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# A Revised Historical Light Curve of Eta Carinae and the Timing of Close Periastron Encounters

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## ABSTRACT

The historical light curve of the 19th century "Great Eruption" of $\eta$ Carinae provides a striking record of the violent instabilies encountered by the most massive stars. In this paper we report and analyze newly uncovered historical estimates of the visual brightness of $\eta$ Car during its eruption, and we correct some mistakes in the original record. The revised historical light curve looks substantially different from previous accounts: it shows two brief precursor eruptions in 1838 and 1843 that resemble modern supernova impostors, while the final brightening in December 1844 marks the time when $\eta$ Car reached its peak brightness. We consider the timing of brightening events as they pertain to the putative binary system in $\eta$ Car: (1) The brief 1838 and 1843 events rose to peak brightness within weeks of periastron passages if the pre-1845 orbital period is $\sim$5% shorter than at present due to the mass loss of the eruption. Each event lasted only $\sim$100 days. (2) The main brightening at the end of 1844 has no conceivable association with periastron, beginning suddenly more than 1.5 yr *after* periastron. It lasted $\sim$10 yr, with no obvious influence of periastron encounters during that time. (3) The 1890 eruption *began* to brighten at periastron, but took over 1 yr to reach maximum brightness and remained there for almost 10 yr. A second periastron passage midway through the 1890 eruption had no visible effect. While the evidence for a link between periastron encounters and the two brief precursor events is compelling, the differences between the three cases above make it difficult to explain all three phenomena with the same mechanism.

**Key words:** stars: individual (Eta Carinae) — stars: variables: other

## 1 INTRODUCTION

Among massive stars, the enigmatic object $\eta$ Carinae is simultaneously our most scrutinized case study and still among the most mysterious (Davidson & Humphreys 1997). Its bipolar Homunculus Nebula provides proof that massive stars can eject more than 10 $M_\odot$ (Smith et al. 2003b) in a single eruptive event and survive, while the present-day star and its putative binary companion present a number of enduring challenges.

The central mystery concerning $\eta$ Car is the cause of its spectacular "Great Eruption" in the mid-19th century (Davidson & Humphreys 1997), when it displayed erratic variability and briefly became the second brightest star in the sky despite its distance of $\sim$2.3 kpc (Smith 2006). Observing $\eta$ Carinae at the Cape of Good Hope in the early to mid-19th century, J.F.W. Herschel first described the "sudden flashes and relapses" of $\eta$ Argus, as it was called at the time, and remarked that this star was "fitfully variable to an astonishing extent" (Herschel 1847). At times it rivaled Sirius and Canopus in brightness, but with an orange-red colour. Innes (1903) compiled a list of known 19th-century observations and published the familiar lightcurve that has been often reproduced and supplemented by modern observations. The lightcurve was updated and corrected for scale errors by Frew (2004).

The complex Homunculus Nebula surrounding $\eta$ Car is a prototypical bipolar nebula, made famous in spectacular images made with the *Hubble Space Telescope* (*HST*) (e.g., Morse et al. 1998). It had long been suspected that the Homunculus originated from the Great Eruption (Gaviola 1950; Ringuelet 1958; Gehrz & Ney 1972), and proper-motion measurements of the expanding nebula later confirmed this, with estimated ejection dates of 1841 (Currie et al. 1996), 1844 (Smith & Gehrz 1998), and 1846–1848 (Morse et al. 2001). That the historical brightening event was ob-

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served and that we can now study its expanding ejecta make $\eta$ Car uniquely valuable.

Multiple eruptive episodes in $\eta$ Car point to an enduring phase of instability, marked by repeated sequences of outburst and recovery. In addition to the multiple peaks during the Great Eruption that we discuss in this paper, the star brightened again around 1890 when it ejected another bipolar nebula called the Little Homunculus (Ishibashi et al. 2003; Smith 2002, 2005). Additional nebulosity outside the Homunculus suggests major ancient eruptions 500–2000 yr ago (Walborn & Blanco 1988; Walborn et al. 1978; Smith & Morse 2004; Smith et al. 2005). The star has also been brightening in a non-steady way in modern times, with a jump in the 1940s (de Vaucouleurs & Eggen 1952) and again in the late 1990s (Davidson et al. 1999).

As our best studied example, $\eta$ Car serves as the prototype for a class of transient sources known variously as giant LBV eruptions, Type V supernovae (SNe), SN impostors, or $\eta$ Car analogs, which are thought to represent non-terminal eruptions of massive stars. Smith et al. (2010) recently provided a comprehensive study and review of this class of objects and related transient sources. Although $\eta$ Car is often held as the prototype for this class, it is hardly a typical case. Its multiple peaks and long duration are unusual, although not unique (Smith et al. 2010). Unlike all extragalactic SN impostors, its nebula can be studied in detail, and linking clues from the spatially resolved ejecta to the timing of brightening events is a critical piece of the puzzle. As such, here we aim to provide the definitive historical light curve of $\eta$ Car after reviewing all available historical documentation. A detailed discussion of each observation in the historical light curve of $\eta$ Carinae known at that time was given by Frew (2004). In this paper, we collect and present 51 previously unpublished estimates of the brightness of $\eta$ Car from C.P. Smyth and Thomas Maclear in the 1840s. In combination with the data from Frew (2004), this archival data set of new measurements has allowed the first detailed look at the photometric behavior of $\eta$ Carinae during critical points in its Great Eruption of 1837–1858. Including the new archival data, the character of the light curve is different from previous reports concerning the period of time centered around the peak of the Great Eruption, as we discuss below.

**Table 1.** Observations of $\eta$ Argus by Smyth and Maclear

| Observer | Date (year) | $m_v$ (mag) | err (mag) |
|---|---|---|---|
| Maclear, T. | 1842.213 | 1.0 | 0.4 |
| Maclear, T. | 1842.995 | 0.7 | 0.2 |
| Maclear, T. | 1842.997 | 0.2 | 0.2 |
| Maclear, T. | 1843.000 | 0.3 | 0.2 |
| Maclear, T. | 1843.005 | 0.3 | 0.2 |
| Maclear, T. | 1843.022 | 0.3 | 0.2 |
| Maclear, T. | 1843.027 | 0.3 | 0.2 |
| Maclear, T. | 1843.030 | 0.3 | 0.2 |
| Maclear, T. | 1843.033 | 0.3 | 0.2 |
| Maclear, T. | 1843.036 | 0.3 | 0.2 |
| Maclear, T. | 1843.038 | 0.3 | 0.2 |
| Smyth, C.P. | 1843.044 | 0.4 | 0.2 |
| Smyth, C.P. | 1843.047 | 0.4 | 0.2 |
| Smyth, C.P. | 1843.049 | 0.6 | 0.2 |
| Smyth, C.P. | 1843.079 | 0.4 | 0.2 |
| Smyth, C.P. | 1843.088 | 0.4 | 0.2 |
| Smyth, C.P. | 1843.112 | 0.4 | 0.2 |
| Smyth, C.P. | 1843.137 | 0.3 | 0.2 |
| Smyth, C.P. | 1843.164 | 0.3 | 0.2 |
| Smyth, C.P. | 1843.170 | 0.3 | 0.2 |
| Smyth, C.P. | 1843.175 | 0.2 | 0.2 |
| Smyth, C.P. | 1843.186 | 0.2 | 0.2 |
| Maclear, T. | 1843.192 | -0.8 | 0.3 |
| Smyth, C.P. | 1843.195 | -0.3 | 0.2 |
| Smyth, C.P. | 1843.197 | -0.5 | 0.2 |
| Maclear, T. | 1843.200 | -0.8 | 0.3 |
| Smyth, C.P. | 1843.205 | -0.4 | 0.2 |
| Maclear, T. | 1843.208 | -0.5 | 0.3 |
| Maclear, T. | 1843.211 | -0.5 | 0.3 |
| Smyth, C.P. | 1843.211 | -0.5 | 0.2 |
| Maclear, T. | 1843.214 | -0.5 | 0.3 |
| Maclear, T. | 1843.227 | -0.4 | 0.3 |
| Smyth, C.P. | 1843.230 | -0.4 | 0.2 |
| Maclear, T. | 1843.238 | -0.3 | 0.3 |
| Smyth, C.P. | 1843.244 | -0.5 | 0.3 |
| Leps | 1843.249 | -0.7 | 0.3 |
| Smyth, C.P. | 1843.260 | -0.8 | 0.3 |
| Smyth, C.P. | 1843.282 | -0.5 | 0.3 |
| Smyth, C.P. | 1843.299 | -0.8 | 0.3 |
| Smyth, C.P. | 1843.323 | -0.5 | 0.3 |
| Smyth, C.P. | 1843.326 | -0.3 | 0.2 |
| Smyth, C.P. | 1843.359 | -0.3 | 0.2 |
| Smyth, C.P. | 1843.389 | -0.1 | 0.2 |
| Smyth, C.P. | 1843.400 | -0.3 | 0.2 |
| Smyth, C.P. | 1843.411 | -0.3 | 0.2 |
| Maclear, T. | 1844.05 | 0.2 | 0.4 |
| Maclear, T. | 1844.71 | 0.2 | 0.3 |
| Smyth, C.P. | 1844.92 | -1.0 | 0.3 |
| Maclear, T. | 1844.96 | -1.0 | 0.3 |
| Smyth, C.P. | 1845.00 | -1.0 | 0.3 |
| Smyth, C.P. | 1845.79 | -0.6 | 0.3 |

