ETA CARINAE’S 2014.6 SPECTROSCOPIC EVENT: THE EXTRAORDINARY He II AND N II FEATURES*

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ABSTRACT
Eta Carinae’s spectroscopic events (periastron passages) in 2003, 2009, and 2014 differed progressively. He II λ4687 and nearby N II multiplet 5 have special significance because they respond to very soft X-rays and the ionizing UV radiation field (EUV). Hubble Space Telescope (HST)/STIS observations in 2014 show dramatic increases in both features compared to the previous 2009.1 event. These results appear very consistent with a progressive decline in the primary wind density, proposed years ago on other grounds. If material falls onto the companion star near periastron, the accretion rate may now have become too low to suppress the EUV.

Key words: circumstellar matter – stars: individual (η Carinae) – stars: massive – stars: variables: general – stars: winds, outflows – X-rays: stars

1. HE II λ4687 EMISSION IN η CAR’S SPECTROSCOPIC EVENTS
The appearance of η Car has evolved rapidly in the past 15 years (Martin et al. 2006a, 2010; Mehner et al. 2010b, 2012). The primary wind may be returning to its pre-eruption state (Humphreys et al. 2008; Davidson 2012), but in any case the spectrum and brightness have changed much faster than before. Extraordinary clues are provided by “spectroscopic events” that occur near each periastron passage of the companion star in its 5.5 yr orbit—see many references in Corcoran & Ishibashi (2012), Davidson (2012), and Humphreys & Martin (2012). The events observed in 1998, 2003, and 2009 did not match each other (Davidson et al. 2005; Kashi & Soker 2009b; Mehner et al. 2011b). Here we report major differences between the 2014.6 event and its predecessors, observed with the Space Telescope Imaging Spectrograph (HST/STIS).

The 2003.5 and 2009.1 spectroscopic events seemed alike in their early stages, but their X-rays and exotic He II emission differed after periastron. Broad He II λ4687 emission occurred during the first half of each event (Steiner & Damineli 2004; Martin et al. 2006b; Mehner et al. 2011b; Teodoro et al. 2012), even though neither star can ionize He II* enough to produce this recombination line. Martin et al. noticed its anti-correlation with the 2–10 keV X-rays and explored relevant physics. They concluded that a flood of 50–700 eV photons arose as the colliding-wind shocks became unstable near periastron, indirectly exciting He II λ4687. Those soft X-rays carried far more energy than the 2–10 keV photons, but cannot be observed except via He II λ4687.

In 2009, unlike 2003, definite λ4687 emission briefly reappeared after periastron. (Concerning the 2003 record, see Section 5 below.) The hard X-rays reappeared immediately thereafter, much earlier than in 1998 and 2003. Most likely, λ4687 emission signaled the re-formation of large-scale shock structure that produces hard X-rays. These and other data appear consistent with lower gas densities in 2009 compared to 2003 (Kashi & Soker 2009b; Mehner et al. 2010b, 2011b; Corcoran et al. 2010).

Thus, a qualitative extrapolation of the 1998–2003–2009 data suggested that η Car’s 2014.6 event might have a brighter He II λ4687 “second flash.” Here we report HST/STIS observations which confirm that suspicion. Equally significant, they also reveal unexpected strength in a nearby UV-excited N II multiplet that was only barely visible in 2003 and 2009.

2. OBSERVATIONS AND DATA REDUCTION
HST/STIS plays a unique role in our knowledge of η Car. Unlike ground-based spectrographs, STIS can observe the central object without serious contamination by ejecta located 150–500 mas from the star (Hamann et al. 2012; Remmen et al. 2012; Martin et al. 2006a). It also provides unrivaled data homogeneity over the time period 1998–2014, immune to atmospheric effects—though it was not operational during the 2009.1 event. Moreover, STIS allows UV coverage. For all these reasons, HST data provide necessary anchoring points for ground-based observations (see Section 5 below).

The STIS/CCD observations reported here cover wavelength range 4562–4841 Å with a 100 mas slit width and an integration time of 25.5 s on each occasion. The observing dates in 2014 are listed in Table 1. The setup was like that described in earlier papers, especially Martin et al. (2006b). Details can be found in the STScI and η Car Treasury Program archives, where the data will become publicly available in 2015. Additional wavelength ranges will be reported in later papers, but He II λ4687 and the special N II emission are most critical.

