The Altered State of η Carinae: HST’s Photometric Record 1998–2021

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ABSTRACT

Hubble Space Telescope photometry of η Carinae spans 23 years, including five spectroscopic events. The rapid brightening rate decreased after 2010, and the spectroscopic events in 2014 and 2020 had light curves different from their predecessors. Together with other indicators, these developments probably foretell the conclusion of η Car’s change of state.

1. Since the 1990’s, the central star of η Car has brightened by several magnitudes at UV-to-red wavelengths (Martin et al. 2006, 2010; Davidson et al. 1999) without much change in luminosity (Mehner et al. 2019). The most likely cause is a rapid decrease of circumstellar extinction, consistent with spectral changes that indicate a decline in the mass outflow rate (Mehner et al. 2010, 2012; Davidson et al. 2018). But the rate of brightening has diminished since 2010, and spectroscopic evidence of its companion star near periastron has also changed. These facts suggest that η Car has nearly recovered from its 1830-1860 Great Eruption. The Hubble Space Telescope (HST) has been essential for this problem (see below) but is not expected to produce significantly more data for this topic. Hence it is appropriate now to summarize the HST photometric record from 1998 to 2021.

For general information about η Car, see reviews by many authors in Davidson & Humphreys (2012), hereinafter “Revs2012.” This is the only supernova impostor that is close enough and recent enough to provide abundant clues to the post-eruptive structure. HST’s spatial resolution is essential, because ground-based data are severely contaminated by bright ejecta within 0.5″ of the star (Martin et al. 2006, 2010; Fig. 1 in Davidson et al. 2015). Over the past 23 years HST/WFPC2, HST/ACS, and HST/STIS have recorded the star’s apparent brightening. The synthetic STIS photometry, being immune to variable atmospheric seeing, is the most homogeneous time series ever done for η Car.

Figure 1 shows the main results expressed as STMAG values (see caption), with no attempt to correct for any extinction. F250W and F330W fluxes are equivalent to medium-bandwidth UV
photometry at $\lambda \approx 250$ nm and 330 nm, see Martin et al. (2006, 2010). They include absorption and emission lines. The blue 477 nm and red 690 nm fluxes, however, represent narrow continuum intervals with no substantial absorption or emission features (cf. figures in Davidson et al. 2015). They used a 0.1″ × 0.2″ sampling aperture, with crude throughput corrections of 1.5× at 477 nm and 1.7× at 690 nm. These correction factors are uncertain by perhaps ±10% because the central object is not a point source; but random errors in the brightness variations were usually less than 4%. The rapid up-and-down fluctuations in 2014 and 2020 appear to be real, not caused by imperfect pointing, since the recorded spacecraft jitter and other details were similar to the pre-2004 observations.

Two different phenomena are obvious in Fig. 1: progressive brightening, and brief minima at 5.54-year intervals. The brightening trend probably indicates a declining circumstellar extinction, due to a lessening rate of dust formation. According to standard temperature arguments, dust grains should form at $r \sim 100–300$ AU in the star’s mass outflow, in material that was ejected 1–5 years earlier. This explanation is consistent with spectroscopic evidence for a decreasing mass loss rate (Davidson et al. 2018 and many refs. therein), and no satisfactory alternative has been proposed. The apparent color measured from the star’s visual continuum has changed remarkably little, but this may be acceptable since $\eta$ Car notoriously forms very large dust grains (Revs2012). In any case, if we fit a smooth upper envelope to each light curve in Fig. 1, the brightening rate averaged 0.18 magn/y in 2000–2010 but only 0.08 magn/y in 2010–2020.

Abrupt temporary changes in 1998, 2003, 2009, 2014, and 2020 coincide with “spectroscopic events” when high excitation lines and other features in the spectrum react to the companion star’s periastron passages (Revs2012). The primary star was not eclipsed at those times. Deep minima in the 250 nm waveband are caused by a forest of Fe II UV absorption lines, and the 330 nm brightness is largely Balmer continuum, but otherwise the short-term brightness changes have not yet been explained. Size and time scales (several AU, several weeks) were far too small for dust formation. Conceivably the line-of-sight extinction might vary rapidly if dust destruction by the star’s radiation competes with grain formation, a subtle idea which we hope to discuss in a later paper. Alternatively, if the photosphere is located in an opaque outflow, it can be perturbed by tidal effects as well as varying photoionization by the O4-type secondary star.

