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INTENSE RADIO OUTBURST FROM THE SUPERMASSIVE STAR η CARINAE

R. A. DUNCAN,[1] S. M. WHITE,[2] J. LIM,[3] G. J. NELSON,[4] S. A. DRAKE,[5] AND M. R. KUNDU[2]

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ABSTRACT

On five occasions between 1992 June 29 and 1994 May 3, we have used the Australia Telescope Compact Array to image η Carinae at a wavelength of 3 cm and a resolution of 1″. These observations have revealed remarkable activity. Since 1992 June, the total flux density has increase from 0.8 to 2.2 Jy, and the original single compact source has grown to a complex of sources spread over an area of about 16 arcsec^2 (Fig. 1). Strong hydrogen recombination-line spectral emission has appeared at the site of the strongest of these new sources. This recombination emission has the largest spectral width ever observed from a star, ± 250 km s^{-1}, and reveals gas with turbulent velocities as great as 250 km s^{-1} approaching us at an average velocity of about 200 km s^{-1}. We believe that this radio outburst has been caused by a more than threefold increase of ultraviolet luminosity, and consequent ionization of previously neutral gas clouds.

Subject headings: circumstellar matter — H II regions — radio lines: stars — stars: activity — stars: individual (η Carinae) — supergiants

1. INTRODUCTION

With a mass variously estimated between 100 and 150 $M_\odot$ (Meaburn et al. 1983; van Genderen & Thé 1984), η Carinae is thought to be the most massive star in the Galaxy and has long been famous for its variability and nova-like mass ejections. An outburst which began during the 1830s (Innes 1903; Gratton 1963; Walborn & Liller 1977) raised its visual magnitude to -1, making it for 15 years the second brightest star in the sky.

Subsequently, it dimmed to its present-day visual magnitude of 7. This dimming is mainly attributable to a resultant dust envelope and consequent conversion of its immense visual and ultraviolet energy to infrared. Currently, η Car's bolometric luminosity is $6 \times 10^6\ L_\odot$ (Westphal & Neugebauer 1969), making it at 10 and 20 μm the brightest extra-solar system infrared source in the sky (Neugebauer & Westphal 1968; Robinson, Hyland, & Thomas 1973; Aitken & Jones 1975).

Radio waves pass freely through dust, but until recently there has been no radio telescope in the Southern Hemisphere with the arcsecond resolution needed to study this object. The Australia Telescope Compact Array (ATCA), commissioned in 1988, has remedied this deficiency, and on four recent occasions, 1992 June, 1993 June, and 1994 January and May, we have used this instrument to image η Car at a wavelength of 3 cm. The first high-resolution image of η Car was obtained on 1992 June 29 (White et al. 1994). Further observations (the latter including both continuum and the H91α recombination line) were made on 1993 June 18, 1994 January 30, and 1994 May 1 and 3. Progressive changes in this series of images show that η Car is in the throes of a radio outburst; the flux density has almost tripled in this period, and many new morphological features have appeared.

[1] Australia Telescope National Facility, P.O. Box 76, Epping, NSW 2121, Australia.

[2] Department of Astronomy, University of Maryland, College Park, MD 20742.

[3] Solar Astronomy 264-33, Caltech, Pasadena, CA 91125; and Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 1-87, Nankang, Taipei, Taiwan 115, Republic of China.

[4] Australia Telescope National Facility/Paul Wild Observatory, P.O. Box 94, Narrabri, NSW 2390, Australia.

[5] Laboratory for High Energy Astrophysics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

2. OBSERVATIONS

The configuration used comprised six 22 m antennas spaced along a 6 km east-west array such that the baselines were almost equally spaced from 337 to 5939 m. At the observing wavelength of approximately 3 cm, this set of baselines was insensitive to structure larger than about 30″ and so resolved out the general Carina Nebula, but imaged structure close to η Car with a nominal resolution of about 1″, and in practice, because of the excellent signal-to-noise ratio, an actual resolution of about 0.″5.

In all but one session, the ATCA's ability to observe simultaneously at two similar but independent wavelengths was used to check the results. In 1994 May the results were checked instead by independent observations on two adjacent days. Details of the observing dates, frequencies, and other parameters are given in Table 1.

The observations in 1993 June, 1994 January, and 1994 May included the H91α recombination-line spectrum. In 1993 June the second frequency was set on the H90α line and, reassuringly, gave an identical profile. In 1993 June the spectrum covered a usable velocity range of ± 800 km s^{-1}, while in 1994 January and May it covered a range of about ± 1700 km s^{-1}.

Images and spectra were obtained through the use of the AIPS and MIRIAD software packages.

