The circumstellar environment of rotating Wolf–Rayet Stars and the implications for GRB afterglows

BY JOHN J. ELDRIDGE*

Astrophysics Research Centre, Queen’s University Belfast, Belfast BT7 1NN, UK

If Wolf–Rayet stars are the progenitors of gamma-ray bursts (GRBs), they must rotate rapidly to produce the GRB. This rotation may affect their stellar-wind bubbles and possibly explain why so many GRB afterglows occur in a constant density medium.

Keywords: gamma-ray bursts; massive stars; stellar-wind bubbles

1. Introduction

Wolf–Rayet (WR) stars are the likely progenitors of long gamma-ray bursts (GRBs). The more massive WR stars produce black holes at core-collapse and their radius is small enough for the relativistic jets to reach the stellar surface and produce the prompt GRB emission. WR stars have dense high-velocity winds that produce large stellar-wind bubbles through which the afterglow jet will propagate after the GRB event. Observations of a few afterglows agree with models of the stellar wind bubbles, e.g., Panaitescu (2005).

A problem remains that the free-wind region of the bubbles, where the density scales as $r^{-2}$, is always large and should be observed in every GRB afterglow. However, for many GRB afterglows a constant density medium (CDM) has been inferred from afterglow observations. There is some uncertainty in estimating the circumburst environment but CDMs tend to be preferred. van Marle et al. (2006) have investigated how to move a CDM into closer proximity with the progenitor and found a number of possible effects, such as stellar motion through the ISM.

However, there is another possibility that the GRB progenitors must be rapidly rotating at the time of core collapse to ensure that the material around the forming black hole has enough angular momentum to produce an accretion disc. Stellar rotation can produce a strong effect on the stellar-wind bubble that has not been considered. Ignace et al. (1996) investigated the effect of rotation on stellar winds for various stellar types. They found that even moderate rotation of a WR star will affect the density of the wind at different latitudes on the stellar surface; decreasing the polar wind-density while increasing the equatorial wind-density. This affects the position of the wind termination shock by varying the ram pressure $\left( p_{\text{ram}}(\theta) = \rho(\theta)v_{\text{wind}}^2 = (M(\theta)v_{\text{wind}})/(4\pi r^2) \right)$ with latitude. Their

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* j.eldridge@qub.ac.uk

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work is supported by observations of Wolf–Rayet binary CX Cephei. The light from the star is strongly polarized (approx. 4 per cent) which was used to infer that the WR star is rotating resulting in an equator-to-pole wind density ratio of 5 (Villar-Sbaffi et al. 2006).

2. Results

Using the results of Ignace et al. (1996), we produced models of the distorted wind bubbles modifying the code used by Eldridge et al. (2006). We assume that the wind density is asymmetric due to the rotation and varies with latitude so that the polar wind density is one-fifth of the equatorial wind density. We normalize the mass-loss so the mass-loss rate is the same as in the non-rotating symmetric case. We use a WR star model with a final mass of 11 with \( n_{\text{wind}} Z = 1800 \text{ km s}^{-1} \), and the initial ISM density was \( 10^3 \text{ cm}^{-1} \). With an asymmetric wind, the decreased wind density reduces the ram pressure of the wind along the polar direction. Therefore, as the pressure in the stalled-wind region is constant the extent of the free-wind region and the distance to the CDM is reduced from 0.75 to 0.27 parsecs. Therefore, in this case, the afterglow jet is more likely inferred to be propagating through a CDM.

How close the CDM can move to the progenitor depends on how asymmetric the wind becomes due to rotation. This, in turn, depends on how quickly the wind is accelerated and the rate of rotation. For a standard WR star an equator-to-pole wind density ratio of 5 requires a rotation rate of 45 per cent of the stellar break-up velocity. We are currently working to determine how this effect changes for different WR stars. Such calculations are complicated as WR winds are optically thick so common assumptions of line driven winds cannot be applied. It is important to note that if the star is rotating close to break-up velocity then it may become highly distorted and the mass-loss geometry may become very different from that shown here (Owocki et al. 1996).

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