## 2 OBSERVATIONS

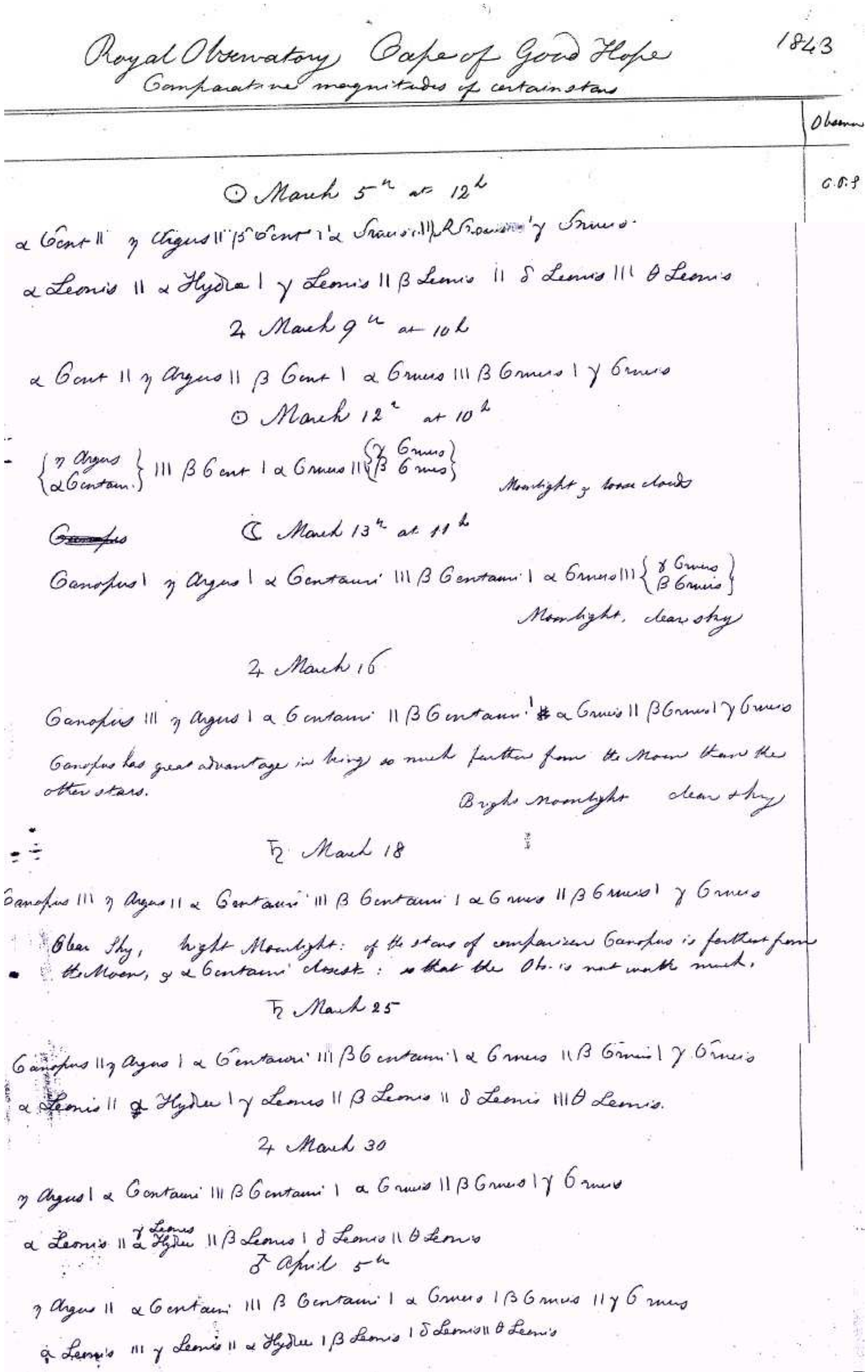
### 2.1 New Archival Data

The recent digital publication of the Royal Astronomical Society's Herschel Archives (Hoskin 2005) has been a boon to historians of astronomy. An examination of this resource has revealed an important new data set of $\eta$ Carinae's brightness in 1842–43, compiled by Charles Piazzi Smyth, which has now been fully reduced. This data set was not summarised by Herschel (1847), and it was not available at the time Frew (2004) compiled the historical light curve for $\eta$ Car. We also took the opportunity to examine the Royal Society Archives that were available on microfilm from the University Publications of America (1990). We perused more than 100 letters from Thomas Maclear and C.P. Smyth (both were observers at the Cape of Good Hope) to Sir John Herschel between 1838 and 1865, in order to search for any additional unpublished observations. The index of Crowe, Dyck & Kevin (1998) permitted an efficient search through the archival letters.

These new observations have cleared up some ambiguities and inconsistencies in the data summarised by Herschel (1847). The discrepancies pointed out by Müller & Hartwig (1918) have now been clarified after examining these original archival letters. We have reproduced a page from Smyth's (1843) manuscript as Figure 1 to illustrate the nature and scope of the source material.

### 2.2 Reduction Procedure

Following the procedure used in Frew (2004), all brightness estimates were reduced to the photopic visual system, with the zero point equivalent to Johnson $V$ for an A0 star. Almost all visual observers naturally use photopic (foveal) vision, with an effective wavelength, $\lambda_{\rm eff}$ of 5600 Å, only slightly redward of Johnson $V$ ($\lambda_{\rm eff}$ of 5450 Å). We note that



Royal Observatory Cape of Good Hope 1843
Comparative magnitudes of certain stars
Observer

☉ March 5th at 12h C.P.S.
α Cent || η Argus || β Cent | α Crucis || β Crucis | γ Crucis
α Leonis || α Hydræ | γ Leonis || β Leonis || δ Leonis ||| θ Leonis

♃ March 9th at 10h
α Cent || η Argus || β Cent | α Crucis ||| β Crucis | γ Crucis

☉ March 12th at 10h
{η Argus, α Centauri} ||| β Cent | α Crucis || {γ Crucis, β Crucis} Moonlight & loose clouds

~~Canopus~~ ☾ March 13th at 11h
Canopus | η Argus | α Centauri ||| β Centauri | α Crucis ||| {γ Crucis, β Crucis}
Moonlight, clear sky

♃ March 16
Canopus ||| η Argus | α Centauri || β Centauri | α Crucis || β Crucis | γ Crucis
Canopus has great advantage in being so much farther from the Moon than the other stars. Bright moonlight clear sky

♄ March 18
Canopus ||| η Argus || α Centauri ||| β Centauri | α Crucis || β Crucis | γ Crucis
Clear sky, bright Moonlight: of the stars of comparison Canopus is farthest from the Moon, & α Centauri closest: so that the Obs. is not worth much.

