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Andrea Mehner
University of Minnesota

Kris Davidson
University of Minnesota

Roberta M. Humphreys
University of Minnesota

John C. Martin
University of Illinois at Springfield

Kazunori Ishibashi
Nagoya University, Japan

See next page for additional authors

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Authors

Andrea Mehner, Kris Davidson, Roberta M. Humphreys, John C. Martin, Kazunori Ishibashi, Gary J. Ferland, and Nolan R. Walborn

A SEA CHANGE IN ETA CARINAE*[†]

ANDREA MEHNER¹, KRIS DAVIDSON¹, ROBERTA M. HUMPHREYS¹, JOHN C. MARTIN², KAZUNORI ISHIBASHI³, GARY J. FERLAND⁴,
AND NOLAN R. WALBORN⁵

¹ Department of Astronomy, University of Minnesota, Minneapolis, MN 55455, USA; mehner@astro.umn.edu

² University of Illinois Springfield, Springfield, IL 62703, USA

³ Department of Physics, Nagoya University, Nagoya 464-8602, Japan

⁴ Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506, USA

⁵ Space Telescope Science Institute, Baltimore, MD 21218, USA

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ABSTRACT

Major stellar-wind emission features in the spectrum of η Car have recently decreased by factors of order 2 relative to the continuum. This is unprecedented in the modern observational record. The simplest, but unproven, explanation is a rapid decrease in the wind density.

Key words: circumstellar matter – stars: emission-line, Be – stars: individual (Eta Carinae) – stars: variables: general – stars: variables: S Doradus – stars: winds, outflows

1. INTRODUCTION

Today, 150 years after the close of its Great Eruption, η Car has not yet returned to thermal and rotational equilibrium (Maeder et al. 2005; Davidson 2005). This fact is important because the “supernova (SN) impostor” phenomenon and its aftermath constitute a major gap in the theory of massive stars, and η Car is the only example that can be studied in detail; see reviews by many authors in Humphreys & Stanek (2005). Its recovery has been unsteady, with unexplained photometric and spectral changes in the 1890s and 1940s (Humphreys et al. 2008).

This object may have entered a phase of accelerated development 12–15 years ago. From 1953 to the mid-1990s, ground-based “V” photometry of star plus ejecta brightened at a rate of $0.024 \text{ mag yr}^{-1}$, with brief deviations smaller than $\pm 0.3 \text{ mag}$ (Figure 2 in Davidson et al. 1999b). In the past decade, however, it has risen 0.6 mag above that earlier trend line (Figure 3 in Fernández-Lajús et al. 2009). The central star shows a more dramatic increase, a factor of more than 3 in UV-to-visual *Hubble Space Telescope* (*HST*) data since 1998 (Martin & Koppelman 2004; Martin et al. 2006; Davidson et al. 2009). A decrease in the amount of circumstellar dust may be responsible, but that requires some change in the wind and/or radiation field. Meanwhile, the periodic “spectroscopic events” of 1998.0, 2003.5, and 2009.0, defined in Section 2, differed in major respects (Davidson et al. 2005; Richardson et al. 2010; Corcoran 2010). Very likely the mass-loss rate has been decreasing at an inconstant pace, while rotational spin-up may play a role (Humphreys et al. 2008; Martin et al. 2006; Davidson et al. 2005; Smith et al. 2003).

All those discussions, however, seemed to face an embarrassing observational contradiction. From the first *HST* spectroscopy in 1991 until the Space Telescope Imaging Spectrograph (STIS)

failed in 2004, η Car’s spectrum showed no major change except during the temporary spectroscopic events. One might have expected some sort of spectral evolution to accompany the rapid brightening after 1998.

In this Letter, we report a novel development: observations in 2007–2010 with Gemini/GMOS and *HST*/STIS reveal major spectral changes. They are not subtle; evidently, the wind has been altered, at least temporarily and perhaps for the indefinite future.

2. DATA AND ANALYSIS

For long-term trends, we need quantitative spectra of η Car with consistent instrument characteristics, sampled over at least several years. Unfortunately, no suitable data set exists prior to the *HST* observations, which began with the Faint Object Spectrograph (FOS) in the 1990s (Davidson et al. 1995; Humphreys 1999) and continued with STIS after 1997. Here, we use *HST* spectroscopy of the central star with spatial resolution better than $0''.3$, almost free of contamination by nearby ejecta. Gemini/GMOS spectra of the central $1''$ in 2007–2010 provide valuable independent information.

