

Eta Carinae: a South African perspective

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η Carinae is one of a kind: it is one of the most curious and enigmatic stars in our Galaxy. It is also an archetypal astronomical object that can be only fully characterized by studies across the entire electromagnetic spectrum — with something for everyone. At the time of writing (December 2005), NASA's Astrophysics Data System¹ lists 1131 papers which mention η Car in their abstracts, 427 of them written since 2000. I make no attempt here to review this huge corpus, but I hope to give an overall impression of why we might be interested in η Car and what we have learned about it to date, with a deliberate emphasis on observations made from South Africa.

Introduction

The literature contains a variety of reviews of this star at both a popular^{1,2} and a technical level.³ Figure 1 shows the Carina Nebula of which η Car is a part, while Fig. 2 shows one of the famous Hubble Space Telescope (HST) pictures of the star. The nebulosity, which reflects the light of the star embedded at its centre, is known as the 'Homunculus', or little man, from the description by Gaviola.⁴

The distance to η Car might have been difficult to determine

¹http://adsabs.harvard.edu/abstract_service.html

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except that it is part of a cluster of very massive stars whose distance is well determined at 2300 ± 200 pc (7500 light years). Its total luminosity, which can be measured directly as most of it emerges at infrared wavelengths (see below), is 1.9×10^{33} J s⁻¹ (1.9×10^{40} erg s⁻¹ or $10^{6.7}$ times the luminosity of the Sun), to an accuracy of about 10%.³ This luminosity could only be achieved by a star with an initial mass approximately 150 times that of the Sun; less massive stars burn their nuclear fuel too slowly. Its present-day mass is much less certain, but typical estimates are of the order of 100 times that of the Sun.

This extremely high mass is one principal reason for η Car's peculiarity and interest to astronomers past and present. Stars with such large initial masses live for less than a million years and are therefore extremely rare; contrast this age with that of our Sun, which will survive for around 10 billion years and is currently in early middle age. Only two other candidates for comparable initial masses are known in our Galaxy, both at distances too large to make them amenable to detailed study. It is generally thought that η Car is very close to the upper mass limit reachable by the current generation of stars.

There are several different reasons why modern astronomers regard hyper-massive stars as important to understand. First, as we build bigger and better telescopes, we are able to resolve individual stars in ever more distant galaxies. The stars most easily resolved at great distances are the brightest ones, that is, those like η Car. If we want to know what we are seeing at millions of parsecs, then we must understand the analogues in

