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STELLAR WIND VARIABILITY FROM IUE SPECTRA OF EPSILON ORIONIS

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Abstract. 21 IUE spectra of ϵ Ori (HD 37128), B0 supergiant, were studied to analyze variations in the profiles of the resonance lines of N V, C IV, Si IV and Si III. The largest variations in the profiles of resonance doublets of N V, C IV and Si IV are found in blue wings of the lines at velocities from –1500 to –2000 km/s, reaching in some spectra up to 50 % of the continuum level. Profile variations of the singlet resonance line Si III take place at smaller velocities, from –300 to –1000 km/s. The observed line profile variations can be explained by the presence either of shells or high velocity clumps in the wind. Corresponding narrow absorption components appear in the blue wings at the velocity about –1700 km/s and sometimes also at –1400 km/s. They are variable both in strength and in radial velocity, their characteristic life-times being from some days to about a week.

Key words: stars: ultraviolet spectra, line profiles, mass-loss, individual: ϵ Ori (HD 37128)

1. INTRODUCTION

Numerous observations show that variability in ultraviolet resonance lines is a common property of stellar winds in early-type supergiant stars. The form of the resonance line profiles and their variability are crucial for studying the structure of stellar winds of early-type stars. The most direct information about their structure is obtained by studying the narrow or discrete absorption components (NACs or DACs) in UV resonance lines of the IUE high-resolution spectra.

Resonance line profiles are a key element in understanding the state and dynamics of stellar winds and phenomena in them, which partly originate from stellar surface layers. A general picture of the structure of stellar winds can be obtained by analysis of profiles of resonance spectral lines.

We have studied variability in the profiles of UV resonance lines of ϵ Orionis, one of the brightest B0 Ia stars. Its effective temperature $T_{\rm eff}$ has been found to be in the interval 24800–28500 K, its $\log g \approx 3.0$ and $R_\star = (34\text{–}37)R_\odot$ (Olson & Castor 1981, Lamers & Leitherer 1993, Villata 1992). From the observed profiles of strong UV resonance lines values from 1500 to 2200 km/s have been obtained as the terminal velocity $v_{\rm t}$ of the wind. The corresponding characteristic time of mass outflow is $R_\star/v_{\rm t} \approx 10^4$ s. The mass loss rate for ϵ Ori is $(1\text{–}3)\times10^{-6}$ $M_\odot$/yr (Abbott et al. 1980, de Jager et al. 1988, Gathier et al. 1981).

2. OBSERVATIONS AND DATA REDUCTION

We have studied 13 IUE spectra of ϵ Ori obtained from the IUE archive of Villafranca, 5 spectra obtained from the National Data Archive and Distribution Service (NDADS) and 3 from GSFC, observed by A. Sapar. All these spectra have been exposed with the high-resolution SWP camera. Their list is given in Table 1 together with the results of tentative identifications of narrow absorption components. The reseau mark contaminated NACs are labeled by *R* and strong or peculiar features are marked by !. In Table 1 we also present the data for the exposures SWP 6727 and SWP 3403 lacking in the Figures because they do not differ from SWP 6728 and SWP 3402, respectively. The reduction of all the spectra of ϵ Ori has been carried out by methods and algorithms described in our previous paper (Sapar & Sapar 1984). The observed wavelengths were transformed to the heliocentric ones, removing the Doppler shifts due to orbital motion of the Earth and the satellite. The wavelengths have been corrected also for radial velocity of ϵ Ori which is 26 km/s. We have studied the resonance lines of N V, C IV, Si IV and Si III, which have typical P Cygni profiles with blue-shifted absorption and red-shifted emission components.

3. VARIABILITY IN THE RESONANCE LINE PROFILE OF C IV

The profile of the resonance doublet line C IV 154.820, 155.077 nm must be generated in the hottest region of stellar wind, because the ionization potential is high, χ(C III)= 47.887 eV. The terminal (more exactly the maximal) velocity of stellar wind obtained from C IV reaches about 2200 km/s. The wavelength difference of the doublet components corresponds only to 498 km/s and thus the two absorption components of this doublet strongly overlap. The observed profiles of the resonance doublet line C IV are given in Fig. 1. The ordinate of the subsequent spectral plots has been shifted by 0.5. To make the line profile variations better observable, we have also plotted the mean spectrum (dashed line) based on a short-time series of observations in 1987 as standard. In our figures the continuum flux is scaled to unity. Note a considerable blue slope shift due to variations of the wind in the region from –1500 to –2000 km/s. The location of the blue slope of the line varies to 400 km/s and the flux in this region of the line profile varies to 0.5 of the continuum level.