We used the data reduction methods employed by Martin et al. (2006b) and Mehner et al. (2010b), developed for the HST η Car Treasury Project in 2002–2004—providing better spatial resolution than the standard STScI pipeline (Davidson et al. 2006). They allowed us to extract reliable spectra with spatial widths of 150 mas and slightly unsharp edges to minimize pixelization effects. At η Car’s distance, 150 mas corresponds to a projected size of about 340 AU, larger than the

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5 http://archive.stsci.edu/hst/ and http://etacar.umn.edu/.
Table 1
STIS Observations of 4561–4841 Å in 2014

| Date       | MJD (days) | t (days) | \( f_\lambda (4745 \text{ Å}) \) | EW1 (Å) | EW2 (Å) |
|------------|------------|----------|----------------------------------|---------|---------|
| 2014 Jul 13| 56851.2    | −31.8    | 1.74                             | 1.68    | 2.77    |
| 2014 Jul 30| 56868.1    | −14.9    | 1.99                             | 0.01    | 0.69    |
| 2014 Aug 15| 56884.3    | +1.3     | 1.47                             | 0.17    | 0.90    |
| 2014 Aug 31| 56900.4    | +17.4    | 1.45                             | 0.89    | 2.53    |
| 2014 Sep 17| 56917.0    | +34.0    | 1.53                             | 0.51    | 1.15    |
| 2014 Nov 09| 56970.7    | +87.7    | 1.54                             | 0.02    | 0.01    |

\( a \) Days from the standard zeropoint at MJD 56883.0; phase = t/(2023 days).
\( b \) Apparent continuum in units of \( 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \), not corrected for slit throughput.

...in absorption (Section 4 below), and a possible weak emission bump can be seen near 4687 Å.

Figure 2 shows our recent STIS spectra. Elevated fluxes near 4687 Å—the shaded areas in the figure—occur only during spectroscopic events.

Results for the \( \lambda4687 \) emission strength appear in Figure 3. This is a contentious topic, and the chief issue is whether the emission differed substantially between 2014.6 and 2009.1. Therefore we employ two largely independent measures of the emission strength and they both support the same conclusion.

EW1 samples only the "obvious bump" in the spectrum with a peak near 4687 Å (e.g., top panel in Figures 1 and 2); this is easy to measure but it omits much of the flux. EW2 includes a larger fraction of the emission but requires an accurate measure of the true continuum.

For EW1 we simply estimate a linear pseudo-continuum based on data within the narrow range 4670–4700 Å, and calculate net equivalent width in the usual way. A dashed line in the top panel of Figure 1 shows an example. EW1 amounts to a lower limit, because its pseudo-continuum level often lies well above the true continuum. EW1 in the 2009.1 and 2014.6 events is shown in Figure 3(a), where small data points represent Gemini/GMOS observations in 2009 (Mehner et al. 2011b), while heavier black dots are the STIS results for 2014. Limit marks on each STIS data point indicate a range of ±1.5% in the local pseudo-continuum; levels outside this range do not appear credible when plotted with the data. Uncertainties are dominated by possible systematic errors, and our limit marks are probably about 60% more pessimistic (wider range) than conventional one-sigma error bars.

During the first half of each spectroscopic event, EW1 was noticeably larger in 2014 compared to 2009 (Figure 3(a)). But the second half of the event, particularly \( t \approx +17 \) days, showed a more dramatic difference: the second flash in 2014 was roughly twice as strong as its predecessor in 2009.

Figures 2 and 3(b) show that EW1 is less than half of the story, because broader emission fills the region around 4687 Å during an event. Martin et al. (2006b) showed that flux levels near 4605 and 4745 Å measured \( \eta \) Car’s continuum sufficiently well in the 1998–2004 STIS data. When \( \text{He}\eta \lambda4687 \) was not present (i.e., at any time outside an event), linear continua \( f_\lambda' \) fit the 4605, 4685, and 4745 Å levels very well; e.g., 2003.88 in Figure 1. The apparent slope was small, with \( f_\lambda' (4685 \text{ Å}) \approx 0.99 f_\lambda' (4745 \text{ Å}) \). Estimating the continuum in this way, and integrating the emission between 4675 and 4694 Å, we find a second equivalent width EW2 which is often much larger than EW1. Martin et al. (2006b); Mehner et al. (2011b), and Teodoro et al. (2012) used this procedure. Emission outside the 4675–4694 Å interval is blended with strong unrelated spectral features.

In 2014, a set of unusual \( \text{N}\eta \) lines disqualified the 4605 Å window for continuum sampling (Figure 2 and Section 4). We must therefore base the underlying continuum on just the 4745 Å window plus earlier experience and known features. Since 4687 and 4745 Å differ by only 1.2% in wavelength, no likely process would alter the continuum ratio \( f_\lambda' (4687 \text{ Å}) / f_\lambda' (4745 \text{ Å}) \) by more than a fraction of a percent. (4687 Å is on the insensitive Rayleigh–Jeans side of \( \eta \) Car’s SED.)

