

Radiatively driven winds: shaping bipolar LBV nebulae

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Abstract. Massive stars which are fast rotators can give rise to asymmetric winds. These winds may result in the formation of aspherical wind-blown nebulae. In this work the theory of radiatively-driven winds from massive stars is used to model the formation of bipolar nebulae around LBV stars.

1. Introduction

Nebulae around Luminous Blue Variable (LBV) stars are characterized by asymmetric, often bipolar shapes. A classic example is the Homunculus Nebula around the massive star η Carinae. In the standard interpretation of the generalized interacting stellar winds models, the asymmetry in shape is attributed to an asymmetry in the density structure of the ambient medium. However, the observational evidence does not support this. In this work we use scaling relations derived from the theory of radiatively driven winds, to model the outflows from LBV stars. Rotation of the star, and the latitudinal variation of the stellar flux due to gravity darkening is taken into account. It is shown that a star, rotating close to its critical velocity, will emit a wind whose velocity is higher at the poles than the equator, which can give rise to an asymmetric, bipolar wind-blown nebula. Inclusion of gravity darkening shifts the relative density toward the poles, but does not change the overall shape of the interaction front.

2. Scaling relations

For a star with luminosity L , the CAK line-driven mass loss rate (Castor, Abbott & Klein 1975) can be written in terms of the mass flux $\dot{m} \equiv \dot{M}/4\pi R^2$ at the stellar surface radius R , which then depends on the surface radiative flux $F = L/4\pi R^2$ and the effective surface gravity $g_{\text{eff}} \equiv (GM/R^2)(1-\Gamma)$ (Owocki, Cranmer & Gayley 1998; Dwarkadas & Owocki 2002), where Γ is the Eddington parameter. For a rotating star, reduction by the radial component of the centrifugal acceleration yields an effective gravity that scales with co-latitude θ as $g_{\text{eff}}(\theta) = g[1 - \kappa_e F(\theta)/gc - \Omega^2 \sin^2 \theta]$ where $\Omega \equiv \omega/\omega_c$, with ω the star's angular rotation frequency, and $\omega_c \equiv \sqrt{g/R}$. The mass flux is given by:

$$\frac{\dot{m}(\theta)}{\dot{m}(0)} = \left[\frac{g_{\text{eff}}(\theta)}{g_{\text{eff}}(0)} \right]^\beta = \left[1 - \tilde{\Omega}^2 \sin^2 \theta \right]^\beta. \quad (1)$$

For a uniformly bright, rotating star $\tilde{\Omega} = \Omega/(1-\Gamma)$ and $\beta = 1-1/\alpha$ where $\alpha < 1$ is the CAK parameter. The mass flux increases from the pole ($\theta=0$) to the

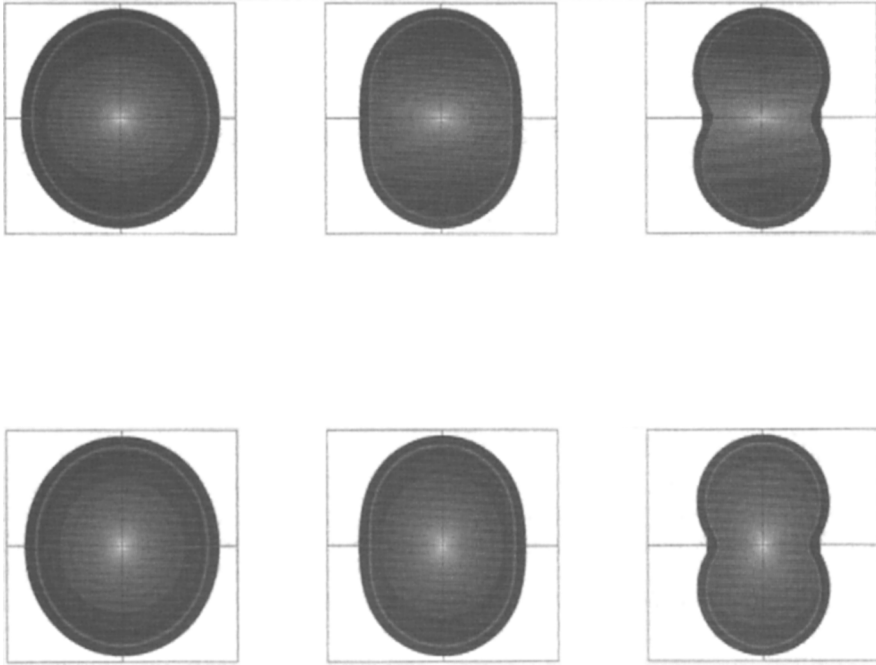


Figure 2. When gravity darkening is included, the morphology is similar to the case of pure rotation, although the interior density distribution is different.

equator ($\theta = 90$). However, if $F(\theta) \propto g(1 - \Omega^2 \sin^2 \theta)$ (gravity darkening effect, von Zeipel 1924) then $\tilde{\Omega} = \Omega$ and $\beta = 1$. The mass flux is highest at the poles, and decreases towards the equator. In the presence of rotation, the wind terminal speed is maximum at the poles, and decreases towards the equator as:

$$\frac{v_{\infty}(\theta)}{v_{\infty}(0)} = [1 - \tilde{\Omega}^2 \sin^2 \theta]^{1/2} \quad (2)$$

Figures 1 and 2 show density contours from numerical simulations using these scalings to describe the stellar wind, expanding into a constant density medium. Further details are given in Dwarkadas & Owocki (2002).

Acknowledgments. VVD is supported by NASA grant NAG5-3530, and by a grant from NASA administered by the American Astronomical Society.

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