Massive Stars Near and Far
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Red Supergiants in M31: The Humphreys-Davidson limit at high metallicity

Sarah L. E. McDonald[1], Ben Davies[1] and Emma R. Beasor[2]

[1]Astrophysics Research Institute, Liverpool John Moores University, Liverpool Science Park ic2,146 Brownlow Hill, Liverpool, L3 5RF, UK
email: s.e.mcdonald@2015.ljmu.ac.uk

[2]NSF's National Optical-Infrared Astronomy Research Laboratory, 950 N. Cherry Ave., Tucson, AZ 85719, USA

Abstract. The empirical upper limit to Red Supergiant (RSG) luminosity, known as the Humphreys-Davidson (HD) limit, has been commonly explained as being caused by the stripping of stellar envelopes by metallicity-dependent, line-driven winds. As such, the theoretical expectation is that the HD limit should be higher at lower metallicity, where weaker mass-loss rates mean that higher initial masses are required for an envelope to be stripped. In this work, we test this prediction by measuring the luminosity function of RSGs in M31 and comparing to those in the LMC and SMC. We find that $\log(L_{\rm max}/L_\odot) = 5.53 \pm 0.03$ in M31 (Z $\gtrsim$ Z$_\odot$), consistent with the limit found for both the LMC (Z $\sim$ 0.5 Z$_\odot$) and SMC (Z $\sim$ 0.25 Z$_\odot$), while the RSG luminosity distributions in these 3 galaxies are consistent to within 1σ. We therefore find no evidence for a metallicity dependence on both the HD limit and the RSG luminosity function, and conclude that line-driven winds on the main sequence are not the cause of the HD limit.

Keywords. stars: late-type, stars: fundamental parameters, Hertzsprung-Russell diagram, stars: mass loss

1. Introduction

It is well established that there is an empirical upper limit to Red Supergiant (RSG) luminosity (Stothers 1969; Sandage & Tammann 1974), often referred to as the 'Humphreys-Davidson (HD) Limit' (Humphreys & Davidson 1979). The HD limit is often explained as being a manifestation of mass loss (e.g. Humphreys & Davidson 1979) during the lifetime of the star, caused by strong stellar winds or episodic periods of mass-loss, where the fraction of mass lost from the stellar envelope is dependent on the initial mass of the star. Under this explanation, lower initial mass supergiants ($\sim 8M_\odot - 15M_\odot$) experience winds which are not strong enough to remove the entire hydrogen envelope on the main sequence (MS, Maeder 1981; Maeder & Meynet 2003) so the star is able to evolve to the RSG phase, where it resides before dying as a core-collapse supernova. Higher initial mass stars ($\sim 15M_\odot - 30M_\odot$) can lose a considerable fraction of their envelope, causing the star to undergo only a brief RSG phase before evolving to a Wolf Rayet (WR) star (Stothers & Chin 1979). At even higher masses ($\gtrsim 30M_\odot$), the entire envelope can be lost by the time hydrogen in the core is exhausted, preventing evolution to the cool red side of the Hertzsprung-Russell (HR) diagram. These stars instead evolve directly from the