The traditional slow acceleration theory of stellar wind is unable to explain the very wide, fully obscured plateau extending in the line profile from –400 km/s to –1500 km/s and even at $V = 0$ the flux has about 0.2 of its value in the continuum. Due to the presence of such a wide dark plateau with variable slopes, we usually cannot observe any presence of narrow absorption components (NACs). The best observable one is at about –1700 km/s in the Si IV resonance doublet profile.

The NAC at –1860 km/s is observable in the C IV resonance line profiles of exposures SWP 30249, SWP 30257, SWP 30266 and SWP 30204. On some exposures we can observe only the deformation of the steep slope due to NAC giving a stair-like indentation. In observations made before 1987 we can also see NACs in the C IV resonance line profiles in some exposures at lower velocities (–1615, –1700 km/s, see Table 1). Unfortunately, most of them are distorted by reseau marks.

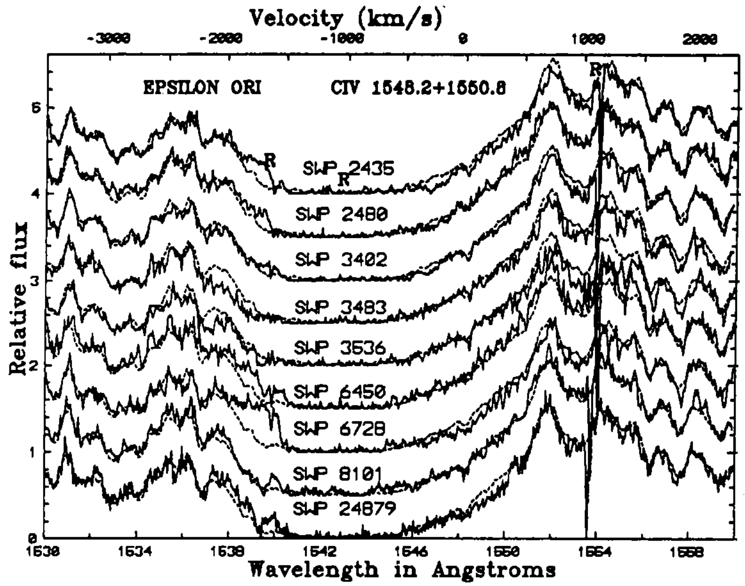
In accordance with the theoretical picture of frequency redistribution due to light scattering in the wind, there is a good correlation between the broadening of the blue valley and the growth of the red elevation of the line profile. From ten exposures, made between January 28 and February 6, 1987, we conclude that the shifts are correlated at least during some days, while the fast clumps in the wind

Table 1. List of IUE spectra of ϵ Ori and a tentative identification of NACs. All velocities of NACs in the table are negative.

SWP	Date	C IV	S IVb	Si IVr	N Vb	N Vr	Si III
2435	1978 Sep 1	1615R	1610	1615	1200	-	800
2480	1978 Sep 4	1615R	1600	-	970	-	800
3402	1978 Nov 21	-	-	-	970	860	850
3403	1978 Nov 21	-	-	-	970	860	850
3483	1978 Nov 29	-	900R	1460	-	-	930!
				890			780
3536	1978 Dec 5	1740R	1650	1310	1640	-	1010
					980		780
6450	1979 Sep 9	1700R	1680	1400	1650	1200!	930R
				930	1220!		750
6727	1979 Oct 3	-	1400!	1400	-	-	750!
6728	1979 Oct 3	-	1400!	1400	-	-	750!
8101	1980 Mar 1	1670R	1670!	1670	1650	860!	760
			1400!	1390!	950		
24879	1985 Jan 10	1700R	1700	-	1650	-	1050
					940		960
30177	1987 Jan 28	-	1710!	1700!	1640!	-	-
30196	1987 Jan 30	1750	1720!	1710!	1650!	1010	1150
30204	1987 Jan 31	1860	1710!	1685!	1650	1010	1170
					970		995
30216	1987 Feb 1	-	1690	1715	-	870	995
30225	1987 Feb 1	1740	1730	1780	1580	-	-
			1610	1590			
30242	1987 Feb 2	-	1620	1615	1630	900	-
30249	1987 Feb 3	1860	1610	1590	1630	870	-
30257	1987 Feb 5	1860	1640	1660	-	870	-
30266	1987 Feb 6	1860	1650	1670	1740	-	-
30272	1987 Feb 6	-	1670	1660	1740	-	-