Even without a clear theory, however, Fig. 1 shows that the 2014 and 2020 events differed from their predecessors. At wavelengths longer than 300 nm, the light curve for the 2003 and 2009 events resembled a well-defined square root symbol ($\sqrt{\cdot}$) preceded by relatively smooth two-year declines of roughly 0.3 magnitude and with a smooth rapid increasing flux after minimum. In 2014 and especially 2020, however, brightness spikes occurred several weeks before minimum and then the post-minimum brightening had a much smaller amplitude than before. (Details will appear in a later paper.) These differences arose soon after the observed spectroscopic change of state before 2009 or 2010 (Mehner et al. 2010; Davidson et al. 2015; Mehner et al. 2015).

Indeed, our HST/STIS data show that the 2020 event spectroscopically resembled its predecessor in 2014, but greatly differed from earlier instances (analysis currently in progress). Temporary shortages of ionizing UV, from the secondary, defined the periastron events before 2010, but not since. In the simplest hypothesis proposed so far, accretion from the primary wind quashed the secondary star’s EUV near periastron before 2010 (Kashi & Soker 2009 and earlier refs. cited therein), but later the declining primary wind density could not provide sufficient accretion (Davidson et al. 2015).
To some extent we can foresee η Car’s near-future appearance. Its continuum brightness has lately risen to $V \approx 4.8$, not including emission lines and the Homunculus ejecta-nebula. If the rate of brightening continues to follow the upper-envelope curve implied in Fig. 1, it will level off near $V \approx 4.0$ about two decades from now – close to the brightness that Halley recorded in 1677 (Innes & Kapteyn 1903; Frew 2004). Meanwhile, with declining gas and dust densities, the hot secondary star will begin to photoionize the Homunculus. It will then resemble a titanic planetary nebula with a surface brightness far more intense than any familiar planetary nebula.

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Figure 1. Apparent brightness of the central star measured by HST, expressed as $\text{STMAG} = -2.5 \log_{10}(f_{\lambda}/f_0)$ where $f_0 = 3.63 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Most points are synthesized from STIS calibrated spectra, while ACS and WFPC2 data fill the 2005–2009 hiatus in STIS coverage. For methods and details, see Martin et al. (2010).
Table 1. Table of the magnitudes plotted in Figure 1.

| Epoch   | 690 nm (mag) | 477 nm (mag) | F330W (mag) | F250W (mag) |
|---------|--------------|--------------|-------------|-------------|
| 1994.28 | 8.22         |              |             |             |
| 1997.43 | 7.77         |              |             |             |
| 1997.52 | 8.01         |              |             |             |
| 1998.00 | 7.44         |              |             |             |
| 1998.21 | 7.20         | 7.99         | 7.96        | 8.35        |
| 1999.14 | 6.63         | 7.377        | 7.12        | 7.39        |
| 1999.44 |              | 7.20         |             |             |
| 2000.77 | 6.56         |              |             |             |
| 2001.29 |              | 7.13         | 7.10        | 7.27        |
| 2001.42 |              |              | 6.85        |             |
| 2001.75 | 6.38         |              |             |             |
| 2002.05 | 6.50         | 7.17         | 6.91        | 7.05        |
| 2002.51 | 6.52         |              |             |             |
| 2002.51 | 6.58         | 7.19         | 6.91        | 6.97        |
| 2002.78 |              |              | 7.11        | 7.16        |
| 2002.78 |              |              | 7.16        |             |
| 2002.78 |              |              | 7.10        |             |
| 2002.96 | 6.60         |              |             |             |
| 2002.96 | 6.68         |              |             |             |
| 2003.12 | 6.54         |              | 7.09        | 7.08        |
| 2003.12 | 6.58         |              |             |             |
| 2003.12 | 6.57         | 7.24         | 7.09        | 7.08        |
| 2003.24 | 6.60         |              | 7.20        |             |
| 2003.34 | 6.52         |              |             |             |
| 2003.34 | 6.56         |              | 7.29        |             |
Table 1 (continued)