♄ March 25
Canopus || η Argus | α Centauri ||| β Centauri | α Crucis || β Crucis | γ Crucis
α Leonis || α Hydræ | γ Leonis || β Leonis || δ Leonis ||| θ Leonis.

♃ March 30
η Argus | α Centauri ||| β Centauri | α Crucis || β Crucis | γ Crucis
α Leonis || γ Leonis α Hydræ || β Leonis | δ Leonis || θ Leonis

♀ April 5th
η Argus || α Centauri ||| β Centauri | α Crucis | β Crucis || γ Crucis
α Leonis ||| γ Leonis || α Hydræ | β Leonis | δ Leonis || θ Leonis

**Figure 1.** Example presenting the original source material, showing the list of comparisons by C.P. Smyth (1843). Reproduced from the Herschel Archives of the Royal Astronomical Society.

scotopic (peripheral or rod) vision ($\lambda_{\rm eff} \simeq 5100$ Å) is considerably bluer than $V$, but is almost never used for stellar brightness estimation; see Schaefer (1996b) and Frew (2004) for a fuller discussion.

As before, $V$ magnitudes for the comparison stars were taken from the Lausanne photometric database (Mermilliod, Mermilliod, & Hauck 1997). No corrections for differential extinction were applied, as any factor is likely to be smaller than the adopted uncertainties of the visual magnitudes, derived from the interpolative method used.

The brightness descriptions of Smyth (1843) are in raw form and are equivalent to the traditional Argelander step method, where the difference in brightness of stars along a defined sequence is estimated. Smyth (1843) described his observing method as follows: "The stars are here put down in their order of lustre as estimated by the naked eye. The vertical strokes are intended to show the supposed number of grades between any two."

An extract from his manuscript is reproduced here as Figure 1, and we use his data to determine the visual magnitude of $\eta$ Carinae by interpolation. We illustrate our reduction method using Smyth's observations for March 18, 1843; the values in parentheses are the grades in brightness estimated by Smyth:

> Canopus (3) $\eta$ Argus (2) $\alpha$ Centauri (3) $\beta$ Centauri (1) $\alpha$ Crucis (2) $\beta$ Crucis (1) $\gamma$ Crucis

Utilising the comparison star magnitudes given in Table 3 of Frew (2004), it can be seen that $\eta$ Carinae had $m_{\rm V} = -0.5 \pm 0.2$ on this date. We note that on this night, the magnitude of each grade or step was not constant along the sequence, ranging from 0.09 mag between Canopus and $\alpha$ Centauri to 0.37 mag between $\beta$ and $\gamma$ Crucis. This is in fact typical of each night's data. Using all of the data from Smyth's manuscript leads us to adopt a mean step value of $\Delta$m = 0.24 $\pm$0.13 mag ($n$ = 160). On some nights (e.g., April 19, 1843) $\eta$ Carinae was brighter than the brightest comparison star, so the derived $\Delta$m value has been used to determine the magnitude of $\eta$ Carinae from extrapolation, with a larger uncertainty of 0.3 mag adopted as a result (see also Frew 2004).

Our derived visual magnitudes are denoted throughout by $m_{\rm V}$, and realistic uncertainties have been determined for each data point. For the majority of observers there will be only a small colour term between the visual system and Johnson $V$ for most naked-eye stars, but the difference between the $m_{\rm V}$ and $V$ systems for an emission-line star like $\eta$ Carinae might be substantial. We do not currently have enough information to quantify the effects of the emission-line spectrum during the eruption, but we note that any error is likely to be less than the generous adopted uncertainty of $\pm$0.2–0.5 mag.

The observations of Thomas Maclear are reduced in a similar way (Maclear 1842, 1843, 1844a,b). Maclear also used a step method, but his descriptions are more verbose and less precise. An example from March 24, 1843 is typical (Maclear 1843):

> "Decidedly not so brilliant as Canopus, brighter than $\alpha^{1,2}$ Centauri."

From this description, the concluded magnitude is $m_V$ = $-0.5$ $\pm$0.2. Another example is Maclear's observation of Mar 19, 1842. Maclear (1842) wrote:

> "...it was considerably less than Rigel, less than $\alpha$ Crucis & much greater than $\alpha$ Hydrae."

The qualitative description and large difference in brightness between Rigel ($\beta$ Ori, $V$ = 0.15) and $\alpha$ Hydrae ($V$ = 1.98) precludes an accurate estimate for $\eta$ Car in this case. An approximate magnitude of 1.0 $\pm$0.5 is inferred, since $\eta$ Car was somewhat closer in brightness to Rigel. The brightness of $\alpha$ Crucis sets an upper limit of $m_V$ = +0.75. Since a brightness 'grade' is $\sim$0.2 mag, we again conclude that $\eta$ Car had $m_V$ = 1.0 on this date. Importantly, this observation clarifies a discrepancy first noticed by Müller & Hartwig (1918). Herschel (1847) had mistakenly recorded the wrong date (Mar 19, 1843) for this observation when compiling his summary of the available data. The extensive series of observations recorded in the letter by Maclear (1843) includes no such date. This error by Herschel has led later workers to conclude that $\eta$ Car underwent a fast dip and recovery in early 1843 (e.g., Li et al. 2009). The light curve presented in Figures 2 and 3 corrects this error.

### 2.3 Results

Table 1 summarises the new $m_{\rm V}$ magnitudes derived here. The columns sequentially list the observer, UT date (as decimal year), the derived apparent visual magnitude, and the adopted error on the magnitude.

The first definitive observation of the variability of $\eta$ Car came from the explorer and naturalist William Burchell in 1827 (see Frew 2004, for a full account of Burchell's observations). Writing from Brazil on 1827 July 17, Burchell described it as "now of the first magnitude, or as large as $\alpha$ Crucis." (Herschel 1847).

The star was monitored between 1834 and 1838 by Sir John Herschel at the Cape of Good Hope (Herschel 1847). From 1834–37, the star was essentially constant, with $m_V$ = 1.2 $\pm$0.2 (Frew 2004). Assuming a distance of 2300 pc (Smith 2006), $(m-M)_0 = 11.8$ mag, $A_V = 1.4$ mag, $M_{\rm bol} = -12.0$ mag, and a bolometric correction of zero at maximum light (consistent with an F-type photosphere), we expect an apparent magnitude of $m_V \simeq 1.2$ out of eruption. The observed brightness before 1838.0 is very consistent with this estimate (see Figure 2).

The Great Eruption is widely considered to have begun at the close of 1838 when Herschel noted a rapid brightening of $\sim$1 mag over a period of less than two weeks (Frew 2004). The star then faded over the following months but unfortunately we have not recovered any observations between late 1838 and 1841, so there may have been other short-duration peaks in brightness that were missed, or the star may have faded considerably (but see below). In 1842, the magnitude was approximately as it was prior to the commencement of the Great Eruption; our estimate is $m_{\rm V}$ = 1.0 $\pm$0.4 mag. It was about 0.5 mag brighter in early 1843 when the brightness suddenly increased. The brightness peaked at about $m_{\rm V} = -0.8 \pm 0.2$ mag in late March 1843. The star again faded in subsequent weeks, and for most of 1844 it was constant at $m_{\rm V}$ = 0.2 $\pm$0.2 mag. At the close of 1844, the star again brightened, and by January 1845 had reached $m_{\rm V} = -1.0 \pm 0.3$ mag, which is brighter than Canopus ($V$ = $-0.74$).