Note: R means the reseau contaminated feature, b is the blue component, r is the red component.

cover a distance equal to tens of stellar radii. From Fig. 1 (see also figures in Sapar & Sapar 1995) it follows that the long-term variations can exceed about twice the daily variations. The supersonic clumps or shells collide and interact with the surrounding more quiescent



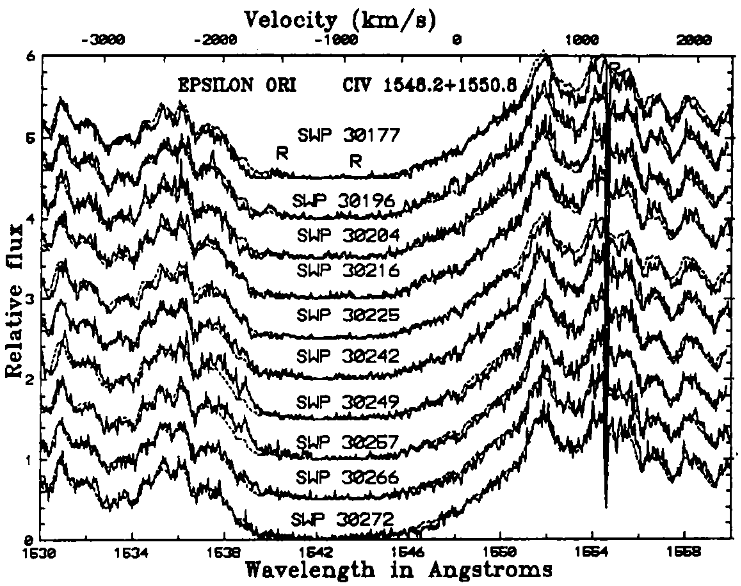


Fig. 1. The merged resonance doublet of C IV (154.820+155.077 nm), long-term (upper) and short-term (lower) profile sequences. Note the presence of a wide dark plateau, explicable in terms of presence of decelerating wind, supersonic turbulence and large clumps or of structurated shell waves. On some spectra a NAC is seen.

wind and between themselves, generating shock waves and hot superionized regions which emit the observed variable X-radiation.

4. PROBLEMS OF MODELING

The wide dark plateaus in the resonance line profiles cannot be formed purely in the accelerating quiescent extended wind even in the case of totally saturated line profiles (see Castor & Lamers 1979). The observed broadening of absorption features towards the red (extending to 600 km/s) can partly be due to the underlying photospheric absorption line. In addition, it is physically hard to specify the location of the hot overionized region in the photosphere.

Another possibility is the presence of C IV ions of lower velocities in the outer layers of the wind. This can be explained either by the presence of decelerating regions of the wind or, what seems to be more realistic, by the presence of a high velocity raising and dropping wind clumps. We have come to the conclusion that supersonic clumps are very numerous or, in other words, there is supersonic turbulence in the wind. In this case the dominant backscattering of photons takes place and it results in the formation of wide and deep dark plateaus in resonance line profiles. We have elaborated a corresponding theory which will be published elsewhere.

