

Structure in the Stellar Winds of O-type Stars

R. Blomme

Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussel, Belgium

Abstract. There is considerable evidence for the existence of structure in the stellar winds of early-type stars. Two models have been proposed to explain this structure. On the one hand, Co-rotating Interaction Regions can explain some of the observational data. On the other hand, it is known that the driving mechanism of the wind is unstable and, therefore, the material gets clumped into shells bounded by shocks. It is not clear which of the two types of structure is predominant. To be able to decide this issue, we implemented a 3D model of radiative transfer to study the effect of Co-rotating Interaction Regions on continuum and line formation.

1. Introduction

Luminous hot stars provide an important input of momentum, energy and matter to the surrounding medium through their strong, radiatively driven stellar winds. The amount of mass ejected in the winds is also an important factor for the evolution of the star. Furthermore, hot-star winds can provide an independent means to measure distances up to the Virgo and Fornax clusters, by relying on the success of the radiatively-driven-wind theory to account for time-averaged outflow properties (Kudritzki & Puls, 2000). The standard theory assumes that the outflow is smooth.

However, observations at various wavelengths show that the stellar wind has structure (in the form of inhomogeneities, clumps, shocks, ...). The presence of structure needs to be taken into account to correctly translate the spectral information into parameters of the star and stellar wind: e.g. mass loss rates will be too high if not corrected for the effect of structure.

2. Observational evidence for structure

We list only the more important indicators of structure:

X-rays. Because the effective temperature of O stars is 20,000 – 40,000 K, they are not a priori expected to be detectable at X-ray wavelengths. Observations however show that they have a considerable amount of X-ray emission ($L_X \approx 10^{-7} L_{\text{bol}}$, see e.g. Berghöfer et al. 1997). This indicates that some of the material must be at high temperatures ($10^6 - 10^7$ K), which can be explained by shocks in the stellar wind.

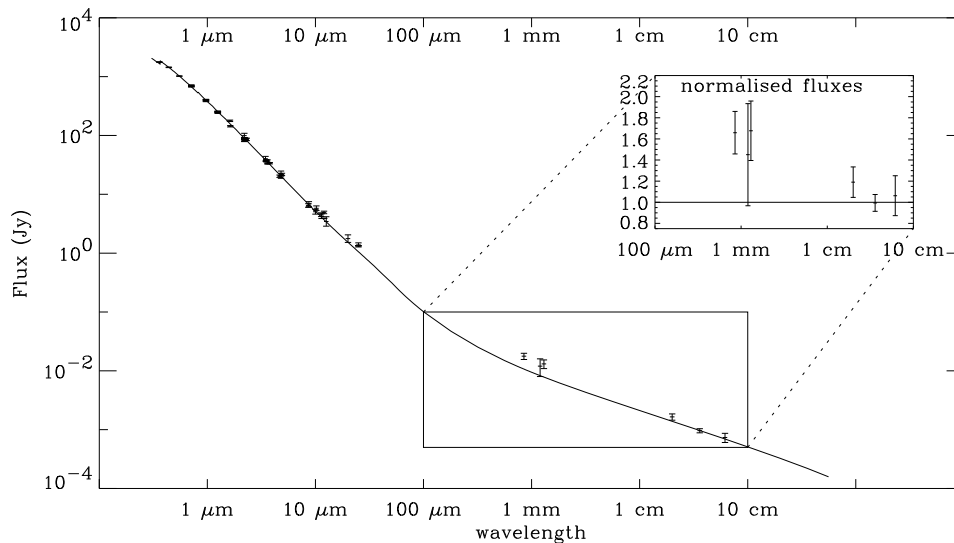


Figure 1. The observed continuum fluxes of ϵ Ori are compared to a smooth wind model (Blomme et al. 2002). The inset shows the flux ratio between the observations and the model for the millimetre and radio wavelengths. The existence of wind structure is indicated by the millimetre fluxes which are $\sim 60\%$ higher than the smooth wind prediction.

Ultraviolet resonance lines. The resonance spectral lines in the ultraviolet show P Cygni profiles. Superimposed on those P Cygni profiles that are unsaturated, Discrete Absorption Components (DACs) can be seen, that move through the profile (see e.g. Massa et al. 1995). The recurrence time scale of the DACs is related to the rotation period of the star.

