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New perspectives on red supergiants

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Abstract

There is a high interest in cool supergiants (CSGs), because they play a key role in the understanding of the evolution and death of massive stars: most high-mass stars pass through this phase at some point of their evolution, and the physical conditions during it will determine their subsequent evolution. In addition, these stars are a powerful high-mass stellar formation tracers and also the main progenitors of core-collapse supernovae (SNe). Despite this, they are poorly characterized in some aspects: their extreme sizes and peculiar conditions defy the predictions of present-day atmospheric and evolutionary models. To bring perspective to this topic, we investigate the behaviour of CSGs as a population. For this, we studied the largest homogeneous multiepoch spectroscopic sample of CSGs (from the SMC and LMC) to date (> 500). Our results give a new global view about the physical conditions of CSGs and their evolution.

1 Introduction

When stars with initial masses between 10 and 40 $M_\odot$ evolve off the main sequence ([5, 9]), they become much cooler (by a factor of ~ 10), but keeping their high luminosity roughly constant. In consequence, their atmospheres increase their size dramatically, reaching radii between 400 and 1 700 $R_\odot$ ([14, 15, 1]). They become cool supergiants (CSGs), the largest stars known. Depending on their SpT, CSGs are known as red supergiants (RSGs; for K and M types) or yellow supergiants (YSGs; for G or slightly earlier types). Although CSGs are evolved stars, they are very young ($8-25$ Ma; [9]). Moreover, the higher their initial masses, the shorter their lives: they reach the CSG phase sooner and stay on it for shorter times (see Fig. 1). There are several reasons to study CSGs, but we highlight three of them:

- As CSGs are evolved stars with short lives, they represent a strong constraint for evolutionary models. Thus, their observational characterization is a key piece to improve evolutionary tracks.

- CSGs and OB stars are very young and luminous stars ($L \sim 10^{4.5} - 10^{5.8}\,\mathrm{L}_\odot$ in the case of CSGs; [13]). Thus they are very useful to track recent high-mass stellar formation. However, RSGs have a clear advantage over OB stars: because of their low temperatures their emission peak is in the near infrared. Thus, they can be detected easily even in very obscured regions, such as the inner Galaxy.

- RSGs are the main progenitors of core-collapse supernovae (SNe). Thus, a better understanding of their physical conditions and mass loss history will help to improve the parameter determination of observed SN progenitors [2].

There are, however, some major open questions about CSGs. A fundamental issue is the relation of SpT with luminosity and mass loss. The RSG population of a given galaxy presents a distribution of SpTs around a central value, which is the most frequent. It has been known for long ([10]) that this SpT range depends on the metallicity of the galaxy, with later types at higher metallicities. In addition, it is suspected ([6]) that stars with the latest SpTs are also those with the highest luminosities and mass-loss rates, but this relation have not been proved through a statistically significant sample. Finally, YSGs and RSGs have been studied as different populations, with most papers focusing on RSGs (as they are the dominant population in the Milky Way), but there are hints ([16]) of YSGs being part of the same population as RSGs in low metallicity environments.

To answer these questions, we observed and studied the largest homogeneous spectroscopic sample of CSG to date, from both the Small and the Large Magellanic Cloud (SMC and LMC respectively).

