Continuum and Spectral Observations of $\eta$ Carinae at Wavelengths of 3 & 6 Centimeters

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\textbf{Abstract.} Since June 1992, a program of continuum and spectral observations of $\eta$ Carinae with the Compact Array of the Australia Telescope at Narrabri, New South Wales about 420 km north-west of Sydney, has yielded images with a resolution (at a wavelength of 3 cm) of about $0''5$, and spectra with a resolution (for the H91\alpha line) of 70 km s$^{-1}$. The radio images have shown dramatic variations over this 6-year period. In this paper we review, and more carefully interpret, earlier observations (White et al. 1994; Duncan et al. 1995, 1997), describe more recent observations, and show that the observed behavior is well-explained by a binary-star model (Damineli et al. 1997).

1. Introduction

We have monitored $\eta$ Carinae with the Compact Array of the Australia Telescope at Narrabri, New South Wales, about 420 km north-west of Sydney, since June 1992. This array comprises six 22 m antennas spaced along a 6 km east-west track such that the baselines are almost equally spaced from 337 m to 5939 m. At an observing wavelength of 3 cm the array resolves out structures larger than about $30''$, and so resolves out the general Carina nebula, but images structure close to $\eta$ Carinae with a nominal resolution of about $1''$. Similarly, at a wavelength of 6 cm the nominal resolution is $2''$.

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Images have been made through the use of the MEM maximum entropy algorithm, and because we have observed η Carinae regularly and on some occasions have observed on 2 adjacent days, or simultaneously at 2 adjacent wavelengths, we have been able to check the accuracy and resolution of these images. These checks show that in the faint outer regions the achieved resolutions are similar to the nominal values, but that in the bright central region they are twice as good; i.e., θ'5 and 1'' at wavelengths of 3 cm and 6 cm, respectively.

The observations have also yielded spectra of the H91α (3 cm) hydrogen recombination line with a resolution of 70 km s⁻¹, and the H106α (6 cm) line with a resolution of 109 km s⁻¹.

In the following sections we shall describe the results of these observations, and show that they are well-explained by the binary-star model of η Carinae (Damineli et al. 1997). This model comprises a very hot secondary in an eccentric orbit around a massive evolved primary. The hot secondary provides the UV responsible for the ionization of the surrounding gas, but at periastron, when the secondary submerges in the dense gas and dust close to the massive primary, most of this UV is quenched.

2. Radio Images

Figure 1 shows the image obtained from observations with the 6-km array, at a wavelength of 6 cm, in April 1996, i.e., close to the epoch of maximum radio-brightness. This 6 cm image, although having poorer spatial resolution than a 3-cm image, has better brightness sensitivity, and is thus better suited for mapping faint outlying regions. The large outer oval running SE to NW corresponds to the optical Homunculus, i.e., the two polar bubbles, prominent in optical images (e.g., Morse et al. 1998), and known to have originated in the Great Eruption of 1837-1860 (Currie et al. 1996). The isolated feature centered at about (−10'', −5'') corresponds to the optical SW shell, that may be debris thrown out in an early unrecorded eruption. The Homunculus and SW shell are both extremely faint; the brightness levels of the outer 8 contours decrease exponentially, so that the brightness on the outermost contour is only one thousandth that of the central peak. In Fig. 1 we see also a bright inner region (the innermost 8 contours), and we discuss this in the next paragraph.

Because, other things being equal, high resolution is always an advantage, the bright inner region, where sensitivity is not a problem, is better studied at a wavelength of 3 cm. Figure 2 shows the 3-cm wavelength image for April 1996. To ensure a true impression of the source of the strong emission, only linearly spaced contours have been used. This image is displayed in two forms; the contours on the left describe the brightness distribution quantitatively, but the 'profiles' on the right are perhaps more graphic. The bright inner region thus revealed resembles Davidson et al.'s (1997) optical image of the inner region in that it is asymmetrically situated in relation to the star; it appears to be a semi-circle with its diameter crossing the position of the star. We believe that it corresponds to the near, or NW, half of the equatorial skirt seen in optical images (e.g., Morse et al. 1998). We believe that the hot star orbits in the plane of this equatorial skirt, and that the far, SE, side of the skirt is not seen because it is shadowed from the companion hot star's UV by the very dense inner part of
the skirt close to the primary star. (For an alternative explanation see Damineli et al., this issue.)

