η Carinae 2009.0: One of the Most Remarkable Stars in the Sky

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η Carinae is one of the most luminous and massive stars in the Galaxy. The star underwent a major eruption in 1838, followed by a second maximum a few decades later and a low-gradient brightening to the present. The central source of η Car is a highly-eccentric binary with a period of 5.54 years. The photometric and interferometric monitoring programmes with ESO telescopes are summarised. On the occasion of the forthcoming periastron passage in 2009.0, the star will be the target of intensive photometric, spectroscopic and interferometric monitoring from Chile and other southern observatories.

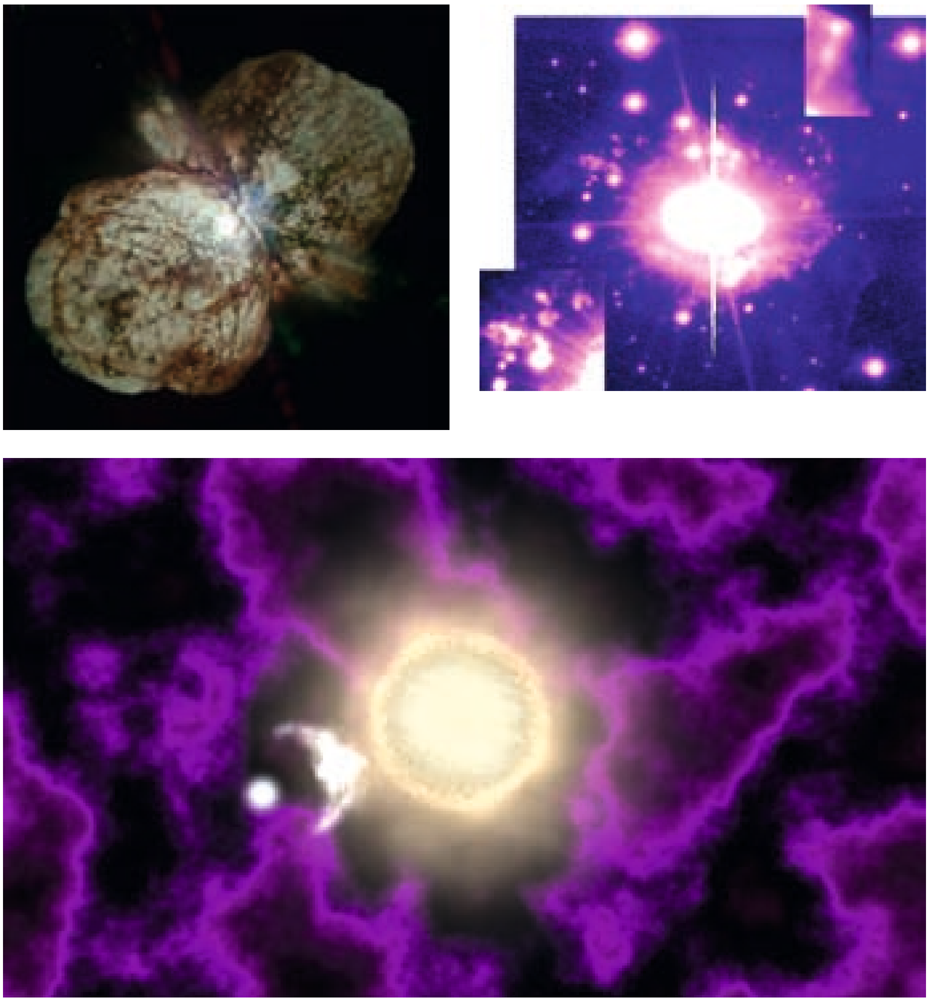

Figure 1: Images of η Carinae: HST image from Morse et al. (1998) (top left); VLT/UT1 First Light Photo No. 5, (top right); artist's impression of the binary configuration, courtesy S. Ivarsson (bottom).

η Car: an extreme LBV

S Doradus variables – commonly known as Luminous Blue Variables (LBVs) – are evolved massive stars that undergo four major types of intrinsic photometric variability: microvariations, S Doradus phases, stochastic variability, and eruptions. For a detailed discussion of these types of variabilities, and for a very complete review of the state of affairs at the end of the second millennium, we refer to van Genderen (2001). These stars were labelled S Dor variables in the General Catalogue of Variable Stars on the basis of their behavioural similarities with the prototype star S Doradus. The Armagh 2000 definition (see ASP Conference Series 233, page 288) states: "S Doradus variables are hot, luminous stars that show photometric and/or spectroscopic variations like S Doradus and which have undergone – or possibly will undergo – an η Carinae or P Cygni-type outburst."

