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The evolution of Red Supergiant mass-loss rates

Emma R. Beasor\textsuperscript{1}\textsuperscript{*} & Ben Davies\textsuperscript{1}

\textsuperscript{1}Astrophysics Research Institute, Liverpool John Moores University, Liverpool, L3 5RF, UK

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ABSTRACT
The fate of massive stars with initial masses $>8\,M_{\odot}$ depends largely on the mass-loss rate ($\dot{M}$) in the end stages of their lives. Red supergiants (RSGs) are the direct progenitors to Type II-P core collapse supernovae (SN), but there is uncertainty regarding the scale and impact of any mass-loss during this phase. Here we used near and mid-IR photometry and the radiative transfer code DUSTY to determine luminosity and $\dot{M}$ values for the RSGs in two Galactic clusters (NGC 7149 and $\chi$ Per) where the RSGs are all of similar initial mass ($M_{\text{initial}}\sim16M_{\odot}$), allowing us to study how $\dot{M}$ changes with time along an evolutionary sequence. We find a clear, tight correlation between luminosity and $\dot{M}$ suggesting the scatter seen in studies of field stars is caused by stars of similar luminosity being of different initial masses. From our results we estimate how much mass a $16M_{\odot}$ star would lose during the RSG phase, finding a star of this mass would lose a total of $0.61^{+0.92}_{-0.31}M_{\odot}$. This is much less than expected for $\dot{M}$ prescriptions currently used in evolutionary models.

Key words: stars: massive – stars: evolution – stars: supergiants – stars: mass-loss

1 INTRODUCTION
Single stars with initial masses between 8 - 25 $M_{\odot}$ are predicted to evolve to become red supergiants (RSGs) before they end their lives as core collapse supernovae (SNe). During this phase, the stars become extremely luminous and undergo strong mass-loss. The driving mechanism for these winds remains uncertain and so mass-loss rates ($\dot{M}$) undergo strong mass-loss. The fate of massive stars with initial masses $>8M_{\odot}$ depends largely on the mass-loss rate ($\dot{M}$) in the end stages of their lives. Red supergiants (RSGs) are the direct progenitors to Type II-P core collapse supernovae (SN), but there is uncertainty regarding the scale and impact of any mass-loss during this phase. Here we used near and mid-IR photometry and the radiative transfer code DUSTY to determine luminosity and $\dot{M}$ values for the RSGs in two Galactic clusters (NGC 7149 and $\chi$ Per) where the RSGs are all of similar initial mass ($M_{\text{initial}}\sim16M_{\odot}$), allowing us to study how $\dot{M}$ changes with time along an evolutionary sequence. We find a clear, tight correlation between luminosity and $\dot{M}$ suggesting the scatter seen in studies of field stars is caused by stars of similar luminosity being of different initial masses. From our results we estimate how much mass a $16M_{\odot}$ star would lose during the RSG phase, finding a star of this mass would lose a total of $0.61^{+0.92}_{-0.31}M_{\odot}$. This is much less than expected for $\dot{M}$ prescriptions currently used in evolutionary models.

Key words: stars: massive – stars: evolution – stars: supergiants – stars: mass-loss

\textsuperscript{*} E-mail: e.beasor@2010.ljmu.ac.uk

Evolution of RSG mass-loss rates
factor of 2 during the RSG phase, as suggested by Georgy (2012).

We now present a similar study, this time focussing on two Galactic clusters, NGC 7419 and χ Per. Both clusters contain RSGs at different evolutionary stages all of a similar initial mass and Solar metallicity. Using near and mid-IR photometry we have derived Ms and luminosities for 13 RSGs, allowing us to study how M changes with evolution at a fixed metallicity. In Section 2 we discuss our modelling procedure and justifications for the parameters chosen. In Section 3 we discuss the application of our fitting methodology to Galactic clusters NGC 7419 and χ Per and the results we derive. In Section 4 we compare our results with commonly used M prescriptions, and calculate the total mass lost for an RSG of a given initial mass during the RSG phase. In Section 5 we present our conclusions.