Many of the fine-scale structures also correspond in the radio and optical images. Ebbets et al. (1997) have already identified the radio-bright region 1" to the NW of the star as the inner part of the optical feature termed the ‘Paddle’, and, as we shall detail later, we identify the radio-bright ridge crossing the position of the star with an inner counterpart of the optical NE ray. Both features are believed to lie in the plane of the equatorial skirt (Duschl et al. 1995). The radio-faint area in the SW quadrant of the skirt (Figs. 2 and 4) also has a counterpart in the optical image (Morse et al. 1998); it coincides with a tenuous region in the skirt through which one can see the NW polar bubble.

Our explanation of the radio-dark region to the SE side of the stars, i.e., the lack of emission from the far side of the equatorial skirt, needs refinement. If this were the result of the shadowing of the hot star’s UV by a compact globular dense gas and dust core at the skirt center, then this shadow would be cone-shaped with the apex at this center. In fact, however, the boundary between the radio-bright and radio-dark regions is not a cone but a straight edge. This bright ridge and edge has the position and orientation (38° E of N) of the equatorial ‘NE jet’ seen in optical images, and as we have foreshadowed, we now associate, not only the bright ridge, but also the shadow to the SE of...
Figure 2. Continuum images of $\eta$ Carinae as observed at a wavelength of 3 cm in April 1996. The map center is at the position of optical star. Left: Simple linearly spaced contours. Peak brightness 455 mJy arcsec$^{-2}$; contour intervals 45.5 mJy arcsec$^{-2}$. Right: 3-dimensional profile representation of the same image.

this ridge, to that optical ray. We conclude that within about 2$^{\prime\prime}$ of the primary star, the ray extends both to the NE and SW of the star, and that it is dense, its near surface strongly ionized by UV from the hot secondary star, and the skirt on its far side shadowed. Falcke et al. (1996), from speckle imaging, have also concluded that the NE ray has an inner counterpart.

We have also observed $\eta$ Carinae with Australia’s long baseline array, the shortest baseline of which is about 100 km; this is insensitive to structure larger than about 0$^{\prime\prime}$1 but sensitive to milli-arcsec structure. Though the 5 sigma limit is better than 20 mJy, no such milli-arcsec structure has been found, which suggests that $\eta$ Carinae’s radio image has no non-thermal stellar core.

3. Evolution of the Radio Continuum Emission

In the years from 1992 to 1998, $\eta$ Carinae’s radio image evolved dramatically. When first observed with the Australia Telescope, in June 1992, it was a small, barely resolved source with a rising spectrum, no polarization, and a total flux density of 0.6 Jy; that is what one would expect from thermal emission from a dense stellar wind. However, when next observed, one year later, the source area had increased, and the continuum flux had almost doubled to 1.1 Jy. Subsequent monitoring showed that $\eta$ Carinae was in an expansion phase; both its source area and complexity, and total flux density, steadily increased until November and December 1995, when its total flux reached 2.8 Jy: almost fivefold its June 1992 value. Thereafter its evolution reversed and it began to shrink and fade.

Figure 3 details the history of the 3-cm wavelength total radio flux. Observers at other wavelengths have all seen maxima or minima (which we now interpret as signatures of periastron) in January 1998, but, in contrast, the ra-
dio flux is still falling. This itself is not surprising; radio emission is a measure of ionization, and because of finite recombination and dissociation times, such a lag between the ionizing activity and the radio flux is to be expected. The disconcerting question is 'why did not a similar lag occur at periastron in June 1992?' This is the one facet of η Carinae's behavior not simply explained by the binary-star model; the fitted sinusoid in Fig. 3 suggests a cycle of, not 5.5, but 6.5 years.

Cox and his colleagues (Cox 1997) have measured η Carinae's flux at mm wavelengths. The mm-wave fluxes show a variation very similar to that of the 3-cm fluxes described above.

We now discuss the corresponding changes in image morphology. The outer Homunculus and SW shell have a brightness of only a few hundredths of the central peak and are unchanging; changes from periastron to apastron occur only in the bright inner region, which corresponds to the near, or NW, side of the equatorial skirt. Therefore, to avoid undue emphasis of the faint outer regions, we again look at images with linearly spaced brightness levels. Figure 4 confirms that at periastron (June 1992) the radio flux arose from a small source coincident with the optical stars. We believe that this is because at periastron the hot star was submerged in the dense and dusty inner part of the equatorial skirt, so that (in the plane of the skirt) its ionizing, and hence radio-emission generating, UV penetrated only a short distance. An analogy would be looking at a light through a thick fog.