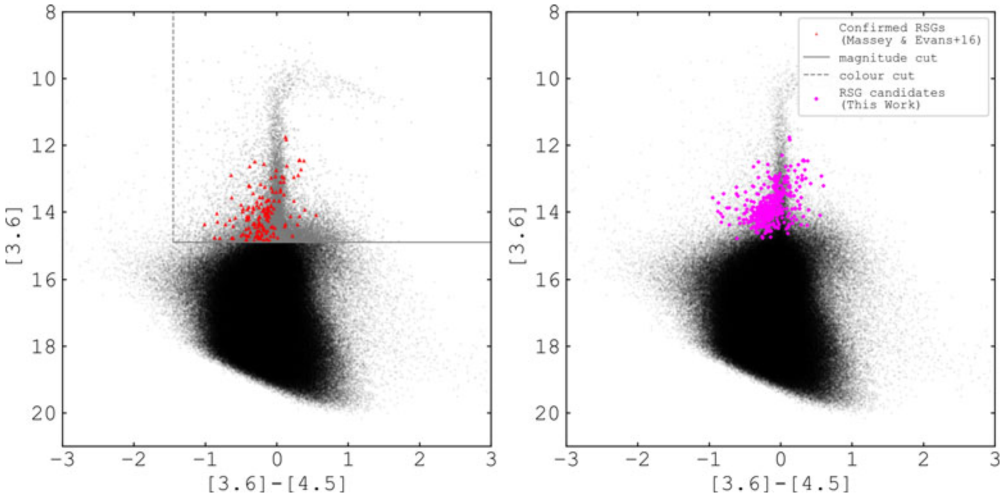

Figure 1. (a) A colour magnitude diagram, where the black points in both panels indicate all the M31 point sources detected by Spitzer IRAC/MIPS (Khan 2017). The grey points show the sources which fit the criteria to be a likely RSG candidate based on the colour (dashed grey line) and magnitude (solid grey line) cuts applied, to find the first constraint towards establishing a sample of RSG candidates. The red triangles indicate known M31 RSGs with determined spectral classifications by Massey & Evans (2016) from which we have based our colour and magnitude cuts around. (b) The magenta points indicate all the RSG candidates we find and use in the present work after all photometric and astrometric cuts have been applied.

MS to a WR star, completely bypassing the RSG phase (Stothers & Chin 1978). Under this scenario, the HD limit therefore represents the luminosity which corresponds to the most massive star that may still experience a RSG phase.

Evolutionary models predict that lower metallicity environments should produce more luminous supergiants due to this dependency of mass loss on metallicity (Kudritzki et al. 1987; Maeder & Meynet 2003). This means the HD limit should therefore also be metallicity dependent.

The HD limit has been measured previously in the literature, the first being a hard upper limit of $\log(L/L_{\odot}) = 5.8 \pm 0.1$ inferred by Humphreys & Davidson (1979), using a sample of cool supergiants in the Milky Way and the Large Magellanic cloud (LMC) (later revised to $\log(L/L_{\odot}) = 5.66$ in Humphreys (1983)). Davies, Crowther & Beasor (2018, hereafter, DCB18) revisited the HD limit in the Magellanic Clouds, with higher precision multi-wavelength photometry, finding an upper limit of $\log(L/L_{\odot}) = 5.5$ for both the Small Magellanic Cloud (SMC) and the LMC.

In this work, we complement the study of DCB18 with focus on the high luminosity end of the M31 RSG luminosity function as well as make quantitative comparisons with RSG populations in lower metallicity galaxies.

2. Method

2.1. *Compiling the sample of RSGs*

To locate our target stars, we constructed colour-magnitude diagrams (CMDs) using the Spitzer photometry (Khan 2017), see Figure 1, and overplotted a sample of known RSGs from Massey & Evans (2016) to define the location of RSGs in mid-IR colour-magnitude space. The total number of stars rejected from our sample are discussed further in Sections 2.1 and 3.3 in McDonald et al. (2022), where reasons for rejection are outlined in detail. These stars were then cross-matched to Local Group Galaxy Survey

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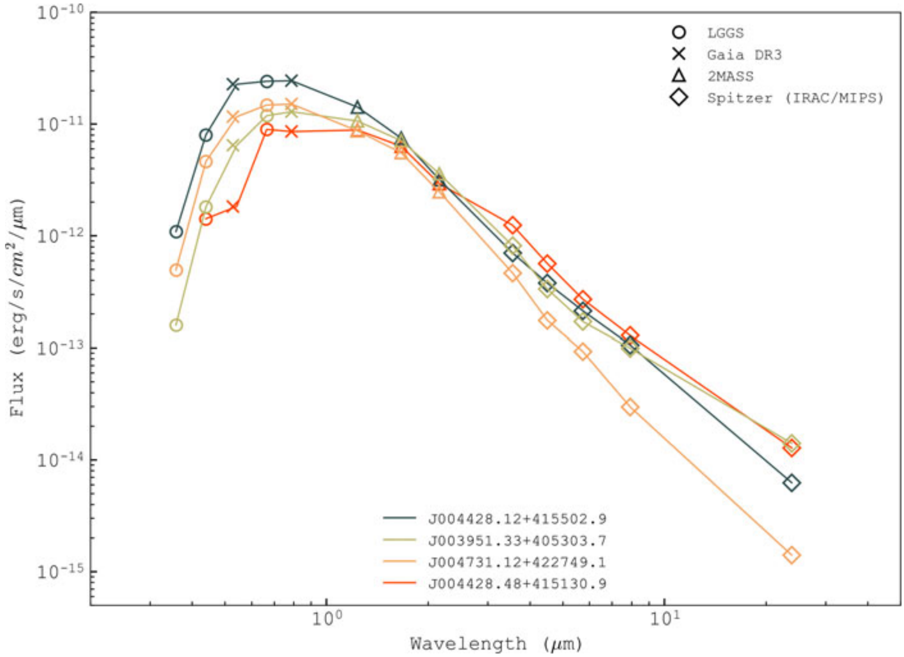

Figure 2. Spectral energy distributions of the most luminous Red Supergiant (RSG) candidates. These have $\log(L/L_{\odot}) > 5.4$ with complete de-reddened photometry ranging from the optical through to the mid-infrared. The symbols in the upper legend indicate the catalogue source of the photometry and the lower legend provides the LGGS star name for each candidate.

