

## VLT UVES OBSERVATIONS OF THE BALMER LINE VARIATIONS OF $\eta$ CARINAE DURING THE 2003 SPECTROSCOPIC EVENT

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### ABSTRACT

We present high spectral resolution echelle observations of the Balmer line variations during the 2003.5 “spectroscopic event” of  $\eta$  Carinae. Spectra have been recorded of both  $\eta$  Car and the Homunculus at the “FOS4” position in its southeast lobe. This spot shows a reflected stellar spectrum that is less contaminated by nebular emission lines than ground-based observations of the central object itself. Our observations show that the spectroscopic event is much less pronounced at this position than when seen directly on  $\eta$  Car using the *Hubble Space Telescope* Space Telescope Imaging Spectrograph. Assuming that the reflected spectrum is indeed latitude-dependent, this indicates that the spectral changes during the event seen pole-on (FOS4) are different from those closer to the equator (directly on the star). In contrast to the spectrum of the star, the scattered spectrum of FOS4 always shows pronounced P Cygni absorption with little variation across the spectroscopic event. After that event an additional high-velocity absorption component appears. The emission profile is more peaked at FOS4 and consists of at least three distinct components, of which the reddest one shows the strongest changes through the event. The data seem to be compatible with changes in latitudinal wind structure of a single star, with or without the help of a secondary star, or the onset of a shell ejection during the spectroscopic event.

*Key words:* stars: individual ( $\eta$  Carinae) — stars: peculiar — stars: variables: other

### 1. INTRODUCTION

$\eta$  Carinae is among the most massive and luminous unstable stars of our Galaxy. During its “great eruption” (about 1838–1858) it became one of the visually brightest stars in the sky. Today the star itself is hidden in a bipolar nebula known as the Homunculus. It is, because of the dust within the expanding lobes scattering light from  $\eta$  Car, mainly a reflection nebula (e.g., Thackeray 1956, 1961; Visvanathan 1967; Warren-Smith et al. 1979; Allen & Hillier 1993).

Temporary spectral changes were recorded on several occasions beginning in 1948 (see references cited by Damineli et al. 1999) and occur approximately every 5.5 yr (Damineli 1996). The same timescale had earlier appeared in infrared photometry (Whitelock et al. 1994) and was confirmed by successful predictions of spectroscopic events around 1997.9 and 2003.5. In each case the excitation and ionization level of the spectrum

decreased for several months (see, e.g., Zanella et al. 1984; Davidson 1999; Davidson et al. 1999; McGregor et al. 1999; Damineli et al. 1999). At the same time the X-ray emission first peaked and then plummeted during the event (Ishibashi et al. 1999b).

The 5.54 yr periodicity led many authors to suggest that  $\eta$  Car has a companion star (Damineli et al. 1997; Davidson 1997; Ishibashi et al. 1999a). Zanella et al. (1984) proposed earlier that each event involves a shell ejection or similar event. The periodicity suggests that a companion star may regulate the cycle, but neither of these conjectures has been confirmed. In general the phenomenon has not yet been explained.

$\eta$  Car was observed regularly at high spatial resolution with the *Hubble Space Telescope* (HST) Space Telescope Imaging Spectrograph (STIS) from 1998 through 2002 to separate the star from its nearby ejecta, which contaminates all ground-based spectroscopy. The HST Treasury program carried out an intensive monitoring with more frequent observations during its 2003 “spectroscopic event.” To complement this program with

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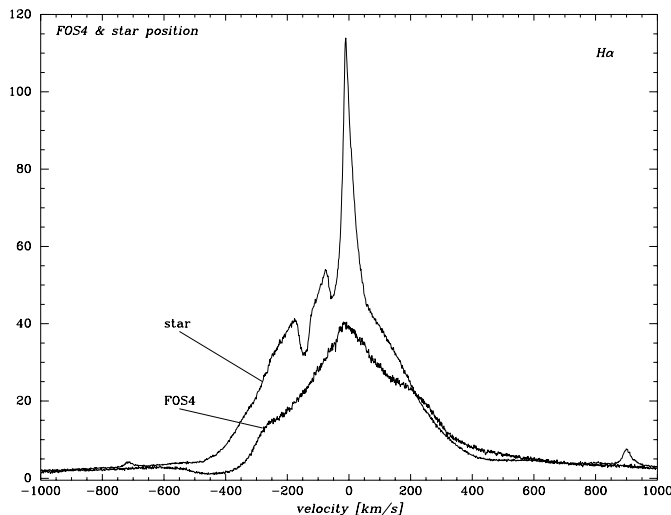