2 APPLICATION TO GALACTIC CLUSTERS

2.1 Sample selection

In this paper we have chosen to study the Galactic clusters NGC 7419 and χ Per (also known as NGC 884), both of which contain a number of RSGs at Solar metallicity. These clusters have been found to be of similar ages (~14Myr, Marco & Negueruela 2013; Currie et al. 2010), which means all of the RSGs within each cluster have comparable initial masses (in this case 16M⊙, see Section 2.2). As the RSG phase is short (~10^6yrs, Georgy et al. 2013) we can assume the stars are all coeval, i.e. any spread in age between the stars is small compared to the lifetime of the cluster. A coeval set of RSGs also allows us to use luminosity as a proxy for evolution, since those stars with higher luminosities have evolved slightly further up the RSG branch. The photometry used in this work is shown in Table 1 and is taken from 2MASS, WISE and MSX (Skrutskie et al. 2006; Wright et al. 2010; Price et al. 2001). The stars selected were known cluster members. For χ Per we picked RSGs within 6' of cluster centre, which is the distance to the edge of the h & χ Per complex, to maximise the probability that the stars were cluster members and hence were formed at the same time. However, Currie et al. (2010) showed that everything within the h & χ Per complex, including the surrounding region, is the same age to within the errors.

2.2 Initial masses

To estimate initial masses for the RSGs, we need to know the age of the cluster. We have taken the best fit isochrone for both clusters (~14Myr from Padova isochrones, Marco & Negueruela 2013; Currie et al. 2010) as well as Geneva rotating and non-rotating isochrones. We compare the best fit turn off mass to that of other evolutionary models to determine a model dependent age for each cluster, and therefore the model dependent mass for the RSGs. From this, we are also able to ensure that we are comparing a self consistent age and mass for each evolutionary model.

From the original Padova isochrone, a turn-off mass of 14M⊙ is found and an RSG mass of ~15.5M⊙ for both clusters. The non-rotating Geneva models suggest the cluster’s turn-off mass is best fit by a 10Myr isochrone, giving an RSG mass of 17-18M⊙. The rotating models suggest an age of 14Myrs, with an RSG mass of 15-16M⊙. For the rest of this paper we will assume the initial mass for the stars across both MW clusters is 16M⊙, in between the rotating and non-rotating estimates.

3 DUST SHELL MODELS

The dust shell models used in this project were made using DUSTY (Ivezic et al. 1999) which solves the radiative transfer equation for a central star surrounded by a spherical dust shell of a certain optical depth (τV, optical depth at 0.55μm), inner dust temperature (Tin) at the inner most radius (rIn) and radial density profile (ρr). Below we briefly describe our choices for the model input parameters and our fitting methodology, for an in depth discussion see Beasor & Davies (2016).

3.1 Model Setup

The dust layer surrounding RSGs absorbs and reprocesses the light emitted from the star, with different compositions of dust affecting the spectral energy distribution (SED) in different ways. We have opted for oxygen rich dust as specified by Draine & Lee (1984) and a grain size of 0.3μm (e.g. Smith et al. 2001; Scicluna et al. 2015). To calculate mass-loss rates we have assumed a steady state density distribution falling off as r^-2. Departure from this law has been suggested for some RSGs (e.g. Shenoy et al. 2016), a matter which we discuss in detail in Beasor & Davies (2016). As we do not have outflow velocity measurements for the RSGs in our sample, we have assumed a uniform speed of 25±5 km s^-1, consistent with previous measurements (e.g. Van Loon et al. 2001; Richards & Yates 1998).

We have also assumed a gas-to-dust ratio (rgd) of 200 and a grain bulk density (ρd) of 3 g cm^-3. From this, we can then calculate M values from the following equation

\[ M = \frac{16πRr_{in}Vρd}{QV} \rho r \] (1)

where QV is the extinction efficiency of the dust (as defined by the dust grain composition, Draine & Lee 1984).

The stellar effective temperature Teff changes the position of the peak wavelength of the SED. For NGC 884, the RSGs are of spectral types M0 - M3.5, corresponding to an approximate temperature range of 3600K - 4000K (taken from the temperature scale of Levesque et al. 2005). In contrast Gazak et al. (2014) found a narrower Teff spread among the stars in χ Per, 3720K - 4040K. In this work, we have opted for a fiducial SED of 3900K for the analysis of this cluster, with the errors on Lbol found by rerunning the

1 The evolutionary models suggest that for a single age cluster (e.g. Geneva rotating, 14Myrs) the difference in initial mass between stars at the start of the RSG phase and stars at the end of the RSG phase is ~0.8M⊙. A significant dispersion in initial masses between the RSGs in our sample is therefore unlikely.
Evolution of RSG mass-loss rates

Table 1. Observational data for RSGs in $\chi$ Per & NGC 7419. All fluxes are in units of Jy. All photometry for WISE 1 and 2 are upper limits.

