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 η Carinae provides a striking record of the violent instabilities encountered by massive stars. In this paper, we report and analyse newly uncovered historical estimates of the visual brightness of η 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 1844 December marks the time when η Car reached its peak brightness. We consider the timing of brightening events as they pertain to the binary system in η Car. (1) The brief 1838 and 1843 events rose to peak brightness within weeks of periastron passages if the pre-1845 orbital period was ~5 per cent shorter than that at present due to the mass-loss of the eruption. Each event lasted only ~100 d. (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 ~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 mid-way 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: instabilities – binaries: close – stars: individual: Eta Carinae – stars: massive – stars: mass-loss.

1 INTRODUCTION
Among massive stars, the enigmatic object η Carinae is simultaneously our most scrutinized case study and still one of the most mysterious (Davidson & Humphreys 1997). Its nebula provides proof that massive stars can eject more than 10 M⊙ (Smith et al. 2003b) in a single eruptive event and survive, while the present-day star and its binary companion present enduring challenges.

The central mystery concerning η 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 ~2.3 kpc (Smith 2006). Observing η 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 η Argus, as it was called at the time, and remarked that this star was ‘futarily variable to an astonishing extent’ (Herschel 1847). At times it rivalled 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 light curve that has been often reproduced (e.g. Humphreys & Davidson 1994; Humphreys, Davidson & Smith 1999). The light curve was updated and corrected for scale errors by Frew (2004).

The Homunculus nebula surrounding η Car is a prototypical bipolar nebula, made famous in spectacular images from 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 1846–48 (Morse et al. 2001). The observed historical brightening event and its expanding ejecta make η Car uniquely valuable.

Multiple eruptive episodes 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 & Thackeray 1978; Walborn & Blanco 1988; Smith & Morse 2004; Smith, Morse & Bally 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, η Car serves as the prototype for a class of transient sources known variously as giant luminous blue variable (LBV) eruptions, Type V supernovae (SNe), SN impostors or η Car analogues, which are thought to represent non-terminal eruptions of massive stars. Smith et al. (2011) recently provided a comprehensive study and review of this class of objects. Although η Car is often held as the prototype for this class, it is hardly a typical case. Its multiple peaks and long duration are unusual (Smith et al. 2011). 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. Here we aim to provide the definitive historical light curve of η Car after reviewing all available historical documentation. A detailed discussion of each observation in the historical light curve of η 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 η 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 behaviour of η Carinae during critical points in its Great Eruption of 1837–58. Including the new archival data, the character of the light curve is different from previous reports concerning the period of time centred around the peak of the Great Eruption, as we discuss below.

2 OBSERVATIONS

2.1 New archival data

The recent digital publication of the Royal Astronomical Society’s Herschel Archives has been a boon to historians of astronomy (Royal Astronomical Society 2004; see also Bennett 1977; Hoskin 2005). An examination of this resource has revealed an important. new data set of η Carinae’s brightness in 1842–43, compiled by Smyth (1843), which has now been fully reduced. This data set was not summarized by Herschel (1847), and it was not available at the time Frew (2004) compiled the historical light curve for η Car. We also took the opportunity to examine relevant letters in the Royal Society Archives that were available on microfilm from the University Publications of America (Crowe 1990; Kesaris 1990).

We perused 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 et al. (1998) permitted an efficient search through the archival letters (see Table 1).

These new observations have cleared up some ambiguities and inconsistencies in the data summarized by Herschel (1847). The discrepancies pointed out by Müller & Hartwig (1918) have now been clarified after examining these original archival letters, explained further in Section 2.2. We have reproduced a page from the manuscript of Smyth (1843) as Fig. 1 to illustrate the nature and scope of the source material.

