Detection of high-velocity material from the wind-wind collision zone of Eta Carinae across the 2009.0 periastron passage[★]

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Received 21 December 2009 / Accepted 21 March 2010

ABSTRACT

We report near-infrared spectroscopic observations of the Eta Carinae massive binary system during 2008–2009 using the CRIRES spectrograph mounted on the 8 m UT 1 Very Large Telescope (VLT Antu). We detect a strong, broad absorption wing in He I $\lambda 10833$ extending up to -1900 km s^{-1} across the 2009.0 spectroscopic event. Analysis of archival *Hubble Space Telescope*/Space Telescope Imaging Spectrograph ultraviolet and optical data identifies a similar high-velocity absorption (up to -2100 km s^{-1}) in the ultraviolet resonance lines of Si IV $\lambda 1394$, 1403 across the 2003.5 event. Ultraviolet resonance lines from low-ionization species, such as Si II $\lambda 11527$, 1533 and C II $\lambda 11334$, 1335 , show absorption only up to -1200 km s^{-1} , indicating that the absorption with velocities -1200 to -2100 km s^{-1} originates in a region markedly more rapidly moving and more ionized than the nominal wind of the primary star. Seeing-limited observations obtained at the 1.6 m OPD/LNA telescope during the last four spectroscopic cycles of Eta Carinae (1989–2009) also show high-velocity absorption in He I $\lambda 10833$ during periastron. Based on the large OPD/LNA dataset, we determine that material with velocities more negative than -900 km s^{-1} is present in the phase range $0.976 \leq \phi \leq 1.023$ of the spectroscopic cycle, but absent in spectra taken at $\phi \leq 0.947$ and $\phi \geq 1.049$. Therefore, we constrain the duration of the high-velocity absorption to be 95 to 206 days (or 0.047 to 0.102 in phase). We propose that the high-velocity absorption component originates in shocked gas in the wind-wind collision zone, at distances of 15 to 45 AU in the line-of-sight to the primary star. With the aid of three-dimensional hydrodynamical simulations of the wind-wind collision zone, we find that the dense high-velocity gas is along the line-of-sight to the primary star only if the binary system is oriented in the sky such that the companion is behind the primary star during periastron, corresponding to a longitude of periastron of $\omega \sim 240^\circ\text{--}270^\circ$. We study a possible tilt of the orbital plane relative to the Homunculus equatorial plane and conclude that our data are broadly consistent with orbital inclinations in the range $i = 40^\circ\text{--}60^\circ$.

Key words. stars: winds, outflows – stars: early-type – stars: individual: η Carinae – stars: mass-loss – binaries: general – stars: atmospheres

1. Introduction

Eta Carinae offers a unique opportunity to study the evolution of the most massive stars and their violent, giant outbursts during the luminous blue variable (LBV) phase. Eta Car is located at a distance of $2.3 \pm 0.1 \text{ kpc}$ (Walborn 1973; Hillier & Allen 1992; Davidson & Humphreys 1997; Smith 2006) in the Trumpler 16 OB cluster in Carina and consists of a very luminous central object ($L_\star \geq 5 \times 10^6 L_\odot$, Davidson & Humphreys 1997) enshrouded

in massive ejecta of $\sim 12\text{--}20 M_\odot$ (the Homunculus nebula, Smith et al. 2003b).

The optical and near-infrared spectra of Eta Car exhibit low-ionization permitted and forbidden lines mainly of H I, Fe II, N II, [Fe II], and [Ni II] (Thackeray 1953). Since 1944, high-ionization forbidden lines, such as [Fe III], [Ar III], and [Ne III], have been detected in optical spectra of Eta Car (Gaviola 1953; Humphreys et al. 2008; Feast et al. 2001). High-spatial resolution imaging and spectroscopy have shown that the narrow emission component of the low- and high-ionization forbidden lines arise in the ejecta (Davidson et al. 1995; Nielsen et al. 2005; Gull et al. 2009), in condensations known as the Weigelt blobs (Weigelt & Ebersberger 1986; Hofmann & Weigelt 1988; Zethson 2001; Hartman et al. 2005). At some epochs, the

[★] Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme IDs 381.D-0262, 282.D-5043, and 383.D-0240; with the *Hubble Space Telescope* Imaging Spectrograph (HST/STIS) under programs 9420 and 9973; and with the 1.6 m telescope of the OPD/LNA (Brazil).

high-ionization forbidden lines were found to become weaker and eventually vanish, and then recover their normal strength after several months (Gaviola 1953; Whitelock et al. 1983; Zanella et al. 1984; Damineli 1996; Damineli et al. 1998, 2000, 2008b,a). Throughout this paper, we refer to these epochs when the high-ionization lines disappear as a spectroscopic event, and to the time interval between consecutive spectroscopic events as a spectroscopic cycle.

Extensive monitoring of the optical spectrum of Eta Car showed that the spectroscopic events repeat periodically every 5.54 yr (Damineli 1996; Damineli et al. 2000, 2008b,a). This led to the suggestion that Eta Car is a binary system (Damineli et al. 1997) consisting of two very massive stars, Eta Car A (primary) and Eta Car B (secondary), amounting to at least $110 M_{\odot}$ (Hillier et al. 2001). The spectroscopic events are related to the periastron passage of Eta Car B, and the binary scenario is supported by numerous multiwavelength observations from X-ray (Corcoran et al. 1997; Pittard et al. 1998; Pittard & Corcoran 2002; Ishibashi et al. 1999; Corcoran et al. 2001; Corcoran 2005; Hamaguchi et al. 2007; Henley et al. 2008), ultraviolet (Smith et al. 2004; Iping et al. 2005), optical (van Genderen et al. 2003, 2006; Fernández-Lajús et al. 2003, 2009, 2010; Steiner & Damineli 2004; Nielsen et al. 2007; Damineli et al. 2008b,a), near-infrared (Feast et al. 2001; Whitelock et al. 2004), and radio wavelengths (Duncan & White 2003; Abraham et al. 2005). Although most orbital parameters of Eta Car are uncertain, the wealth of multiwavelength works mentioned above are consistent with a high eccentricity ($e \sim 0.9$) and an orbital period of 2022.7 ± 1.3 d (Damineli et al. 2008b; Fernández-Lajús et al. 2010).

Significant advancement in obtaining the properties of Eta Car A has been achieved, confirming that it is an LBV star with a high mass-loss rate (2.5×10^{-4} to $10^{-3} M_{\odot} \text{ yr}^{-1}$) and a wind terminal velocity in the range 500 to 600 km s $^{-1}$ (Davidson et al. 1995; Hillier et al. 2001; Pittard & Corcoran 2002; Smith et al. 2003a; Hillier et al. 2006). Several observational studies have suggested that the wind of Eta Car A is latitude-dependent (Smith et al. 2003a; van Boekel et al. 2003; Weigelt et al. 2007), the polar wind having the higher densities and larger velocities. Smith et al. (2003a), based on H α absorption profiles obtained with HST/STIS during 1998–2000, found evidence of material with velocities of up to ~ 1200 km s $^{-1}$ during most of the spectroscopic cycle but only in the polar wind of Eta Car A. Smith et al. (2003a) also suggested that the wind of Eta Car A became roughly spherical during the 1998.0 spectroscopic event, with a terminal velocity around 600 km s $^{-1}$. A significant amount of material moving faster than 3000 km s $^{-1}$ was discovered by Smith (2008) in distant ejecta far from the Homunculus nebula, which is understood to be related to the Giant Eruption and not (at least directly) to Eta Car B.

Little is known about Eta Car B, since it has never been observed directly. The role of Eta Car B in the giant outbursts and on the long-term evolution of Eta Car A is not yet understood. Earlier analysis of the ionization of the ejecta around Eta Car have inferred an O-type or WR nature for Eta Car B (Verner et al. 2005; Teodoro et al. 2008). Mehner et al. (2010) demonstrated that a broad range of luminosities (10^5 to $10^6 L_{\odot}$) and effective temperatures (36 000 to 41 000 K) of Eta Car B are able to account for the relatively high ionization stage of the ejecta, adding further uncertainty to the evolutionary stage and exact position of Eta Car B in the HR diagram.

X-ray observations require that Eta Car B must have a wind terminal velocity on the order of 3000 km s $^{-1}$ (Pittard & Corcoran 2002; Okazaki et al. 2008; Parkin et al. 2009). X-ray

studies have also shown that a strong and variable wind-wind collision zone is present between Eta Car A and Eta Car B (Hamaguchi et al. 2007; Henley et al. 2008). The wind of Eta Car B probably influences the geometry and ionization of the dense wind of Eta Car A, since numerical simulations have suggested that Eta Car B creates a cavity in the wind of Eta Car A (Pittard & Corcoran 2002; Okazaki et al. 2008; Parkin et al. 2009). The extended outer interacting wind structure has been shown to produce broad (~ 400 km s $^{-1}$), time-variable, forbidden line emission (Gull et al. 2009).

Spectroscopic observations of the near-infrared He I $\lambda 10833$ ¹ line in Eta Car indicate a brief appearance of fast-moving material up to ~ 1500 km s $^{-1}$ during previous periastron passages (Damineli et al. 1998; Groh et al. 2007; Damineli et al. 2008a). Ultraviolet observations with the International Ultraviolet Explorer (IUE) obtained during the 1980 spectroscopic event suggested that the resonance lines of Si IV $\lambda \lambda 1394$, 1403 show absorptions of up to ~ 1240 km s $^{-1}$ (Viotti et al. 1989). X-ray observations of high-ionization emission lines of Si and S showed broad line widths (1000 to 1500 km s $^{-1}$) during the 2003.5 spectroscopic event, implying that these lines originate in the inner, hotter part of the wind-wind collision zone (Henley et al. 2008) or from jets (Behar et al. 2007). There has not yet been a clear detection of very high-velocity material ($v > 1500$ km s $^{-1}$) coming directly from Eta Car B or from the wind-wind collision zone in the ultraviolet, optical, and infrared, in particular because the flux of Eta Car A is several orders of magnitude higher than that of Eta Car B at these wavelengths (Hillier et al. 2006). The relative flux between Eta Car B and Eta Car A increases towards the ultraviolet, but the absorptions of the wind of Eta Car A probably modifies – and masks – the UV spectrum of Eta Car B.