FIG. 1.—Difference of ground-based spectra taken at the position of the star and taken on the FOS4 position. The narrow and very strong emission peaks originate from the so-called Weigelt knots, which are close ( $<0''.3$ ) to the star and are not resolved in ground-based observations. Since 1998, the star brightened considerably while the ejecta did not, based on STIS high spatial resolution spectra. The FOS4 spectrum plotted has been shifted by  $-93 \text{ km s}^{-1}$  to match the center of the star's spectrum. The shift is due to the expansion of the Homunculus.

improved temporal sampling during the event, we observed  $\eta$  Car with the Ultraviolet and Visual Echelle Spectrograph (UVES) at the European Southern Observatory (ESO) between 2002 December and 2004 March. We observed the reflected spectrum of the star at the “FOS4” position (about  $2''.6$  south and  $2''.8$  east of the star; Humphreys et al. 1999), which allows us to view the star and the event from a different angle. At FOS4 there is also only a modest amount of contamination by nebular emission from the vicinity of the star (mainly the Weigelt knots at a distance of only  $0''.1$ – $0''.3$ ; Weigelt & Ebersberger 1986; Hofmann & Weigelt 1988). Spectra taken on the star's position and at FOS4 are shown in Figure 1 for comparison. At FOS4, spectral changes in the stellar spectrum can be observed after a light-travel delay time of roughly 3 weeks. We also observed the star itself less frequently but coordinated with the *HST* STIS Treasury program.

The scattering surface in the southeast lobe at the FOS4 position “sees” the star from a roughly polar direction (Smith et al. 2003), whereas our direct line of sight sees a spectrum representative of the intermediate latitudes (Davidson et al. 2001). Thus, these two lines of sight allow us to follow the event from different angles. For example, in the *HST* STIS spectra of the central star, a deep P Cygni  $H\alpha$  absorption was present during the 1997–1998 event but disappeared a few months later. Meanwhile, however, the P Cygni absorption did not disappear in the star's spectrum reflected by dust in the southeast Homunculus lobe. A possible explanation for the P Cygni absorption discrepancy is that  $\eta$  Car's wind may be denser toward its poles except during each spectroscopic minimum, as discussed by Smith et al. (2003). In any case, some important observational questions arise. To what extent does the reflected “polar”  $H\alpha$  profile differ from the feature that we observe directly? Does the polar  $H\alpha$  emission vary during a spectroscopic event, and, if so, in what manner? Here we present partial answers to these questions, and we describe some important details omitted by Smith et al. A companion paper by Davidson et al. (2005) describes the *HST* STIS Balmer line observations of the central star during 2003, which significantly differed from the previous one observed in 1997–1998.

## 2. THE OBSERVATIONS

The data presented here are based on observations obtained in service mode between 2002 December and 2004 March with UVES at the Nasmyth platform B of ESO's VLT UT2 (Kueyen) on Cerro Paranal, Chile.<sup>2</sup> For all observations the standard settings DIC1, 346+580 (blue arm centered at  $3460 \text{ \AA}$  and red arm centered at  $5800 \text{ \AA}$ ), and DIC2, 437+860 (blue arm centered at  $4370 \text{ \AA}$  and red arm at  $8600 \text{ \AA}$ ), were used. The observed wavelength range extends continuously from  $3100$  to  $10200 \text{ \AA}$  except for small gaps due to the space between the two CCDs of the detector mosaic in the red channel. The primary objective was to observe the reflected stellar spectrum at the FOS4 position (about  $2''.6$  south and  $2''.8$  east of the star) in the Homunculus. The slit was aligned across the southeast lobe of the Homunculus at a position angle of  $160^\circ$  (see Fig. 2). To monitor the 2003 event, spectra were taken about every week during the event (mid-May to the end of July) and every month before and after the event time. No spectra could be taken between mid-August and late November because of the very low elevation of  $\eta$  Car at Paranal during this time of year. Integration times were between 1 s (on the star) and 770 s (on the FOS4 position).

