In our quest for gamma-ray burst (GRB) progenitors, it is relevant to consider the progenitor evolution of normal supernovae (SNe). This is largely dominated by mass loss. We discuss the mass-loss rate $\dot{M}$ for very massive stars up to $300M_\odot$. These objects are in close proximity to the Eddington $\Gamma$ limit. We describe the new concept of the transitional mass-loss rate, enabling us to calibrate wind mass loss. This allows us to consider the occurrence of pair-instability SNe in the local Universe. We also discuss luminous blue variables and their link to luminous SNe. Finally, we address the polarization properties of Wolf–Rayet (WR) stars, measuring their wind asphericities. We argue to have found a group of rotating WR stars that fulfil the required criteria to make long-duration GRBs.

1. Introduction

In order to identify the progenitors of gamma-ray bursts (GRBs), we also need to consider the progenitors of ‘normal’ supernovae (SNe). While Smartt and others have established that red supergiants (RSGs) are the progenitors of ordinary type II plateau SNe, the progenitors of SNe Ibc and ‘special’ types IIn, IIb, etc., remain largely elusive. The evolution of the more massive objects is largely determined by mass loss, especially for very massive stars (VMS) up to $300M_\odot$.

2. Very massive stars and the Eddington limit

There is growing evidence for the existence of stars more massive than the canonical $150M_\odot$ limit. Crowther et al. [1] argued for masses twice as high for the hydrogen-rich Wolf–Rayet (WNh) objects in dense clusters like R136a. Bestenlehner et al. [2] found an equally high luminosity for the ‘isolated’ WNh star VFTS 682 in comparison with that derived for the third brightest monster within R136a.
Accurate mass-loss rates are required to determine the fate of VMS. Stellar winds from massive stars are thought to be driven by radiation pressure on Fe lines. The approach we use to compute new $\dot{M}$ for VMS is similar to the approach used for normal O-type stars [3]. Until 2008, our methodology was semi-empirical, as we assumed a velocity law that reached a certain empirical wind terminal velocity $v_\infty$. In the new Vink et al. [4] computations, we use the Müller & Vink [5] line-force concept, and express $\dot{M}$ as a function of the Eddington limit $\Gamma = \frac{g_{\text{rad}}}{g_{\text{grav}}} = \frac{\kappa L}{(4\pi c GM)}$. We found a steep dependence for which we have also found empirical support [6].

In order to address the question of whether VMS may produce pair-instability SNe (PISNs), it is of paramount importance to have confidence in the absolute values of the predicted mass-loss rates. This is particularly relevant given that a debate has arisen regarding the relevance of stationary wind mass loss. The reason is that winds have been found to be clumped, which results in the reduction of unclumped empirical $\dot{M}$. Most stellar evolution models however employ theoretical Vink et al. [3] rates which are already reduced. Vink & Gräfener [7] introduced the model-independent transition mass-loss rate $\dot{M}_{\text{trans}}$ and used it to calibrate stellar-wind strength. This supports the levels of the Vink et al. [3] rates.

Using these rates for 300$M_{\odot}$ stars, we find that these monsters lose more than half their initial masses on the main sequence. Considering increased mass-loss in helium and later burning phases would thus imply an ‘evaporation’ of such massive objects. This means that PISNs are unlikely to occur at solar $Z$, but the door for the occurrence of PISNs at lower $Z$ remains completely open.
3. Luminous blue variables

The stellar winds of O stars are fast (≈2000–4000 km s$^{-1}$), while those from lower $T_{\text{eff}}$ B supergiants are slow (≈100–1000 km s$^{-1}$). The reason is that O-star winds are driven by high Fe ionization states, while those of B supergiants are driven by lower Fe ionization states (wind bi-stability).

Luminous blue variables (LBVs) are known to change their radii on time scales of approximately 10 years. These Hertzsprung–Russell diagram excursions result in winds with variable $v_{\infty}$ and $M$. If the LBV wind changes instantly at the O versus B bi-stability discontinuity, this might explain the double-throughed $H\alpha$ absorptions seen in LBV spectra (figure 1) [9]. Such double-throughed $H\alpha$ line profiles have also been noted in the IIn/Ia SN 2005gj, which was suggested to have an LBV progenitor [10]. The same physics was also used to initially suggest the link between LBVs and SNe II [11].

What causes LBVs to change their radii remains as yet unknown, but envelope inflation in close proximity to the Eddington limit—recently proposed by Gräfener et al. [12]—may be the most promising solution, as this may account for the characteristic LBV S Dor variations. If the envelope inflation happens in nature this would have important consequences for the radii of LBV and Wolf–Rayet (WR) stars, just prior to their final explosions.
4. Do we expect long gamma-ray bursts exclusively at low $Z$?

The issue of mass loss and evolution at low $Z$ is particularly relevant for the progenitors of long GRBs. Within the MacFadyen & Woosley [13] collapsar model, GRB progenitors should (i) have rapidly rotating stellar cores and (ii) lack hydrogen envelopes. GRB progenitors are thus thought to be rotating WR stars. The potential problem is that WR stars have high mass-loss rates, removing the angular momentum.

In the rapidly rotating ‘quasi-homogeneous’ stellar models of Yoon & Langer [14], the objects are subjected to a strong magnetic coupling between the core and envelope. If rapid rotation can be maintained due to lower mass loss at low $Z$, the objects could avoid slow-down during the RSG/LBV phase. If the WR winds also depend on Fe driving [15], the WR stars can maintain rapid rotation towards the very end, making GRBs—but exclusively at low $Z$.

Recent GRB data however suggest that GRBs are not restricted to low $Z$. So, there seems to be a need for a GRB channel at high $Z$. We have recently identified a sub-group of rotating Galactic WR stars—allowing for a solution to this problem [16,17]. Figure 2 shows the degree of linear polarization in the special WR star 134. By contrast, the majority of WR stars are unpolarized; i.e. they have spherically symmetric winds, indicative of slow rotation. We found the spinning sub-group to be surrounded by ejecta nebulae, thought to be ejected during a recent RSG/LBV phase, suggesting these special WR stars are still young and rotating.

If the core–surface coupling were strong enough, the cores would not be expected to rotate rapidly enough to make a GRB, but if the core–envelope coupling is less efficient, they may have the required angular momentum in their cores to make GRBs. In most high $Z$ cases, these stars nonetheless still be expected to spin down due to mass loss, but within our post-RSG/LBV scenario one would not exclude the possibility of a high $Z$ GRB. Yet, low $Z$ environments are still preferred due to weaker WR winds.

References