While previous spectroscopic observations of He I $\lambda 10833$ had only moderate spectral resolving power ($R \simeq 7000$) and seeing-limited spatial resolution ($1''.5$), we monitored Eta Car across the 2009.0 spectroscopic event at much higher spectral ($R \simeq 90\,000$) and spatial ($0''.3$) resolutions in the near-infrared, where the strong, unblended He I $\lambda 10833$ line is present. We obtained spectroscopic observations with the highest spectral and spatial resolutions obtained so far for longslit spectroscopy of Eta Car in the near-infrared. We combined our data with multiwavelength diagnostics from the ultraviolet to the near-infrared. The goals of this paper are to characterize the origin, formation region, physical conditions, and the phase interval when the high-velocity material can be detected in He I $\lambda 10833$, and possibly constrain the orbital parameters of the Eta Car binary system. In particular, we attempt to constrain the longitude of periastron ω , given that some previous studies determined ω to be about $240^\circ - 270^\circ$, i.e., Eta Car B to be behind Eta Car A during periastron (e.g., Damineli et al. 1997; Pittard & Corcoran 2002; Nielsen et al. 2007; Corcoran 2005; Iping et al. 2005; Henley et al. 2008; Okazaki et al. 2008; Parkin et al. 2009), while others found ω to be $\sim 50^\circ - 90^\circ$, i.e., Eta Car B to be in front of Eta Car A during periastron (e.g., Abraham et al. 2005; Abraham & Falceta-Gonçalves 2007, 2009; Falceta-Gonçalves et al. 2005; Falceta-Gonçalves & Abraham 2009; Kashi & Soker 2007, 2008b, 2009). Sideway orbital orientations (i.e., $\omega = 0^\circ$ or 180°) have also been suggested in the literature (e.g., Ishibashi et al. 1999; Smith et al. 2004).

¹ Vacuum wavelengths and heliocentric velocities are adopted in this paper. The spectra presented here have not been corrected for the systemic velocity of -8 km s $^{-1}$ of Eta Car (Smith 2004).

This paper is organized as follows. Section 2 describes the near-infrared spectroscopic data obtained at the 8 m Very Large Telescope (VLT) during 2008–2009, the archival ultraviolet and optical *HST*/STIS from 2002–2003, and the archival and new near-infrared observations recorded at the 1.6 m OPD/LNA telescope. Section 3 reports the detection of a strong high-velocity ($\sim 1900 \text{ km s}^{-1}$), broad-absorption wing in He I $\lambda 10833$ during the 2009.0 periastron passage. A similar high-velocity absorption component is also seen in the ultraviolet resonance lines in spectra obtained with *HST*/STIS during 2003.5 and in the OPD/LNA data. In Sect. 4, we derive the timescale for the presence of the high-velocity absorption component. In Sect. 5, we discuss possible scenarios for explaining the detection of high-velocity gas in Eta Car during periastron, and argue that our observations provide direct detection of high-velocity material flowing from the wind-wind collision zone in the Eta Car binary system.

2. Observations

The multiwavelength spectroscopic observations used in this paper are summarized in Tables 1–3. Since we are interested in studying material with velocities well above the terminal speed of the wind of Eta Car A, in this paper the designation “high-velocity” means velocities more negative than -900 km s^{-1} .

Throughout this paper, we use the ephemeris obtained by Damineli et al. (2008b)² to calculate the phases ϕ across a given spectroscopic cycle E : $\text{JD}(\text{phase zero}) = 2452819.8 + 2022.7(E - 11)$. We note that phase zero is defined according to the disappearance of the narrow component of He I $\lambda 6678$ and does not necessarily coincide exactly with the time of periastron passage. However, given the high orbital eccentricity of the Eta Car system, the periastron passage is expected to occur close to the phase zero of the spectroscopic cycle. We adopt the nomenclature described by Groh & Damineli (2004) to label the spectroscopic cycles of Eta Car, so that cycle #1 started after the event observed in 1948 by Gaviola. Therefore, phase zero of the 1992.5, 1998.0, 2003.5, and 2009.0 spectroscopic events corresponds to $\phi = 9.0$, $\phi = 10.0$, $\phi = 11.0$, and $\phi = 12.0$, respectively.

2.1. VLT/CRIRES high-resolution near-infrared spectroscopy

Spatially resolved spectra of Eta Car were recorded with the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES, Kaeufel et al. 2004) mounted on the 8-m VLT Unit Telescope 1. Spectra were obtained in 2008 May 05 ($\phi = 11.875$), 2008 Dec. 26 ($\phi = 11.991$), 2009 Jan. 08 ($\phi = 11.998$), 2009 Feb. 09 ($\phi = 12.014$), and 2009 Apr. 03 ($\phi = 12.040$), and are summarized in Table 1. The air-mass (< 1.4) and seeing ($< 0''.8$ in the V band) during the observations led to an excellent performance of the multi-conjugate adaptive-optics system and to an image quality with $0''.23$ – $0''.28$ FWHM at $20587 \text{ \AA}$ and $0''.31$ – $0''.35$ FWHM at $10833 \text{ \AA}$ for a standard star. All data were recorded with a $31'' \times 0''.2$ slit at position angle $\text{PA} = 325^\circ$, with a plate scale of $0''.085/\text{pixel}$. To avoid saturation and to enhance the signal-to-noise ratio, 55 exposures of 1 s were coadded. Normal and interleaved grating settings (see the CRIRES User Manual) were used to obtain the desired spectral coverage and some wavelength overlap around He I $\lambda 10833$ and He I $\lambda 20587$.

² The Damineli et al. (2008b) definition of phase zero is shifted by -0.002 in phase (or -4 d) from the date of X-ray minimum: $\text{JD}(\text{X-ray minimum}) = 2450799.8 + 2024(E - 10)$ (Corcoran 2005).

Table 1. Summary of VLT/CRIRES Eta Car spectroscopic observations used in this paper.

Date	ϕ	JD	High-velocity absorption
2008 May 05	11.875	2454591.53	No
2008 Dec. 26	11.991	2454826.82	Yes
2009 Jan. 08	11.998	2454839.80	Yes
2009 Feb. 09	12.014	2454871.77	Yes
2009 Apr. 03	12.040	2454924.61	No

The spectra were reduced in a standard way using IRAF and other custom IDL data reduction routines specific for CRIRES developed by one of us (JHG). The spectral resolving power is estimated to be $R \sim 90\,000$ using unresolved calibration lamp lines. The spectra were extracted by averaging 3 pixels in the spatial direction, centered on the central source of Eta Car, thus corresponding to a $0''.26 \times 0''.20$ spatial region. The spectra were corrected to the heliocentric rest frame and normalized to continuum. The error in the continuum normalization is estimated to be smaller than 5%. Using as reference the Th-Ar spectral line database from Kerber et al. (2008), an error in the wavelength calibration of $\approx 0.5 \text{ km s}^{-1}$ was achieved.

2.2. OPD/LNA medium-resolution near-infrared spectroscopy

We use a large amount of archival near-infrared medium-resolution spectroscopic observations, obtained during 1989–2004 (Damineli et al. 1998, 2008a; Groh et al. 2007), and gathered additional spectra of Eta Car during 2004–2009 with the 1.6-m telescope of the Brazilian Observatorio Pico dos Dias/Laboratorio Nacional de Astrofisica (OPD/LNA). The data reduction was performed using standard near-infrared spectroscopic techniques as described in Groh et al. (2007) and Damineli et al. (2008a). These spectra cover the He I $\lambda 10833$ line with a moderate spectral resolving power ($R \approx 7000$) and seeing-limited spatial resolution ($\sim 1''.5$), but have excellent time-sampling of the order of days around the 2003.5 spectroscopic event. The 2009.0 event was covered with a time sampling of the order of a month. The time evolution of the emission component of the He I $\lambda 10833$ line in the OPD/LNA dataset from the 2003.5 event was extensively discussed in Groh et al. (2007) and Damineli et al. (2008a). Table 2 lists the OPD/LNA dataset used in this paper.

2.3. HST/STIS ultraviolet and optical spectroscopy

Spectroscopic observations of Eta Car were obtained with the Hubble Space Telescope Imaging Spectrograph (*HST*/STIS) from 1998 Jan. 1 until 2004 Mar. 6. In this paper, we use ultraviolet and optical archival data obtained across the 2003.5 spectroscopic event, which was covered by the *HST* Eta Car Treasury project³. These spectra were described extensively in previous works (e. g., Davidson et al. 2005; Hillier et al. 2006; Nielsen et al. 2007; Gull et al. 2009), and here we summarize their main characteristics. Ultraviolet observations were conducted using the MAMA echelle grating E140M, providing a spectral resolving power of 30 000 throughout the 1170–1700 $\text{\AA}$ spectral range. An aperture of $0''.2 \times 0''.2$ or $0''.3 \times 0''.2$ was used, and the data reduction was accomplished using STIS GTO IDL

³ The reduced data are available online at <http://etacar.umn.edu>

Fig. 1. Continuum-normalized He I $\lambda 10833$ CRILES spectrum from the inner $0''.26 \times 0''.20$ spatial region around the central source of Eta Car obtained before/during (*top panel*) and during/after (*bottom panel*) the 2009.0 spectroscopic event. The grey region corresponds to the excess absorption due to the high-velocity material in Eta Car during the 2009.0 spectroscopic event. The 2009 Jan. 08 spectrum is repeated in both panels for clarity. Note that the many narrow absorption features blueward of ~ -800 km s $^{-1}$ seen in the Feb. 2009 spectrum (red line), except the -1050 km s $^{-1}$ feature, are residuals from the removal of telluric lines. The broad emission between -600 and -1500 km s $^{-1}$ seen in the 2008 May 05 spectrum is due to electron scattering.

CALSTIS software. A 7-pixel ($0''.0875$) extraction centered on the central source was adopted to minimize contamination from the extended ejecta. We refer to [Nielsen et al. \(2005\)](#) and [Hillier et al. \(2006\)](#) for further details of the observations and an extensive analysis of the *HST*/STIS ultraviolet spectrum of Eta Car, in particular the dataset obtained in 2002 Jul. 04. For the optical range, the G430M and G750M gratings were used, yielding a resolving power of 6000–8000 across the 1640–10 100 Å spectral range. Spectra were extracted using 6 half-pixels ($0''.152$). Table 3 summarizes the *HST*/STIS data used in this paper.

3. High-velocity gas (up to 2000 km s $^{-1}$) in Eta Car during the spectroscopic events

Herein we discuss the behavior of key line profiles across the two most recent spectroscopic events: 2003.5 ($\phi = 11.0$) and 2009.0 ($\phi = 12.0$). The ideal case would have been for all observations to have been performed during the same spectroscopic event, but the availability of instrumentation did not permit such. We note that the 1998.0 and 2003.5 spectroscopic events were nearly identical in behavior in X-rays ([Corcoran 2005](#)), but that the duration of the X-ray minimum was substantially shorter in the 2009.0 spectroscopic event ([Corcoran et al. 2010](#), in prep.). However, optical spectroscopy indicated that the H α line profile was flat-topped in 2003.5 but not in the 1998.0 spectroscopic event ([Davidson et al. 2005](#)). Our understanding of the changes in spectroscopic profiles presented here suggests that while small changes in the wind profiles may be caused by secular variability

(Sect. 3.2), the major changes we see are periodic variations caused by the binary nature of Eta Car.

