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Radio evidence of recent mass ejection from η Carinae

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ABSTRACT

The luminous blue variable η Carinae is almost certainly a double star: a hot secondary in an eccentric orbit around a massive primary. Radio observations with the Australia Telescope Compact Array at a wavelength of 3 cm, covering the period from 1992 to 2002, suggest that at the time of last periastron, 1998.0, material was tidally lifted from the primary star into its equatorial disc.

Key words: binaries: general – circumstellar matter – stars: individual: η Carinae – stars: mass-loss.

1 INTRODUCTION

Eta Carinae is situated in the Carina arm, at a distance of approximately 2.5 kpc, and with an initial main-sequence mass of at least 100 $M_{\odot}$, a luminosity of 6×10^6 $L_{\odot}$ and a history of giant eruptions (Innes 1903) is possibly the most luminous, spectacular and active star in our Galaxy. It is surrounded by the 'Homunculus', a dust and gas nebula 45 000 au in extent, most of which was expelled from the star during a giant eruption that reached its peak in 1843 March (Gaviola 1950; Currie et al. 1996; Kellog & Morse 1999). During this outburst η Carinae briefly brightened to magnitude -1, and outshone every star except Sirius. Eta Carinae is variable at all wavelengths from radio, to infrared, visible and X-rays, and although the nature and phase of these variations differs greatly from wavelength to wavelength, it is now known that all are well explained by the presence of a hot close binary companion orbiting with a period of 5.52 yr along an eccentric ellipse (Damineli 1996; Ishibashi et al. 1999; Duncan et al. 1999; Damineli et al. 2000) (for a contrary view see Davidson 1999; Davidson et al. 2000).

During the 1800s η Carinae suffered a series of dramatic outbursts, the largest of which, as we have said, resulted in the formation of the present Homunculus nebula. An optical image of the Homunculus can be seen on the Space Telescope Science Institute website (2002). These outbursts also occurred at intervals of 5.5 yr, and indeed at times that are now known to have been times of periastron (Damineli 1996). The most likely explanation is that at periastron tidal stress on a primary already close to the Eddington limit caused catastrophic mass ejection. The last of this series of spectacular mass ejections occurred in 1890; suggesting that this finally removed sufficient mass and energy to restore η Carinae to relative stability. However, it is the purpose of this paper to suggest that tidal mass ejection has not entirely ceased; radio observations at a wavelength of 3 cm suggest that some mass ejection occurred during the most recent periastron, 1998.0.

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2 OBSERVATIONS BETWEEN 1992 AND 1998: DESCRIPTION AND INTERPRETATION

Between 1992 and 1998, we monitored η Carinae with the Australia Telescope Compact Array (at Narrabri New South Wales) at approximately 4-monthly intervals (Duncan, White & Lim 1997). These imaging observations were conducted at two wavelengths, 3 and 6 cm, but here we confine ourselves to the 3-cm observations. Between 1992 and 1998 the radio image of η Carinae evolved dramatically. A barely resolved ($<$1-arcsec) source with a flux density of 0.6 Jy in 1992 June had by 1995 December grown to a complex source 4 arcsec in extent with a total flux density of 2.9 Jy. Thereafter its growth reversed and by 1998 January it had shrunk back to a small source of flux 1.0 Jy (Fig. 1).

Our interpretation of these observations has been outlined by Duncan et al. (1999); here we restate and refine it. Briefly, optical images show η Carinae to have a spoked equatorial disc (Duschl et al. 1995; Currie et al. 1996; Morse et al. 1998), and, although high-dynamic-range images show radio emission from the whole Homunculus – 16 arcsec in extent (Duncan et al. 1999), 99 per cent of the 3-cm radio emission we observe arises as thermal bremsstrahlung from within this disc.

A number of features of the apastron radio image (1995 December, Fig. 1) and the *Hubble Space Telescope* optical image (Currie et al. 1996) correspond. As Ebbets et al. (1997) have remarked, the radio-bright spot 1-arcsec NW of the primary star corresponds to the inner part of the optical feature known as the 'Paddle'. Similarly, the radio-faint region in the SW quadrant of the disc coincides with a tenuous patch of the optical disc, through which one can see the NW polar bubble. The bright bar in the radio image has the position and orientation (40° E of N) of the equatorial 'NE jet' seen in the optical images (e.g. Falke et al. 1996). Neither the optical nor the radio images show the SE half of the disc. In the optical images,

