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Line-Profile Variability in the Massive Binary System HD 149404 [1]

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Abstract. Over the last years, research on colliding winds in massive binaries has made significant progress. For instance, it has been shown that the observation of phase-locked variability of prominent optical emission lines can be used as a diagnostic to study the properties of the wind interaction in these systems.
We report here on our analysis of the binary system HD 149404. Using a large set of spectroscopic observations, we determine new spectral types and a new orbital solution. We also analyse the line-profile variability of several emission lines and we briefly discuss a possible model for this system.

1. Introduction

HD 149404 has been known as a spectroscopic binary with a period of about 10 days since the late seventies (Conti, Leep, & Lorre 1977). Two orbital solutions exist in the literature. The first one was obtained by Massey & Conti (1979) using photographic plates, while the second one by Stickland & Koch (1996) is based on IUE data. This binary displays an interesting spectrum with a large number of variable emission lines and deserves a detailed study with modern high-resolution spectrographs as pointed out by Stickland & Koch (1996).
We have obtained an extensive set of spectra of HD 149404, using various instruments at ESO (La Silla) and CTIO. Details on these observations will be given in a forthcoming paper (Rauw et al. 2001, in prep.). In the present contribution, we will focus on our high-resolution echelle spectra that were obtained with the BME spectrograph at the 1.5 m CTIO telescope, the FEROS spectrograph at the ES0 1.5 m telescope (La Silla) and the CORALIE instrument on the 'Euler' Swiss telescope (La Silla).

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

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2. Spectral types

One of the problems that hampers spectroscopic studies of HD 149404 is the severe blending of the absorption lines of the two components over large parts of the orbit. Using the least blended spectra of our data, we tried to assess the spectral types of the components by measuring the equivalent-width ratio of the He I λ 4471 and He II λ 4542 absorption lines in the spectrum of each component (Conti 1973). For the primary, this ratio yields a spectral type between O6.5 and O7.5 depending on the orbital phase. In fact, the different spectral types result from variations of the He I equivalent width of the primary star as a function of orbital phase. A variation is also present for the secondary star, and it appears anticorrelated with that of the primary (see Fig. 1). However, this variation does not result in a significant change of the secondary's spectral type, which is determined to be O9.7 all around the orbit.

The variation of the He I λ 4471 equivalent width can at least partially be

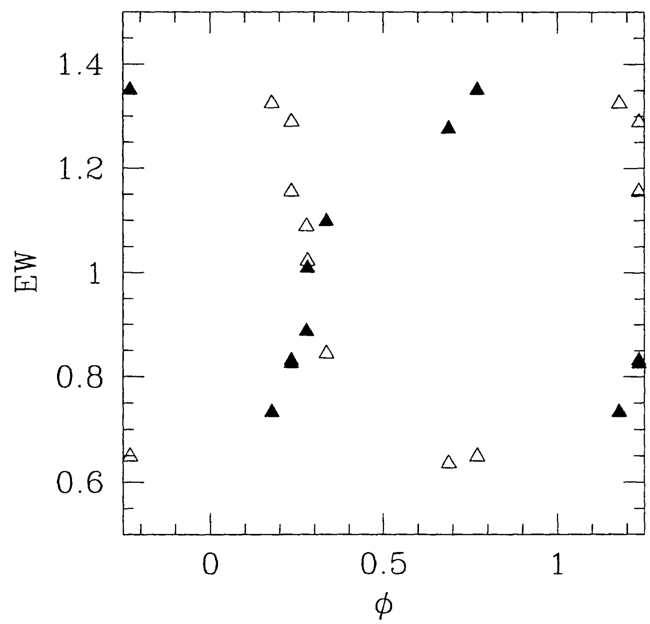

Figure 1. Equivalent widths of the primary (open triangles) and secondary (filled triangles) He I λ 4471 lines in the spectrum of HD 149404 as a function of orbital phase. Individual EWs of each component were divided by the corresponding mean EW averaged over the entire orbit.

explained by an emission feature hidden in this line. The presence of a strong emission component in He I λ 5876 suggests that a weaker emission might be present in He I λ 4471. As a matter of fact, we see a very weak emission in the latter line near the conjunctions. At phases near $\phi = 0.75$, the probably red-shifted emission is most likely blended with the primary's absorption, so that it reduces the equivalent width of the absorption, resulting in an apparently earlier spectral type. Therefore, we prefer an O7.5 classification for the primary, as this type is determined when the equivalent width of the primary's absorption is least affected by the emission.