3.1. Detection during the 2009.0 spectroscopic event by VLT/CRILES

The He I $\lambda 10833$ absorption line profile, as displayed in Fig. 1, evolved considerably during the 2009.0 spectroscopic event. In all recorded spectra, a relatively broad (~ 100 km s $^{-1}$), blueshifted emission feature is seen at -250 km s $^{-1}$, and is caused by gas in the equatorial plane of the Homunculus ([Smith 2002](#); [Teodoro et al. 2008](#)).

The spectrum obtained at $\phi = 11.875$, well before periastron, exhibits strong He I $\lambda 10833$ absorption extending from ~ -150 km s $^{-1}$ up to an edge at a velocity $v_{\text{edge}} \simeq -750$ km s $^{-1}$, and the strongest absorption occurring at $v_{\text{black}} \simeq -580$ km s $^{-1}$. This value of v_{black} from He I $\lambda 10833$ is remarkably similar to those derived from UV resonance lines such as C II $\lambda 1335$ and Mg II $\lambda 1240$ (-600 ± 50 km s $^{-1}$, [Hillier et al. 2001](#)). This range of velocities is consistent with He I $\lambda 10833$ being formed in the wind of Eta Car A. Eta Car B might significantly influence the He I $\lambda 10833$ line profile if it is able to photoionize He in the outer parts of the wind of Eta Car A. In this case, the amount of emission and absorption seen in He I $\lambda 10833$ will strongly depend on the orbital parameters of the system. Nevertheless, at phases sufficiently far from periastron such as at $\phi = 11.875$, there is no evidence for additional velocity fields in our line-of-sight, such as one would expect if the absorption were formed

Table 2. Summary of OPD/LNA Eta Car spectroscopic observations used in this paper.

Date	ϕ	JD	High-velocity absorption?
1989 Mar. 28	8.4263	2 447 614.50	No
1990 Jan. 25	8.5761	2 447 917.50	No
1990 Jun. 16	8.6463	2 448 059.50	No
1990 Dec. 30	8.7442	2 448 257.50	No
1991 Jan. 29	8.7590	2 448 287.50	No
1991 May 25	8.8164	2 448 403.50	No
1992 Mar. 20	8.9647	2 448 703.50	Yes
1992 May 27	8.9976	2 448 769.50	Yes
1992 Jun. 02	9.0006	2 448 775.50	Yes
1992 Jun. 03	9.0011	2 448 776.50	Yes
1992 Jul. 16	9.0228	2 448 820.40	Yes
1997 Jul. 22	9.9285	2 450 652.39	No
1998 Jan. 20	10.0181	2 450 833.70	Yes
1998 May 07	10.0713	2 450 941.31	No
1998 May 12	10.0738	2 450 946.27	No
1998 Jun. 14	10.0897	2 450 978.53	No
1998 Jul. 08	10.1020	2 451 003.40	No
1999 Apr. 26	10.2460	2 451 294.56	No
1999 Jul. 02	10.2795	2 451 362.41	No
2000 Dec. 12	10.5407	2 451 890.76	No
2001 Jun. 09	10.6296	2 452 070.46	No
2001 Jun. 10	10.6301	2 452 071.41	No
2001 Jun. 12	10.6311	2 452 073.43	No
2002 Feb. 14	10.7528	2 452 319.70	No
2002 Feb. 19	10.7552	2 452 324.62	No
2002 Apr. 29	10.7898	2 452 394.48	No
2002 Apr. 30	10.7903	2 452 395.46	No
2002 Jul. 20	10.8303	2 452 476.39	No
2002 Nov. 04	10.8829	2 452 582.76	No
2002 Dec. 21	10.9061	2 452 629.76	No
2003 May 13	10.9771	2 452 773.41	Yes
2003 May 15	10.9781	2 452 775.44	Yes
2003 May 25	10.9830	2 452 785.38	Yes
2003 Jun. 17	10.9944	2 452 808.45	Yes
2003 Jun. 22	10.9969	2 452 813.45	Yes
2003 Jun. 24	10.9979	2 452 815.43	Yes
2003 Jun. 26	10.9989	2 452 817.38	Yes
2003 Jun. 28	10.9998	2 452 819.36	Yes
2003 Jun. 29	11.0003	2 452 820.38	Yes
2003 Jul. 03	11.0023	2 452 824.37	Yes
2003 Jul. 04	11.0028	2 452 825.33	Yes
2003 Jul. 08	11.0048	2 452 829.46	Yes
2003 Jul. 09	11.0053	2 452 830.40	Yes
2003 Aug. 11	11.0216	2 452 863.38	No
2003 Aug. 13	11.0226	2 452 865.39	No
2003 Dec. 15	11.0835	2 452 988.67	No
2004 Feb. 29	11.1212	2 453 064.83	No
2004 Apr. 30	11.1516	2 453 126.41	No
2005 Mar. 25	11.3143	2 453 455.47	No
2005 Jul. 26	11.3751	2 453 578.37	No
2006 Mar. 14	11.4893	2 453 809.47	No
2006 Jun. 06	11.5308	2 453 893.43	No
2006 Aug. 11	11.5634	2 453 959.38	No
2007 Jun. 28	11.7221	2 454 280.43	No
2007 Jun. 29	11.7226	2 454 281.39	No
2007 Jun. 30	11.7231	2 454 282.39	No
2007 Aug. 02	11.7394	2 454 315.36	No
2008 May 19	11.8833	2 454 606.40	No
2008 Dec. 05	11.9819	2 454 805.74	Yes
2008 Dec. 07	11.9828	2 454 807.70	Yes
2008 Dec. 09	11.9838	2 454 809.70	Yes
2009 Jan. 08	11.9986	2 454 839.60	Yes
2009 Feb. 19	12.0193	2 454 881.57	No
2009 Apr. 20	12.0494	2 454 942.46	No

Table 3. Summary of *HST*/STIS Eta Car spectroscopic observations used in this paper.

Date	ϕ	JD	High-velocity absorption?
2002 Jan. 20	10.738	2 452 240	No
2002 Jul. 04	10.820	2 452 460	No
2003 Feb. 13	10.930	2 452 683	No
2003 Jun. 01	10.984	2 452 792	Yes
2003 Jun. 22	10.995	2 452 813	Yes
2003 Jul. 05	11.001	2 452 825	Yes
2003 Jul. 29	11.013	2 452 851	Yes

in the wind of Eta Car B or in high-velocity material from the wind-wind collision zone.

The spectra at $\phi = 11.991$ and $\phi = 11.998$ have very different He I $\lambda 10833$ absorption profiles than that from $\phi = 11.875$. The low-velocity absorption strengthened, becoming nearly saturated from -40 to -580 km s $^{-1}$, with the exception of the equatorial ejecta emission at -250 km s $^{-1}$. A broad, high-velocity absorption ranging from -580 to -1900 km s $^{-1}$ had appeared by $\phi = 11.991$ and strengthened by $\phi = 11.998$. We would not expect this high-velocity absorption to be produced by the velocity field of the wind of Eta Car A, as seen in the spectrum at $\phi = 11.875$. Therefore, the He I $\lambda 10833$ absorption line profile strongly indicates that, in addition to the wind of Eta Car A, at least one more velocity structure crosses our line-of-sight to Eta Car. This high-velocity absorption component is transient because, as the spectrum observed at $\phi = 12.014$ shows, it has faded considerably and is present only up to -900 km s $^{-1}$. By $\phi = 12.041$, the He I $\lambda 10833$ profile is quite similar to that recorded at $\phi = 11.875$, but the -40 to -580 km s $^{-1}$ absorption is saturated, indicating a higher column density of He I.

The He I $\lambda 10833$ and He I $\lambda 20587$ line profiles, recorded at $\phi = 11.998$, demonstrate that the high-velocity absorption component is much stronger in He I $\lambda 10833$ than in the He I $\lambda 20587$ line (Fig. 2). While noticeable from -600 to -1000 km s $^{-1}$, the absorption is much weaker in the range of -1100 to -1600 km s $^{-1}$. The He I $\lambda 10833$ line ($2s^3S-2p^3P$) absorption originates from the metastable triplet state, while the He I $\lambda 20587$ line ($2s^1S-2p^1P$) originates from the metastable $2s^1S$ state. The population of the $2s^1S$ energy level can be increased by means of photoexcitation from 584 Å UV photons, which would cause increased He I $\lambda 20587$ absorption. The much weaker high-velocity absorption in the He I $\lambda 20587$ line profile indicates that photoexcitation by hard UV photons is negligible in the region responsible for the high-velocity absorption. The oscillator strength of He I $\lambda 10833$ is about 5 times higher than that of He I $\lambda 20587$ and, thus, the observed He I $\lambda 10833$ absorption is much stronger, as expected (Fig. 2).

The high-velocity absorption is not seen in H α or any other hydrogen lines during periastron, since these lines have an edge velocity in the range -800 to -1000 km s $^{-1}$ (Weis et al. 2005; Stahl et al. 2005; Davidson et al. 2005), implying that hydrogen is predominantly ionized ($H^0/H^+ \lesssim 10^{-5}$) in the region responsible for the He I high-velocity absorption. In addition, the absence of high-velocity H α absorption in the range -1000 to -2000 km s $^{-1}$ during periastron indicates that this material is either He rich, or it places an upper limit on the electron density (n_e) in that region. Although detailed radiative transfer calculations are needed, we estimate an upper limit of $n_e \leq 10^{10}$ cm $^{-3}$.

Fig. 2. Comparison between the continuum-normalized He I $\lambda 10833$ (blue) and He I $\lambda 120587$ (black) spectral lines from the inner $0''.26 \times 0''.20$ spatial region around the central source of Eta Car. The many narrow spikes around He I $\lambda 120587$ are residuals from the removal of telluric lines. Note that a -146 km s^{-1} absorption component is present in He I $\lambda 120587$ and might also be present in He I $\lambda 10833$. The emission feature from 500 to 1300 km s^{-1} is due to a blend of Fe II lines.

3.2. The OPD/LNA datasets from the 2003.5 and 2009.0 spectroscopic events

As mentioned before, ground-based data of Eta Car have shown a weak absorption wing of up to -1500 km s^{-1} associated with He I $\lambda 10833$ during previous spectroscopic events (Damineli et al. 1998; Groh et al. 2007; Damineli et al. 2008a). The new spectra obtained during the 2009.0 event again showed evidence of this high-velocity absorption during a brief time interval, which strongly suggests that it is related to the periastron passage of Eta Car B. Figure 3 displays the temporal evolution of the He I $\lambda 10833$ absorption during the 2003.5 and 2009.0 spectroscopic events, while Fig. 4 compares the He I $\lambda 10833$ line profiles at a similar phase during the 2003.5 and 2009.0 spectroscopic cycles ($\phi = 10.998$ and $\phi = 11.998$, respectively), with the VLT/CRIRES spectrum acquired simultaneously with the OPD/LNA data at $\phi = 11.998$.

