Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Clumping-corrected mass-loss rates of Wolf-Rayet stars: comparison with the optically thick wind model

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Abstract. Clumping-corrected mass-loss rates of Wolf-Rayet stars lie in the range $0.2\text{–}10 \times 10^{-5}\,M_{\odot}yr^{-1}$. It was found that optically thick wind models can lead to the observed mass-loss rates of WR stars at certain energy supply conditions in the subsonic zone.

1. Introduction

Mass loss is a dominant feature of massive star evolution, deeply influencing all stellar properties. For the study of wind-triggering and driving mechanisms, it is needed to know the correct luminosities and masses of WR stars. We use a sample of Galactic Wolf-Rayet stars with well determined stellar and mass-loss parameters. The total number of Galactic WR stars studied by us is 69, about one third of the number of known Galactic WR stars.

2. Parameters of Wolf-Rayet stars and optically thick wind model

Clumping-corrected mass-loss rates of WR stars were determined by Nugis *et al.* (1998). For additional stars, we determined $\dot{M}$ using subtype-dependent relationships between mass-loss rate and emission-line equivalent width. Mass-loss rates of WR stars lie in the range $0.2\text{–}10 \times 10^{-5}\,M_{\odot}yr^{-1}$. Masses of WR components in binary systems were adopted from spectroscopic orbit solutions using recently published data. Masses of single WR stars and of binary WR stars lacking correct spectroscopic orbit solution were derived from their luminosities using a theoretical (evolutionary modeling) relation $L = f(M)$ (Schaerer & Maeder 1992). To determine the bolometric corrections for WR stars, we need to know the absolute visual magnitudes and stellar luminosities. We followed the scheme used by Smith & Maeder (1989) and Smith *et al.* (1994). This approach assumes the knowledge of stellar masses and theoretical (evolutionary modeling) relation $L = f(M)$. Bolometric corrections for different subclasses were derived as weighted means. The luminosities of WR stars have been determined either directly from the theoretical relation $L = f(M)$ (for well determined stellar masses) or via absolute visual magnitudes and subclass-dependent mean bolometric corrections.

The main acceleration in the WR winds takes place at large values of frequency-averaged optical depths (below the photosphere), where radiation forces due to true continuum absorption are no more negligible as regarded in the line-driven wind models. The first attempts to apply "optically thick wind" codes to WR stars have been made by Kato & Iben (1992) and by Pistinner & Eichler (1995). "Optically thick wind" is usually defined as a steady wind in

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which the acceleration of matter is due to continuum absorption occuring below the photosphere. A self-consistent solution of an optically thick wind assumes the computing of a model for the whole star, taking into account both the nuclear burning core and the radiatively expanding envelope. Our purpose is to find out whether the "optically thick wind" models can lead to the observed mass-loss rates, and the specific properties of WR stars at low expansion velocities (below the sonic point). We used the evolutionary modeling relations $L = f(M)$ and analyzed whether the optically thick wind model with the observed supersonic acceleration can lead to the existence of critical (sonic) point and to the observed mass-loss rates of WR stars. In the present study we used a somewhat modified β-velocity law:

$$v = v_0(1 - aR_s/r) + (v_\infty - v_0)(1 - R_s/r)^\beta. \quad (1)$$

The constants v_0 and a are adjustable parameters which must be determined from the sonic-point requirements for first- and second-order velocity derivatives, and R_s is the radius of the sonic (critical) point. The results of our analysis are not sensitive to the choice of R_s. We searched for the combinations of β, f_s and α (the latter are the parameters describing the change of L_r near the sonic point: $L_r = L_c - f_s\,(R_s/r)^\alpha \dot{M}GM/R_s$, where L_c is the stellar-core luminosity) which lead to the observed mass-loss rates. We found that only at certain combinations of β, f_s and α it is possible to get the observed mass-loss rates of WR stars. This same optically thick wind scheme is applicable also for the LBVs P Cygni and η Carinae. There exists substantial difference in energetics of subsonic zones between LBV and WR stars (f_s is negative for WR stars and positive for LBV stars).

3. Concluding remarks

Mass-loss rates are not well correlated with mass, *i.e.*, mass-loss rates of WR stars are not depending on mass only, as was proposed from evolutionary modeling simulations by Langer (1989). Langer's formula strongly over-estimates mass-loss rates, especially for more massive WR stars. The optically thick wind model can lead to the observed mass-loss rates of WR stars at certain energy-supply conditions in the subsonic zone. Agreement with mass-loss rates was possible for values of the velocity-law parameter in the range $\beta \simeq 1$–5, whereas lower values of β demand a higher energy supply near the sonic point (higher negative values of the parameter f_s).

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