For the luminosity classes, we used the criterion based on the equivalent width ratio of the Si IV λ 4088 and He I λ 4143 absorptions as suggested by Conti &

Alschuler (1971). The latter line is however very weak, especially in the spectrum of the primary and we can only set an upper limit on the equivalent width of the primary's line, which yields in turn a lower limit on the equivalent width ratio. For both stars we determine a supergiant luminosity class. In summary, we derive an O7.5 I(f) + O9.5 I classification[5] rather than O7 III(f) + O8.5 I as suggested by Massey & Conti (1979).

3. Orbital solution

Using our high-resolution spectra, we have also determined a new orbital solution for HD 149404 (see Table 1 and Fig. 2). To do this, we used the He I λ 4471 and He II λ 5412 lines which are the strongest and least blended absorption lines in the optical spectrum. The radial velocities (RVs) were determined by fitting two gaussians to the profiles, whenever the separation between the lines was sufficient to do so. At orbital phases near conjunction, we determined the RVs by cross-correlating the observed profile with the gaussian profiles derived from the fit near quadrature. Since we suspect the He I line to be affected by a weak emission feature, we used the RVs of the He II line to check the orbital solution derived from the former line. Both solutions overlap within their errors.

Table 1. Orbital solution derived from the RVs of the He II λ 5412 line and assuming $e = 0.0$. T_0 corresponds to the conjunction with the secondary in front. An orbital period of 9.81475 days was adopted.

	Prim.	Second.
T_0(JD-2450000)	1680.367 ± 0.447	
γ (km s^{-1})	-45.7 ± 6.2	-43.0 ± 2.9
K (km s^{-1})	61.7 ± 6.9	99.8 ± 3.9
$a \sin i$ ($R_\odot$)	12.0 ± 1.3	19.3 ± 0.8
$m \sin^3 i$ ($M_\odot$)	2.65 ± 0.38	1.64 ± 0.36
$R_{RL}/(a_1 + a_2)$	0.421 ± 0.009	0.338 ± 0.009

Finally, we also used the correlation method developed at the Geneva Observatory to determine the RVs of the binary components. In this technique, the observed spectra are cross-correlated with a mask, based on a synthetic spectrum, and the RVs are obtained by fitting gaussians to the correlation peaks. Again, the orbital parametres deduced from the different techniques agree within their error boxes. However, the simultaneous use of a large number of absorption lines in the Geneva cross-correlation technique significantly reduces the scatter around the least square orbital solution (Rauw et al. 2001). This is the first time that the Geneva technique is applied to a massive binary system. This method has been successfully applied to low-mass binaries and seems also very promising for massive systems.

[5]The (f) tag indicates that the bulk of the N III $\lambda\lambda$ 4634/40 seems to follow the primary.

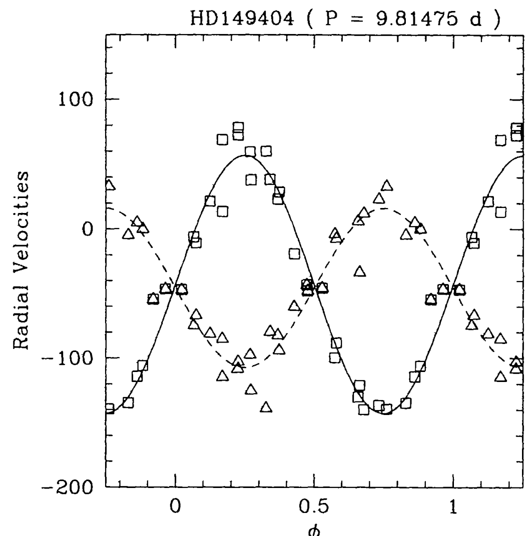

Figure 2. Radial velocity curve of HD 149404 as determined from the RVs of the He II $\lambda\,5412$ line.

4. Emission lines

The spectrum of HD 149404 exhibits a large number of emission features. The most prominent emission lines are N III $\lambda\lambda\,4634$-40, He II $\lambda\,4686$, Hβ, C III $\lambda\,5696$ and Hα. We notice also the presence of many weaker lines of N II (e.g. $\lambda\lambda\,5932$, 5942) as well as of the unidentified Of emissions near 4486 and 4504Å.
A clear indication of an interaction between the components of HD 149404 comes from the phase-locked variability of some of the optical emission lines. For instance, the strong Hα emission appears double-peaked at phases near conjunction, whereas it displays a single peak around quadrature. The double-peaked line morphology was already noted by Massey & Conti (1979) and more recently by Thaller (1997 & 1998).