Eta Car has a complex 5.54 year spectroscopic cycle, most likely regulated by a companion star in an eccentric orbit, as discussed by many authors in Humphreys & Stanek (2005). (The periodicity was discovered in stages by Zanella et al. 1984, Whitelock et al. 1994, and Daminieli 1996.) High-excitation emission lines temporarily vanish during periodic “spectroscopic events,” e.g., around 1998.0, 2003.5, and 2009.0, perhaps near periastron. The spectrum change described in this Letter is more conspicuous than any of those events, and there is no strong reason to assume that it is related to the 5.54 year cycle. But such a linkage might exist, and in any case the cycle may influence any data comparison. Therefore, we compare spectra at corresponding phases of successive cycles. Here, “phase” is defined by $P = 2023.0 \text{ days}$ and $t_0 = \text{MJD } 50814.0 = \text{J1998.00}$, consistent with the η Car *HST* Treasury Program Archive.⁶ Phases 0.00, 1.00, and 2.00 mark the 1998.0, 2003.5, and 2009.0 spectroscopic events.

* Based on observations made with the NASA/ESA *Hubble Space Telescope*. Space Telescope Science Institute (STScI) is operated by the Association of Universities for Research in Astronomy, Inc., under the NASA contract NAS 5-26555.

[†] Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership.

⁶ <http://etacar.umn.edu/>; see comments at the end of Section 2 in Mehner et al. (2010).

After a 5 year hiatus, STIS obtained new spectra of η Car beginning in mid-2009. Our observations in 2009 August and 2010 March occurred at phases 2.10 and 2.20, and fortunately some STIS data had been obtained approximately one and two cycles earlier, at phases 1.12 in 2004 and 0.21 in 1999. It is also prudent to examine data sets taken one cycle apart during 1998–2004. Therefore, we compare spectra of the star at phases 0.04 versus 1.03, 1.12 versus 2.10, and 0.21 versus 2.20.⁷ The 0.04/1.03 data were close to spectroscopic events but not within them; in most proposed orbit models, they represent longitudes 100° – 140° past periastron, with star–star separations 2–5 times larger than at periastron. The 0.21/2.20 phases were well outside the events (Mehner et al. 2010; Martin et al. 2010).

Improved STIS data reduction techniques were developed for the η Car *HST* Treasury Program (Davidson 2006). However, in early 2010 the software has not yet been adapted to some format changes necessary for the new data. On the other hand, the current Space Telescope Science Institute (STScI) data pipeline could not easily be applied to some of the 1998–2004 data.⁸ Therefore, we used Treasury Program methods for the 1998–2004 STIS data and the STScI pipeline for the 2009–2010 data. We extracted one-dimensional spectra of the star with a sampling width of $0''.25$. This was broader than we would have chosen if the Treasury Program techniques had been employed throughout, but it is narrow enough to exclude most of the ejecta.

In principle, the use of two reduction procedures might cause illusory spectrum differences, but they would be no worse than a few percent. The $0''.25$ extraction width amounts to five CCD rows, broad enough for good agreement in the interpolation and integration steps. These statements are confirmed by random checks of a few 1998–2004 spectra reduced by both methods. We also examined semi-raw data files—flat-fielded and with cosmic ray hits removed, but otherwise unprocessed—and they show the same large effects as the reduced spectra (Section 3). Our results do not depend on absolute flux calibrations or precise spatial sampling.

We verified and extended our findings with Gemini/GMOS observations in 2007–2010, reduced with the Gemini IRAF package. They sampled wavelengths 3600–7200 Å with slit width $0''.5$; see Martin et al. (2010).

3. RESULTS

During 1991–2004, *HST*/FOS and *HST*/STIS showed no definite secular change in η Car’s stellar-wind spectrum. The $H\beta$ equivalent width, for instance, varied only $\pm 10\%$ (rms) outside spectroscopic events (Davidson et al. 2005). Figure 1(a) illustrates the similarity of broad wind features in two successive cycles before 2004. The qualitative ground-based record from 1900 to 1990 shows no discernible instance of a change like that reported below; see references in Humphreys et al. (2008).