As described by Frew (2004), there is good evidence for marked fluctuations in brightness (amplitude up to 1 mag on time scales of days to weeks) during the Great Eruption. The brightening event in Mar/Apr 1843 was remarkable (see observations of Maclear and C.P. Smyth described above), as was the brightening at the close of 1844. After 1846, the observed variations were superposed on a slow decline (Frew 2004), with fluctuations noted by Jacob (1849) and Gilliss (1855, 1856). Between 1846 and 1856, $\eta$ Car faded at an approximate rate of 0.1 mag yr$^{-1}$. It was still a star of the first magnitude at the close of 1857, before the rate of fading suddenly increased by 1859. This may be due to the onset of dust condensation from the stellar wind, or the Great Eruption may have ceased.

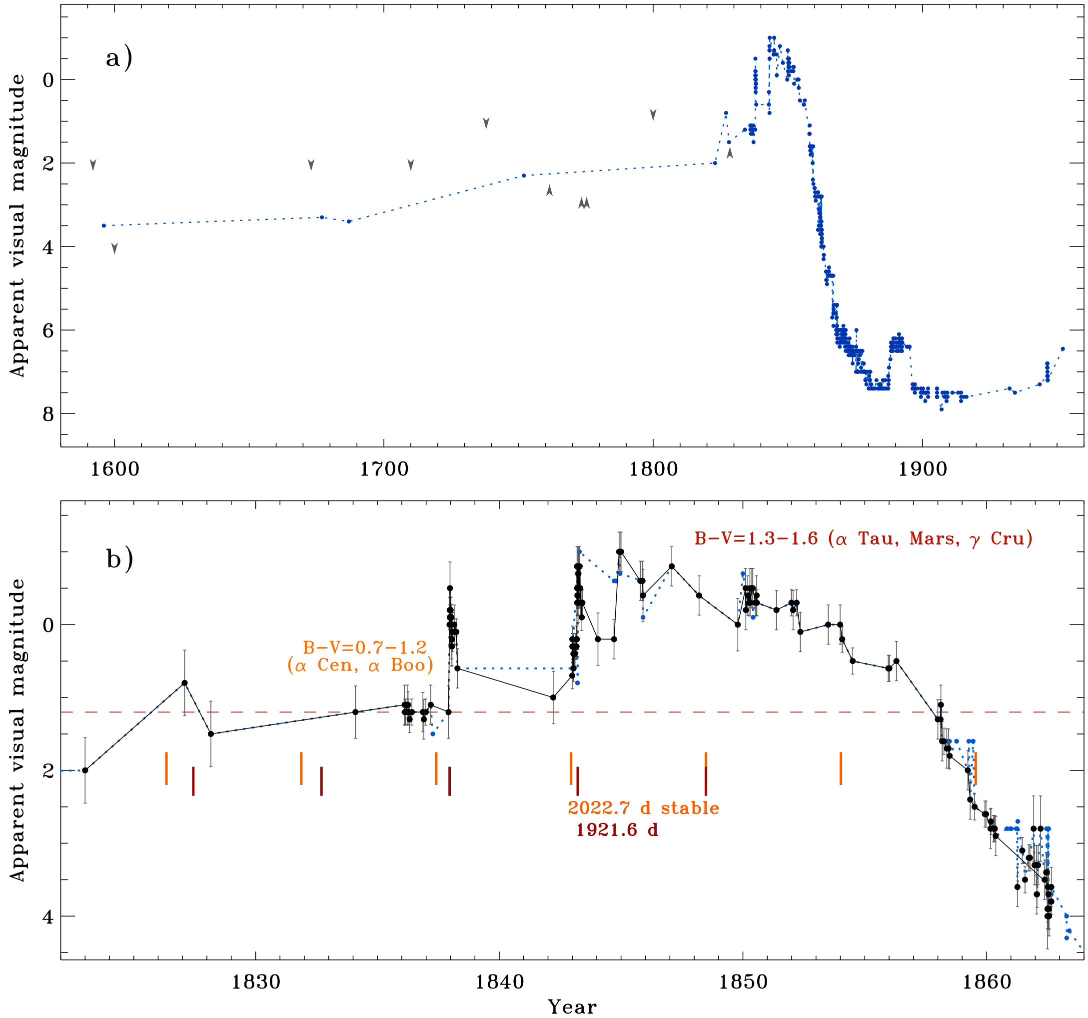



**Figure 2.** The historical light curve for $\eta$ Carinae. Panel (a) shows the full historical light curve from Frew (2004) in blue, with limits in gray. Panel (b) zooms in on the Great Eruption during 1822–1864. During this time interval, the previous light curve from Frew (2004) is in blue (points and dotted lines), while the revised light curve with new archival data that we discuss in this paper appears as black dots with error bars. Notes about the apparent color are listed above the light curve. The orange vertical dashes show predicted times of periastron passage if one simply extrapolates back from the currently-observed orbital cycle with a stable 2022.7 day period (Damineli et al. 2008), whereas the red hash marks are similar but with a shorter (95%) period before 1848. The dashed red horizontal line shows the quiescent magnitude of $\eta$ Car as it would appear with zero bolometric correction.

Nearly all contemporary reports during the Great Eruption describe $\eta$ Car as 'reddish' or 'ruddy' (e.g. Mackay 1843; Smyth 1845; Jacob 1847; Moesta 1856; Gilliss 1856; Abbott 1861; Tebbutt 1866), these observers sometimes making direct comparison of its colour with other stars, or even Mars. We have estimated an approximate $B-V$ colour index from the these direct comparisons, as summarised in Table 2. The nominal uncertainties on these visually estimated colours are approximately $\pm 0.3$ mag, following Schaefer (1996a). We stress that these values should not be taken as indictive of the true continuum temperature, as $\eta$ Car probably had very intense H$\alpha$ emission that would make it appear considerably redder to the naked eye than its actual (and unknown) $B-V$ colour index would otherwise indicate. Nevertheless, the values in Table 2 can be used as a *relative indicator* to show that Eta tended to redder colours during the laters stages of the Great Eruption. This was partly due to a changing H$\alpha$ equivalent width, but possibly also due to increasing circumstellar reddening due to dust condensation during the eruption (note that the grain condensation timescale is roughly 5–10 yr; see Smith 2010).

The gap in the light curve between 1838 and 1841 is unfortunate. Is it possible that other brief outbursts occurred during this period? While Maclear and Smyth were at the Cape of Good Hope after Herschel's departure in 1838, they were occupied by other astronomical pursuits. However, it is likely they would have noticed if Eta had brightened beyond zero magnitude, even though they were not to specifically monitor its brightness until 1842. Interestingly, the brief outburst in Mar/Apr 1843 was noticed by three non-professional observers, specifically Maclean, Leps and Mackay (see Leps 1843; Baily 1843; Mackay 1843). Apparently once $\eta$ Car appeared brighter than mag 1, even casual observers noticed it (see also Spreckley 1850). In this con-

