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Searching for Colliding-Wind Signatures in a Sample of O-Star Binaries[1]

G. Rauw[2], H. Sana, J.-M. Vreux, E. Gosset[3]

Institut d'Astrophysique et de Géophysique, Université de Liège, 5, Avenue de Cointe, B-4000 Liège, Belgium

I.R. Stevens

School of Physics & Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom

Abstract. We have selected a sample of O-star binaries that display a substantial *EINSTEIN* X-ray excess luminosity. This excess X-ray emission is usually considered to be an indication of a colliding-wind phenomenon and these systems are therefore good candidates to search for the signature of such an interaction at other wavelengths. In this contribution, we discuss the results of our optical monitoring of two particular binary systems: HDE 228766 (O7.5 + O5.5) and HD 93403 (O5.5I + O7V).

1. Introduction

The observational signatures of colliding-wind interactions have been found over a broad wavelength range from the radio to the X-ray domain. One of the most prominent observational indications of the interacting-wind phenomenon is the excess X-ray emission observed in massive binaries (e.g. Chlebowski & Garmany 1991). This excess X-ray emission is believed to arise at the shock front between the two winds (e.g. Stevens, Blondin, & Pollock 1992).

In this context, we started an extended observing campaign of a sample of O-star binaries that were selected according to their excess X-ray luminosity. The aim of our programme is to search for phase-locked variability of line profiles in the optical spectra of these systems and to quantify the contribution of the shocked plasma to the optical emission lines. The results of this study will set constraints on the temperature distribution in the shocked winds and eventually help us to understand the cooling processes in the shock region.

Results for a few systems from our sample have been published: Cyg OB2 no. 5 (Rauw, Vreux, & Bohannan 1999), HD 152248 (Sana et al., this volume)

[1]Based on observations collected at the Observatoire de Haute Provence, the European Southern Observatory (La Silla, Chile) and the Cerro Tololo Inter-American Observatory (CTIO).

[2]Postdoctoral Researcher FNRS, Belgium

[3]Research Associate FNRS, Belgium

and HD 149404 (Nazé, Carrier, & Rauw, this volume). In the present paper, we will focus on two previously rather poorly studied binaries: HDE 228766 and HD 93403. These systems display large *EINSTEIN* X-ray luminosities of $\log(L_x/L_{\rm bol}) = -6.05$ (HDE 228766) and -5.71 (HD 93403) that are well in excess compared to the 'typical' $\log(L_x/L_{\rm bol}) \simeq -7$ relation for O-stars (Chlebowski & Garmany 1991).

2. Observations and data reduction

Our observations of HDE 228766 were collected during two observing campaigns in July and August 1999 with the Aurélie spectrograph fed by the 1.52 m telescope of the Observatoire de Haute-Provence (OHP). We used a 300 lines/mm grating blazed at 6000 Å providing a reciprocal dispersion of 33 Å/mm over the wavelength range from 4100 to 4950 Å. The detector was a Thomson TH7832 linear array with a pixel size of 13 μm. The spectral resolution was $\sim$1.2 Å. The data were reduced using the MIDAS software developed at ESO and the spectra were normalized using properly chosen continuum windows.

A full description of our HD 93403 observing campaign and the data reduction can be found in Rauw et al. (2000). In the present paper we focus on the echelle spectra obtained with the FEROS instrument on the ESO 1.52 m telescope at La Silla and the BME spectrograph at the 1.5 m CTIO Ritchey-Chretien telescope. These data were gathered during four observing runs in May-June 1999 and May 2000.

3. HDE 228766

HDE 228766 was classified as an O7.5 + O5.5f binary with an orbital period of 10.7424 days by Massey & Conti (1977, hereafter MC77). Our spectra reveal that most of the absorption lines remain either blended over the main part of the orbital cycle or suffer from contamination by a variable wind emission (He I λ 4471, Hγ, Hβ). The only spectral feature in our data that seems suited to set up an orbital solution is the He II λ 4542 absorption line.

To measure the radial velocities of the two stars, we first built a template of the He II λ 4542 line in the spectrum of each star by fitting two gaussians to the blend around maximum separation. At the other orbital phases, we used these templates in the frame of a cross-correlation technique to deblend the lines of the two components.

Our orbital solution yields a significantly larger mass ratio ($q = 1.49$) than the value ($q = 1.04$) obtained by MC77. MC77 cautioned that due to the serious blending problems, their measurements of the absorption lines were at least partly subjective. Our new RVs obtained through a cross-correlation technique are in principle less subjective, provided that the He II λ 4542 line is not affected by strong line profile variations.