| Epoch | 690 nm (mag) | 477 nm (mag) | F330W (mag) | F250W (mag) |
|-------|--------------|--------------|-------------|-------------|
| 2003.37 | 7.04         | 7.16         |             |             |
| 2003.38 | 6.46         | 7.19         |             |             |
| 2003.41 | 6.38         | 7.13         | 6.92        | 7.06        |
| 2003.42 | 6.46         |              |             |             |
| 2003.42 | 6.37         |              |             |             |
| 2003.45 |              | 6.87         | 7.09        |             |
| 2003.47 | 6.31         | 6.88         | 7.20        |             |
| 2003.47 | 6.25         |              |             |             |
| 2003.47 | 6.30         |              |             |             |
| 2003.48 |              | 6.98         |             |             |
| 2003.51 | 6.39         | 6.95         |             |             |
| 2003.51 | 6.24         |              |             |             |
| 2003.51 | 6.29         |              |             |             |
| 2003.50 |              | 6.98         | 7.50        |             |
| 2003.58 | 6.32         | 6.94         | 7.01        | 7.62        |
| 2003.58 | 6.39         |              |             |             |
| 2003.58 | 6.33         |              |             |             |
| 2003.58 | 6.26         |              |             |             |
| 2003.60 |              | 6.88         |             |             |
| 2003.72 | 6.09         | 6.75         | 6.86        | 7.55        |
| 2003.72 | 6.13         |              |             |             |
| 2003.87 |              | 6.71         | 7.28        |             |
| 2003.87 |              | 6.77         |             |             |
| 2003.88 | 6.05         | 6.64         |             |             |
| 2003.88 | 6.11         |              |             |             |
| 2004.18 | 6.07         | 6.55         | 6.52        | 6.81        |
| 2004.18 | 5.99         |              |             |             |
| 2004.18 | 6.05         |              |             |             |
| 2004.93 |              | 6.24         | 6.46        |             |
| 2005.53 |              | 6.20         | 6.35        |             |
| 2005.85 |              | 6.00         | 6.27        |             |
| 2006.59 |              | 5.85         | 6.15        |             |
| 2007.06 | 6.09         | 6.23         |             |             |
| 2007.64 | 6.14         | 6.30         |             |             |

Table 1 continued on next page
### Table 1 (continued)

| Epoch  | 690 nm (mag) | 477 nm (mag) | F330W (mag) | F250W (mag) |
|--------|--------------|--------------|-------------|-------------|
| 2008.12| 6.26         | 6.33         | 6.26        | 6.30        |
| 2008.69| 6.29         | 6.32         | 6.27        | 6.30        |
| 2008.88| 6.26         | 6.30         | 6.27        | 6.30        |
| 2009.01| 6.07         | 6.21         | 6.07        | 6.21        |
| 2009.02| 6.04         | 6.44         | 6.04        | 6.44        |
| 2009.03| 6.04         | 6.63         | 6.04        | 6.63        |
| 2009.04| 6.12         | 6.96         | 6.12        | 6.96        |
| 2009.07| 6.40         | 7.26         | 6.40        | 7.26        |
| 2009.11| 6.39         | 7.30         | 6.39        | 7.30        |
| 2009.33| 5.89         | 6.47         | 5.89        | 6.47        |
| 2009.49| 5.58         |              |             |             |
| 2009.63| 5.26         | 5.55         | 5.63        | 6.12        |
| 2009.63| 5.20         |              |             |             |
| 2010.17| 5.30         | 5.50         | 5.55        | 5.89        |
| 2010.17| 5.23         |              |             |             |
| 2010.17| 5.49         |              |             |             |
| 2010.17| 5.38         |              |             |             |
| 2010.63| 5.29         | 5.39         | 5.35        | 5.65        |
| 2010.63| 5.17         |              |             |             |
| 2010.82| 5.42         |              |             |             |
| 2011.89| 5.25         | 5.43         |             |             |
| 2011.89| 5.17         |              |             |             |
| 2012.80| 5.22         | 5.35         |             |             |
| 2012.80| 5.14         |              |             |             |
| 2013.70| 5.21         | 5.43         | 5.38        | 5.69        |
| 2013.70| 5.19         |              |             |             |
| 2014.53| 4.87         | 5.15         | 5.07        | 5.31        |
| 2014.58| 4.82         | 5.01         | 5.08        | 5.76        |
| 2014.62| 5.11         | 5.33         | 5.61        | 6.49        |
| 2014.66| 5.06         | 5.34         | 5.53        | 6.35        |
| 2014.71| 5.06         | 5.29         | 5.46        | 6.18        |
| 2014.86| 5.05         | 5.29         | 5.29        | 5.76        |

Table 1 continued on next page
| Epoch    | 690 nm (mag) | 477 nm (mag) | F330W (mag) | F250W (mag) |
|----------|--------------|--------------|-------------|-------------|
| 2015.70  | 4.94         | 5.15         | 5.08        | 5.41        |
| 2018.14  | 4.77         | 4.84         | 4.87        | 5.18        |
| 2018.14  |              |              | 4.82        |             |
| 2020.05  | 4.77         | 5.04         | 4.79        | 4.96        |
| 2020.11  | 4.49         |              | 4.74        |             |
| 2020.12  |              | 4.64         | 5.40        |             |
| 2020.15  | 4.80         |              | 5.06        | 5.92        |
| 2021.01  | 4.73         | 4.84         | 4.65        | 4.94        |
| 2020.20  | 4.92         | 5.16         | 5.26        | 5.88        |
| 2020.22  | 4.87         | 5.14         | 5.10        | 5.72        |
| 2020.27  | 4.67         | 4.82         | 4.84        | 5.38        |
| 2020.35  | 4.83         | 5.02         | 4.97        | 5.31        |