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The Radio Cycle of Eta Carinae

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Abstract. We briefly summarize recent radio observations of the η Car cycle, including the surprising failure to detect a velocity shift from binary motion in the system.

Microwave Emission from η Carinae

We have monitored the microwave emission from η Carinae with the Australia Telescope now for just over two 5.5 year cycles (White et al. 1994; Duncan et al. 1995, 1997; Duncan & White 2003). Figure 1 shows the microwave light curve from 1992 to 2004: the flux plotted is the total flux at 8.6 GHz, including a small contribution from the Homunculus nebula. However, the images show that the bulk of the flux comes from a region of dimension just $4''$ across. The changes in the spatial morphology that accompany the flux changes are illustrated in Figure 2. The three epochs shown correspond to a 5.5 year cycle from a flux maximum (1995 November) through a flux minimum at a spectroscopic event (1998 January) and back to the next flux maximum (2000 March). These images are made using super–resolution techniques that emphasize small–scale structure at the expense of poorer dynamic range, so the fainter outer regions of radio emission are not visible in Fig. 2. The radio emission has a peak brightness temperature of order 10^4 K and has a rising flux spectrum. Recombination line data show that all the radio–emitting features are blue–shifted. The system contains a luminous blue variable (LBV) and a massive unseen companion. The interpretation that fits these observations is that the radio emission arises in gas in the dense outflow from the LBV that is photo–ionized by an ultraviolet source. The LBV is too cool to ionize the gas, but the inferred companion is a hot star that can supply ionizing photons. The elliptical binary orbit provides a natural explanation for the radio cycle. When the hot companion is close to the LBV, all its ionizing photons are swallowed by the extreme density in the LBV wind, whereas at apastron the hot star is a long way from the LBV and ionizing photons can escape and ionize more distant regions of the outflow. The observed ionized gas is always blue–shifted because at apastron the hot star happens to be on our side of the system, and hence most easily ionizes gas even closer along our line of sight that, by geometry, must be blue–shifted in an outflow.

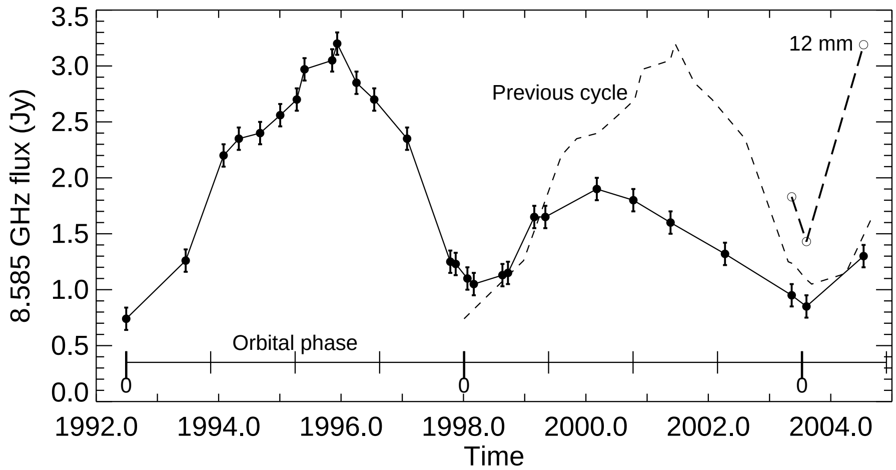

Figure 1. The light curve of η Carinae at 8.6 GHz, from imaging observations with the Australia Telescope Compact Array. Recent flux measurements at 21 GHz (12 mm) are also shown.

