Mem. S.A.It. Vol. 88, 350

Memorie della

Mass-loss rates and luminosities of evolved stars in the Magellanic Clouds

M. A. T. Groenewegen[1] and G. C. Sloan[2,3,4]

[1] Koninklijke Sterrenwacht van België, Ringlaan 3, B-1180 Brussel, Belgium
e-mail: martin.groenewegen@oma.be
[2] Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY 14853-6801, USA
[3] Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255, USA
[4] Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA

Abstract. Stars on the asymptotic giant branch (AGB) stars play an important role in the chemical evolution of their host galaxies and the life cycle of dust in the interstellar medium. A detailed and quantitative understanding of they lose mass and eject their envelopes remains elusive, particularly how that process depends on metallicity. Groenewegen & Sloan (2017, hereafter GS17) recently presented dust radiative transfer models for 225 carbon stars and 171 oxygen-rich evolved stars in the Magellanic Clouds and four nearby dSphs which were observed with the Infrared spectrograph on the *Spitzer Space Telescope*. They applied a minimisation procedure to fit models to spectral energy distributions constructed from the infrared spectra and the available optical and infrared photometry for each star to determine its luminosity and dust mass-loss rate (MLR). In this contribution two items from that paper are highlighted: an update on MSX SMC 055, which Groenewegen et al. (2009) suggested could be a super-AGB star, and a discussion of synthetic colour-colour and colour-magnitude diagrams expected from the James Webb Space Telescope.

Key words. circumstellar matter – infrared: stars – stars: AGB and post-AGB – stars: mass loss – Magellanic Clouds

1. Introduction

Most intermediate-mass stars ($\sim$ 0.9–8 $M_{\odot}$) will evolve onto the asymptotic giant branch (AGB), which is their final phase of nuclear fusion. From there, they will become planetary nebulae and finally, (carbon-oxygen) white dwarfs. The topic of this conference is the super-AGB (SAGB) stars, which have masses between ~6.5 and 12 $M_{\odot}$. These stars will develop an oxygen-neon core (see various contributions in this volume, and Doherty et al. 2017 for all details). Stars with larger initial mass will become red supergiants (RSGs), and they may end their lives as supernovae. In all of these cases, mass loss dominates the final evolutionary stages of the star.

We have learned a great deal by studying evolved stars in the Galaxy, but uncertainties in distances limit the accuracy of estimated luminosities and mass-loss rates (MLRs). Nearby dwarf galaxies in the Local Group are at wellknown distances, and in addition, they make it possible to study how metallicity affects the mass-loss process.

The sensitivity of the Infrared Spectrograph (IRS) on the *Spitzer Space Telescope* has been the key to studying the spectra of evolved stars in the Magellanic Clouds and more distant dwarf spheroidals. Groenewegen et al. (2007) modelled the spectral energy distributions (SEDs) and IRS spectra of an initial sample of 60 carbon (C) stars. Groenewegen et al. (2009, hereafter G09) followed up with an expanded Magellanic sample of 101 C stars and 86 oxygen-rich AGB stars and RSGs (hereafter referred to as M stars for simplicity).

GS17 examined an even larger sample, nearly double that of G09 with 19 C stars in four nearby dwarf spheroidal galaxies (dSphs). IRS spectra of the expanded sample are available to anyone interested in further analysis on the CASSIS website (Lebouteiller et al. 2011). GS17 made several changes in methodology. Compared to G09, these include:

- The use of the "More of DUSTY" (MoD) code (Groenewegen 2012) to estimate the best-fitting dust optical depth, luminosity, temperature at the inner radius, T_c, and index of the density distribution, $\rho \sim r^{-p}$. For a given dust composition and stellar photospheric model, MoD minimizes the residuals between the photometric and spectral data for a star by iteratively calling a subroutine based on an updated version of the *DUSTY* dust radiative transfer (RT) code (Ivezić et al. 1999).
- The stellar models have been updated, using C-star models from Aringer et al. (2009), and M-star models based on the MARCS model photospheres (Gustafsson et al. 2008)
- The optical constants for the dust have changed. As highlighted by GS17, the choices of optical constants can have a large effect on the derived MLRs, as these are inversely proportional to the dust opacity.

