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UV LINE PROFILE VARIATIONS IN WOLF-RAYET STARS

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RESUMEN. Presentamos observaciones de estrellas Wolf-Rayet de la Secuencia WN obtenidas con el Satélite IUE que muestran variaciones en el tiempo en los perfiles de las líneas de emisión. Se describen varias interpretaciones para explicar estas variaciones.

ABSTRACT. IUE observations of line-profile variability in Wolf-Rayet stars are presented. Different mechanisms are discussed which are expected to produce these variations.

Key words: LINE PROFILE -- STARS-SPECTRUM VARIABILITY -- STARS-WOLF-RAYET

I. INTRODUCTION

Although one of the well known characteristics of Wolf-Rayet (WR) stars is their line-profile variability, very little is understood of the mechanisms responsible for these variations. In general, the question of variability has been deliberately avoided whenever an understanding of WR stars is sought. This is easily understood, since just the "static" spectrum of WR stars presents complications from a theoretical standpoint, thus, perturbations which must be introduced to explain variations in the spectrum only make the problem more difficult. However, the study of profile variability can yield fruitful results even if we lack a profound understanding of the mechanisms producing these variations.

There are basically two general mechanisms which can produce emission line profile variations: 1) interaction in binary systems and 2) wind instabilities. Either one or both of these are usually invoked when profile variations are detected. However, an analysis of some of the specific mechanisms at work in each of these two cases has only recently been initiated. This point is of particular interest since, for example, the presence of periodic profile variations can be applied to the detection of single-line spectroscopic binaries if it can be shown that certain variations result from interaction effects. The detection of wind instabilities, on the other hand, may be indicative of stellar pulsations, rotation (magnetic fields?), or inhomogeneities in the wind.

The UV wavelength region contains resonance lines which let us "see" the outer regions of the wind, where the density is already fairly low. But it also contains lines arising from excited lower states, which involve smaller regions of the wind. The optical lines which are observed reflect conditions mainly in the innermost regions of the wind, where the density is high enough that low-probability transitions result in observable spectral lines. Thus, by studying line profile variations in the UV one can probe the entire wind simultaneously. For example, variations which involve only resonance lines are suggestive of perturbations in the outermost regions of the wind, while changes in lines such as N IV 1718, unaccompanied by resonance line variations, indicate perturbations which originate closer to the stellar core.

[1]Guest Observer International Ultraviolet Explorer.

In this paper we present observational evidence for three phenomena which can produce profile variations in the spectra of WR stars. The first mechanism, selective atmospheric eclipses, is prevalent among binaries with luminous companions and favorable orbital inclinations, and is the simplest to understand since it does not involve modifications of the WR wind structure. Variations which result from selective atmospheric eclipses must be repetitive, with periods consistent with the orbital period. The second and third mechanisms are rather speculative at the moment, although there are theoretical models which predict their existence: a) instabilities (shocks) which arise in radiation-pressure driven winds, and b) large-scale alterations of the ionization and velocity structure of the wind, which may be related to stellar pulsations.

SELECTIVE ATMOSPHERIC ECLIPSES

Given the large extension of the WR wind, even if a binary system does not present eclipses in the continuum, selective atmospheric eclipses may occur. That is, as the O star passes along the far side of the WR, ions in the WR wind absorb part of the O-star's continuum, resulting in a strengthening of absorption components in the WR spectrum. This effect was originally detected in the spectra of V444 Cyg by Munch (1950). The corresponding variations in the UV spectra have now been detected for V444 Cyg, HD90657, HD94546, HD186943, HD211853 (Koenigsberger and Auer, 1985; Eaton et al. 1985a; Hutchings and Massey, 1983) and CV Ser (Eaton et al. 1985b). All but the last one are WNE stars.