The 2009–2010 STIS data, however, reveal *the weakest broad-line spectrum ever seen in modern observations of this object*, relative to the underlying continuum. We note several effects:

1. Low-excitation emission created in the stellar wind became far less prominent. For example, Figure 1 shows blends of Fe II, [Fe II], and Cr II near 4600 Å. Phases 0.04 and

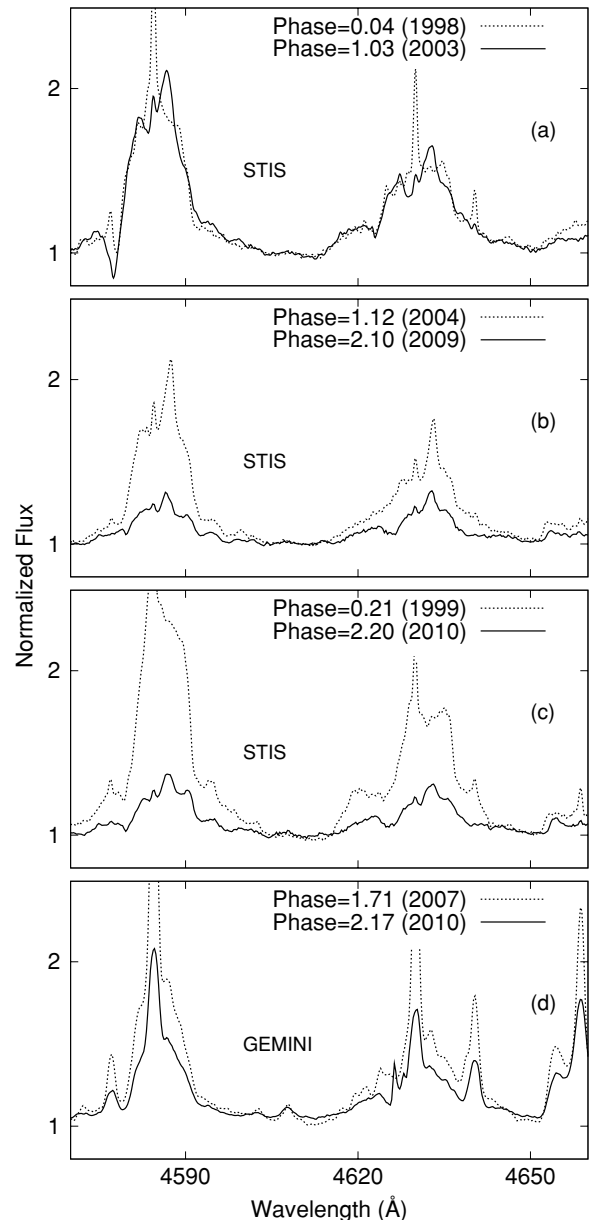


Figure 1. Blends of Fe II, [Fe II], Cr II, and [Cr II] near 4600 Å, 1998–2010. Flux is normalized to unity at 4605 Å. Panels (a)–(c) show *HST*/STIS data in successive spectroscopic cycles (see the text), while (d) shows two Gemini/GMOS spectra. Spatial resolution was about $0''.25$ for STIS and $1''$ for GMOS. The narrow features are not crucial here, since they originate far outside the stellar wind; their decrease relative to the star may be merely an indirect consequence of changes in circumstellar extinction. The blends shown here are dominated by Fe II $\lambda\lambda 4584.1, 4585.1, 4630.6$, [Fe II] $\lambda 4641.0$, and Cr II $\lambda 4589.5$.

- 1.03 (1998 and 2003) were mutually consistent, but W_λ decreased by factors of 2–4 between phases 1.12 and 2.10 and likewise between 0.21 and 2.20 (Table 1). Most of the broad lines originate in the primary star’s wind; see papers and references in Humphreys & Stanek (2005).
2. The profile of $H\alpha$, the strongest emission line in the violet-to-red spectrum, is altered and weakened in the recent STIS data (Figure 2). $H\alpha$ had a low flat-topped profile during the 2003.5 event and then partially recovered (Davidson et al. 2005); but now it is even weaker (Table 1). The narrow $H\alpha$ absorption near -145 km s^{-1} indicates unusual nebular physics far outside the wind (Johansson et al. 2005). Always present in 1998–2004, this feature had weakened by 2007

⁷ Calendar dates 1998 March 19/2003 September 22, 2004 March 7/2009 August 19, and 1999 February 21/2010 March 3; MJD 50891/52904, 53071/55062, and 51230/55258.

