The Evolving ISM in the Milky Way & Nearby Galaxies

Mass-loss from AGB stars in Local Group galaxies

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ABSTRACT

We have carried out a Spitzer survey of AGB stars in the satellite galaxies to the Milky Way. The stars cover a metallicity range down to [Fe/H]=-1. The results show that at sub-solar metallicity, AGB mass-loss is strongly dominated by carbon stars. The mass return from oxygen-rich stars is strongly suppressed at low metallicity. Carbon stars show little dependence of the mass-loss rates on metallicity. This is attributed to the difference in dust formation efficiency.

Subject headings: galaxies: local group — infrared: stars — infrared: AGB — ISM: dust

1. Introduction

The late stages of the evolution of Low and Intermediate-mass stars (M $\sim$ 1–8 $M_\odot$: LIMS) are characterised by an intense mass-loss phenomenon, the superwind. This leads to the formation of a circumstellar envelope made of gas and dust. The chemistry of the envelope is strongly dependant on the C/O ratio. As the CO molecule is very stable, if C/0>1 the all the oxygen is trapped in the CO molecule leading to a carbon-rich chemistry (e.g. C_2H_2, HCN, SiC, amorphous carbon). For C/O<1, metal oxides and silicate dust are observed.

Dredge-up of newly nucleosynthesised material enrich this envelope and can make the star become a carbon star. Eventually, the mass loss strips the entire hydrogen envelope,

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enriched by primary light elements. The degenerate C/O core subsequently becomes a white dwarf. The ejecta, containing both gas and dust, briefly become ionised by the hot white dwarf (the planetary nebula phase) before merging with the interstellar medium. This superwind is an important source of light elements (C, N), and is at the present time the main source of dust in the ISM. Approximately half the local ISM originates from mass loss by AGB stars.

The mass-loss mechanism of AGB stars is not fully understood. A two-step process is involved. First, shocks due to pulsations from the star extend the atmosphere and leads to dust formation. Second, radiation pressure on the dust drives an outflow. The gas is carried along through friction with the dust particles. Pulsations alone can drive mass-loss rates up to about $10^{-7} M_{\odot}\mathrm{yr}^{-1}$, but the much higher rates observed require dust-driven winds (Bowen & Wilson 1991). Evolutionary models do not yet predict mass-loss rates: instead various but uncertain parametrisation are used. Very little is known about the metallicity dependence, but it is generally accepted that the superwind will be reduced at lower metallicity. Theoretical work by Bowen & Willson (1991) predicts that for metallicities below [Fe/H]$= -1$ dust-driven winds fail, and the wind becomes pulsation-driven. This would affect the evolution of a low metallicity host galaxy by releasing less dust to the ISM.

The *Spitzer Space Telescope* (Werner et al. 2004) for the first time provides the sensitivity necessary to obtain mass-loss rates for the whole range of AGB masses and luminosities in the Magellanic Clouds, where distances are known and absolute mass-loss rates and luminosities can be measured. In addition, several other galaxies orbiting the Milky Way are within reach. These systems trace in general metal-poor stars with a range of metallicity and ages. They will provide a unique opportunity to quantify at least the metallicity dependence.

2. The survey

Different Spitzer programs have obtained mid-infrared spectroscopy of AGB stars in the LMC and the SMC, Fornax and the Sgr dSph galaxies. The description below refers mainly to works published in Zijlstra et al. (2006), Matsuura et al. (2006), Lagadec et al. (2007), Groenewegen et al. (2007), Matsuura et al. (2007), Lagadec et al. (2008) and Lagadec et al., in preparation.

All four systems show a range of metallicities. We take as representative values [Fe/H]$= -0.3$ for the LMC, -0.7 for the SMC, -1 for Fornax and -0.55 for Sgr. The distance moduli are taken as 18.54, 18.93, 20.66 and 17.02, respectively.

The observations were made with the InfraRed Spectrograph, on board the *Spitzer Space*

Telescope. We used the low-resolution Short-Low (SL) and Long-Low (LL) modules to cover the wavelength range 5-38μm.

3. Luminosity

The important onset of the superwind is best traced by the luminosity distribution of the dusty stars, compared to those of unreddened AGB stars.

Fig. 1 shows the distribution of the AGB carbon star populations in the LMC and SMC (bottom panels; left and middle). These were taken from spectroscopically identified catalogues of carbon stars. The bolometric magnitude was derived using the $J-K$, K magnitudes; the bolometric correction was taken from Whitelock et al. 2006.

