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The effect of metallicity on the mass–loss from AGB stars

An observer's point of view

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Abstract. Studying the effect of metallicity on the mass-loss process is important in order to constrain stellar evolution models and to understand the formation and evolution of dust in different galaxies. At low metallicity, less seeds are present for dust formation, so one might expect dust formation to be less efficient and thus the mass-loss rates to be lower. Our Spitzer survey of AGB stars in the Local Group have shown that the amount of dust ejected by carbon stars was independent of the metallicity. But those stars are too distant to be observed in CO, and thus to study their total (gas+dust) mass-loss rates. We have extensively studied a sample of newly discovered metal-poor carbon stars in the halo. CO observations (JCMT), combined with infrared ones using Spitzer and the VLT have allowed us to study both the dust and gas content of these stars and to get better quantitative constraints on the effect of metallicity on the mass-loss process. Our JCMT observations have shown that the expansion velocity was decreasing with metallicity. Our global view of the current understanding of the effect of metallicity on this mass-loss process is presented here.

Key words. circumstellar matter – infrared: stars — carbon stars — AGB stars — stars: mass-loss

1. Introduction

The mass-loss mechanism of AGB stars is a two step process. Shocks due to pulsation extend the atmosphere so that the material ejected by the star becomes dense and cold enough for dust to form. Due to its opacity, dust absorbs the radiation from the star and is driven away by radiation pressure, the friction carrying the gas along with it. At low metallicity less seeds are present for dust formation, so one might expect dust formation to be less efficient and thus the mass-loss rates to be lower.

Theoretical work by Bowen & Willson (1991) predicts that for metallicities below [Fe/H]=-1 dust-driven winds fail, and the wind must stay pulsation-driven. However, observational evidence for any metallicity dependence is still very limited (Zijlstra 2004). More recent observational (Matsuura et al. 2009; Lagadec et al. 2009; Groenewegen et al. 2007) and theoretical works (Wachter et al. 2008; Mattsson et al. 2008) indicate that the mass-loss rates

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Table 1. Properties of our observational survey

Galaxy name	Mean [Fe/H]	distance kpc	number of stars observed
LMC	-0.3	50	24
SMC	-0.7	59	32
Sgr	-0.55	24.4	6
Fornax	-1	138	2
Sculptor	-2.2	87	1

from carbon stars in metal-poor environments are similar to those observed in our galaxy.

To obtain the first observational evidence on mass-loss rates at low metallicity, we have carried out an infrared survey with the *Spitzer Space Telescope* of AGB stars in nearby dwarf galaxies. Infrared observations allow us to measure the dust density distribution around the star. To derive a total (gas+dust) mass-loss rate, one needs to know the gas-to-dust mass ratio, the expansion velocity and the luminosity of the star.

The main uncertainty arises from the unknown expansion velocity. There is some evidence that expansion velocities are lower at low metallicity, from measurement of OH masers (Marshall et al. 2004). However, OH masers are found only in oxygen-rich stars, which appear to have suppressed mass-loss at low metallicities. For carbon-rich stars, the only available velocity tracer is CO. Currently, extra-galactic stars are too distant for CO measurements. However, there are a number of carbon stars in the galactic halo, which are believed to have similarly low metallicity.

These stars are the closest metal-poor carbon stars known, and they are bright enough to be detected in CO using ground-based millimeter telescopes. We have carried out observations of six halo carbon stars in the CO J = 3 $\rightarrow$ 2 transition. This allowed us to determine the expansion velocity of these stars. Our current understanding of the effect of metallicity on the mass-loss from AGB stars is presented here.

2. The Spitzer infrared survey

To obtain the first observational evidence on mass-loss rates at low metallicity, we have carried out several surveys with the *Spitzer Space Telescope* of stars in nearby dwarf galaxies. These show significant mass-loss rates down to Z=1/25 $Z_\odot$ (Sloan et al. 2009; Lagadec et al. 2007; Matsuura et al. 2007), but only for carbon-rich stars. The current evidence indicates that oxygen-rich stars have lower mass-loss rates at lower metallicities. For carbon stars, no evidence for a dependency of mass-loss rate on metallicity has yet been uncovered. Dust production by a carbon star in a galaxy with primitive abundances (Sculptor [Fe/H]~ -2.2) raises the possibility that carbon stars contributed carbonaceous dust in the early universe (Sloan et al. 2009).