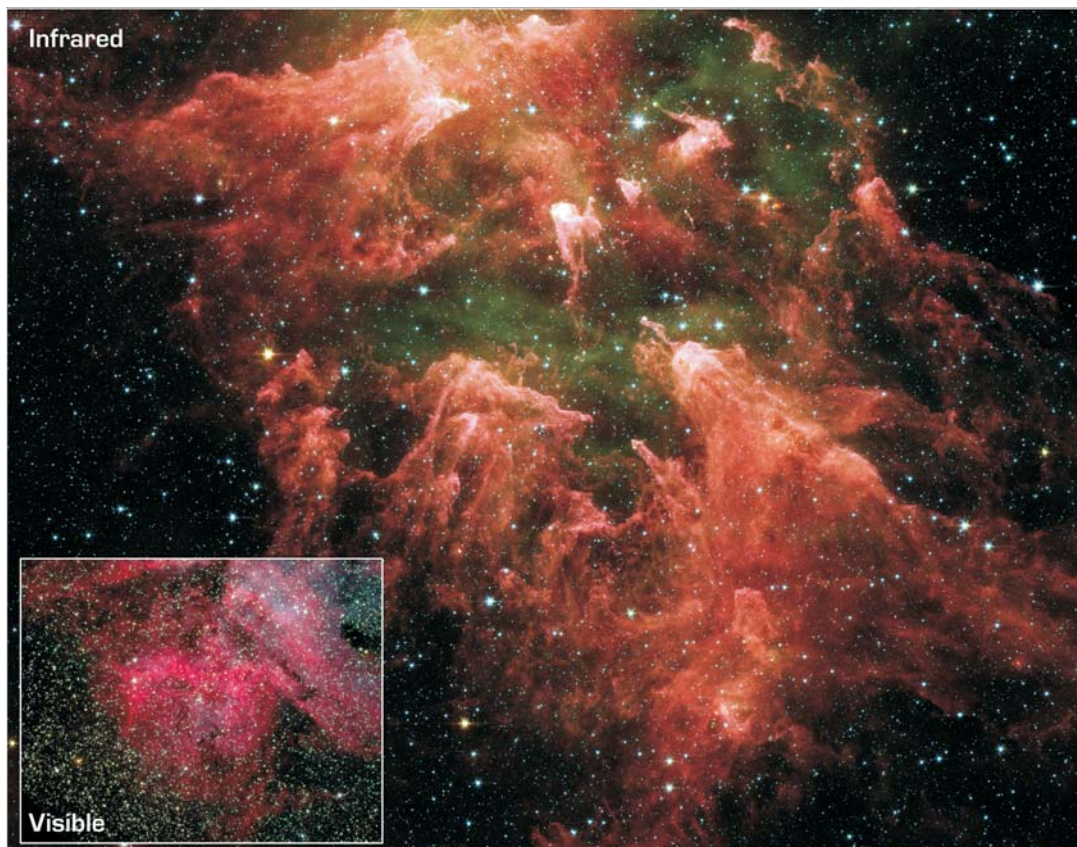


Fig. 1. Infrared (from Spitzer satellite) and visual images of the Carina nebula in which η Car lies. (Credit: NASA.)

our own neighbourhood. Secondly, theoreticians tell us that the very first stars formed after the big bang were probably much more massive than those found in the local universe, perhaps several hundred times the mass of the Sun. While η Car is undoubtedly very different from those stars, in particular it is rich in heavy elements that were entirely absent from stars forming out of primordial hydrogen and helium, it is again our best opportunity to learn something of those first generation objects. Finally, η Car is a potential progenitor for a supernova, possibly even a γ -ray burster, the most luminous objects ever observed.

The historical variable star

η Car is a southern object, with a declination of -60° , and therefore easily visible from South Africa for much of the year. Its photometric history goes back to 1596⁵ (see Fig. 3), although Burchell seems to have been the first to note its variability.⁶ It attracted serious attention only during what is now known as the 'Great Eruption' in the 1830s and 40s. This is clearly illustrated in the definitive 19th-century light-curve published by Innes⁶ from observations made from Australia, South America, India and various parts of Africa as well as from the Cape Observatory (now the headquarters of the South African Astronomical Observatory, SAAO). There were a number of well-known people among η Car's observers from Africa, including: Lacaille, Fallows, Burchell, Herschel and Maclear. John Herschel was in the Cape in the 1830s as η Car started to brighten. He recognized the importance of this star, as is clear from his numerous writings on the subject, for example, 'there is perhaps no other sidereal object which unites more points of interest than this',⁷ and the interest of others probably followed from his enthusiasm.

For a few years during the Great Eruption, η Car was among the very brightest stars in the sky, comparable to Sirius and Canopus. In the late 1850s, it began a steep decline that eventually took it below the minimum brightness visible to the naked eye. There was a second, 'Lesser Eruption' in the 1880s followed by a decline in the 1890s. Between 1915 and 1950, very few observations were recorded, but over the last 50 years η Car has been slowly but steadily brightening with a few rather minor erratic changes.⁸

Prior to the invention of photographic and later of photoelectric techniques (turn of the 20th and mid-20th century, respectively), the brightness of a star such as η Car was measured by a visual comparison with other non-variable stars. This method has many sources of error, some of them systematic, as discussed in