For a reference spectrum preceding the spectroscopic event, we used spectra obtained during the UVES commissioning (1999 December 21) from the ESO archive. They were obtained with the identical setup as our spectra, but with different slit orientation. The position angle of the slit was  $45^\circ$ , i.e., about perpendicular to the axis of symmetry of the Homunculus with offset to the FOS4 center. Exposure times for these spectra were 60 s. Observational dates of all spectra used for this analysis are listed in Table 1.

<sup>2</sup> Programs 70.D-0607(A), 71.D-168(A), and 72.D-052(A); PI: K. W.

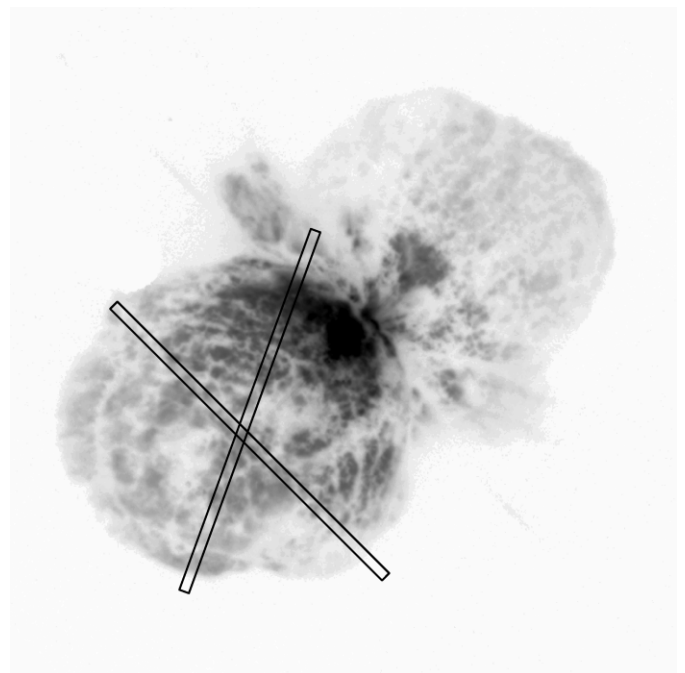


FIG. 2.—*HST* Advanced Camera for Surveys High Resolution Channel image in the F550M filter of  $\eta$  Car and the Homunculus. North is up and east to the left, and both slit positions (P.A. =  $160^\circ$  and  $45^\circ$ ) are indicated. The slits are drawn to their full (maximum possible) width and length. FOS4 is an area of  $\approx 1'' \times 1''$  located approximately at the intersection of the two slits.

TABLE 1  
OBSERVING DATES

Date	UT	MJD	Phase
1999 Dec 21 .....	1999.961	51,534	0.363
2002 Dec 8 .....	2002.937	52,617	0.898
2002 Dec 26 .....	2002.986	52,635	0.907
2002 Dec 31 .....	2003.000	52,640	0.910
2003 Jan 3 .....	2003.008	52,643	0.911
2003 Jan 19 .....	2003.052	52,659	0.919
2003 Jan 23 .....	2003.063	52,664	0.921
2003 Feb 4 .....	2003.100	52,675	0.927
2003 Feb 14 .....	2003.123	52,685	0.932
2003 Feb 25 .....	2003.153	52,696	0.937
2003 Mar 7 .....	2003.180	52,706	0.942
2003 Mar 12 .....	2003.195	52,711	0.945
2003 Apr 30 .....	2003.329	52,760	0.969
2003 May 5 .....	2003.342	52,765	0.971
2003 May 12 .....	2003.361	52,772	0.975
2003 May 29 .....	2003.408	52,789	0.983
2003 Jun 3 .....	2003.423	52,794	0.986
2003 Jun 8 .....	2003.436	52,799	0.988
2003 Jun 12 .....	2003.447	52,803	0.990
2003 Jun 17 .....	2003.460	52,808	0.993
2003 Jun 22 .....	2003.474	52,812	0.995
2003 Jun 30 .....	2003.496	52,820	0.999
2003 Jul 5 .....	2003.510	52,825	1.001
2003 Jul 9 .....	2003.521	52,829	1.003
2003 Jul 16 .....	2003.540	52,836	1.007
2003 Jul 20 .....	2003.551	52,840	1.009
2003 Jul 26 .....	2003.567	52,846	1.012
2003 Jul 31 .....	2003.581	52,851	1.014
2003 Nov 25 .....	2003.901	52,968	1.072
2003 Dec 17 .....	2003.962	52,991	1.083
2004 Jan 2 .....	2004.005	53,007	1.091
2004 Jan 25 .....	2004.068	53,030	1.102
2004 Feb 20 .....	2004.140	53,056	1.115
2004 Mar 11 .....	2004.192	53,076	1.125

NOTE.—Phase has been computed with zero point of MJD = 50, 800 and a period of 2023 days.

