Observations of non-thermal radio emission in O-type stars

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Abstract: The non-thermal radio emission of O-type stars is due to synchrotron radiation from relativistic electrons. These electrons are accelerated in shocks. Most probably, these shocks are due to colliding winds in a binary or multiple system. We present new VLA observations of the non-thermal radio emitter Cyg OB2 No. 8A, which was only recently discovered to be a binary. For this star, the radio fluxes show a good correlation with the phase in the binary period. This result is actually quite surprising because the high free-free optical depth should prevent us from detecting the synchrotron radiation emitted by the colliding-wind region. We can only explain the observations by introducing porosity in the model. We also present a complete series of archive VLA observations on the triple system HD 167971. The radio lightcurve shows a more complicated behaviour than for Cyg OB2 No. 8A: it is difficult to detect the binary period in the observations, but we found a clear variation that occurs on a $\sim$ 20-year timescale.

1 Introduction

Two distinct physical processes are responsible for the radio emission in early-type stars. First of all, there is thermal emission, which is due to free-free processes in the material of the stellar wind. All stars with an ionized wind have such thermal emission. Secondly, there is non-thermal radio emission, which is due to synchrotron radiation by relativistic electrons. It is this second process that links radio emission to high-energy astrophysics. Typically, one needs electrons with energies of 100 MeV in a 0.1 G magnetic field to have a peak synchrotron radio flux at 6 cm. Electrons attain such high energies by scattering around a shock: due to the first-order Fermi mechanism part of the shock energy is transferred to the electrons (Bell 1978).

It was believed for some time that wind-embedded shocks in single O stars were responsible for the relativistic electrons (Chen & White 1994). However, Van Loo et al. (2005, see also Van Loo, these proceedings) showed that the shocks in the outer wind are not strong enough to explain the observed dependence of the non-thermal flux on wavelength. Therefore all non-thermal radio-emitting O stars are most probably binaries, where the synchrotron emission is caused by the two shocks on either side of the colliding-wind region.

We studied the radio fluxes of two non-thermal sources which are known O-type binaries: Cyg OB2 No. 8A and HD 167971.

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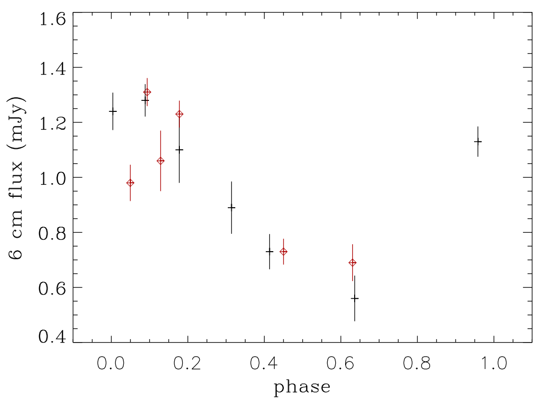

Figure 1: VLA 6 cm fluxes of Cyg OB2 No. 8A, plotted as a function of phase, based on the spectroscopic 21.908 d period. The two different symbols and colours indicate results from two orbits.

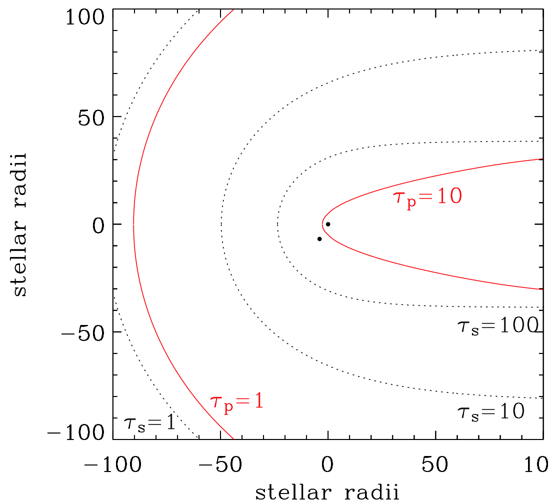

Figure 2: Contour lines of constant optical depth (at 6 cm), for an observer situated to the left. The dotted lines represent the $\tau = 1$, 10 and 100 contours of a smooth wind. The solid line shows contours for $\tau = 1$ and 10 of a wind where porosity was included. The two dots near the centre represent the binary components.

2 Cyg OB2 No. 8A

Cyg OB2 No. 8A was for a long time thought to be a single star, until De Becker et al. (2004) provided spectroscopic evidence that it is a binary, with an orbital period of 21.908 days. The binary consists of an O 6 + O 5.5 star, probably a supergiant and a giant.

We obtained 6 cm radio observations using the NRAO Very Large Array[1] (VLA) during February - March 2005. The measured fluxes show excellent phase-locking when folded with the spectroscopic period (Fig. 1).

