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Radiative Interaction in Be + sdO Binaries

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Abstract. Only one confirmed and two proposed binary systems are known in the Be + subdwarf O phase. The problems in identifying such objects are outlined. In the presently known systems, a common variability pattern was found that may serve as a tool in identifying these stars from both new and archival observations. The observed variability can be modeled physically as the radiative interaction of a hot, compact secondary, ionizing a sector of the disk of the primary. This reproduces the radial velocity variable emission features, and in equatorially seen stars it additionally explains the time-variable shell lines.

1. Introduction

Be stars are rapidly rotating B main-sequence stars with equatorial, quasi-Keplerian disks, being formed by the star itself (i.e. these are not accretion disks, as in Herbig Be stars, or mass-transferring binaries). It is not believed that Be stars rotate critically. But their rapid rotation of $< v > \approx 0.65 \ldots 0.75 v_{\rm crit}$ is certainly one of the basic reasons for these stars to develop a disk, although there must be some additional mechanism responsible for the actual ejection of matter into the circumstellar environment (e.g. Rivinius et al., 1998). The question if the rotational velocities of Be stars reflect the initial distribution of angular momentum, or how many of these objects have been spun up by binary evolution is, therefore, a fundamental one in understanding Be stars.

Evolutionary scenarios of binary Be stars propose a higher fraction of binary systems with evolved companions than observed (Pols et al., 1991). About 5 % of all Be stars are expected to have an evolved companion (e.g. Waters et al.,

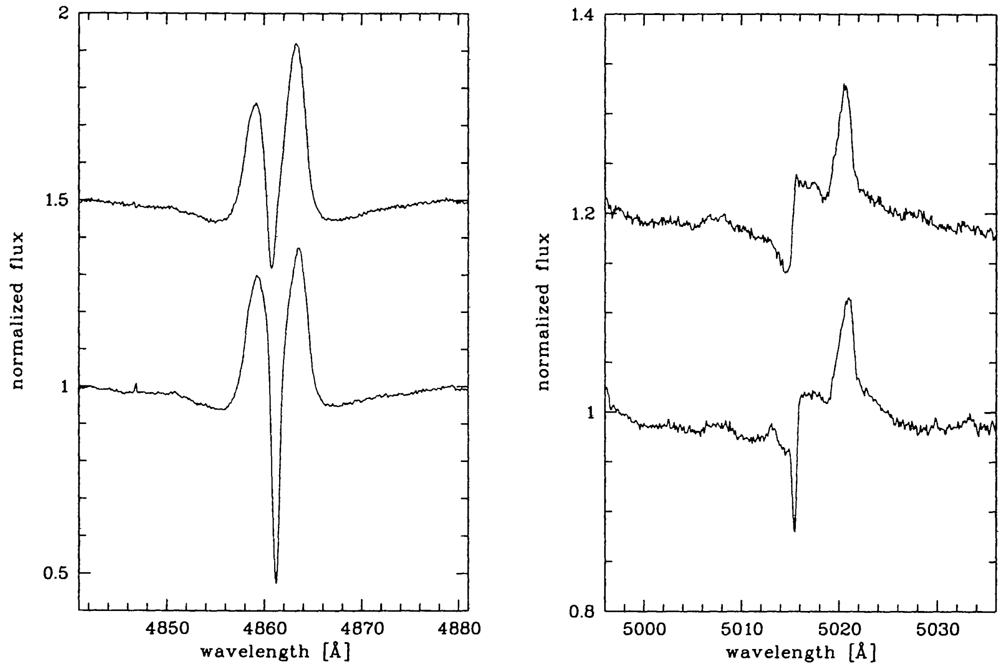

Figure 1. The Hβ (left) and HeI 5016 (right) lines of ϕ Per, during one of the periodically enhanced shell phases (lower spectrum) and as seen normally (upper spectrum). HeI 5016 has only absorption components, both photospheric and circumstellar. The emission is due to the FeII 5018 line, the blue emission peak being blended with HeI 5016

1989; van Bever & Vanbeveren 1997). However, binary evolution as a *major* process for Be-star formation has also been proposed (Gies, 2000).