P Cygni and η Carinae (Figure 1) are the historically best-documented cases of eruptive behaviour of S Dor stars. P Cygni was discovered by the Dutch chartmaker Willem Adriaensz Blaeu in 1600. The star faded, becoming invisible to the naked eye until 1658, when it flared again to a secondary maximum, followed by another return to oblivion and a subsequent very weak increase during a centuries-long brightening phase. η Carinae was observed in a similar eruption by John Herschel at the Cape in 1838, and the historical light curve (Figure 2) illustrates a pattern very similar to the light history of P Cygni: a major eruption (also called the Great Eruption), followed by a second maximum a few decades later, and then a steady low-gradient brightening during more than a century.

It became obvious that the central star of η Car is a true S Dor variable: the star migrates in the Hertzsprung-Russell diagram (at constant luminosity) so that brightness increases are accompanied by redder colours, and vice versa (see Figure 3 for a partial light curve and colour curve between 1992 and 2000). Such a migration cycle is called an S Doradus phase.

η Carinae is one of the most luminous and massive stars in the Galaxy, with a luminosity of $L \sim 5 \times 10^6\,L_\odot$ and a mass of $M \sim 100\,M_\odot$, a mass loss rate of $\dot{M} \sim 10^{-3.3}\,M_\odot$ for a distance of d = 2.3 kpc. The system consists of a bright hollow bipolar nebula, called the Homunculus, and an apparently much fainter (currently 2.4 mag) central star. In reality,

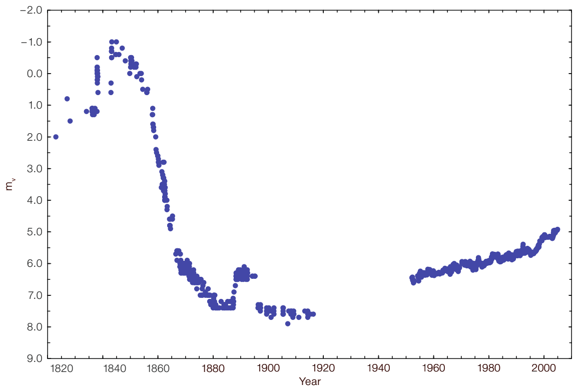

Figure 2: Visual light curve of η Carinae. The Great Eruption extended from 1837 to about 1856. Source: Frew (2004).

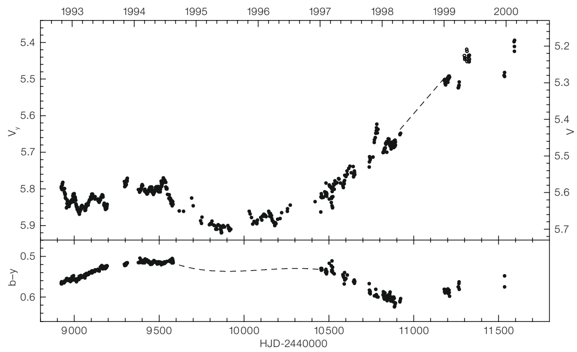

Figure 3: V_y (•, based on Geneva *V* and Strömgren *y*) light curve (left *Y*-axis) and *b–y* colour index of η Car, with an approximate indication of visual magnitude on the Johnson *V*-scale (right *Y*-axis). The dashed line in the light curve is based on broadband visual estimates and CCD photometry and fills in the seasonal gap in 1998; the dashed line in the colour curve is based on broadband colour data. ∘ represent measurements through a *V*-filter. The narrow peak at HJD-24410800 coincides with the time of the 1997.9 event. Source: Sterken et al. (2000).

this central star is much brighter, but appears fainter due to nebular extinction. The Homunculus is now 16 arcsec across, which corresponds to 0.2 pc. During the S Dor-eruption phase in the 1840s, one peak reached an exceptional brightness of $M_{bol} \sim -14$ (van Genderen and Thé 1984).

η Car, a highly-eccentric binary

A variety of observations have suggested that the central source of η Car is a highly eccentric binary. Augusto Damineli first noticed the 5.5-year periodicity in the spectroscopic changes of this object (see Damineli et al. 2000 and Whitelock et al. 2004). The periastron separation is only ~ 2 AU, whereas at apastron the separation is ~ 20 AU, corresponding to ~ 9 milliarcseconds. Smith et al. (2004), on the basis of Hubble Telescope images, removed most doubts on the existence of a hot companion. Iping et al. (2005) state that the companion star was seen in the far-UV spectrum shortly before the 2003.5 event. The orbital parameters however are still a matter of debate. Figure 4 is a schematic drawing of the binary configuration (for the 2003.5 periastron passage, based on orientation B of Akashi et al. 2006).

