

## Bipolarity from Radiatively Driven Mass Loss

Stan Owocki

*Bartol Research Institute, University of Delaware, Newark, DE 19350*  
*USA*

### 1. Overview

Most of the concepts for this “Eta Carina Legends” talk are documented in other conference or journal papers, as I outline here. The central idea is that the bipolar shape exhibited by the Homunculus nebula in Eta Carina might simply reflect the properties of radiatively driven mass loss from a rapidly rotating, gravity darkened core. The general concept dates back to work done originally to model rapidly rotating Be stars (Owocki, Cranmer, and Gayley 1996), wherein it was found that inclusion of gravity darkening of the equator (von Zeipel 1924) tended to make a line-driven stellar wind from a rapidly rotating star have both a higher mass loss and higher flow speed from the relatively bright stellar *pole*. Shortly after this initial work, I was invited to attend the Kona, HI workshop on Luminous Blue Variables (LBVs), and to present an overview on “The Physics of Stellar Winds Near the Eddington Limit”. The associated conference paper (Owocki and Gayley 1997; [www.bartol.udel.edu/~owocki/preprints/kona.pdf](http://www.bartol.udel.edu/~owocki/preprints/kona.pdf)) discusses various issues also covered in the present review, namely the role of convection at the Eddington limit, and how the finite energy of the radiation flux implies that a flow initiated with too high a mass loss rate would necessarily stagnate due to “photon tiring”. But the paper also ends with a discussion of the effect of rotation and gravity darkening on the latitudinal variation of wind velocity and mass flux, and specifically speculates that this might provide an alternative to previous models (e.g., confinement of a spherical outburst by a pre-existing equatorial disk; e.g., Frank et al. 1994; Langer et al. 1999) for the prolate, bipolar form of the Eta Carina Homunculus (see also papers by Maeder & Desjacques 2001; Dwarkadas and Owocki 2002).

Another theme of my Eta Carina Legends talk was to discuss recent ideas put forward by Shaviv (1998; 2000; 2001) on how atmospheres near and above the Eddington limit can become laterally structured, and how the associated “porosity” of the medium could effectively reduce the continuum radiative force, since then the radiative flux would tend to avoid denser, more opaque regions. For a star that is above the formal Eddington limit, this can reduce the effective radiative force to below the gravitational force, and so keep the denser, inner layers in an overall hydrostatic stratification. But as the lower density structures in the outer layers become optically thin, the net radiative force can exceed gravity and thus drive a net outflow. Shaviv (2000) has made a compelling case that such a porosity-modulated, continuum driven, SuperEddington outflow provides a basic paradigm for the giant outburst in Eta Carina.

As it happens, these general ideas were a major focus of my recent review talk on “Instabilities in Massive Stars”, presented at the IAU Symposium 212 in Lanzerote in June 2002. So to avoid repetition, I simply refer to those proceedings for further review and discussion (Owocki 2002; [www.bartol.udel.edu/~owocki/preprints/iaus212\\_owocki.pdf](http://www.bartol.udel.edu/~owocki/preprints/iaus212_owocki.pdf)).

But I do want just briefly to mention here one new question addressed while preparing for this Eta Carina workshop, namely whether such a porosity-modulated, continuum-driven flow would exhibit a bipolar shape if driven from a rapidly rotating star.

One part of the answer regards the flow speed. For a wide range of wind driving mechanisms, the terminal flow speed tends to scale with the “effective escape speed” from the wind base. For a rapidly rotating star, centrifugal terms lower the effective gravity near the equator, and this should generally lead to a lower equatorial flow speed. When tracked back to the specific time of the enhanced mass loss of the giant eruption, one can then generally expect that the overall form of the nebula will have a narrower equatorial waist, and a radially elongated pole, i.e. a bipolar form.

In this sense, the overall “peanut” shape of the Homunculus a form that could arise pretty directly from rapid stellar rotation of the underlying star, without depending too much on the details of the driving mechanism of the outburst, or whether the stellar radiation is gravity darkened.