Millimetre continuum. Continuum fluxes at millimetre and radio wavelengths are due to free-free emission of the material in the wind. The emission mechanism depends on the density squared, and is therefore sensitive to structure. Figure 1 shows a flux excess (compared to a smooth wind model) around $\lambda = 1$ mm, indicating the presence of structure in the wind.

3. Theoretical explanations

Two theoretical models have been proposed to explain structure. The fundamental difference between these two models is whether the structure is large-scale or small-scale.

The *large-scale* structure model assumes that there are irregularities on the surface of the star (due to magnetic fields or non-radial pulsations). The differences in surface flux create local differences in the radiative acceleration of the wind material. The fast material collides with the slow material, creating a Co-rotating Interaction Region (CIR).

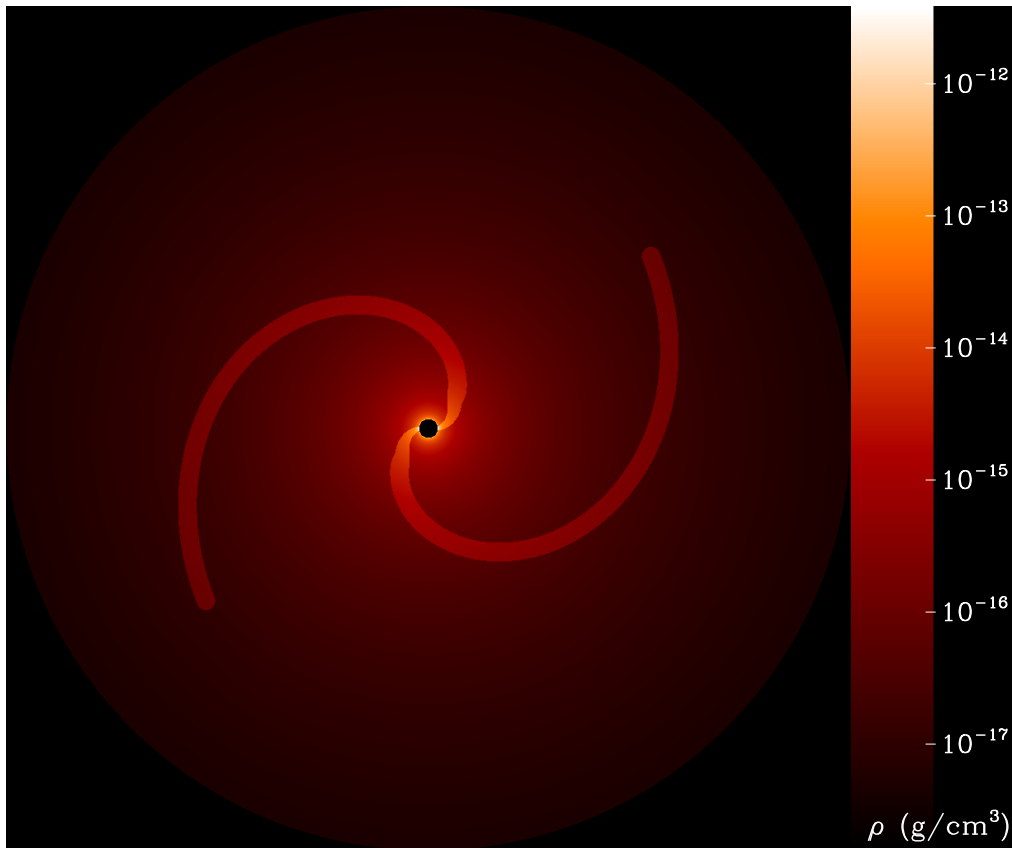


Figure 2. Plot of the density structure in the equatorial plane, as used in the numerical model. The spiral-shaped structures are a simplified version of CIRs. Each spiral has a circular cross-section. At larger distances from the star, the radius of this cross-section is $1 R_*$. This radius decreases smoothly to $0.2 R_*$ at the stellar surface.

Two-dimensional hydrodynamical models for such CIRs have been calculated by Cranmer & Owocki (1996). They also calculated the resulting spectral lines and showed that their model can explain the DACs. As the cause of the structure is rooted on the stellar surface, the model can also explain very well why the recurrence time scale of the DACs is related to the rotation period.