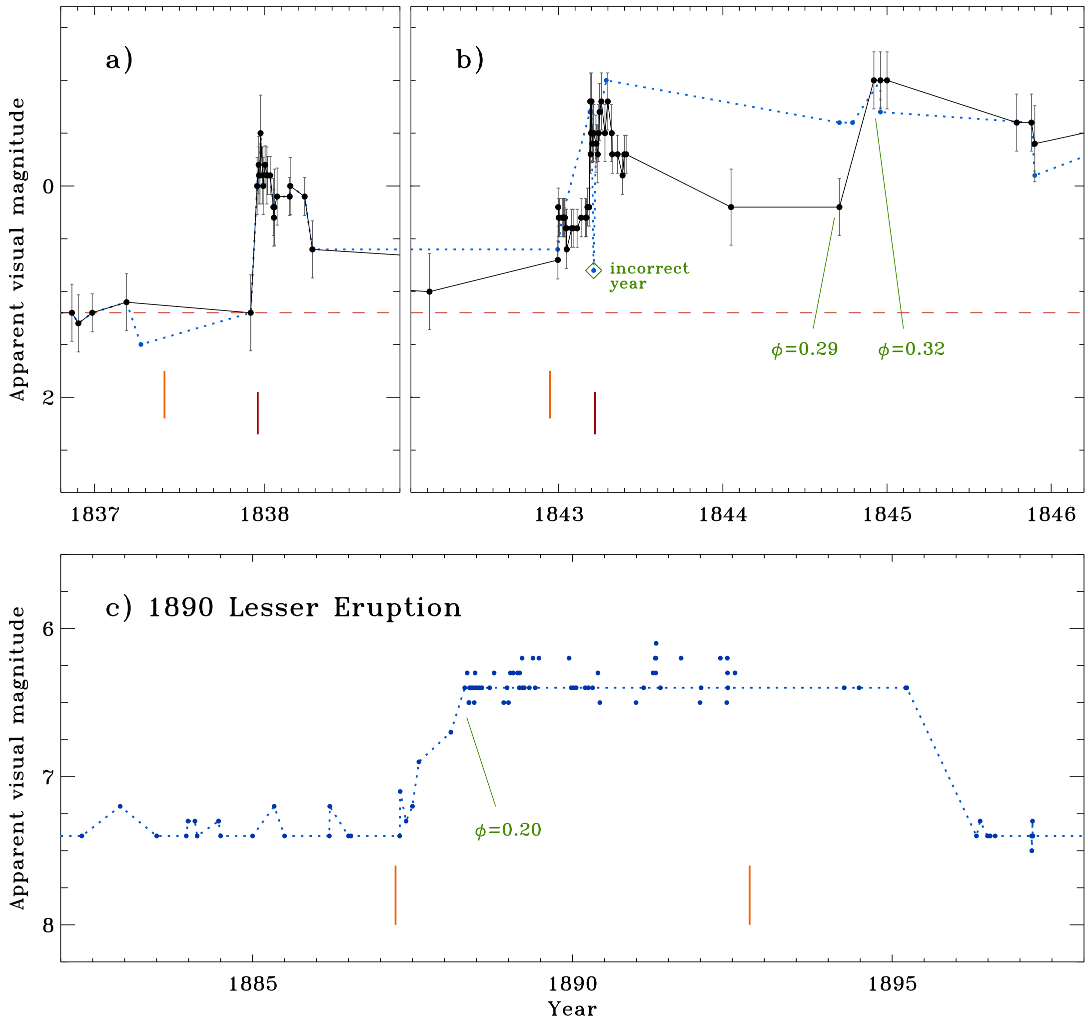



**Figure 3.** Same as Figure 2, but zooming in on the events in (a) 1837-1838, (b) 1843-1845, and (c) the so-called "Lesser Eruption" around 1890.

**Table 2.** Colour estimates of $\eta$ Carinae

| Observer | Year | Comparisons | $B - V$ | Reference |
|---|---|---|---|---|
| Herschel | 1834–38 | = $\alpha$ Cen, $\alpha$ Boo | 0.9: | Herschel (1847) |
| Herschel | 1837 Dec 19 | = $\alpha$ Cen | 0.7 | Evans et al. (1969) |
| Mackay | 1843 Mar | = $\alpha$ Boo | 1.2 | Mackay (1843) |
| Jacob | 1845.88 | redder than $\alpha$ Boo | >1.2 | Jacob (1847) |
| Gilliss | 1850 Feb 9 | = Mars | 1.4: | Gilliss (1856) |
| Gilliss | 1850 May 28 | = $\alpha$ Tau | 1.6: | Gilliss (1856) |
| Moesta | 1856 Jan-Aug | = Mars | 1.4: | Moesta (1856) |
| Abbott | 1858 Mar 6 | $\gamma$ Cru 'somewhat deeper' | 1.3: | Abbott (1861) |
| Abbott | 1858 Apr 8 | = $\gamma$ Cru | 1.6: | Abbott (1861) |

text, it is germane to mention that indigenous Australians also appear to have noted $\eta$ Car during its Great Eruption (Stanbridge 1861; Hamacher & Frew 2010), incorporating it into their skylore. From this we conclude that it seems unlikely that any significant brightenings between 1838 and 1842 were missed.

Finally, we revisit the observations of Kulczycky (1865), who observed $\eta$ Car in the 1860s to be brighter than other observers have recorded (Polcaro & Viotti 1993). Feast, Whitelock & Warner (1994) and Frew (2004) have cast doubt on the veracity of this report, based on contemporary data.

## 3 TIMING OF BRIGHTENING EPISODES

By modern standards, there is admittedly substantial uncertainty in the accuracy of reported visual magnitudes of historical accounts. They are subject not only to atmospheric conditions, transformations of photometric systems, and variation in the response of the eye from one observer to the next, but they are subject also to unusually red colors of $\eta$ Car that may change with time and probably extremely strong H$\alpha$ line emission. We have attempted to mitigate these factors in the historical light curve presented here, and have been appropriately generous with the uncertainty.

The *timing* of relative brightening/fading episodes are quite reliable, however. Rare mistakes of transcribed dates in letters notwithstanding (see above), the timing of reported events are generally accurate to better than a day. This provides a powerful tool to investigate the sequence of events during $\eta$ Car's Great Eruption, especially as it may pertain to the times of periastron passage in the putative $\sim$5 year orbit of the binary system.

Damineli (1996) discovered a repeating 5.52 year cycle of spectroscopic changes in $\eta$ Car that were linked to near-IR brightening events (Whitelock et al. 1994). Damineli et al. (1997) proposed that these cyclical events were associated with close periastron passages of a companion star in an eccentric orbit, and the detailed nature of the orbit and interacting winds has been a topic of spirited discussion and debate since then. Damineli (1996) also noted that three peaks during the Great Eruption seem to coincide roughly with expected times of periastron, but he only considered the sparsely sampled data in the light curve of Innes (1903). The better sampling in the data presented here and by Frew (2004) allows a closer investigation of the relative timing of eruptions and periastron passages.

Figure 2 shows expected times of periastron passage, extrapolating back in time from modern events, adopting a period of 2022.7 days and phase 0.0 at year 2003.49 (Damineli et al. 2008). The orange vertical hash marks adopt a stable 2022.7 day period throughout the Great Eruption. One can see that expected periastron passages do not coincide very well with the brief brightening episodes in 1838 and 1843. In particular, periastron occurs a few months before the sharp brightening in 1843 and about 6–7 months before the onset of the 1838 event; this can be seen more clearly in Figure 3, which conveys the same information but zooms-in on the time of the individual events. There may of course be some slight lag time between the exact time of periastron and the brightening, depending on exactly how the complicated interaction occurs physically, but at least *we should expect it to be roughly the same for both events* if they are related to binary interactions. This provides for an unsatisfying link between periastron passages and brightening events.

A critical point, however, is that the extrapolation above simply assumed a *constant* period throughout the eruption. This is certainly invalid. Observations of the Homunculus indicate that a very large mass of more than 12.5 $M_{\odot}$ was ejected in the Great Eruption (Smith et al. 2003b). Smith & Ferland (2007) note that the mass could be as high as 20 $M_{\odot}$ but probably not much more, so $\sim$15 $M_{\odot}$ is a favored value for the mass of the Homunculus[1]. As noted in the Introduction, we know that this mass was ejected during the Great Eruption because of proper motion measurements of the expanding nebula. The exact date of origin for the nebula is still debated; Currie et al. (1996) give 1841.2 ($\pm$0.8 years), although subsequent authors questioned this date and the optimistic uncertainty because this study used images taken in different filters, a short time baseline of only 2 years, and used abberated pre-COSTAR images with the WFPC camera on *HST*. Smith & Gehrz (1998) used a 50-year time baseline and estimated an ejection date of 1843.8 ($\pm$7 yr), while Morse et al. (2001) used corrected *HST*/WFPC2 images with a longer baseline than Currie et al., and derived dates of 1846–1848 in different imaging filters. It is not known if the ejection was a sudden singular event (as in a hydrodynamic explosion) or spread over several years (as in a wind or multiple ejections). We consider it likely, however, that the effective ejection date was around or after the main brightening event in December 1844, after which $\eta$ Car remained bright for years. This is only a working hypothesis. Renewed examination of *HST* images may be worthwhile since the revised light curve we have presented in this paper raises interesting questions about the exact time of ejection.

