Luminosities and mass-loss rates of AGB stars and Red Supergiants in the Magellanic Clouds

Martin A.T. Groenewegen and Gregory C. Sloan

Koninklijke Sterrenwacht van België - Royal Observatory of Belgium, Brussels, and
Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, USA

The Introduction

Mass loss is one of the fundamental properties of Asymptotic Giant Branch (AGB) stars, and through the enrichment of the interstellar medium, AGB stars are key players in the life cycle of dust and gas in the universe. However, a quantitative understanding of the mass-loss process is still largely lacking, particularly its dependence on metallicity.

To investigate the relation between mass loss, luminosity, pulsation period, and metallicity we have modelled a large sample of evolved stars in the Small and Large Magellanic Cloud, and the Fornax, Carina, and Sculptor dwarf spheroidal galaxies (dSphs), all observed with the IRS spectrograph on board *Spitzer*.

This study extends the work of Groenewegen et al. (2007) who modelled the spectral energy distributions (SEDs) and IRS spectra for a sample of 60 carbon (C) stars, and Groenewegen et al. (2009, hereafter G09) who expanded this to 101 C stars and 86 oxygen-rich AGB stars and RSGs (hereafter referred to as M stars for simplicity) in the MCs. The work described below has been published in Groenewegen & Sloan (2018).

The Sample

Several groups have obtained *Spitzer* IRS data of evolved stars in the LMC and SMC. The publically available data from the following programmes are considered: 200 (P.I. J. Houck), 1094 (F. Kemper), 3277 (M. Egan), 3426 (J. Kastner), 3505 (P. Wood), 3591 (F. Kemper), 30155 (J.R. Houck), 30788 (R. Sahai), 40159 (X. Tielens), 40519 (A. G. G. M. Tielens), 40650 (L. Looney), 50167 (G. Clayton), 50240 (G. Sloan), and 50338 (M. Matsuura). In addition, a sample of 19 C stars in the Sculptor, Carina and Fornax dSphs were included from program 20357 (P.I. A. Zijlstra, see Sloan et al. 2012). The total sample includes 225 C-stars and 171 M-stars (including about 10 foreground objects)

The spectra considered here were obtained with the low-resolution modules of the IRS: Short-Low (SL, 5.1–14.2 μm), and Long-Low (LL, 14.0–37.0 μm). Both modules have a resolution ($\lambda/\Delta\lambda$) of $\sim$60–100. For some of the fainter sources, spectra were obtained using only SL. Sloan et al. (2016) describe the data reduction in detail.

For all stars additional broad-band photometry ranging from the optical to the mid-IR was collected from the literature, primarily using VizieR and the NASA/IPAC Infrared Science Archive.

The Modelling

The models are based on the "More of DUSTY" (MoD) code (Groenewegen 2012) which uses a slightly updated and modified version of the *DUSTY* dust radiative transfer (RT) code (Ivezić et al. 1999) as a subroutine within a minimization code. The code determines the best-fitting dust optical depth, dust temperature at the inner radius, and luminosity by fitting photometric data and spectra, for a given dust composition and model atmosphere.

We masked those portions of the IRS spectra with poor S/N or those affected by background subtraction problems and did not include them in the minimisation procedure. In addition, regions where strong molecular features dominate that are not included in the simple model atmospheres are also excluded.

The photospheric models for C stars are from Aringer et al. (2009). For the LMC, respectively the SMC and the other LG galaxies, models of 1/3, respectively, 1/10 solar metallicity have been adopted. The M stars are modelled by a MARCS stellar photosphere model (Gustafsson et al. 2008). For the LMC, respectively the SMC and the other LG galaxies, models of −0.5, respectively −0.75 dex have been adopted.