<table>
<thead>
<tr>
<th>Name</th>
<th>2MASS-J</th>
<th>2MASS-H</th>
<th>2MASS-Ks</th>
<th>WISE1</th>
<th>WISE2</th>
<th>WISE3</th>
<th>WISE4</th>
<th>MSX-A</th>
<th>MSX-C</th>
<th>MSX-D</th>
<th>MSX-E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(3.4 µm)</td>
<td>(4.6 µm)</td>
<td>(11.6 µm)</td>
<td>(22 µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZ Per</td>
<td>48.18±3.32</td>
<td>70.32±4.84</td>
<td>67.79±6.56</td>
<td>–</td>
<td>&lt;64.90</td>
<td>9.33±0.06</td>
<td>4.43±0.06</td>
<td>12.20</td>
<td>10.90</td>
<td>6.52</td>
<td>4.13</td>
</tr>
<tr>
<td>RS Per</td>
<td>95.69±6.83</td>
<td>146.93±13.38</td>
<td>158.20±21.27</td>
<td>&lt;152.05</td>
<td>&lt;317.56</td>
<td>51.70±39.43</td>
<td>43.88±0.07</td>
<td>57.60</td>
<td>59.50</td>
<td>42.80</td>
<td>41.10</td>
</tr>
<tr>
<td>AD Per</td>
<td>70.94±4.95</td>
<td>104.30±8.66</td>
<td>111.38±14.90</td>
<td>&lt;349.83</td>
<td>&lt;115.72</td>
<td>18.09±2.05</td>
<td>11.16±0.36</td>
<td>20.80</td>
<td>20.40</td>
<td>13.10</td>
<td>11.30</td>
</tr>
<tr>
<td>V439 Per</td>
<td>35.52±2.46</td>
<td>52.71±3.80</td>
<td>55.98±6.24</td>
<td>&lt;119.42</td>
<td>&lt;45.69</td>
<td>4.29±0.05</td>
<td>1.85±0.02</td>
<td>7.33</td>
<td>5.18</td>
<td>3.20</td>
<td>2.39</td>
</tr>
<tr>
<td>V430 Per</td>
<td>25.85±0.80</td>
<td>42.22±0.00</td>
<td>42.66±14.29</td>
<td>&lt;0.25</td>
<td>&lt;0.02</td>
<td>2.89±0.02</td>
<td>0.93±0.01</td>
<td>5.31</td>
<td>2.71</td>
<td>1.83</td>
<td>1.86</td>
</tr>
<tr>
<td>V441 Per</td>
<td>65.12±4.84</td>
<td>105.66±9.43</td>
<td>101.76±11.87</td>
<td>&lt;51.75</td>
<td>&lt;165.28</td>
<td>16.54±1.17</td>
<td>11.55±0.47</td>
<td>19.30</td>
<td>16.80</td>
<td>13.30</td>
<td>11.10</td>
</tr>
<tr>
<td>SU Per</td>
<td>118.27±10.64</td>
<td>173.42±16.55</td>
<td>174.58±26.64</td>
<td>&lt;1099.16</td>
<td>&lt;315.23</td>
<td>39.14±25.30</td>
<td>27.13±1.01</td>
<td>43.80</td>
<td>40.00</td>
<td>24.10</td>
<td>30.10</td>
</tr>
<tr>
<td>BU Per</td>
<td>53.91±4.24</td>
<td>86.84±6.64</td>
<td>88.39±9.27</td>
<td>&lt;467.15</td>
<td>&lt;170.70</td>
<td>32.05±1057.73</td>
<td>28.15±1.11</td>
<td>33.10</td>
<td>36.78</td>
<td>26.30</td>
<td>30.20</td>
</tr>
</tbody>
</table>

For MY Cep, as the $\tau_V$ range in our initial model grid was not high enough to match the observed photometry, we had to use a coarser model grid with a large range of $\tau_V$ values.