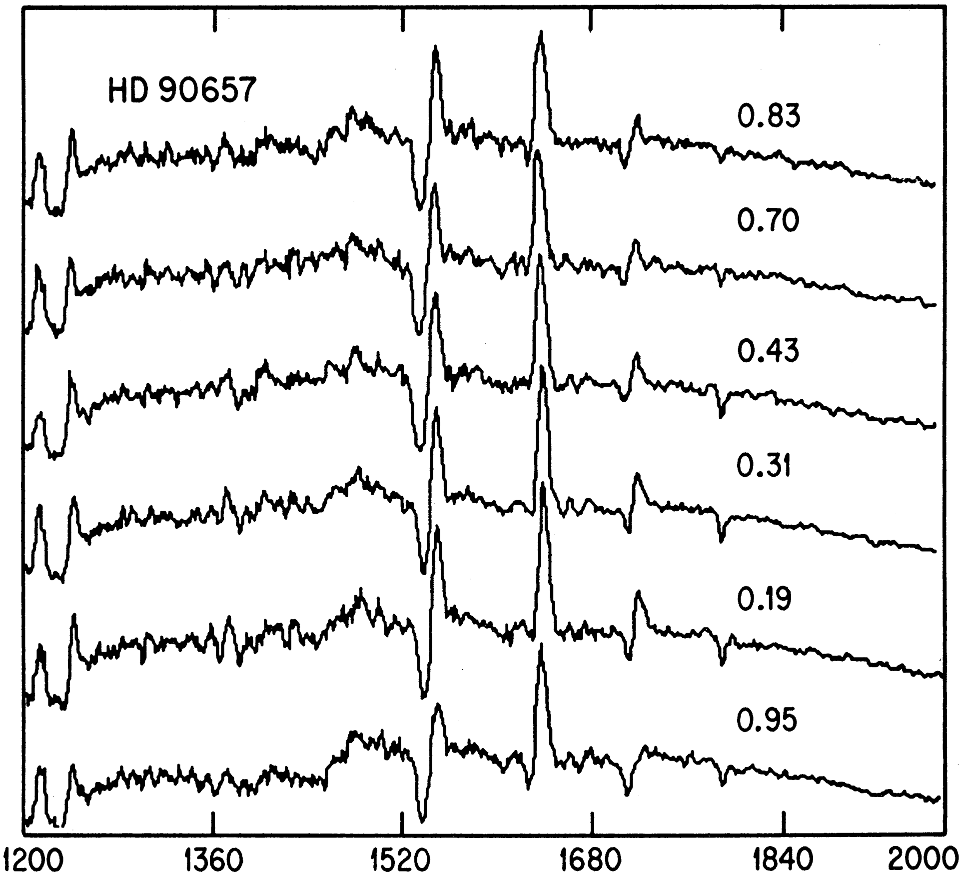

Figure 1. IUE low dispersion spectra of HD90657. The numbers indicate the orbital phase. At phase 0.0 the WR is "in front" of the O-star. Profile changes due to selective atmospheric eclipses are clearly visible in the N IV 1718 Å line.

Figure 1 presents an example of this phenomenon. The IUE low dispersion spectra of HD90657 have been plotted in order of increasing orbital phase so as to illustrate the variations. Note that at $\phi \sim 0$ the emission component of N IV 1718 has nearly vanished, while the absorption component has increased in strength. All lines arising in the WR wind present the same behavior which is repeated consistently at these phases. We have additional IUE spectra of this system taken 3 years after those of Figure 1 which show the same effect. Thus, these variations are stable over timescales of years.

An interesting consequence of atmospheric eclipses is that the absorption of the O-star continuum by the ions in the WR wind is not just shortward-shifted with respect to the local rest wavelength, but it is also shifted to longer wavelengths. This is because the photons leaving the O-star surface encounter absorbers moving not only away from them, but also toward them. Hence, the longest wavelength at which absorption occurs, as compared to the shortest wavelength, provides information on the wind structure in the direction of the O-star. With high dispersion, high signal to noise spectra it should be possible to determine whether effects such as wind-wind collisions occur before the WR wind has reached terminal speeds, or the degree to which the WR wind ionization structure is altered by the O-star's radiation field.

The analysis of selective atmospheric eclipses can also provide information on the wind structure of the WR (Koenigsberger 1983; Eaton et al. 1985a, 1985b; Koenigsberger and Auer, 1985), although the interaction of the O-star's wind and radiation field with the WR wind introduces complications which have not been assessed as yet.