The most striking feature of our new solution is the huge difference of $\gamma_1 - \gamma_2 \sim 150\,{\rm km\,s^{-1}}$ between the *apparent* systemic velocities of the two components. This value is much larger than the $45\,{\rm km\,s^{-1}}$ difference reported by MC77. It is however difficult to compare these results since we refer here to the RVs of the He II

Table 1. Orbital solution for HDE 228766 as derived from the RVs of the He II λ 4542 line assuming P = 10.7424 days and $e = 0.0$.

	Primary	Secondary
γ (km s^{-1})	33.4 ± 3.6	-118.1 ± 14.1
K (km s^{-1})	133.9 ± 4.7	199.8 ± 17.8
$a \sin i$ ($R_\odot$)	28.4 ± 1.0	42.3 ± 4.0
$m \sin^3 i$ ($M_\odot$)	24.8 ± 4.8	16.6 ± 2.8

λ 4542 line only, while MC77 used the mean RVs of several lines.

The equivalent width ratios of the O-star classification lines He I λ 4471 and He II λ 4542 yield spectral types O7 and O6 for the primary and secondary respectively. Though this is in fair agreement with the classification proposed by MC77 (O7.5 + O5.5f), we caution that this result is rather uncertain due to the serious blending of the classification lines of both stars. Moreover, at least in the spectrum of the secondary star, it seems likely that none of the classification lines is of purely photospheric origin. Indeed, the considerable blue-shift of the secondary's He II λ 4542 line (with respect to the primary) is most probably indicative of an incipient P-Cygni profile and the line is thus at least partially formed in the strong wind of the secondary.

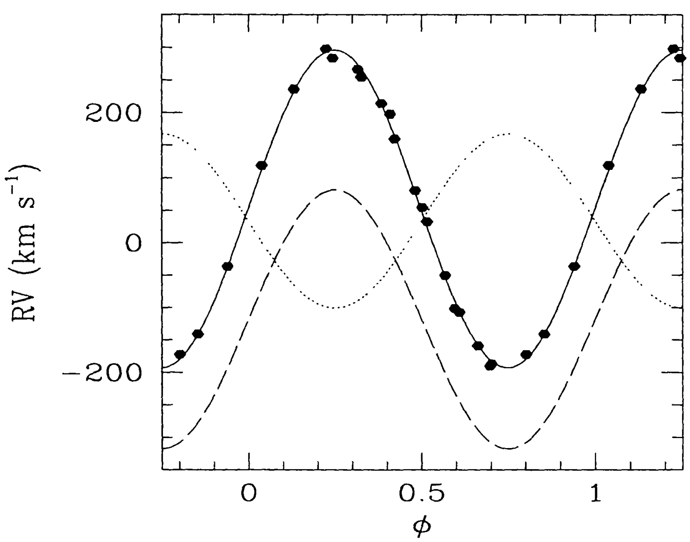

Figure 1. Radial velocity curve of the He II λ 4686 emission line in the spectrum of HDE 228766. The orbital solutions of the primary (dotted line) and secondary (dashed line) are shown for comparison.

Blue-shifted He II λ 4542 absorption (as seen in the spectrum of the secondary in HDE 228766) is found in the most extreme Of stars which resemble the least extreme WN stars in many respects (Crowther & Bohannan 1997). In this context, it is worth recalling that HDE 228766 had been tentatively classified as a WR + O binary by Hiltner (1951) based on the presence of the N IV λ 4058, N III $\lambda\lambda$ 4634-40 and He II λ 4686 emission lines. HDE 228766 further displays He II λ 10124 in emission (Vreux & Andrillat 1979), which is a common feature of Wolf-Rayet stars, but quite unusual for O-stars. The overall properties of the secondary's spectrum point therefore towards a late WN spectral type rather than an O6 or O5.5 classification.

The He II λ 4686 line is the most prominent emission in the spectral range covered by our observations. The line appears as a strong, rather symmetric feature that mimics the orbital motion of the secondary star without any indication of a significant phase lag (see Fig. 1). This finding is in very good agreement with the result of MC77 though we derive a somewhat larger semi-amplitude of the He II λ 4686 RV-curve (244 km s^{-1}) than they did (218 km s^{-1}). The He II λ 4686 line displays no significant profile variability. The line exhibits however some intensity variations with a peak to peak variation of the EW of about 20%.