In any case, 15 $M_{\odot}$ is a huge amount of ejected mass. It is enough to significantly change the orbit, because mass loss must reduce the total system mass and gravity, and must therefore make the period longer after the mass is ejected (that longer post-eruption orbital period obviously corresponds to the cycle observed in modern times). The favored value for the current total stellar mass of the binary system is $\sim$130 $M_{\odot}$ (assuming a $\sim$100 $M_{\odot}$ primary and a 30 $M_{\odot}$ secondary), which is based on a number of factors including models of the X-ray light curve and constraints on the ionizing fluxes and luminosities of the two stars (see Parkin et al. 2009; Okazaki et al. 2008; Pittard & Corcoran 2002; Smith et al. 2004; Hillier et al. 2001; Corcoran 2005; Mehner et al. 2010). The ejected nebular mass of $\sim$15 $M_{\odot}$ is therefore $\sim$11% of the total remaining stellar mass. When this mass was still contained within the star, the gravity was stronger and the orbital period must have therefore been shorter, at roughly 90–95% of its present value.

The red hash marks in Figures 2 and 3 therefore show times of periastron passage if we reduce the period by about 5% before 1844 (to do this we aligned the 1848 periastron passage with the former value, and used the shorter period before that). This shorter period is 1921.6 days (5.26 years). With this adjusted period, it is quite interesting that the rather sudden beginnings of the brief 1838 (Figure 3a) and 1843 (Figure 3b) brightening events both coincide to within a few weeks with these adjusted times of periastron. It seems unlikely that this is a mere coincidence. There is also a brightening observed in 1827, which is poorly sampled in time, but is at least plausibly associated with another periastron passage.

An obvious conjecture, then, is that (somehow) these brief brightening events are actually *triggered* at times of periastron by the close passage of a companion, as speculated several times before (e.g., Innes 1914[2]; Gallagher 1989;

[1] Higher estimates of $\sim$40 $M_{\odot}$ based on submm emission from cold dust (Gomez et al. 2010) include dust outside the Homunculus, and possibly free-free emission from ionized gas, so 40 $M_{\odot}$ is a generous upper limit to the mass ejected in the Great Eruption.

[2] Amusingly, the suggestion by Innes that "the outbursts of light which have occurred in the past have been caused by periastral

Moreno et al. 1997 [in the context of HD 5980]; Iben 1999; Smith et al. 2003a; Frew 2004; Kashi & Soker 2010). One hypothetical way this might work is if tidal forces from the close companion push it past a stability threshhold (see Smith et al. 2003a), although the detailed physics of such an encounter have not been explored. A more violent encounter may also be possible (Smith 2011; in prep.). If true, there should also have been a similar event in 1831 that was unfortuntely not observed. A binary-induced mass ejection could in principle cause the very brief brightening events if it somehow leads to the ejection of an optically thick shell. It seems that theoretical work on the actual effects of grazing periastron passages that may induce mass ejection in already unstable stars would be an interesting theoretical pursuit in the context of eruptive transients.

What happened after 1843? A new result of the present study is that $\eta$ Carinae faded again after the peak of the 1843 event — making this a brief episode akin to the 1838 event — and it then rose again to its true peak in December 1844, after which it remained bright. If December 1844 really was the beginning of the main phase of the Great Eruption, then what caused it? It began suddenly about 1.5 yr *after* periastron at orbital phase $\phi \approx 0.3$, so *there is no periastron passage that can plausibly be associated with the main brightening event*, and subsequent periastron passages do not appear to induce comparable disturbances during the the rest of the Great Eruption. One must conclude, therefore, that close interactions with a companion at periastron are not the only mechanism that governs the physics of the Great Eruption, although these interactions may have pushed an already unstable star past a critical point.

As first pointed out by Frew (2004), the beginning of the smaller eruption around 1890 is also close to a periastron passage in 1887 (Figure 3c). (This assumes a stable period. We do not expect the period to have been altered by the 1890 eruption, since the total mass ejected was only of order 0.1–0.2 $M_{\odot}$; Smith 2005.) Curiously, though, the rise time and duration of the event are extremely different from the brief 1838 and 1843 episodes, which lasted only a few months. The delay between periastron passage and the time when the star rose to maximum brightness is over 1 year, as opposed to a few weeks in the previous events. The maximum of the 1890 eruption is actually achieved when the companion star is near its apastron distance. Additionally, the 1890 event lasted for about 9 years at roughly constant brightness (Figure 3c), and there is no indication of a major disturbance during the periastron event that occurs halfway through this eruption (although the data are quite sparse at the relevant time). For some unknown reason, the primary star did not relax after this event was initiated, and the 1892 periastron passage apparently had little influence. Altogether, the stark differences between the 1890 event and the earlier brief events in the Great Eruption raise doubt that the 1890 event was triggered by the same mechanism at a periastron passage; for such a model to work, we must understand why the 1890 event exhibited such different timescales.

grazings” was based on the first sighting of a faint “companion” of $\eta$ Car, which is now known to be a very distant dust condensation in the equatorial ejecta of the Homunculus (see Smith & Gehrz 1998). Nevertheless, it illustrates the attractiveness of binary systems to explain mysterious circumstances.

Independently, Kashi & Soker (2010) also investigated the possible relationship between the timing of periastron passages and brightening events, although they favored a very different scenario from the one we have outlined above. In an extended series of papers, Kashi & Soker (2010; and several references therein) have advocated a model wherein the secondary star accretes material from the primary wind at periastron, increasing the luminosity through accretion and driving a pair of jets that shape the Homunculus. One problem with such a model in the current context is that accretion of a substantial amount of mass by the companion will tend to contract the orbit and shorten the period, such that the orbital period would have been *longer* before the Great Eruption than it is now. As we have seen above, however, agreement between times of periastron and brightening events require the opposite – that the orbital period was about 5% *shorter* prior to the Great Eruption (Figures 2 and 3). Since mass accretion is expected to occur at periastron, this would appear to contradict a key prediction of the accretion model. To mitigate the shortening of the period due to accretion, Kashi & Soker (2010) adjusted the model so that the primary star ejects enough mass to compensate for the accretion and thereby makes the period longer instead, as we have suggested above, but with a much larger amount of mass and gravity involved. In order to adjust the period enough to match the timing of brightening events and periastron passages, the favored model of Kashi & Soker requires an ejected mass of 40 $M_{\odot}$, as well as present-day stellar masses of 200 and 80 $M_{\odot}$ for the primary and secondary, respectively. These exceed current observational estimates by factors of 2–3, and would imply an astonishing initial mass for the primary star of more than 300 $M_{\odot}$. It seems more straightforward to conclude that the evolution of the orbital period is dominated simply by the mass known to be lost from the system by the primary with conventional stellar parameters, as we proposed above.

## 4 QUALITATIVE COMPARISON WITH SUPERNOVA IMPOSTORS

A key result of the new historical magnitude estimates presented here is that the brightening in 1843 was a brief event, similar to the precursor brightening in 1838, after which the star faded on a timescale of a few months before finally surging to its peak at the end of 1844 when the extended brightening of the Great Eruption began. Not only is the brief 1843 event similar to the one in 1838, but it also resembles several examples of so-called “SN impostors” discovered in modern times in the course of SN searches. In the discussion below, we borrow from a more detailed discussion and comparison of SN impostors by Smith et al. (2010); the reader is referred to that paper for more details of the general phenomenon.

Figure 4 shows the revised light curves for the brief eruptions of $\eta$ Car in 1838 (Figure 4a) and 1843 (Figure 4b), shown on an absolute magnitude scale. These are compared to the $V$ or $R$ band light curves for several other SN impostors, taken from Smith et al. (2010).