The dynamics of clumps so far has been studied mainly in one-dimensional shell approximation, where the primary photospheric density perturbations are taken to be sinusoidal. From them develop highly structurated velocity and density fields in the form of expanding shells (see Puls et al. 1993, Owocki et al. 1988). The presence of such shells and clumps makes the monochromatic picture of the stellar surface extremely variegated, strongly dependent on the wavelength in the spectral line and having rapid variability. The most rapidly raising clumps create a partial eclipse of the stellar disk at the frequences of spectral line profile, observed as a slanting blue slope. Large clumps are generating also the observed NACs. Alternatively, such a slope can also be generated by a rapidly accelerated thin wind (Sapar & Sapar 1994). In this case the resonance line profiles are very sensitive to the $v(r)$ law at saturated line profiles, contrary to the low acceleration wind case. Most of the features will be lost due to the observational integration of flux over the stellar disc. However, the variability of the averaged picture in spectral lines survives and can be recorded.

5. CHANGES IN PROFILE OF RESONANCE LINE OF SI IV

The only observed doublet resonance line of the wind which has but slightly overlapping components is Si IV 139.375+140.277 nm (for it $V(\Delta\lambda)$ corresponds to 1940 km/s and χ(Si III)=33.492 eV). The studied profiles of Si IV and their variations are plotted in Fig. 2.

Studying the plots we see that the Si IV resonance doublet line profile is variable and its variations are similar and correlated to those of the C IV resonance line both in the shifts and in the depth of the slanting blue slopes. On some exposures we can distinguish small profile elevations at the Doppler shift –1000 km/s on both doublet component profiles. The dark region of the blueward doublet component (from –800 to –1300 km/s) is much narrower than the dark plateau of the merged resonance doublet profile of C IV. The red doublet component has no low-flux plateau due to its overlap with the red-wing elevation of the doublet blue component. Considerable variations take place due to blue wing shifts at the velocities from –1400 to –2000 km/s. The largest flux variations take place at about –1700 km/s, where on most of exposures a NAC, which on some exposures is quite strong, is superimposed on the slanting blue slope of both doublet components.

A series of spectra, exposed from January 28 to February 6, 1987 give evidence that NACs show rapid changes. For the short-term observation series, the differences in flux are large only in the region of narrow absorption components, giving a picture of their formation, decrease and shift variations. So, the NAC at –1700 km/s is the strongest in SWP 30177, after that it weakens in successive images and in SWP 30225 there appear two weak NACs at velocities of about –1750 km/s and –1600 km/s. In the later image SWP 30242 the NAC is well seen again, but at a somewhat lower velocity of about –1615 km/s. On subsequent exposures of ϵ Ori (SWP 30249, SWP 30257, SWP 30266 and SWP 30272) the velocity of the NAC increases slowly, however, a value of –1700 km/s is never reached. The changes in the red slopes are in the opposite direction relative to the variations of the blue wings, in accordance with the theory of frequency redistribution of the scattered light over the line profile.

Cassinelli et al. (1983) have tried to find a short time variability in the ultraviolet resonance lines of ϵ Ori and in the X-ray region of its spectrum. They have observed ϵ Ori simultaneously with the *Einstein* Observatory, the *International Ultraviolet Explorer* and the *Copernicus* satellite. The X-ray observations spanned period of seven