However, near apastron (April 1996) the radio flux arose from a semicircular area with the position, patchiness, and shape of the near, or NW, half of the optical equatorial skirt (e.g., Morse et al. 1998). Duncan et al. (1997) have shown that between June 1992 and November 1995 the NE trending ridge (Figs. 2 and 4) progressively brightened and lengthened. As we have said, we identify this radio ridge as a dense inner counterpart of the (NE) optical ray with the same center and orientation. Furthermore we believe that at periastron immersion of the hot companion star in this dense inner ray largely quenched its
Figure 4. The evolution of η Carinae’s 3-cm (8585 MHz) continuum images from 1992 till 1998. Images at three epochs: June 1992 (periastron), April 1996 (shortly after apastron), and January 1998 (shortly after periastron).

UV, but that as it moved out from this ray its UV reached and ionized, not only other parts of the equatorial skirt, but also a progressively greater length of the ray itself, thus causing its counterpart, the radio ridge, to lengthen. Gas on the far (SE) side of the skirt, however, remained at all times shadowed by the NE ray and unionized.

By January 1998, η Carinae’s 3-cm image had shrunk and faded markedly, but was still not as small and weak as it had been in June 1992. As we saw in the total flux curve (Fig. 3), minimum radio emission, i.e., minimum total ionization, is currently lagging periastron (January 1998).

4. Evolution of the Spectral Emission

η Carinae’s hydrogen recombination line emission has been studied at cm wavelengths in Australia, and at mm wavelengths by Cox et al. (1995) using the SEST telescope in Chile.

Our search for 6-cm (H106α) recombination emission began late and has often been unsuccessful. We first looked for it, and found weak emission, in September 1994, but we began to regularly monitor at this wavelength only in November 1995 and by then it had become undetectable. However at the last observing session, January 1998, it reappeared. It seems therefore that the 6-cm spectral emission is strongest near periastron.

Monitoring of the 3-cm (H91α) recombination emission has been regular and consistently successful. We first looked for the H91α line in June 1993, i.e., about a year after periastron. Then we found a double-peaked spectrum; the larger peak lying at -240 km s⁻¹, and the smaller at -35 km s⁻¹ (These velocities are approximate as our channel width is 70 km s⁻¹). Six months later, in January 1994, these peaks had broadened and merged (Fig. 5). Since then, although being slightly stronger and broader at apastron, the spectra have remained much the same. On the evidence of X-ray and optical observations, periastron has now past, yet, when last observed in January 1998, though the radio spectral flux had halved, the spectral width was still great. In this tardy
response to periastron, the evolution of the spectral emission resembles that of the continuum.

Figure 6 shows the sky position of the emission contributing to each of the spectral peaks seen in Fig. 5. In June 1993 the less blue-shifted, \((-35 \text{ km s}^{-1}\)) emission arose near the star (or stars), and the more highly blue-shifted \((-240 \text{ km s}^{-1}\)) emission arose further out, near the ‘Paddle’. Later, in January 1994, when a much greater part of the near half of the skirt was ionized, the spectral emission, though centered on the Paddle, arose from a wide area, and the spectrum broadened, so that the two earlier peaks merged.

The mm-wave recombination lines, observed by Cox et al. (1995), are much stronger than those we observe at cm wavelengths. This strengthening of spectral emission as one goes to shorter wavelengths continues the pattern from 6 to 3 cm, and is expected theoretically. Furthermore, their mm-wave spectra, although very broad and blue-shifted by normal standards, are much less so than ours at cm wavelengths; they found a blue-shift of \(-50 \text{ km s}^{-1}\) and a width of about 100 km s\(^{-1}\).

We believe that the observed blue-shifts and spectral widths are consistent with the known Hubble-like pattern of gas ejection in the skirt (Currie et al. 1996). We see only blue-shifted emission because only the near side of the skirt is ionized. We expect mm emission to arise in high density regions, close to the stars, and there ejection velocities are low; the observed spectral velocity \((-50 \text{ km s}^{-1}\)) is in fact similar to the measured proper-motion velocity in the vicinity of the Weigelt blobs (Currie et al. 1996). Similarly, in June 1993, we saw 3-cm emission with a velocity of \(-35 \text{ km s}^{-1}\) from close to the stars. Further out, in the vicinity of the Paddle, the observed spectral velocity is \(-240 \text{ km s}^{-1}\),
Figure 6. Images of $\eta$ Carinae's spectral (H91$\alpha$) emission at the annotated velocities and dates (contours), superimposed on images of the concurrent continuum emission (grayscale).

and again, this is similar to the measured proper-motion velocity in this vicinity (Currie et al. 1996).

Because of the radial gradient of the ejection velocity, spectral widths will be proportional to the radial range from which the emission arose. In January 1995, when the emission came from a large radial range, the spectral width was large.

References

Cox, P. 1997, ASP Conf. Ser., 120, 277
Ebbets D., Morse, J., Davidson, K., & Walborn, N. 1997, ASP Conf. Ser., 120, 249
Section C. Proper Motions