Photometric monitoring at ESO

Photometric monitoring of the integrated brightness of η Car at ESO La Silla was started in 1979 when the 90-cm telescope of the Leiden Southern Station (South Africa) was moved to Chile, where it became known as the Dutch Telescope. The telescope, equipped with the Walraven *VBLUW* system, was decommissioned in 1999. Between 1983 and 2000 the observations were then continued with the ESO 50-cm and Danish SAT telescopes in other photometric systems, mainly as part of the *Long-Term Photometry of Variables* (LTPV) Group (see The Messenger 33, 10), between 1994 and 1998 with the 70-cm Swiss Telescope, and later on with the Danish 1.54-m. The combination of the data, obtained over such a long time base of an extended emission-line object measured with different detectors and photometric systems, is a real challenge.

Between 1992 and 1994, when η Car was observed very intensively in the optical, microvariations typical for S Dor variables were identified with a quasi-period of 58.6 days. Note that oscillation periods of this order of magnitude are often present during the low-brightness stages of S Dor variables. Peculiar UV colour-variations indicate that part of the light variations must be due to non-stellar causes. For example, the flux of the relatively strong Balmer continuum glow (coming from the equatorial disc) shows a modulation of 0.1 mag in concert with the 5.5-year binary revolution, but is asymmetric with respect to the periastron passages. However, it is not unlikely that short-cycle oscillations in the Balmer-continuum radiation (200–400 days) are, in fact, caused

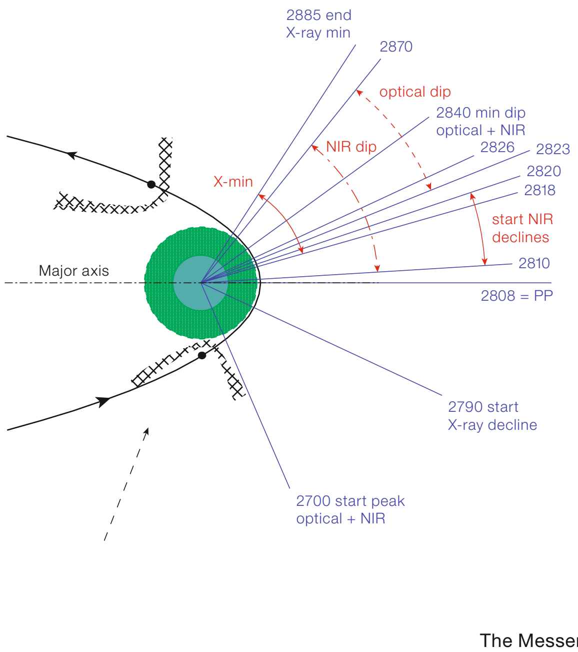

Figure 4: A schematic drawing of the binary system (for the 2003.5 periastron passage and e = 0.9, seen pole-on and not to scale, viewing angle ~ 45°) based on orientation B described by Akashi et al. (2006). Central circle and small dot: the primary and secondary, respectively. Large circle (dashed): the wind envelope of the primary. Hatched area: the shocked secondary wind. A number of features are indicated by time marks (JD-2450000).

by stellar oscillations. Some starlight variability seems to be induced by tidal forces of the secondary acting on the primary and its extended envelope, like the long timescale optical and near-IR light maxima coinciding with the periastron passages and the shorter light peaks (van Genderen et al. 2006, and references therein).

All the observed variations are superimposed on a slow 'secular brightening' (documented since 1935), partly due to a decrease of self-extinction of the expanding lobes. Note that in 1935 the Homunculus was only 60 % of its present size. The near-IR also shows a secular brightening, but it seems that a gradual enhancement of circumstellar free-free emission could be the major cause of the brightening in the *JHK* bands (Whitelock et al. 2004).

As the lobes of the Homunculus are nearly pure reflection nebulae, and have large dimensions, the important question was raised whether the observed variations are in fact a mix of genuine variations of the core and time-delayed reflected and scattered light (against the inner and outer walls of the lobes), and of time-delayed ionisation and recombination processes in the equatorial plane. Such light-time effects can amount to weeks and months. Consequently, if these time-delay effects would be quantitatively substantial, one would inevitably obtain false timescales and amplitudes for the observed variations. The much steeper brightening of the central star as seen by the HST in 1998 and 1999 compared to that of the Homunculus (Figure 5), noted by the HST Treasury Program Team, led them to conclude that serious smearing-out effects do exist. Consequently, there arose the general feeling that ground-based integrated optical photometry of the Homunculus is an unreliable means for studying the variability of the central star, and that the only valid photometry is photometry from space-borne telescopes. Figure 5 shows the combination of schematic light curves from the ground and HST data obtained between 1998 and 2003. Apart from the above-mentioned steeper brightening of the central star in 1998 and 1999, due to decreasing extinction in front of the core (with an anomalous extinction law R ~ 5.3; van