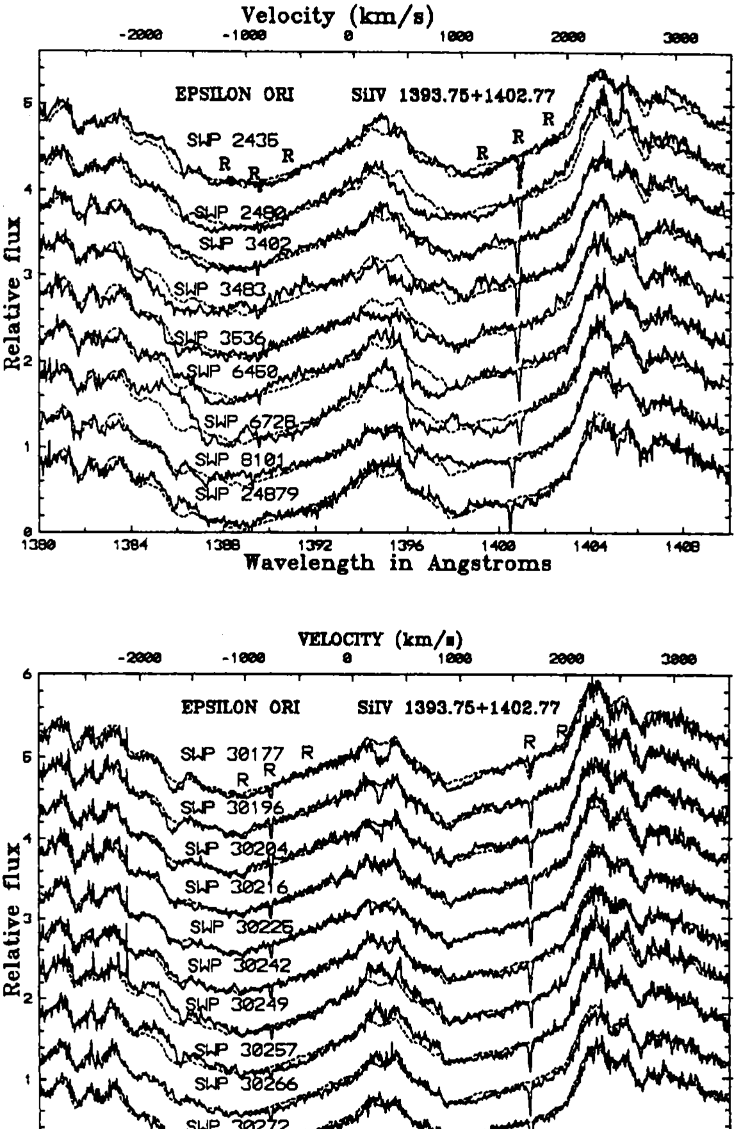


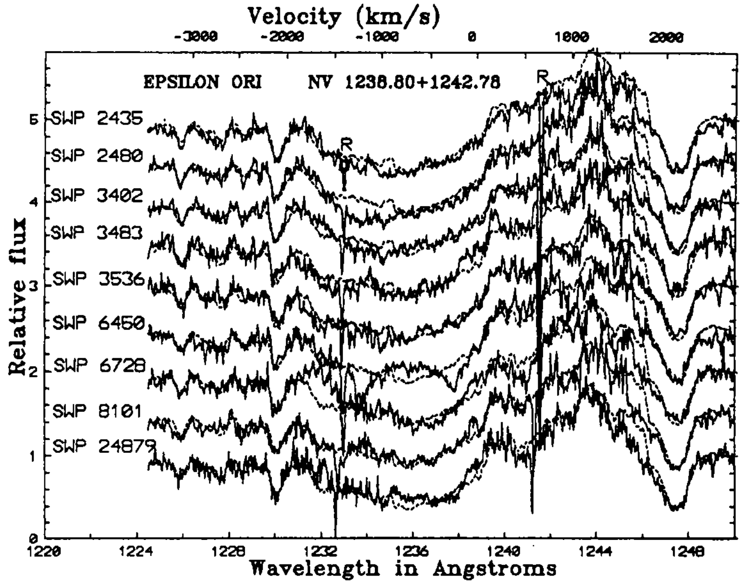
Fig. 2. Resonance doublet of Si IV (139.375+140.277 nm), long-term (upper) and short-term (lower) profile sequences. The long-term correlated flux variations considerably exceed the short-term (daily) variations. See NAC at about V=–1700 km/s, its variability and a possible presence of daily correlations in shifts.

hours and no variations were detected in the X-ray flux. Flux distribution of X-rays of ϵ Ori gave for the temperature of the X-ray source an estimate of $T = 10^{6.1}$ K. They have studied 31 IUE spectra of ϵ Ori exposed during 15 hours on March 1 and 2, 1980 (from which only SWP 8101 has been used by us). The study showed that there was no obvious short-time overall variability of the ϵ Ori spectrum but two sharp NACs were found at velocities of –1400 and –1670 km/s in the Si IV resonance doublet. They are well observable in all 31 IUE spectra. The NAC at –1400 km/s is seen clearly only in SWP 6727, SWP 6728 and SWP 8101 spectra. Such variability gives evidence of the presence of large-scale clumps or shells in stellar wind.