4 MODELLING RESULTS

We ran our fitting procedure for all of the RSGs in our sample. Our results for $\chi$ Per and NGC 7419 are shown in Table 2. Figure 1 shows the best fit model for the brightest star in these clusters, SU Per, with all contributions to the output spectrum. The left panel of the plot shows the best fit model spectra (green line), the models within our error range (blue dotted lines) as well as the photometric points, where the black crosses shown the real photometry and orange circles show the model photometry. The right hand panel shows our best fit model located on a $T_{\text{eff}}-\tau$ plane with the mass loss rate isochronals overplotted.

Both clusters are affected by foreground reddening. To correct for this we used the published extinction laws for the 2MASS, MSX and WISE photometry (Koornneef 1983; Messineo et al. 2005; Gontcharov 2010). We adopted foreground V-band extinctions of 1.66 and 5.27 for the clusters $\chi$ Per and NGC 7419 respectively (Currie et al. 2010; Marco & Negueruela 2013). There is evidence that differential extinction is present in each cluster. For $\chi$ Per, Currie et al. (2010) find a V-band dispersion of 0.09 mag (estimated from J-K colours), equivalent to $\sim$0.01 mag in $K_s$. This level of differential extinction is smaller than the errors on our photometry and hence will not effect our modelling results. Similarly, the differential reddening across NGC 7419 is approximately 0.2 mag in $K_s$ (Marco & Negueruela...
5.1 The Reimers (1975), Van Loon et al. (2005) and Goldman et al. (2017) prescriptions also are commonly used for RSGs. We also include results from NGC 2100 (BD16).

When plotting $L_{\text{bol}}$ versus $M$ a clear positive correlation can be seen (see Fig. 2), demonstrating an increasing $M$ with evolution. We also include results from NGC 2100 (BD16). Overplotted are also some commonly used $M$ prescriptions (assuming a $T_{\text{eff}}$ of 3900K), including: De Jager et al. (1988), Reimers (1975), Van Loon et al. (2005) and Goldman et al. (2017).

### Table 2. Fitting results for the RSGs in $\chi$ Per and NGC 7419.

<table>
<thead>
<tr>
<th>Star</th>
<th>$T_{\text{bol}}$ (K)</th>
<th>$rV$</th>
<th>$M$ ($10^{-5}$M$_{\odot}$ yr$^{-1}$)</th>
<th>$L_{\text{bol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZ Per</td>
<td>1000±200</td>
<td>0.15±0.08</td>
<td>0.30±0.18</td>
<td>4.64±0.06</td>
</tr>
<tr>
<td>RS Per</td>
<td>600±200</td>
<td>0.51±0.13</td>
<td>3.03±2.31</td>
<td>4.95±0.18</td>
</tr>
<tr>
<td>AD Per</td>
<td>600±600</td>
<td>0.21±0.15</td>
<td>0.97±0.50</td>
<td>4.86±0.08</td>
</tr>
<tr>
<td>V439 Per</td>
<td>1200±60</td>
<td>0.11±0.02</td>
<td>0.10±0.01</td>
<td>4.53±0.06</td>
</tr>
<tr>
<td>V403 Per</td>
<td>1200±60</td>
<td>0.00±0.00</td>
<td>0.06±0.02</td>
<td>4.12±0.05</td>
</tr>
<tr>
<td>V441 Per</td>
<td>600±200</td>
<td>0.21±0.02</td>
<td>0.93±0.30</td>
<td>4.75±0.10</td>
</tr>
<tr>
<td>SU Per</td>
<td>600±100</td>
<td>0.25±0.10</td>
<td>1.42±0.72</td>
<td>4.99±0.05</td>
</tr>
<tr>
<td>BU Per</td>
<td>500±200</td>
<td>0.56±0.10</td>
<td>3.24±1.33</td>
<td>4.67±0.07</td>
</tr>
<tr>
<td>MY Cep</td>
<td>600±200</td>
<td>0.24±0.11</td>
<td>10.92±4.34</td>
<td>5.19±0.07</td>
</tr>
<tr>
<td>BMD 139</td>
<td>900±300</td>
<td>0.10±0.08</td>
<td>0.27±0.04</td>
<td>4.55±0.08</td>
</tr>
<tr>
<td>BMD 921±56</td>
<td>-</td>
<td>&lt;0.05</td>
<td>&lt;0.06</td>
<td>4.45±0.10</td>
</tr>
<tr>
<td>BMD 696±122</td>
<td>700±500</td>
<td>0.08±0.08</td>
<td>0.22±0.04</td>
<td>4.68±0.08</td>
</tr>
<tr>
<td>BMD 435</td>
<td>1100±300</td>
<td>0.16±0.08</td>
<td>0.18±0.04</td>
<td>4.54±0.11</td>
</tr>
</tbody>
</table>