The histograms of the absolute bolometric magnitudes distributions for the dusty stars observed with Spitzer, are shown in the upper panels of Fig. 1. For these, the luminosity was obtained by integrating over the Spitzer spectra and broadband colours.

We also show some corresponding data for the Sgr dwarf spheroidal galaxy. However, the magnitude distribution of its unreddened stars is much less well determined. The observed distribution clearly shows that the foreground confusion from the Galactic bulge is still major, and relatively few bona-fide stars from the Sgr AGB are included. We also do not know how many of these stars are carbon-rich. A comprehensive survey for carbon stars in Sgr is clearly needed.

Table 1 gives some representative numbers for the galaxies, derived from the distributions in Fig. 1. The second column lists the magnitude where the luminosity function of the unreddened carbon stars becomes flat: this identifies the point where the large majority of AGB stars has become carbon-rich. The third column indicates the life time of the carbon star phase: this is derived from the width of the flat part of the luminosity function, converted to a time scale using the relation $dM_{\rm bol}/dt = -8.25\times10^{-7}\,{\rm mag\,yr^{-1}}$ (Wood 1990). The last column indicates the bolometric magnitude at which the onset of the superwind occurs: this is taken as the point where the luminosity distribution of the mass-losing stars reached its maximum. These numbers should be used with caution: especially the last column is affected by low-number statistics.

For the LMC, the Table and Figure show that the mass loss starts shortly after the star becomes carbon rich. For the SMC, there is longer delay. Also, for the LMC, most stars become carbon-rich late on the AGB. For the SMC, the shift coincides with the tip of the RGB, which is approximately the same as the onset luminosity for thermal pulses. Thus, for

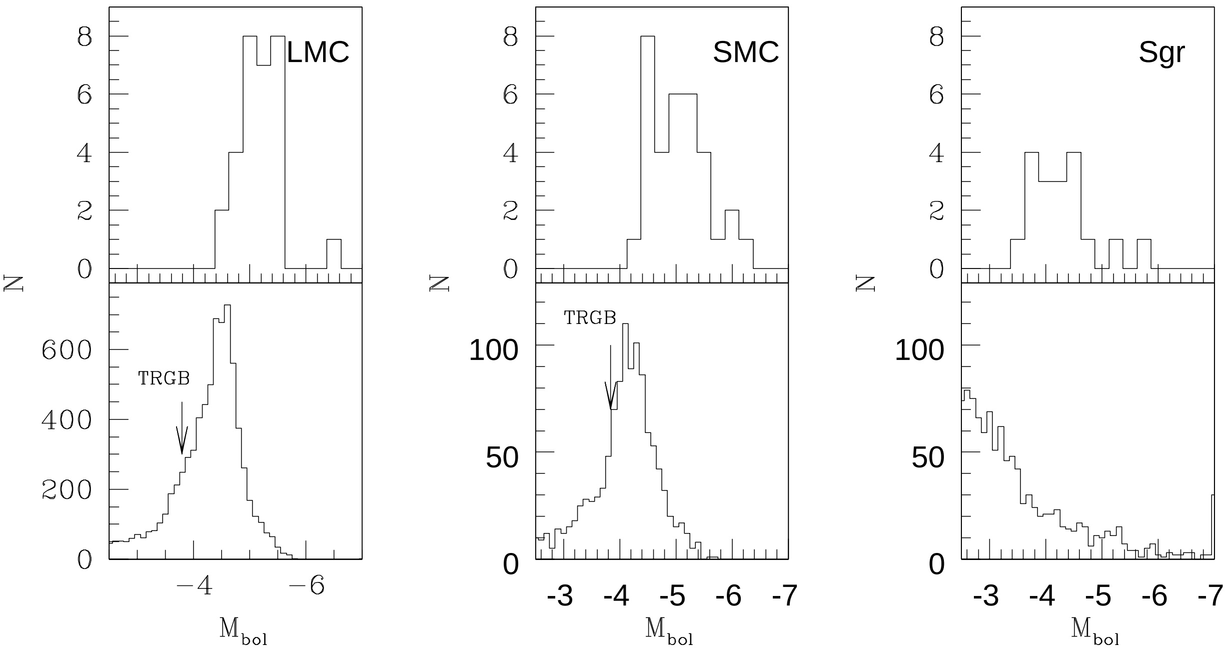

Fig. 1.— Bolometric magnitudes for the observed stars (top panels) and for field stars. For the LMC and SMC, only field carbon stars are included. For Sgr, the field population is for the red colour sequence only, which primarily includes non-carbon stars.