CHANGES IN IONIZATION/ VELOCITY STRUCTURE: STELLAR PULSATIONS?

In Figure 2 we present the profile of N IV 1718 in three low dispersion IUE images of HD90657, obtained during the same observing shift, and corresponding to orbital phase 0.79 +0.01. The time between the first and the third image is ~3 hrs. The change from the first (top) to the second profile is evident: The P Cyg absorption component becomes double, less deep, and in general broader while the emission component becomes narrower and weaker. These changes are accompanied by the following changes in other lines:

a) Although at the resolution limit, the P Cyg absorption components of the Si IV resonance lines also develop shortward-shifted components.

b) The maximum intensities of the C IV 1550 and He II 1640 emission lines decrease. However, there is no change in the C IV P Cyg absorption component.

c) Resolvable lines such as 1360, 1377, and 1470-1520 also become weaker.

d) The N V 1240 resonance line remains unchanged, or is perhaps slightly stronger.

The third IUE image shows a N IV 1718 profile rather similar to the first spectrum. However, the noise level was very high during this exposure and it is thus of lower quality.

The first point to make is that the variations most likely occur in the WR wind, since, except for the extreme cases, N IV 1718 is not in emission in O stars (Walborn et al. 1985).

The N IV 1718 line arises from the transition between two excited states, and thus represents material which lies, on the average, closer to the stellar core than that in which the resonance lines are produced. The strong change in N IV 1718 absorption component, unaccompanied by a similar change in the C IV 1550 absorption implies a modification of the internal regions of the stellar wind. Further evidence in favor of this interpretation is the change in emission maxima of He II and C IV since the maxima in the emission is produced at the smallest line of sight expansion speeds. Given an accelerating wind, the smallest speeds occur closest to the stellar core (and in the gas flowing perpendicular to the line-of-sight to the system). We thus conclude that the variations observed in Figure 2 represent changes in the inner wind structure.

The question we now ask is what process can generate such a change in the wind structure on a timescale of 90 minutes. HD 90657 is a WN4 + O4-6 binary system. Vreux (1985) has

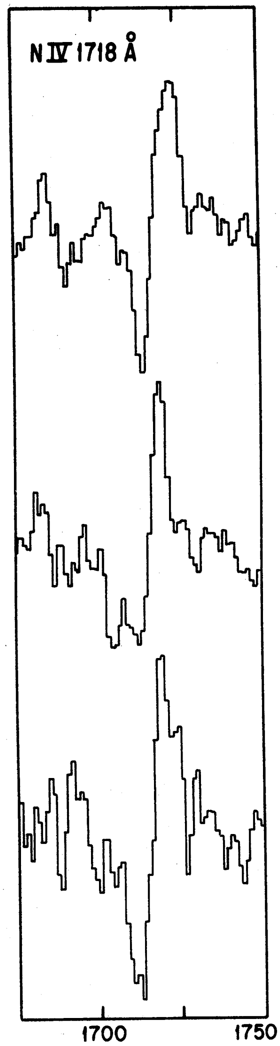

Fig. 2. Variations in HD 90657. Spectra are from top to bottom SWP24630, SWP24641, SWP24644.

suggested that the WR star in this system is undergoing non-radial pulsations. There are as yet no convincing models for non-radial pulsations in WR stars (see discussion by Vreux 1986). However, Maeder (1985) has found WR stars to be unstable to radial pulsations with pulsation periods of 30-60 minutes. Thus, we speculate that the observed profile variations shown in Figure 3 may be the response of the wind to the pulsations of the underlying stellar core. This response may involve a modification of the large-scale velocity and ionization structures .

VARIABLE NARROW ABSORPTION COMPONENTS

Narrow absorption components in resonance lines in the UV spectra o OB stars were first observed in rocket spectra and Copernicus scans (Underhill 1975; Morton 1976; Snow and Morton 1976). Recently, Prinja and Howarth (1986) have analyzed these components in a sample of IUE spectra of OB-stars, and we refer the reader to this paper for a thorough discussion and further references.