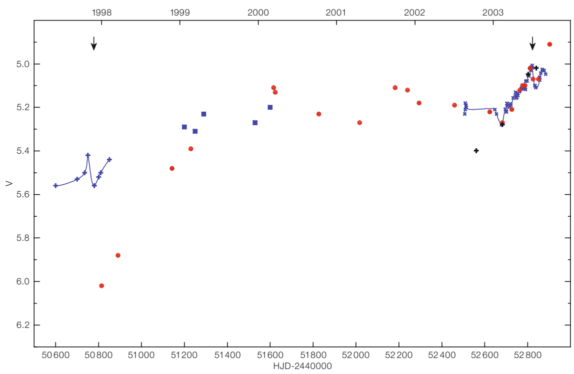

Figure 5: Schematic light curves between 1997 and 2004. The *V* scale is close to the *UBV* system. The arrows at the top indicate the computed events (or periastron passages). The short full curves on the left and right and the blue squares are for the whole Homunculus (van Genderen et al. 2006). For the central region, points refer to HST data (aperture 0.1″): red symbols are the broadband *V* daily averages, +'s are the narrowband *V* daily averages from Martin et al. (2004), shifted in magnitude for a good match between their 2002.8–2003.6 curve and the short full curve to the right.

Genderen et al. 2006), most data points of the central star fit the light curve and show that the Homunculus mimics the light variations originating in the core quite well. Thus, light-time effects and any other smearing effects are negligible, although substantial time delay effects exist between parts of the Homunculus and individual clouds inside the Homunculus and the central region.

Interferometric monitoring at ESO

One of the keys to understanding η Carinae is to resolve its central region using ESO's Very Large Telescope Interferometer (VLTI). The AMBER instrument (Astronomical Multi-BEam Recombiner) at the VLTI combines the near-infrared light collected by three VLT Unit Telescopes to attain an angular resolution 16 times higher than the resolution of each of the 8.2-m telescopes alone (Malbet et al. 2007). Therefore, VLTI/AMBER measurements can unveil details about the outflowing stellar wind in the innermost stellar environment. Using AMBER, it was possible, for the first time, to study η Car with the fascinating spatial resolution of 5 milliarcseconds (11 AU) *and the high spectral resolution of 12 000* (Weigelt et al. 2007). In η Car's innermost region, the observations are dominated by the extremely dense stellar wind, which totally obscures the central star. It was possible to resolve η Car's optically thick wind region and to measure its diameter of 4.0 ± 0.2 milliarcseconds (Gaussian FWHM, fit range 28–89 m baseline length), in good agreement with previous VLTI/VINCI observations.

The AMBER observations are also in good agreement with the NLTE radiative transfer model from Hillier et al. (2001). In the continuum, an elongation of the wind zone along a position angle of 120 ± 15 degrees and with a projected axis ratio of 1.18 ± 0.10 was found. The AMBER observations show that the extensions of the regions where the continuum radiation, the Brγ 2.166 μm and He I 2.059 μm line emission originate are remarkably different. While the size of the dense stellar wind in the continuum is only 10 AU, AMBER measured an extension that is twice as large for the line-emitting regions. The non-zero differential and closure phases measured within the Brγ line can be explained by a simple geometric model of an inclined, latitude-dependent wind zone (see Figure 6). The AMBER observations support theoretical models of anisotropic winds from fast-rotating, luminous hot stars with enhanced high-velocity mass loss near the polar regions.

HST STIS observations show that the He I lines are strongly variable and blue-shifted throughout most of the 5.54-year variability period. These observations cannot be explained in the context of a single-star wind model. It now appears likely that a large fraction of the He I line emission originates in a wind-wind interaction zone in the binary system. The blue-shift of the He I emission line can be explained if this line is produced in the portion of the primary wind which is flowing towards the observer. Furthermore, our AMBER observations show that there is an obvious difference between the observed He I visibility profiles and the model predictions. This discrepancy can also be explained by additional He I emission from the wind-wind interaction zone between the binary components and by the primary's ionised wind zone caused by the secondary's UV light. If this model