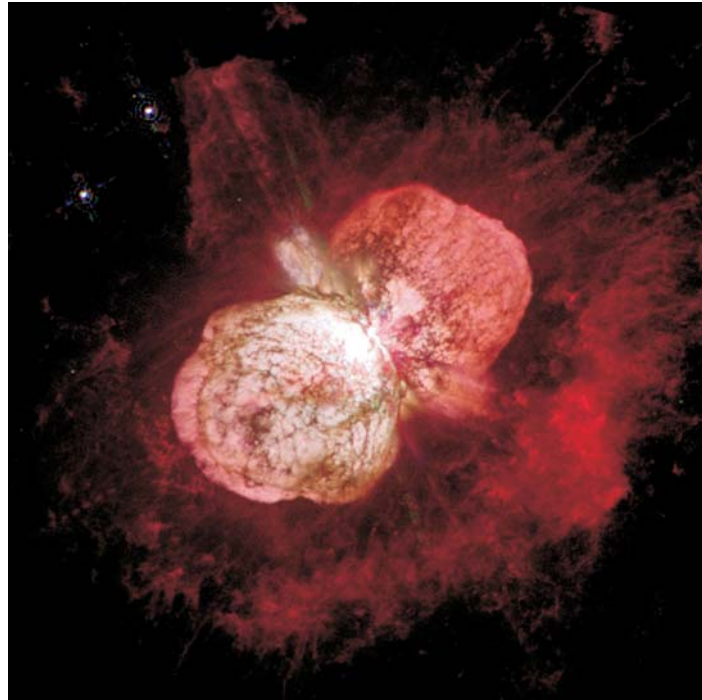


Fig. 2. Hubble Space Telescope image of η Car showing the outer nebulosity in addition to the Homunculus nebula. (Credit: NASA, J. Hester, Arizona State University.)

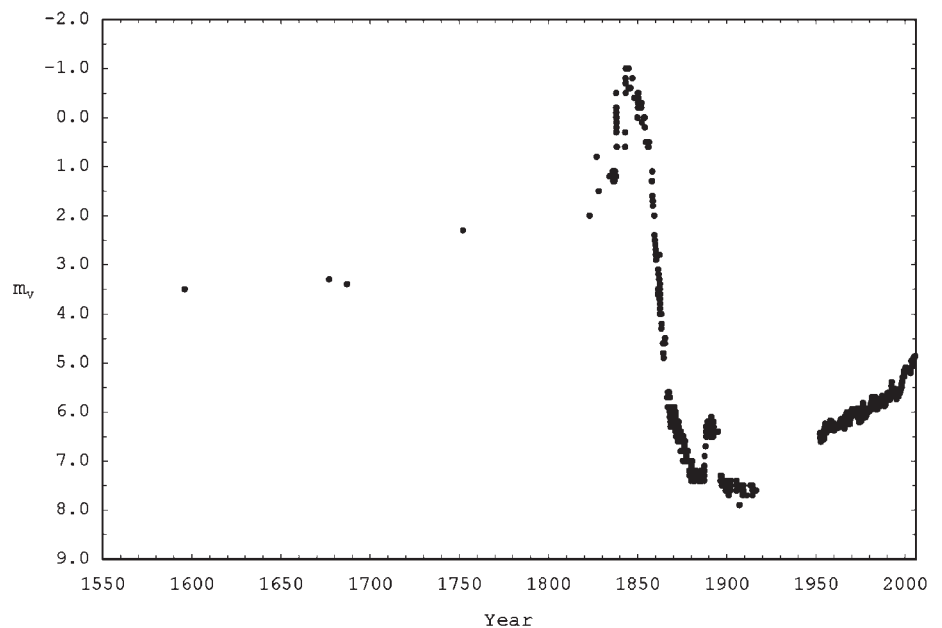


Fig. 3. The historical light-curve from visual magnitudes.⁵

detail by Frew.⁵ The literature contains suggestions of significant changes beyond those noted above and illustrated in the light curve, which have not been substantiated.⁹

The first good photograph of η Car was taken by Sir David Gill at the Cape in March 1892, an exposure of twelve hours spread over four nights.¹⁰ It caused a great deal of interest because it differed from sketches of the same region made by Herschel before maximum light. Although it would not have been obvious at the time, the differences were almost certainly real and caused by the vastly reduced visual and ultraviolet output from η Car after the dust formation described below, which in turn led to less illumination of the surrounding Carina nebula.

The early writings on this star make fascinating reading and

seem very emotional when measured against modern scientific prose; for instance, from Agnes Clerke's¹⁰ book, where a description of sketches and early photographs can be found: 'At the eastern edge of the northern key-hole lies the extraordinary variable, η Carinae, the vicissitudes of which cannot but be related to the tumultuous processes of change doubtless going on in the seething chaos around.' The 'key-hole' mentioned is a part of the Carina nebula (see Fig. 1), sketched by Herschel, which changed dramatically following the Great Eruption.