One short and one long exposure were obtained with the DIC1 (346+580 setting) to record both the extremely bright  $H\alpha$  emission and the fainter lines with good signal-to-noise ratio (S/N). The slit width of all observations was  $0''.3$  and  $0''.4$  in the red and blue ranges, respectively, resulting in a spectral resolution of 80,000 in the blue arm and 110,000 in the red arm. The pixel scales and slit lengths were, respectively,  $0''.246 \text{ pixel}^{-1}$  and  $7''.6$  in the blue arm and  $0''.182 \text{ pixel}^{-1}$  and  $11''.8$  in the red arm. The data were reduced and two-dimensional spectra extracted using mostly the standard ESO pipeline software for UVES. An exception was the order-merging procedure in which the ESO software did not produce satisfactory results for our data, mainly because the merging of overlapping echelle orders led to less than optimum S/N. Therefore, the order merging was carried out using software developed at the Landessternwarte Heidelberg (Stahl et al. 1999). All spectral frames were converted after reduction to the same (heliocentric) wavelength scale.

Each spectrum presented here is an average of an area of about  $0''.55$  along the slit (two rows in the blue and three rows in the red long-slit spectra) extracted at the FOS4 position. We searched for the best extraction region in the long slit but had to settle for this small extraction region on FOS4 to avoid smearing due to velocity shifts across the lobe. Smith et al. (2003) encountered similar limits using *HST* STIS spectra. All spectra

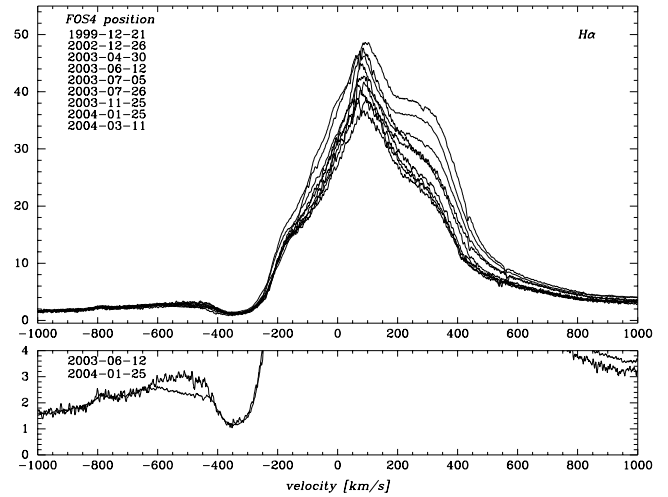


FIG. 3.— $H\alpha$  profiles from some of the spectra. The bottom panel shows the changes in the P Cygni absorption for two of the spectra.

plotted in this paper are normalized to continuum being unity. Our July 26 spectrum shows the minimum in the intensities of the high excitation lines such as  $\text{He I } 6678 \text{ \AA}$  and therefore represents the best “event spectrum” in our data. The November spectrum indicates that the affected lines brightened significantly afterward.

### 3. DISCUSSION

#### 3.1. The VLT UVES Spectra

The time variation of the  $H\alpha$  lines of selected spectra at FOS4 is given in Figures 3 and 4. They seem to be composites of several components. Most obvious are at least three principal emission components, which are preliminarily fitted by Gaussians plus a P Cygni absorption. All Gaussian profiles themselves may again be composites of several components. It is also possible that a broader absorption (e.g., on the blueshifted side) causes one component to appear as two separate ones. However, for simplicity we used three Gaussians. The centroids of the Gaussians are roughly at  $-130 \text{ km s}^{-1}$  (FWHM  $\sim 180 \text{ km s}^{-1}$ ),  $70 \text{ km s}^{-1}$