We have determined the radial velocities of the most prominent emission lines as a function of orbital phase (see examples in Figs. 3 & 4). To derive constraints on the origin of these emission lines, we have performed a simple analysis which consists of fitting a sine-wave to the measured RVs of the emission lines (e.g. Richards, Jones, & Swain 1996; Rauw, Vreux, & Bohannan 1999). The results can be represented on a Doppler map (Fig. 4). Each coordinate (v_x, v_y) of this velocity space corresponds to a particular amplitude and phase shift of the sine wave. The orbital motion of the center of mass of the primary and secondary are indicated, respectively, by the lower and the upper cross in Fig 4, whereas the dashed line is the equivalent of the Roche lobe in the velocity space. The location of the line-emitting volume in velocity space (as derived from the sine-wave fit) yields information on the motion of the emitting material (see e.g. Rauw et al. 1999).

Our analysis of the RVs of the emission lines reveals that the peaks of the C III $\lambda\,5696$ and N III $\lambda\lambda\,4634$-40 emissions follow roughly the orbital motion of the primary. Interestingly, the unidentified Of emission lines appear to move

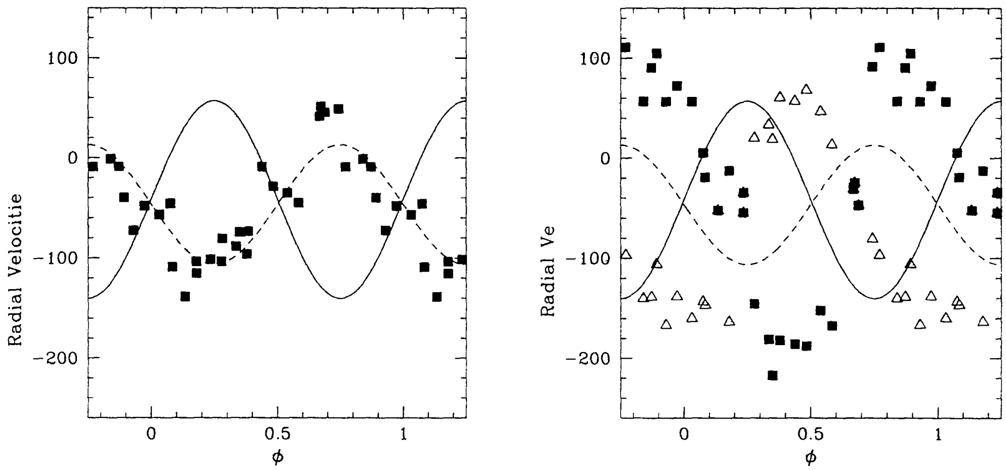

Figure 3. Radial velocities of the emission peaks of the C III λ 5696 (left panel) and the Hα lines (right panel). The dashed and the continuous line correspond to the orbital solution of the primary and secondary respectively.

with the secondary star. This seems to indicate that the unidentified lines are probably not associated with N III. On the other hand, the N II $\lambda\lambda$ 5932, 5942 lines appear to belong to the secondary. Although, we can certainly not rule out that the unidentified lines might be associated with the N II ion, we point out that the locations in velocity space of the two sets of lines (N II vs. unident.) are slightly different.

The two Hα peaks are clearly not associated with either of the two stars. These emissions most probably arise somewhere between the binary components. Massey & Conti (1979) proposed that the Hα profile might be a signature of an ongoing Roche lobe overflow process. However, the minimum masses derived from our orbital solution point towards a very low orbital inclination and therefore, we could not tell whether any of the stars fills its Roche volume. Thaller (1998) favored an alternative explanation where the Hα emissions come from two focused winds streaming towards a colliding wind zone between the two stars. The locations of the Hα emission regions in velocity space seem more consistent with emission coming from the arms of the shock region of two nearly equally strong winds (see Rauw et al. 2001, for a full discussion).

5. Conclusion

We have presented a preliminary analysis of the early-type binary HD 149404. Our data reveal that several emission lines arise in the photosphere or in the inner wind regions of the binary components, while other lines, such as the strong Hα emission are clearly of a different origin. We suggest that the latter lines are formed in a wind interaction zone between the two stars and more specifically, in the arms of a shock region bent by the Coriolis effect.