The Great Eruption and the Homunculus nebula

η Car was one of the first stars examined by David Thackeray,¹¹ with the newly installed 1.9 m telescope at the Radcliffe Observatory in Pretoria (eventually moved to SAAO Sutherland) and his observations continued up to a few days before his death. He made one of the first sensible distance estimates and was probably the first to appreciate the extreme luminosity achieved by η Car during the Great Eruption.¹² This led him to suggest that η Car was a very slow supernova. Current estimates³ put the extra luminosity during the eruption at over 10^{42} J, with an approximately equal amount released as kinetic energy, all with considerable uncertainty because we know very little about emissions outside of the visual wavelength range during the eruption.

While it is still not clear what actually triggered the Great Eruption, we now understand the consequences and it was the advent of measurements at infrared wavelengths that resulted in this insight. Westphal and Neugebauer¹³ measured η Car at 10 and $20\ \mu\text{m}$ and found it to be the brightest $20\ \mu\text{m}$ object in the sky outside of our own solar system. At least to a first approximation, η Car is still emitting the same amount of energy as it was during the Great Eruption, though now that energy is coming out in the thermal infrared rather than at visual wavelengths.

It appears that during the Great Eruption a very considerable amount of material was ejected from η Car, although quantitative estimates vary. As these ejecta moved outwards, they cooled and dust condensed, forming what we now call the Homunculus Nebula. This dust absorbs the optical and ultraviolet emissions from the star and reradiates them at infrared wavelengths.

Interestingly, Thackeray¹⁴ already had strong evidence for dust in η Car from polarization measurements he made photographically through a sheet of Polaroid, in 1956. These revealed extraordinarily high degrees of polarization (over 35%) in the Homunculus. However, because he suspected η Car to be a very slow supernova, he made an analogy with the Crab nebula, a supernova remnant, and identified synchrotron emission as the cause of the polarization, rather than scattering by dust.

It is now clear that the main part of the nebula surrounding η Car comprises two expanding hollow lobes,³ each with a diameter of about 8.5 arcsec (about one third of a light year, or 0.1 pc). There is also an equatorial 'skirt', only properly recognized with HST images, which like the lobes was probably ejected during the Great Eruption. Less-dense diffuse material outside the Homunculus was recognized and described by Thackeray.¹⁵ This outer material is seen in emission and some of it reaches velocities¹⁶ in excess of $2000\ \text{km s}^{-1}$. The shocked gas gives rise to X-ray emission which is clearly seen in images taken by the Chandra satellite (Fig. 4).

Modelling of detailed mid-infrared images indicates that dust with a range of temperatures is present in the Homunculus and around the core of η Car.¹⁷ The coolest material ($T \sim 140\text{--}200\ \text{K}$) is on the outer edges of the lobes of the nebula, whereas warmer material ($T > 250\ \text{K}$) is distributed in a torus around the central source. The total mass of material present is strongly dependent on assumptions made about the dust grain properties and distri-



Fig. 4. Chandra X-ray image of η Car. The central blue object is a hard X-ray source, which disappears during the eclipses discussed in the text. The softer emission, which comes from a horseshoe-shaped region, is the result of shocked gas outside the Homunculus nebulae. This image is about 90 arcsec across and covers a slightly larger area than Fig. 2. (Credit: NASA Chandra project 1999.)

butions and the relative proportions of dust and gas. It is therefore very uncertain, but 10 to 20 solar masses of material is quite possible.

Inside the Homunculus, there appears to be a 'little Homunculus', which was only recently recognized from data taken with the Space Telescope Imaging Spectrograph (STIS).¹⁸ The expansion velocities for this indicate it was ejected during the Lesser Eruption.

Spectra and abundances

Soon after the McClean telescope was set up in Cape Town, and partly to test its performance, Gill took an objective-prism spectrum of η Car.¹⁹ Because this showed 'a very remarkable bright line spectrum', he decided to follow it with a slit spectrogram (the first ever obtained). This he duly obtained in April 1899 with a total exposure of 6 h 10 min over 4 days! He noted the similarity of the spectrum to that of a nova.

In more modern times, Thackeray²⁰ made a series of detailed studies identifying numerous permitted and forbidden lines, many of them never previously identified elsewhere, astronomically or in the laboratory; the FeII and [FeII] spectra were particularly rich. Sharp emission and absorption lines originating from the ejecta around the central object are superimposed on very broad emissions from, for example, H I, He I and [FeII]. As observed by Thackeray, the broad lines are all redshifted, by around $900\ \text{km s}^{-1}$. He correctly understood that these originated from the central object (what we now understand to be its optically thick stellar wind), which was obscured from direct view, but seen in reflection from the Homunculus. The high positive velocity is the moving mirror effect of the expanding scattering material. Recent high spatial- and spectral-resolution work with STIS²¹ has refined the details of this model.

