The Magellanic System: Stars, Gas, and Galaxies
Proceedings IAU Symposium No. 256, 2008
Jacco Th. van Loon & Joana M. Oliveira, eds.

DOI: 00.0000/X000000000000000X

The trigger of the AGB superwind: the importance of carbon

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Abstract. The driving mechanism of the AGB superwind has become controversial in recent years. The efficacy of dust-driven mass loss has been queried. Spitzer observation of AGB stars in Local Group Galaxies show the surprising result that at low metallicity, AGB mass loss occurs at low luminosity, possibly lower than in the Galaxy, but only for carbon-rich stars. Oxygen-rich stars in the Galaxy and in lower metallicity galaxies have similar mass-loss rates only at high luminosities. To explain this dichotomy, we propose that the superwind has a dual trigger. The superwind starts either when sufficient excess carbon builds up for efficient formation of carbonaceous dust (which we propose occurs when $X_{\rm CO} = ({\rm C}-{\rm O})/{\rm O}_\odot = 0.1$), or when the luminosity reaches a value sufficient for a silicate-dust-driven wind (proposed at $L = 10^4 Z^{-4/3}\,{\rm L}_\odot$). We show that this dual trigger fits the current observational constraints: the luminosity at which the superwind begins, and the predominance of carbon superwind star at low metallicity. We use stellar evolution models to check the consistency of our explanations and present detailed predictions of the luminosities at which the superwind is triggered for different metallicities and initial stellar masses.

Keywords. Magellanic Clouds, Local Group, circumstellar matter, infrared: stars, carbon stars, AGB stars, stars: mass loss

1. Introduction

The late phases of stellar evolution are crucial to galactic evolution. Stars in this phase eject much of their gas into space, enriched by the products of nuclear burning and newly formed dust. AGB stars are important contributors to the enrichment of the Interstellar Medium (ISM) by sources internal to the galaxy.

At the low effective temperature of AGB stars, the ejecta are largely molecular. The first stable and abundant molecule to form is CO: this locks up the least abundant of the C and O atoms. Other molecules and dust form from the remaining atoms. Dredge-up of primary carbon causes the C/O ratio to increase over time. In carbon stars, the C/O ratio (by number) exceeds unity, and carbon-rich molecules and carbonaceous dust result, whilst in oxygen stars (C/O<1), metal oxides and silicate dust form.

The mass-loss mechanism of AGB stars, thought to be a two-step process, is likely involved. First, shocks due to pulsations from the star extend the atmosphere leading to dust formation. Second, radiation pressure on the dust drives an outflow; the gas is carried along through friction with the dust particles. Pulsations can drive mass-loss rates up to about $10^{-6}\,{\rm M}_\odot{\rm yr}^{-1}$; the much higher rates observed are explained by dust-driven winds (Bowen & Wilson 1991). This simple distinction between weak pulsation winds and dusty superwinds (Winters et al. 2000) has recently been disputed. Woitke (2006) find in their models that the dust opacity of silicates is insufficient to drive a wind, while for carbon dust the winds become very chaotic (Woitke & Niccolini 2005). For low-metallicity stars, dust-driven winds may fail due to the lack of dust (Zijlstra 2004): theoretical work

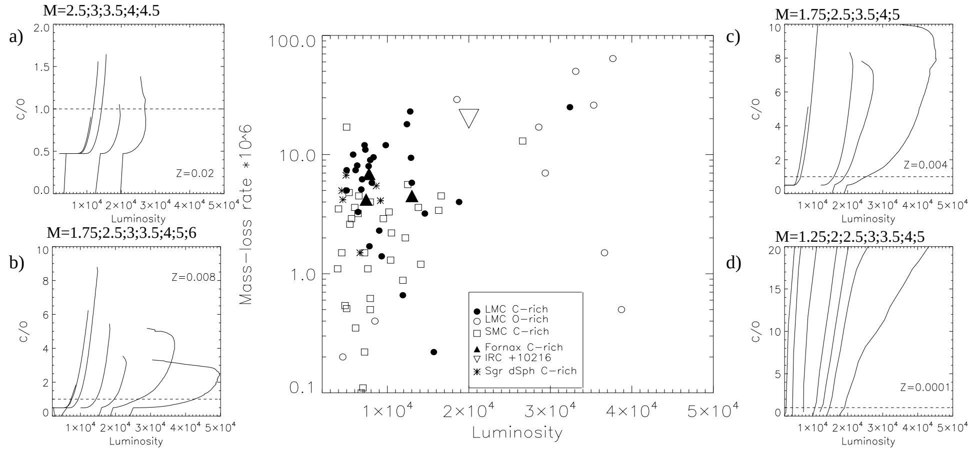

Figure 1. Mass-loss rates as a function of luminosity for different Local Group AGB stars. Panels a,b,c and d show the evolution of the C/O ratio with luminosity using the models described in Karakas & Lattanzio (2007.). Values of the different initial masses in solar units are on top of each panel.

