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Hyperionization phenomena in the coronal and post-coronal regions of the moving atmosphere of the Oe star HD 66811 (ζ Puppis)

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Abstract. In this paper we study the regions of the O4I(n) star HD 66811 (ζ Puppis), where the Si IV, N IV, C IV and NV spectral lines are created. Our study is based on the model proposed by Danezis et al., announced for the first time at the JENAM 1998 in Prague, also submitted in IAU Symposium 210 (Uppsala, 2002). This model suggests that the regions where the ions that present DACs are created, are not continuous but they consist of many independent absorbing density layers of matter, followed by an emitting and finally by an external general absorption region. The model reproduces the profiles of all the spectral lines of Oe and Be stars, that we have studied until now. In this paper we intend to test the proposed model, as well as to extract some first general conclusions about the accurate values of the expansion / contraction velocities and the rotation velocities of the regions where the Si IV, N IV, C IV and NV resonance lines are created.

1. Introduction

The hottest of the bright Of stars is ζ Puppis, for which Walborn (1972) gave the spectral type O4I(n)f. Conti & Leep (1974) classified it as O4ef, while Lesh (1972) retained the historic type of O5f.

The main parameters of the star were summarized by Lamers & Morton (1976). The determination of the effective temperature yields large problems. The value derived from the angular diameter and the UV flux distributions is $T_e = 32510 \pm 1930^{\circ}K$ according to Code et al. (1976) or $31900 \pm 1800^{\circ}K$ according to Brune et al. (1979). These values are similar to those of the later type stars ζ Oph (O9.5V) and τ Sco (B0V) and seem, therefore, much too low. A higher T_e value ($50000^{\circ}K$) and log(g)=4.0 was found from a study of COPERNICUS observations of the helium spectrum by Snijders & Underhill (1975), who compared observations of HeII lines with non-LTE predictions obtained for assumed non-LTE-plane-parallel model atmospheres by Auer & Mihalas (1972).

Lamers & Morton (1976) gave a detailed description of P Cygni profiles in ζ Puppis using high resolution spectral scans obtained with the COPERNICUS satellite. Rocket-UV spectra of ζ Puppis has been described by Carruthers

(1968), Morton et al. (1969), Stecher (1970), Smith (1970) and Burton et al. (1973,1975). An absolutely calibrated rocket spectrum (12 to 15 Å resolution) was obtained by Brune et al. (1979). These investigations revealed strong P Cygni lines of C IV, N IV, N V, O IV, Si IV, S IV and S VI in the far ultraviolet. Additionally, Snijders & Underhill (1975) analyzed the He II observed by the COPERNICUS satellite along with those available from ground-based spectra. Finally, Franco et al. (1983) found line profile variability in ζ Puppis and suggested that two different mechanisms could produce the observed ionization stages.

In this paper we apply the model proposed by Danezis et al. (1984, 1986, 1991, 2000, 2002) to the star HD 66811 (ζ Puppis) and we present some first results deriving from this application. This model is also presented at IAU Symposium 210.

2. The model – Mathematical expression

Considering an area of gas consisting of i independent absorbing shells followed by a shell that both absorbs and emits and an outer shell of general absorption, we conclude to the function:

$$I_\lambda = [I_{\lambda 0} \prod_i exp\{-L_i\xi_i\} + S_{\lambda e}(1 - exp\{-L_e\xi_e\})]exp\{-L_g\xi_g\}$$

where:

$I_{\lambda 0}$: the initial radiation intensity,

L_i, L_e, L_g : functions of the rotation and the expansion/contraction velocities ($vsini$, $v_{ex/c}$),

$\xi = \int_0^s \Omega\rho ds$ is an expression of the optical depth τ, where Ω is an expression of k_λ and has the same units k_λ,