This highly interesting result is, however, difficult to explain theoretically. The high free-free optical depth creates a 'radio photosphere', which should block the synchrotron radiation emitted by the colliding-wind region and therefore no phase-locked variation should be seen. Calculations of the optical depth show that the colliding-wind region should be well inside the $\tau = 100$ surface (Fig. 2). Neither can we explain the observations by assuming that the relativistic electrons escape from the colliding-wind region and become detectable once they are outside the radio photosphere: because of inverse Compton scattering, these electrons will quickly lose their energy.

Clumping might be considered as a possible solution to this problem. There are many indicators of clumping in stellar winds, but we mention just two. Kramer et al. (2003) introduce it to explain why the X-ray lines are formed so close to the stellar surface and Bouret et al. (2005) require it in their non-LTE modelling to obtain a better fit for the P Cygni profiles of

[1]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

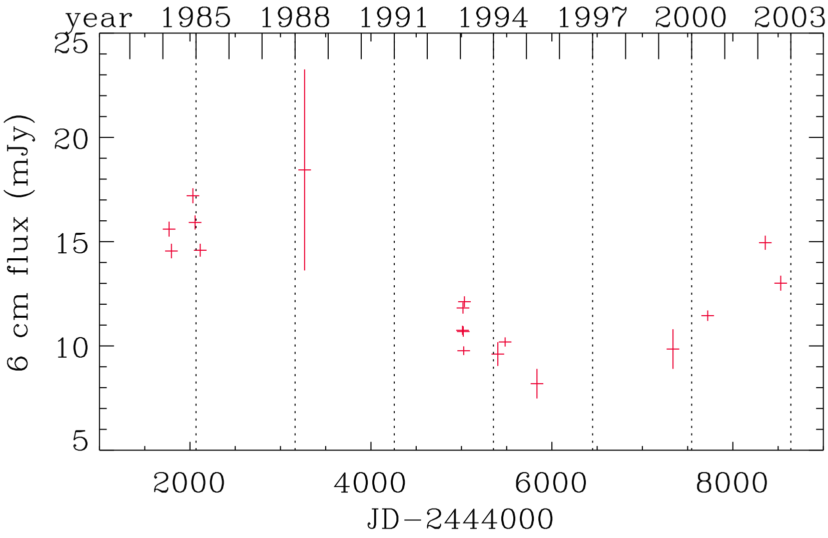

Figure 3: VLA 6 cm radio light curve of HD 167971.

HD 190429. Using the Abbott et al. (1981) formula for clumping does not solve the problem however: the surfaces where a certain optical depth is reached are the same for a clumped wind as for a smooth one, provided we require that the resulting radio flux is the same.

Porosity (e.g., Owocki et al. 2004) does provide a way out. Contrary to the clumping formalism, porosity allows the clumps to become optically thick. It is therefore possible to introduce a porosity-law (as a function of distance) that substantially reduces the optical depth, while still providing the same radio flux. Fig. 2 compares a smooth wind model to one that includes porosity. The (somewhat arbitrary) porosity model shown in Fig. 2 uses a clumping factor of 4.0 and clump-size that starts at 0.1 R_* at the stellar surface and increases outward, proportionally with distance. One component of the binary is now well outside the $\tau = 10$ surface, making it much more likely that we will detect at least some of the synchrotron emission.

3 HD 167971

Leitherer et al. (1987) discovered that HD 167971 is a triple system, consisting of a 3.3213-day period eclipsing binary and a third component, which may, or may not, be gravitationally bound to the binary. The binary is of spectral type O 5-8 V + O 5-8 V, the third component is probably an O 8 supergiant.

We obtained VLA observations of HD 167971 and complemented those with VLA archive observations. The resulting radio lightcurve at 6 cm is shown in Fig. 3. There are clear variations on a long timescale (of order 20 years). Superimposed on that are variations on a shorter timescale. We checked whether these short-term variations were related to the 3.3-day optical period, but this turned out not to be the case.

Using a porosity model (as for Cyg OB2 No. 8A) shows that we should have been able to see the 3.3-day variations due to the colliding-wind region between the two stars of the eclipsing binary. The fact we do not detect them could be due to the third component somehow blocking the radio flux. Or, more probably, it shows that the idea of porosity should not be pushed too far: there could be differences between supergiants and main-sequence stars. This would tie in well with other observations that show that clumping is usually needed in supergiants, but less so in main sequence stars.

4 Conclusions

Non-thermal radio emission is due to synchrotron radiation emitted in the colliding-wind region of a binary. Because the synchrotron radiation has to traverse the free-free radio absorption region of at least one of the two stars, one would expect to detect the non-thermal emission only for long-period binaries: only when the components are at a large enough separation will the colliding-wind region be outside the radio photosphere.

Surprisingly, the 21.9-day period of Cyg OB2 No. 8A is already sufficiently long for us to detect synchrotron emission from the colliding-wind region. It does not seem possible to explain this quantitatively with a smooth or clumped wind; rather a wind with porosity needs to be applied. The HD 167971 observations, on the other hand, caution us not to push this porosity idea too far, as for this system the 3.3-day period is not detected in the data.

The introduction of porosity will reduce the mass-loss rates that are traditionally derived from radio observations. This conclusion is of course highly relevant for models of stellar and Galactic evolution.

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