by Bowen & Willson (1991) predicts that for metallicities below [Fe/H]$= -1$ the wind becomes pulsation-driven. Mattsson et al. (2008) argue that pulsation can drive a strong wind at low metallicity, set by the pulsation energy of the star. Recent theoretical models produce similar mass-loss rates for AGB stars with SMC, LMC and solar metallicities (Wachter et al. 2008).

2. The AGB stars sample, luminosity and mass-loss rates

Several different Spitzer programs have obtained mid-infrared spectroscopy of AGB stars in the Local Group. The description below refers mainly to works published in Zijlstra et al. (2006); Matsuura et al. (2006); Groenewegen et al. (2007); Lagadec et al. (2007) and Sloan et al. (2006; 2008) for carbon rich stars in the the Magellanic Clouds (27 stars in the LMC and 33 in the SMC) and van Loon et al. (1999) for the oxygen-rich stars in the LMC (26 objects) and Lagadec et al. (2008) for 6 others in the Sagittarius Dwarf spheroidal galaxy. All three systems show a range of metallicities. We take as representative values [Fe/H]$=-0.3$ for the LMC, -0.7 for the SMC and -0.55 for Sgr dSph. The distance moduli are taken as 18.54, 18.93 and 17.02, respectively. Table 1 gives some representative parameters for the carbon stars in each galaxy, derived from the distribution of M_{bol} (see Lagadec & Zijlstra 2008).

The mass-loss rates of stars observed with Spitzer have been estimated by fitting spectra using a 1-d radiative transfer code (Groenewegen et al. 2007; Matsuura et al. 2007; Lagadec et al. 2008). The results for the LMC, SMC, Sgr dSph and Fornax are shown in Fig.1. We added the O-rich stars sample from van Loon et al. (1999) and the well-studied Galactic carbon star IRC+10216. The figure shows that the mass-loss rates are highest for the LMC stars, and tend to be lower for the SMC. Overall, there is no evidence that peak (gas) mass-loss rates depend on Z for carbon-rich stars.

3. The trigger of the superwind

At lower metallicity, more stars become carbon stars. Less dredge-up is required to overcome the original oxygen abundance, and acquire the C/O>1 needed to form a carbon star. Based on the luminosities, the progenitor masses of the mass-losing carbon stars are $\sim 1.5{-}2.5\ M_\odot$ (Zijlstra et al. 2006).

Table 1. Approximate numbers for life times and magnitudes of carbon stars, derived from the current samples. $M_{\rm bol}^{\rm init}$ indicates the magnitude where the large majority of stars have become carbon-rich: i.e, the luminosity function becomes flat. $M_{\rm bol(SW)}$ indicates the onset of the superwind. Life times of the carbon-rich phase are taken from Lagadec et al. (2007).

	[Fe/H]	$M_{\rm bol}^{\rm init}$ [mag]	life time [yr]	$M_{\rm bol(SW)}$ [mag]
LMC	−0.3	−4.3	3×10^5	−4.7
SMC	−0.7	−3.9	6×10^5	−4.5
Sgr dSph	−0.55	—	——	−4.5 :

The picture that emerges from this is that, at LMC metallicity, all stars in the $\sim 1.5-2.5$ $M_\odot$ range are C stars by the time they develop substantial mass loss rates and they remain C stars until their AGB evolution is terminated. The more luminous and massive, but rare, OH/IR stars in the LMC (e.g. Marshall et al. 2004) can survive as O-rich objects well into the dust-enshrouded superwind phase, possibly to the end of their AGB evolution.