2.2 Reduction procedure

Following the procedure used by 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 λ_eff of 5600 Å, only slightly redward of Johnson V (λ_eff of 5450 Å). We note that scotopic (peripheral or rod) vision (λ_eff ≈ 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 data base (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 the 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 Fig. 1, and we use his data to determine the visual magnitude of η Carinae by interpolation. We illustrate our reduction method using Smyth’s observations for 1843 March 18; the values in parentheses are the grades in brightness estimated by Smyth:

| Star       | Brightness Description |
|------------|------------------------|
| Canopus    | 3                      |
| Α Argus    | 2                      |
| Centauri   | 3                      |
| Β Centauri | 1                      |
| Α Crucis   | 2                      |
| Β Crucis   | 1                      |

Utilizing the comparison star magnitudes given in table 3 of Frew (2004; see also Mermilliod et al. 1997), it can be seen that η Carinae had m_V = −0.5 ± 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 α Centauri to 0.37 mag between β and γ 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 Δm = 0.24 ± 0.13 mag (n = 160). On some nights (e.g. 1843 April 19) η Carinae was brighter than the brightest comparison star, so the derived Δm value has been used to determine the magnitude of η 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_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_V and V systems for an emission-line

| Reference Date | Archive | CDK | Other |
|----------------|---------|-----|-------|
| Maclear (1838a) 1838-1-24 RS:HS 12.183 | 3626 | WW84 |
| Maclear (1838b) 1838-1-28 RS:HS 12.100 | 3630 | WW84 |
| Maclear (1842) 1842-3-28 RS:HS 12.131 | 5140 | – |
| Maclear (1843) 1843-12-17 RAS:JH 3/1.1.2 | 5670 | – |
| Maclear (1844a) 1844-9-17 RAS:JH 3/1.1.3 | 5936 | – |
| Maclear (1844b) 1844-11-2 RS:HS 12.132 | 6005 | – |
| Maclear (1860) 1860-10-21 RS:HS 12.165 | 11449 | FFW94 |
| Maclear (1863) 1863-5-17 RS:HS 12.168 | 12230 | FFW94 |
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 1843 March 24 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 1842 Mar 19. 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 (β Ori, $V = 0.15$) and α Hydrae (V = 1.98) preclude an accurate estimate for η Car in this case. An approximate magnitude of $1.0 \pm 0.5$ is inferred, since η Car was somewhat closer in brightness to Rigel. The brightness of α Crucis sets an upper limit of $m_V = +0.75$. Since a brightness ‘grade’ is $\sim 0.2$ mag, we again conclude that η Car had $m_V = 1.0$ on this date. Importantly, this observation clarifies a discrepancy first noted by Müller & Hartwig (1918). Herschel (1847) had mistakenly recorded the wrong date (1843 Mar 19) for this observation when compiling his summary of the available data. The summary table in Herschel (1847, p. 36) records the observation as being made on 1842 Mar 19, but the specific wording in the text of Herschel (1847, p. 35) led Müller & Hartwig (1918) and Frew (2004) to assume that the year was in fact 1843. Furthermore, the extensive series of observations recorded in the letter by Maclear (1843) includes no such date. This error by Herschel led later workers to conclude that η Car underwent a fast dip and recovery in early 1843 (e.g. Li et al. 2009). The light curve presented in Figs 2 and 3 corrects this error.

Some of the other data have been modified from Frew (2004). In some cases, the descriptions of Herschel (1847) were found to be a brief summary of the data contained in the original letters. The new, original estimates of Maclear and Smyth have allowed a greater density of points to be plotted during the crucial early stages of the 1843 brightening (see Table 2). Another important revision in the light curve concerns the brightness during 1844 (see panel b of Fig. 3). Herschel (1847) had only partially quoted from Maclear’s description, leading Frew (2004) to incorrectly assume that η Car was marginally (‘scarcely’) fainter than Canopus in 1844 September, with an estimated magnitude of $m_V = -0.6$. However, looking at the original text in Maclear (1844a) shows clearly that he estimated η Car as mid-way in brightness between α¹,² and β Centauri (i.e. $m_V = +0.2 \pm 0.4$). Maclear further stated that ‘the star is and has been for 8 months stationary, & scarcely as bright as Canopus.’ We can hence infer that the star was apparently constant in brightness at $m_V = 0.2 \pm 0.4$ from $\sim 1844.05$ to 1844.71.