$S_{\lambda e}$: the source function, which, at the moment when the spectrum is taken, is constant and

$$L = \begin{cases} \sqrt{1 - cos^2\theta_0} & \text{, if } cos\theta_0 < 1 \\ 0 & \text{, if } cos\theta_0 \geq 1 \end{cases},$$

where $cos\theta_0 = \dfrac{-\lambda_0 + \sqrt{\lambda_0^2 + 4\Delta\lambda^2}}{2\Delta\lambda z_0}$, where $2\theta_0$ is the angular width of the equatorial disk of matter, λ_0 is the wavelength of the center of the spectral line and $\lambda_0 = \lambda_{lab} + \Delta\lambda_{exp}$, with λ_{lab} being the laboratory wavelength of the spectral line produced by a particular ion and $\Delta\lambda_{exp}$ the radial Doppler shift and $\dfrac{\Delta\lambda_{exp}}{\lambda_{lab}} = \dfrac{V_{exp}}{c}$

$z_0 = \dfrac{V_{rot}}{c}$ where V_{rot} is the apparent rotation velocity of the i density shell of matter and

$\Delta\lambda = |\lambda_i - \lambda_0|$, where the values of λ_i are taken in the wavelength range we want to reproduce.

The spectral line's profile, which is formed by the i density shell of matter, must be accurately reproduced by the function $e^{-L_i\xi_i}$ by applying the appropriate values of V_{roti}, V_{expi} and ξ_i. Using the best model's fit for a complex spectral line, we can calculate the apparent expansion (or contraction) velocity (V_{expi}), the apparent rotation velocity (V_{roti}) and an expression of the optical depth (ξ_i) of the region in which the spectral line and its satellite components are constructed.

3. Data

This project is based on three different spectra of ζ Pup (HD 66811), taken with the IUE satellite, listed below:

- SWP 05963 (27/7/1979)
- SWP 33538 (16/5/1988)
- SWP 53460 (17/1/1995)

We study the structure of the spectral lines of:

- Si IV $\lambda\lambda$ 1393.755, 1402.730 Å
- N IV λ 1718.80 Å
- C IV $\lambda\lambda$ 1548.155, 1550.774 Å
- N V $\lambda\lambda$ 1238.821, 1242.804 Å

4. Application of the model to the spectral lines of the Be star HD 45910 (AX Mon)

4.1. The model's fit

In figure 1 we present one of the spectral lines we studied (black line) as well as its fitting as it derived from the model (grey line). The differences between the real spectrum and its fit are hard to see, as we have accomplished the best fit.

4.2. Tables and figures of expansion/contraction and rotation velocities

By applying the model to the spectral lines Si IV, N IV, C IV, and N V of HD 66811 we calculated the apparent expansion / contraction V_{expi} and rotation velocities V_{roti} of the observed layers of matter, as well as their mean values. In tables 1 to 8 we present the mean values of the above mentioned velocities and in figures 2 and 3 we present their variation with time for the Si IV region.