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6 The precise apparent slope is slightly influenced by focus effects (Davidson et al. 2006), but what matters here is long-term consistency, which has been excellent with STIS.
In terms of EW2, Figure 3(b) shows that the second λ4687 flash in 2014 was more than twice as strong as in 2009. The small horizontal bar above each data point shows the value if we decrease \( f_\lambda \) (4687 Å) by 1%, arguably more likely as noted above.

Various objections to our measurements can be proposed, but they are weak when examined. The temporal sampling is adequate to establish the brightening, since all data in 2009 showed a continuous rise and decline through about 45 days. Our 2014 observations sampled the rise, the near-maximum, and the decline, and all three were much brighter than corresponding phases in 2009. (If the true maximum was substantially higher, then the 2009–2014 increase is even larger than we report.) We cannot prove that extra emission in 4675–4694 Å (shaded in Figure 2) was entirely due to \( \text{He}\eta \); but something changed in EW2 between 2009 and 2014, and it correlated with EW1 which certainly represents \( \text{He}\eta \) emission. Errors in the continuum slope cannot be large enough to affect the issue, for physical reasons mentioned above. No evident process can enhance the continuum in a wavelength range less than 100 Å wide. The narrow interval near 4745 Å is indeed the best continuum sample, because emission and absorption features are known to affect all other wavelengths between 4550 and 4800 Å during the spectroscopic event. A Thomson-scattered wing of \( \text{He}\eta \lambda 4714 \) cannot account for much of EW2, because that would entail a detectable slope in \( f_\lambda \) around 4687 Å; and, also, the corresponding long-wavelength wing is not strong enough. Altogether, EW2 is well justified and EW1 behaved similarly. Conceivably the values for 2009 were severely underestimated because of ground-based defects mentioned above, but that would not explain why the second flash around \( t \sim +20 \) days changed far more than the first flash around \( t \sim -30 \) days.

In summary, the combination of EW1 and EW2 in Figure 3 establishes a conspicuous difference between the 2014.6 and 2009.1 events. Its physical significance will be noted in Section 5 and in later papers.

4. SPECIAL N II FEATURES AND THE EUV

\( \text{N}\eta \) multiplet 5 at 4603–4644 Å, barely noticeable in 2009, became quite conspicuous in 2014; compare especially the 2014.57 panel in Figure 2 to any spectrum in Figure 1. This development indicates a strengthened EUV radiation field. The multiplet’s lower level has energy 18.5 eV, far too high for normal thermal excitation. As explained by Mehner et al. (2011a), it is populated in \( \eta \text{ Car} \)’s primary wind by photons from the hot companion star. Consequently multiplet 5 can scatter ambient radiation, thus producing absorption and/or pseudo-emission lines, depending on viewing direction.

In late 2013 this set of features appeared mainly in absorption (2013.70 in Figure 1), but during the 2014.6 event they became mainly emission (Figure 2). Mehner et al. sketched the geometrical circumstances in their Figure 5. In late 2013 the secondary star passed between us and the primary, except for the orbit inclination. Thus it excited \( \text{N}\eta \) along our line of sight to the primary wind, causing absorption in multiplet 5. In mid-2014 the secondary star moved to the far side of the primary, unfavorable for absorption but allowing apparent emission which was really light scattered in gas around the sides of the configuration. By 2014 November the radiative excitation weakened because the size scale had increased.

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**Figure 1.** Representative STIS data in 2003 and 2013, and ground-based data in 2009. Each tracing shows \( f_\lambda \) relative to the adopted value near 4745 Å. Baselines with small slopes in the 2003.47 and 2003.88 panels indicate continuum fits. A short dashed line in the 2003.47 panel shows the base for a typical EW1 estimate, see text. The bottom panel shows Gemini/GMOS data in the first half of the 2009 event; note the weakness of \( \text{N}\eta \) features around 4610 Å compared to Figure 2. Like all other ground-based spectra of \( \eta \) Car, the Gemini data include narrow features emitted by outlying ejecta.
Why were these features strong in 2014 but not in 1998, 2003, and 2009? N II multiplet 5 requires photons with $\hbar \nu \gtrsim 14.5$ eV to create N$^+$, and $\hbar \nu \approx 18.5$ eV to excite it. Normally these come from the hot secondary star. During the earlier spectroscopic events, its UV was effectively suppressed (Zanella et al. 1984 and other references in Davidson 2012). Evidently the 2014.6 event was characterized by a stronger EUV radiation field, presumably from the secondary star.

The N II velocities vary in much the same way as some other features (Mehner et al. 2011a, 2011b). We do not discuss their kinematics here, because their strength has a more immediate significance as outlined above.