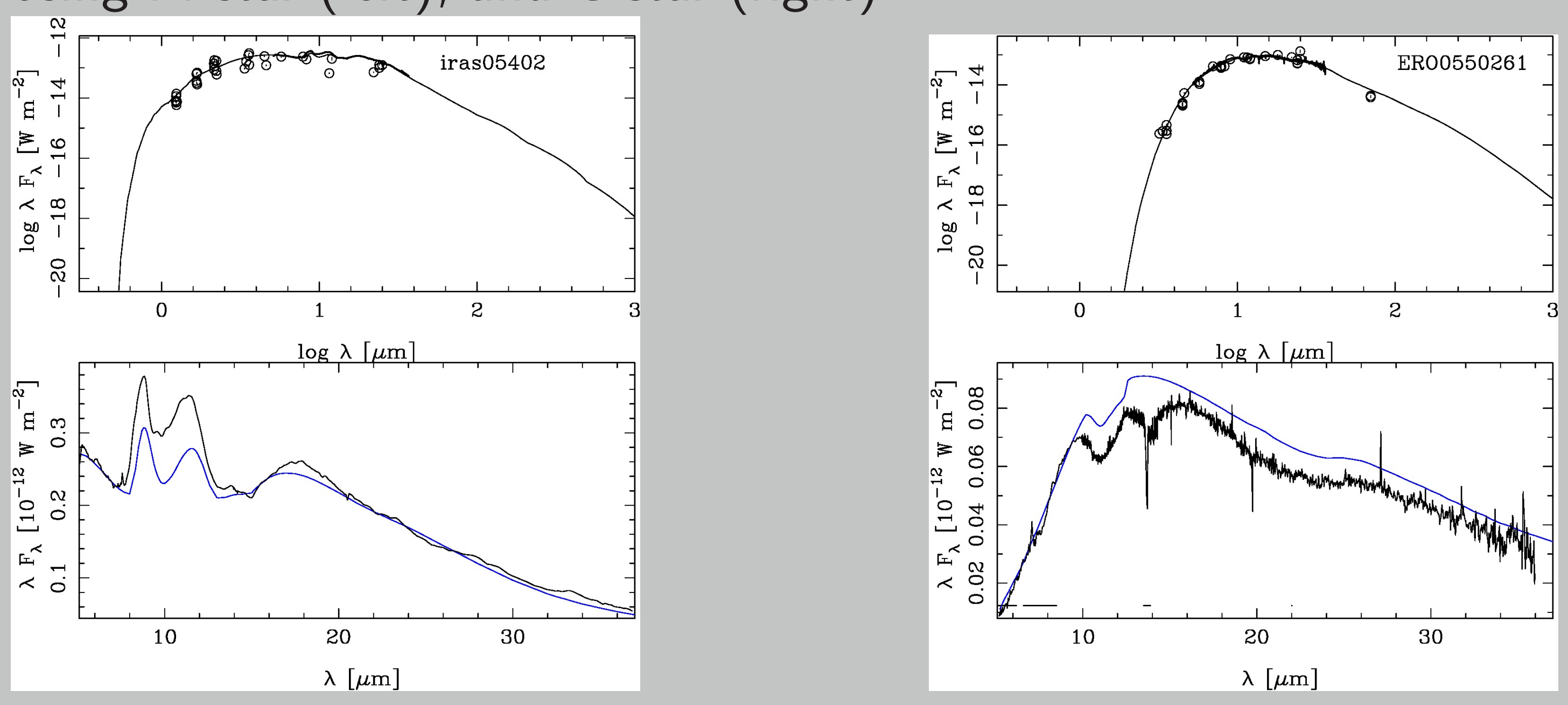
The dust around the C stars is assumed to be a combination of amorphous carbon (AMC), silicon carbide (SiC), and Magnesium Sulfide (MgS).

For M stars the dust chemistry is richer that that for C stars and more species have been considered: Olivine (amorphous $MgFeSiO_4$), compact amorphous aluminum oxide and iron, for most stars, and for a few crystalline Forsterite ($Mg_{1.9}Fe_{0.1}SiO_4$) as well. Single-sized grains of 0.1, 0.2 and 0.5 μm have been considered. The absorption and scattering coefficients have been calculated assuming *a distribution of hollow spheres* (Min et al. 2003) with a maximum volume fraction of vacuum of 70%.