Figure 1 shows two example of such fits to the SEDs and IRS spectra.

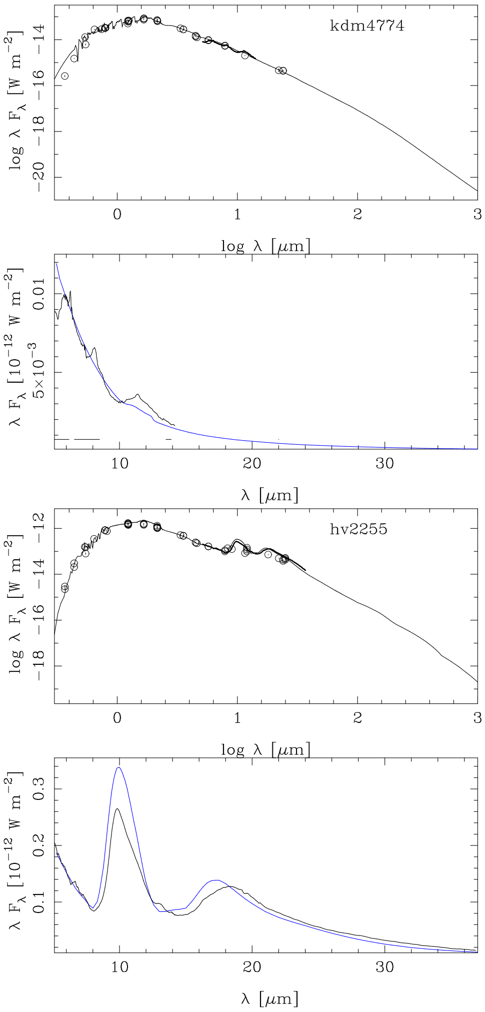

Fig. 1. Example of models fitted to the SED and IRS spectrum of a C star (top panel) and M star with little dust emission.

2. A super-AGB star candidate

G09 noted that MSX SMC 055 (or IRAS 00483−7347) had an unusually high luminosity ($M_{\rm bol}$ = −8.0), which in combination with its very long pulsation period (1749 days) and significant pulsation amplitude (1.6 mag peak-to-peak at I) made it a good candidate for a super-AGB (SAGB) star. Its pulsational properties distinguish it from a luminous RSG. The updated models of GS17 improved the estimates of its stellar and mass-loss properties.

Groenewegen & Jurkovic (2017) used 5–11 $M_\odot$ initial-mass Cepheid models by Bono et al. (2000) to derive a relation between period, luminosity, mass, temperature, and metallicity. Using P= 1810 ± 50 days, L= 85350 ± 8500 $L_\odot$, $T_{\rm eff}$= 2500 ± 100 K, and Z= 0.004 ± 0.001 (uncertainties are adopted), GS17 estimated the current pulsation mass to be 8.5 ± 1.6 $M_\odot$, where the uncertainty in mass is dominated by the uncertainty in effective temperature. Applying the simpler period-mass-radius relation for fundamental-mode pulsators from Wood (1990) leads to a similar value: 9.2 ± 1.8 $M_\odot$.

Assuming a conservative gas-to-dust ratio of 200 gives a current MLR of 4.5 $\times 10^{-6}$ $M_\odot$ yr^{-1}, SAGB stars do not spend much time in the thermal-pulsing phase (10^{4-5} years; e.g. Doherty et al. 2017), but given that the MLR of MSX SMC 055 could exceed 10^{-5} $M_\odot$ yr^{-1}, that is still enough time for its initial mass to be 1 $M_\odot$ larger than its current mass.