Different Spitzer programs have obtained mid-infrared spectroscopy of AGB stars in the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), Fornax and the Sagittarius Dwarf Spheriodal (Sgr dSph) galaxies. The description below refers mainly to Sloan et al. (2006), Zijlstra et al. (2006), Matsuura et al. (2006), Lagadec et al. (2007), Groenewegen et al. (2007), Matsuura et al. (2007), Lagadec et al. (2008), Sloan et al. (2009) and Lagadec et al. (2009).

All 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 (Table 1). The observations were made with the InfraRed Spectrograph, on board the *Spitzer Space Telescope*, using the low-resolution Short-Low (SL) and Long-Low (LL) modules to cover the wavelength range 5-38 μm.

Fig. 1 shows the Spitzer spectra for the LMC stars. We show average spectra for three different groups, to illustrate the important fea-

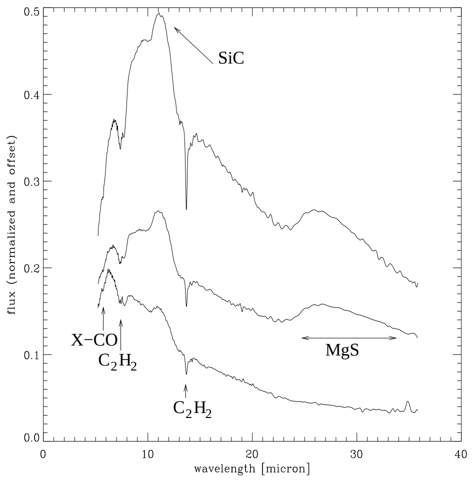

Fig. 1. Spectra of the LMC carbon stars. We show averages over three different groups, with strong MgS, weak MgS and no MgS.

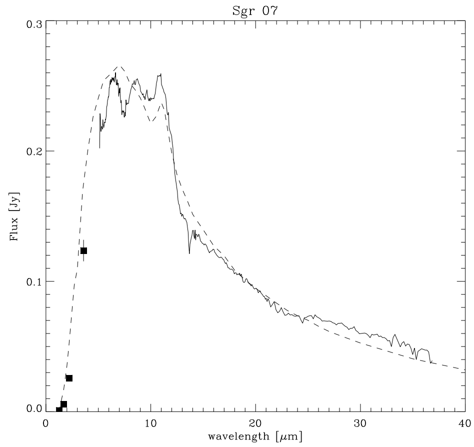

Fig. 2. Example of a radiative transfer model (dashed line) to fit a Spitzer spectrum (solid lined), in order to estimate a mass-loss rate.

tures. All the observed stars are carbon-rich and their dust continuum is featureless, 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. Our work has shown that the SiC feature is weaker at low metallicity. This can be explained by the lower abundance of Si at low Z (Lagadec et al. 2007). However recent observations reveal that in metal-poor environments the SiC feature in post-AGB stars is stronger than it metal-rich stars (Bernard-Salas et al. 2009). C_2H_2 appears to be stronger at low metallicity (Matsuura et al. 2006). This can be explained by the fact that at low Z, the initial C/O ratio of stars is larger, making the dredge up of carbon more efficient, thus leading to AGB stars with a larger fraction of carbon.

3. Mass-loss rates

To determine the mass-loss rates, we fit the spectra using a 1-D radiative transfer code, including amorphous carbon dust and silicate carbide dust (Fig. 2). The fitting process and results are described in Groenewegen et al. (2007), Matsuura et al. (2007) and Lagadec et al. (2009). 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.

Fig. 3 shows the mass-loss rates as a function of the [6.3]−[9.4] color. The correlation with the [6.3]−[9.4] color is due to the optical depth: higher optical depth correspond to higher mass-loss rates.

The mass-loss rates are around $10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$ 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.