Table 1 lists the bolometric magnitude at which the onset of the superwind occurs. This happens at a somewhat lower luminosity ($L \sim 5 \times 10^3\,{\rm L}_\odot$) than is found in our Galaxy ($L \sim 10^4\,{\rm L}_\odot$; $M_{\rm bol} \approx -5.5$). The difference between the LMC and the Galaxy is that in the former stars become carbon stars at a point on the AGB where the latter are still oxygen-rich. We interpret this as an indication that carbon-rich stars are more efficient at mass loss, even where the O-rich stars are more metal-rich. The finding agrees with (but is less extreme than) the prediction of Woitke (2006). The few oxygen-rich stars in our MCs sample show mass-loss rates $1-2$ orders of magnitude less than the carbon stars (Sloan et al., 2008).

To estimate the evolution of the carbon and oxygen abundances in the circumstellar envelopes of the AGB stars we observed, we used the stellar structure models described in Karakas & Lattanzio (2007). The evolution of the C/O ratio with luminosity for four different metallicities are shown in Fig.1 At low metallicity, third dredge-up is more efficient in making stars carbon rich: the same amount of primary carbon will have a larger effect on more metal-poor stars. This immediately affects the potential amount of amorphous carbon dust, which will depend on the amount of "free" carbon.

Instead of the C/O ratio, a more relevant parameter is $X_{\rm C} = \frac{\rm C-O}{\rm O_\odot}$ which measures the excess carbon by number. $X_{\rm C}$ rapidly increases towards lower metallicity. The corresponding increase in the C_2H_2 abundance is in fact seen, with the acetylene bands becoming much stronger (larger equivalent width) in the sequence Galaxy–LMC–SMC (Lagadec et al. 2007). The dust formation efficiency may depend primarily on $X_{\rm C}$ (the seeds required for the dust formation). For mass loss driven by radiation pressure on carbonaceous dust, we make the assumption that *the superwind is triggered when a limiting value for $X_{\rm C}$ is reached*. For Galactic stars, this occurs for C/O= 1.1 ($X_{\rm C} = 0.1$) (Ohnaka et al., 2000). We predict that for the LMC the superwind begins at C/O= 1.25 and for the SMC at C/O= 1.5.

For oxygen-rich stars, Galactic stars show a superwind for luminosities of $\sim 10^4\,{\rm L}_\odot$. Scaling from the Galaxy, we then expect that an O-rich dust-driven superwind (OSW, larger than $10^{-7}{\rm M}_\odot{\rm yr}^{-1}$) is triggered for (Lagadec & Zijlstra 2008):

$$L_{\rm OSW} = 10^4 \left(\frac{Z}{{\rm Z}_\odot}\right)^{-4/3} {\rm L}_\odot$$

For the LMC and SMC this corresponds to 3.4×10^4 and $8.5 \times 10^4\,{\rm L}_\odot$ respectively. Fig.

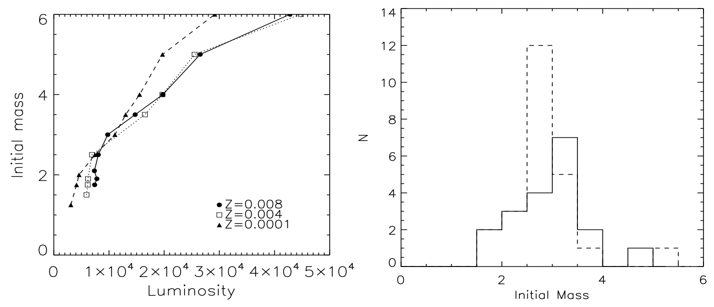

Figure 2. Left: Initial mass of the stars as a function of the luminosity at which their C/O ratio becomes > 1. Right: Distribution of the initial mass of the AGB stars in our LMC (black line) and SMC sample (dashed line) as derived from the relations on the left (values in solar units.)

1 shows that the least luminous OSW star in the LMC has $L \sim 1.8 \times 10^4\,\mathrm{L}_\odot$. At lower luminosities, O-rich stars have much lower mass-loss rates than do C-rich stars.

For luminosities below this limit, a superwind is seen only for carbon-rich stars (Fig.1). There is no clear evidence of increasing mass-loss rates with increasing luminosity. The carbon-rich superwind (CSW) in low Z AGB stars occurs even at luminosities below $1{\times}10^4\,\mathrm{L}_\odot$, showing the efficacy of carbon dust in driving mass loss.

Fig.2 shows the relation between the initial mass of the star and the luminosity at which $\mathrm{X}_C \sim 0.1$ according to the stellar models. If the superwind is triggered when $\mathrm{X}_C \sim 0.1$, then we can estimate the initial mass of the observed stars using this relation. The histograms of the observed stars in the LMC and SMC are shown in Fig.2.

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