (these Proceedings). It is clear that in such systems the determination of the mass of each component is very difficult.

An important point concerns the number of Be stars in which a cool companion overflows its Roche lobe. The number of such systems is in fact very small. In the past, several Be binaries have been proposed as Be stars associated with cool giant companions, but this has never been really established. The presence of a cool companion was not confirmed in ζ Tau (Floquet *et al.* 1989) and in HR 2142 (Waters *et al.* 1991). Baade (1992) did not succeed in finding new candidates in a survey in the southern hemisphere. However, some detections were nevertheless confirmed, as in the cases of KX And (Floquet & Hubert 1991) and CX Dra. This last example has been revealed as an interacting system. There is evidence for a gas stream and the satellites of UV resonance lines depend on the orbital phase (Horn *et al.* 1992 and references therein). Disruption of the axial symmetry of the envelope has been detected from the variation in polarization (Huang *et al.* 1989), in agreement with the model of Brown & Fox (1989).

The possibility of a high mass-transfer rate was investigated in the case of several interacting binaries with Be primaries. The answer is negative for AX Mon, which has revealed no significant change of its orbital period over 20 years (Mastenova 1989), and positive for β Lyr (Harmanec 1990 and references therein). Furthermore, a flux excess in the mid-UV region attributed to the presence of an accretion disc, has been detected in some Be stars with giant companions (Parsons *et al.* 1988). While some Be binaries may have an accretion disc, it is clear that the circumstellar envelope of the majority of Be stars in binary systems is produced by ejection from the star itself. According to Pols *et al.* (1991), companions to Be stars should preferentially be helium stars and compact objects.

Newly-discovered spectroscopic Be binaries include 17 Tau, η Tau, 48 Per, β CMi (Jarad *et al.* 1989), κ Dra (Juza *et al.* 1991), V923 Aql (Koubský *et al.* 1989), *o* And B (Hill *et al.* 1988), HD 45677 (Halbedel 1989) and the X-ray transient source V568 Cyg (Blanco *et al.* 1990).

The periodic V/R variations may be explained either by obscuration due to a binary companion, or a hot spot created by the stream impact upon the accretion disc, or composite emission from an ionized region created by a compact object and from the Be star envelope (Apparao & Tarafdar 1989). Recently Chakrabarti & Wiita (1993) proposed that the V/R variations could also be the result of effects of spiral shocks on the disc.

6. Long-term Quasi-periodic Variations

The history of variable shell stars is mainly based on spectroscopic information. During the last few years, photometric and polarimetric data have been progressively obtained (e.g. Percy *et al.* 1992, McDavid 1990; see also Borkjman, Arsenijevic *et al.* and Pavlovski *et al.* in these Proceedings). The study of the correlations between long-term variations of light, colour, emission-line strengths, radial velocities of shell lines, and polarization levels will introduce new constraints on quantitative envelope models. In particular, polarization should be a very powerful tool for studying the morphology of envelopes. A partial illustration of such correlations is given in Figs. 1a and 1b.

6.1. Long-term V/R Variations

The most important studies in recent years concern EW Lac (Hubert *et al.* 1987a), V1294 Aql (Ballereau & Chauville 1989), 59 Cyg (Doazan *et al.* 1989), γ Cas (Horaguchi *et al.* 1993, Telting *et al.* 1993), ζ Tau (Mon *et al.* 1992), and V923 Aql, the twin of ζ Tau (Koubský *et al.* 1989), whose observed radial-velocity variation arises from a superposition of cyclic long-

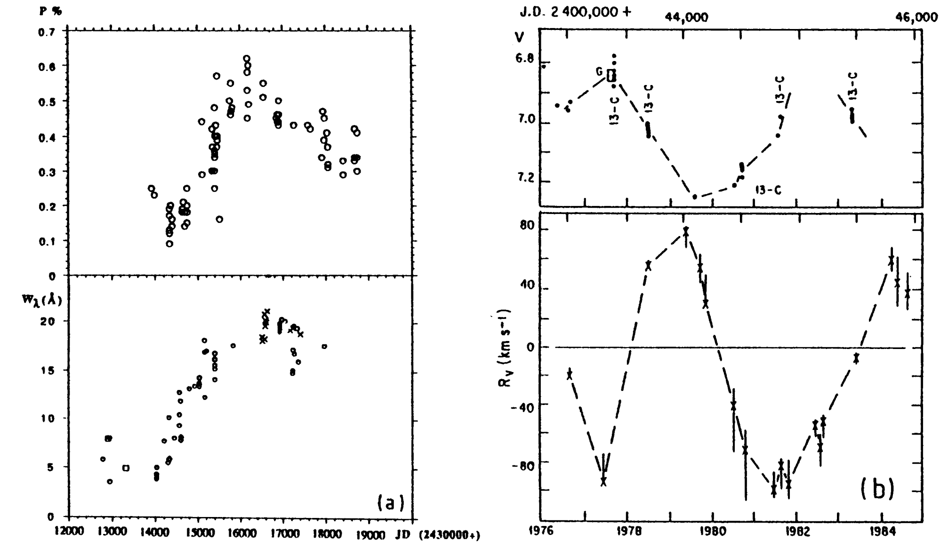

Fig. 1. **(a) The relation between the equivalent width of the Hα emission line (OHP + literature) and the intrinsic polarization (Belgrade Obs.—Arsenijevic and coworkers) in κ Dra. (b) The relation between the magnitude variation and the radial velocities of shell lines in V1294 Aql (Alvarez *et al.* 1987).**

term velocity variations of variable amplitude and with cycle length of an orbital period.