3. RESULTS

3.1. *Continuum*

The continuum image for 1992 June has been given by White et al. (1994), though with logarithmic intervals which emphasized weak outlying emission. The continuum images for all four epochs are shown with linear contour intervals in Figure 1 (Plate L9). There, images obtained by using the CLEAN algorithm (contours) are superposed on those obtained by using the MEM algorithm (Cornwall & Braun 1989) (gray scale). The CLEAN algorithm achieved a resolution of about 1″. In regions where the flux density is strong, the MEM algorithm does somewhat better (Narayan & Nityananda 1986), and in the central part of the MEM images we estimate the resolution to be about 0.″5. All observations were replicated either at adjacent frequencies or on adjacent

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TABLE 1

OBSERVING PARAMETERS

Date	First Frequency (MHz)	Second Frequency (MHz)	Bandwidth (MHz)	Number of Channels
1993 Jun 18.....	8585 (H91α)	8873 (H90α)	64	64
1994 Jan 30.....	8585 (H91α)	8730	128	64
1994 May 1.....	8585 (H91α)	...	128	64
1994 May 3.....	8585 (H91α)	8500	128	64

days (see Table 1), and in Figure 1 such replicated data are combined.

Many considerations attest to the fidelity of these images. Although the four images shown in Figure 1 were observed at widely separated times and under greatly differing observing conditions, many common features can be seen. More significantly, in all sessions except 1994 May we observed at two well-spaced frequencies in the 3 cm band simultaneously, and in every case the images for the two frequencies were in excellent agreement. Finally, in 1994 May independent observations were made on two separate days, May 1 and 3, and again excellent agreement was obtained.

Figure 1 reveals a dramatic evolution of the radio source between 1992 June and 1994 May; over this period the radio source increased markedly in both total flux and extent. In 1992 June the continuum image comprised a single peak with an integrated continuum flux of 0.8 Jy (in White et al. 1994 we reported 0.7 Jy, but the flux of our prime calibrator, 1934−638, has since been reassessed). By 1993 June another, almost equally bright source had appeared about 1″ to the northwest of the earlier peak and the integrated flux had increase to 1.2 Jy. By 1994 January more patches of radio emission had appeared, and the total flux had increased to 2.2 Jy. Only a small change was seen in 1994 May; by then the outburst appeared to have stabilized.

As reported earlier, observations within the 3 cm band during 1992 June showed that the flux increased slightly with increasing frequency (White et al. 1994). Additional observations in 1994 January at 6 and 3 cm (not listed in Table 1) confirmed this rising spectrum.

3.2. *Spectral Emission*

Figure 2 shows spectra of the H91α hydrogen recombination-line emission. The spectrum observed in 1993 June showed two pronounced peaks. The smaller peak on the right arose from gas approaching us at 35 km s^{-1}, that is, at the systemic velocity of η Car. The larger peak on the left arose from gas approaching us at 240 km s^{-1}. By 1994 January a single broad peak centered at −200 km s^{-1} had enveloped both earlier peaks, and this single broad peak was seen again in 1994 May.

The overall width of the spectral peaks seen in 1994 January and May, ±250 km s^{-1}, is, we believe, the largest ever observed from a star; the previous greatest width, ±125 km s^{-1}, was observed from the star G25.5+0.2 (Subrahmanyan et al. 1993). This great width indicates extreme turbulence.

Lack of space prevents our presenting images for each frequency channel, but Figure 3 (Plate L10) shows representative examples. Both the −35 km s^{-1} emission observed in 1993 June and emission in the red and blue wings of the broad spectral peaks observed in 1994 January and May arose about