Thackeray²² noted the strength of the nitrogen lines and the weakness of the oxygen lines in a near-infrared spectrum of η Car. However, it was only realized by Davidson *et al.*²³ (who in addition to near-ultraviolet data made use of some of Thackeray's

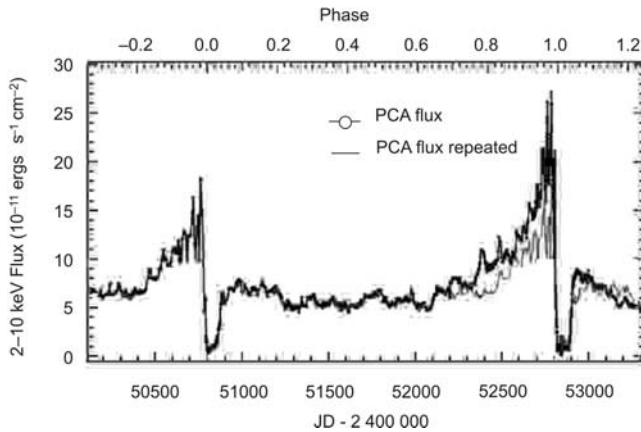


Fig. 5. X-ray light-curve showing the two eclipses now observed at these wavelengths.²⁸ (The plot shows the Julian date JD, which counts the days from 0 on 1 January 4713 BC.)

unpublished spectra) after the analysis of the relatively simple ultraviolet spectra from the outer ejecta that the spectroscopic evidence indicated that the ejecta of η Car within the Homunculus have been processed through the CNO cycle. Thus, we can be certain that it is in a post-main sequence evolutionary phase. Very recent work²⁴ has revealed an [OIII] emission cocoon around the Homunculus, which is probably the result of mass lost in an earlier evolutionary phase. Further study of this outer material could enable the chemical enrichment and mass-loss history to be traced.

Evidence for a binary system

Thackeray²⁵ recorded that from time to time the spectrum of η Car went into a low excitation state, when HeI, [NeIII] and various other high excitation lines disappeared entirely. In 1996, Daminieli²⁶ suggested that he had discovered a 5.52-year periodicity of these low excitation events via studies of the intensity of the HeI λ 1.083 μ m line, which was correlated with near-infrared variations. This he attributed to a binary period. Furthermore, he predicted that the next low excitation phase was to be expected in late 1998 and early 1999. The available evidence for periodicity in HeI was not at all convincing, and the near-infrared variations were not strictly periodic (see below); nevertheless, many of us observed during the critical phase with fascinating results.

The spectroscopists did indeed observe the predicted low excitation phase and were able to time its duration for the first time.²⁷ Indeed, some sort of change was observed at almost every wavelength, the most spectacular result coming from X-rays. Observations²⁸ in the 2–10-keV X-ray band with the Rossi X-Ray Timing Explorer (RXTE) show a drop by a factor of about 100 for a period of about 3 months. X-rays are insignificant contributors to the bolometric flux, so this did not affect the overall energy balance. The observations are illustrated in Fig. 5, which covers not only the 1998/9 event, but the 2003 one as well.

The X-ray emission is thought to arise in a shocked region where the wind from η Car collides with the wind from a companion star to produce a very high temperature plasma. The light curve can be qualitatively reproduced if the two stars are in highly elliptical orbits, so that the emission increases as the stars approach each other (periastron), but is then greatly attenuated when our line of sight passes through the optically thick wind of the primary star.²⁹ The specific details of what is observed are more difficult to reproduce.³⁰

The next low excitation event in the 5.52-year cycle, which occurred in 2003, was monitored even more closely and changes

were again seen in almost every waveband, including extremely complex variations of the spatially resolved spectra observed with STIS³¹ that have yet to be published. A notable event was the detection of HeII, just prior to the X-ray eclipse, from ground-based spectra,³² indicating higher temperatures than any implied by any previous line measurements. Thackeray²⁰ had thought he detected HeII in one of his spectra, but the identification was very tentative.