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. $M_{\rm bol(superwind)}$ indicates the onset of the superwind. Life times of the carbon-rich phase are taken from Lagadec et al. 2007.

	$M_{\rm bol}^{\rm init}$	life time	$M_{\rm bol(superwind)}$	
	[Fe/H]	[mag]	[yr]	[mag]
LMC	−0.3	−4.3	3×10^5	−4.7
SMC	−0.7	−3.9	6×10^5	−4.5
Sgr	−0.55	–	–	−4.2

the SMC stars become carbon-rich very soon after the thermal pulses begin.

The last column, surprisingly, seems to indicate that the mass loss starts at a lower luminosity, i.e. earlier on the AGB, for the SMC than it does for the LMC. One should note that the samples were not selected in quite the same way, and so any conclusion would require more work.

4. Spectra

All the observed stars are carbon-rich and their dust continuum featureless, thus due to emission from amorphous carbon. The IRS spectra of all the observed stars show dust emission and molecular absorption features. Absorption features from C_2H_2 at 7.5 and 13.7 μm are clearly observed in all the stars. The 11.3 μm feature observed in all the spectra is due to emission from SiC. A broad emission feature around 30 μm attributed to MgS is clearly observed in the spectra of the reddest stars. This can be explained by the formation sequence of MgS which starts around 600K and is complete around 300K.

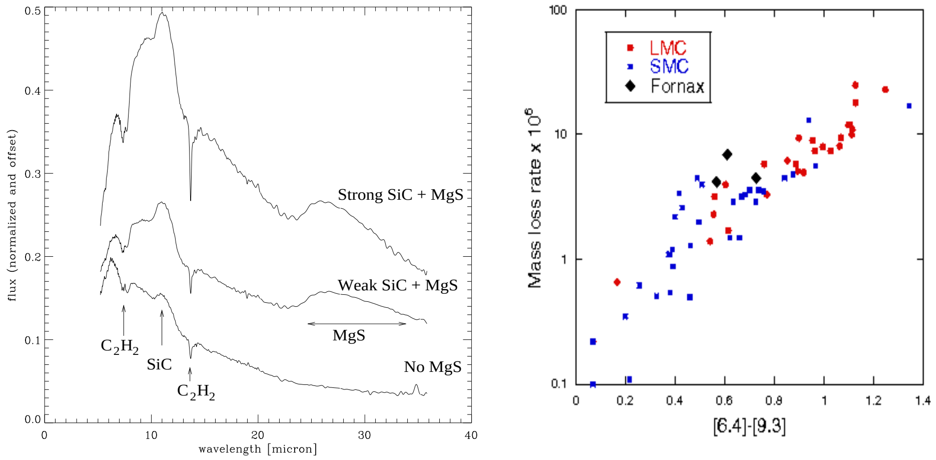

Fig. 2.— Left:Spectra of the LMC carbon stars. We show averages over three different groups, with strong MgS, weak MgS and no MgS. Right: Derived mass loss rates for stars in the LMC, SMC and Fornax

The left panel of Fig. 2 shows the Spitzer spectra for the LMC stars. We show average spectra for three different groups, to illustrate the important features.

5. Mass loss rates

We fit the spectra using a 1-d radiative transfer code, including amorphous carbon dust and silicate carbide dust. The fitting process and results are described in Groenewegen et al. (2007) and Matsuura et al. (2007). The fit yields the dust mass and radial distribution, where we assume a constant wind giving a r^{-2} density profile. Conversion to a mass-loss rate requires an expansion velocity (where we assume $10\,\mathrm{km\,s^{-1}}$) and a gas-to-dust ratio (taken as 200). Both parameters are likely metallicity dependent, but this is not yet quantified.

The right panel of Fig.2 shows the mass-loss rates as a function of the [6.3]−[9.4] colour. The correlation with the [6.3]−[9.4] colour is due to the optical depth: higher optical depth correspond to higher mass-loss rates.

The mass-loss rates are around $10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ which is in the same range as the high mass-loss stars in the Galaxy. A few Galactic stars may reach rates up to ten times higher, but even in the galaxy, such stars are very rare. Overall, we do not yet find evidence that peak (gas) mass-loss rates depend on metallicity.

