Can single O stars produce non-thermal radio emission? Or are they binaries?

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Abstract: We present qualitative models for the non-thermal radio emission of single O stars, in terms of synchrotron emission by wind-embedded shocks. When we include the fact that shocks weaken as they move out with the wind, as predicted by time-dependent hydrodynamical simulations, these models produce a radio spectrum with a positive slope (as function of frequency), in contradiction with the observed negative slope. We conclude that non-thermal radio emission cannot originate from wind-embedded shocks, and is likely to be caused by a wind-colliding shock. A radio light curve analysis of two non-thermal O stars that are generally assumed to be single supports this conclusion.

1 Introduction

Many O stars are observable at radio frequencies, due to free-free emission from the circumstellar ionised gas. The emergent *thermal* radio spectrum is of the form $F_\nu \propto \nu^{+0.6}$, where the power +0.6 is referred to as the spectral index. However, a significant fraction of the brightest O stars have a radio spectrum that differs strongly from thermal wind emission (Bieging et al. 1989). Instead of the characteristic positive index, the radio spectrum has a negative spectral index, i.e. the flux decreases as a function of frequency. This *non-thermal* radio emission is synchrotron radiation from relativistic electrons gyrating in a magnetic field (White 1985). These synchrotron-emitting electrons are accelerated to relativistic energies by the first-order Fermi mechanism at shocks (Bell 1978).

A fundamental question regarding non-thermal radio emission is its correlation with binarity. For Wolf-Rayet stars, the evolutionary descendants of O stars, this link is already well established, i.e. a binary component is a prerequisite for non-thermal radio emission (Dougherty & Williams 2000). For binaries, the shocks needed for the acceleration of the electrons arise where two stellar winds collide (Eichler & Usov 1993). The situation is less clear for the O stars. Roughly two thirds of the non-thermal O stars are confirmed binary or multiple systems. For the other stars, binarity has not been established. In these single stars, shocks are generated by the line-deshadowing instability of the radiative driving mechanism (Owocki et al. 1988).

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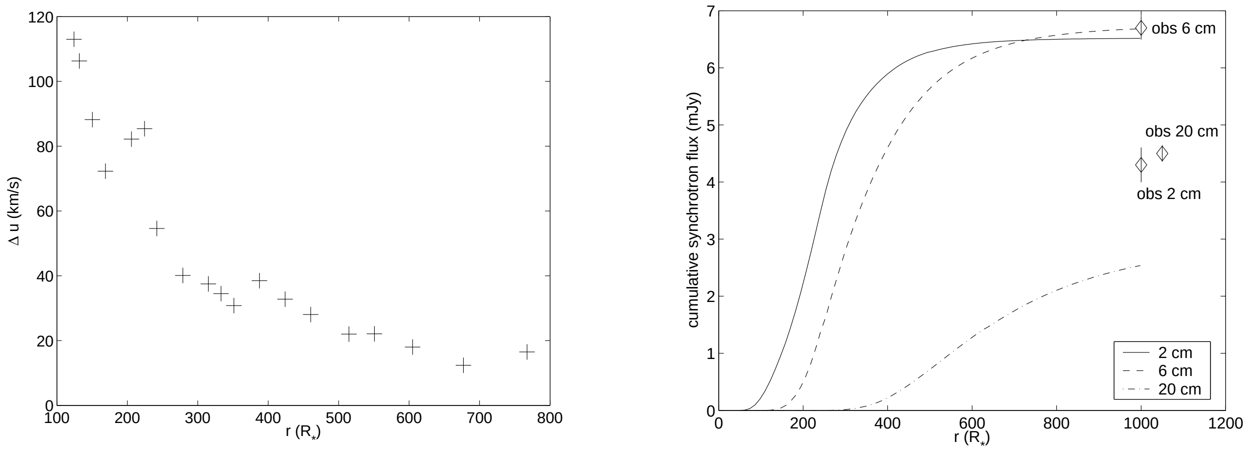

Figure 1: (a) *left panel*: The shock velocity jump (plus signs) of a typical strong shock in the periodic box model of Runacres & Owocki (2005), as function of radius. (b) *Right panel*: Emergent synchrotron fluxes due to all shocks between the stellar surface and a position r in the wind, at 2 cm (solid line), 6 cm (dashed) and 20 cm (dash-dotted). The diamonds are the observed synchrotron fluxes of Cyg OB2 No. 9 and also the error bar is given.