Goldenman et al. (2017) studied RSG winds across a range of metallicities, stating that lower metallicity environments yield slower wind speeds for stars. As $M$ is directly proportional to the expansion velocity of the wind (see Equation 1), a lower wind speed will result in a lower derived $M$. Goldman et al. (2017) measure a relation between expansion velocity of the wind and metallicity ($v_{\text{exp}}/\zeta L_{0.4}$), with derived expansion velocities then being compared to mass-loss rates. From this we can estimate how large the effect of varying metallicity is on $M$. It is therefore possible that the $v_{\text{exp}}$ we have assumed for the RSGs in NGC 2100 (an LMC metallicity cluster) is systematically high. However, we estimate this would reduce the $M$ values for these stars by around 25%, bringing these results into even better agreement with the Galactic clusters. The effect of varying metallicity is therefore unlikely to be enough to cause the factor of 10 scatter seen in previous relations.

The RSGs we have observed in NGC 2100, $\chi$ Per and NGC 7419 are all of a similar initial mass, but different metallicities (LMC, Solar and Solar, respectively). Despite this, there is still a tight correlation when all of the clusters are plotted together. In this case, the effect of varying metallicity is therefore unlikely to be enough to cause the factor of 10 scatter seen in previous relations. As these previous studies have focussed on field stars only, this internal scatter may be caused by inhomogeneity in the initial masses and/or metallicities of the stars in their samples (i.e. the stars are of different masses and ages at the same luminosity).

### 5 DISCUSSION

#### 5.1 The $M$ - Luminosity Relation

There are many empirical studies of RSG mass loss (e.g. Reimers 1975; De Jager et al. 1988; Van Loon et al. 2005; De Beck et al. 2010; Bonanos et al. 2010; Goldman et al. 2017) all showing significant scatter. For example the calibration of Mauron & Joselin (2011) has a large peak-to-peak dispersion of a factor of $\sim 10$. As these previous studies have focussed on field stars only, this internal scatter may be caused by inhomogeneity in the initial masses and/or metallicities of the stars in their samples (i.e. the stars are of different masses and ages at the same luminosity).

\[ \log(M/M_{\odot}\text{yr}^{-1}) = a + b\log(L_{\text{bol}}/L_{\odot}) \]

where $a = -24.56 \pm 1.65$ and $b = 3.92 \pm 0.35$, derived using IDL program FITEXY. We find a much steeper relation between mass loss and luminosity than previous studies, with a root mean square scatter of $\pm 0.4$ dex. Our data suggest that when stars first join the RSG phase they have very low mass loss rates, implied by the small amount of circumstellar material present. The mass loss rate then increases by a factor of 100 throughout the RSG lifetime. This may be dependent on metallicity (Goldman et al. 2017)

Throughout this work we have assumed a constant gas-to-dust ratio for all stars in our sample. It is possible that this may change.
5.2 The luminosity distribution of RSGs

To determine the mass-loss rate at a given time-step, stellar evolution calculations use a mass-loss rate prescription (usually dJ88) in conjunction with the star’s luminosity at that time step. If the luminosity is incorrectly estimated the adopted mass-loss rate during this phase will also be incorrect.

We are able to test the implementation of $\dot{M}$ in evolutionary models by looking at luminosity distributions. Luminosity distributions were generated by uniformly sampling RSG masses from a standard Salpeter IMF and assuming a uniform age for all stars. We simulated a large number of stars ($10^5$) within the relevant mass range and then normalised the distribution to match the total number of stars across both MW clusters. We also included the effect of measurement errors on the simulated luminosity distributions.