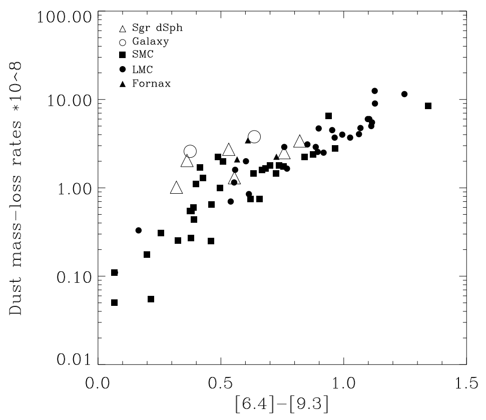

Fig. 3. Derived mass-loss rates for stars in the LMC, SMC, Sgr dSph and Fornax, as a function of the [6.4]-[9.3] color. This color is a proxy of the optical depth.

4. 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 (MCs). 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 $M_\odot$.

The picture that emerges from this is that, at LMC metallicity, all stars in the ~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 by the transition towards the planetary nebula phase of evolution.

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.

At low metallicity, third dredge-up is more efficient in making stars carbon rich and, 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 and so 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 $X_C = C - O/O_\odot$, 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_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 practice, 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).

Our 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 $X_{CO} = (C - O)/O_\odot = 0.1$), or when the luminosity reaches a value sufficient for a silicate-dust-driven wind (proposed at $L = 10^4 Z^{-4/3}\, L_\odot$) (Lagadec & Zijlstra 2008).

5. Toward a better determination of the mass-loss rates

As we indicated, the mass-loss rates were determined so far using infrared observations. This method is sensitive to dust emission only and one needs to make some assumptions (expansion velocity, gas-to-dust mass ratio) in order to estimate a gas mass-loss rate.

To get a quantitative measurement of the effect of metallicity on the total (gas+dust) mass-loss rate of AGB star, we observed the brightest halo carbon stars. Mauron et al. (2004, 2005, 2007) and Mauron (2008) have discovered ~100 carbon stars in the galactic halo, adding to the sample of ~50 described by Totten & Irwin (1998). All of these stars are spectroscopically confirmed carbon stars and are the only metal-poor carbon stars bright enough to be observed in CO. We selected the six stars with the highest IRAS 12 μm flux observable with the James Clerk Maxwell Telescope (JCMT, Mauna Kea, Hawaii). The emission from an AGB star at 12 μm is due to thermal emission from the dust in the envelope. Thus, one expects the stars with the largest 12 μm flux to be the brightest in CO. All the observed stars have $3 < J \;\; K < 4$ and thus have a similar dust optical depth and a large circumstellar dusty envelope.

The observations allowed us to directly measure the expansion velocity for a sample of carbon stars in the halo. Our measured expansion velocities are in the range 3−16.5 $\mathrm{km\,s^{-1}}$. The expansion velocity of carbon stars increases during the evolution on the AGB, i.e. when the dusty envelope becomes optically thicker. To compare the expansion velocities we measured in halo carbon stars with carbon stars in the disc, we took a sample of carbon stars in the disc with colors similar to our sample. We selected all of the carbon stars with $3<J-K<4$ in the extensive catalog of CO observations of evolved stars by Loup et al. (1993). These observations also allowed us to show that two of the observed stars are halo stars, one belongs to the Sgr dSph stream and the three others belong to the thick disc. The halo carbon stars clearly have a lower mean expansion velocity.

The three stars in the halo and the Sgr dSph stream have $V_{\rm exp}$ in the range 3−8.5 $\mathrm{km\,s^{-1}}$, while the three stars associated with the thick disc have velocities ranging from 11.5 to 16.5 $\mathrm{km\,s^{-1}}$. The latter range is at the low end of expansion velocities for AGB stars with similar near-infrared colors in the thin disc. Radiative transfer models indicate that these stars are losing mass with rather large dust mass-loss rates in the range 1-3.3$10^{-8}\,\mathrm{M_\odot\,yr^{-1}}$, similar to the ones observed for similar stars in the galaxy.

The wind expansion velocities of the observed stars are lower compared to carbon stars in the thin disc, and are lower for the stars in the halo and the Sgr dSph stream than in the thick disc. These low expansion velocities probably result from the low metallicity of the halo carbon stars. This implies that metal-poor carbon stars lose mass at a rate similar to metal-rich carbon stars, but with lower expansion velocities, as predicted by recent theoretical models.