2 Synchrotron models for single stars

Electrons are accelerated at a shock by the first-order Fermi acceleration mechanism (Bell 1978). By crossing the shock front many times, an electron can be accelerated to relativistic energies. Once the electron leaves the shock front, the acceleration ceases and cooling mechanisms - such as inverse Compton scattering and adiabatic cooling (e.g. Chen 1992) - will reduce its energy. The synchrotron-emitting electrons cannot travel far from the shock front before being completely thermalised. Therefore the synchrotron emission is limited to narrow layers behind a shock.

Van Loo et al. (2005a) showed that the synchrotron flux F_ν produced by a single shock is proportional to Δu^3, where Δu is the velocity jump across the shock. The dependence of the synchrotron emission on the compression ratio χ of the shock is more complicated, but the flux also increases with χ. This means that the shocks with the highest χ and Δu dominate the synchrotron emission. Therefore, the distribution and strength of instability-generated shocks has important consequences for the results of our synchrotron models.

Time-dependent hydrodynamical simulations show that a hot-star wind is filled with shocks out to very large distances in the wind (e.g. Runacres & Owocki 2005). In Fig. 1a we show the shock velocity jump of a typical strong shock as a function of radius. The shocks are strongest close to the star, and gradually weaken as they move outward with the flow. As the flux is a strongly increasing function of the shock velocity jump (i.e. $F_\nu \propto \Delta u^3$), this means that the synchrotron emission declines rapidly as a function of radius.

Due to the large free-free opacity of the wind at radio wavelengths, only photons produced at large distances can be observed. All the photons emitted too close to the star are absorbed. By analogy we call the radius of unit optical depth at e.g. 2 cm the *radio photosphere* at that wavelength. Due to the wavelength-squared dependence of the free-free opacity, the size of the radio photosphere increases with wavelength. For the non-thermal emitter Cyg OB2 No. 9, the radio photosphere at 2 cm is 90 R_* and 190 R_* at 6 cm.

The emergent flux is determined by the interaction between the non-thermal emission and the thermal absorption. Let us concentrate on the flux produced at 2 and 6 cm. Due to the free-free absorption, the synchrotron emission at 2 and 6 cm is produced in different regions of the wind. For Cyg OB2 No. 9, the 2 cm photons are absorbed within 90 R_* of the star, while at 6 cm the photons are absorbed up to 190 R_* (see Fig. 1b). Thus the inner-wind shocks contribute more to the flux at 2 cm than at 6 cm. Recall that these inner-wind shocks also produce more emission. It is then difficult to produce much more 6 cm flux than 2 cm flux (see Fig. 1b). Adding the contribution by free-free emission of the wind, the emergent radio spectrum has a positive spectral index, contrary to the observations (Van Loo et al. 2005b).

We have investigated some possibilities by which we can reconcile the results of the hydrodynamical simulations with the observed non-thermal emission. We find that the observations can only be reproduced by counteracting the rapid radial decrease of the synchrotron emission. As the emission is directly proportional to the shock velocity jump, a natural way to get a slower decline is to assume a weaker radial dependence of Δu. Numerical simulations show that, to reproduce the non-thermal spectrum, the shock velocity jump must be nearly constant between 100 and 1 000 R_*. However, it is highly unlikely that the shock strength is constant over such large distances.