First, when comparing spectra obtained with OPD/LNA at similar orbital phases close to periastron, we notice that the high-velocity He I $\lambda 10833$ absorption changes from cycle to cycle, and is stronger in the spectrum for the 2009.0 event. This trend in the cycle-to-cycle variability was also noticed in optical He I lines (Groh & Damineli 2004), but for low velocities within the line. Whether this is caused by changes in the continuum or in the line-absorbing region, or both, still remains to be seen. Secular variability from one (or both) stellar winds in the Eta Car system cannot be excluded.

Second, we note that the He I $\lambda 10833$ high-velocity absorption is stronger and extends to higher velocities in the VLT/CRIRES than in the OPD/LNA spectrum. This is not due to the different spectral resolutions, and we argue that the small aperture and higher spatial resolution of the VLT/CRIRES instrument ($\sim 0''.3$) spatially resolves extended scattered continuum and He I $\lambda 10833$ line emission, which are otherwise included in

Fig. 3. Evolution of the He I $\lambda 10833$ line as a function of orbital phase, for the 2003.5 (bottom panel) and 2009.0 spectroscopic events (upper panel). The spectra were interpolated in phase for visualization purposes, and the continuum-normalized flux is color-coded linearly between 0 (black) and ≥ 1 (red) to emphasize the absorption structure. The black horizontal tick marks on the left correspond to the observed phases. The feature running vertically at -1050 km s^{-1} is probably formed outside the Homunculus nebula and is not relevant for the purpose of this paper.

the OPD/LNA spectra, since they have a lower spatial resolution ($1''.5$) than the VLT/CRIRES data.

3.3. Detection during the 2003.5 spectroscopic event by HST/STIS

3.3.1. Ultraviolet resonance lines

We analyzed the archival HST/STIS ultraviolet spectra of Eta Car searching for evidence of high-velocity absorption in UV resonance lines. The time variability of the UV spectrum across the spectroscopic cycle is complex and will be analyzed in detail elsewhere (Nielsen et al. 2010, in prep.). To illustrate the variability of the UV spectrum of Eta Car for selected UV resonance lines, we computed color-coded intensity plots by stacking the spectra in velocity space as a function of phase, and by interpolating in phase the flux between the observations (Figs. 5 and 6).

We found that some of the UV resonance lines show evidence of high-velocity absorption during the 2003.5 spectroscopic event, but two other effects influence the interpretation of the spectra. First, because of the increasingly high line density toward shorter wavelengths, the ultraviolet continuum level of Eta Car cannot be accurately determined (Hillier et al. 2001, 2006). Second, the line profiles of UV resonance lines are

Fig. 4. Comparison between continuum-normalized He I $\lambda 110833$ line profiles obtained at different spatial resolutions and similar orbital phases (but different cycles). The dashed black line shows the spectrum from Daminieli et al. (2008a) obtained with the 1.6-m telescope of the Brazilian OPD/LNA, which has $R \approx 9000$, and aperture and spatial resolution of roughly $1''.5$. The CRIRES spectrum (solid blue line) has an aperture and spatial resolution of $\sim 0''.3$ and was convolved with a Gaussian to match the spectral resolution of the OPD/LNA spectrum.

affected by strong blending primarily due to Fe II lines (Hillier et al. 2001; Nielsen et al. 2005; Hillier et al. 2006). In addition, the UV flux begins decreasing about six months before the spectroscopic event (Smith et al. 2004; Nielsen et al. 2005) and recovers well after minimum. As seen in the optical (Nielsen et al. 2007; Daminieli et al. 2008a), the emission and absorption of lines from Fe II strongly increase after $\phi = 11.0$ in the UV. Both the change in continuum level and the blending due to Fe II lines hamper the precise determination of the strength and maximum velocity of the absorption component across the spectroscopic event. Therefore, we focus here on the evolution of the spectra leading up to $\phi = 11.0$.

We scaled the UV spectra obtained at $\phi = 10.820$ (2002 Jul. 04), $\phi = 10.930$ (2003 Feb. 13), and $\phi = 10.984$ (2003 Jun. 01) to approximately match the continuum of the spectrum from $\phi = 10.995$ (2003 Jun. 22). As reference, we used a “control” spectral interval located sufficiently far ($>10\,000 \text{ km s}^{-1}$) from the rest wavelength of the line of interest. Our reason for scaling the spectra was to distinguish changes in the line profile due to the high-velocity absorption, from changes in the continuum level, which could otherwise be misinterpreted as increases in absorption strength. We verified that the “control” regions, which are also affected by Fe II lines, do not change appreciably in the scaled spectra as a function of phase before $\phi = 11.0$. Thus, we investigate the temporal behavior of the remaining relative changes in the scaled line profiles, which are intrinsic to the UV resonance lines.

The scaled line profiles of the strongest, more isolated UV resonance lines in Eta Car are presented in Fig. 7, where the grey region shows the difference between the spectrum taken at $\phi = 10.820$ and at $\phi = 10.995$, corresponding to the excess absorption occurring across the spectroscopic event due to the

Fig. 5. Similar to Fig. 3, but showing the evolution of the Si IV $\lambda\lambda 1394, 1403$ lines as a function of orbital phase. The velocity scale refers to Si IV $\lambda 1394$. To illustrate the global decrease in the UV flux close to the spectroscopic event, no flux scaling was applied in this particular figure. The spectra were interpolated in phase for visualization purposes and intensity color-coded between the minimum flux (black) and max flux (red) seen across the spectroscopic cycle. The black horizontal tick marks on the right correspond to the observed phases.

Fig. 6. Similar to Fig. 5, but for C IV $\lambda\lambda 1548, 1551$ (upper panel), C II $\lambda\lambda 1334, 1335$ (middle panel), Si II $\lambda\lambda 1526, 1533$ (bottom panel).

Fig. 7. Montage of profiles of resonance lines seen in ultraviolet spectra of Eta Car obtained with *HST*/STIS across the 2003.5 event at $\phi = 10.820$ (blue line), $\phi = 10.930$ (green), $\phi = 10.984$ (black), and $\phi = 10.995$ (red). The continuum level of the spectra taken at $\phi = 10.820$, $\phi = 10.930$, and $\phi = 10.984$ were scaled to approximately match the continuum level of the spectrum taken at $\phi = 10.995$. The grey region shows the difference between the spectrum taken at $\phi = 10.820$ and at $\phi = 10.995$, corresponding to the excess absorption due to the high-velocity material in Eta Car. *Left panel:* high-ionization lines. *From top to bottom*, resonance lines of Si IV $\lambda 1394$, Si IV $\lambda 1403$, C IV $\lambda 1548$, and a “control” region around 1483 Å are shown. We note that little changes are seen in the “control” region as a function of phase, indicating that the relative variability seen in the UV resonance lines are intrinsic to these lines, and not due to blending. *Right panel:* low-ionization lines. *From top to bottom*, C II $\lambda\lambda 1334, 1335$, Si II $\lambda 1526$, Si II $\lambda 1533$, and Al II $\lambda 1671$ are displayed. We note that part of the Si II $\lambda 1533$ line profile, from -1200 to -2100 km s $^{-1}$, is contaminated by Si II $\lambda 1526$.

high-velocity material in Eta Car. The absorption components of the low-ionization and the high-ionization resonance lines behave quite differently across the 2003.5 event. Low-ionization resonance lines, such as C II $\lambda\lambda 1334, 1335$, Si II $\lambda\lambda 1526, 1533$, and Al II $\lambda 1671$, show a gradual development of an absorption wing increasing from -500 to -900 km s $^{-1}$ between $\phi = 10.820$ and $\phi = 10.984$. At $\phi = 10.995$, the spectrum shows a significant increase in the strength of the absorption from -500 to -900 km s $^{-1}$ (Fig. 7, right panel), but the low-ionization UV resonance lines do not show evidence of high-velocity absorption from -1000 to -2000 km s $^{-1}$ before $\phi = 11.0$, as He I $\lambda 10833$ did just before $\phi = 12.0$.

The high-ionization ultraviolet resonance lines, Si IV and C IV, also show an increase in absorption from -500 to -900 km s $^{-1}$ before $\phi = 11.0$, with most of the changes occurring between $\phi = 10.820$ and $\phi = 10.984$. This is a different timescale than that of the low-ionization lines. More noticeable changes occurred after $\phi = 10.984$. High-velocity absorption from -1200 up to -2100 km s $^{-1}$ is seen in the high-ionization Si IV $\lambda\lambda 1394, 1403$ doublet and possibly in the C IV $\lambda 1548$ line. This high-velocity component becomes noticeably stronger between $\phi = 10.984$ and $\phi = 10.995$ (Fig. 7, left panel). The reality of the high-velocity absorption is confirmed by its presence in both of the Si IV doublet lines. The weaker C IV $\lambda 1551$ line

is severely blended with the stronger C IV $\lambda 1548$ line, and it is impossible to unambiguously judge whether the high-velocity absorption is present in C IV $\lambda 1551$ or not.

Therefore, ultraviolet resonance lines from low-ionization species, such as Si II $\lambda\lambda 1527, 1533$, C II $\lambda\lambda 1334, 1335$, and Al II $\lambda 1671$, show absorption up to -800 km s $^{-1}$, and possibly -1200 km s $^{-1}$, but the UV resonance lines from high-ionization species, specifically Si IV, show absorption from -1200 to -2100 km s $^{-1}$. Thus, the high-velocity absorption originates in a region that is far more ionized than the wind of Eta Car A.

3.3.2. Optical He I lines

Optical He I singlet and triplet line profiles were analyzed by Nielsen et al. (2007), and profiles from the same observations are reproduced in Fig. 8. A noticeable high-velocity absorption is apparent in the two triplet line profiles, He I $\lambda 3888$ and $\lambda 5876$, extending to -900 , and possibly -1000 km s $^{-1}$, at $\phi = 10.995$ (2003 Jul. 05). The profiles of singlet lines, such as He I $\lambda 6680$, show weaker absorption up to -800 km s $^{-1}$. As noted by Nielsen et al. (2005), the He I $\lambda 4714$ line is much weaker and contaminated by [Fe III] $\lambda 4702$ emission. Stahl et al. (2005) also detected similar absorption up to -750 km s $^{-1}$ for He I $\lambda 6680$ from the polar spectrum reflected in the Homunculus. The optical depths of

Fig. 8. Montage of continuum-normalized He I line profiles obtained with *HST*/STIS across the 2003.5 event. From top to bottom, we present He I λ 3889 (highly-contaminated by H I λ 3890, in particular at velocities $v > -800$ km s⁻¹), He I λ 4714 (contaminated by [Fe III] λ 4702 emission), He I λ 5877, and He I λ 6680 line profiles. The bottom panel displays optical He I line profiles observed with *HST*/STIS at $\phi = 10.995$ (2003 Jun. 22) with the near-infrared He I λ 10833 line profile observed with VLT/CRIRES at $\phi = 11.998$ (2009 Jan. 08).

all of these optical He I lines are substantially less than even that of the He I λ 20587 line. Hence, the likelihood of seeing absorptions up to -2000 km s⁻¹ in the He I optical lines is low.