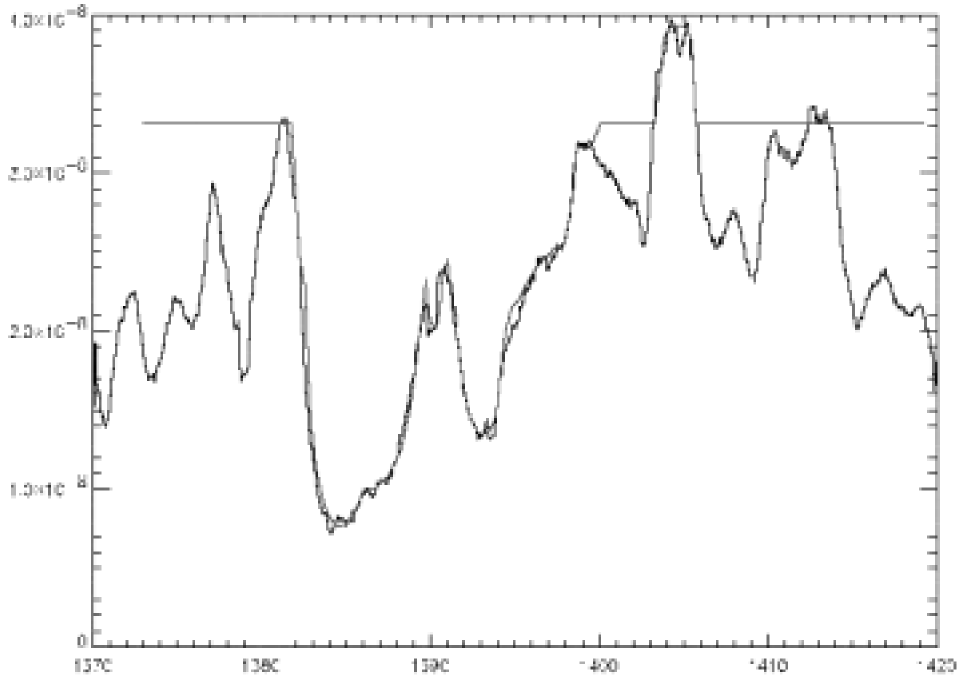

Figure 1. Each of Si IV $\lambda\lambda$ 1393.755, 1402.730 Å resonance lines of HD 66811 shows a characteristic P Cygni profile which is formed as a composition of three independent absorption and one emission components.

Table 1.
Expansion/Contraction velocities of the Si IV region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	Emission
1979	-2093 ± 7	-1492 ± 5	-720 ± 2	$+434 \pm 34$
1988	-2093 ± 7	-1514 ± 5	-677 ± 13	$+433 \pm 12$
1995	-2146 ± 3	-1589 ± 16	-737 ± 2	$+552 \pm 109$

Table 2.
Rotation velocities of the Si IV region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	Emission
1979	415 ± 15	710 ± 10	140 ± 0	195 ± 15
1988	390 ± 10	745 ± 5	150 ± 10	230 ± 25
1995	400 ± 0	748 ± 8	145 ± 0	240 ± 10

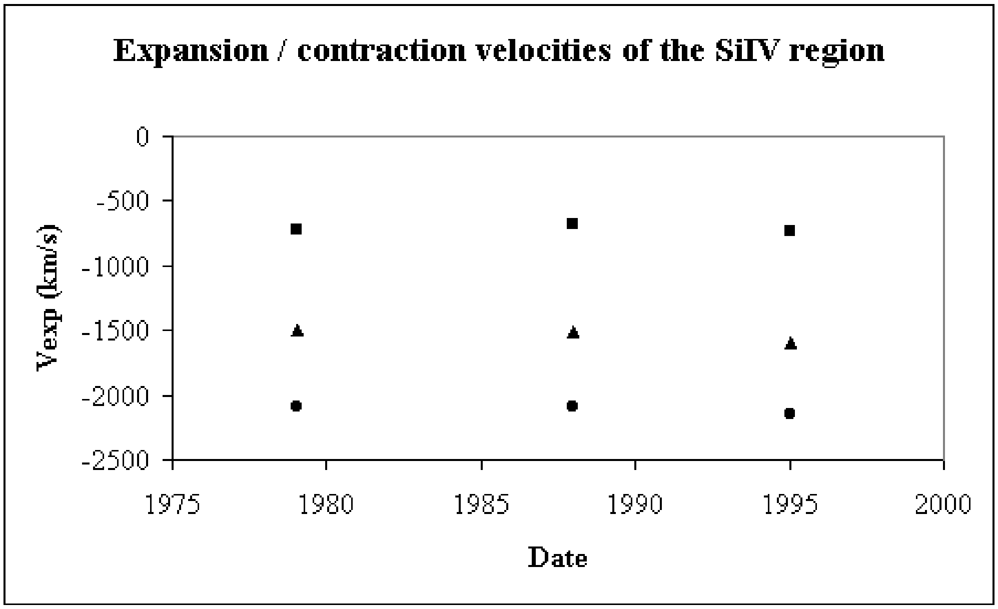

Figure 2. Mean radial expansion/contraction velocities of all the observed layers of matter as a function of time.