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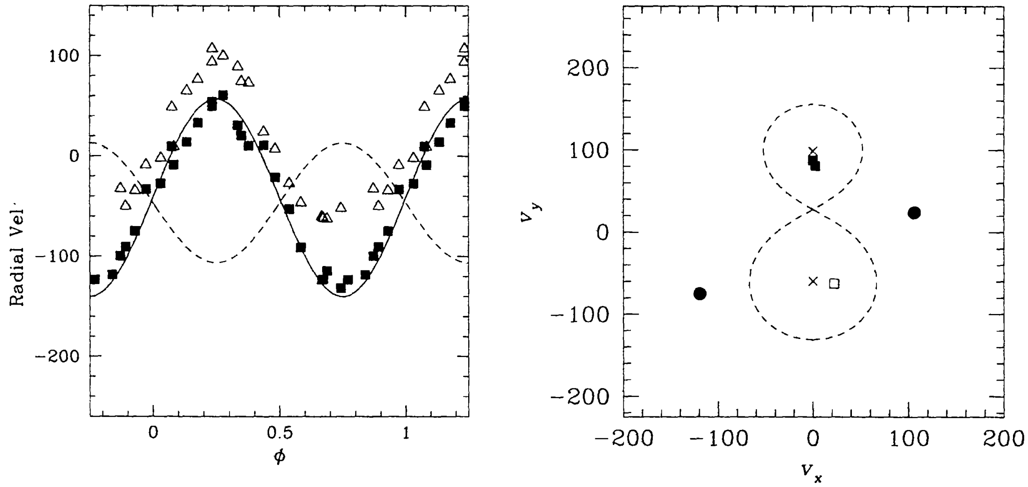

Figure 4. Left: same as Fig. 3 but for the λ 4486 (squares) and λ 4504 (triangles) emission features. Right: Doppler map of HD 149404. The different symbols correspond to different lines: open square = C III λ 5696; filled squares = $\lambda\lambda$ 4486, 4504; bullets = Hα.

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Discussion

Allan Willis: Certainly a comment. I think this NII unidentified Of thing is the greatest result I have ever seen considering this problem. A lot of people have been thinking about NIII or higher ionisation species to try to identify those unidentified Of lines. And you are now saying for certain it is lower ionisation, corresponding to NII or below. I think it is a fabulous result. And the atomic physics people are going to have to go back and redo their searches in the low ions. Unfortunately, there are a hell of a lot more lines in the low ions.

Gloria Koenigsberger: Do you have any information on the rotational velocities of the stars and on the orbital inclination?

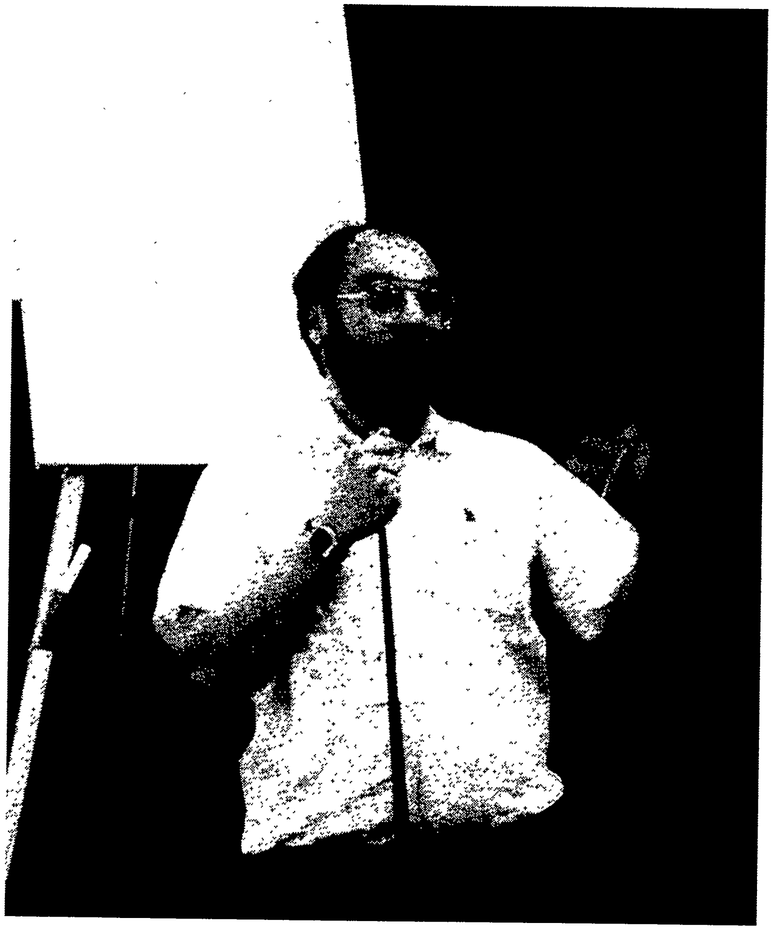
Yael Nazé: On the rotation, no. But on the orbital inclination, there was a polarimetric study by Luna (1988, A&AS, 74,427), but it could only put an upper limit on the inclination. So the inclination I have put here in fact is a choice we made based on the typical masses for the spectral types of the stars we have and the masses we determined from the calculation of the orbit. And for both stars it is rather the same value of 21°.