4. Duration of the high-velocity absorption component

We use the ground-based OPD/LNA data from 1989 to 2009, which are a homogeneous dataset with a fine time-sampling, to estimate the timescale for the presence of the high-velocity absorption in He I λ 10833. Figure 9 displays the maximum velocity of the He I λ 10833 absorption component as a function of phase, combining data from all cycles available folded around $\phi = 1.0$. The timescale depends on the velocity of the material, the highest velocities most likely corresponding to the briefest of time intervals. However, because of the low S/N of the observations and normalization errors, it is not possible to derive quantitatively the variation in the timescale as a function of velocity for the OPD dataset. For that purpose, one needs a much larger amount

Fig. 9. Top: maximum absorption velocity (v_{edge}) observed in the He I λ 10833 line profile as a function of phase of the spectroscopic cycle for the OPD/LNA dataset from 1989 to 2009, encompassing four cycles, with the data folded around $\phi = 1.0$. For clarity, errorbars are presented only in the bottom panel. Bottom: zoom-in around the spectroscopic event. To help the reader, in both panels, the horizontal red dashed line denotes the $v_{\text{edge}} = -900$ km s⁻¹, while the vertical blue dashed lines represent the range where the high-velocity absorption is detected in He I λ 10833.

of high spatial and spectral resolution VLT/CRIRES data during periastron than those presented in Sect. 3.1. Thus, we are unable to compare the duration of the absorption at -2000 km s⁻¹ to the absorption at -900 km s⁻¹, for instance. Henceforth, we opted to determine the timescale when gas with velocities more negative than -900 km s⁻¹ is present, since this velocity is well above the terminal speed of the wind of Eta Car A and should provide a characteristic value for the timescale of the high-velocity absorption component.

Absorptions with velocities bluer than -900 km s⁻¹ are detected across -47 d $\leq \Delta t \leq +46$ d ($0.976 \leq \phi \leq 1.023$), while the high-velocity absorption is absent in spectra taken at $\Delta t \leq -106$ d ($\phi \leq 0.947$) and $\Delta t \geq +100$ d ($\phi \geq 1.049$). Hence, based on the large OPD/LNA dataset, we constrain the duration of the high-velocity absorption component to be 95 to 206 d. During most of the spectroscopic cycle, the maximum absorption velocity is ~ -650 km s⁻¹ (Fig. 9).

Since a very limited amount of high spatial resolution observations with VLT/CRIRES and *HST*/STIS are available, only a lower limit to the timescale of the high-velocity absorption can be obtained, but this estimate agrees well with the value obtained above for the OPD/LNA dataset. The VLT/CRIRES data (Fig. 1) for the 2009.0 event is consistent with the He I λ 10833 high-velocity absorption (-1000 to -2000 km s⁻¹) appearing between $\phi = 11.875$ (2008 May 05) and $\phi = 11.991$ (2008 Dec. 26), and disappearing before $\phi = 12.041$ (2009 Apr. 03). The UV resonance line of Si IV λ 1394 present in the *HST*/STIS data indicates that the high-velocity absorption appears between $\phi = 10.984$ (2003 Jun. 01) and $\phi = 10.995$ (2003 Jun. 22). The analysis of the ultraviolet absorption is hampered by severe blending with Fe II lines after $\phi = 11.0$; consequently, the high-velocity absorption and its timescale are less accurately determined.

5. Discussion: origin of the high-velocity material in Eta Car

In the following subsections, we discuss three distinct possibilities for the origin of the high-velocity absorption in the spectrum of Eta Car. Although many exotic scenarios can be envisioned,

the high-velocity material is most likely to be produced either by a transient episode of high-velocity material ejected by Eta Car A (Sect. 5.2), directly by the wind of Eta Car B crossing the line-of-sight to Eta Car A (Sect. 5.3), or in a dense, high-velocity part of the wind-wind collision zone (Sect. 5.4). Since we analyze absorption lines, the high-velocity absorption region must be between the continuum source and the observer. Therefore, the source of the continuum emission is crucial when interpreting the origin of the high-velocity gas, and is briefly discussed below.

5.1. Source of the continuum emission at $1.0\ \mu\text{m}$

The radiative transfer models of Hillier et al. (2001) suggested that Eta Car A has an extended photosphere in the near-infrared caused by the presence of its dense wind (see their Fig. 8). This generates a huge amount of extended free-free and bound-free emission that can explain the quiescent continuum emission at $1.0\ \mu\text{m}$ from the inner regions measured by *HST*/STIS (see Fig. 4 of Hillier et al. 2001). The extended near-infrared continuum emitting region at $2\ \mu\text{m}$ was directly resolved by interferometric measurements (van Boekel et al. 2003; Weigelt et al. 2007), confirming that the observed size of the $2\ \mu\text{m}$ continuum emission (50% encircled-energy radius of 4.8 AU) is well reproduced by the Hillier et al. (2001) wind model of Eta Car A. This implies that most, if not all, of the quiescent K-band emission is indeed due to free-free and bound-free emission from the wind of Eta Car A, and that the contribution from hot dust to the K-band emission is negligible within 70 milli-arcsec of Eta Car A. We note that the amount of emission from hot dust would be even smaller at $1.08\ \mu\text{m}$ than in the K-band. Of course, hot dust is well-known to be present in Eta Car on spatial scales larger than 70 milli-arcsec (see, e.g., Chesneau et al. 2005), and will certainly contaminate measurements performed for data collected with larger apertures.

Several studies have proposed that dust forms in Eta Car during periastron (Falceta-Gonçalves et al. 2005; Kashi & Soker 2008a), although Smith (2010) showed that the dust formation is cycle-dependent, occurring preferentially in the earlier documented spectroscopic events of 1981.4 and 1992.5. Significant dust formation is uncertain during the 2003.5 event Smith (2010), and no near-infrared photometry has been reported for the 2009.0 event. The *J*-band flux increased by ca. 25% just before the 2003.5 event (Whitelock et al. 2004), which was interpreted as being due to free-free (Whitelock et al. 2004) or hot dust emission (Kashi & Soker 2008a). More importantly, interferometric observations in the K-band conducted during the 2009.0 spectroscopic event, simultaneously with our VLT/CRIRES measurements, do not suggest any significant change in the size of the K-band emitting region (Weigelt et al. 2010, in preparation), arguing against significant emission from hot dust in the inner 70 milli-arcsec of Eta Car.

Therefore, a photospheric radius of Eta Car A at $1.08\ \mu\text{m}$ of 2.2 AU is hereafter assumed as the size of the continuum emission, based on the direct interferometric measurements in the K-band (van Boekel et al. 2003; Weigelt et al. 2007) scaled to $1.08\ \mu\text{m}$ and on the value that we computed using the CMFGEN radiative transfer model of Eta Car A (Hillier et al. 2001).

5.2. Transient fast material in the wind of Eta Car A?

If a binary companion is evoked, the periodicity might be related to brief ejections of high-velocity material by Eta Car A

triggered during each periastron passage. However, this scenario presents several difficulties, given that previous spectroscopic observations suggested that the wind of Eta Car A becomes roughly spherical during periastron (Smith et al. 2003a). It would also imply that, during periastron, material from Eta Car A at $\sim 2000\ \text{km s}^{-1}$ (instead of the usual $500\text{--}600\ \text{km s}^{-1}$) collides with the shock front. The higher velocity of the material ejected from Eta Car A would produce a much higher X-ray luminosity than currently observed. Both issues could be circumvented if the density and volume-filling factor of the $\sim 2000\ \text{km s}^{-1}$ transient wind are sufficiently low so as not to affect the X-ray luminosity and the H α absorption profiles measured by Smith et al. (2003a). However, it is unlikely that this thin wind would produce detectable absorption in He I $\lambda 10833$.

The existence of a brief high-velocity wind from Eta Car A would be very unlikely in a single star scenario, although we cannot rule out that possibility based on our present data. In particular, a single-star scenario would have to invoke a yet unknown mechanism that would produce a periodic episode of high-velocity wind like clockwork every 2022.7 ± 1.3 days, as measured by Damineli et al. (2008b).

5.3. Direct observation of the wind of Eta Car B?

The edge velocity of the high-velocity absorption component seen in He I $\lambda 10833$ and Si IV $\lambda 1394$, 1403 appears to approach the velocity expected of the wind of Eta Car B, $3000\ \text{km s}^{-1}$, based upon X-ray spectroscopic modeling by Pittard & Corcoran (2002). To date, Eta Car B has not been observed directly. Could the high-velocity absorption component form directly in the wind of Eta Car B? In the next two subsections, we investigate that possibility.

5.3.1. The wind of Eta Car B absorbs its own continuum radiation

This hypothesis would correspond to the classical detection of a companion in normal massive binary systems, such as in WR+OB binaries. However, the flux of Eta Car B is several orders of magnitude lower than that of Eta Car A in the near-infrared continuum around the He I $\lambda 10833$ (Hillier et al. 2006). Therefore, even if the wind of Eta Car B were to produce a saturated He I $\lambda 10833$ absorption profile when observed in isolation, an undetectable amount of absorption ($\sim 0.5\text{--}1\%$) would be seen in the combined spectrum of Eta Car A and B.

5.3.2. The wind of Eta Car B absorbs the continuum radiation from Eta Car A

One possible way to observe the wind of Eta Car B, should it contain significant amounts of neutral He, would be if its He I $\lambda 10833$ absorption zone is extended and dense enough to absorb continuum radiation from Eta Car A, in a “wind-eclipse” scenario. To detect the wind of Eta Car B only during a brief period, at phases $0.976 \leq \phi \leq 1.023$ (i.e., 95 d), the binary system would again have to be oriented in the sky with a longitude of periastron of $\omega \sim 90^\circ$, since Eta Car B would need to be located between the observer and the continuum source for only a brief period around periastron passage. In addition, the material in the wind of Eta Car B must have a sufficiently high column density of neutral He to absorb enough He I $\lambda 10833$ photons, but this is not predicted by the Hillier et al. (2006) radiative transfer model either. A much higher $\dot{M}$ and/or lower T_{eff} would again be needed to produce a sufficiently high optical depth in the wind

Fig. 10. Illustration of the pole-on orbital geometry of the Eta Car binary system for different orbital parameters, assuming $P = 2022.7$ d, $\omega = 90^\circ$, and $i = 90^\circ$ (the observer is located to the right, along the x axis). The part of the orbit highlighted in green corresponds to phases when the wind of Eta Car B could be able to absorb continuum photons from Eta Car A (the “wind-eclipse” scenario). The red highlighted part of the orbit represents the phases when the high-velocity absorption component is observed in the He I $\lambda 10833$ line assuming, for simplification, that the phase zero of the spectroscopic cycle coincides with the periastron passage. In **a**) we assume masses of 90 and $30 M_\odot$ for Eta Car A and B, respectively, a photospheric radius of Eta Car A at $1.08 \mu\text{m}$ of 2.2 AU, and $e = 0.9$. In **b**) we vary the eccentricity to $e = 0$; **c**) assumes unrealistic masses of $4 M_\odot$ for both Eta Car A and B; and **d**) assumes a photospheric radius of Eta Car A at $1.08 \mu\text{m}$ of 5.5 AU.

of Eta Car B for He I $\lambda 10833$. In principle, this would be indicative of a Wolf-Rayet (WR) instead of an O-type star companion, since WRs have a higher wind density than O-type stars.