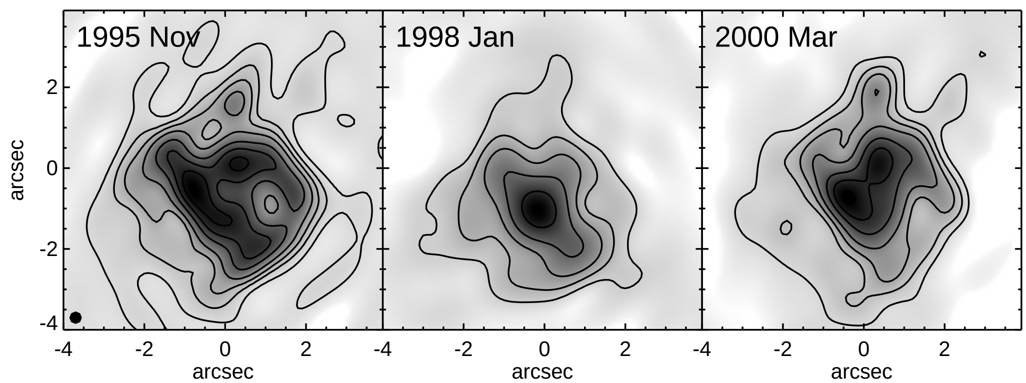

Figure 2. The evolution of the spatial distribution of the radio flux over the 5.5 year cycle. These are 8.6 GHz images from the ATCA with contours at brightness temperatures of 200, 500, 1000, 2000, 4000, 6000 and 8000 K. The image in 1998 was acquired close to the time of the spectroscopic event, and the peak in this image is assumed to be at the location of the stellar system. The beam size is 0.3″ (shown in the lower left corner).

Fig. 1 shows that there is considerable hysteresis in the radio light curve. Every 5.5 years we do see the same spatial features in general (compare the left and right panels in Fig. 2), but there are sufficient differences that the light curve is affected. The hysteresis could be due to changes in the raw UV output of the hot star, changes in the amount of UV that reaches the more distant parts of the outflow, and/or changes in the gas blobs that are ionized by the UV. By comparison of the left and right panels of Fig. 2, it appears that there was a large difference in the amount of ionized gas in the "equatorial skirt" of the system, i.e., the high density region in the equatorial plane that separates the two polar lobes of the Homunculus nebula, visible as the bright bar of emission running diagonally across the panel from upper left to lower right.

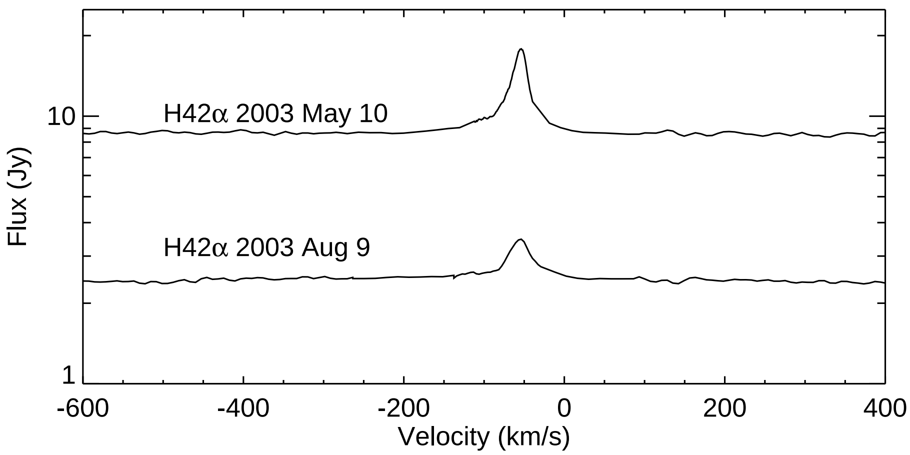

Figure 3. The spectrum of the millimeter continuum and the H42α recombination line at 85.7 GHz prior to (May) and after (August) the 2003 spectroscopic event. The vertical axis is plotted on a logarithmic scale.

Millimeter–wavelength Emission from η Carinae

Recently receivers have been added to the Australia Telescope for 12 and 3 mm bands. These allow us to achieve much higher spatial resolution than is possible at microwave frequencies, and in addition to investigate the masing recombination lines at millimeter wavelengths known from SEST observations (Cox et al. 1995; Cox 1997). The theory of masing recombination lines is reasonably well understood (Strelnitski et al. 1996a,b). Maser action requires the presence of a dense region of photo–ionized gas. It is reasonable to assume that the most likely place in the η Car system for such a maser to occur is in the wind of the LBV. We carried out 3 and 12 mm observations in May and August of 2003 to look for the velocity shift of order 50 km/s predicted for the LBV as it went through periastron in June 2003 (Damineli et al. 1997; Corcoran et al. 2001). At 3 mm only 3 antenas were available so imaging was not possible but excellent spectra were obtained, while high quality images were made at 12 mm. The radio spectrum of the H42α recombination line at 85.7 GHz is shown for the two epochs in Figure 3. The data are consistent with a point source smaller than $1''$. The spectra show a very strong continuum together with a remarkable masing line superimposed at a velocity of -55 km/s. In the 2003 May observations, before periastron, the continuum level was 8.6 Jy and the masing line is another 8 Jy above the continuum. However, after periastron in 2003 August, the continuum was just 2.4 Jy and the line was only 0.8 Jy above the continuum. An important result is that there is no detectable shift in the velocity of the line to better than 1 km/s, implying either that the masing line does not arise in the wind of the LBV, or (less likely) that the LBV is not in a binary. The dramatic drop in flux between May and August must represent gas that recombines because it is no longer exposed to ionizing photons. A 10^4 K stellar wind of 10^{-3} $M_\odot$/yr at 500 km/s should produce a continum flux of 0.7 Jy at 3 mm, so even in August the observed millimeter continuum flux was too large to come from the stellar wind alone. The inferred 10^4 K source size of $0.2''$ needed to explain the flux is