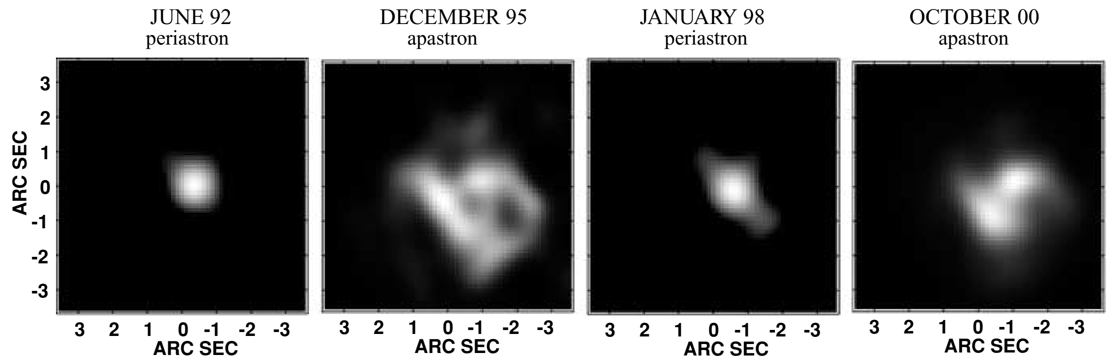

Figure 1. 3-cm radio images of η Carinae at four epochs. All images are centred on the position of the optical star. Although because of a plotting software idiosyncrasy the frames differ slightly in size, the scales and grid marks are identical and accurate.

the obvious explanation is that the SE disc is behind, and hidden by, the SE polar bubble. In the radio image this explanation is less plausible – the SE polar bubble should be transparent to radio waves – but we shall suggest an alternative explanation later.

The thermal radio emission of the disc requires that the gas of the disc be ionized, and thus that it be illuminated by ultraviolet light. However, we believe that very dense gas and dust in the innermost part of the disc, adjacent to the primary star, prevent the ultraviolet of the primary star penetrating to, and ionizing, the outer parts of the disc. Instead, accepting the evidence from observations at other wavelengths that a hot companion star orbits in the plane of the disc with apastron and periastron distances of approximately 14 and 3 au, respectively (Damineli 1996; Damineli, Conti & Lopes 1997), we believe that most of the ultraviolet needed to ionize the outer parts of the disc originates from this hot companion.

Fig. 2 is a model of the equatorial disc, though not a complete or detailed model; the real disc has a radius greater than 8000 au, Fig. 2 shows only the innermost 36 au; the real disc has spokes and clumps, in Fig. 2 gas and dust density depends only on radius. None the less Fig. 2 suffices to illustrate our explanation of the changes in source morphology seen in Fig. 1. At periastron the companion star, orbiting as it does in the plane of the dusty equatorial disc of the primary star, plunges into the denser dust and gas within a few au of the primary star, and its ultraviolet is able to penetrate and ionize only a small immediately surrounding volume, with a corresponding decrease of radio source-size and flux. At apastron, in contrast, the companion star rises clear of the region of very dense dust and successfully illuminates and ionizes most of the northwest half of the disc in which it is then situated. As no other plausible disturbance could travel fast enough to cause prompt brightening and fading of radio emission in distant regions of the disc (Duncan et al. 1997), this explanation seems compelling.

We believe that the SE half of the equatorial disc is radio-dark because it is shadowed by the NE ray seen in both the radio and optical images. On its NW side, the ray is brightly illuminated by the companion star, resulting as we have said in the radio bar, but to the SE the disc is shadowed by this ray.

Although differing in detail, the obscuration of the companion star at periastron described above resembles the obscuration of the binary pulsar PSR B1259-63 at periastron (Johnston et al. 2001).

Fig. 3 shows a plot of the observed 3-cm flux against time, plus a fitted curve. This fitted curve, comprising a simple sinusoid plus a linear secular increase, is based on data from 1992 to 1998 only, and its main purpose is to highlight the difference in behaviour during this interval from that after 1998. None the less we can ask how well Fig. 2 supports the binary-star model described above.

At first sight there may seem to be discrepancies; first, the period of the best-fitting curve is, not 5.52, but 6.1 yr, and secondly, the time of maximum radio flux lags the time of aphelion (i.e. phase 0.5) by approximately 7 or 8 months. However, neither of these apparent discrepancies contradict the binary-star model. The failure of the fit to find a period agreeing exactly with the orbital period of 5.52 yr is not surprising. One would not expect the observed light curve to

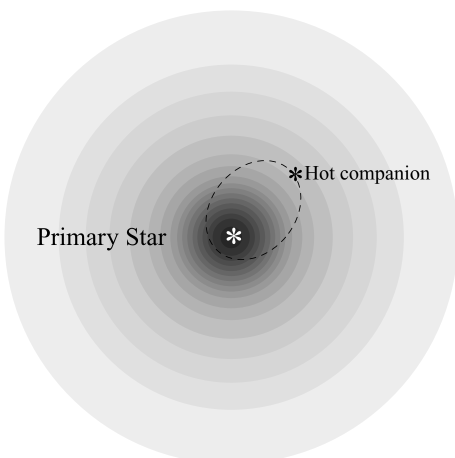

Figure 2. Model of the centrally concentrated dusty equatorial disc of the primary star, and the eccentric co-planar orbit of the companion star.