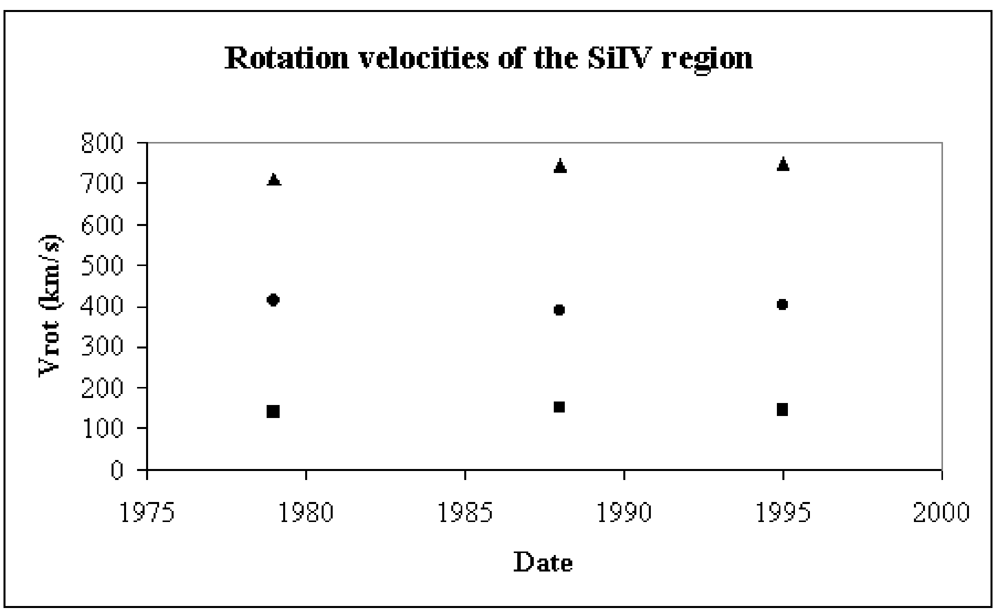

Figure 3. Mean apparent rotation velocities of all the observed layers of matter as a function of time.

Table 3.
Expansion/Contraction velocities of the N IV region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	d' comp	Emission
1979	-1309	-873	-611	-244	+517
1988	-1398	-970	-634	-314	+509
1995	-1290	-1012	-676	-366	+433

Table 4.
Rotation velocities of the N IV region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	d' comp	Emission
1979	558	580	570	80	450
1988	558	576	608	80	450
1995	570	600	580	100	470

Table 5.
Expansion/Contraction velocities of the C IV region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	Emission
1979	-1466 ± 1	-2183 ± 2	-171 ± 0	$+913 \pm 1$
1988	-1486 ± 1	-2241 ± 2	-111 ± 0	$+932 \pm 1$
1995	-1505 ± 1	-2247 ± 23	-59 ± 29	$+1029 \pm 1$

Table 6.
Rotation velocities of the C IV region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	Emission
1979	733 ± 13	748 ± 2	177 ± 0	790 ± 0
1988	750 ± 0	810 ± 0	210 ± 0	740 ± 0
1995	780 ± 10	800 ± 0	180 ± 10	730 ± 0

Table 7.
Expansion/Contraction velocities of the N V region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	Emission
1979	-2080 ± 28	-920 ± 2	-1412 ± 11	$+1463 \pm 2$
1988	-1973 ± 41	-948 ± 1	-1262 ± 2	$+1482 \pm 10$
1995	-2109 ± 3	-936 ± 11	-1331 ± 2	$+1566 \pm 3$

Table 8.
Rotation velocities of the N V region of HD 66811 (km/s)

Year	a' comp	b' comp	c' comp	Emission
1979	600 ± 0	570 ± 0	550 ± 0	480 ± 0
1988	590 ± 0	610 ± 0	470 ± 0	505 ± 5
1995	620 ± 10	640 ± 0	500 ± 0	510 ± 0