One of the characteristics of these features is that they are found, in general, in the absorption through P Cyg resonance lines at about 0.75 V_{∞}.

We have found stable (on a timescale of 7 days) absorption components displaced by -1220 km s^{-1} with respect to the undisplaced interstellar lines associated with the resonance lines of Si IV and C IV in the IUE high dispersion spectrum of HD 193077 (Koenigsberger and Auer, this symposium). We also report the presence of numerous very narrow, unidentified absorption lines, and speculate that they may be narrow components of lines arising from transitions between excited levels of ions such as N IV, Si IV, and perhaps Fe V and Fe VI. These components would be displaced by -1000 to -1600 km s^{-1} with respect to lines of common interstellar species.

A careful inspection of the calcomp plots of individual images in the region of the N IV 1718 P Cyg absorption component reveals the presence of multiple and variable very narrow absorptions. Table 1 is a list of the more obvious features, with the wavelength, FWHM and speed (if they are due to N IV 1718.5 A) given in Columns 1-3. Note that the strongest and most stable components are at ∿ 1200 - 1240 km s^{-1}. The variable components, however, must be regarded with caution since this region lies very near an echelle interorder overlap, where oscillations in the data tend to occur.

In Figure 3 we present the region 1415 - 1460 A of the six IUE high dispersion images of this system. The ranges marked "IO" correspond to the echelle interorder overlap, where variations may not be trusted. A careful inspection of this figure discloses subtle, but clear changes in the narrow absorptions which are superposed on the WR emission lines. Since these are very narrow absorptions, the FWHM being nearly at the resolution limit, and since many are also at noise level, extreme caution is required. However, there is a systematic trend from spectrum A to F: the superposed absorptions on 1430 and 1440 become weaker and those on 1420 become stronger as if there were an ionization change. One cannot help but speculate that the superposed absorptions on the first two are due to displaced N IV (1338.4 and 1446.1) lines while those on 1420 A are due to Multiplet 11.52 and/or 11.75 of C III.

Any conclusions must await a more detailed and quantitative analysis of the entire spectrum. However, it is tempting to speculate that, if real, these absorption lines reflect the presence of shocks at the lower and middle end of a shock spectrum within the wind, the upper end of which is responsible for the soft X-rays (Lucy, 1983). But as an alternative interpretation, these narrow absorptions may result from the same mechanism which produces the variations shown