⁸ The reason was merely a lack of certain wavelength calibration files which are otherwise irrelevant here.

Table 1
Equivalent Widths of Some Stellar-Wind Emission and Absorption Lines Measured with STIS

Date	Phase	EW (Fe II, Cr II) ^a (Å)	EW (H α) ^b (Å)	EW _{abs} (He I 4714) (Å)	EW _{abs} (He I 6680) (Å)
1998 Mar 19	0.04	11.47	830.26	-0.06	-0.20
1999 Feb 21	0.21	17.79	899.37	-0.10	-0.01
2003 Sep 22	1.03	11.03	614.18	-0.11	-0.63
2004 Mar 7	1.12	9.69	822.71	-0.18	-0.59
2009 Jun 30 ^c	2.08	3.62	...	-0.47	...
2009 Aug 19	2.10	2.90	483.35	-0.61	-1.10
2010 Mar 3	2.20	3.89	492.73	-0.39	-0.70

Notes.

^a Measured between 4570 and 4600 Å, continuum at 4605 Å and 4744 Å.

^b Measured between 6510 and 6620 Å, continuum at 6500 Å and 6620 Å.

^c H α and He I λ 6680 were not observed on this occasion.

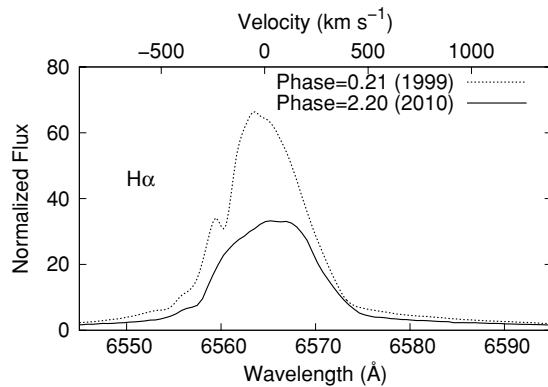


Figure 2. H α about 400 days after the 1998 and 2009 events. Flux is normalized to 1.0 at 6620 Å. Note the disappearance of external narrow absorption near -145 km s⁻¹.

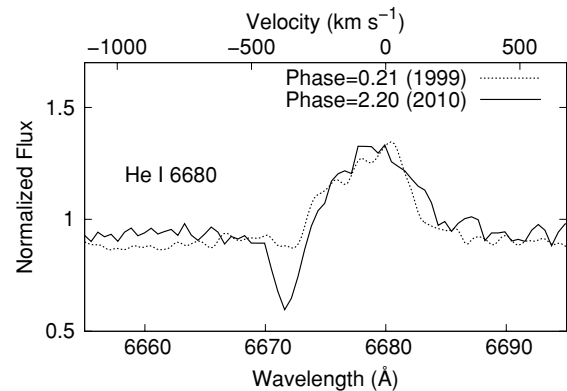


Figure 3. He I λ 6680 about 400 days after the 1998 and 2009 events. Flux is normalized at 6620 Å. The strengthened absorption feature is also seen in other He I lines such as $\lambda\lambda$ 4027, 4714.

but reappeared during the 2009.0 event (Ruiz et al. 1984; Davidson et al. 1999a, 2005; Martin et al. 2010; Richardson et al. 2010). By 2010 March it had practically vanished.

- High-excitation He I emission did not weaken along with the features noted above, but the P Cygni *absorption* features of helium greatly strengthened after the 2009 event (Figure 3). This requires caution because He I varies intricately during each cycle. Note, however, that only a few occasions in 1998–2004 showed absorption as deep as that seen at phase 2.20 in 2010 March; and phase 0.21 showed practically none.

Table 1 lists the equivalent widths of emission and absorption features mentioned above. Similar changes occurred throughout the violet-to-red wind spectrum. UV emission lines around 2600 Å weakened relative to the continuum, while the overall brightness in that wavelength region increased by 20%–30% between 2009 August and 2010 March. STIS observations by other researchers in 2009 June, covering a smaller set of wavelengths, are consistent with our results.⁹

Gemini/GMOS observations in 2007–2010 confirm the reality of these spectrum changes (Figure 1(d)). In 2010, the GMOS data show stronger emission lines than the STIS data does (Figure 1(d) versus Figure 1(c)), merely because the 1'' ground-based spatial resolution allows significant contributions by ejecta far outside the stellar wind. Nevertheless, equivalent widths of low-excitation emission blends in the GMOS data

decreased by factors of about 2 between 2007 June and 2010 March. Most of our GMOS data at intermediate times were of lower quality, but they strongly suggest that the spectral change was progressive rather than abrupt.