The NACs found by Cassinelli et al. (1983) are located at about the same positions as in the spectra studied by us. From these spectra we conclude that large changes in the resonance line profiles take place typically in about a week. Taking into account that the wind covers a distance equal to a stellar radius during some hours, it follows that such flux variations probably can be ascribed to a single very stable large-scale clump or to a shell but they can also be of a statistical nature. Variations of the violet slopes of both components of Si IV resonance doublet are also accompanied by opposite-directed variations of red slopes of both resonance doublet components.

7. RESONANCE LINES OF N V AND Si III

The N V 1238.8+1242.7 Å resonance doublet line profiles, plotted in Fig. 3 show a strong overlap ($V(\Delta\lambda) = 960$ km/s and χ(N IV) = 77.472 eV), merging into one wide profile. The line is unsaturated and has a strong red-wing elevation, pointing out that it originates in the extended wind. This region of SWP exposures with N V and Si III resonance lines is noisy and therefore it is difficult to study NACs. In some exposures in the red emission wing of N V resonance doublet there is an absorption band ($\lambda \approx 124.05$ nm) extending to 400 km/s. In September 1979 (SWP 6450) two strong absorption components appeared at a velocity of –1200 km/s in both components of the resonance doublet of N V. The enigmatic run of the feature somewhat reminds the presence of strong photospheric lines. This behavior is rather similar to deep and highly blue-shifted absorption features in Hα in B-type supergiants (Kaufer et al. 1996), described as the high velocity absorption (HVA). At the end of the blue slope of the N V resonance doublet there is a moderate line of



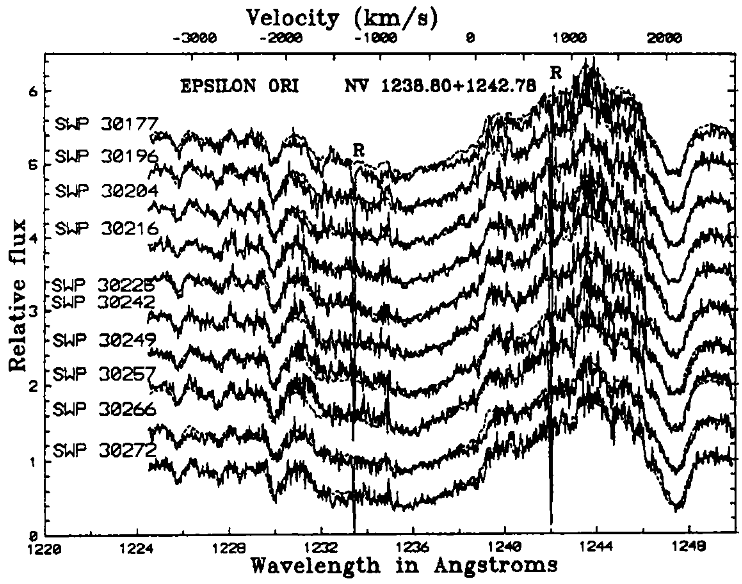


Fig. 3. Merged and shallow profile of the resonance doublet of N V (123.88+124.27 nm). Note the peculiarity of the SWP 6450 curve where two strong and wide absorption features centered at velocities of –1200 km/s of both doublet components are observed.