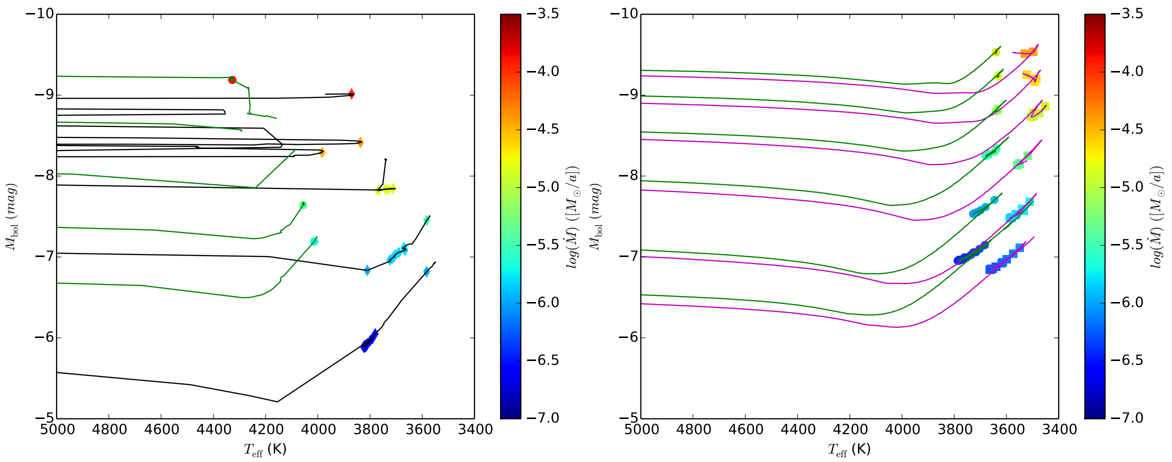

Figure 1: Theoretical evolutionary tracks for CSGs. The colour of the tracks indicates metallicity: black for $Z = 0.014$, magenta for LMC typical metallicity, and green for SMC typical metallicity. The points along the tracks are separated by 0.1 Ma, and their colours indicate mass loss. **Left (1a):** Geneva models, from [8] and [11]. From bottom to top, tracks for stars with initial masses of 12, 15, 20, 25 and 32 $\mathrm{M}_\odot$. **Right (1b):** Models from [5]. From bottom to top, tracks for stars with initial masses of 12, 15, 20, 25, 30 and 35 $\mathrm{M}_\odot$.

2 The sample

We constructed the samples from the SMC and the LMC using different sources. On one hand, we selected previously known CSGs from the literature ([10, 17, 18]). On the other hand, we made a photometric selection of candidates, through the reddening-free parameter $Q_{\mathrm{IR}} = (J - H) - 1.8 \cdot (H - K_{\mathrm{S}})$ (see [12] for details).

The samples were observed using the dual beam multiobject spectrograph AAOmega (at the Anglo-Australian Telescope). We chose this spectrograph because its wide field of view (2 deg) and its almost 400 fibres allow us to observe large samples, covering most of the SMC and the LMC. We used the gratings 580V (covering a range of 2 100 Å with $\lambda/\delta\lambda \sim 1\,300$ at its centre: 4500 Å) and 1500V (covering a range of 800 Å with $\lambda/\delta\lambda \sim 2\,700$ at its centre: 5200 Å) to observe their optical range.

We classified all the observed targets in SpT and luminosity class (LC). For this, we used classical criteria for the optical spectral range (see [12]). Among our photometrically selected candidates, we found a significant number of previously unknown CSGs. We also confirmed their membership in the Clouds through their radial velocities. In total, our sample has more than 500 CSGs (303 from the SMC and 224 from the LMC). Finally, we calculated their absolute bolometric magnitudes (M_{bol}) using the distance to the Clouds, and the relation given in [3] for the colour $(J - K)$.

3 Spectral type, luminosity, and mass loss

When we plotted SpTs against M_{bol} (see Fig. 2) we found a clear trend between them in both galaxies. However, only those CSGs with mid to high luminosities (LC Ia or Iab, or $M_{\mathrm{bol}} \leq 6$ mag) follow this trend. Low luminosity CSGs (LC Ib or Ib-II) form a broad stripe below $M_{\mathrm{bol}} = 6$ mag without a clear trend between SpT and luminosity. We did not study Ib CSGs because these stars were not the main focus of our programme. Thus, the sample of Ib CSGs is clearly incomplete and we cannot extract any conclusion from them, beyond stating that their behaviour as a population is not the same as that of Ia and Iab CSGs.

As can be seen in Fig. 2, mid- to high-luminosity CSGs tend to have later SpTs at higher luminosities. Moreover, CSGs from both galaxies present this trend despite their different SpT ranges. Thus, our data confirm the relation between SpT and luminosity for significant large samples, and for two environments with substantially different metallicities. This result is in clear conflict with theoretical predictions. Evolutionary models (see Fig. 1) predict a weak trend between temperature (which dominates SpT; [7]) and luminosity, but only for a small range of luminosities. For high luminosity CSGs, they predict the same or warmer temperatures as for mid luminosity ones. Moreover, Geneva models ([8, 11]) indicate that high-luminosity CSGs do not last there for a significant fraction of their lifetime, returning to higher temperatures quickly.

