*Death of Massive Stars: Supernovae and Gamma-Ray Bursts*
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# The Red Supergiant Problem: Circumstellar dust as a solution

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**Abstract.** We investigate the red supergiant problem: the apparent dearth of Type IIP supernova progenitors with masses between 16 and 30 $M_{\odot}$. Although red supergiants with masses in this range have been observed, none have been identified as progenitors in pre–explosion images. We show that, by failing to take into account the additional extinction resulting from the dust produced in the red supergiant winds, the luminosity of the most massive red supergiants at the end of their lives is underestimated. We re–estimate the initial masses of all Type IIP progenitors for which observations exist and analyse the resulting population. We find that the most likely maximum mass for a Type IIP progenitor is $21^{+2}_{-1}\,M_{\odot}$. This is in closer agreement with the limit predicted from single star evolution models.

**Keywords.** .stars: evolution – supernovae: general – stars: supergiants

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## 1. The problem

It is generally acknowledged that all Type IIP supernovae are the result of core–collapse in either asymptotic giant branch (AGB) stars or red supergiants (RSGs). The strong hydrogen lines and the plateau in the light curve imply a considerable mass of hydrogen in these progenitors. We know from observations that stars with masses between about 12 and 25–30 $M_{\odot}$ will evolve into RSGs. However surveys of Type IIP progenitors have failed to identify high–mass RSGs among them. This is the red supergiant problem: how do massive RSGs end their lives?

## 2. Our solution

Most of the proposed solutions involve alternative fates for the massive RSGs, such as sudden mass-loss episodes or direct collapse to a black hole. We suggest that because mass–loss increases with stellar mass these stars explode whilst surrounded by large amounts of wind material of their own creation. This causes a considerable amount of additional extinction in observations of the progenitors, resulting in underestimates for the luminosities and hence the deduced masses. Evidence for this includes the abnormally high observed extinction values for certain massive RSGs, reaching several $A_V$ in some cases (Massey *et al.* 2005).

We do not try to model the dusty wind behavior. It is a complex and variable 3D process and we lack the information to calibrate the inputs. Instead we use the work of Massey *et al.* (2005), who measured the dust production rates for a population of RSGs and plotted them against their bolometric luminosity. This gave a least-squares fit, allowing us to calculate an empirical average dust mass rate for a star.

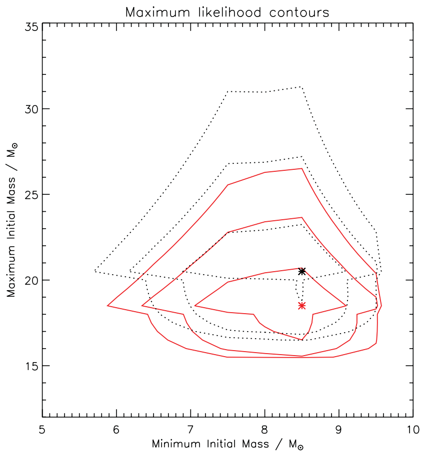


**Figure 1.** The optimal solutions and the maximum-likelihood contours for the 68, 90 and 95 per cent confidence regions. The solid lines are for the original dust–free models and the dotted lines are for the models with dust included.

We used this relation to modify a grid of stellar models produced with the Cambridge STARS code (Eldridge & Tout 2004). This gave the magnitudes in various pass-bands, both with and without the effect of extra dust. We deduced the dust mass rate at each time step and interpolated to get it as a function of time. We then integrated this to get the dust mass in shells around the star and then found the total extinction due to these shells.

## 3. Our results

We analysed observations of six stars known to be progenitors of Type IIP SNe. We also considered twelve instances where the progenitor was not identified but where the sensitivity of the instrument gave an upper limit to its luminosity. We use the compilation of SN detections and non-detections of Smartt *et al.* (2009). All progenitor information can be found in that paper and the references therein. We supplement this with SN 2009md (Fraser *et al.* 2011).

We deduced mass ranges for these 18 SNe and performed maximum-likelihood calculations to find the most probable upper and lower progenitor mass limits (Figure 1). We find that when the effect of circumstellar dust is ignored, the most probable upper limit is 18 $M_\odot$ and the 90 per cent confidence limit is 23 $M_\odot$. However, the dust models give 21 $M_\odot$ for the upper limit and, more significantly, a 90 per cent limit of 27 $M_\odot$. This means that, with the current data, it is difficult to argue that the red supergiant problem really exists. Without accurate measures of the stellar, as opposed to the local, extinction, the increase of dust production with mass leads to aliasing at higher masses.

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