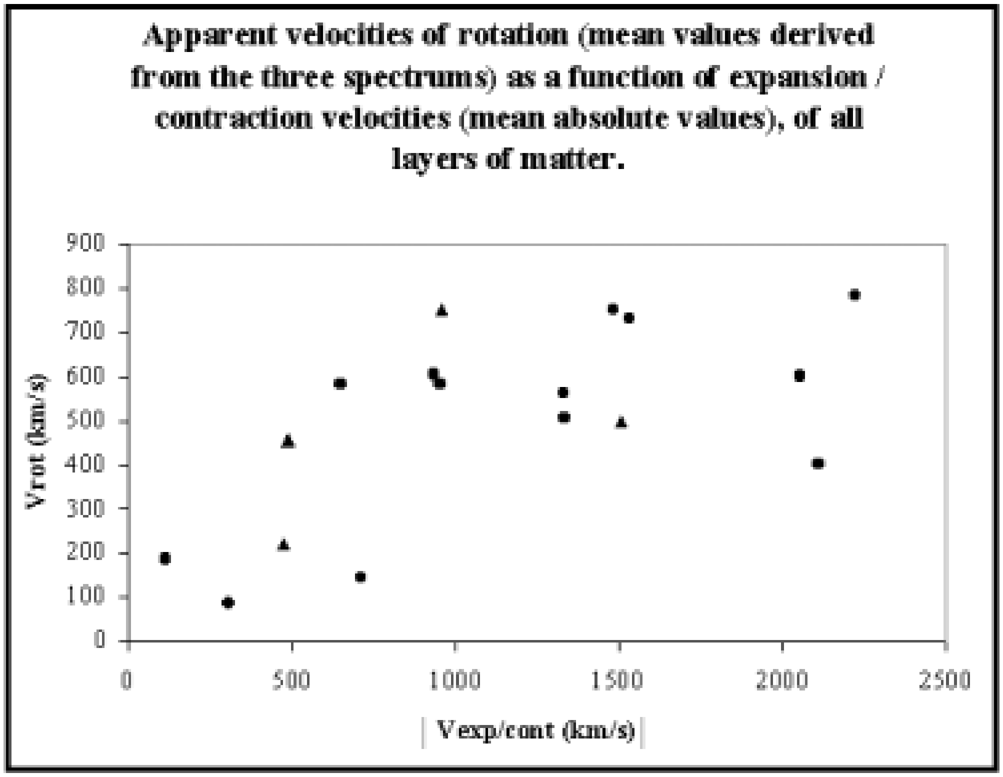

Figure 4. The absolute mean velocities of expansion or contraction as a function of mean apparent rotation velocities, for all layers of matter (absorbing and emitting). Velocities related to absorbing layers of matter are shown with circles. Velocities related to emitting layers of matter are shown with triangles.

5. Conclusions

We would like to point out that:

1. By applying the proposed by Danezis et al. (1984, 1986, 1991, 2000, 2002), model we are able to reproduce the profiles of the spectral lines of the star HD 66811 (ζ Puppis) that we studied with great accuracy. This means that the model allowing the existence of successive, independent density shells of matter in the regions where the DACs are created, represents accurately the structure of these regions of ζ Puppis atmosphere.

2. The best fit of all lines derived by the model we described leads to the conclusion that the layer of matter in the region we studied 33eV (Si IV)-78 eV(N V) is structured as the model describes:

   (a) An area of gas consisting of i independent absorbing layers of matter.

   (b) One emitting layer of matter, which follows the absorbing layers.

   (c) Occasionally, an external absorption layer of matter.