There are two possible explanations for the existence of luminous, late-type CSGs. On one hand, models can be underestimating the minimum temperatures of high-mass CSGs, as well as the fraction of their lifetime that they spend at low temperatures. On the other

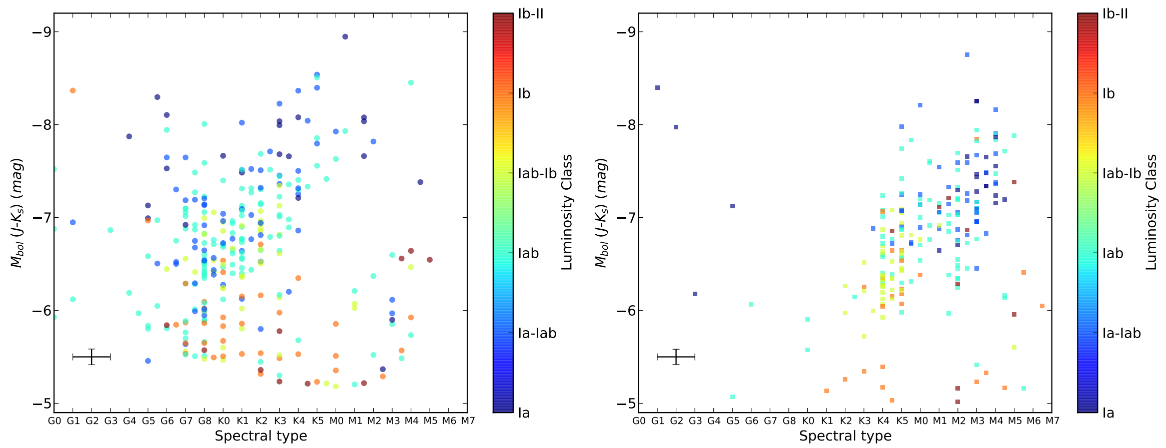

Figure 2: Spectral type against M_{bol}. Colour indicates the LC of each RSG in both figures. The median uncertainties are represented by the black cross. **Left (2a):** CSGs from the SMC. **Right (2b):** CSGs from the LMC.

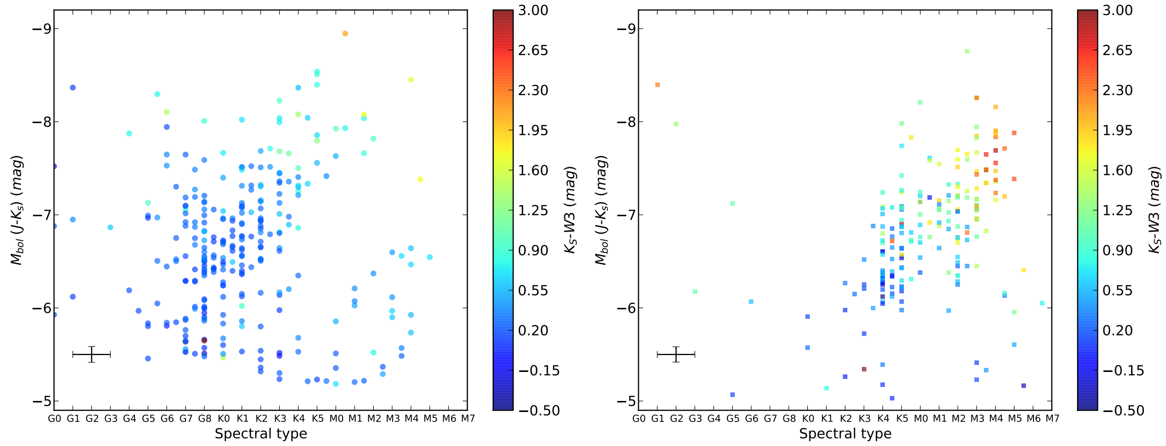

Figure 3: Spectral type to M_{bol}. Colour indicates the mass-loss rate. Median uncertainties are given by the black cross. To facilitate the comparison, both figures are given in the same scale. **Left (3a):** CSGs from the SMC. **Right (3b):** CSGs from the LMC.

hand, these luminous, late CSGs could be lower-mass supergiants that have increased dramatically their luminosity close to the end of their lives. However, for these masses, models predict luminosity increases with evolution much smaller than those required to explain the observations. Further work is required to understand the origin of the disagreement between theoretical predictions and observations about high-luminosity CSGs.

Finally, as mentioned, the trend between SpT and luminosity is believed to also relate with the mass-loss rates in CSGs. To test this idea, we used infrared photometry available in catalogues to estimate the mass losses of our CSGs. We adopted the ($K_{\mathrm{S}} - [W3]$) colour for this task (see [7] for details), taking K_{S} from 2MASS [19] and the $[W3]$ band from WISE

([20]). We show the values of mass loss derived in Fig. 3. As can be seen, mass loss is related to both, SpT and luminosity. However, this relation differs from one Cloud to the other, with higher values of mass loss for CSGs from the LMC (confirming previous works, e.g. [4]).

