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Are all non-thermal radio-emitting O stars binaries?

S. Van Loo

Royal Observatory of Belgium, Brussels, Belgium
School of Physics and Astronomy, University of Leeds, UK

Abstract. We present qualitative models for the non-thermal radio emission of single O stars, in terms of synchrotron emission from relativistic electrons. These electrons are accelerated in shocks generated by the instability of the driving mechanism of the stellar wind. Hydrodynamical simulations show that wind-embedded shocks decay as they move outward with the flow. When we include this effect in our synchrotron models, we find that the observed non-thermal emission cannot be explained by synchrotron emission from wind-embedded shocks. The most likely alternative is that relativistic electrons are accelerated in shocks generated by the collision of two stellar winds. The non-thermal radio emitters are therefore all binary or multiple systems. This hypothesis is supported by periodic radio light curves of two presumably single O stars.

1. Introduction

Many O stars are observable at radio frequencies due to free-free radiation produced in the ionised stellar wind. The emergent *thermal* flux, F_ν, has a characteristic spectral shape, i.e. $F_\nu \propto \nu^{0.6}$ where 0.6 is usually referred to as the spectral index. However, a significant number of O stars emit more radio emission than can be expected from thermal emission alone (Bieging et al. 1989). Also, the radio spectrum of the excess emission has, instead of a typical thermal index, a negative spectral index, i.e. the flux decreases as a function of frequency. This *non-thermal* radio emission is synchrotron emission from relativistic electrons spiralling around magnetic field lines. The synchrotron-emitting electrons are accelerated to relativistic speeds by the first-order Fermi mechanism acting at shocks (Bell 1978).

The presence of shocks in the stellar winds of non-thermal radio emitters is crucial and even leads to a fundamental question whether non-thermal radio emission is correlated with binarity. In binaries, the shocks needed to accelerate the electrons are provided by colliding winds. For Wolf-Rayet stars, the evolutionary descendants of O stars, binarity appears to be a prerequisite for non-thermal emission (Dougherty & Williams 2000). For O stars, the situation is less clear. A priori there is no need for non-thermal emitters to be binaries. The driving mechanism of O-star winds is known to be subject to a line-deshadowing instability (Owocki & Rybicki 1984). Time-dependent hydrodynamical simulations including this instability show that the wind is pervaded by (wind-embedded) shocks. A failure of wind-embedded synchrotron models to explain the observations would then strongly suggest a colliding-wind origin of the non-thermal radio emission.

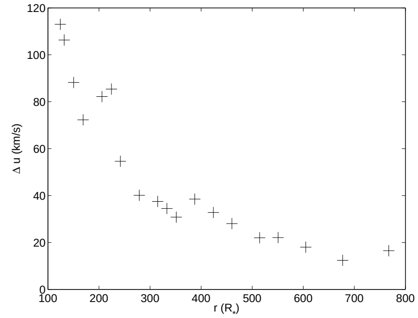

Figure 1. Velocity jump (plus signs) of a typical shock in the periodic-box model of Runacres & Owocki (2005), as a function of radius.

2. Synchrotron model for single stars

In the presence of shocks and a magnetic field, an electron is accelerated to relativistic energies (Bell 1978). When a relativistic electron leaves the shock front, the acceleration ceases and energy-loss mechanisms, such as inverse Compton cooling and adiabatic losses, will rapidly cool the electron below radio-emitting energies (Chen 1992). As a result, relativistic electrons cannot travel very far from a shock. Therefore, relativistic electrons (and thus also the synchrotron emission) are limited to narrow layers behind a shock.

The synchrotron emission produced in these narrow layers depends strongly on the velocity jump Δu of the shock, with the flux $F_\nu \propto \Delta u^3$ (Van Loo et al. 2005a). Thus the strongest shocks in the stellar wind tend to dominate the synchrotron emission. Time-dependent hydrodynamical simulations (e.g. Runacres & Owocki (2005)) show that the strongest shocks are found close to the star (see Fig. 2.). These shocks gradually decay as they move outward with the flow. The synchrotron emission is then also rapidly decreases as function of radius.

Due to the very large opacity of the wind, all photons emitted below the radius of unit optical depth $R_{\tau=1}$ are absorbed (Wright & Barlow 1975). Therefore, the synchrotron emission must be formed outside $R_{\tau=1}$. We loosely refer to this radius as the radio photosphere, by analogy with the optical photosphere. Because of the wavelength-squared dependence of the free-free opacity, the size of the radio photosphere increases with wavelength. For the best-studied non-thermal O star Cyg OB2 No. 9, we find $R_{\tau=1}(2\ \mathrm{cm}) = 90\ R_*$, $R_{\tau=1}(6\ \mathrm{cm}) = 90\ R_*$ and $R_{\tau=1}(20\ \mathrm{cm}) = 450\ R_*$. Thus the strongest shocks will only emit at the shortest wavelengths.

The emergent flux is determined by the tight interplay between non-thermal emission and thermal absorption. The strong shocks close to the star contribute more to the flux at short wavelengths (where the free-free opacity is smaller) than at long wavelengths. The radio spectrum will therefore have a tendency toward a positive spectral index, contrary to the observations. The observed negative spectral index can only be reproduced by counteracting the rapid decline of the synchrotron emissivity. None of the investigated possibilities to do so - a slower radial decline of the velocity jump, re-acceleration of electrons in multiple shocks and a lower mass-loss rate - appears physically plausible (Van Loo et al. 2005b).

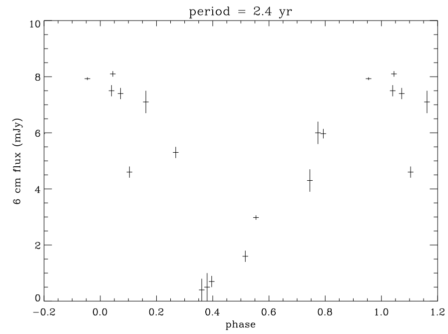

Figure 2. The 6 cm radio fluxes of Cyg OB2 No. 9, folded with a 2.4 yr period (Van Loo 2005). Note that some observations are plotted twice. Phase 0.0 was arbitrarily set at 1 Jan 1980.

The non-thermal radio emission cannot be caused by wind-embedded shocks associated with an unstable, chaotic wind.

3. Synchrotron emission from colliding winds

The most likely alternative is synchrotron emission from colliding winds, as is the case for Wolf-Rayet stars. The simplest case is a classical colliding-wind binary (e.g. WR 140). The radio fluxes in such a system changes due to changes in the orbital motion. Therefore a radio light curve should show good repeatability from one period to another. In the radio light curve of Cyg OB2 No. 9 (a star currently believed to be single), we found an unambiguous periodicity (see Fig. 3.). For HD 168112 (also believed to be single), we found a similar result (Blomme et al. 2005).

These results highly support a colliding-wind interpretation of the observed non-thermal radio emission. Therefore, all non-thermal radio-emitting O stars should be binaries. Additional observations (interferometric, radio monitoring and imaging, etc....) are necessary to confirm that colliding winds are the source of the non-thermal radio emission.

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