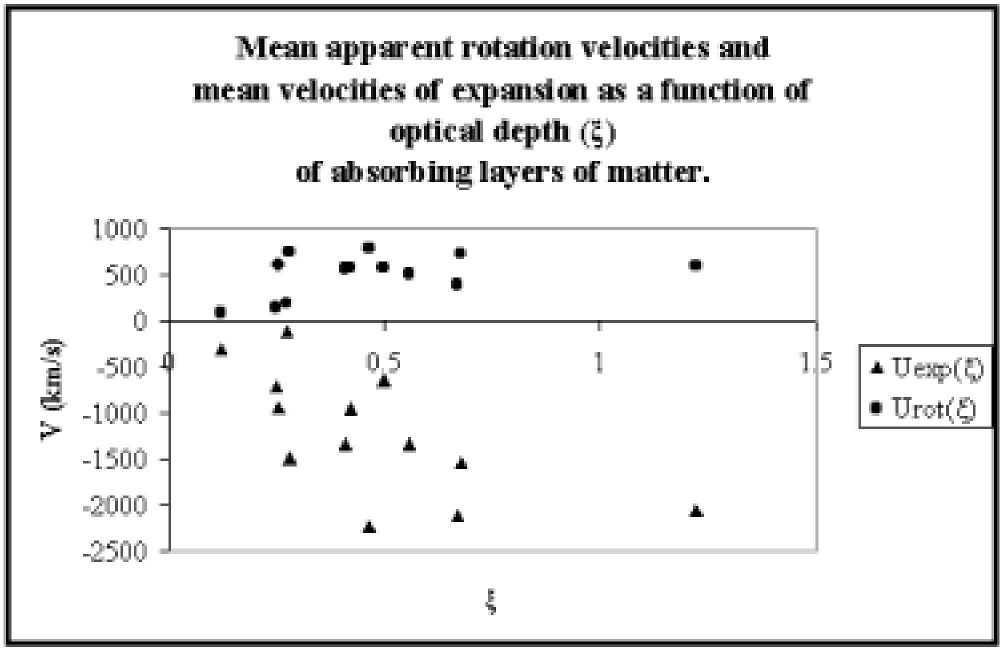

Figure 5. Mean apparent rotation velocities and mean velocities of expansion as a function of the optical depth (ξ), of the absorbing layers of matter.

3. It is interesting to point out the presence, in the region we study, of successive shells that expand or contract with velocities between -2247 km/s and +1566 km/s, while the apparent rotation velocities in this region vary between 433 km/s and 1566 km/s.

4. The apparent rotation velocities and the expansion/contraction velocities of each layer of matter show an insignificant variation between the three different spectra we used.

5. The correlation between rotation and expansion velocities is remarkable. A layer of matter which shows high rotation velocity shows high velocity of expansion and vice versa.

6. Rotation and expansion velocities vary as a function of the optical depth uniformly. As the optical depth increases rotation and expansion velocities (absolute values) increase too.

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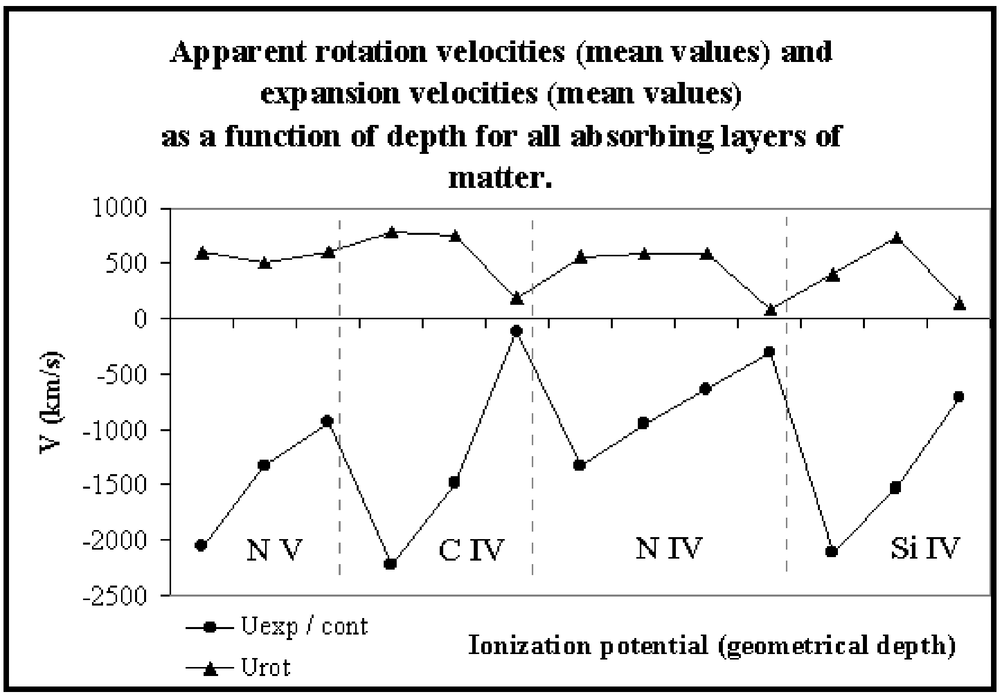

Figure 6. Rotation and expansion velocities vary as a function of depth uniformly.

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