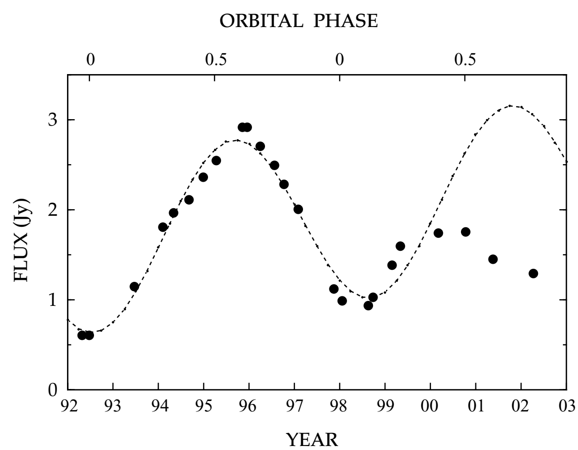

Figure 3. Evolution of the 3-cm radio flux of η Carinae from 1992 to 2002.

have a precisely, or even approximately, sinusoidal shape; its exact shape will depend on factors such as ionization and recombination rates and on the radial distribution of dust in the disc. Therefore, fitting a curve over a single cycle will give only an approximate period. In fact, if we omit a linear increase from the fit, we find a different period again, 6.5 yr (Duncan et al. 1999).

The lag between apastron and maximum radio flux, is similarly expected. Because of a finite ionization time, one would expect maximum ion density, and hence radio flux, to lag maximum ultraviolet illumination. A similar lag between periastron and minimum radio flux is less apparent, but this too is to be expected; at periastron most of the ionization is constricted to the region of high gas density close to the primary star where recombination will be rapid.

3 OBSERVATIONS BETWEEN 1998 AND 2002

After 1998, having monitored η Carinae throughout a full 5.52-yr orbital cycle, we (and more importantly the Time Assignment Committee) were confident that the radio flux variation would simply repeat its previous pattern, and consequently we reduced our monitoring to approximately once every 8 months. However, surprisingly, the radio flux failed to repeat its previous pattern; after the 1998.0 periastron the radio flux only partly recovered (Figs 1 and 3). The maximum radio flux reached during this cycle (1.7 Jy in 2000 October) was only 60 per cent of the maximum (2.9 Jy in 1995 December) observed during the previous cycle.

4 DISCUSSION

If one accepts the explanation given in Section 2 for the variation of the radio emission between 1992.5 and 1998.0, then the failure of the radio flux to fully recover after 1998.0 means that after the 1998.0 periastron ultraviolet obscuration in the disc increased. This, in turn, suggests that at or near periastron, stellar material was tidally transported to the disc. This conclusion is consistent with the series of large-mass ejections that occurred during the 1800s; Damineli (1996), as we have mentioned, pointed out that these outbursts had occurred close to times now known to have been times of periastron. Much earlier, Warren-Smith et al. (1979) had suggested that the equatorial disc ‘was formed by overflow from the outer Lagrangian points of a close binary star’.

Changes at other wavelengths also suggest mass loss at the time of the 1998.0 periastron. Corcoran et al. (2001) observed a reduction in X-ray flux, and deduced a 20-fold increase in the mass-loss rate from η Carinae during the 80 d following periastron. *Hubble Space Telescope* Imaging Spectrograph observations by Davidson et al. (1999) show that the apparent near-UV, visual and near-IR brightness of η Carinae increased by a factor of 2 in the period following the 1998.0 periastron.

One could ask why brightnesses at these wavelengths should have increased, whereas X-ray and radio brightnesses decreased. In our model, the reason is that the X-ray and radio emission are controlled by conditions in the equatorial disc and that obscuring gas and dust in the disc increased. In contrast, an observer on the Earth (and thus not in the plane of the disc) sees ultraviolet and visible emission arising from the surface of the primary star. Tidal mass-transport into the disc, by removing the outermost stellar surface, will therefore reveal a hotter and more luminous surface, just as it did during the great eruptions of the 1800s.

In conclusion, we believe that at or near the recent (1998.0) periastron of η Carinae and its companion, material was tidally lifted from the primary star into its equatorial disc.

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