The 1838 eruption has a peak magnitude of −13.5, most similar to N300-OT, and intermediate between SN 2002bu

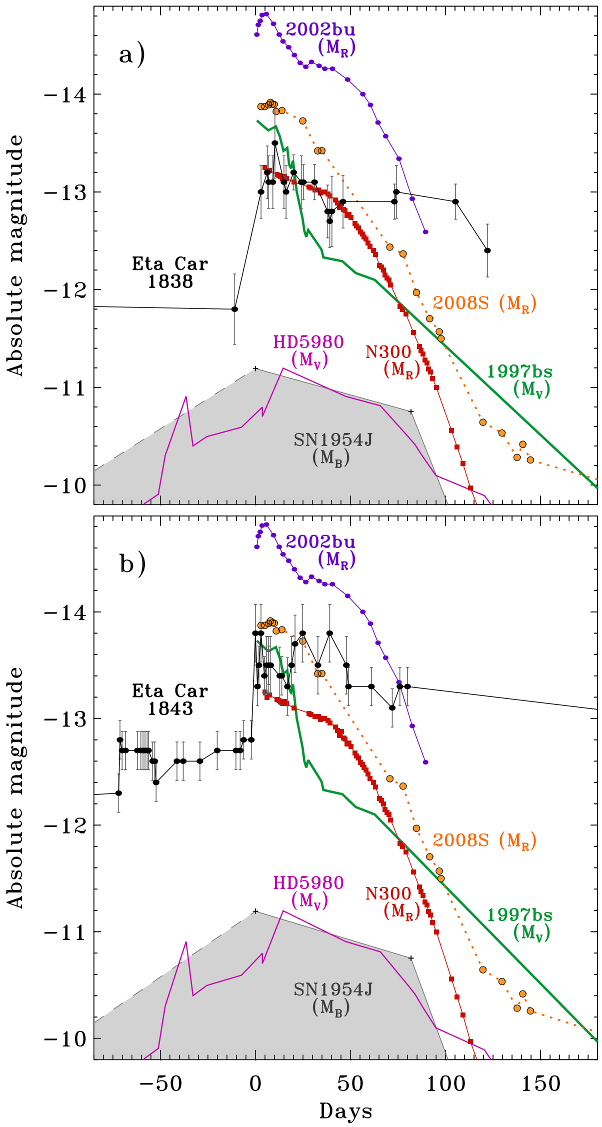



**Figure 4.** A comparison of the revised visual light curves of $\eta$ Car's brief eruptions in 1838 (a) and 1843 (b) to several SN impostors. This is adapted from Smith et al. (2010), where more details on each object can be found. The SN impostors are V12/SN 1954J in NGC 2403 (shaded gray; from Tammann & Sandage 1968), HD 5980 the SMC (magenta; this is the smoothed version of the light curve that appeared in Smith et al. 2010), SN 1997bs (green; from Van Dyk et al. 2000), SN 2002bu (purple; from Smith et al. 2010), SN 2008S (orange; from Smith et al. 2009), and the 2008 transient NGC 300-OT (red; from Bond et al. 2009).

(one of the most luminous) and SN 1954J or HD 5980. It appears to fade after 100-120 days. In Figure 4a, we only plot the light curve up to about day 120, because after that point there are no observations available until the beginning of the 1843 event several years later, so we do not know how quickly or how much it faded. Still, the rate of decline up to that point appears to be somewhat slower but similar to the other impostors shown. The 1843 event had a slightly more luminous peak magnitude of around −13.8, comparable to SN 1997bs or SN 2008S. It remained luminous for about 80 days, but the behavior after that is difficult to judge due to a lapse in the observational record. It seems likely that a primary difference between these brief precursor events of $\eta$ Car and the other SN impostors in Figure 4 is that $\eta$ Car did not fade very much afterward. This is probably because it was a more luminous star to begin with, and also because it was obviously not yet finished erupting by this point. The similarity of $\eta$ Car's brief events to the SN impostors is interesting, and may eventually provide insight to understand the physical parameters and causes of these extragalactic events. So far, two other extragalactic SN impostors have exhibited repeated eruptions: Pastorello et al. (2010) recently reported that SN 2000ch (LBV1 in NGC 3432; see Wagner et al. 2004; Smith et al. 2010) suffered at least three similar brief eruptive events in 2008 and 2009, and Drake et al. (2010) have just recently reported another outburst of SN 2009ip. Given that we have noted a clear connection between the brief eruptions and times of periastron in the binary system of $\eta$ Car, it is interesting to speculate that something similar may be occurring in these repeated events in SN 2000ch/LBV1 and SN 2009ip, and possibly in other SN impostors. Continued observations may reveal or rule-out true periodicity in the brightening events.

Following the 1843 event, $\eta$ Car faded to a magnitude that was somewhat brighter than its expected quiescent magnitude (Figure 2) for about a year. It then rebrightened dramatically in December 1844, finally reaching its peak absolute magnitude at the start of 1845, and remaining luminous for a decade thereafter. This behavior is unlike any of the SN impostors shown in Figure 4, but there are other SN impostors or LBV giant eruptions that evolve more slowly and stay bright for years. Some well-known examples are P Cygni, UGC 2773-OT, and V1 in NGC2366 (see Smith et al. 2010 for more details). We will discuss the historical light curve of P Cygni in an upcoming paper that is in preparation. The cause of these longer-duration giant eruptions is still unknown, and it is not clear if they represent the same phenomenon as the brief SN impostor events. Studies of a larger number of these events over longer time intervals are needed.

## 5 CONCLUSIONS

In this paper, we have revisited the historical 19th century light curve of $\eta$ Carinae, based on 51 newly uncovered historical estimates of its apparent brightness made at critical times near the peak of its Great Eruption. These new estimates correct some previous mistakes and misconceptions about the light curve, hopefully providing a definitive historical record, and lead us to several main conclusions:

1. The light curve clearly shows two brief (∼100 day) peaks during the time leading up to the eruption, in 1838 and 1843. $\eta$ Car then faded by ∼1 mag after the 1843 event, before rebrightening to its true maximum brightness in December 1844. This last brightening in late 1844 probably marks the true beginning of the Great Eruption, which lasted until about 1858 when the star faded below its quiescent luminosity.

2. The brief 1838 and 1843 events do not coincide with times of periastron in the eccentric binary system if we simply extrapolate the currently observed orbital period back to

that time. However, if the pre-1844 orbital period is *shorter* by ∼5% — as it should be due to the considerable mass lost from the system — then the peaks of the brief 1838 and 1843 events both occur within weeks of periastron. We therefore speculate that these brief brightening events are somehow triggered at periastron.

3. A possible brightening may also be associated with an expected time of periastron in 1827, but the available data are too sparsely sampled to draw a more firm conclusion.

4. The final rise to peak in late 1844 occurred at orbital phase $\phi \approx 0.3$, more than 1.5 yr after periastron, so we conclude that this final event is not triggered by the same mechanism as the previous brief outbursts. Similarly, although the *beginning* of the lesser 1890 outburst seemed to occur around periastron, it took over a year to brighten and reached its maximum brightness when the system was near apastron, remaining bright for a decade thereafter. Furthermore, periastron events that should have occurred halfway through the ∼10 yr duration of both the Great Eruption and the 1890 eruption seemed to have little effect. Thus, periastron encounters are not likely to be directly responsible for these two long-duration events.

5. The light curves of the brief 1838 and 1843 events of $\eta$ Car are very similar to several other SN impostors. We speculate that SN 2000ch, SN 2009ip, and perhaps other brief outbursts may be related to similar periastron encounters like the 1838 and 1843 eruptions of $\eta$ Car. This will be discussed more fully in a separate paper (Smith 2011, in prep.).