4 Spectral type distributions

When we plotted the SpT distribution of the CSGs from each Magellanic Cloud (see Fig. 4), the results were unexpected. In the case of the SMC, the histogram showed that the mean SpT for mid- and high-luminosity CSGs is significantly earlier (K1) than previously thought (K5 − K7;[17] and [16]). This shift toward earlier types happens because of two reasons. Firstly, previous works focused on high luminosity CSGs, which have later types, while our sample includes a large number of mid-luminosity objects. Secondly, we have observed a large number of G stars, while previous works studied only RSGs. As can be seen in Fig. 4a, G YSGs seem to belong to the same distribution as RSGs, supporting the idea that all these stars are only one population, as suspected in [16].

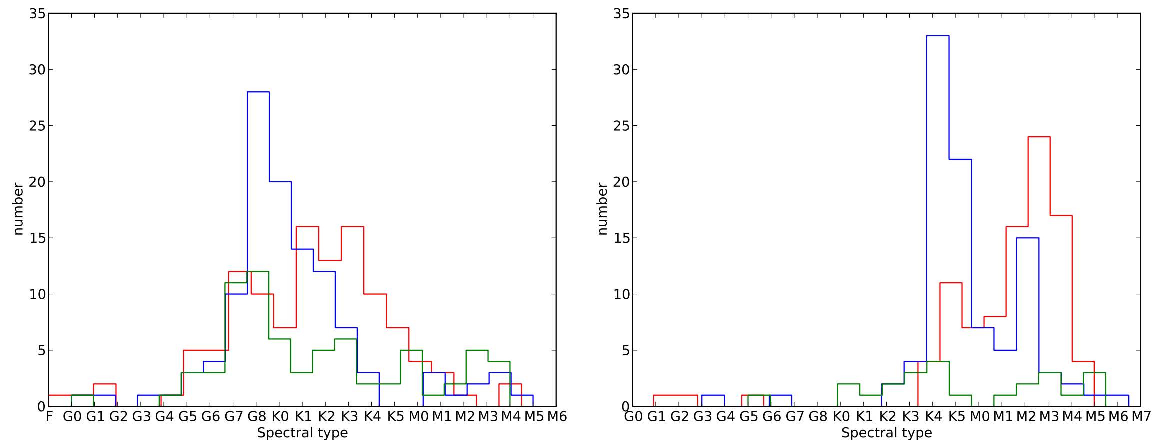

Figure 4: Spectral type distributions for stars in the Magellanic Clouds, segregated by luminosity (Red: $M_{\text{bol}} < -6.88$; Blue: $-6 > M_{\text{bol}} \leq -6.88$; Green: $M_{\text{bol}} \leq -6$). **Left (4a):** CSGs from the SMC **Right (4b):** CSGs from the LMC.

In the case of the LMC, the distribution is bimodal (see Fig. 4). We analysed if this effect could be caused by systematic errors or selection biases, but we found no evidence (see [7] for details). Moreover, when we segregated the distribution by luminosity (by LC or by M_{bol}), we found that one peak (centred at M2 − M3) is dominated by Ia CSGs, while the other (centred at K4 − K5) is dominated by Iab CSGs. This bimodality has not been reported before, likely because most previous works studied mainly high luminosity CSGs. Indeed, the typical SpT of our Ia objects, M2 − M3, is the same as in previous works.

The CSGs in the later peak present significantly higher mass-loss rates than the mid-luminosity CSGs. Even more, the difference between the mean mass-loss rates of Ia and Iab CSGs in the LMC is larger than the most extreme difference found among SMC CSGs.

These results seem to suggest the possible existence of two different evolutionary phases among LMC CSGs: state I, with CSGs having earlier SpTs, mid luminosities (mainly Iab), and lower mass-loss rates; and state II, whose CSGs are later, more luminous (mostly Ia), and with significantly higher mass-loss rates. Finally, as there is a clear gap between these two peaks, we think that the shift from one state to the other is very quick. However, there is not any reason to think that all CSGs evolve from state I to state II. High-luminosity CSGs may evolve directly to state II, while less luminous Iab CSGs, although increasing their luminosity along their evolution during the CSG phase, perhaps do never reach state II.

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