5. DISCUSSION

A wealth of evidence affirms the rapid and progressive changes in $\eta$ Car since 1998; see Mehner et al. (2012) and many references therein. But this development has occasionally been disputed (e.g., Damineli et al. 2011; Teodoro et al. 2012; Madura et al. 2013). For He II $\lambda$4687, Teodoro et al. (2014) report “no significant changes between 2009.0 and 2014.6.” Figure 3 contradicts that assessment, and the two events differed in other respects concerning the UV radiation field. The most natural explanation continues to be a progressive decline of the primary wind density; see the many references in Davidson (2012) and Mehner et al. (2012). Since the photosphere is located in the wind, decreasing densities favor smaller photospheric radii, higher radiation temperatures, and higher ionization states.
Whatever caused the “extra emission” around $4687 \text{ Å}$ (shaded areas in Figure 2), it manifestly correlates in time and wavelength with the undoubted $\text{He}\,\,\,\, \lambda 4687$ feature measured by EW1. In the absence of any other credible candidate, broadened $\text{He}\,\,\,\, \lambda 4687$ emission is the simplest interpretation and its physics appears reasonable (Martin et al. 2006b). Column densities near periastron (Corcoran & Ishibashi 2012) are large enough to produce Thomson scattering, which broadens some of the $\lambda 4687$ emission but also reflects much of it away from us. The $\lambda 4687$ minimum around $t \sim -10$ days may conceivably have been a quasi-eclipse by gas near the primary star, and the “second flash” may have been stronger in 2014 merely because intervening densities were lower than in 2009. Quantitative models will require elaborate simulations of colliding-wind shock instability, breakup, and reformation, and there are more adjustable parameters than truly independent observables. The main point at present is that $\eta$ Car’s successive spectroscopic events do indeed differ in a progressive way.

Subtle effects in ground-based data have occasionally led to misunderstandings. For example, Teodoro et al. (2012) stated that weak $\lambda 4687$ persisted between events, with a strength that would have been obvious in the STIS data. In fact this was presumably emission from outlying ejecta at $r \sim 0.3-1$ arcsec, as explained in Section 4.2 of Mehner et al. (2011b) and Section 6.3 of Martin et al. (2006b). Teodoro et al. also stated that a second $\lambda 4687$ flash occurred in 2003, based on two or three instances of EW2 $\sim 0.6 \text{ Å}$ from a relatively modest instrument. Between those observations, however, STIS showed EW2 $< 0.2 \text{ Å}$ at $t = +15$ days. Teodoro et al. speculated that this was a “bad datum,” which is highly unlikely in view of the proven nature of the instrument and the multiple consistency of Figure 5 in Martin et al. (2006b). Since STIS was the more capable instrument, and hard X-rays did not reappear soon after that time, most likely there was no strong $\lambda 4687$ flash near $t \sim +15$ days in 2003.

We mention these examples because they illustrate why excellent data with high spatial resolution are essential for this problem. The bottom panel in our Figure 1, and also Figure 2 in Teodoro et al. (2012), shows that even the best ground-based spectra of $\eta$ Car have obvious contamination by outlying narrow-line ejecta. (Compare them with the STIS spectra.) Data obtained with wider slits or inferior atmospheric conditions may be appreciably worse, and the relative brightness of the ejecta is changing with time (Mehner et al. 2012). The extraneous features cast doubt on continuum estimates and other sensitive measures that rely only on ground-based data. STIS, by contrast, has far better spatial resolution, excellent S/N, and good long-term stability; see especially Section 4.2 in Mehner et al. (2011b). Moreover, its data are publicly available.

$\text{N}\,\,\,\,\,\lambda$ multiplet 5 samples different physical parameters than either the helium lines or the low-excitation features. It depends mainly on EUV photons with energies between 14 and 20 eV, supplied by the hot companion star (Mehner et al. 2011a). At most times the secondary star has $T_{\text{eff}} \sim 40,000 \text{ K}$, producing copious radiation at 14–20 eV (Mehner et al. 2010a). The $\text{N}\,\,\,\,\,\lambda$ features arise in relatively normal parts of the primary wind, not the shocked regions. Their prominence in 2014 implies a substantial EUV radiation field.

Traditionally, $\eta$ Car’s spectroscopic events were defined by a temporary lack of ionizing UV (Zanella et al. 1984). Either (1) the hot secondary star moved inside the diffuse primary photosphere, and/or (2) it accreted primary-wind material near periastron, thereby reducing its $T_{\text{eff}}$ (Soker 2003, 2005, 2007; Kashi & Soker 2009a, 2009b). Both of these possibilities require ambient densities above some critical level. Therefore, the unpredicted strength of $\text{N}\,\,\,\,\,\lambda$ multiplet 5 in 2014 strongly suggests that gas densities were lower than they were in previous events, consistent with a progressively decreasing primary wind (Mehner et al. 2010b, 2011b; Davidson 2012) and references therein). In any case it signals another physical difference between the 2014.6 event and its predecessors.

Additional HST/STIS results on $\eta$ Car’s 2014.6 event will be reported in subsequent papers.

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