Figure 3 shows a comparison for the luminosity distribution of the RSGs in the two MW clusters compared to the predicted luminosity distribution for 13 RSGs in the best fit Geneva non-rotating and Geneva rotating models (see Section 3.2). The observed luminosity distribution for the RSGs in the two clusters is peaked at a luminosity of log($L/L_\odot$) $\sim$ 4.5, see the top panel of Fig. 3. As the age spread between the RSGs in our sample is likely small, we can say that the different luminosities show the stars at slightly different stages of evolution. The concentration of stars in each luminosity bin indicates the relative amount of time the star spends at each interval. When comparing to the Geneva models, we see that RSGs are predicted by Geneva to spend most of their lives at much higher luminosities than observed, between log($L/L_\odot$) $\sim$ 4.6 - 5.1, see Fig. 3. As $\dot{M}$ is scaled from luminosity in evolutionary models, this will lead to $\dot{M}$ being overestimated by models throughout the RSG phase.

As previously noted we have assumed a uniform age for all of the stars in the sample. However, given the errors on the age estimates for both clusters it is possible that an age spread exists between the RSGs. Currie et al. (2010) estimate the age error on $\chi$ Per to be $\pm$ 1 Myr, while Marco & Negueruela (2013) estimate the age error on NGC 7419 to be $\pm$ 2 Myr. These numbers provide an upper limit to the age spread that exists within the clusters.

We now investigate what effect a 2 Myr age spread would have on the observed luminosity distribution of the RSGs. We used Geneva isochrones and generated luminosity distributions for ages between 12 and 14 Myr (rotating models) at intervals of 0.1 Myr. We assumed a uniform age distribution, simulating a constant star formation rate for 2 Myr. This had no visible effect on the luminosity distribution, with the peak and width remaining the same. We could also have looked at what effect a Gaussian or exponentially declining star formation rate would have on the luminosity distribution, but as the constant rate would have the greatest impact it is unlikely either of these more complicated age spread functions would affect our conclusions. We can therefore rule out a non-instantaneous starburst as being the cause of the difference between the observed and predicted luminosity distributions.

5.2.1 Estimating the total mass lost during the RSG phase

Having determined $M$ as a function of evolutionary phase, we now use our results to estimate the total mass lost as a 16$M_\odot$ star evolves up the RSG branch. This is important as the amount of mass lost can effect the appearance of the resulting SN. For example, while theory predicts RSGs to be the progenitors to Type II-P SN, there is the possibility that if the star were to lose a large enough mass it would appear instead as a Type IIn SN (e.g. Smith et al. 2009, 2016). The narrow lines of a Type IIn SN are visible when a star ex-
plodes into a dense circumstellar medium, and for an RSG it would require \(\sim 1\,M_\odot\) material to be present around the star (Smith et al. 2009). There is increasing observational evidence for a continuum between II-L, IIn and II-P SN as opposed to the SN being produced by distinct progenitors. For example Morozova et al. (2017) found that II-L light curves could be fit by ordinary RSGs with dense CSM. Likewise, SN PTF11iqb showed narrow emission lines for it’s first two days before they weakened and the light curve quickly began to resemble a II-L and II-P SN (Smith et al. 2015), which experienced enhanced mass-loss in the years preceding the SN.

We now investigate the total mass lost during the RSG phase for a typical 16\(M_\odot\) star based on the RSGs in the two MW clusters. For a 16\(M_\odot\) star, all major evolutionary codes agree that the lifetime of the RSG phase is 1Myr \(\pm 15\%\) (Ekström et al. 2012; Eldridge & Stanway 2009; Dotter 2016). Using the luminosity distribution for the RSGs in \(\chi\) Per and NGC 7419, we can deduce how much time an RSG spends at each evolutionary stage. As we know how \(M\) varies with luminosity, it is possible to determine how \(M\) varies with time. To convert luminosity into a time, we take the cumulative distribution of \(L_{bol}\) and interpolate this onto a time axis of \(10^6\) years. We then integrate \(\dot{M}\) with respect to time and estimate the total amount of mass that would be lost during the RSG phase for a 16\(M_\odot\) star.

Figure 2. Plot showing \(M\) versus \(L_{bol}\) for all clusters we have studied. We also overplot our \(M\)- luminosity relation for a 16\(M_\odot\) star.
To estimate the error, we used a Monte-Carlo (MC) method. For each star studied, we randomly sampled its $\dot{M}$ from an asymmetric Gaussian distribution centred on its best-fit value, with upper and lower 1-sigma widths determined by the upper and lower error bars. In each MC trial, we then integrated the $\dot{M}$ of all stars with respect to time to find the total mass lost in that trial. By repeating $10^4$ times, we were able to determine the most likely total mass lost and the upper and lower 68% confidence limits, comparable to a 1-sigma error bar.