While estimates for the total number of Be stars that underwent binary evolution differ, the computations result in comparable fractions of such systems for a given type of companion: For each Be + neutron star, ten or more Be + Helium stars should exist, and the Be + white dwarf systems should be almost as abundant as the Be + He stars (Pols et al., 1991).

Observationally, on the other hand, numerous Be + neutron star binaries are known due to their X-ray properties, but of the theoretically more abundant Be + Helium stars only one system is confirmed and two others have been proposed. Of the Be + white dwarf systems not a single one is known reliably.

2. Identifying Be binaries with compact companions

Excluding the Be + neutron star binaries, the X-ray flux from most Be stars is quite understandable as wind emission, as in normal B stars (Casinelli, 1994). However, some low-luminosity X-ray Be stars have been proposed as Be + WD systems ($L_X \approx 10^{29} \ldots 10^{33}\,\mathrm{erg\,s^{-1}}$). γ Cas, often considered to be a prototypical Be star, is the best observed example (Haberl, 1995; Kubo et al., 1998; Owens et al. 1999). But as Smith, Robinson, and coworkers in a series of papers have

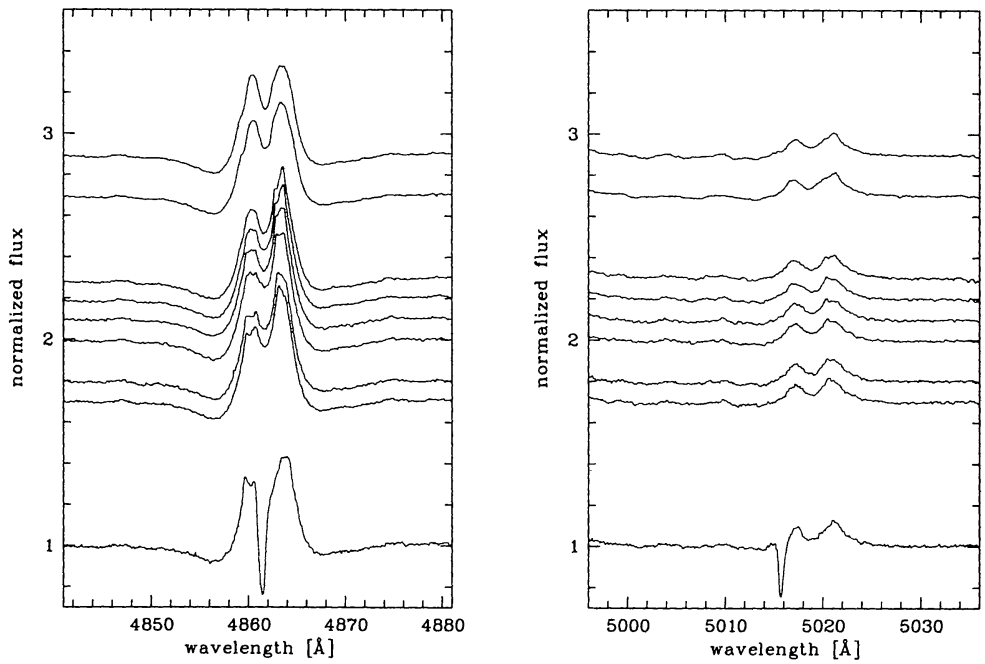

Figure 2. Time series of Hβ (left) and the HeI 5016 absorption line (right) of HR 2142, showing the shell enhancement. The vertical offset is proportional to time. Time runs upwards; ten days are equivalent to one continuum unit. The right panel also shows the FeII 5018 emission line, blended with HeI 5016. Like most other lines, FeII 5018 does not take part in the shell line variability

shown, the X-ray variability of this star is also very well understandable as that of a single object, if a magnetic flaring scenario of the disk formation is adopted (for the most recent works see Cranmer, Smith, & Robinson, 2000; Robinson, & Smith, 2000).