4. HD 93403

The very first SB2 orbital solution for the early-type binary HD 93403 (O5.5 I + O7 V, P = 15.093 days, e = 0.234) was recently presented by Rauw et al. (2000). These authors noticed a phase-dependence of the relative strength of the absorption lines of the two components of HD 93403. While the intensities of the primary's absorptions remain roughly constant over the orbital cycle, we observe substantial changes in the equivalent width of the secondary's lines. The latter lines appear stronger at orbital phases when the secondary is moving towards us. This is very similar to the 'Struve-Sahade' effect described by Stickland (1997). The effect is most prominent for the C IV $\lambda\lambda$ 5801, 5812 lines whereas it appears less pronounced for the He I λ 4471 and O III λ 5592 lines. This latter result is somewhat surprising since the C IV doublet and the O III line have all a rather high excitation potential and are thus most probably all formed quite deep within the photospheric layers.
We emphasize that the Struve-Sahade effect also affects the C III λ 5696 emission lines. In fact, both components of HD 93403 show this line in emission and the RVs indicate that the emission is most likely of photospheric origin, in agreement with the theoretical models of Nussbaumer (1971) and Cardona-Núñez (1978). To our knowledge, this is the first time that the Struve-Sahade effect is reported for an emission line.

The He II λ 4686 line consists of a mixture of emission and absorption features. We have measured the RVs of the absorption component and it became immediately clear that this absorption is associated with the secondary star (see Fig. 2). The emission component seems to be made up of at least two contributions: a rather weak emission associated with the primary star and a much broader and asymmetric emission usually with an extended red wing. Though a full analysis of these profiles seems difficult because of the severe blending problems and the Struve-Sahade variability of the absorption, we have measured the RVs of the strongest emission peak whenever this was possible. The result is displayed in Fig. 2. The RV of the emission peak varies roughly in phase with

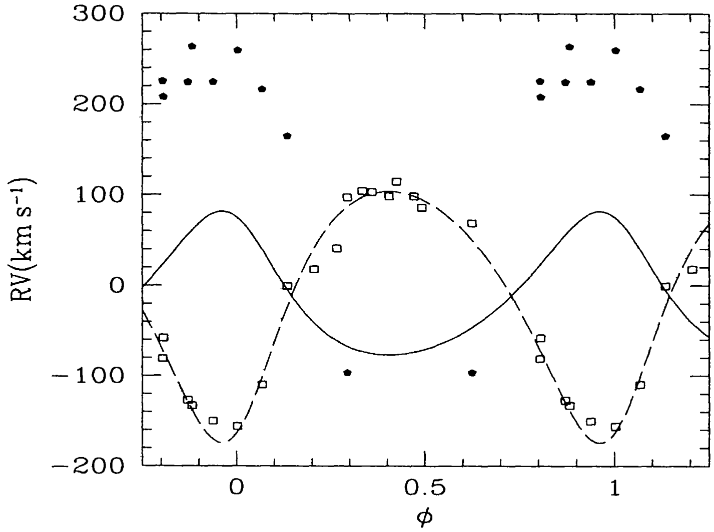

Figure 2. Radial velocities of the He II λ 4686 line in HD 93403. Open squares correspond to the RVs of the absorption component whereas filled pentagones stand for the RVs of the emission peak. The continuous and the dashed line indicate the RV solution for the primary and the secondary respectively. Phase $\phi = 0.0$ corresponds to periastron passage.

the primary's RV, though the emission peak is clearly red-shifted between phase 0.80 and 0.15 and slightly blue-shifted at phases 0.29 and 0.63. We further notice that the emission vanishes at orbital phases around apastron ($\phi = 0.5$). A possible explanation could be that the stronger emission component is generated in the interaction between the two stars and scales roughly with some power of $1/D$ where D is the instantaneous separation between the binary components.

Thaller (1997) reported some variability of the Hα line in the spectrum of HD 93403. Our observations reveal a complex Hα profile consisting of a mixture of absorption and emission. The interpretation of this profile is further complicated by the presence of a rather strong nebular Hα emission and by the effect of telluric water vapor absorptions. The stellar line seems to consist of an absorption belonging to the secondary and a blue-shifted (most likely P-Cygni - type) absorption that is probably associated with the primary. Underlying these features, there is a broad emission line extending over about 70 Å. The only noticeable variations of the Hα line that are not readily explained by 'simple' blending effects are some slight variations of the intensity of this broad emission component that are a bit reminiscent of the variations seen in the He II λ 4686 line, though they appear less prominent in the Hα line.