From this we find a 16$M_\odot$ star would lose $0.61^{+0.92}_{-0.31}$ $M_\odot$ throughout the RSG phase. As this mass is lost over a long period of time ($10^6$ yrs) it is unlikely there would be enough CSM close to the star to have an effect on the appearance of the resulting SN. Since the amount of envelope mass lost is small we can also expect there to be a long plateau in the SN light curve.

We now compare our measurement of the total mass lost with predictions from stellar evolutionary models. Figure 4 shows how much mass is lost during the RSG phase as a function of initial mass for Geneva, STARS and MIST models (Ekström et al. 2012; Eldridge & Stanway 2009; Dotter 2016). This figure shows that compared to our observations for a 16$M_\odot$ star, all evolutionary models employ mass-loss rates that are too high, and hence over-predict the total mass lost during the RSG phase, with Geneva rotating models having the biggest offset from what we observe. In this figure we can also see that at ~ 20$M_\odot$, the predicted total mass lost during the RSG phase from Geneva models deviates from the STARS model by around a factor of 3. This could be due to the Geneva group artificially enhancing $\dot{M}$ by a factor of 3 for stars which exceed the Eddington limit in their envelopes by a factor of 5 (Ekström et al. 2012).

Figure 4 suggests that evolutionary models are in fact over predicting mass loss during the RSG phase, and increasing $\dot{M}$ (as suggested to solve the RSG problem, e.g. Georgy 2012) would only exacerbate this. Instead, a reappraisal of $\dot{M}$ prescriptions is needed to better inform stellar evolutionary models and allow more accurate predictions to be made. This is also a wider problem for massive star evolution, including hot star winds and luminous blue variables (LBVs, Smith 2014). Future work will involve observing stars with different initial masses to fully understand the effect of $\dot{M}$ throughout the RSG phase, at different , and hence determine a new $\dot{M}$ luminosity relation.

However, we have also shown that the luminosity distributions used in models are skewed to higher luminosities than observed in $\chi$ Per and NGC 7419. It may therefore be necessary to find a new way to implement $\dot{M}$ in evolutionary models, since employing an empirical $\dot{M}$-luminosity relation will result in an $\dot{M}$ which is too high if the models are over-predicting the RSG luminosities.

6 CONCLUSIONS

In this paper we have re-appraised the $\dot{M}$-luminosity relation using stars in young massive clusters. By focussing on RSGs within clusters we are effectively seeing the same star at different stages of evolution and can therefore observe how $\dot{M}$ varies as the star evolves towards SN. We have determined $\dot{M}$'s and luminosities for RSGs in Galactic clusters NGC 7419 and $\chi$ Per, both of which are approximately the same age and hence we are able to assume the RSGs are all of similar initial mass (~16$M_\odot$). From our study we can conclude the following:

(i) At fixed initial mass $\dot{M}$ increases with time during the RSG evolution of the star, in a relation with little scatter. We suggest that the reason the correlation is tight compared to previous $\dot{M}$ prescriptions is due to keeping $M_{\text{initial}}$ constrained. We also find that this relation does not depend on the metallicity of the star, as we have studied both Galactic and LMC clusters and still find a tight correlation. From this we are able to present a new $\dot{M}$ prescription for stars
Figure 4. Plot showing the amount of mass lost for a star of a given initial mass for various stellar evolution models. The single pink circle shows the total amount of mass lost during the RSG phase for a 16$M_\odot$ star.

with initial masses of $\sim 16M_\odot$ that depends only on the luminosity of the star.

(ii) We have also compared the observed luminosity distribution for the RSGs in the two Galactic clusters to evolutionary models. We find that these models overpredict how much time the RSGs spend at high luminosities, and thus overpredict the total amount of mass-loss during the RSG phase.

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REFERENCES

De Jager C., Nieuwenhuijzen H., Van Der Hucht K., 1988, Astronomy and Astrophysics Supplement Series, 72, 259
Ekström S., et al., 2012, Astronomy & Astrophysics, 537, A146
Georgy C., 2016, Astronomy Letters, 42, 445
Georgy C., et al., 2013, Astronomy & Astrophysics, 558, A103
Koornneef J., 1983, Astronomy and Astrophysics, 128, 84
Marco A., Negueruela I., 2013, Astronomy & Astrophysics, 552, 60
APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.