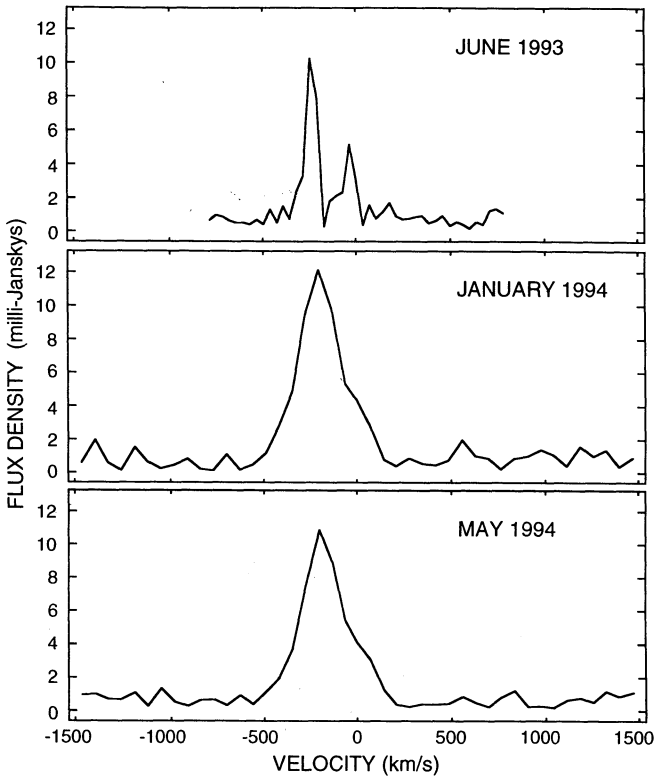

FIG. 2.—Radio spectra of the H91α recombination line at successive epochs. In 1993 June the observations covered a band of ±800 km s^{-1}. In 1994 January and May the observations covered a band of ±1700 km s^{-1}, but the regions outside of ±1500 km s^{-1} were featureless and are not shown.

0″.5 northwest of the original 1992 June continuum source (Fig. 3). Emission at the center of the −240 km s^{-1} peak seen in 1993 June arose close to, and emission at the center of the 200 km s^{-1} peak seen in 1994 January and May coincided with, the northwest continuum source (Fig. 3).

4. INTERPRETATION

4.1. *Continuum*

As reported earlier (White et al. 1994), and seen again in Figure 1, the 1992 June observations showed a single radio source. This completely lacked polarization and, at the continuum peak, showed a flux which rose with frequency. Therefore, although lacking subarcsecond optical astrometry, largely because of the poor registration of the optical and radio reference frames in the far southern sky, we concluded that this single radio source coincided with the optical star, and that the emission arose as thermal bremsstrahlung in a dense stellar wind, i.e., as suggested by Davidson (1971), that η Car is a compact H II region. This conclusion, we believe, remains substantially true, although it is now less certain how the emission should be apportioned between a central stellar wind and peripheral gas clouds.

Any interpretation of the observations must explain the rapidity of the changes seen in Figure 1. Consider, for example, the change between 1992 June and 1993 June. The new peak (Fig. 1) lies 1″ northwest of the old peak. If the old peak is assumed to be the star and the new peak is assumed to have arisen from a disturbance propagated from the star, and we accept η Car to be at a distance of 2.5 kpc (Walborn 1973; Feinstein, Marraco,

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& Muzzio 1973; Thé, Bakker, & Antalova 1980), the implied velocity is $\geq 12{,}000$ km s^{-1}. The distant northern peak seen in 1994 January and May (Fig. 1) implies a velocity $\geq 50{,}000$ km s^{-1}. For any object other than a supernova, such velocities are too fast for mass ejecta.

Two further considerations suggest that high-velocity ejecta are not involved. First, such high-velocity material would inevitably excite strong shock waves and consequent nonthermal emission, yet, as we have said, the spectral index and null polarization suggest thermal emission. Second, the new sources which appeared between 1992 June and 1994 May did not subsequently move but simply brightened.

We therefore believe that a disturbance propagating from the star has excited preexisting low-velocity gas clouds, i.e., gas clouds expelled from the star in much earlier eruptions. The only plausible disturbance which could travel with the required velocity is electromagnetic radiation. We therefore suggest that the observed changes have been caused by an outburst of ultraviolet radiation. Historical observations of outbursts of 1 mag in visual brightness suggest that such an ultraviolet outburst is possible (de Vaucouleurs & Eggen 1952).

As Strömgren (1939) showed, hot stars are surrounded by a sharply bounded region of almost completely ionized gas. Outside the boundary, the degree of ionization drops abruptly to zero. The volume of (or, more strictly speaking, the number of ions in) this "Strömgren sphere" is proportional to the UV luminosity of the star. We retain the idea (White et al. 1994) that the single radio peak seen in 1992 June arose from a dense ionized stellar wind surrounding the star, but suggest that a subsequent UV outburst has increased the extent of the Strömgren sphere so that it now encompasses preexisting clumps of gas, probably expelled in the 1840s eruptions. Possibly these clouds are compact dense lumps of neutral gas, even now ionized only on the surface facing the star. The present observations appear to be the first detection of a strong stellar ultraviolet outburst through its effect on a surrounding ultracompact H II region; Hughes (1993) and Hughes, Cohen, & Garrington (1994) have reported changes in some of the components in Cepheus A, but these appear to be of a different nature.