But a second issue regards the equator-to-pole distribution of mass flux and/or density, and this can be sensitive to such details. For line-driven flows, the enhanced polar mass flux from a gravity-darkened star stems from its stronger sensitivity to radiation flux than gravity. To see how this comes about, note that for the maximal, CAK mass flux  $m = \rho v$ , the gravity  $g$ , inertia  $vv'$ , and line-acceleration  $g_{cak}$  are all nearly equal,

$$vv' \sim g \sim g_l \sim F(vv'/m)^\alpha, \quad (1)$$

where  $F$  is the radiative flux. When solved for the mass flux  $m$ , this yields the scaling

$$m \sim F^{1/\alpha} g^{1-1/\alpha}. \quad (2)$$

For a von Zeipel (1924) gravity darkening scaling for the latitudinal variation of radiative flux with effective gravity,  $F(\theta) \sim g(\theta)$ , this yields

$$m(\theta) \sim F(\theta) \sim g(\theta) \sim 1 - \Omega \sin^2 \theta, \quad (3)$$

where  $\Omega \equiv V_{rot}^2/V_{crit}^2$ , with  $V_{rot}$  and  $V_{crit}$  ( $= \sqrt{GM/R}$ ) the rotation and critical (orbital) speeds at the stellar equator. The key point is that the difference in the exponents for the scaling with flux vs. gravity, viz. the “1” in the “1-1/α” exponent for the gravity, stems from the scaling of the line-force with velocity gradient, which in turn scales with gravity.

In particular, let us contrast this with the expected scalings for a flow driven by a continuum opacity that is modulated by porosity. For this one can anticipate something of the form

$$vv' \sim g \sim g_c \sim F(1/\rho)^\alpha, \quad (4)$$

where now the power index refers to some statistical distribution of the clump strength (instead of line-strength); for a single, fixed clump strength,  $\alpha = 1$ . When solved for the mass flux  $m \sim \rho$ , this now yields the scaling

$$m \sim (F/g)^{1/\alpha}, \quad (5)$$

which, for a Von Zeipel gravity darkening  $F(\theta) \sim g(\theta)$  now yields a mass flux that is *independent* of latitude,  $m(\theta)=\text{constant!}$

To the extent that estimates of the mass distribution of the Homunculus indicate a higher mass toward the polar caps – as some discussions at this meeting seem to imply – then this is a feature that a continuum-driven model of the giant outburst may not naturally produce. Moreover, recent slit-spectra of the Homunculus seem to indicate that Eta Carina’s present-day wind has both a higher speed *and higher mass flux* over the pole (Smith et al. 2002; and this meeting). This thus suggests that the present mass loss is driven by lines instead of by a porosity-modulated continuum. This is consistent with the estimate that Eta Car is currently near but below the classical Eddington limit, so that its wind may just represent an extreme form of the standard CAK-type, line-driven outflow commonly inferred for more normal OB-type stars.

*Acknowledgements.* This research was supported in part by NASA grant NAG5-3530 and NSF grant AST-0097983 to the Bartol Research Institute at the University of Delaware.

## References

- Castor, J., Abbott, D., & Klein, R. 1975, ApJ, 195, 157 (CAK).
- Dwarkadas, V. and Owocki S. 2002, ApJ, submitted.
- Frank, A., Balick, B., and Davidson, K. 1994, ApJ, 441, L77.
- Langer, N., Garcia-Segura, G., and MacLow, M. 1999, ApJ, 520, L49.
- Maeder, A. and Desjacques, V. 2001, *a*, 372, L9.
- Owocki, S. and Gayley, K. 1997, *Luminous Blue Variables: Massive Stars in Transition*, A. Nota and H. Lamers, eds., A.S.P. Conf. Ser. 120, 121.
- Owocki, S. 2002, in *A Massive Star Odyssey, from Main Sequence to Supernova*, IAUS 212, K. van der Hucht, A. Herrero, & C. Esteban, eds.
- Shaviv, N. 1998, ApJ, 494, L193.
- Shaviv, N. 2000, ApJ, 529, L137.
- Shaviv, N. 2001, ApJ, 549, 1093.
- Smith, N., Davidson, K. Ishibashi, T. and Gull, T. 2002, in *A Massive Star Odyssey, from Main Sequence to Supernova*, IAUS 212, K. van der Hucht, A. Herrero, & C. Esteban, eds.
- von Zeipel, H. 1924, MNRAS, 84, 665.