### 2.3 Results

Table 2 summarizes the new $m_V$ magnitudes derived here. The columns sequentially list the observer, UT date (as decimal year), the derived apparent visual magnitude, the adopted error on the magnitude and the reference from which the magnitude is derived. If the interval between comparison star magnitudes is large, then the adopted uncertainty on the magnitude of η Car will be greater than the nominal uncertainty of $\pm 0.2$ mag. In these cases, the uncertainty

![Figure 2](https://example.com/figure2.png)

**Figure 2.** The historical light curve for η Carinae. Panel (a) shows the full historical light curve from Frew (2004) in blue, with limits in grey arrows. Panel (b) zooms in on the Great Eruption during 1822–64. 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 colour 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 d period (Damineli et al. 2008), whereas the red hash marks are similar but with a shorter (95 per cent) period before 1848. The dashed red horizontal line shows the quiescent magnitude of η Car as it would appear with zero bolometric correction.
is usually taken to be half the difference between the comparison star magnitudes. For ease of use, we have included all observations between 1842 and 1845 in Table 2, and these data supersede the magnitudes presented by Frew (2004). For observations before and after this period, the reader should consult the tabulated data in Frew (2004).

The first definitive observation of the variability of η 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 α 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 to 1837, 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, $M_{bol} = -12.0$ mag and a bolometric correction of zero at the 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 Fig. 2).

The Great Eruption is widely considered to have begun at the close of 1838 when Herschel noted a rapid brightening of ~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 $m_V = 1.0 \pm 0.4$ mag. It was about 0.5 mag brighter in early 1843 when the brightness suddenly increased. The brightness peaked at about $m_V = -0.8 \pm 0.2$ mag in late 1843 March. The star again faded in subsequent weeks, and for most of 1844 it was constant at $m_V = 0.2 \pm 0.2$ mag. At the close of 1844, the star again brightened, and by 1845 January it had reached $m_V = -1.0 \pm 0.3$ 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 1843 March/April was remarkable (see observations of Maclear and 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, η 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.

Nearly all contemporary reports during the Great Eruption describe η Car as 'reddish' or 'ruddy' (e.g. Mackay 1843; Smyth 1845; Jacob 1847; Gilliss 1855, 1856; Moesta 1856; Abbott 1861; Tebbutt 1866), these observers sometimes make direct comparison...
of its colour with other stars, or even Mars. We have estimated an approximate $B - V$ colour index from these direct comparisons, as summarized in Table 3. 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 indicative 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 3 can be used as a relative indicator to show that $\eta$ Car tended to redder colours during the later stages of the Great Eruption. This may have been 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 time-scale 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 that 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 1843 March/April was noticed by three non-professional observers (see Baily 1843; Leps 1843; Mackay 1843). Apparently once $\eta$ Car appeared brighter than 1 mag; even casual observers noticed it (see also Spreckley 1850). In this context, it is germane to mention that indigenous Australians also appear to have noted $\eta$ Car during its Great Eruption (Stanbridge 1858, 1961; Hamacher & Frew 2010), incorporating $\eta$ Car 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 claimed to have observed $\eta$ Car in the 1860s to be brighter than other observers have recorded (Polcaro & Viotti 1993). Feast et al. (1994) and Frew (2004) have cast doubt on the veracity of this report, based on contemporary data, so we exclude the estimates of Kulczycky from our analysis.

### 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 colours of $\eta$ Car that appear to change with time and may be influenced by 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 is 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 $\sim 5$ yr orbit of the eccentric binary system. Damineli (1996) discovered a repeating 5.52-yr cycle of spectroscopic changes in $\eta$ Car that were linked to near-infrared brightening events (Whitelock et al. 1994). Damineli, Conti & Lopez (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.

