The Radio Outburst of η Carinae

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Abstract. A major radio outburst of the famous southern star η Carinae commenced in 1992/1993 and has made it one of the brightest stellar radio sources in the sky. The increase in flux is associated with the appearance of new regions of emission within several arcseconds of the star. Broad recombination lines are detected from the new sources, indicating that the radio outburst is due to the ionization of a large amount of previously–neutral gas in the immediate vicinity of the star. It is inferred that a pulse of ionizing radiation passed through material in the equatorial plane of the system.

η Carinae became famous in the 19th century when it brightened visually and was the second brightest star in the sky for a time. It subsequently faded, but was then discovered to be the brightest source of mid–infrared emission in the sky outside the solar system. It is thought to be one of the most massive and luminous stars in the galaxy ($\sim$ 100 $M_\odot$), in an unstable phase of post–main–sequence evolution when its outer layers are unstable and it undergoes sporadic massive ejections. The ejection of the 19th century is estimated to have involved 3 $M_\odot$ of material travelling at $\sim$ 500 km s^{-1}, which now forms a bipolar optical nebula known as the Homunculus. It is widely believed that η Carinae will continue to expel its outer layers via ejections and a stellar wind estimated at 10^{-3} $M_\odot$ yr^{-1} until it becomes a Wolf–Rayet star. Massive stars in this evolutionary state are known as "Luminous Blue Variables" (LBVs), and although few in number they can have a major influence on the interstellar medium because of the enormous amounts of mass, energy and momentum which they deposit in the ISM.

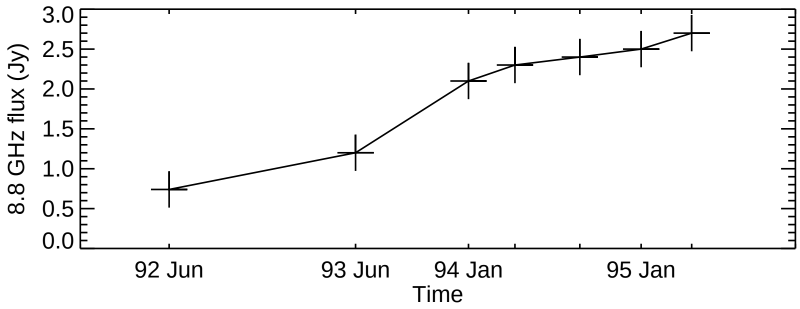

Figure 1. The time evolution of the flux from η Car at 9 GHz.

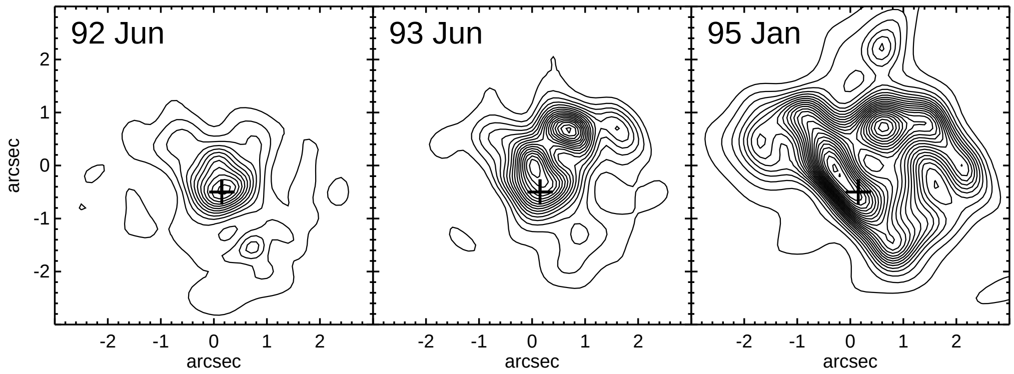

Figure 2. 9 GHz images of η Car at three epochs (contour interval 400 K). The cross in each panel marks the location of the 1992 peak.

Being in the southern sky, η Carinae could not be observed with high–spatial–resolution at radio wavelengths until the Australia Telescope (AT) commenced operation. It has been observed with the AT a number of times since 1992. The initial observation (White et al. 1994) revealed a strong central peak surrounded by lower–level emission distributed quite symmetrically about the peak and showing two axes of symmetry. The overall dimension of the radio source was of order $10''$; the total flux at 9 GHz was 0.7 Jy, with approximately 0.3 Jy concentrated in the central peak. The central peak was consistent with a stellar–wind source corresponding to a mass loss rate of 3×10^{-4} $M_\odot$ yr^{-1} in a symmetric wind with a velocity of 500 km s^{-1}.

In a second observation to look for recombination lines one year later, it was noticed that the flux had increased, and that a new source had appeared $1''$ to the NW of the original peak. A monitoring campaign therefore was initiated (Duncan et al. 1995), with observations every 4 – 8 months (corresponding to the times at which the AT is in its widest configurations and affords the best spatial resolution). The flux continues to rise; a time history at 9 GHz is shown in Figure 1. The nominal resolution for our 9 GHz data is $1\farcs0$, but the signal–to–noise in these images is of order 2000 and we can use some of this signal–to–noise to achieve better spatial resolution. A convenient way to do so is using maximum–entropy deconvolution, which produces maps with an effective resolution which varies spatially according to the local signal–to–noise level.

Figure 2 shows such MEM images at three different epochs. The maps have $0\farcs1$ cell size and we estimate the resolution to be approximately $0\farcs5$ at the peaks. The 92 June image shows the central peak discussed above, which is clearly seen to be extended to the north; lower–level emission extends to the north–west and north–east. One year later the region around this peak has brightened and the maximum has shifted to the north, while a new source has appeared to the north–west. The continued development of the source is shown in the 95 January map, where we see extended emission at a number of locations to the upper right of a line running from south–west to north–east. This line is one of the symmetry axes of the optical Homunculus nebula, which is bipolar with the polar axis running from south–east to north–west and tilted by $\sim 30°$ to the plane of the sky, with the north–western lobe of the nebula believed to be on the far side of the star; thus the SW–NE axis corresponds approximately to the equatorial plane of the system.

Recombination lines are detected from η Carinae (Duncan et al. 1995). This confirms that the new emission is produced by newly–ionized gas which previously was neutral and therefore invisible in the radio images. The detected line emission is blue–shifted with respect to the star: it forms a line approximately 500 km s^{-1} wide (possibly the broadest recombination line of any galactic source), centered at -200 km s^{-1}. The negative velocity appears puzzling at first glance since, as noted above, the emission is predominantly to the north–west of the star and the material in the Homunculus nebula at that location is all red–shifted. Consequently we believe that the gas we see in the radio images is mostly in the equatorial plane on this side of the star, rather than in the polar outflow on the far side of the star.

To explain the newly–ionized gas we require that a pulse of ionization has moved through the material around the star. This is presumed to have been a pulse of UV radiation, although no independent evidence for this hypothesis has yet been reported. The peaks in the radio images have brightness temperatures of 10^4 K, and the radio spectrum has a positive slope at 9 GHz, which is consistent with the interpretation of thermal free–free radiation from gas ionized by a UV pulse. A simple argument (which assumes that the gas is just optically thick) suggests that the minimum mass of newly–ionized gas which can explain the radio flux increase is of order 0.04 $M_\odot$. If the mass loss rate of η Car is 0.001 $M_\odot$ yr^{-1}, this corresponds to 40 yrs of mass loss, and the size of the radio source is consistent with this timescale and an outflow velocity of 500 km s^{-1}.

References

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