(LGGS) UBVRI photometry Massey et al. (2006), Gaia EDR3 photometry (BP and RP bands) and astrometry (proper motion and parallax) Gaia Collaboration (2020) and Two Micron All Sky Survey (2MASS) JHK photometry Cutri et al. (2003).

2.2. *Foreground Extinction*

To correct for foreground extinction, we use an extinction map of M31 from Dalcanton et al. (2015), surveyed by The Panchromatic Hubble Andromeda Treasury project (PHAT, Dalcanton et al. 2012). Each RSG candidate was then de-reddened according to the Cardelli et al. (1989) reddening law for the optical photometry, and Rieke & Lebofsky (1985) for the near-IR.

3. Luminosity Distributions and L_{max}

3.1. *Determining bolometric luminosity*

We converted the de-reddened photometry into fluxes using Vega calibrated zero point fluxes for each filter from the SVO Filter Profile Service (Rodrigo & Solano 2020). Using these fluxes, we plot spectral energy distributions (SEDs) for each RSG candidate and integrate under the SED to determine bolometric luminosity. Figure 2 shows the SEDs of the most luminous candidates.

The observational luminosity function of M31 RSGs is seen in Figure 3. The light grey distribution shows the number of RSG candidates per log luminosity bin for M31. The two darker grey distributions show the number of RSG candidates we use in this study which are also found in previous M31 RSG studies. Each of these luminous RSGs are discussed in more detail in McDonald et al. (2022).

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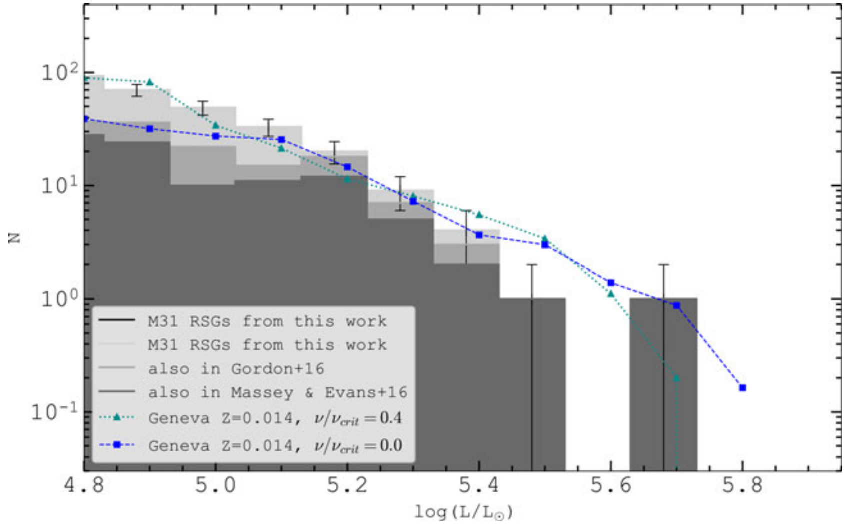

Figure 3. The Red Supergiant luminosity distribution for M31. The observed luminosity distribution from this work is shown in light grey, with the two darker grey distributions showing the number of RSG candidates we use in this study that are also found in previous M31 RSG studies. Over-plotted are the rotating ($\nu/\nu_{crit} = 0.0$) and non-rotating ($\nu/\nu_{crit} = 0.4$) model predicted distributions from the GENEVA models at solar metallicity (Z=0.014) from Ekström et al. (2012). N.b. The brightest star at $\log(L/L_{\odot}) = 5.71$ cannot be definitively ruled out, but is a borderline M31 candidate due to its proper motion.

4. Statistical Analysis

To make a broader test of the metallicity dependence of $L_{\max}$ and the luminosity function, we perform two comparisons. Firstly, we compare the empirical luminosity functions of the LMC and SMC with M31. Secondly, we compare the M31 luminosity function and $L_{\max}$ to theoretical expectations of lower metallicities using population synthesis.