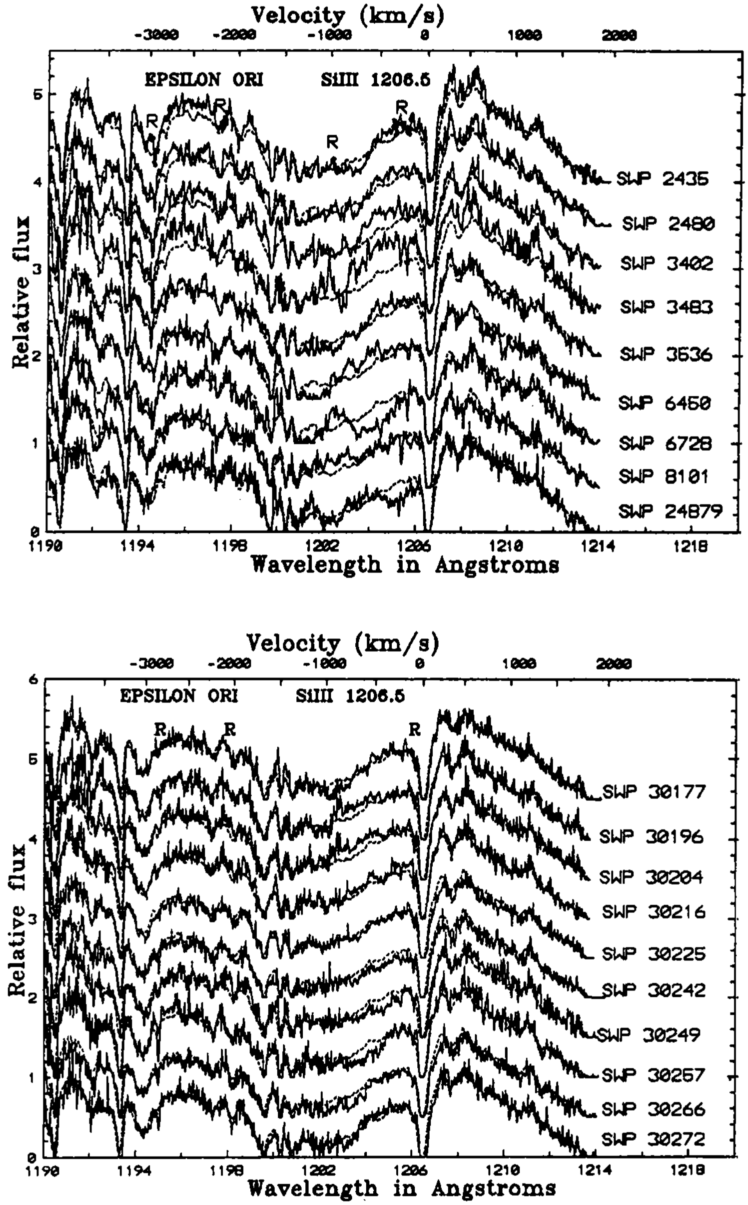


Fig. 4. The singlet resonance line profile of Si III (120.65 nm). Note the red wing cutoff by Lα and the presence of an interstellar Si III line. The dominant variations of the spectrum cover the region from −300 to −1000 km/s. The observable NACs are located at about −1000 km/s.

C II at 123.0 nm distorting the line profile. The variations of the profile of N V, both daily and long-term ones, correlate with variations of Si IV and C IV resonance lines.

The profile of the singlet resonance line Si III 120.65 nm, plotted in Fig. 4 has an unsaturated wide profile. The ionization potential is relatively low, χ(Si II) = 16.345 eV, and therefore the Si III ions are abundant at much lower temperatures than the other ions studied above. In its red wing there is an interstellar and geocoronal Lα cutoff and in its core there is a strong interstellar Si III resonance line absorption. In comparison to the rest of UV resonance lines studied above, it has considerable variations in the profile region from –300 to –1000 km/s. At radial velocities of –1400 to –1700 km/s there are interstellar lines of N I(1) 119.955+120.07 nm and S III(1) 120.097 nm which are strong in all images and do not shift. Whether the profile variation of this spectral line described above is due to large-scale clumps or expelled shells, remains open. Generally, variations in Si III do not correlate with variations in other resonance lines due to the above mentioned circumstance that Si III is more abundant in the lower temperature layers of the wind than the rest of ions studied. The only observable NAC in the Si III resonance line profile is located at about –1000 km/s.