Even in the unlikely possibility that the wind of Eta Car B could significantly absorb He I $\lambda 10833$ photons, the “wind-eclipse” scenario also fails to reproduce the observed duration of the high-velocity absorption component for the assumed orbital parameters, even allowing for significant uncertainties in these parameters. We show in Fig. 10a a sketch of a pole-on view of the geometry of the orbit for the “wind-eclipse” scenario, assuming masses of 90 and $30 M_\odot$ for Eta Car A and B, respectively, an orbital period of $P = 2022.7$ d, semi-major axis of $a = 15.4$ AU, eccentricity of $e = 0.9$, and $\omega = 90^\circ$. A photospheric radius at $1.08 \mu\text{m}$ of 2.2 AU is assumed for Eta Car A, as discussed in Sect. 5.1. In this subsection, we assume an inclination angle of $i = 90^\circ$ to derive an upper limit for the timescale of the “wind-eclipse”. For (more realistic) lower inclination angles, an even shorter timescale will be obtained.

From Fig. 10a, it is apparent that, for the parameters described above, the wind of Eta Car B is in front of the continuum source originating in Eta Car A during a much shorter (by a factor of ~ 4) time interval ($0.994 \leq \phi \leq 1.006$, green line) than observed (at least $0.976 \leq \phi \leq 1.023$, red line). Unrealistic values for the eccentricity ($e = 0$, Fig. 10b), combined mass of the stars (maximum of $8 M_\odot$, Fig. 10c), or a larger photospheric radius of Eta Car A (5.5 AU, Fig. 10d) would be required for this scenario to reproduce the observed duration of the high-velocity absorption. Alternatively, unrealistically large amounts of hot dust emission located conveniently behind the wind of Eta Car B, which seems unlikely and is not supported by the available observations, would be required.

An additional issue is the amount of absorption observed in He I $\lambda 10833$. Since the observed high-velocity absorption spans velocities from -800 up to -2000 km s^{-1} , the absorption

necessarily has to occur in the acceleration zone of Eta Car B, before the wind reaches the supposed terminal velocity of 3000 km s^{-1} . Based on the CMFGEN radiative transfer model of the wind of Eta Car B (Hillier et al. 2006), the acceleration zone of the wind of Eta Car B is relatively compact compared to the size of the photosphere of Eta Car A. Consequently, if the wind of Eta Car B is to absorb continuum photons from Eta Car A, the coverage of this continuum source would be very small.

We conclude that it is unlikely that the high-velocity absorption component originates in the wind of Eta Car B.

5.4. High-velocity, shocked material from the wind-wind collision zone

The high-velocity absorption may originate in shocked material from the wind-wind collision zone that crosses our line-of-sight to Eta Car briefly across periastron. This hypothesis was suggested by Damineli et al. (2008a) to explain the behavior of He I $\lambda 10833$, assuming $\omega = 270^\circ$, and by Kashi & Soker (2009), who instead derived $\omega = 90^\circ$ from their analytical modeling.

Here we use three-dimensional (3-D) hydrodynamical simulations of the Eta Car binary system to investigate where high-velocity material can be found in the system, and at which epochs. We qualitatively compare our observations with the 3-D hydrodynamical simulations with the goal of constraining which orbital orientation is more consistent with our data. We aim in particular to ascertain the inclination angles and orbital orientations at which there is high-velocity gas, of velocities between -800 and -2000 km s^{-1} , along the line-of-sight to Eta Car A during the observed duration of the high-velocity absorption, and at which distances that gas is located. High-velocity gas along the line-of-sight is a necessity, but an insufficient condition for the presence of high-velocity absorption in a given spectral line. The amount of line absorption depends on the population of the lower energy level related to that line, which is regulated by the ionization stage of the gas. The 3-D hydrodynamical simulations allow us to analyze the hydrodynamics of the material flowing from the wind-wind collision zone with a much higher precision than in the analytical models of Kashi & Soker (2009), in particular for epochs across periastron, when the high-velocity material has been detected. For these epochs, the structure of the wind-wind collision zone is severely distorted, and the arms of the bowshock are wrapped around Eta Car A (Okazaki et al. 2008; Parkin et al. 2009).

We use 3-D simulations that are similar to and have the same parameters as those presented in Okazaki et al. (2008), with the exception that adiabatic cooling has been included⁴. The simulations assume the following parameters: for Eta Car A, a mass of $90 M_\odot$, radius of $90 R_\odot$, mass-loss rate of $2.5 \times 10^{-4} M_\odot \text{ yr}^{-1}$, and wind terminal velocity of 500 km s^{-1} ; for Eta Car B, a mass of $30 M_\odot$, radius of $30 R_\odot$, mass-loss rate of $10^{-5} M_\odot \text{ yr}^{-1}$, and wind terminal velocity of 3000 km s^{-1} ; an orbital period of $P = 2024$ d, eccentricity of $e = 0.9$, and semi-major axis of $a = 15.4$ AU. We refer the reader to Okazaki et al. (2008) for further details. Figure 11 presents 2-D slices of the wind-wind collision zone geometry based on the 3-D hydrodynamical simulations of Eta Car to visualize the geometry of the binary system and the observer’s location according to ω .

Time-dependent, multi-dimensional radiative transfer modeling of the outflowing material from the wind-wind collision zone is needed to determine the physical conditions of the

⁴ 3-D simulations from Parkin et al. (2009) show similar hydrodynamics as in the Okazaki et al. (2008) simulations.

Fig. 11. Illustration of the wind-wind collision and orbital geometry from different vantage points of the Eta Car system, based on snapshots from the 3-D hydrodynamic simulations similar to those of Okazaki et al. (2008), but including adiabatic cooling. The color scale refers to the 2-D density structure, and the spatial scales are in units of the semi-major axis a of the orbit ($a = 15$ AU). The top row shows the system configuration during apostron, while the bottom row refers to periastron. The wind from Eta Car A, the wind-wind collision zone, and the wind from Eta Car B are seen from a pole-on view (left panels) and from the equator (right). The white arrow corresponds to $\omega = 270^\circ$, while the green arrow corresponds to $\omega = 90^\circ$.

high-velocity gas. That is well beyond the scope of this paper, and we defer this analysis to future work. Since we did not compute a multi-dimensional radiative transfer model, we are able to obtain only *total* column densities from the SPH simulations, but not the column density of the population of the lower energy level of He I $\lambda 10833$ ($2s^3S$). The total column density computed here (hereafter referred to as “column density”) provides an upper limit to the amount of absorption. Thus, a low column density at higher velocities implies that no high-velocity absorption will be present. However, a high column density does not necessarily mean that a strong absorption line will be detected. In particular, the current 3-D simulations that we use do not account for radiative cooling, which makes it difficult to estimate the temperature and ionization structure of the high-velocity material in the wind-wind collision zone. In this Section, we assume that this material is able to efficiently cool and to produce the observed high-velocity absorption if the column density and velocity in the line-of-sight to Eta Car A are high enough.

Hereafter, for simplicity we assume that the phase zero of the spectroscopic cycle (derived from the disappearance of the narrow emission component of He I $\lambda 6678$) coincides with phase zero of the orbital cycle (periastron passage). We note that in a highly-eccentric binary system such as Eta Car the two values are not expected to be shifted by more than a few weeks. This time shift would only cause a small change of 10° – 20° in the most likely value of ω , which will not affect our conclusions.

As discussed in Sect. 5.1, the main source of continuum radiation at $1.0 \mu\text{m}$ is the free-free and bound-free emission from

the wind of Eta Car A, and we analyze the physical conditions of the gas between the observer and Eta Car A.

5.4.1. Orbital plane is aligned with the Homunculus equatorial plane

We investigate the hydrodynamics of the material along the line-of-sight to Eta Car A by viewing the system from different ω , and assuming that the orbital plane is aligned with the Homunculus equatorial plane and, thus, the inclination of the orbit is $i = 41^\circ$ (Smith 2006). Since we analyze an absorption line, Fig. 12 presents the one-dimensional density, velocity, and column density structure of the gas for different lines-of-sight to Eta Car A at orbital phases when VLT/CRIRES observations were available.

For $\omega = 90^\circ$, the line-of-sight to Eta Car A contains only high-density material from the wind of Eta Car A, with $v \sim -500 \text{ km s}^{-1}$, before periastron (Fig. 12g, h). After periastron, a patch of shocked material crosses the line-of-sight, but it does not contain material moving more rapidly than -800 km s^{-1} and, as a consequence, produces a negligible column density of high-velocity material in the range of -800 to -2000 km s^{-1} (Fig. 12i). For a lower value of $\omega = 50^\circ$, part of the wind of Eta Car B crosses our line-of-sight to Eta Car A after periastron, producing a considerable amount of column density of high-velocity material up to -1300 km s^{-1} (Fig. 12d–f). This is exactly the “wind-eclipse” scenario described above (Sect. 5.3.2) and, as one can see in Fig. 12f, the duration of the high-column density of high-velocity material along the line-of-sight to Eta Car A is very short. Therefore, based on the hydrodynamics predicted from detailed 3-D hydrodynamical simulations, we can rule out that the Eta Car system has orbital orientations around $\omega \sim 50^\circ$ – 90° if the high-velocity gas originates in shocked material from the wind-wind collision zone. We also found that orbital orientations with $\omega = 0^\circ$ (Fig. 12a–c) and $\omega = 180^\circ$ (Fig. 12j–l) do not provide high-velocity gas with sufficient column density along the line-of-sight to Eta Car A during the observed duration of the high-velocity absorption.

We find that the 3-D hydrodynamical simulations require an orbital orientation with ω in the range 240° – 270° to produce high-velocity gas with high enough density along the line-of-sight towards Eta Car A (Figs. 12m–o, p–r). For these orbital orientations, the density of the high-velocity gas is approximately an order of magnitude higher than expected from the wind of Eta Car B, while the velocities are significantly lower than the value expected for the wind of Eta Car B. These physical conditions indicate that the dense, high-velocity gas that is along our line-of-sight to Eta Car A originates from shocked material from the wind-wind collision zone. For $\omega = 243^\circ$, the high-velocity material is located between 1 and 3 semi-major axis (15 to 45 AU; Fig. 12m–o). The radial dependence of the density roughly follows an r^{-2} law, which closely resembles that of a stellar wind and might explain why the observed high-velocity absorption profiles are rather smooth and broad.