An examination of spectra of the central object taken by Thackeray between 1951 and 1978 revealed three previously unrecorded epochs of low excitation.³³ Since 1948 at least, these states have occurred regularly on the 5.52-year cycle and they last about 10% of the cycle. However, early slit spectra from a variety of sources, obtained between 1899 and 1919, show that at that time η Car was always in the low excitation state. These are just some of the variations that any complete model of η Car must take into account.

Near-infrared variability

At SAAO we have been monitoring η Car at near-infrared wavelengths using broadband photometry through *JHKL* filters (centred at 1.25, 1.65, 2.2, and 3.45 μ m, respectively).^{33–37} The programme was initiated in 1972 by Michael Feast and most of the observations were obtained with the 0.75-m telescope at Sutherland. The light-curves from this unique database are illustrated in Fig. 7 and cover over 33 years, including recently obtained unpublished material. Many observers have contributed to this over the years, but the largest number of observations has been made by Fred Marang, now an operator with the Southern African Large Telescope.

The importance of this study lies in the fact that it was carried out in a consistent way over such a long period of time, providing insight on the changes, periodic and temporal, that have taken place. Interestingly, through *JHK* filters we see much closer to the central stars than at shorter wavelengths (which are dominated by light scattered from dust in the Homunculus) or at longer wavelengths (at which we see thermal emission from the Homunculus).

The sources of emission in the 1–4- μ m spectral region are less than obvious. For many years people assumed that hot dust would dominate, but it is clear from the prominence of the hydrogen lines in the spectrum (Fig. 6) that there must be a significant contribution from hot plasma. Based on a small number of high spatial resolution near-infrared images,³⁸ our best estimate³⁷ for our *K* measurement in late 1998 is that it is made up very approximately as:

- Unresolved core [free–free emission (that is, from electrons not bound to atoms) from extended atmosphere] 30%
- Free–free emission from around the core 20%
- Free–free emission from torus 30%
- Emission lines close the core 5%
- Scattered light from dust 15%

Hot ($T > 500$ K) dust might contribute as much as 30% of the flux measured through the *L* filter, but it is unlikely to add much at shorter wavelengths.

The light-curves in Fig. 7 exhibit three types of variability: secular, periodic and quasi-periodic. It is clear that η Car brightened at *JHK* wavelengths over the last 33 years, the overall change being largest at the shortest wavelength, $\Delta J > 1$ magnitude. The overlying quasi-periodic variations render it essentially impossible to determine what the secular brightening actually is, or if the rate is changing, although it does seem to have increased in recent times. It may be that the secular changes are episodic and associated with mass-loss triggered by periastron passage.³⁷

It is often said that the gradual brightening, which is also evident in visual light,⁵ is due to the thinning, through expansion, of the dust produced in the Great Eruption. However, most of the visual light comes from dust scattering. As the dust cloud expands and the absorption goes down, the amount of scattering will also decrease and, given the complexity of the system, it is not obvious what the net effect will be.

The dotted lines in Fig. 7 mark phase zero on the cycles with respect to the first observed X-ray minimum and assume a 2023-day period.³⁷ The secular changes observed in the *JHK* bands make a detailed comparison of cycles difficult, but at *L* the secular changes are much smaller. Figure 8 compares the last two eclipses in the near-infrared and in X-rays.³⁹ It is important to recognize that these eclipses are strictly periodic and are identifiable, although not well defined, in earlier *JHKL* photometry. The morphology of the light curves, including the differences between the 1998/9 and 2003 events, is remarkably similar in the X-ray and *L* light-curves. There can be little doubt that a significant fraction of the *L* flux must originate from the same volume as the X-rays.

In addition to the secular brightening and eclipses, η Car also shows quasi-periodic variations on the same 5.5-year timescale as the spectroscopic events. The broad maximum of these variations occurs around or just after the eclipses at *J*, while at *L* it always occurs just before the event (like the X-ray brightening). It is notable that the *J* changes are anti-correlated with intensity variations at radio wavelengths,⁴⁰ where the emission will be optically thick. They are probably the consequence of orbitally modulated excitation of gas close to the central object in circumstances where optical depth variations are important.

Conclusion

In attempting to understand this extraordinary star, we acknowledge and use observations made over 100 years ago, while simultaneously benefiting from the very best that modern astronomical techniques can offer in the way of spectral coverage and spectral and spatial resolution. Despite great strides in understanding, there are some huge and obvious gaps in our knowledge; for instance, we are still unsure what caused the Great Eruption.