8. RESONANCE LINES OF O VI AND S IV

Shortward of the IUE spectral range there are stellar wind generated ultraviolet resonance lines of O VI and S IV. Cassinelli et al. (1983) concluded from their study of the *Copernicus* ϵ Ori spectra that there is no variability in the O VI resonance doublet component lines. We analysed the *Copernicus* spectrum of ϵ Ori given in the catalogue by Snow & Jenkins (1977) and in the atlas by Walborn & Bohlin (1996). The O VI resonance line profile is very wide, in the given wavelength calibration its terminal velocity is about –2500 km/s and it has a steep blue and a slanted red slope. Its two components (103.19 nm and 103.76 nm, $V(\Delta\lambda)$ = 1648 km/s) are overlapping, and the form of profile is complicated. The minimum of the deep bottom of the violet component lies at a velocity of about –1700 km/s and a strong absorption feature, being probably a NAC, is located on it at a velocity of about –1190 km/s. The slanted red slope ends with the absorption profile due to the red component of the doublet having almost flat bottom from –1680 km/s to –1330 km/s, which is widened probably by NACs. The red wing of this

O VI resonance line component has narrow steep lines at 103.62 and 103.68 nm. Probably they are due to O VI resonance line absorption in hot interstellar gas clouds. The wavelength shift of about –0.1 nm shows not sufficiently exact calibration and thus the velocities found from the *Copernicus* data analysis can be somewhat overestimated. The presence of possible errors in the wavelength calibration of *Copernicus* reaching ± 1 Å has been noted by us earlier (Sapar & Sapar 1989).

The observed resonance doublet of S IV (106.27, 107.30 nm) in the *Copernicus* spectrum of ϵ Ori has wide component profiles and overlap with a strong narrow line of Si IV (106.66 nm) at the blue edge of the red component. The form of the doublet component profiles of S IV is peculiar, having a steep red slope and a slanting blue slope. The blue component of this doublet has an extension corresponding to about 1000 km/s, the minimum of the absorption profile corresponds to zero velocity and there are no dips of absorption superimposed on the main asymmetric profile. The red component of the doublet has a wide but weaker absorption profile with minimum at the zero outflow velocity. It has superimposed dips of absorption in the blue wing at velocities of –780 km/s and –1340 km/s. The absence of line center shifts shows the presence of underlying photospheric line profiles. The analysis of the structure of resonance line profiles of O VI and S IV also shows that stellar wind of ϵ Ori is inhomogeneous.

9. GENERAL REMARKS

The variation of the spectrum of ϵ Ori is a good example to study the presence of supersonic turbulence, large-scaled clumpy structures and shells in the stellar wind of hot supergiants and to understand their generation and dynamics. The extremal velocity of the wind is rather constant but the blue slope of all the studied resonance lines varies considerably and its shape cannot be explained by the theory of extended and stable wind. Especially this holds for wide dark plateaus of the resonance lines and for the observed NACs and their variations, giving evidence on the presence of instabilities, which originate both from stellar atmospheres and stellar wind, generating clumpiness and shell structure both in velocity and density of supersonic turbulence distributions.

ϵ Ori also shows a variability in Hα profiles, and the wings of this line extend only to about ± 700 km/s while the edge velocity from UV resonance line profiles is much larger (Ebbets 1982, Olson & Ebbets 1981). This shows that the Hα line profile is formed in the lower wind layers having lower outflow velocities. Ebbets points out that the observed variable structure of the central part of emission component of Hα suggests the presence of density inhomogeneities, which is in good agreement with the conclusions from the analysis of UV resonance line profiles.

Prinja (1994) and Henrichs et al. (1995) found that wind variability in OB stars is related to the observable Doppler shift due to stellar rotation, determined by $v \sin i$. Namely, the formation and recurrence of the narrow absorption components show correlation with the period of stellar rotation. For ϵ Ori ($v \sin i = 85$ km/s), the maximum rotation period is 20.8 days. We tried to determine the NAC recurrence time but without success, because our data sets are too short. For establishing the recurrence of NACs it is necessary to have a coverage of at least 4–5 successive periods. If stellar variability is connected with rotation and if there are periodical features, then it is difficult to avoid a conclusion that the features stem from the stellar surface.

There are also some peculiar features which are observed only in a single exposure. Thus, SWP 6728 differs considerably from other exposures showing in all resonance lines studied here, i.e. in Si III, Si IV, C III, C IV, N V and Al III resonance lines, an additional strong absorption at the blue slope of line profiles. The SWP 6450 exposure is also peculiar: in it two strong absorption features, corresponding to a shift of –1200 km/s, are superimposed on the usual flat profile of the N V resonance line.

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