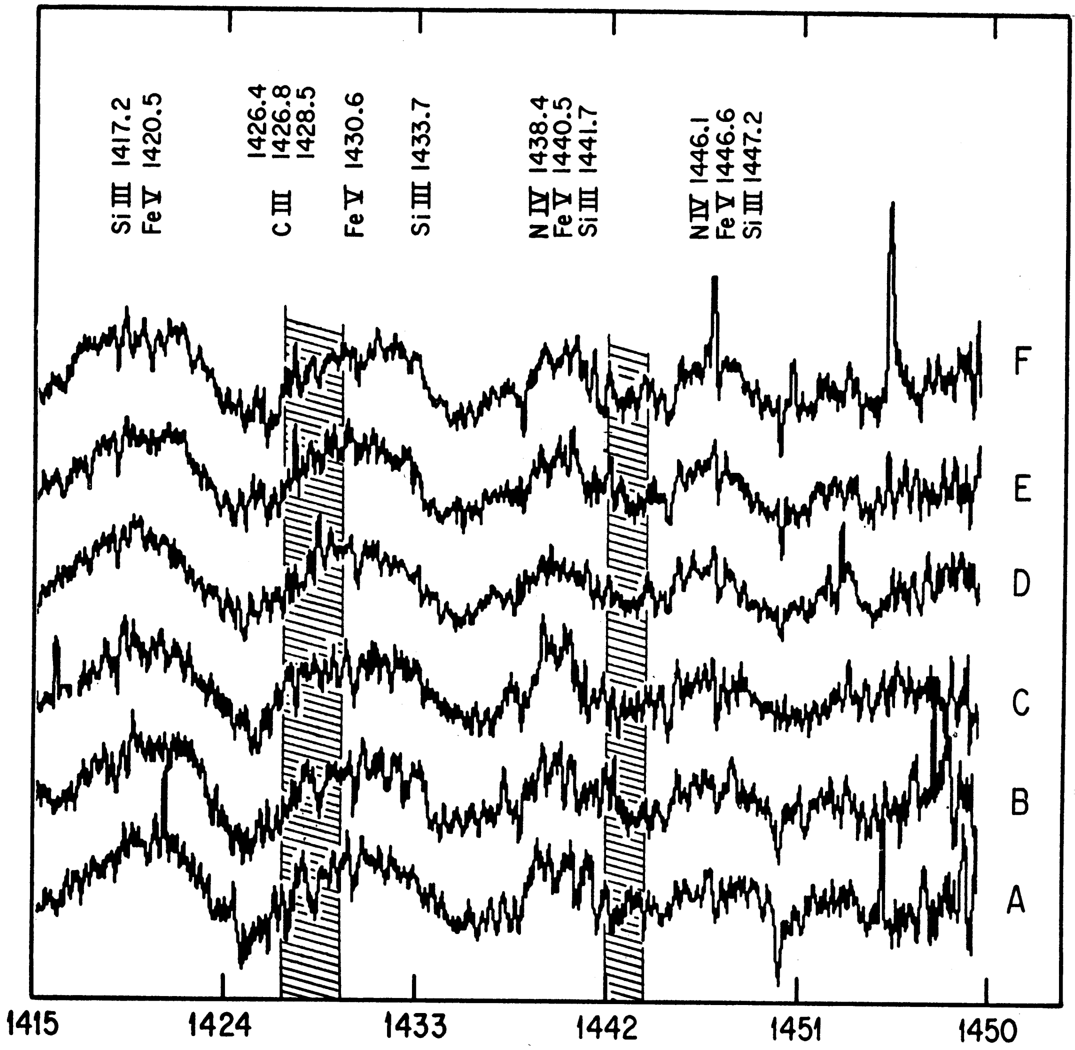

Figure 3. The wavelength region λλ1415-1450Å of the high dispersion spectra of HD193077 obtained over 7 consecutive days. Time increases from image A to F, and dark strips indicate the positions of echelle inter-order overlap regions. A five-point smoothing function was applied to the data.

in Figure 2, (i.e., a response to stellar pulsations), in which case we may be observing the same phenomenon on different scales.

CONCLUSIONS

We stress the importance of detailed observations of profile variability, since its detection and analysis can provide very useful information on the nature of WR stars. Also, it would be very convenient if effects of an oscillating radiation field on a radiation-pressure driven wind were to be assessed.

TABLE 1. N IV 1718 Å POSSIBLE NARROW COMPONENTS

B SWP 15582			C SWP 15596			D SWP 15613		
λ (Å)	FWHM(Å)	V(km s^{-1})	λ (Å)	FWHM(Å)	V(km s^{-1})	λ (Å)	FWHM(Å)	V(km s^{-1})
1712.2	>0.3	-1100.	1710.2	0.2	-1450.	1711.5	>0.2	-1220.
1711.8	0.2	-1170.	1709.8	<0.1	-1520.	1710.2	0.1	-1450.
1711.4	0.2	-1240.				1709.5	0.2	-1570.
1710.6	0.1	-1380.						

E SWP 15625			F SWP 15641		
λ (A)	FWHM(A)	V(km s^{-1})	λ (A)	FWHM(A)	V(km s^{-1})
1712.2	0.2	-1100.	1711.6	<0.1	-1200.
1711.6	>0.1	-1200.	1709.5	0.2	-1570.
1711.4	<0.2	-1240.			
1710.6	0.1	-1380.			
1709.9	0.1	-1500.			

DISCUSSION

STEINER: You mentioned that one of the causes of variability in WR stars may be x-ray ionization. Are there direct detections of x-rays in these stars?

KOENIGSBERGER: X-ray observations of HD 50986 may be consistent with x-rays emitted by a collapsed companion (Moffat, Firmani and McLean). However, if the collapsed companion is too embedded in the stellar wind, the opacity to low-energy x-rays is too large.

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