We also examined the effect of re-acceleration - the main mechanism by which previous authors (Chen 1992) were able to reproduce the observed non-thermal spectra. These authors included the ad-hoc shock model of Lucy (1982) in their synchrotron models. In the Lucy model, relativistic electrons can travel from one shock to another before being thermalised. Relativistic electrons are then accelerated in subsequent shocks, leading to a larger population of relativistic electrons in the outer wind. Thus re-acceleration substantially slows down the decrease of the synchrotron emission. However, in time-dependent hydrodynamical simulations (e.g. Runacres & Owocki 2005), shocks always occur in pairs at either side of a dense shell. Electrons can then only encounter a single shock before being trapped in a shell. Consequently, re-acceleration is highly unlikely in a instability-generated shock structure and of no importance in our models (Van Loo et al. 2005b).

Based on the models, we conclude that the observed emission is probably not from wind-embedded shocks associated with the line-deshadowing instability.

3 Synchrotron model for binary stars

In the previous section we showed that the observed non-thermal emission cannot be produced in the wind of a single star. As all non-thermal Wolf-Rayet stars appear to be in a binary system, the most likely alternative is that, in non-thermal O stars, the emission is also produced in a wind-collision shock associated with a binary or multiple system.

In the simplest case of wind-collision system, i.e. a binary, the radio flux changes are due to changes in the orbit (e.g. WR 140). This means that the flux variations are repeatable from period to period. In the radio light curve of Cyg OB2 No. 9 (a star currently believed to be single), we find an unambiguous period of ~ 2.4 yr (see Fig. 2). A similar result is found for HD 168112 (also believed to be single), where we find a period of 1.4 yr (Blomme et al. 2005).

How the period from the radio light curve relates to an orbital period is yet unclear. For WR 140, the best studied wind-collision binary, the radio period is identical to the orbital period (White & Becker 1995). However, this is not true for Cyg OB2 No. 5. Although the orbital period of the O-star binary Cyg OB2 No.5 is only 6.6 days, the radio flux changes over a period of the order of years (Miralles et al. 1994). A solution was offered when high-resolution radio imaging revealed a secondary source in this system, i.e. a wind-collision region where the O-binary wind collides with a nearby B star (Contreras et al 1999). However, the observed flux changes are predominantly due to the binary and are not coming from the wind-collision region (Dougherty, pers. comm.). Therefore, the fact that a period is found in the radio light

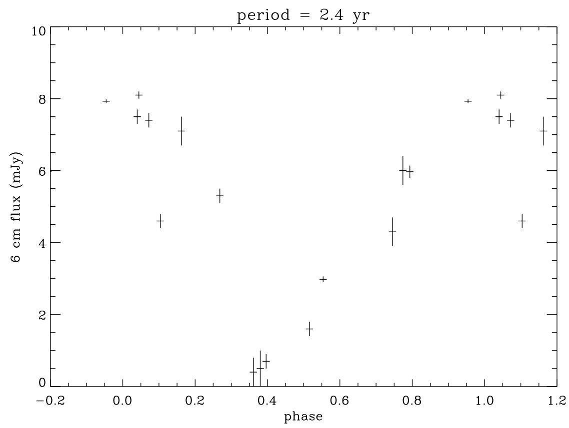

Figure 2: The 6 cm radio fluxes of Cyg OB2 No. 9, folded with a 2.4 yr period (Van Loo 2005). Note that some observations are plotted twice. Phase 0.0 was arbitrarily set at 1 Jan 1980.

curves of Cyg OB2 No. 9 and HD 168112 is only an indication that these stars are binaries.

4 Conclusions

We found that the observed non-thermal radio spectra cannot be produced by instability-generated shocks associated with a chaotic, unstable wind. The most likely alternative is synchrotron emission from shocks associated with colliding winds. All non-thermal O stars should thus be members of a binary or multiple system. Additional observations (radio monitoring, interferometry, radio imaging, etc ...) are necessary to confirm this hypothesis.

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