4.1. *Observational comparisons between the LMC and SMC*

We look at the cumulative RSG luminosity function for M31 and compare with the empirical SMC and LMC distributions from (Davies, Crowther & Beasor 2018), looking at all RSGs with $\log(L/L_{\odot}) > 5$, where our sample is considered to be complete. The left panel of Figure 4 shows the similarities of the observed cumulative luminosity functions for M31, SMC and LMC. We perform a Kolmogorov-Smirnov (KS) test to evaluate these similarities by measuring the differences between the cumulative distribution functions. We find for the empirical M31 distribution compared with the SMC and LMC, a 60% and 44% probability, respectively, that they are drawn from the same parent distribution. Hence, the probability that the RSG luminosity function in the three galaxies are consistent with one another is within 1σ. Furthermore, each galaxy has the same $L_{\max}$ to within 0.1dex, at $\log(L/L_{\odot}) \sim 5.5$.

We do the same for the model cumulative luminosity function of RSGs at SMC-like (Z=0.002) metallicity (SMC-like tracks are from Georgy et al. 2013) when compared with M31, seen in the right panel of Figure 4. Here we find a probability of 5% (rotating) and 0.1% (non-rotating) for the M31 models compared with observations and a 0.02% (rotating) and 10^{-6}% (non-rotating) probability for the SMC models compared with observations. These low probabilities lead us to conclude that there is little similarity

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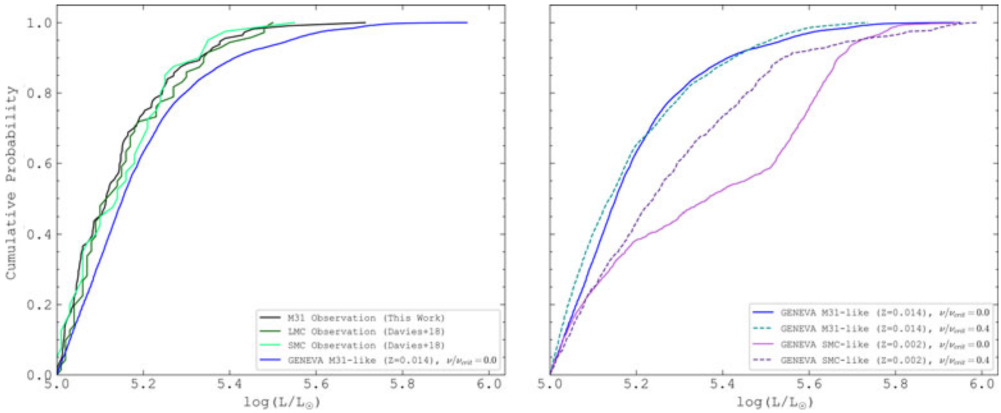

Figure 4. Left Panel: The cumulative luminosity distribution of all the Red Supergiants with an observational luminosity $\log(L/L_\odot) > 5$ in M31 from this work, as well as for the Large and Small Magellanic Clouds from Davies, Crowther & Beasor (2018). Right Panel: Cumulative luminosity distribution of the cool supergiants with a luminosity $\log(L/L_\odot) > 5$ from the model luminosity functions predicted by GENEVA, at both solar (from Ekström et al. 2012) and SMC-like metallicities (from Georgy et al. 2013) for both the rotating and non-rotating models. We include the 'M31-like' non-rotating model predicted distribution in the left panel for comparison.

between the model distributions in the two galaxies and they are unlikely to be drawn from the same parent distribution.

4.2. *Comparisons to theoretical predictions of $L_{\rm max}$*

To investigate the effects of sample size on $L_{\rm max}$, we perform another Monte Carlo experiment to find the average $L_{\rm max}$ for each sample size of N cool supergiants with $\log(L/L_\odot) > 5$. The results of this Monte Carlo are shown in Figure 5 where the empirical $L_{\rm max}$ for the sample size we observe for that galaxy is denoted by the black star. Although M31 shows agreement within 3σ, the SMC shows a disagreement beyond the 99.7% confidence limit. In summary, we find no significant difference in $L_{\rm max}$ within the errors across a metallicity baseline of ($0.25Z_\odot$ to $\gtrsim Z_\odot$). This is in clear disagreement with theoretical expectations because $L_{\rm max}$ predictions from the models are simply too high compared to observational measurements and this effect is predicted to only increase with decreasing metallicity.

5. Conclusions

We compiled a sample of mid-IR selected cool supergiants to measure the luminosity function of the red supergiant (RSG) population in M31 to investigate the Humphreys-Davidson limit ($L_{\rm max}$).

• We find that the luminosity function of RSGs is independent of metallicity, based on the range of metallicities studied here (from SMC-like to M31-like).