Such rapid ionization and heating will of course cause strong local gas flows and consequent turbulence and shocks. Nonetheless, the prime cause remains UV radiation, and the prime emission mechanism, thermal bremsstrahlung.

At first sight it might appear that new emission is confined to the west of the original 1992 June source (Fig. 1), but this is not so. Strong new emission has appeared to the east of the original source, but this new emission lies very close to, and (at the available resolution) has merged with and enlarged, the original source. This suggests that to the east and southeast a dense neutral gas and dust cloud lies very close to the star and that this has shielded more outlying southeastern regions from UV radiation.

An increase in UV radiation increases the radius of the H II region because, by the very act of ionizing the hydrogen, the UV radiation decreases the region's opacity. Evaporation of dust which is thought to lie close to the star (Robinson et al. 1973; Joyce 1975; Hyland et al. 1979; Warren-Smith et al. 1979) by the enhanced UV emission would reinforce this effect. Observed decreases in reddening suggest that decreases in dust density have occurred in the past (e.g., between 1930 and 1940; van Genderen & Thé 1984). Thus dust evaporation may be a contributing factor.

In summary, we believe that the progressive growth and brightening of the radio continuum source in Figure 1 have been caused by an increase in the star's UV luminosity and a consequent increase in the volume surrounding the star subject to ionization. The new continuum sources comprise preexisting gas clouds newly encompassed within the Strömgren sphere. If the region were optically thin to thermal radio emission, and if the fraction of UV radiation absorbed by dust remains constant, then the increase of radio emission would be a measure of the increase of UV luminosity (Aller 1984, p. 225). On this basis, the UV luminosity must have increased by a factor of about 3. In terms of ionizing flux, the increase is $10^{47.9}$ photons s^{-1} (see Snell & Bally 1986), that is, the equivalent of an O9 star (Thompson 1984). However, the rising continuum spectrum (White et al. 1994) shows that the brighter regions of radio emission are marginally optically thick; hence not all the radio emission is observed, and the actual increase of UV luminosity must exceed the above estimates.

By assuming that the gas is homogeneous and marginally optically thick at our observing frequency, one can estimate the minimum mass of additional ionized gas required to cause the observed increase in radio flux (1.4 Jy). This minimum mass is approximately 0.04 $M_\odot$. This ionized gas should produce optical line emission. For example, if the gas is optically thin at Hβ, the Hβ flux should be 4.5×10^{-10} ergs cm^{-2} s^{-1} (see Milne & Aller 1975), which, although expected to be spread over the radio-emitting region, should be easily detectable. Nondetection of such Hβ emission would argue against our model (although it could simply mean that the radio-emitting region is optically obscured), but detection would strongly support it.

4.2. *Spectral Emission*

By observing the H91α recombination-line spectrum, we had hoped to obtain velocities for each of the optical features evident in the *HST* images of η Car and its surrounding "homunculus" nebula (Hester et al. 1991; NASA 1994). In the event, recombination-line emission was detected only from small regions with no obvious counterpart in the optical images. However, that it escaped detection elsewhere is, with hindsight, unsurprising; recombination-line strengths depend sensitively on the temperature, density, and population distribution of excited levels (Goldberg 1966). Our detection threshold was about 3 mJy, so that all that can be said is that line emission from other areas was at least 5 times weaker than that from the vicinity of the northwest continuum peak.

The high-velocity spectral emission seen in all observations since 1993 June was close to or coincided in position with the new northwest continuum source. At 3 cm, line emission is favored by high density (Aller 1984, p. 96), so that if the northwest peak represents a dense ionized cloud, this coincidence is understandable.

In the *HST* image of η Car and its surrounding gas clouds published by Hester et al. (1991), and more clearly in the improved *HST* image recently released by NASA (1994), structure to the southeast seems to lie in front of and to occult structure to the northwest. On this evidence, therefore, one might conclude that the gas cloud responsible for the new northwest continuum and line emission source is more distant than η Car. However, the cloud's approach velocity of 200 km s^{-1} suggests instead that it lies in front of η Car. If this is true, it has no obvious optical counterpart.

Emission from the wings of the spectral peak arose closer to

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the original 1992 June radio source, which we believe represents the optical star. We suggest, therefore, that the spectral emission seen in 1994 January and May has two components: a very broad component arising from very turbulent gas near the star, plus a narrower component, centered on -200 km s^{-1}, arising from the dense gas cloud responsible for the northwest continuum peak.

4.3. *Summary*

In summary, we believe that the dramatic increase in the continuum and recombination-line radio emission from η Car during the 18 months from 1992 June to 1994 January was caused by a threefold increase of UV luminosity, and consequent ionization of preexisting gas clouds.

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