# Non-thermal radiation from single O stars

Sven Van Loo

*Royal Observatory of Belgium, Ringlaan 3*
*B-1180 Brussels, Belgium*

**Abstract.** For some of the most luminous O stars non-thermal radio emission has been observed. It is understood that synchrotron radiation from relativistic particles can account for this emission. These particles are accelerated to such high energies by shocks in the wind. In this article we discuss the use of two different wind models for reproducing the observational data.

## 1. Introduction

Stars of spectral type O have very strong stellar winds, driven by the line-scattering of stellar radiation. Besides energy, photons also carry momentum, which they transfer to the ions that scatter the radiation. Line-scattering can be seen as an absorption immediately followed by a re-emission. Because most absorbed photons come from the star and the emission is in a random direction, line-scattering creates a net outward force.

Due to line-scattering, the scattering ions, however, quickly block the limited flux available within the width of the spectral line. This line saturation reduces the effectiveness of line driving. An extra ingredient must be taken into account for line driving to be effective: Doppler sweeping of the lines. Because of the velocity gradient in the wind, ions get more and more red-shifted as they move away from the star. Hence they can absorb ever bluer stellar photons. In this way a line is swept across a broad spectral region, about 100 times wider than the spectral line itself. For luminous stars, this outward force is able to counteract the inward gravity.

The same Doppler effect is the reason for the instability of line-driven flow, as was realised by Milne (1926). If an ion is exposed to a positive velocity perturbation, it moves out of the shadow of the underlying material (in other words: the line desaturates). Hence it will be exposed to fiercer radiation and will be further accelerated. A small perturbation quickly becomes non-linear, giving rise to a wind with shocks and dense shells. For the production of non-thermal radio emission, shocks are crucial. Note that for close binaries these shocks could come from colliding winds. In this study we limit ourselves to single stars.

## 2. Thermal radio emission

Radio observations show deviations from pure black body emission. In fact, the circumstellar ionized gas in the wind is the origin of free-free emission (Bremsstrahlung) that causes the star to be observable at radio wavelengths. Wright & Barlow (1975) showed that the spectral index of the radio spectrum (the constant $\alpha$ in the expression $F(\lambda) \propto \lambda^{-\alpha}$) is 0.6, which fits the observations of O stars quite well (see Fig. 1).

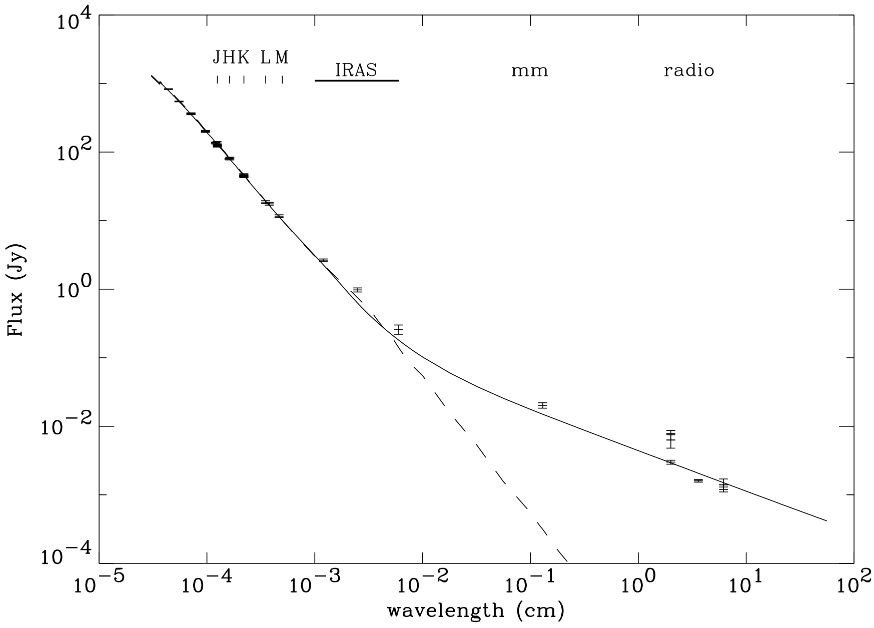

Figure 1. Observed and theoretical continuum fluxes for $\zeta$ Pup, an O4f supergiant. The dashed line is pure black-body radiation ($\alpha$ =2), the full line is thermal wind emission with $\alpha$ =0.6

Due to the very large free-free opacity of the wind at radio wavelengths, only photons originating from large distances can escape the stellar wind. Photons emitted too close to the star cannot be observed. This means that a resolved radio image would show a larger star than a resolved visual image. It is then justified to call the effective radius of the star at radio wavelengths the *radio photosphere*, as an analogy to the optical photosphere. The radio photosphere for $\zeta$ Pup is about $100\,R_*$.