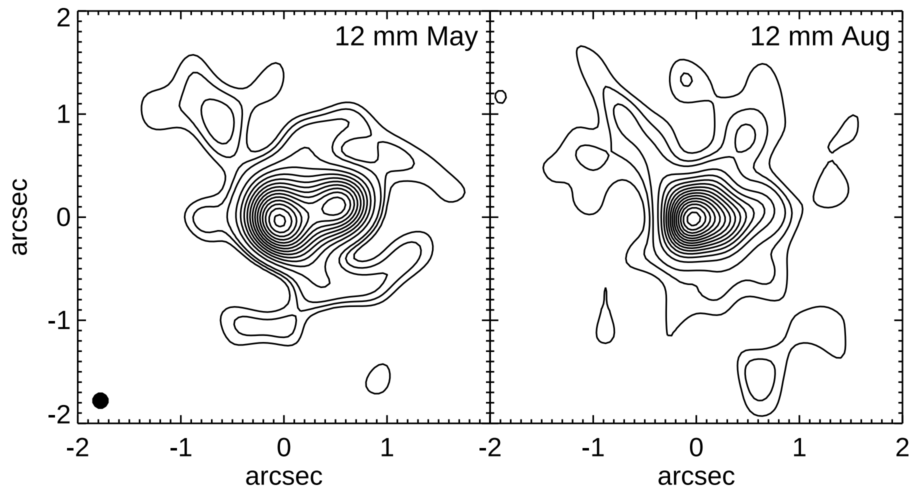

Figure 4. Images of the emission at 21 GHz before (May) and after (August) the 2003 spectroscopic event. The spatial resolution is 0.15″ (shown in the lower left corner). Contours are plotted at brightness temperatures of 150, 300, 500, 1000, 1500, ..., 7000 K. At both epochs the peak brightness temperature is 7200 K.

much larger than the orbit dimension (0.005″). The drop in the strength of the recombination line from May to August is even more dramatic than the change in continuum, but perhaps this is consistent with an origin outside the binary system where the UV flux is more likely to drop near periastron. The 12 mm images (Fig. 4) are of high quality, and show that a strong feature was present 0.5″ to the west of the main source in May but had weakened considerably by August. Further work is needed to understand the nature of this feature. The May image suggests the presence of a faint ring around this western source, and both images show emission to the northeast of the central source along the direction of the equatorial skirt. Images at 3 mm, available in the next few years, should be able to clarify the relationship of different sources and the nature of the recombination line maser.

References

Corcoran, M. F., Ishibashi, K., Swank, J. H., & Petre, R. 2001, Astrophys. J., 547, 1034

Cox, P. 1997, in ASP Conf. Ser. 120: LBVs: Massive Stars in Transition, 277

Cox, P., Martín–Pintado, J., Bachiller, R., Bronfman, L., Cernicharo, J., Nyman, L.-A., & Roelfsema, P. R. 1995, Astron. Astrophys., 295, L39

Damineli, A., Conti, P. S., & Lopes, D. F. 1997, New Astronomy, 2, 107

Duncan, R. A. & White, S. M. 2003, Mon. Not. Roy. Astron. Soc., 338, 425

Duncan, R. A., White, S. M., & Lim, J. 1997, Mon. Not. Roy. Astron. Soc., 290, 680

Duncan, R. A., White, S. M., Lim, J., Nelson, G. J., Drake, S. A., & Kundu, M. R. 1995, Astrophys. J. (Lett.), 441, L73

Strelnitski, V. S., Ponomarev, V. O., & Smith, H. A. 1996a, Astrophys. J., 470, 1118

Strelnitski, V. S., Smith, H. A., & Ponomarev, V. O. 1996b, Astrophys. J., 470, 1134

White, S. M., Duncan, R. A., Lim, J., Nelson, G. J., Drake, S. A., & Kundu, M. R. 1994, Astrophys. J., 429, 380