The *small-scale* structure model is based on the inherent instability of the radiative driving mechanism. Hydrodynamical models (such as those by Runacres & Owocki 2002) show that shocks form and wind material gets clumped. This type of model has been used to explain the observed X-ray flux and the flux excess at millimetre wavelengths.

4. Modelling CIRs

It is not clear if large-scale or small-scale structure best explains the whole set of observations. It is quite possible that both explanations could apply, in

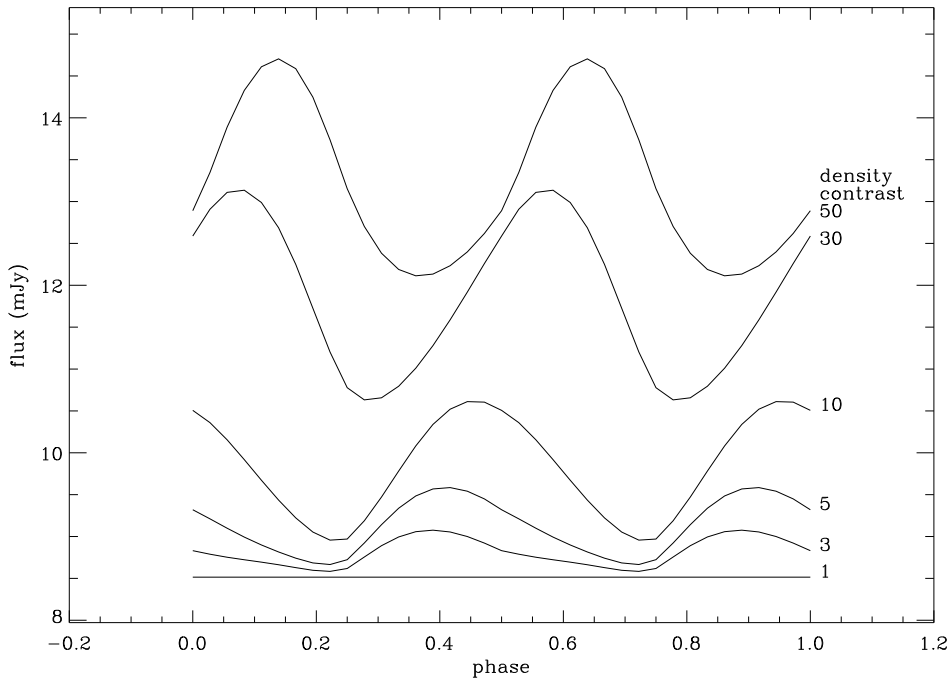


Figure 3. The predicted 1.3 mm flux, as a function of the phase in the rotational cycle. It is assumed that we see the star equator-on.

different regions of the wind. Using a radiative transfer code, we can check what observations can be explained by which model.

To investigate the CIR model, we developed a 3D radiative transfer code (following Adam 1990), based on the finite volume method. In this code we introduced a simplified model of a CIR (see Fig. 2). At the moment, only continuum radiative transfer is treated.

As an example of what the code can produce, we calculated the flux at $\lambda = 1.3$ mm (see Fig. 3). First of all, note that with sufficiently high density contrast of the CIR, we can explain the 60 % flux excess observed for ϵ Ori (Fig. 1). Furthermore, the model predicts variability that should be detectable. We still need to check if a model with such a density contrast is consistent with other observational indicators.

5. Future work

Currently, the 3D radiative transfer code can only treat the continuum. Once spectral line formation is included as well, the code will be used to interpret previous and future observational data from a wide range of wavelengths. This will allow us to test how many of the observational indicators can be explained by the CIR model.

References

- Adam, J. 1990 *A&A*, 240, 541
Berghöfer T. W., Schmitt, J. H. M. M., Danner, R., & Cassinelli, J. P. 1997, *A&A*, 322, 167
Blomme, R., Prinja, R. K., Runacres, M. C., & Colley, S. 2002, *A&A*, 382, 921
Cranmer, S. R., & Owocki, S. P. 1996, *ApJ*, 462, 469
Kudritzki, R. P. & Puls, J. 2000, *ARA&A*, 38, 613
Massa, D., Fullerton, A. W., Nichols, J. S., et al. 1995, *ApJ*, 452, L53
Runacres, M. C., & Owocki, S. P. 2002, *A&A*, 381, 1015