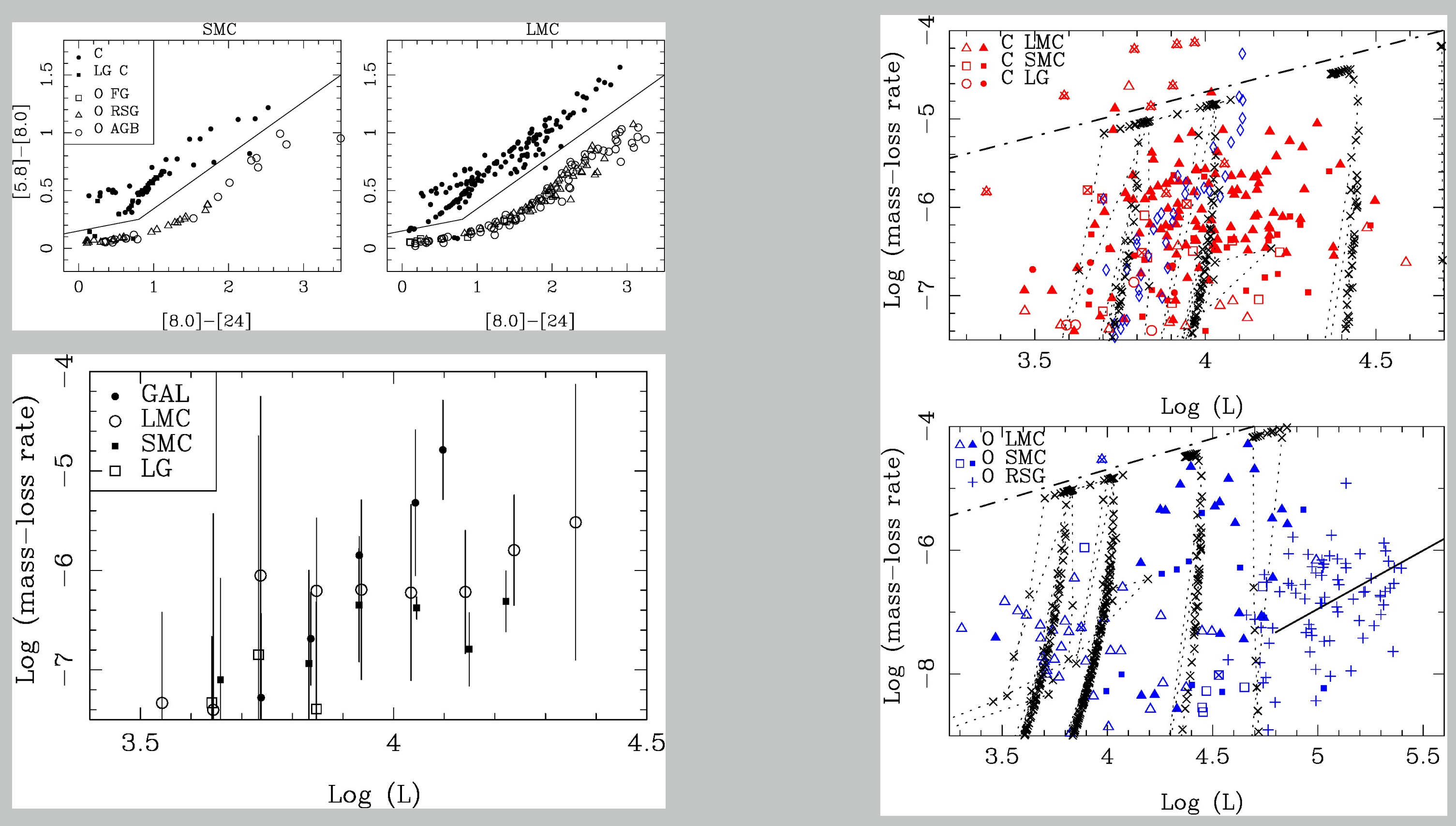
Total mass-loss rates (MLRs) are calculated assuming a dust-to-gas ratio (Ψ) of 1/200, and an expansion velocity of the outflow of 10 km s^{-1} for all stars.

The Results

The first Figure shows typical fits to the SED and IRS spectra for a very high mass-losing M star (left), and C star (right).



The Figure below shows in the top-left corner a colour-colour diagram for the SMC (left) and LMC (right) using IRAC and MIPS colours, [5.8]−[8.0] vs. [8]−[24]. Overall, the separation between M and C stars is excellent.



The right-hand panels show the MLR versus luminosity for C stars (top, red colours) and M stars (bottom, blue colours) for the evolutionary models of Vassiliadis & Wood (VW; 1993). Objects with Mira-like pulsation amplitudes are plotted with filled symbols, objects with smaller amplitudes as open symbols, and with a additional cross if no information on pulsation is available. RSG are plotted as plus-signs independent of host galaxy and pulsation amplitude. The VW models are plotted as crosses connected by the dotted line for initial masses of 1.5, 2.5, 5.0 and 7.9 M$_\odot$ at 5000-year intervals. Not every track is visible in every panel. The dot-dashed line indicates the single scattering limit for a velocity of 10 km s^{-1}. The solid line is the relation found by Verhoelst et al. (2009) for Galactic RSG.

The larger sample changes the qualitative results from G09. Before, only three C stars were slightly above the single-scattering limit, which was consistent with expections. Now, many C stars are above that limit, by up to a factor of 10. If confirmed, our models show that the artificial cut-off in the VW models at $\beta = 1$ is too conservative. A cut-off (if any) at a larger β would result in shorter AGB lifetimes.

The panel in the lower-left corner presents the results differently, where the MLRs of the C stars have been binned (bin size of 0.1 dex in $\mathbf{L}$) and median averaged in $\log \dot{\mathbf{M}}$ and plotted if there were five or more objects in a bin. MLRs are also included for Galactic stars (Groenewegen et al. 1998).

The MLR increases globally with luminosity, but any dependence on metallicity remains difficult to assess. The issue of accurate distances (hence luminosities) remains a limiting factor for any Galactic sample.

The models in the present work point to a larger dust MLR in the LMC than in the SMC for a given luminosity, but this could also arise from the difference in the underlying populations (see Ventura et al. 2016) and/or differences in expansion velocity (Groenewegen et al. 2016).

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martin.groenewegen@oma.be