η Car will provide an interesting target for the Southern African Large Telescope.⁴¹ In particular, spectropolarimetry with the Prime Focus Imaging Spectrograph (Steve Potter, pers. comm.) could well lead to a deeper understanding of the properties

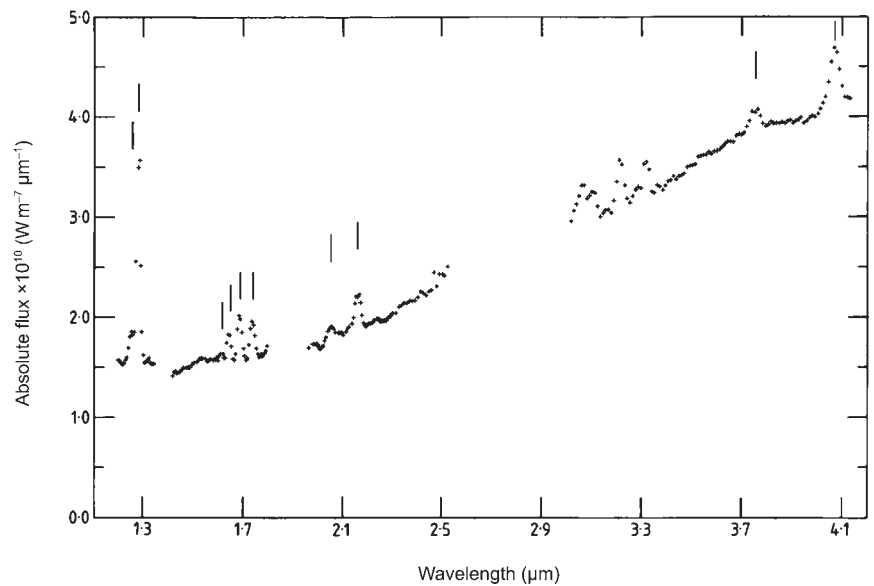


Fig. 6. The first published spectrum covering the *HKL* bands and part of the *J* band. The marked lines belong to H I (Paschen, Brackett and Pfund series) and to He I emissions. This spectrum was obtained with the 1.9 m telescope at Sutherland in April 1981.³⁵