Only one star by now can be identified positively as a Be + Helium star, ϕ Persei, by detecting and analyzing the companion spectroscopically in the UV (Gies et al., 1998). The companion of ϕ Per is a sdO star of about $1.14\,M_{\odot}$, $T_{\rm eff} = 53\,000\,K$, and $\log g = 4.2$.

ϕ Per was initially proposed to be such a binary by Poeckert (1981), who found HeII emission, presumably from a secondary disk around the companion. In addition, ϕ Per was well known to show periodically enhanced shell lines with $\mathcal{P}$ = 127 days (Fig. 1). Radial velocity and line-profile variable HeI emission was described by Gies et al. (1993), but the interpretation remained subject to discussion. Recently, Štefl, Hummel, & Rivinius (2000) re-investigated the system and concluded that the HeI variability can be understood best as formed in a sector of the outer part of the main disk, excited by the secondary radiatively.

A second Be star with known orbital phase variation, HR 2142, was proposed to have an evolved companion by Waters, Coté, & Pols (1991). However, an Algol-type nature is also not yet excluded for this star. Shell events like in ϕ Per were detected in this star (Fig. 2), and shortly thereafter they were found

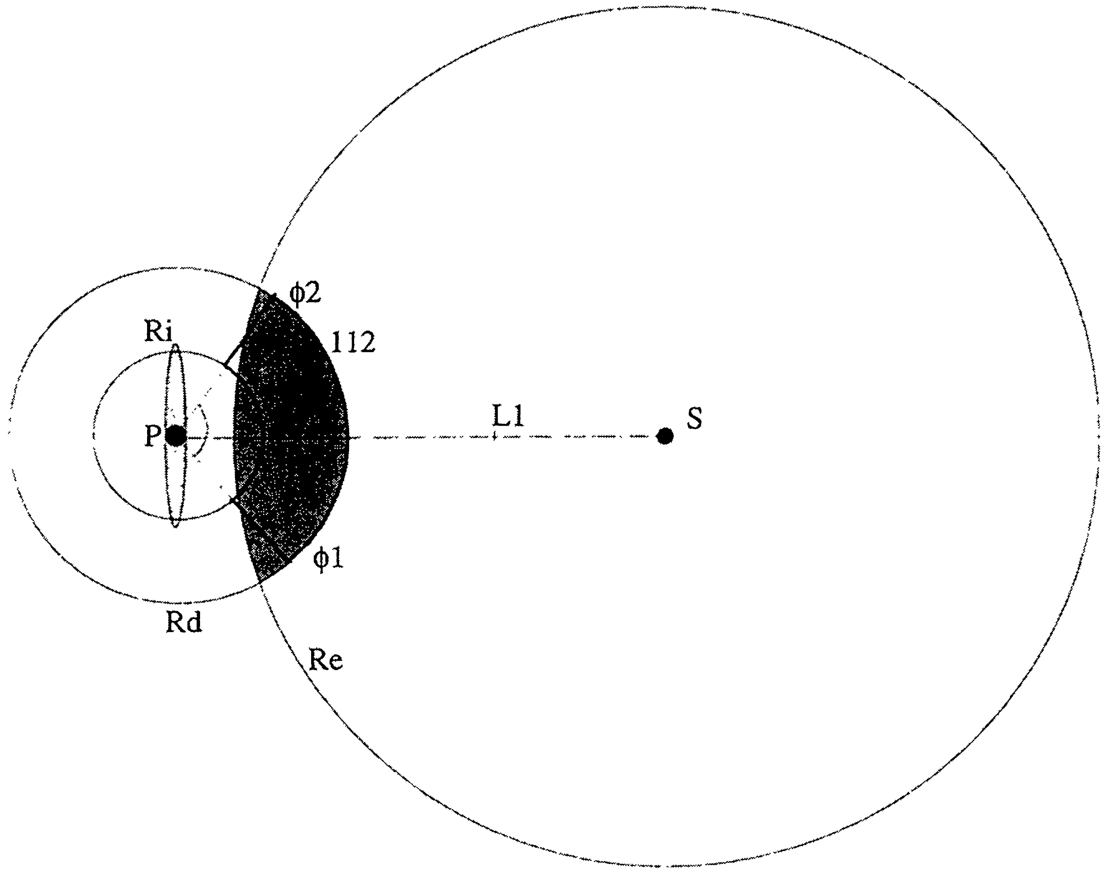

Figure 3. Sketch of the model geometry used by Hummel & Štefl (2001) to model the Helium line variability of ϕ Per. The ionized region was modeled as a sector of the disk (bold outline), and as an intersection of a modified Strömgren sphere with the disk (dark area)

to be periodic with $\mathcal{P}$ = 81 days (Peters, 1971). Peters (1983) observed radial velocity variations and derived a mass function of only 0.007 $M_{\odot}$.

The shell signature is clearly visible in most Balmer lines and the observed HeI lines originate from 2^1S and 2^3S lower levels (HeI 3889, 3964, 5016). It is seen less well in HeI 5876, 6678, which originate from 2^1P and 2^3P, but neither in HeI 7065, 7281, which also originate from 2^1P and 2^3P with similar ΔE, nor in any other observed HeI line, between 3700 and 9000 Å.

Only very recently have Rivinius & Štefl (2000) reported HeI emission line variability in 59 Cyg, similar to that in ϕ Per, with a period of 28 days. This period could be traced back to at least 1978 with the help of IUE data. A radial velocity curve was derived and an orbital solution given with a mass function of 0.05 $M_{\odot}$. An indication for HeII emission was even found.