For $\omega = 270^\circ$, the increase in column density around $\phi = 11.991$ – 11.998 occurs at a velocity region around -1200 to -1800 km s^{-1} , and the column density of the gas with velocities -800 to -1200 km s^{-1} actually decreases before periastron and increases after periastron (Fig. 12p–r). Qualitatively, we would expect the opposite behavior to explain the increase in high-velocity absorption. However, ionization and radiative transfer effects might also play a role in determining the amount of absorption.

Fig. 12. *Left:* log density of material as a function of line-of-sight distance to Eta Car A (in units of the semi-major axis $a = 15.4$ AU) for selected orbital phases. *Middle:* line-of-sight velocity of material along the same assumed line-of-sight to Eta Car A. *Right:* log of the column density (in units of cm^2 per 50 km s^{-1} bin) along the same assumed line-of-sight to the primary star. All panels assume $i = 41^\circ$ and, from top to bottom, $\omega = 0^\circ, 50^\circ, 90^\circ, 180^\circ, 243^\circ,$ and 270° , respectively. The grey region corresponds to the observed range of high-velocity absorption.

Fig. 13. 2-D slices in the plane containing the observer's line-of-sight and Eta Car A for our preferred orbital orientation of $i = 41^\circ$ and a longitude of periastron of $\omega = 243^\circ$, based on 3-D hydrodynamic simulations of the Eta Car binary system similar to those presented by Okazaki et al. (2008). The observer is located on the right, along the abscissa axis (indicated by the black thick arrows on the right of each panel). The semi-major axis of the orbit is the white arrow labeled x , the semi-minor axis the white arrow y , and the orbital axis the white arrow z . From top to bottom, each row corresponds to orbital phases of $t = 0.875, 0.991, 0.998, 1.014$, and 1.041 , respectively. *Left*: density in logarithmic scale as a function of line-of-sight distance from Eta Car A, in units of the semi-major axis $a = 15.4$ AU. *Right*: line-of-sight velocity of material through the same plane. Material is color coded to line-of-sight velocity towards (blue) or away (red) from the observer.

A better qualitative agreement between our data and the models is obtained for $i = 41^\circ$ and $\omega = 243^\circ$, which is in line with the values obtained by Okazaki et al. (2008) and Parkin et al. (2009) to fit the X-ray lightcurve of Eta Car. For this orientation, there is an overall increase in the column density of the gas with velocities between -800 to -2000 km s $^{-1}$ from $\phi = 11.875$ to $\phi = 11.991$ – 11.998 (Fig. 12m–o), which corresponds to the phase range when the high-velocity component appears in the observations (Sect. 4). The column density is significant at $\phi = 11.875$ at some velocities, in particular around -1600 km s $^{-1}$, which is due to a blob expanding at that velocity. A steep overall decrease occurs at phases $\phi = 12.014$ – 12.040 , agreeing qualitatively with the disappearance of high-velocity absorption. Therefore, it is very likely that the huge changes in the column density of the high-velocity material from the wind-wind collision zone, which occurs during periastron, are one of the main explanations of the brief appearance of the high-velocity absorption component.

For some velocity ranges (e.g., -1100 to -1400 km s $^{-1}$), the column density is higher at $\phi = 11.991$ than at $\phi = 11.998$, which is opposite to what one would naively expect if the total column densities computed here corresponded directly to a certain amount of line absorption. If ionization effects were to occur, the behavior of the column density of the population of the lower energy level of He I $\lambda 10833$ ($2s^3S$) as a function of velocity would differ from that of the total column density. Since the distance of Eta Car B to the high-velocity material and its optical depth change significantly during periastron because of the high orbital eccentricity, ionization effects are indeed expected to happen. These probably play a role in the observed duration of the high-velocity absorption as well as in explaining why no high-velocity material is detected with velocities from -2000 to -3000 km s $^{-1}$, even if a high *total* column density is predicted by the SPH models. We note that, for the qualitative comparison performed here, we do not aim to explain the exact behavior of the column density as a function of velocity, nor to claim that the column density derived from the SPH simulations is able to explain the amount of absorption at each velocity. To do that, a proper radiative transfer model including the ionizing flux of both Eta Car B and the wind-wind collision-zone would be needed, which is well beyond the scope of this paper.

The hydrodynamical structure of the wind-wind interaction zone is extremely complex, in particular during periastron when the high-velocity absorption is observed. To illustrate the complex geometry and dynamics of the wind-wind interaction in Eta Car, in Fig. 13 we present 2-D slices of density and velocity in the plane containing the observer's line-of-sight and Eta Car A for our preferred orientation of $i = 41^\circ$ and $\omega = 243^\circ$. We note that the region responsible for the high-velocity absorption, located between 1 and 3 semi-major axes (15 to 45 AU), is clumpy and increases in density during periastron. However, after periastron, there is a major decrease in the velocity of the material along the line-of-sight to the primary star, explaining the rapid disappearance of the high-velocity absorption.

Using relatively simple analytical models for the wind-wind collision zone, Kashi & Soker (2009) obtained a different value of $\omega = 90^\circ$ from their best-fit toy model. We suggest that the complex hydrodynamics of the Eta Car system during periastron, which was not considered in the Kashi & Soker (2009) calculations, and the different assumption about the source of the continuum emission (extended hot dust emission on scales of ~ 30 AU) are the main reasons for the very different value of ω found by these authors. In Fig. 14 we show 2-D slices of density and velocity in the plane containing the observer's line-of-sight

Fig. 14. 2-D slices in the plane containing the observer’s line-of-sight and Eta Car A, similar to Fig. 13, but for an orientation of $i = 60^\circ$, longitude of periastron of $\omega = 90^\circ$, and orbital phase $\phi = 11.998$. The observer is located on the right, along the abscissa axis (indicated by the arrows in each panel). *Left*: density in logarithmic scale as a function of line-of-sight distance from Eta Car A, in units of the semi-major axis $a = 15.4$ AU. *Right*: line-of-sight velocity of material through the same plane. Material is color coded to line-of-sight velocity towards (blue) or away (red) from the observer. The insets show a zoom-in around the inner $\pm 1a$ region.

and Eta Car A for $i = 60^\circ$ and $\omega = 90^\circ$. As discussed above, there is no high-velocity material from the wind-wind collision zone along the line-of-sight to Eta Car A, and only high-velocity material from the wind of the Eta Car Car B is found along the line-of sight (as in the “wind-eclipse” scenario described in Sect. 5.3.2, which does not explain the observations). Since Kashi & Soker (2009) assumed that the absorption region was compact ($\sim a$ few AU), it is also unclear how this compact region would cover a significant fraction of their extended continuum source (~ 30 AU) to reproduce the significantly high fraction of continuum coverage (30–50%) inferred from the amount of high-velocity absorption reported in our present paper.

5.4.2. A tilted orbital plane relative to the Homunculus equatorial plane?

Recent works have suggested that the orbital plane of the Eta Car binary system might not be aligned with the Homunculus equatorial plane (Abraham & Falceta-Gonçalves 2007, 2009; Okazaki et al. 2008; Henley et al. 2008; Falceta-Gonçalves & Abraham 2009). To verify whether our observations support a tilted orbital axis scenario, we investigate whether the 3-D SPH models show a significant column density of high-velocity gas at other orbital inclinations and the orbital phases corresponding to when the high-velocity absorption was observed. Figure 15 presents, similar to Fig. 12, the one-dimensional density, velocity, and column density structure of the gas for different lines-of-sight to Eta Car A, but inclined at $i = 60^\circ$ and 90° from the plane of the sky.

For longitudes of periastron $\omega \sim 50^\circ$ – 90° , similar to the aligned case, most of the material in the line-of-sight towards Eta Car A originates in its own wind and has a velocity of roughly -500 km s $^{-1}$, except during a brief period after periastron when the “wind-eclipse” scenario occurs (Fig. 15a–f). For inclination angles higher than $i = 41^\circ$, such as 60° and 90° , a higher fraction of the wind of Eta Car B crosses the line-of-sight to Eta Car A and, thus, higher column densities are obtained at higher velocities after periastron. However, this occurs only briefly and remains inconsistent with our observations for the same reasons discussed in Sect. 5.3.2. Hence, our data are not in agreement with the orbital parameters derived by

Abraham & Falceta-Gonçalves (2007) and Falceta-Gonçalves & Abraham (2009) if the high-velocity absorption originates in the wind-wind collision zone.

If the orbital plane is tilted relative to the Homunculus, the hydrodynamics of the 3-D simulations still require that the binary system is seen with an orientation of $\omega \sim 240^\circ$ – 270° , otherwise no dense, extended, high-velocity material from the wind-wind collision zone is along the line-of-sight to Eta Car A during the observed amount of time. The temporal behavior of the column density of the high-velocity gas for $i = 60^\circ$ and $\omega = 243^\circ$ (Fig. 15j–l) is very similar to that obtained for $i = 41^\circ$ and $\omega = 243^\circ$ (Fig. 12g–i). For $\omega = 243^\circ$, the overall relative increase (decrease) in the column density of the high-velocity material before (after) periastron is even higher in the case of $i = 60^\circ$ than for $i = 41^\circ$. For $i = 90^\circ$, there is no significant increase in the column density of the high-velocity material before periastron and, actually, a strong decrease is seen at $\phi = 11.998$ (Fig. 15g–i). Strong ionization effects would be necessary to explain the high-velocity component if indeed $i = 90^\circ$, which seems unlikely. We can also argue that relatively weaker ionization effects would be needed to explain the appearance and disappearance of high-velocity material during periastron if $i = 60^\circ$ than in the $i = 41^\circ$ case. However, since the precise amount of ionization effects caused by Eta Car B is unclear, we conclude that our observations can be explained by the 3-D hydrodynamical models with both $i = 41^\circ$ and $i = 60^\circ$ for $\omega = 243^\circ$, which is consistent with previous X-ray analyses (Okazaki et al. 2008; Henley et al. 2008; Parkin et al. 2009).

6. Concluding remarks

We have shown that VLT/CRIRES observations of Eta Car provide definitive evidence that high-velocity material, up to ~ -1900 km s $^{-1}$, was present in the system during the 2009.0 periastron passage. The broad, high-velocity absorption is seen in He I $\lambda 10833$ in the VLT/CRIRES dataset only in the spectrum obtained at phase $\phi = 11.991$ to 11.998 , showing that it is connected to the spectroscopic event. Near-infrared observations obtained at OPD/LNA from 1989 to 2009 indeed show that the high-velocity absorption in He I $\lambda 10833$ is periodic, and tightly connected to phase zero of the spectroscopic cycle as well. Based on the OPD/LNA dataset, we constrained the timescale of detection of the high-velocity gas from 95 to 206 d (0.047 to 0.102 in phase) around phase zero. We analyzed archival HST/STIS ultraviolet data, showing that the Si IV $\lambda 1394$, 1403 resonance line also presented a high-velocity absorption component up to -2100 km s $^{-1}$.