If we interpret the profile variations of the He II λ 4686 line in terms of a colliding wind interaction, the easiest way to account for most of the properties of the broad emission component is to assume that this emission is coming from the trailing arm of a shock cone around the secondary star. Since the shock occurs deep within the winds, where the outflow has not yet reached very high velocities, the shape of this shock region is probably strongly affected by the effect of the Coriolis forces. This Coriolis deflection most probably accounts for the red wing that is seen in the broad He II λ 4686 emission around periastron ($\phi = 0.0$) when the secondary is moving towards us.

5. Summary and conclusions

The emission lines in the optical spectrum of HDE 228766 provide little evidence for a colliding wind phenomenon in this system. So far, the only indication of a wind interaction in this system comes from its X-ray luminosity.
The strong emission lines seen in the blue spectrum of HDE 228766 belong to the secondary star. All in all, we find that the properties of the secondary are more consistent with a late WN spectral type rather than with an O5.5f classification as suggested by MC77.

HD 93403, on the other hand, exhibits a rather prominent 'Struve-Sahade' effect in the photospheric lines (including the C III λ 5696 emission line) of the secondary star and a strong profile variability of the He II λ 4686 line. In conjunction with the X-ray properties of this system, this behaviour points towards a strong colliding wind interaction. The new orbital solution of Rauw et al. (2000) yields an eccentricity of $e = 0.234$ and we find that the strength of the He II λ 4686 emission seems to vary as a function of the separation between the components of the system. HD 93403 appears therefore as an interesting system to investigate the effects of eccentricity on the properties of the wind interaction zone and the system has thus been selected for a phase-resolved observing campaign with the XMM-Newton observatory.

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Discussion

Sébastien Lépine: Do you really suggest that the emission from the shock cone increases near periastron or could you explain it by some kind of geometry or optical depth effects, like in the models that I showed?

Gregor Rauw: Right. I think that in this case you have to have a dependence on the separation. I would say that there are two features which have to be explained. One is the fact that, if there were geometric effects, we would expect a bow-shock eclipse occurring at orbital phase 0.135 but we don't see that. And even if you have some opacity effect, I don't know why it should just act when the emission is blue-shifted (e.g. $\phi = 0.5$) and not when it is red-shifted (e.g. $\phi = 0.8$). The other thing is that I wouldn't expect the optical depth, due to the primary wind towards the shock cone, to change a lot between periastron and apastron but it is something we have to check. My first impression is that it wouldn't change a lot because the mass-loss rates are quite low.

Sébastien Lépine: Well, it's not a change in optical depth but rather it's due to something like anisotropic emission or a change in the geometry.

Gloria Koenigsberger: I missed whether you had any information on the radii of these stars and also can you comment on the possibility of enhanced mass-loss rate at periastron versus apastron and therefore explaining the HeII emission ?

Gregor Rauw: What we know about the radii is that they are actually well inside the Roche-lobe radius. So that is definitely not an issue. There are no photometric eclipses so we don't know anything about the radii from an observational point of view. The only thing we know is that these are normal stars, for their spectral type. Then there shouldn't be a problem with any kind of Roche-lobe overflow or similar. Now coming to an enhanced mass-loss, yes that is definitely a possibility. It could well be the case that this O5.5 supergiant is providing more mass-loss around periastron. So that may be the reason why we have a higher density in the shock resulting in a stronger emission.

David Eichler: What's the theoretical radius of this star?

Gregor Rauw: It is something like 24 $R_\odot$, which is to be compared to a Roche lobe radius at periastron of about 38 $R_\odot$. We have to make an assumption on the inclination, which is rather low. We find something like 30°.

Sergey Marchenko: What would you see as a possible explanation for the absence of the Struve-Sahade effect in OIII versus CIV lines from the point of view of the formation of the line? Depth effect or any quantum mechanical processes involved?

Gregor Rauw: I must say, I still have to look at it in detail but according to the excitation energy, you wouldn't expect any difference between CIV and OIII. Those are lines that are formed very deep in the photosphere. We also see this emission line which is formed by dielectronic recombination and only under certain circumstances. So I think it is really a tricky thing to explain all these features together. My impression is that it is probably not the temperature that is the main factor but it might well be the density, I don't know. But it's certainly not only one parameter.

Yaël Nazé: How can such a nice person be working on such a violent topic (colliding winds)?