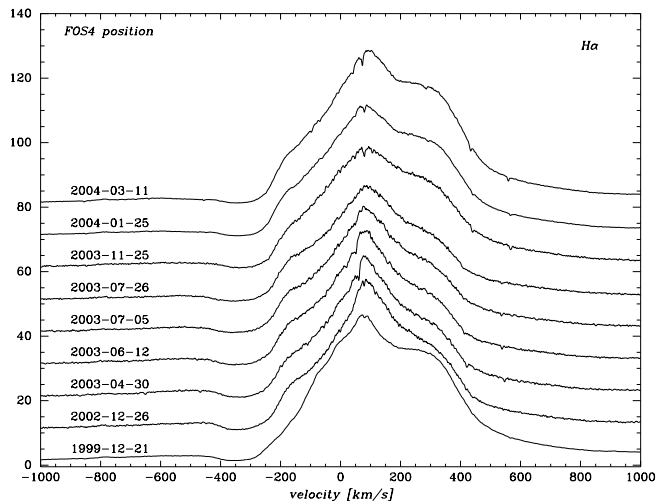


FIG. 4.— $H\alpha$  profiles of selected spectra at the position of FOS4. In order to avoid confusion, each spectrum is offset by an additional 10 continuum units. Spectra are labeled with the observing date. None of the spectra shows a clear flat-topped profile. Note also the evolution of the red hump with time.

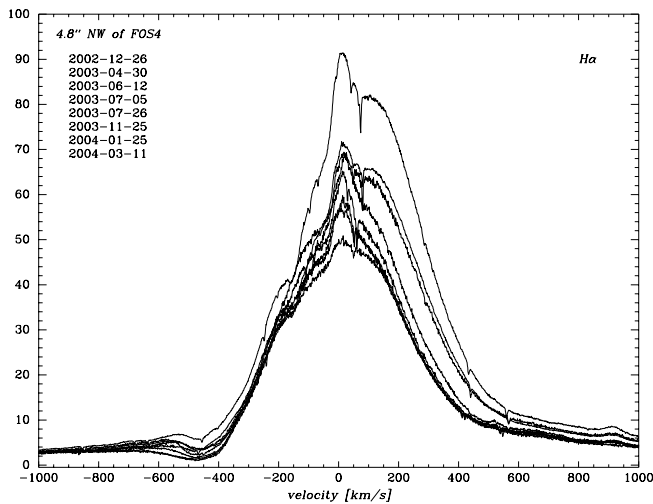


FIG. 5.— $H\alpha$  profiles from the same spectra as in Fig. 3, but now at a position  $4.8''$  northwest of FOS4, closer to the central source. Since the 1999 data had a different position angle, this spectrum is missing here.

(FWHM  $\sim 230$  km s $^{-1}$ ), and  $300$  km s $^{-1}$  (FWHM  $\sim 230$  km s $^{-1}$ ). The P Cygni absorption is centered at  $-340$  km s $^{-1}$ . For a comparison we show in Figure 5 the time variation of the  $H\alpha$  line  $4.8''$  northwest of FOS4, closer to the star.

During the event the  $H\alpha$  profile at FOS4 changes, and all components decrease in intensity. The most notable change is in the  $300$  km s $^{-1}$  profile—the red hump—which disappears nearly completely. The red hump was very prominent in the 1999 spectrum, reappeared after the event in 2003 November, and was present still in 2004 March (see Figs. 3 and 4). Note that the red hump was already weak in 2002 December, long before the event started, as evidenced by brightening in the X-ray (Corcoran 2003) and IR domains (Whitelock et al. 2003, 2004).

The second most important change in the FOS4  $H\alpha$  spectra is in the P Cygni absorption profile. Before and during the event there is almost *no* change in the P Cygni profile. In the more recent VLT spectra (2003 November–2004 March), however, a second component at a higher velocity, centered at about  $-500$  to  $-600$  km s $^{-1}$ , appears. This high-velocity component is first visible in the November spectrum, is deepest in January, and is weaker again in the 2004 March spectrum. Its appearance cannot be explained by the light-travel time but rather shows that this change occurred later and not necessarily in causal connection to the event.