A summary of typical features of long-term V/R variations can be found in Okazaki (1991): cycles range from years to decades, are insensitive to spectral type, and tend to cluster around 7 years on average (e.g. Hirata & Hubert-Delplace 1981). There is a blueward shift of the whole profile when the red emission component is stronger, and vice versa. There are phase lags between V/R cycles of individual lines as in EW Lac (Kogure & Suzuki 1987), in ζ Tau (Hubert *et al.* 1987b) and in γ Cas (Horaguchi *et al.* 1993).

Information on the light variation associated with the radial velocity or the V/R variation is lacking, though it would be very useful for testing various models. There is only one example, that of V 1294 Aql, in which a phase lag of about 0.15–0.20 period is found between the minimum of the radial velocity and the maximum of the light curve (Fig. 1b). Up to the end of the eighties, the cyclic V/R variations were interpreted with qualitative models: a symmetric rotating-pulsating cool envelope or an elongated disc in apsidal rotation (e.g. Telting *et al.* 1993). Though still very simple, a quantitative model has been recently proposed by Kato (1989) and Okazaki (1991): the one-armed oscillating, quasi-Keplerian disc. These authors suggest that the possible global oscillations of a quasi-Keplerian disc are low-frequency and one-armed, since neither global axisymmetric oscillations, nor global non-axisymmetric oscillations are persistent except for these one-armed modes.

The elongated disc model is a geometrical version of the hydrodynamical one-armed oscillation model.

There are two variants of the one-armed oscillating disc: the first one by Okazaki (1991), considers that a modal precession results from pressure forces in the disc. The eigenmodes are strongly dependent on the outer edge of the disc and on the density gradient in the radial direction. Modes are generally retrograde, and periods range from years to decades. They are insensitive to the spectral type of the star, in agreement with observations. As the one-armed oscillation is multiperiodic, a new analysis of previous data is needed to verify this property.

The second variant is by Papaloizou *et al.* (1992) and Savonije & Heemskerk (1993) and takes into account the deviation from a point mass potential for the rotationally flattened star. This deviation forces elliptical particle orbits to precess, and the precession can manifest itself as a low-degree ($m = 1$) mode with a low pattern speed. In this frame, modes are found to be prograde, naturally confined to a few stellar radii, and rather insensitive to the size of the disc or to its density distribution. Observed periodicities of the V/R variations can be reproduced by this model for plausible values for the Mach number of the disc and for the stellar rotational deformation.

According to Okazaki (1991, 1992 and these Proceedings) and Hummel & Hanuschik (these Proceedings), the global one-armed oscillating disc model seems to be promising for explaining:
- the phase lag between the radial velocities of individual lines,
- the long-term variations of Balmer line profiles for both optically thin and optically thick discs and
- the phase lag between the light variations and the radial velocity variations of the shell lines and also the V/R ratio variation.

It must be emphasized that measurements of the Hα disc of γ Cas by the I2T, GI2T and Mark III interferometers (Thom *et al.* 1986, Mourard *et al.* 1989, Quirrenbach *et al.* 1993) seem to favour a deviation from angular momentum conservation in the envelope and support the quasi-Keplerian motion assumed in the theory of the one-armed oscillating model. However, this model does not take in account the effects of viscosity and envelope expansion which is often observed. Detailed comparison with observations must await calculations of the nonlinear evolution of the disc oscillations.

7. Conclusions

This review concerns only variability in the circumstellar envelope. Yet, one of the more crucial problems in Be-star research is the detection of a physical relation between the short-term stellar variations and long-term activity (or active and quiescent phases). This question remains open. A correlation between the amplitude of the line profile variations and Be episodes was found for ζ Oph and for λ Eri by Kambe *et al.* (1993a,b), but Smith (1989) failed to detect such a correlation in the later star. Another fundamental problem concerns the difference between the cool envelope of a Be star and of a Be-shell star. The conclusions given by different authors conflict on this point. A more extensive and denser envelope was found in Be-shell stars by Marlborough *et al.* (1993) in agreement with the work of Dougherty & Taylor (1992), while a lower electron density and a more compact envelope was derived for Be-shell stars by Slettebak *et al.* (1992). On the other hand, Kogure (1990) found a denser, disc-like envelope in Be-shell stars and a spheroidal, more extended envelope, in Be stars. We would like to stress the importance of long-term monitoring of some well-chosen objects using many different techniques in improving our knowledge of the physics of Be stars.

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Discussion

Waters: I would like to point out that the fact that Be stars lose their Hα emission does not necessarily imply that these stars lose their disc altogether. It may be that these stars go through a phase of much lower density without noticeable Hα emission.

Peters: (1) I have been attempting for some time now to find any linkage between long- and short-term variability cycles. In general, it is my opinion that different physical phenomena are responsible for each. In most cases, if the star displays long-term variations, short-term variations are absent or very weak. One exception is λ Eri in which I have recently found that the outbursts recur with a quasi-period of 1.3 yr.

(2) The nature of the secondary in HR 2142 is still an open question. The phase-dependent variations in the strengths and velocities of the shell lines are exactly the same type one sees in conventional Algol systems. This implies the presence of a cool secondary.

Hubert: The energy distribution in the IR range does not reveal the presence of a cool giant companion for HR 2142.

Rountree: Some quiescent Be stars can be detected in the ultraviolet because they have stronger C IV (and sometimes Si IV) lines than "normal" stars of the same spectral type. This is possible only if the spectra are classified by comparing "photospheric" absorption lines with the standards. The wind lines can then be used to detect anomalous conditions.

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