Mattsson et al. (2008) and Wachter et al. (2008) have recently conducted theoretical investigations of the winds from metal-poor carbon stars. Both studies show that metal-poor carbon stars can develop high mass-loss rates, leading to the formation of a large dusty envelope, in agreement with spectroscopic observations from *Spitzer* of AGB stars in metal-poor galaxies.

Wachter et al. (2008) predict that the outflow velocities from carbon stars should be lower in metal-poor environments, because of the lower gas-to-dust mass ratio and because the formation of less dust leads to less efficient acceleration of the wind outside of the sonic region. This interpretation is consistent with our interpretation that the low expansion velocities we have observed in the halo are due to their low metallicities.

6. 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 $10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ 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. A low Z, 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. So far, the effect of metallicity on the mass-loss from carbon-rich AGB stars has been studied primarily from infrared observations of AGB stars in Local Group galaxies, mostly with the *Spitzer Space Telescope*. Infrared observations measure the infrared excess, which can be converted to mass-loss rates by assuming an expansion velocity for the circumstellar material. So far all of the mass-loss rates have been estimated using the assumption that the expansion velocity is independent of the metallicity. The results presented here show that this assumption needs to be reconsidered.

We have recently obtained spectra of some of the present sample with the Infrared Spectrograph on *Spitzer*. Combining our CO observations and these spectra together, and comparing them to *Spitzer* spectra from carbon stars in other galaxies in the Local Group will allow us to quantitatively study the mass-loss from carbon-rich AGB stars in the Local Group and its dependence on metallicity. We plan to determine the metallicities of the observed stars using VLT near-infrared CRIRES observations (observations schedulled in 2010). We will then know the expansion velocities, dust and gas mass-loss rates, dust composition and metallicities of a sample of metal-poor carbon star. This will be a major step towards understanding the effect of metallicity on the mass-loss from carbon stars.

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References

Bowen, G. H. & Willson, L. A. 1991, ApJ, 375, L53
Groenewegen, M. A. T., Wood, P. R., Sloan, G. C., et al. 2007, MNRAS, 376, 313
Lagadec, E. & Zijlstra, A. A. 2008, MNRAS, 390, L59
Lagadec, E., Zijlstra, A. A., Matsuura, M., et al. 2008, MNRAS, 383, 399
Lagadec, E., Zijlstra, A. A., Sloan, G. C., et al. 2007, MNRAS, 376, 1270
Lagadec, E., Zijlstra, A. A., Sloan, G. C., et al. 2009, MNRAS, 396, 598
Loup, C., Forveille, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291
Marshall, J. R., van Loon, J. T., Matsuura, M., et al. 2004, MNRAS, 355, 1348
Matsuura, M., Barlow, M. J., Zijlstra, A. A., et al. 2009, MNRAS, 396, 918
Matsuura, M., Wood, P. R., Sloan, G. C., et al. 2006, MNRAS, 371, 415
Matsuura, M., Zijlstra, A. A., Bernard-Salas, J., et al. 2007, MNRAS, 382, 1889
Matsuura, M., Zijlstra, A. A., van Loon, J. T., et al. 2005, A&A, 434, 691
Mattsson, L., Wahlin, R., Höfner, S., & Eriksson, K. 2008, A&A, 484, L5
Mauron, N. 2008, A&A, 482, 151
Mauron, N., Azzopardi, M., Gigoyan, K., & Kendall, T. R. 2004, A&A, 418, 77
Mauron, N., Gigoyan, K. S., & Kendall, T. R. 2007, A&A, 475, 843
Mauron, N., Kendall, T. R., & Gigoyan, K. 2005, A&A, 438, 867
Sloan, G. C., Kraemer, K. E., Matsuura, M., et al. 2006, ApJ, 645, 1118

Sloan, G. C., Matsuura, M., Zijlstra, A. A., et al. 2009, Science, 323, 353
Totten, E. J. & Irwin, M. J. 1998, MNRAS, 294, 1
Wachter, A., Winters, J. M., Schröder, K., & Sedlmayr, E. 2008, A&A, 486, 497
Zijlstra, A. A. 2004, MNRAS, 348, L23
Zijlstra, A. A., Matsuura, M., Wood, P. R., et al. 2006, MNRAS, 370, 1961