We have presented several reasons why the high-velocity absorption is unlikely to be due to either a transitory high-velocity wind of Eta Car A, or a wind eclipse of Eta Car B. We suggest that our observations provide direct detection of shocked, high-velocity material flowing from the wind-wind collision zone around the binary system. Using detailed 3-dimensional hydrodynamical simulations of the wind-wind collision zone of Eta Car, we have found that dense high-velocity gas is along the line-of-sight to Eta Car A only if the binary system is oriented in the sky such that the companion is behind the primary star during periastron, corresponding to a longitude of periastron of $\omega \sim 240^\circ$ – 270° . Our data is broadly consistent with an orbital inclination in the range $i = 40^\circ$ – 60° . We have obtained that the high-velocity gas is located at distances of 15 to 45 AU along the line-of-sight to Eta Car A. More importantly, we can exclude orbital orientations in the range $\omega \sim 0^\circ$ – 180° for all inclination angles, since these do not produce a significant column density

Fig. 15. Similar to Fig. 12 but, from top to bottom, the following line-of-sights are shown: $i = 60^\circ$ and $\omega = 50^\circ$, $i = 90^\circ$ and $\omega = 50^\circ$, $i = 60^\circ$ and $\omega = 243^\circ$, and $i = 90^\circ$ and $\omega = 243^\circ$, respectively.

of high-velocity gas along the line-of-sight to Eta Car A to match our observations of the high-velocity absorption component.

The current 3-D SPH simulations used in this paper do not account for radiative cooling, which makes it difficult to estimate the ionization stage of the high-velocity material in the wind-wind collision zone. In addition to the increase in the column density of the high-velocity gas, ionization effects caused by the close presence of Eta Car B likely play an important role in explaining the amount of high-velocity absorption seen during periastron. Time-dependent, multi-dimensional radiative transfer modeling of the outflowing gas from the wind-wind collision zone of the Eta Car binary system is certainly warranted, and will allow us to more clearly understand the influence of Eta Car B on the wind of Eta Car A during periastron. This will ultimately provide constraints on both the masses of the stars and the wind parameters of the Eta Car binary system.

Acknowledgements. We wish to thank the kind allocation of ESO Director Discretionary Time that was crucial for the completion of this project, and

the ESO staff at Garching and Paranal, in particular Hugues Sana and Andrea Ahumada, for carrying out the VLT/CRIRES observations. We appreciate many discussions and comments on the manuscript from Michael Corcoran and Nathan Smith. We thank an anonymous referee for the suggestions to improve the original manuscript. J.H.G. thanks the Max-Planck-Gesellschaft for financial support for this work. A.D. and M.T. thanks the FAPESP foundation for continuous support. T.I.M. is supported by a NASA GSRP fellowship. The HST observations were accomplished through STIS GTO, HST GO and HST Eta Car Treasury Team programmes. HST/STIS data were obtained through the HST Eta Car Treasury archive hosted at University of Minnesota.

References

- Abraham, Z., & Falceta-Gonçalves, D. 2007, MNRAS, 378, 309
- Abraham, Z., & Falceta-Gonçalves, D. 2009, MNRAS, 1574
- Abraham, Z., Falceta-Gonçalves, D., Dominici, T. P., et al. 2005, A&A, 437, 977
- Behar, E., Nordon, R., & Soker, N. 2007, ApJ, 666, L97
- Chesneau, O., Min, M., Herbst, T., et al. 2005, A&A, 435, 1043
- Corcoran, M. F. 2005, AJ, 129, 2018
- Corcoran, M. F., Ishibashi, K., Davidson, K., et al. 1997, Nature, 390, 587
- Corcoran, M. F., Ishibashi, K., Swank, J. H., & Petre, R. 2001, ApJ, 547, 1034

- Damineli, A. 1996, *ApJ*, 460, L49
- Damineli, A., Conti, P. S., & Lopes, D. F. 1997, *New Astron.*, 2, 107
- Damineli, A., Stahl, O., Kaufer, A., et al. 1998, *A&AS*, 133, 299
- Damineli, A., Kaufer, A., Wolf, B., et al. 2000, *ApJ*, 528, L101
- Damineli, A., Hillier, D. J., Corcoran, M. F., et al. 2008a, *MNRAS*, 386, 2330
- Damineli, A., Hillier, D. J., Corcoran, M. F., et al. 2008b, *MNRAS*, 384, 1649
- Davidson, K., & Humphreys, R. M. 1997, *ARA&A*, 35, 1
- Davidson, K., Ebbets, D., Weigelt, G., et al. 1995, *AJ*, 109, 1784
- Davidson, K., Martin, J., Humphreys, R. M., et al. 2005, *AJ*, 129, 900
- Duncan, R. A., & White, S. M. 2003, *MNRAS*, 338, 425
- Falceta-Gonçalves, D., & Abraham, Z. 2009, *MNRAS*, 399, 1441
- Falceta-Gonçalves, D., Jatenco-Pereira, V., & Abraham, Z. 2005, *MNRAS*, 357, 895
- Feast, M., Whitelock, P., & Marang, F. 2001, *MNRAS*, 322, 741
- Fernández-Lajús, E., Gamen, R., Schwartz, M., et al. 2003, *Information Bulletin on Variable Stars*, 5477, 1
- Fernández-Lajús, E., Fariña, C., Torres, A. F., et al. 2009, *A&A*, 493, 1093
- Fernández-Lajús, E., Fariña, C., Calderón, J. P., et al. 2010, *New Astron.*, 15, 108
- Gaviola, E. 1953, *ApJ*, 118, 234
- Groh, J. H., & Damineli, A. 2004, *Information Bulletin on Variable Stars*, 5492, 1
- Groh, J. H., Damineli, A., & Jablonski, F. 2007, *A&A*, 465, 993
- Gull, T. R., Nielsen, K. E., Corcoran, M. F., et al. 2009, *MNRAS*, 396, 1308
- Hamaguchi, K., Corcoran, M. F., Gull, T., et al. 2007, *ApJ*, 663, 522
- Hartman, H., Damineli, A., Johansson, S., & Letokhov, V. S. 2005, *A&A*, 436, 945
- Henley, D. B., Corcoran, M. F., Pittard, J. M., et al. 2008, *ApJ*, 680, 705
- Hillier, D. J., & Allen, D. A. 1992, *A&A*, 262, 153
- Hillier, D. J., Davidson, K., Ishibashi, K., & Gull, T. 2001, *ApJ*, 553, 837
- Hillier, D. J., Gull, T., Nielsen, K., et al. 2006, *ApJ*, 642, 1098
- Hofmann, K., & Weigelt, G. 1988, *A&A*, 203, L21
- Humphreys, R. M., Davidson, K., & Koppelman, M. 2008, *AJ*, 135, 1249
- Iping, R. C., Sonneborn, G., Gull, T. R., Massa, D. L., & Hillier, D. J. 2005, *ApJ*, 633, L37
- Ishibashi, K., Corcoran, M. F., Davidson, K., et al. 1999, *ApJ*, 524, 983
- Kaeuff, H.-U., Ballester, P., Biereichel, P., et al. 2004, in *Proc. SPIE*, ed. A. F. M. Moorwood, & M. Iye, 5492, 1218
- Kashi, A., & Soker, N. 2007, *New Astron.*, 12, 590
- Kashi, A., & Soker, N. 2008a, *New Astron.*, 13, 569
- Kashi, A., & Soker, N. 2008b, *MNRAS*, 390, 1751
- Kashi, A., & Soker, N. 2009, *MNRAS*, 394, 923
- Kerber, F., Nave, G., & Sansonetti, C. J. 2008, *ApJS*, 178, 374
- Mehner, A., Davidson, K., Ferland, G. J., & Humphreys, R. M. 2010, *ApJ*, 710, 729
- Nielsen, K. E., Gull, T. R., & Vieira Kober, G. 2005, *ApJS*, 157, 138
- Nielsen, K. E., Corcoran, M. F., Gull, T. R., et al. 2007, *ApJ*, 660, 669
- Okazaki, A. T., Owocki, S. P., Russell, C. M. P., & Corcoran, M. F. 2008, *MNRAS*, 388, L39
- Parkin, E. R., Pittard, J. M., Corcoran, M. F., Hamaguchi, K., & Stevens, I. R. 2009, *MNRAS*, 394, 1758
- Pittard, J. M., & Corcoran, M. F. 2002, *A&A*, 383, 636
- Pittard, J. M., Stevens, I. R., Corcoran, M. F., & Ishibashi, K. 1998, *MNRAS*, 299, L5
- Smith, N. 2002, *MNRAS*, 337, 1252
- Smith, N. 2004, *MNRAS*, 351, L15
- Smith, N. 2006, *ApJ*, 644, 1151
- Smith, N. 2008, *Nature*, 455, 201
- Smith, N. 2010, *MNRAS*, 402, 145
- Smith, N., Davidson, K., Gull, T. R., Ishibashi, K., & Hillier, D. J. 2003a, *ApJ*, 586, 432
- Smith, N., Gehrz, R. D., Hinz, P. M., et al. 2003b, *AJ*, 125, 1458
- Smith, N., Morse, J. A., Collins, N. R., & Gull, T. R. 2004, *ApJ*, 610, L105
- Stahl, O., Weis, K., Bomans, D. J., et al. 2005, *A&A*, 435, 303
- Steiner, J. E., & Damineli, A. 2004, *ApJ*, 612, L133
- Teodoro, M., Damineli, A., Sharp, R. G., Groh, J. H., & Barbosa, C. L. 2008, *MNRAS*, 387, 564
- Thackeray, A. D. 1953, *MNRAS*, 113, 211
- van Boekel, R., Kervella, P., Schöller, M., et al. 2003, *A&A*, 410, L37
- van Genderen, A. M., Sterken, C., Allen, W. H., & Liller, W. 2003, *A&A*, 412, L25
- van Genderen, A. M., Sterken, C., Allen, W. H., & Walker, W. S. G. 2006, *J. Astronomical Data*, 12, 3
- Verner, E., Bruhweiler, F., & Gull, T. 2005, *ApJ*, 624, 973
- Viotti, R., Rossi, L., Cassatella, A., Altamore, A., & Baratta, G. B. 1989, *ApJS*, 71, 983
- Walborn, N. R. 1973, *ApJ*, 179, 517
- Weigelt, G., & Ebersberger, J. 1986, *A&A*, 163, L5
- Weigelt, G., Kraus, S., Driebe, T., et al. 2007, *A&A*, 464, 87
- Weis, K., Stahl, O., Bomans, D. J., et al. 2005, *AJ*, 129, 1694
- Whitelock, P. A., Carter, B. S., Roberts, G., Whittet, D. C. B., & Baines, D. W. T. 1983, *MNRAS*, 205, 577
- Whitelock, P. A., Feast, M. W., Marang, F., & Breedt, E. 2004, *MNRAS*, 352, 447
- Zanella, R., Wolf, B., & Stahl, O. 1984, *A&A*, 137, 79
- Zethson, T. 2001, Ph.D. Thesis, Lunds Universitet, Sweden