## 3. Non-thermal radio emission

About 25% of the brightest O stars have a very different radio continuum, with slopes that differ from the thermal wind emission (Abbott et al. 1984).

Fig. 2 shows clearly that the radio observations have a negative spectral index, rather than the +0.6 expected for thermal emission.

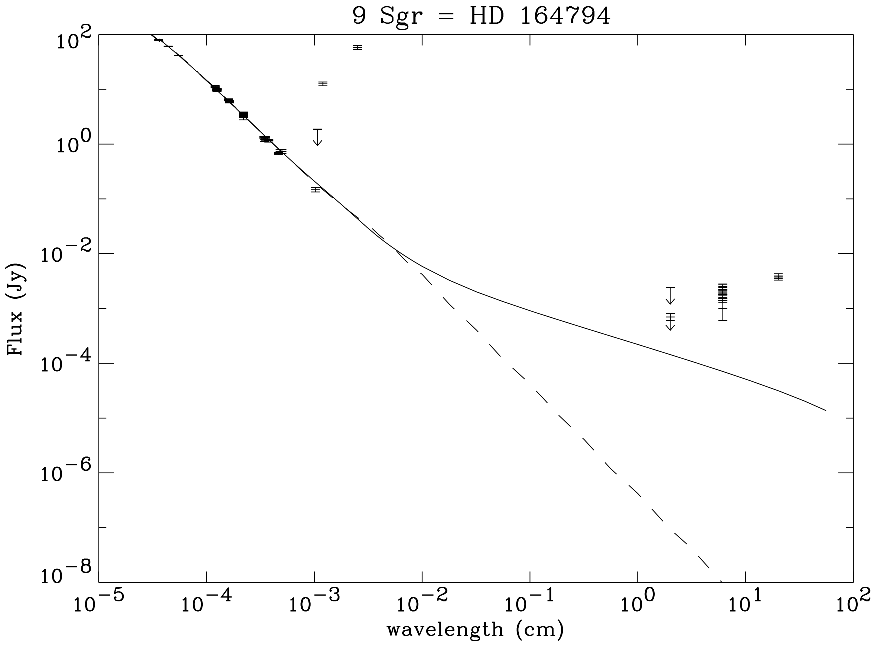

Figure 2. Observations for 9 Sgr (O4V). The lines have the same definition as in Fig. 1. The observations do not match the theory predicting the thermal wind emission. The deviant IR fluxes are contaminations from a nearby nebula (M 8, or Lagoon nebula)

It is believed that the non-thermal emission is synchrotron radiation by relativistic particles (White 1985). To create relativistic particles in the wind, the presence of shocks is needed.

Besides shocks, a magnetic field is required for synchrotron emission. Hot stars are expected to have a surface magnetic field in the range of 10 to 1000 gauss. The upper limit corresponds roughly to the detection limit of the field (no Zeeman splitting has been observed from any spectral line of any O star). The lower limit is set by the Razin effect, because otherwise no synchrotron radiation would be observed.

Due to the free-free opacity, the synchrotron photons must be *emitted* beyond the radio photosphere. Also the relativistic particles need to be *accelerated* where the emission is formed, because Compton cooling prevents relativistic particles from travelling large distances (Chen & White 1994). An important implication of this argument is that shocks are needed far from the star.

## 4. Fermi acceleration and energy spectrum

In the presence of shocks, a small fraction of particles will be accelerated up to relativistic speeds, even though the mean flow only reaches velocities up to 1% of the speed of light. The acceleration mechanism is the so called first order Fermi-acceleration. From the Rankine-Hugoniot relations (see e.g. Zel'dovich & Raizer 1967) it follows that material always streams faster into the shock front than out of it. Hence the pre-shock and post-shock region move toward each other. If a fast particle is elastically scattered in the shocked region, it will gain a small amount of energy, just like a tennis ball that bounces off an approaching wall. The energy gain per round-trip can be calculated in terms of relativistic transformations of energy from a pre-shock reference frame to the post-shock reference frame and vice versa (Bell 1978). Only if a particle is somehow trapped near a shock front, it can make a large number of round-trips, so a considerable amount of energy can be gained.

Depending on the probability of a particle crossing the shock a number of times, a power-law spectrum of particle momenta can be calculated:

$$N(p)dp \sim p^{-(\chi+2)/(\chi-1)}dp \tag{1}$$

where $\chi$ is the shock's compression ratio (or density contrast).

This result shows that the particle density distribution only depends on the strength of the shock. The resulting power law spectrum is also independent of the scattering mechanisms, which is fortunate, because the details of the mechanisms remain uncertain (for more information, see Jones & Ellison 1991).

