Wolf-Rayet Wind Models: Photometric and Polarimetric Variability

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Abstract. We have modelled the observed random variation in broad band intensity and polarization of some isolated Wolf-Rayet stars assuming that their winds have localized, enhanced density regions (blobs). Our model is based on a Monte Carlo code that treats all Stokes parameters of the radiation bundle. This study indicates that the blobs must have sizes comparable to the stellar dimension and be near the base of the envelope. These blobs can be interpreted as a variable structure of large geometric cross section causing the observed polarimetric and photometric variability.

1 Introduction

Wolf-Rayet (WR) stars can present random fluctuations in broad band flux and polarization and also in spectral line profiles. The broad band variations can reach 10% in flux (Antokhin et al. 1995; Marchenko et al. 1998) and 0.5% in polarization (St.-Louis et al. 1987; Drissen et al. 1987; Robert et al. 1989). The changes in the spectral line profiles can be divided in two types. One of them is the small moving bumps which appear in some optical emission lines (Robert 1994). They may be associated to small-scale instabilities intrinsic to a radiative wind (Owocki 1994; Gayley & Owocki 1995). The discrete absorption components (DACs) are also present in WR stars (e.g., Prinja & Smith 1992). They comprise a larger portion of the profile and may be associated with a large amount of mass (Massa, Prinja & Fullerton 1995 and references therein). These structures may have an external origin (relative to the wind) as, for instance, rotation, binarity and/or photospheric processes (Owocki 1994).

2 The model

To study the random variability in WR stars, we have assumed that the envelope has regions of enhanced density which we call blobs. Our goal is to constrain the physical characteristics the blobs may have in order to explain the observed broad band variability. We have solved the radiative transfer in an electron scattering envelope using the Monte Carlo code described in Rodrigues (1997).

The blobs have been assumed spherical and immersed in a spherical envelope. The density law of the envelope can be chosen among many analytical expressions. The density inside the blob follows the same law as the envelope, but it is multiplied by an arbitrary factor which introduces the density enhancement. We are able to treat an arbitrary number of blobs as well. The only source of radiation is a spherical central source emitting isotropically. The use of a Monte Carlo code has allowed us to consider optically thick envelopes characteristic of WR winds.

The photopolarimetric variability may arise in two situations: (1) if the wind changes from a homogeneous configuration to an inhomogeneous one; (2) if the wind is always inhomogeneous, but with a moving blob whose relative position to the source and/or to the line of sight is variable.

3 Results

The code provides us with values of the flux, linear polarization and its position angle as a function of the line of sight under which the system is observed. In order to simplify the analysis, each model has been characterized by only two values: the minimum flux normalized to that of a homogeneous envelope, ΔI; and the maximum polarization, ΔP. In doing that, we have assumed that the flux variation is caused by extinction so that a decrease in flux can only happen if the blob is in the line connecting the source and the observer. In general, the blob also scatters light to any direction and this can produce an increase in the flux (relative to the homogeneous case). However, this increase in our model barely reaches 1%.

We find that the variation in flux does not constrain the physical properties of the blob. An extinction of 10% is achieved for practically any model by simply adjusting the optical depth of the blob. On the other hand, most models tend to produce a polarization smaller than that observed. A value of $\approx 0.5\%$ is only obtained for very specific conditions: blobs of dimensions similar to the star and which are near the base of the envelope. An example of a model which fits the observed values is presented in Tab. 1. The blob in this model covers an solid angle of 0.32 steradians, which is equivalent to 2.5% of total solid angle of the envelope (4π).

The interpretation of these results is that the blobs should have a large geometric cross section (blob radius $\approx$ stellar radius) in order to produce the observed values of polarization. A structure having a smaller cross section could not produce 0.5% of polarization. This result does not depend on the blob density.

4 Conclusions

This work has shown that the structure causing polarization must be relatively large, with its size similar to that of the star. This does not necessarily

Table 1. An example of a model which reproduces the random broad band variability of Wolf-Rayet stars

Parameter	Value
Radius of the envelope	10 $R_\star$
Optical depth of the envelope	2.0
Optical depth of the blob	5.0
Blob position	3 $R_\star$
Radius of the blob	1 $R_\star$
ΔI	11%
ΔP	0.55%
Blob mass	1% of the mass of the envelope

mean that there must be a single huge blob, but that the average enhancement of the density is spread over an large area of the wind. In a forthcoming paper, we will also study how these results correlate with the spectral variations observed in WR stars.