It is noteworthy that this timescale was reported before by several investigators in the Balmer emission lines, but a binary hypothesis was mostly rejected (see references in Rivinius & Štefl, 2000). As 59 Cygni is among the most intensively observed Be stars, this may illustrate the difficulty in identifying such binaries, as such a nature for this binary system was not proposed before, and even now it was revealed only accidentally (Rivinius & Štefl, 2000). So by now the possibility of a major fraction of Be stars being spun up through binary evolution cannot be ruled out observationally.

3. Radiative interaction between secondary and Be star disk

Štefl et al. (2000) investigated the morphology of the variable HeI line emission and shell absorption in ϕ Per, and concluded that the variability originates in the part of the circumprimary disk facing the secondary. Hummel & Štefl (2001) fitted the observed line profile variations by first modeling the non-variable FeII emission to obtain the parameters of the entire disk. The model of the variable shell- and emission-components was based on these parameters, assuming the geometries sketched in Fig. 3. Both of those geometries gave a quite good result for the emission feature. Although the absorption feature was modeled as well, the resulting fit is not as good as for the emission.

The sector geometry seems to make more sense physically, since the ionizing radiation is not absorbed between the secondary and the disk, as it would be in the case of a Strömgren sphere, but only geometrically diluted until it reaches the disk. Therefore, the ionization region would actually be sickle shaped (One can visualize this as a "wrapped up" Strömgren sphere), although the actual model results do not differ strongly.

As this model proved sufficient to explain the observed emission variability, there are probably no additional sources for the circumstellar HeI emission other than the circumprimary disk, with an enhanced excitation region facing the secondary. Although the model was less successful for the shell component, there is no reason to assume any other origin than the excited region of the circumprimary disk for the absorption as well, especially since the absorption *has to* take place in front of the primary.

In ϕ Per, the excitation region passes through the line of sight towards the primary during lower conjunction, when the enhanced shell lines become visible. The same may happen in HR 2142.