6. Discussion

6.1. Carbon star mass loss

One unexpected result of the Spitzer surveys is the almost complete dominance of carbon stars among the mass-losing stars in the Magellanic Clouds. The original selection criteria did not separate the two classes, so that this result shows a real effect: at lower metallicity, more stars become carbon stars. This is because 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, Zijlstra et al. 2006 argue that the progenitor masses of the mass-losing carbon stars are ∼1.5–2.5 $\mathrm{M_\odot}$.

The picture that emerges from this is that, at LMC metallicity, all stars in the ∼1.5–2.5 $\mathrm{M_\odot}$ range are C stars by the time they develop substantial mass loss rates and they remain C stars until their AGB evolution is terminated by the transition towards the planetary nebula phase of evolution.

Table 1 lists the bolometric magnitude at which the onset of the superwind occurs. This happens at a somewhat lower luminosity ($L \sim 5\,10^3\,\mathrm{L_\odot}$) than is found in our Galaxy ($L \sim 10^4\,\mathrm{L_\odot}$; $M_\mathrm{bol} \approx -5.5$). The difference between the LMC and the Galaxy is that the former become carbon stars at a point on the AGB where the latter are still oxygen-rich.

We interpret at that as an indication that carbon-rich stars are more efficient at mass loss, even where the oxygen-rich stars are more metal-rich. The finding agrees with (but is less extreme than) the prediction of Woitke et al. 2006.

The few oxygen-rich stars in our MCs sample show mass-loss rates of 1-2 orders of magnitude less than the carbon stars. Oxygen-rich dust depends on metallicity-limited elements (Si, Al), while amorphous carbon depends on self-produced carbon. Thus, the mass-loss efficiency in oxygen-rich stars is more affected by metallicity.

6.2. C/O ratio

At low metallicity, third dredge-up is more efficient in making stars carbon rich, as discussed above: the same amount amount of primary carbon will have a larger effect on more metal-poor stars. This process does not cease once the star has become carbon rich: further dredge-up will continue to enhance the C/O ratio. We may therefore expect that metal-poor carbon stars have a higher C/O ratio than do metal-rich carbon stars. Matsuura et al. 2005 find evidence that LMC stars have C/O ratios of ~ 1.5, versus ~ 1.1 for typical Galactic carbon stars. Ratios in lower metallicity systems (e.g. SMC) would be even higher.

This immediately affects the C_2H_2 abundance, which will increase towards lower metallicity, together with $X_{\rm C} = {\rm C} - {\rm O}/{\rm O}_\odot$, which measure the amount of 'free' carbon . This is in fact seen, with the acetylene bands becoming much stronger (larger equivalent width) in the sequence Galaxy–LMC–SMC (Lagadec et al. 2007).

Acetylene is a building block of aromatic molecules, and is expected to be important in the formation of amorphous dust. Assuming that mass loss begins at the same value of $X_{\rm C}$, and that for Galactic stars this occurs for C/O= 1.1, we predict that for the LMC the superwind begins at C/O= 1.25 and for the SMC, at C/O= 1.5. In practise, the stronger acetylene bands at lower metallicity suggest these C/O ratios are lower limits, as also suggested by the indicative C/O ratios derived by Matsuura et al. 2005.

7. Conclusions

The Spitzer surveys have allowed us to quantify the AGB mass loss at sub-solar metallicity. In all targeted galaxies, AGB stars were found with high mass-loss rates. Values of $10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}$ are reached, assuming Galactic gas to dust ratios. If the gas to dust ratios are higher at low metallicity, even higher total mass-loss rates may be reached. The first conclusion is therefore that the peak mass-loss rates reached on the AGB does not depend on metallicity, within our accuracies.

A significant difference is found in the chemistry. At low metallicities, AGB mass loss is strongly dominated by carbon stars. This is explained by two effects: first, stars become carbon rich earlier in their evolution, and second, carbon stars are more efficient dust producers than are oxygen-rich stars. The strong acetylene features shows that C_2H_2 is more abundant for lower metallicity stars, indicating a larger amount of free carbon.

The expectation that at lower metallicity, mass loss would be delayed, is not confirmed. Instead, mass loss begins at low luminosity, possibly even lower than in the Galaxy. This also is a consequence of the effect of the carbon stars. in the LMC, mass loss appears to be triggered shortly after the star becomes carbon rich. Galactic stars of the same luminosity are still oxygen rich, for which the dust driving mechanism is less efficient.

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