Knowing the particle distribution law, it is possible to calculate the emergent spectrum of the synchrotron radiation. When the distribution law has the form of a power law, the resulting synchrotron spectrum is also a power-law with, for this specific case, $\alpha \approx -\frac{1}{2(\chi-1)}$ (Rybicki & Lightman 1979). The negative spectral index for the synchrotron radiation is in agreement with the observations for non-thermal radio emission (Fig. 2).

## 5. Models

To calculate the non-thermal radio emission we need a specific model for the stellar wind shocks. Until now a phenomenological model by Lucy (1982) has been used. This model is different in a number of ways from more detailed hydrodynamical simulations (Feldmeier et al. 1997). Lucy proposed a heuristic model with the basic assumption that all shocks travelling in a radial direction, pass at every point with fixed time intervals. In the calculations it was also assumed that the quasi-periodic train of isothermal shocks survived to large distances, beyond the radio photosphere.

Chen & White (1994) calculated the non-thermal radio emission from the Lucy model. The calculated synchrotron spectrum fits the observations quite well, as seen in Fig. 3, after taking into account the free-free absorption and the Razin effect, a background plasma effect.

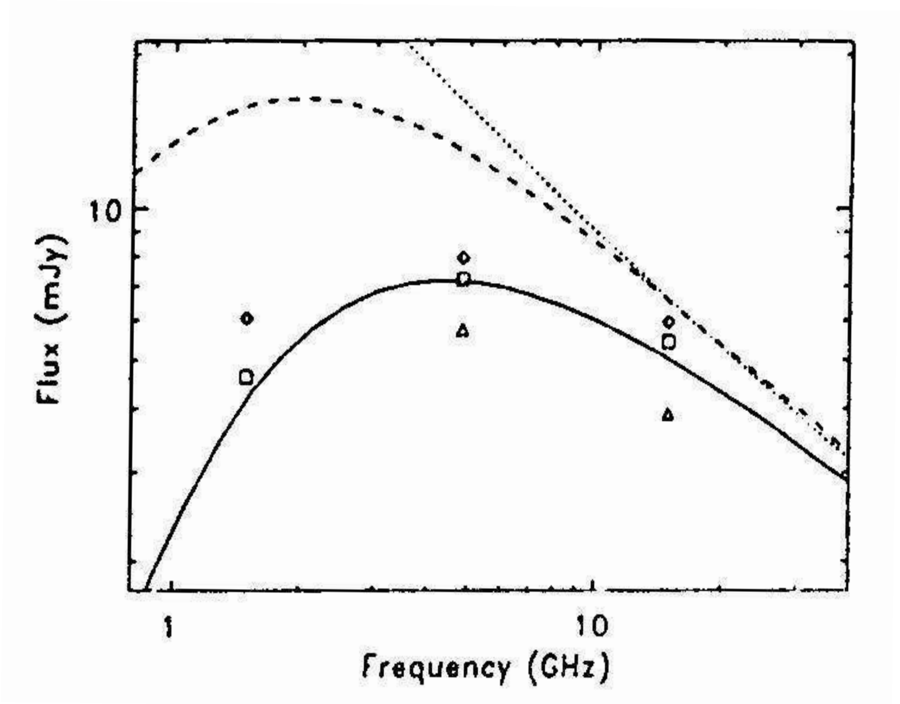

Figure 3. The synchrotron model fitting of the observed non-thermal radio spectra of Cyg OB2 No.9. The dotted line is the pure synchrotron spectrum, including the Razin effect which produces the dashed line. Introducing free-free absorption as well reduces it to the solid line (from Chen & White 1994).

Detailed hydrodynamical models, on the other hand, predict a different picture for the wind. The strongest shocks in the wind are reverse shocks (Feldmeier et al. 1997), whereas in the Lucy model all shocks are forward. Although both kind of shocks move outward in a stellar frame, a reverse shock moves inward through the gas and forward shocks move outward.

The outer wind is made up of dense shells, which are bounded on the front and back sides by a forward and reverse shock pair (ibidem). The main consequence hereof is that a particle encounters at most one shock and then is trapped in the shell. The problem is now whether enough synchrotron radiation will be produced in the hydrodynamical models to account for the observed values.

## 6. Summary

Non-thermal radio emission from single O stars is produced by relativistic particles, accelerated by shocks at large distances from the star. When a phenomenological shock model is used, this acceleration mechanism can explain the observed radio fluxes. It is not clear whether the results of detailed hydrodynamical simulations, which differ from the phenomenological model in a number of ways, will be able to produce enough non-thermal radio emission. This question will be a main part of my PhD research.

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