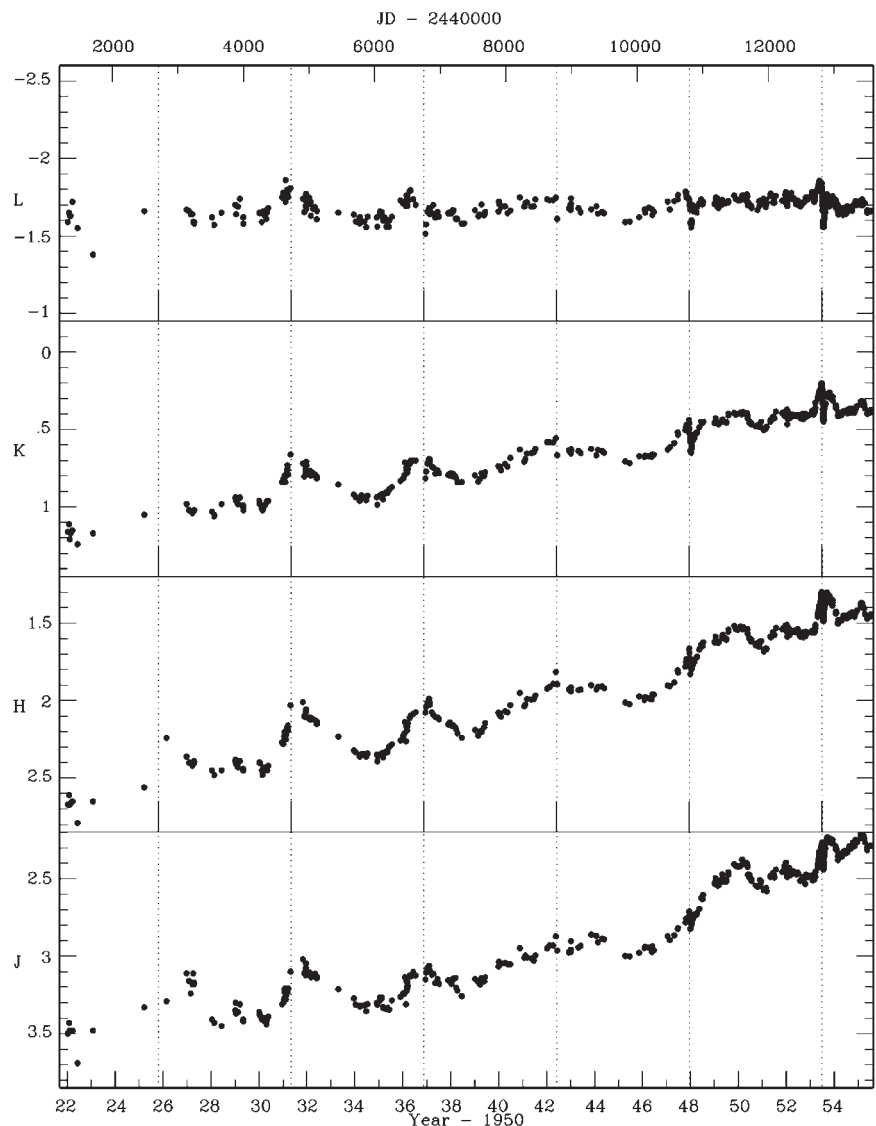


Fig. 7. Infrared (*JHKL*) light-curves for η Car covering the period from 1972 to 2005. The dotted lines mark the epochs of eclipses as discussed in the text.

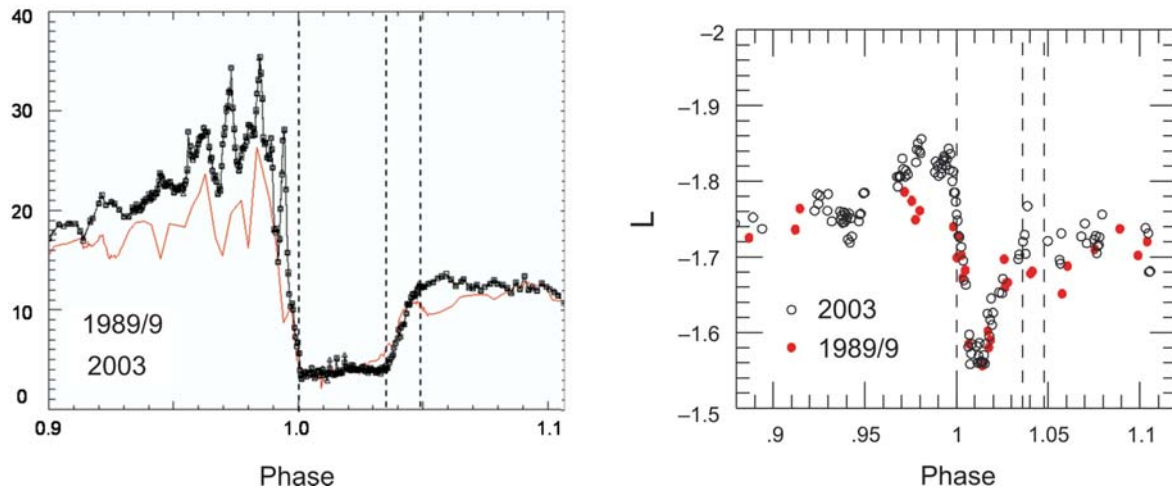


Fig. 8. A comparison of the flux variations in X-rays and in the near-infrared, L band, during the 1989/9 and 2003 eclipses. The dashed lines mark the significant turning points of the X-ray light-curve.³⁹

(size, composition, distribution and shape) of the dust particles making up the Homunculus nebula. Given its multi-wavelength character, η Car will almost certainly also be a prime radio target for the proposed Karoo Array Telescope. It is, however, unlikely that resources will be available to continue monitoring the star at near-infrared wavelengths — which is unfortunate as this was a unique South African capability. For the future we must assume that the combination of systematic observations and exploiting technology will ultimately bear fruit. The future of η Car itself is a source of much speculation; we actually know little about the ultimate fate of very massive stars. It may be that we should expect many more great and/or lesser eruptions before η Car undergoes its final collapse and explodes as a supernova.

I am grateful to Michael Feast for many helpful discussions about η Car and to both him and John Menzies for a critical reading of the manuscript.

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