Since in 59 Cyg the disk is not seen edge-on, the excitation region never passes in front of the star, and, therefore, no shell enhancement phases are observed as in ϕ Per or HR 2142. The HeI emission feature is always seen. If the emission region were very small, one would expect a single peak emission following a radial velocity curve similar to the orbital RV curve. However, the observed complex emission profiles and RV curve in ϕ Per can be explained by an extended emission region (Štefl et al., 2000; their Figs. 8 & 10). The emission line behavior of 59 Cyg is almost identical (Rivinius & Štefl, 2000).

4. Conclusions

Be stars are intensively observed objects, but only in recent years have several breakthroughs been achieved using new techniques, both in observing and modeling. However, with the knowledge acquired, it seems worthwhile to go back to the published databases and search for the signatures of variability as sketched above. This is currently being done, and the first few promising objects, both suspected binaries and alleged single stars, are already being observed.

With sufficient data for 59 Cyg and HR 2142, that will also be taken in the above mentioned campaign, it should be possible to model the variability of both objects. For ϕ Per and HR 2142, the modeling of the shell lines will provide us with a good estimate for the disk inclination. Unfortunately 59 Cyg lacks shell lines, telling us only that the disk is not seen edge-on.

By the end of this project we hope to have acquired a better estimate of the importance of binary evolution for the Be phenomenon.

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Discussion

Tim Harries: Did you use a $1/r^2$ radial density profile for the disc? It seems a bit sharp.

Thomas Rivinius: Yes, $1/r^2$. It is actually quite consistent with what was observed from the radio.

Tim Harries: Is it not a Keplerian disc?

Thomas Rivinius: Yes, it is a Keplerian disc. If you apply the equation of continuity then $1/r^2$ is consistent with a Keplerian disc. The exponents inferred from observations are about 1.5 to 2.5, so $1/r^2$ is not bad.

David Eichler: I have a comment about your list of objects. There is one Be star that has a pulsar companion in it. I haven't heard about it in this meeting but it is a very interesting system with a pulsar companion that has radio eclipses. It can possibly serve as a diagnostic to the disc the way the non-thermal radio emission serves as a diagnostic to the winds that have been talked about. But people in the pulsar community know this system very well; I just wanted to make sure that you realized it exists.

Thomas Rivinius: It might fall in the Be X-ray binary category.

Gloria Koenigsberger: That is 2S0115+63, the one that has the pulse periods changing as a function of orbital phase.

David Eichler: The pulsar is 1259+...

Thomas Rivinius: I never recall the phone numbers of these stars. [Laughter.]

Stan Owocki: You found that it is consistent now that some stars that we didn't know were binaries could really be distant binaries so they really are not responsible for the mass onto the disc. It is still clear that we have to make the disc from inside out.

Thomas Rivinius: The Be star itself is still the classic Be star.

Stan Owocki: Right. One of the things I have always wondered is whether the tidal distortion of a relatively separated binary could be inducing the distortion of the disc and be at the origin of the one-arm modes. You seem to imply that one-arm modes can sort of exist independently of any binary tidal effects. Is it likely that the one-arm modes are excited by the tidal effects of a binary or can they actually happen from the inside?

Thomas Rivinius: We don't really know but it seems possible.

Sergey Marchenko: There are examples when there is an elliptical orbit of the neutron star inside the Be disc/wind. Once it goes to periastron there is a flare in the optical light-curve.

Stan Owocki: Be stars have these very peculiar, many-year V/R variations, which you can only understand in terms of the precession of an elliptical orbit, which you presume could be something that is from an external tidal distortion. Could single Be stars have such long-term V/R variations is? Are the observations telling us that they are all binaries?

Olivier Chesneau: The companion was there before the V/R variations started.

Thomas Rivinius: In ϕ Persei there was a V/R variation for a decade, then it ceased, now it starts again.

An array of colonizers from Belgium (Sana), Germany (Mücke, Rivinius, Kaufer) and Italy (De Marco) enjoying le nouveau monde