The travel delay time from the star to FOS4 can be estimated from the radial velocity of the emission lines. Because of the expansion of the Homunculus, the lines are blueshifted compared with the same lines seen in the star's spectrum. This method, however, depends on a decent model of the expansion of the Homunculus and a good measurement of the radial velocities. We used several sharper [Fe II] lines and derive a radial velocity difference of about  $93$  km s $^{-1}$  between the star and FOS4. This yields a light-travel time of approximately 20 days.

The blue emission component shows only very small changes. Of particular interest is the central  $70$  km s $^{-1}$  emission component. It is intermediate in terms of variation between the red and the blue component.

The  $H\beta$  and  $H\eta$  lines show in general the same behavior as the  $H\alpha$  line (Figs. 6 and 7). The development of the red hump, however, seems to be weaker going from  $H\alpha$  to  $H\eta$ . In addition, the shape of the high-velocity P Cygni component changes from

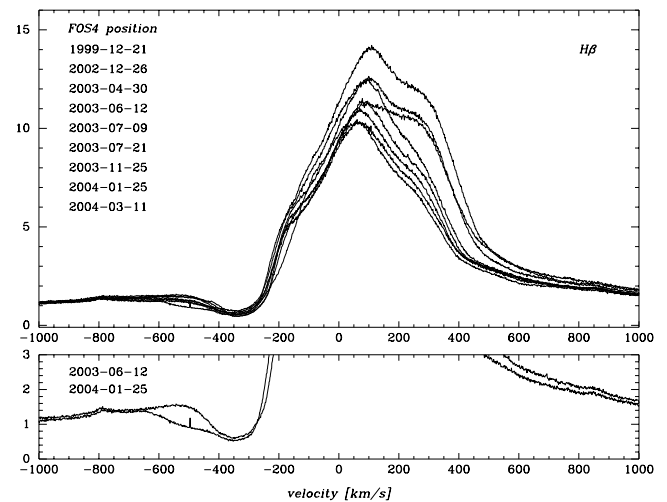


FIG. 6.—Same as Fig. 3, but for  $H\beta$ .

$H\alpha$ , where it is straighter, to  $H\eta$ , where a clear second dip is present.

### 3.2. Comparison with the HST STIS Spectra

Several differences are seen in comparison with the  $H\alpha$  profile in the *HST* STIS spectra described in the Davidson et al. (2005) companion paper. First, a sharp absorption component roughly at  $-150$  km s $^{-1}$  is seen in the *HST* spectra, taken directly at the star. This component is absent in FOS4 observations but appears in our spectra in all positions up to  $1.3''$  northwest of FOS4, as well as in a few observations we made centered on  $\eta$  Car (see Fig. 1). We therefore confirm this component to be present in an extended area (roughly  $3''$  radius) around the star in the southeast lobe.

Relative to the underlying continuum level, and within the uncertainties of measurement, the UVES and *HST* data both show an equally strong long-wavelength wing at velocities above  $+600$  km s $^{-1}$ . This is reassuring, since wings due to Thomson scattering should be approximately isotropic in their appearance. However, the line profile is not symmetric, and the broadening is much larger on the redshifted side. This has also been observed in supernovae (Chugai 1977). A detailed analysis of the scattering processes within the Homunculus is definitely needed to better understand this asymmetry but lies beyond the scope of this

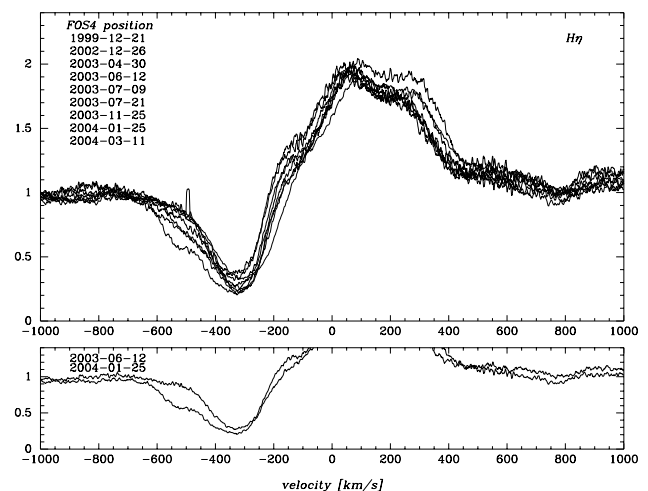


FIG. 7.—Same as Fig. 3, but for  $H\eta$ .

paper and will therefore be addressed elsewhere. It is nevertheless important, since high-velocity components in the P Cygni absorption might not be visible or might be much deeper because of the presence of Thomson-scattering wings.