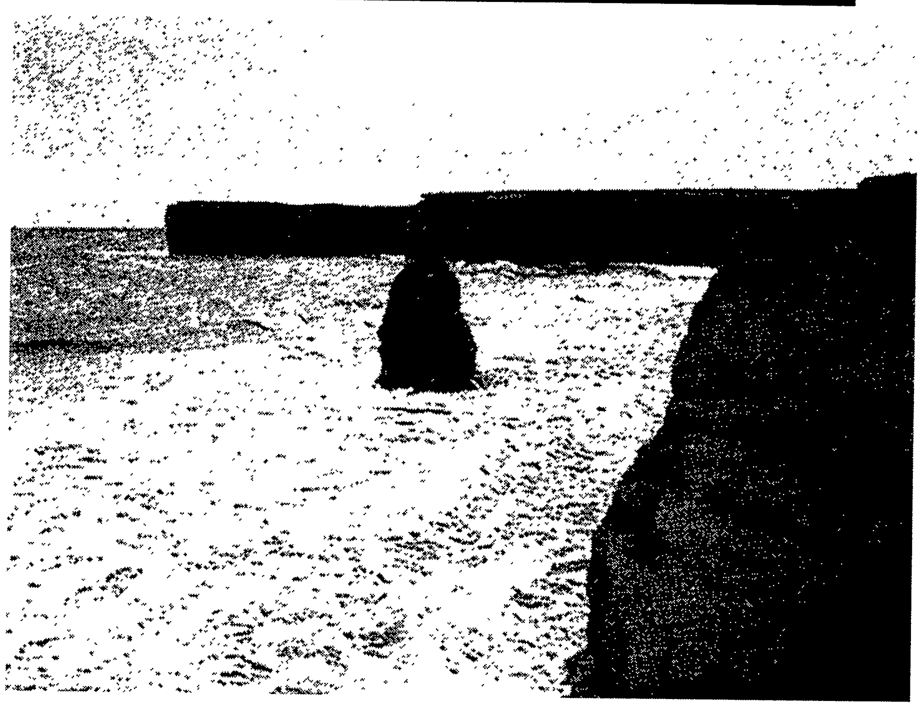
Andreas Kaufer: It is interesting to see that you were able to reduce the scatter in radial velocity, which is large, just by using this mask correlation method from the Geneva people. The idea that you have thousands of lines which are just shifted can be applied to planet searches as well. How does it work with the Wolf-Rayet stars? You only have a few lines and some of them are changing in line profile. I have seen so many bad diagrams in the literature.

Yael Nazé: Yes, this binary also shows profile effects. But it seems that it doesn't have much effect on the correlation method, at least for this star. It is the first time that we have applied this method. It has not been applied to Wolf-Rayet stars but it would be interesting to do that, of course. In fact we use a lot of lines, but of course not the emission lines. We use the strongest lines and also some lines which are quite weak but clear in the spectra.

Andreas Kaufer: Purely absorption lines?

Yael Nazé: Yes, purely absorption lines. However, there are one or two emission lines which are associated with the star, but not Hα. Of course it is double-peaked sometimes but not at the same phases as the star.





Top: Phil Bennett illustrating slow winds of red supergiants with rapid hand motions. Bottom: View from a planet well before the red giant phase of its central star