• $L_{\rm max}$ is also independent of metallicity, where we find the HD limit for M31 is $\log(L/L_\odot) = 5.53 \pm 0.03$, within 0.1dex of the SMC and LMC. We are in agreement with Davies, Crowther & Beasor (2018) who find a lack of evidence for a metallicity dependent $L_{\rm max}$. This suggests that mass loss from line-driven winds are **not** the cause of the HD limit.

• A population synthesis analysis shows that the single star Geneva evolutionary models not only over-predict the number of luminous cool supergiants at the high luminosity end, but also over-predict $L_{\rm max}$, particularly at lower metallicities.

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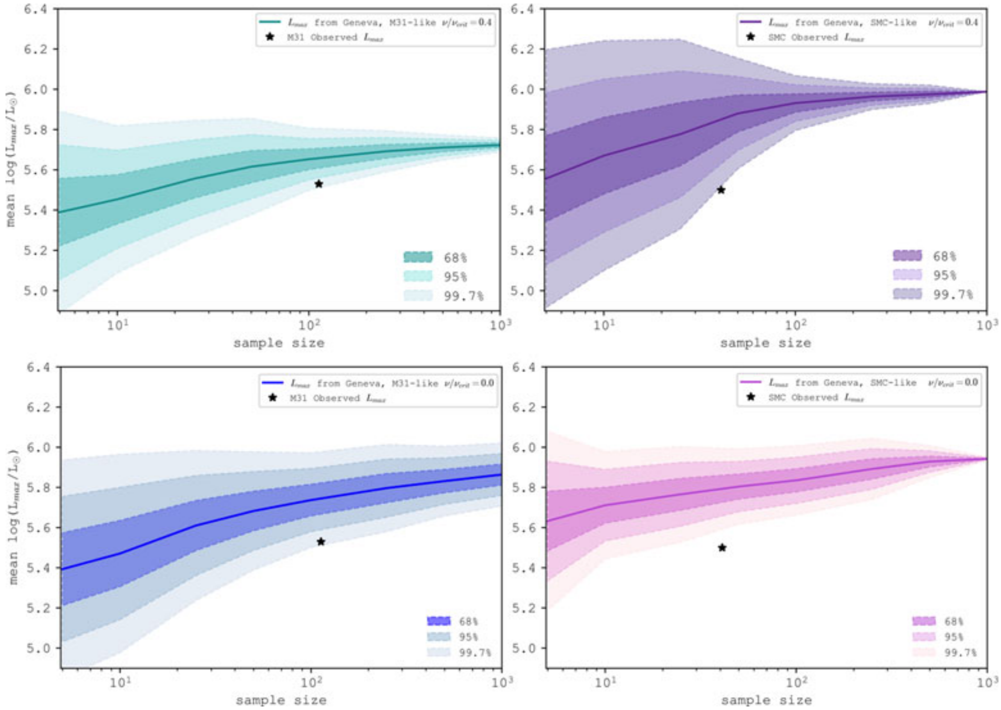

Figure 5. The expected $L_{\max}$ for a range of sample sizes as predicted by the Geneva rotating models for both solar (Z=0.014) and SMC-like (Z=0.002) metallicities. The shaded regions indicate the confidence limits on $L_{\max}$ as shown in the legend and the black stars indicate the observed $L_{\max}$ and sample size for M31 from this work and the same for the SMC from Davies, Crowther & Beasor (2018).

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Discussion

Lee Patrick: How do you think the idea that most of the RSGs that we observe are merger products fits into this picture of of the metallicity independent HD limit?

Sarah McDonald: Given the binary fraction of the most massive RSGs is expected to be high, the contribution to mass loss from a companion star would mean that the most massive stars are losing more mass than would be expected from winds in single stars alone. In this sense, binarity could control Lmax somewhat. We are currently looking into using the BPASS models which implement binarity, so we may soon see if this solves the discrepancy.

Phillip Massey: Did you look into what would happen if you considered subsets of your spatial sampling to see how your comparison of the observed LF with the predicted LF holds up?

Sarah McDonald: The effects of variable SFH is somewhat similar to the stochastic effects which we try to quantify with the Monte Carlo analysis of sample size effects. To some degree, the stochasticity is dominated by the relatively low number of RSGs in the SMC, and so admittedly we havent given too much attention to the SFH. That being said, Philip you are correct that Harris & Zaritsky 2009 (fig 19) implies we are close to the average SF level across all epochs, at the current epoch. i.e. we are not in a particular rut of star formation at current times, and so the HD limit measured in our work should be close to the typical value over all epochs.