The shape of the  $H\alpha$  profile in the *HST* spectra recorded during the 2003 event is mainly flat-topped and has changed since the last event in 1998, in which the shape was more rounded (see Davidson et al. 2005). Contrary to this  $H\alpha$  profile, we observe at FOS4 (as discussed above) a more complex structure of the emission. This is not an effect of the spectral resolution, but an intrinsic difference of the two sight lines.

Before and during the event there is little or no change in the P Cygni profile as viewed from the FOS4 position; the absorption trough is rather stationary at  $-340 \text{ km s}^{-1}$  and only marginally deepens and broadens during the event (by about  $50 \text{ km s}^{-1}$ ; Figs. 3 and 4). This is in remarkable contrast to the *HST* observations. There, the P Cygni absorption is absent before the event, develops during the event, and lies at about  $-500 \text{ km s}^{-1}$ . Taking the expansion velocity of the Homunculus at the FOS4 position into account, this is similar to the central velocity of the P Cygni absorption observed in FOS4. Here the absorption lies at  $-340 \text{ km s}^{-1}$  but is not corrected for the expansion. For a comparison of our FOS4 velocities with measurements from the star, one therefore has to subtract  $\sim 93 \text{ km s}^{-1}$ . Consequently, the P Cygni absorption would lie around  $-433 \text{ km s}^{-1}$ .

The central velocity component (sharp peak at  $70 \text{ km s}^{-1}$ ; see, e.g., Fig. 3) is the second major difference between the UVES spectra at FOS4 and the STIS spectra of the star. Without this component, the  $H\alpha$  profile at FOS4 resembles the  $H\alpha$  profile of the star, if we ignore the much more pronounced amplitude variation in the red hump observed at FOS4. This can be understood if the central component is reflected emission from ejecta near the star visible at the FOS4 position. The peaked emission might come from a gas clump in the vicinity of the star, which would have to be bright. One other quite natural explanation would be that the peak emission is reflected and scattered light of one or more of the Weigelt knots. The Weigelt knots show extremely bright and narrow emission lines (Davidson et al. 1995). Scattering at the thick walls of the Homunculus would broaden these lines and decrease their intensity. Figure 1 shows that velocity of the peak emission in FOS4 agrees well with the radial velocity of the Weigelt knots seen at the star. Last but not least, the peak emission might have its origin in an area called the “Little Homunculus” (Ishibashi et al. 2003). Similar in morphology, the Little Homunculus is a small nebula ( $\sim 2''$  in diameter) within the Homunculus. The width of the peaked line would fit the expansion velocity of the Little Homunculus.

### 3.3. Global Patterns

The observations can be summarized as follows. The scattered spectrum of the Homunculus, which is representative of the more polar region of  $\eta$  Car, is changing far less than the STIS spectrum of the core, which is representative of a more equatorial spectrum (more precisely, it sees the star at an angle of  $45^\circ$ ). During the event, the spectra of pole and equator become more similar. The change in the emission may be partly due to changes in the equatorial region.

It has been shown that the Balmer lines seen at FOS4 show a profile somewhat different from that seen at the star. The pronounced flat-topped profile of the STIS spectra is not observed in the FOS4 UVES spectra, either because we are really seeing different stellar profiles viewing the star more pole-on or because the peak central emission is an additional emission superposed on a more flat-topped profile as seen in the *HST* STIS