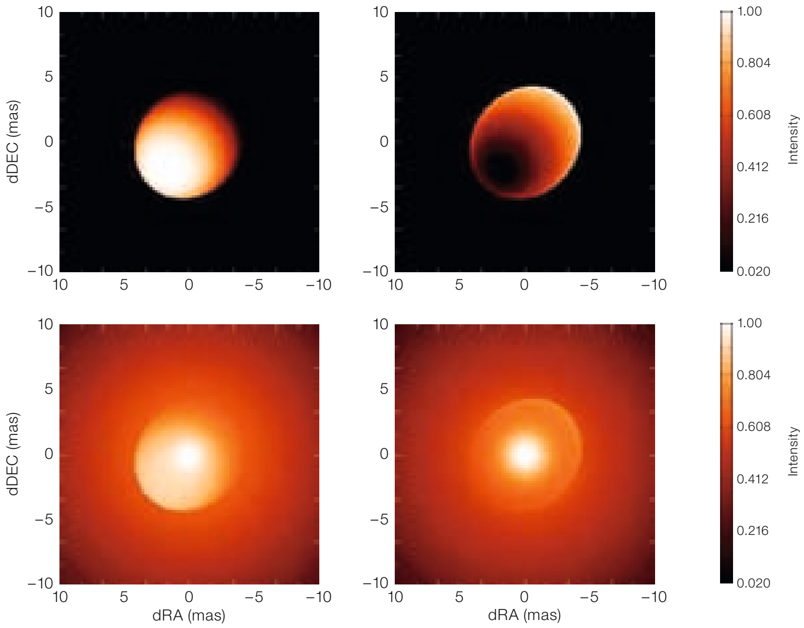

Figure 6: The upper row shows the brightness distribution of the modelled aspheric wind component of η Car in the blue- and red-shifted wings of the Doppler-broadened Brγ line. In the blue-shifted line wing, the south pole region of the wind zone is dominant, whereas in the red-shifted wing, the light near the north pole is dominant (the north pole itself is not visible since it is turned away from us). The pair of figures below show the total brightness distribution after adding the contributions from the two spherical constituents of the model derived from VLTI/AMBER observations (Weigelt et al. 2007).

is correct, the two-dimensional, asymmetrical intensity distribution of the orbiting He I emission region will be strongly variable during the 5.5-year orbital period and offset from the primary star by a few milliarcseconds. The detection of this moving He I zone is one of the goals of our future AMBER observations. Finally, this binary model can also explain the periodic variation of the three ejected speckle objects at separations between 0.1 and 0.3 arcsec from the central object. The UV flux of a hot companion is necessary to explain the excitation of the speckle objects at most orbital phases. However, during periastron passage of the hot companion, its ionising UV radiation is blocked by the dense primary wind for a few months.

The upcoming 2009.0 event

Numerous theories and explanations for the η Car phenomena were put forward, rejected and replaced by others. The outstanding problems of this extremely massive eccentric binary system raised in the course of the many observing campaigns covering the complete electromagnetic spectrum from X-ray to radio wavelengths, have still resulted in too few concrete solutions that lead to a full understanding of its nature. All these riddles are prime motives for continuing the photometric monitoring from La Silla as well as the interferometric and spectroscopic observing campaigns with the VLT telescopes.

η Car will be a prime target during its forthcoming periastron passage in 2009.0, where it will be important to monitor the peculiar optical features, viz. the light-peak event preceding the periastron passage, the following asymmetric eclipse-like dip, and subsequently the recovery of the brightness – perhaps surpassing the previous peak. Repeated near-infrared spectro-interferometric observations will allow us to monitor morphological changes over η Car's spectroscopic 5.5-year period, possibly revealing the motion and structural variation of the orbiting wind-wind collision zone, as predicted by the η Car binary model. Furthermore, future AMBER observations with higher accuracy might be sensitive enough to directly detect the hot companion.

Afterword

η Carinae is a most important object for study (as also summarised by Richichi and Paresce 2003) and can really be considered as the Rosetta stone in studies of
- the formation and evolution of extremely massive stars
- dynamical and chemical interactions with the environment
- stellar instabilities in the outer envelopes of single stars
- periodic tidal forcing by a companion and the formation of asymmetric nebulosity
- the relation of extremely massive stars to peculiar supernovae and hypernovae.

Ground-based monitoring has proven to be as useful as space-borne observations, but possesses the unmistakable advantage of providing data over a long time-baseline at modest cost. As such, the ESO Observatories in Chile will play a key role during the coming periastron passage in 2009.0 in the sense that the subsequent event to occur in July 2014.5 will be poorly observable. By the time the next optimally observable periastron passage occurs in 2020.0, the base line of observational technology will have completely changed, and we should have full use of the the ELT giant facility that will then be operational.

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