More evidence of the SAGB status of MSX SMC 055 comes from high resolution optical spectra, which show that it is very rich in Rubidium, with [Rb/Z] $\gtrsim$+1.7 (García-Hernández et al. 2009). This measurement confirms the activation of the ^{22}Ne neutron source at the s-process site, which means that MSX SMC 055 is either a massive AGB star or a SAGB star. García-Hernández et al. independently estimated an initial mass of at least 6–7 $M_\odot$.

MSX SMC 055 remains the most viable SAGB candidate in either the SMC or LMC.

3. The potential of JWST

The James Webb Space Telescope (JWST), has a planned launch date in October, 2018. The sensitivity of its two imaging instruments, NIRCAM and MIRI, will enable photometric studies of evolved stellar populations in other galaxies, not just in the Local Group but out to distances of a few Mpc. Figure 2 shows the FWHM range of 29 NIRCAM and MIRI filters compared to the SEDs of two C and M stars with increasing MLR.

Kraemer et al. (2017) and Jones et al. (2017) have already investigated which filter combinations appear to be the most useful for distinguishing and characterizing different classes of objects.

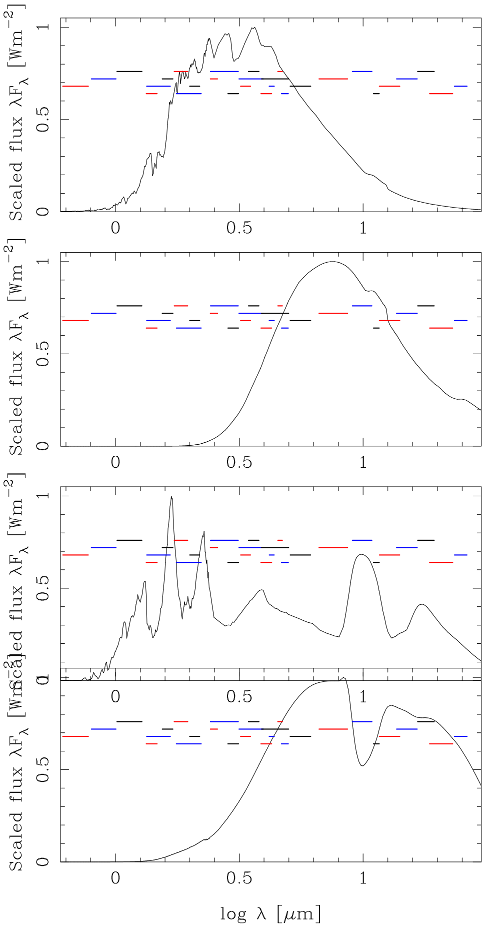

Fig. 2. Normalised SEDs of two C stars (NGC 419 IR1, MIR1) and two M stars (W60 A72 and IRAS 05246−7137) (top to bottom) with moderate and strong mass-loss rates. The horizontal bars indicate the FWHM range of 29 NIRCAM and MIRI filters.

The former paper examined the sample of SMC objects observed by the IRS, using the spectra to confirm the classifications. They found that the 5.6, 7.7, and 21 μm filters best separated C-rich from O-rich stars, while the 5.6, 10, and 21 μm filters best separated young stellar objects (YSOs) from planetary nebulae (PNe). Jones et al. (2017) performed a similar study using over 1000 sources with IRS spectra in the LMC. They discussed how to discriminate O- and C-rich AGB and post-AGB