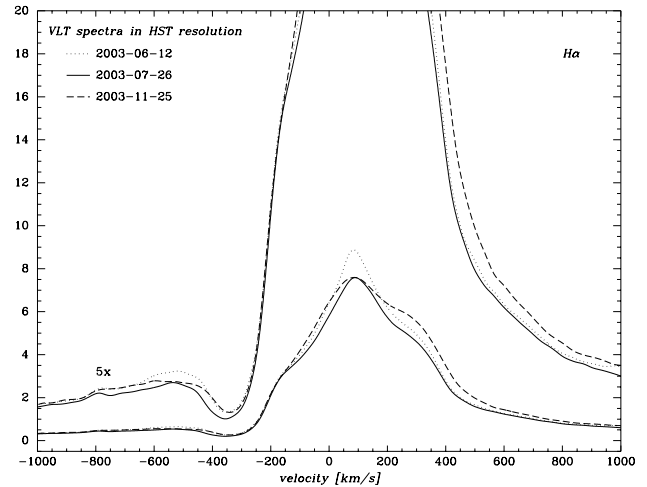


FIG. 8.— $H\alpha$  profile observed at FOS4 with the VLT, but convolved to the spectral resolution of the *HST* STIS data. The plot and dates are chosen to be directly comparable to Fig. 1c of the accompanying paper of Davidson et al. (2005).

data. The first scenario would imply a different appearance of the event viewed at the equator and viewed from a more pole-on direction. In the second case, the peak emission is the result from a circumstellar feature, and the event looks very much alike from both viewing angles. In both directions a flat-topped profile is seen, but in FOS4 with the central emission peak added. Note, however, that the event viewed from FOS4 still is different, since the P Cygni lines are always present as seen from the FOS4 but change as seen from the star.

In Figure 8 we have smoothed our VLT UVES FOS4 spectra to the same spectral resolution as the *HST* STIS data. This figure is directly comparable to Figure 1c in Davidson et al. (2005), with the same line styles used for a data set taken at nearly the same dates, but taking into account the light-travel time. With this delay, however, observations should have been done monthly (as it indeed was planned) between 2003 August and November to compare with the STIS observations in 2003 September. Since no VLT spectra exist between 2003 August and November, we chose the last spectrum before and the first spectrum after this gap to match Figure 1c in Davidson et al. (2005) as well as possible with our data. Figure 8 clearly shows that the flat-topped profile seen in the *HST* spectra are not seen in the VLT FOS4 spectra. The flat-topped profile therefore is not an effect of the lower spectral resolution of the *HST* spectra, but is indeed a real difference from the spectrum seen at the star.

## 4. CONCLUSIONS

The observations presented here show that the spectroscopic event of  $\eta$  Carinae in 2003 underwent different spectral changes when observed from the FOS4 vantage point compared with the line of sight to the star. Whereas a flat-topped  $H\alpha$  profile was found in the *HST* STIS spectra on the star position, the FOS4 spectra show a multicomponent profile with distinct peaks. If we assume that the emission observed at FOS4 is indeed only a scattered spectrum originating from the central source and does not include emission from other sources seen by FOS4, these observations favor a model in which the spectroscopic event is intrinsically different at different stellar latitudes. Thus, the wind of  $\eta$  Car appears to be nonspherical, and the event is also nonspherical, with the polar region being affected quite differently from the equatorial region. If the peaked emission is of

circumstellar origin, the event seen more pole-on is only distinguished by the change of the P Cygni absorption profile, which is present at the star but not prominent at FOS4.

The most prominent change at FOS4 is the gradual development of the red hump, an emission structure. Some additional emission must be present here, either from a companion star, additional stellar wind, or an ejected shell. The same explanation can be put forward for the relatively narrow central  $H\alpha$  component in the UVES FOS4 spectra, if it is not circumstellar. In addition, the appearance of an additional high-velocity P Cygni component hints at new material between us and (the pole region of) the central source. This absorption component can again be the result of an increasingly faster and denser stellar wind or a shell ejected with this velocity.

The fact that P Cygni absorption is always present at FOS4 but only appears in the line of sight to the star during the event as seen in the high spatial resolution *HST* observations has another implication on the density structure around the central object. Note in this context that P Cygni absorption is always present in the *HST* observations of the higher Balmer lines. The

explanation for this may be that each Balmer line is formed at a different distance from the star, implying different optical depth for different Balmer lines. In that scenario the  $H\alpha$  line is formed further out from the star compared with  $H\beta$  or  $H\eta$  (see Fig. 15 in Hillier et al. 2001).

As the event develops, because of either wind-wind collision in a binary system or a shell ejection of the primary star, the optical depth in the line of sight increases and P Cygni absorption can form in the  $H\alpha$  line. Viewed, however, from the poles at FOS4, the optical depth is always high enough to show a P Cygni profile.

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