Fig. 2 shows expected times of periastron passage, extrapolating back in time from modern events, adopting a period of 2022.7 d and phase 0.0 at year 2003.49 (Damineli et al. 2008). The orange vertical hash marks adopt a stable 2022.7 d 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 Fig. 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⊙ was ejected in the Great Eruption (Smith et al. 2003b). Smith & Ferland (2007) note that the mass could be as high as 20 M⊙, but probably not much more, so ~15 M⊙ is a favoured value for the mass of the Homunculus.1

As noted in Section 1, 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 (±0.8 yr), 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 yr, and used aberrated images with the Wide Field Planetary Camera (WFPC) on HST. Smith & Gehrz (1998) used a 50 yr time baseline and estimated an ejection date of 1843.8 (±7 yr), while Morse et al. (2001) used corrected HST/WFPC2 images with a longer baseline than Currie et al. and derived dates of 1846–48 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 1844 December, after which η 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⊙ 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 favoured value for the current total stellar mass of the binary system is ~130 M⊙ (assuming a ~100 M⊙ primary and a 30 M⊙ secondary), 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 Pittard & Corcoran 2002; Smith et al. 2004; Corcoran 2005; Hillier et al. 2006; Okazaki et al. 2008; Parkin et al. 2009; Mehrer et al. 2010). The ejected nebular mass of ~15 M⊙ is therefore ~11 per cent 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. The exact value of the expected period change is a complicated problem of orbital evolution, depending on the change in mass, eccentricity, semimajor axis and possible energy dissipation.

The red hash marks in Figs 2 and 3 therefore show times of periastron passage if we reduce the period by about 5 per cent 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 d (5.26 yr). With this adjusted period, it is quite interesting that the rather sudden beginnings of the brief 1838 (Fig. 3a) and 1843 (Fig. 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 19142; Gallagher 1989; Moreno, Georgiev & Koenigsberger 1997, in the context of HD 5980; Iben 1999; Smith et al. 2004; Gallagher 1989; Moreno, Georgiev & Koenigsberger 1997, in the context of HD 5980; Iben 1999; Smith et al.

1 Higher estimates of ~40 M⊙ based on submillimetre emission from cold dust (Gomez et al. 2010) include dust outside the Homunculus, and possibly free–free emission from ionized gas, so 40 M⊙ 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 grazings’ was based on the first sighting of a faint ‘companion’ of η Car, which is now known to be a very distant dust condensation in the equatorial ejecta of the Homunculus.
there is no periastron at orbital phase (Smith 2005). Curiously, though, prior to the Great Eruption (Figs 2V for the primary and secondary, respectively. These were brighter before the Great Eruption than it is now. As we have seen above, however, agreement between times of periastron and brightening events requires the opposite – that the orbital period was about 5 per cent shorter prior to the Great Eruption (Figs 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 their 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 favoured 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 the 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. (2011); the reader is referred to that paper for more details of the general phenomenon.

Fig. 4 shows the revised light curves for the brief eruptions of $\eta$ Car in 1838 (Fig. 4a) and 1843 (Fig. 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. (2011).

The 1838 eruption has a peak magnitude of $-13.5$, most similar to SN 2002bu and intermediate between SN 1995P and SN 1995K, and SN 1995A. It appears to fade after 100–120 d. In Fig. 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 d, but the behaviour 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 Fig. 4 is that $\eta$ Car did not fade very much afterwards. 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. 2011) 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 (Smith et al. 2010). Given that we have noted a clear connection between the brief eruptions and times of periastron in the binary system of η 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, η Car faded to a magnitude that was somewhat brighter than its expected quiescent magnitude (Fig. 2) for about a year. It then rebrightened dramatically in 1844 December, finally reaching its peak absolute magnitude at the start of 1845 and remaining luminous for a decade thereafter. This behaviour is unlike any of the SN impostors shown in Fig. 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 NGC 2366 (see Smith et al. 2011 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 η 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 as follows.

(1) The light curve clearly shows two brief (∼100 d) peaks during the time leading up to the eruption, in 1838 and 1843. η Car then faded by ∼1 mag after the 1843 event, before rebrightening to its true maximum brightness in 1844 December. 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 per cent – as it could 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 an orbital phase φ ≈ 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 η 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 η Car. This is discussed in more detail in a separate paper (Smith 2011).
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