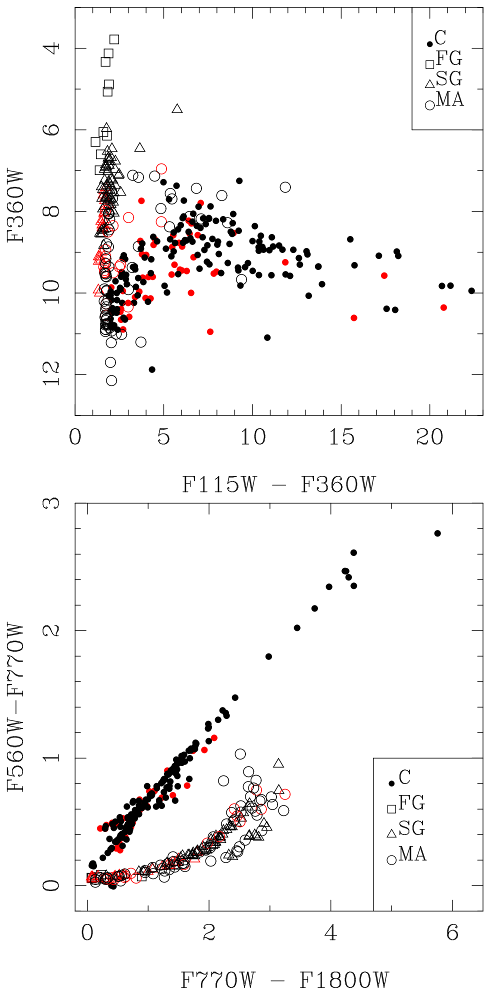

Fig. 3. Colour-Magnitude and Colour-Colour diagrams for the LMC (with the SMC stars, plotted in red, shifted to the distance of the LMC) based on synthetic JWST NIRCAM/MIRI magnitudes.

stars, RSG, HII regions, PNe and YSOs. Both Kraemer et al. and Jones et al. based their CMDs and CCDs on synthetic photometry using the IRS spectra. Therefore, they were limited in showing diagrams to those based on MIRI filters.

The models presented by GS17 extend to shorter wavelengths, and they presented synthetic photometry for their sample of almost 400 evolved stars in about 75 filters, including the 29 medium and wide-band filters available with both NIRCAM and MIRI.

Figure 3 presents two examples. The first is a CMD similar to the diagram presented by G09 plotting the IRAC 3.6 μm magnitude [3.6] versus $J-[3.6]$. In this plot, SMC objects have been shifted to the distance of the LMC. The dustiest objects are generally C-rich, and as the colours grow redder, the spread in F360W magnitude grows smaller. The second example is a CCD similar to a plot from *Spitzer* photometry with [5.8]–[8.0] vs. [8.0]–[24]. Changing the long-wavelength filter from F1800W to F2100W or F2550W produces a similar diagram, but as noted by Jones et al. (2017), for a given integration time, the F1800W filter is ~1 magnitude more sensitive than F2100W and ~3 magnitudes more sensitive than F2550W. Thus the F560W, F770W, and F1800W filters are the most efficient means of separating O-rich and C-rich sources.

References

Aringer, B., et al. 2009, A&A, 503, 913
Bono, G., Castellani, V., & Marconi, M. 2000, ApJ, 529, 293
García-Hernández, D. A., et al. 2009, ApJ, 705, L31
Groenewegen, M. A. T. 2012, A&A, 543, A36
Groenewegen, M. A. T., et al. 2007, MNRAS, 376, 313
Groenewegen, M. A. T., et al. 2009, A&A, 506, 1277 (G09)
Groenewegen, M. A. T. & Jurkovic, M. 2017, A&A, in press (arXiv: 1705.04487)
Groenewegen, M. A. T. & Sloan, G. C. 2017, A&A, submitted
Gustafsson, B., et al. 2008, A&A, 486, 951
Ivezić, Ž., Nenkova M., & Elitzur M. 1999, DUSTY user manual, University of Kentucky
Jones, O. C., et al. 2017, ApJ, submitted (arXiv: 1703.08997)
Kraemer, K. E., et al. 2017, ApJ, 834, 185
Lebouteiller, V., et al. 2011, ApJS, 196, 8
Sloan, G. C., et al. 2016, ApJ, 826, 44
Wood, P. R. 1990, in From Miras to planetary nebulae: which path for stellar evolution?, ed. M. O. Mennessier, & A. Omont (Editions Frontières, Gif-sur-Yvette, France), 67