4. WHAT HAS HAPPENED?

We emphasize that the *stellar-wind* emission lines have weakened relative to the continuum; outlying ejecta will require a separate investigation. The simplest explanation is a decrease in η Car's primary wind density, which seems natural for the long-term recovery as well as other recent data (Davidson et al. 2005; Martin et al. 2006, 2010; Humphreys et al. 2008; Kashi & Soker 2009a). The surprise is in the rapidity of this development. Long ago it was expected that after the year 2050 this object would appear much as it did to Halley and Lacaille three centuries ago—a hot fourth-magnitude star with a transparent rather than opaque wind (Davidson 1987). But now the schedule appears to have been accelerated; if the recent trend continues (which we cannot predict), the star will approach that point in only a decade. Even if the spectrum regresses to its earlier state, these developments are crucial because the observational record shows no precedent for them.

The effects reported in Section 3 do not match the standard traits of luminous blue variables (LBV; Humphreys & Davidson 1994). The energy carried by η Car's wind surpasses a bright classical LBV by a factor of 100 or more, and its emission lines are far stronger. When an LBV experiences a major

⁹ *HST* Program 11506: K. S. Noll, B. E. Woodgate, C. R. Proffitt, & T. R. Gull.

eruption its wind becomes opaque, cools below 9000 K, and develops a rich absorption-line spectrum within a few months. Visual wavelengths brighten but the UV correspondingly fades. Something like that did happen to η Car around 1890; but its recent record, by contrast, shows no perceptible decrease in the UV/visual flux ratio. “LBV” is not a very satisfactory label for this object, since much of its 1830–2010 behavior does not fit that category well. If the recent change proves to be an increase rather than a decrease of the wind—i.e., contrary to the hypothesis that we favor—then η Car may soon mimic a third-magnitude F-type supergiant.

Other alternatives to the decreasing-wind interpretation include, e.g., a change in the latitude dependence of the wind (Smith et al. 2003), or the unusual models for η Car favored by Kashi & Soker (2007, 2009a, 2009b). Many complications exist. For instance, a lessened wind density should cause the photosphere (located in the opaque wind) to shrink and become hotter, eventually leading to a *decrease* in visual-wavelength flux. Indeed this may have occurred in 2006 (Fernández-Lajús et al. 2009; Martin et al. 2010), but circumstellar dust and other factors probably dominate.

Numerous observables figure into the problem. For example, in Section 3 we mentioned that He I lines have behaved differently from the lower-excitation features. Helium emission and absorption processes in η Car’s wind depend on the companion star and have other special characteristics (see Section 6 of Humphreys et al. 2008). Also relevant are the 2–10 keV X-rays formed in the wind–wind collision zone. Kashi & Soker (2009a) have suggested that the earlier-than-expected recovery of X-rays after the 2009.0 spectroscopic event may signal a decrease in the wind density. Independent of that problem, in early 2010 the 2–10 keV flux has been about 20% below the level seen in two previous 5.5 year cycles (Corcoran 2010). This decrease is much less extreme than the spectroscopic changes described in Section 3; perhaps these effects depend on latitude differences between our direct view of the wind and conditions near the wind–wind shocks (Smith et al. 2003; Davidson 2005; Humphreys et al. 2008). Realistic wind models will need to be non-spherical and even non-axisymmetric.

Eta Car’s behavior may provide spectroscopic opportunities not foreseen until recently. For instance, if the wind becomes semi-transparent, then the temperature and radius of the primary star may become observable for the first time. Moderate-sized instruments are valuable because *HST* and large telescopes will provide, at best, only sparse temporal sampling. Fortunately, ground-based observations now show η Car—the star itself—more clearly than they did 10 years ago, because the diffuse ejecta have not brightened as fast as the star. An obvious need is for *instrumentally homogeneous* series of spectra. Since the wind has characteristic size scales of several AU and velocities

of several hundred km s^{−1}, changes may occur on timescales as short as a week.

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