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## REFERENCES


Abbott, F. 1861, MNRAS, 21, 230

Baily, F. 1843, Letter to J.F.W. Herschel, dated Aug 24. Royal Astronomical Society Herschel Archives, Manuscript, JH 3/1.1.1 [5570]

Bennett, J.A. 1977, Mem. RAS, 85, 53

Bond, H., et al. 2009, ApJ, 695, L154

Corcoran, M.F. 2005, AJ, 129, 2018

Crowe, M.J., Dyck, D.R., Kevin, J.R. (eds), 1998, A Calendar of the Correspondence of Sir John Herschel (Cambridge: Cambridge University Press)

Currie, D.G., et al. 1996, AJ, 112, 1115

Damineli, A. 1996, ApJ, 460, L49

Damineli, A., et al. 2008, MNRAS, 384, 1649

Davidson, K., & Humphreys, R.M. 1997, ARAA, 35, 1

Davidson, K., et al. 1999, AJ, 118, 1777

Drake, A., Prieto, J.L., Djorgovski, S.G., Mahabal, A.A., Graham, M.J., Williams, R., McNaught, R.H., Catelan, M., Christensen, E., Beshore, E.C., Larson, S.M., & Howerton, S. 2010, ATel, 2897, 1

de Vaucouleurs, G., & Eggen, O.J. 1952, PASP, 64, 185

Evans, D.S., Deeming, T.J., Evans, B.H., & Goldfarb, S. 1969, Herschel at the Cape: Diaries & Correspondence of Sir John Herschel 1834–1838 (Balkema: Cape Town)

Feast, M.W., Whitelock, P.A. & Warner, B. 1994, A&A, 285, 199

Frew, D.J. 2004, JAD, 10, 6

Gallagher, J.S. 1989, in Physics of Luminous Blue Variables, eds. K. Davidson, A.F.J. Moffat, & H.J.G.L.M. Lamers (Dordrecht: Kluwer), 185

Gaviola, E. 1950, ApJ, 111, 408

Gehrz, R.D., & Ney, E.P. 1972, Sky & Tel., 44, 4

Gilliss, J.M. 1855, The U.S. Naval Astronomical Expedition to the Southern Hemisphere, during the years 1849–50,–51,–52, Vols. I & II (Washington)

Gilliss, J.M. 1856, MNRAS, 16, 133

Gomez, H.L., Vlahakis, C., Stretch, C.M., Dunne, L., Eales, S.A., Beelen, A., Gomez, E.L., & Edmunds M.G. 2010, MNRAS, 401, L48

Hamacher, D.W., & Frew, D.J. 2010, JAHH, submitted

Herschel, J.F.W., 1847, Results of Astronomical Observations Made ... at the Cape of Good Hope (London: Smith, Elder & Co.)

Hillier, D.J., et al. 2006, ApJ, 642, 1098

Hoskin, M. 2005, JHA, 36, 248

Humphreys, R.M. & Davidson K. 1994, PASP, 106, 1025

Humphreys, R.M., Davidson, K., & Smith, N. 1999, PASP 111, 1124

Iben, I. 1999, in Eta Carinae at the Millenium, eds. J.A. Morse et al. (San Francisco: ASP), 367

Innes, R.T.A. 1903, Ann. Cape Obs., 38, 333

Innes, R.T.A. 1914, MNRAS, 74, 697

Ishibashi, K., Corcoran, M.F., Davidson, K., Swank, J.H., Petre, R., Drake, S.A., Damineli, A., & White, S. 1999, ApJ, 524, 983

Jacob, W.S. 1847, MemRAS, 16, 311

Jacob, W.S. 1849, MemRAS, 17, 79

Kashi, A., & Soker, N. 2009, Eprint, arXiv:0912.1439

Kulczycky, A. 1865, Connaissance des temps (for 1867), Additions p. 42

Leps, [M.] 1843, Comptes Rendus, 17, 262

Li, W., Smith N., Miller, A.A., & Filippenko, A.V. 2009, ATel, 2212, 1

Mackay, W.S. 1843, MNRAS, 6, 8

Maclear, T. 1842, Letter to J.F.W. Herschel, dated Mar 28. Royal Society Archives, Manuscript RS:HS 12.131 [5140]

Maclear, T. 1843, Letter to J.F.W. Herschel, dated Dec 17. Royal Astronomical Society Herschel Archives, Manuscript JH 3/1.1.2 [5670]

Maclear, T. 1844a, Letter to J.F.W. Herschel, dated Sep 17. Royal Astronomical Society Herschel Archives, Manuscript JH 3/1.1.13 [5936]

Maclear, T. 1844b, Letter to J.F.W. Herschel, dated Nov 2. Royal Society Archives Manuscript RS:HS 12.132 [6005]

Mehner, A., Davidson, K., Ferland, G.J., & Humphreys, R.M. 2010, ApJ, 710, 729

Mermilliod, J.-C., Mermilliod, M., Hauck, B., 1997, A&AS, 124, 349

Moesta, C.W. 1856, AN, 44, 337

Moreno, E., Georgiev, L., & Koenigsberger, G. 1997, in Luminous Blue Variables: Massive Stars in Transition, eds. A. Nota & H.J.G.L.M. Lamers (San Francisco: ASP), 152

Morse, J.A., et al. 1998, AJ, 116, 2443

Morse, J.A., Kellogg, J.R., Bally, J., Davidson, K., Balick, B., & Ebbets, D. 2001, ApJ, 548, L207

Müller, G., Hartwig, E., 1918, Geschichte und Literatur des Lichtwechsels..., Band 1. Leipzig

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

Pastorello, A., et al. 2010, arXiv:1006.0504

Pittard, J.M., & Corcoran, M.F. 2002, A&A, 383, 636

Polcaro, V.F. & Viotti, R. 1993, A&A 274, 807

Ringuelet, A.E. 1958, Z. Astrophys., 46, 276

Schaefer, B. 1996a, ApJ, 459, 438
Schaefer, B. 1996b, AJ, 111, 1668
Smith, N. 2002, MNRAS, 337, 1252
Smith, N. 2005, MNRAS, 357, 1330
Smith, N. 2006, ApJ, 644, 1151
Smith, N. 2010, MNRAS, 402, 145
Smith, N., & Ferland, G.J. 2007, ApJ, 655, 911
Smith, N., & Gehrz, R.D. 1998, AJ, 116, 823
Smith, N., & Morse, J.A. 2004, ApJ, 605, 854
Smith, N., Davidson, K., Gull, T.R., Ishibashi, K., & Hillier, D.J. 2003a, ApJ, 586, 432
Smith, N., Gehrz, R.D., Hinz, P.M., Hoffmann, W.F., Hora, J.L., Mamajek, E.E., & Meyer, M.R. 2003b, AJ, 125, 1458
Smith, N., Morse, J.A., & Bally, J. 2005, AJ, 130, 1778
Smith, N., Morse, J.A., Collins, N., & Gull, T.R. 2004, ApJ, 610, L105
Smith, N., et al. 2009, ApJ, 697, L49
Smith, N., et al. 2010, MNRAS, submitted (arXiv:1010.3718)
Smyth, C.P. 1843, Royal Astronomical Society Herschel Archives, Manuscript, JH 3/1.1.10
Smyth, C.P. 1845, MNRAS, 6, 242
Spreckley, G.S. 1850, MNRAS, 10, 142
Stanbridge, W.M. 1861, Trans. Ethnological Soc. London, 1, 286
Tammann, G. A., & Sandage, A. 1968, ApJ, 151, 825
Tebbutt, J. 1866, MNRAS, 26, 83
Van Dyk, S.D., Peng, C.Y., King, J.Y., Filippenko, A.V., Treffers, R.R., Li, W., & Richmond, M.W. 2000, PASP, 112, 1532
Walborn, N.R., & Blanco, B.M. 1988, PASP, 100, 797
Walborn, N.R., Blanco, B.M., & Thackeray, A.D. 1978, ApJ, 219, 498
Whitelock, P.A., Feast, M.W., Koen, C., Roberts, G., & Carter, B.S. 1994, MNRAS, 270, 364