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Discussion

M.-M. MacLow: How would your results change if your blobs were sheets instead of spheres; that is, partial shells with, e.g., much less than one steradian solid angle coverage?
C. Rodrigues: For optically thin structures, the geometric depth may be important; for instance, spherical blobs have more scattering material than partial shells of the same cross section. However, for optically thick structures, only the cross section is important (see below).

J. Brown: I would like to comment that Richardson, Brown, & Simmons treated the same problem analytically but for small blobs and small optical depth. We found that, in this case, the only way to make the polarisation variations small enough compared to the photometric variations was for the blobs to be very dense and to produce significant emission (which you neglect). It would be interesting to check whether your high τ blobs really do not contribute much to the total emission.
C. Rodrigues: You are right in the sense that the emission of the blobs (and also from the envelope) must be considered. But in your work you have considered that the photometric variations were caused by scattering out of the line of sight of the blobs; i.e., they represent an increase in flux relative to a "homogeneous envelope". In this case $\Delta I/\Delta P$ must be around 1 based on the scattering properties of electrons. In our work, we have considered ΔI to be caused by extinction. In that case, ΔI is always greater that ΔP.

J. Cassinelli: You say that the change in polarisation depends on the angular size of the blob. However, isn't there also a strong dependence on the optical depth $\Delta\tau$ of the blob (or shock fragment)?
C. Rodrigues: In the optically thin regime, the polarisation grows with angular size and optical depth. However, for optically thick blobs, only the cross section is important because in this case multiple scattering occurs. In other words, for optically thick blobs only the region facing the WR photosphere "produces photons" which have been scattered only once. These are the photons producing polarisation.

P. Veen: The 10 % flux variation of WR stars is wavelength dependent, being higher in the violet. What extinction law is expected in your model?
C. Rodrigues: Our model does not predict any wavelength dependence on extinction since we do not consider emission and/or absorption in the envelope. However, these processes may be included and a wavelength dependence can thus arise.

J. Bjorkman: You point out that the problem you have producing polarisation variations as large as 0.5 % is caused by not having enough surface area in the blob. Could you solve this problem by having three or four blobs?

C. Rodrigues: Partially. If you have two blobs in opposite directions you can enhance the polarisation. But if you think about randomly oriented blobs the polarisation may decrease with a higher number of condensations because we are approaching a more "symmetric" configuration.

A. Moffat: I was somewhat surprised to hear you say that photometric/polarimetric broad-band observations are not seeing the same thing as the spectroscopic observations. After all, both have similarities: e.g., time scales, randomness, etc. On the other hand, our recent spectroscopic analysis of clumps (cf. my talk) shows that they are not optically thick, contrary to your broad-band clumps.

C. Rodrigues: We suggest that the relatively large sizes of the blobs producing polarisation seems to indicate that they are not the small instabilities expected to arise in radiatively driven winds (which may be related to the sub-peaks present in the optical emission lines). More probably, the polarimetric variation may be related to spectroscopic features caused by large-scale strucures. Maybe the small and large-scale structures are not uncorrelated, but have the same physical origin.

About the optical thickness of the blobs: there must be a relatively high density contrast for a measurable polarisation to exist. If the density contrast is decreased, the blob size must be increased in order to get the same amount of polarisation. Anyway, we think that the structures causing the sub-peaks in the emission lines are not the carriers of the polarisation. They are very small and even with a considerable density contrast they can be optically thin.

S. Owocki: It may be true that while continuum polarisation is most sensitive to large-scale blobs, the line-profile bumps are easier to detect for more localised, smaller-scale blobs. Overall, the wind may have a continuous distribution of scales.

A. Moffat: I agree. In fact, we do not have serious enough constraints on clump parameters to be able to give meaningful interpretations of polarisation variability. We might have to wait for a direct resolution of the wind by interferometry.