The Magellanic System: Stars, Gas, and Galaxies
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The production of dust in the Magellanic Clouds

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Abstract. The sensitivity of the Infrared Spectrograph on the *Spitzer Space Telescope* has enabled detailed surveys of mass-losing stars in the Large and Small Magellanic Clouds. Comparisons of samples from these galaxies and the Milky Way reveal how the dust produced by evolved stars depends on the metallicity of the host environment. Oxygen-rich stars show several trends with metallicity. In more metal-poor environments, fewer of them show dust excesses, the circumstellar SiO absorption grows weaker, the quantity of silicate dust decreases, and alumina dust grows rare. As carbon stars grow more metal-poor, the amount of circumstellar acetylene gas increases, while the amount of trace dust elements like SiC and MgS decreases. However, there is little dependence on metallicity in the amount of amorphous carbon dust produced by carbon stars, because they produce the carbon needed to make dust themselves. As galaxies grow more metal-poor, the composition of the dust they produce should grow more carbon rich.

Keywords. stars: AGB and post-AGB, stars: atmospheres, stars: carbon, stars: mass loss, stars: supergiants, Magellanic Couds, infrared: stars

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1. Introduction

The sensitivity of the Infrared Spectrograph (IRS) (Houck *et al.* 2004) on the *Spitzer Space Telescope* (Werner *et al.* 2004) makes possible spectroscopy of individual supergiants and stars on the asymptotic giant branch (AGB) in nearby galaxies to distances of over 100 kpc. As a result, multiple observing programs have investigated mass loss and dust production in several Local Group galaxies. This paper focuses on the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC). Both Clouds have a complex structure and history (as this conference has demonstrated so well). To assume that each system can be described with a single distance and metallicity is somewhat of an oversimplification. Nonetheless, this assumption is the first step in using Local Group galaxies as probes of how mass loss and dust production vary with metallicity. Making this leap reveals trends relevant not just to the Local Group but also to more distant galaxies where *Spitzer* can detect dust but cannot resolve the separate components which produce it.

Five *Spitzer* programs have spectroscopically surveyed evolved stars in the Magellanic Clouds (see the review by Sloan *et al.* 2008b). The majority of the initial papers have focused on the carbon stars in the samples, in both the LMC (Zijlstra *et al.* 2006; Leisenring *et al.* 2008) and the SMC (Sloan *et al.* 2006; Lagadec *et al.* 2007). These papers have led to the discovery of several dependencies of the gas and dust properties around carbon stars on metallicity. As the samples grow more metal poor, the amount of SiC and MgS decreases relative to the dominant component, amorphous carbon, while the absorption from acetylene (C_2H_2) actually grows stronger. In the Milky Way, carbon stars show absorption bands from both acetylene and HCN, but in the Magellanic samples, HCN absorption is generally absent (Matsuura *et al.* 2006).

The MC_DUST program is a guaranteed time program by the IRS team to examine evolved stars in both the LMC and SMC. Sloan *et al.* (2008a) recently presented a detailed analysis of the full spectroscopic sample, giving the first in-depth look at the evolved oxygen-rich stars in both Magellanic Clouds. A comparison of this sample with the carbon stars published by the other groups reveals some fundamental differences between the metallicity dependencies of carbon-rich and oxygen-rich dust.

2. Naked stars

Table 1. Fraction of naked oxygen-rich stars.

	Period (days)		
Sample	$\leqslant 250$	250–700	> 700
Galaxy	2 of 106	5 of 269	0 of 11
LMC	2 of 3	2 of 9	0 of 8
SMC	1 of 1	6 of 7	0 of 1

Naked stars (i.e. stars with no obvious dust emission in their infrared spectra) account for more than one quarter of the total MC_DUST sample. Table 1 compares the fraction of naked stars in the oxgyen-rich MC_DUST sample to the Galactic sample defined by Sloan and Price (1995, 1998) from observations by the Low-Resolution Spectrometer (LRS) on the *Infrared Astronomical Satellite*. Moving to progressively lower metallicities increases the percentage of naked stars, as is most obvious by examining the sources with periods between 250 and 700 days.

Table 2. SiO band strengths.

Sample	W (μm)
Galactic SWS	0.35±0.11
Galactic IRS	0.28±0.06
LMC	0.26±0.11
SMC	0.16±0.08

Most late-type oxygen-rich giants have an SiO molecular absorption band at 8 μm. Table 2 compares the equivalent width of this band in two Galactic samples and the Magellanic Clouds. Heras *et al.* (2002) defined the Galactic SWS sample from observations by the Short Wavelength Spectrometer (SWS) aboard the *Infrared Space Observatory*. The Galactic IRS sample comes from the IRS program of Sloan *et al.* (in preparation). As the sample grows more metal poor, the strength of the SiO absorption weakens. SiO is the building block of silicate dust, and its growing weakness indicates that silicates are more difficult to form in more metal-poor stars.

3. Oxygen-rich dust

The MC_DUST sample contains 17 sources with clearly identifiable silicate dust emission, 14 of which show no evidence of self-absorption at 10 μm. To analyze these spectra, Sloan *et al.* (2008a) applied the technique originally developed for the LRS database by Sloan & Price (1995, 1998). This technique classifies the spectrum by first fitting and

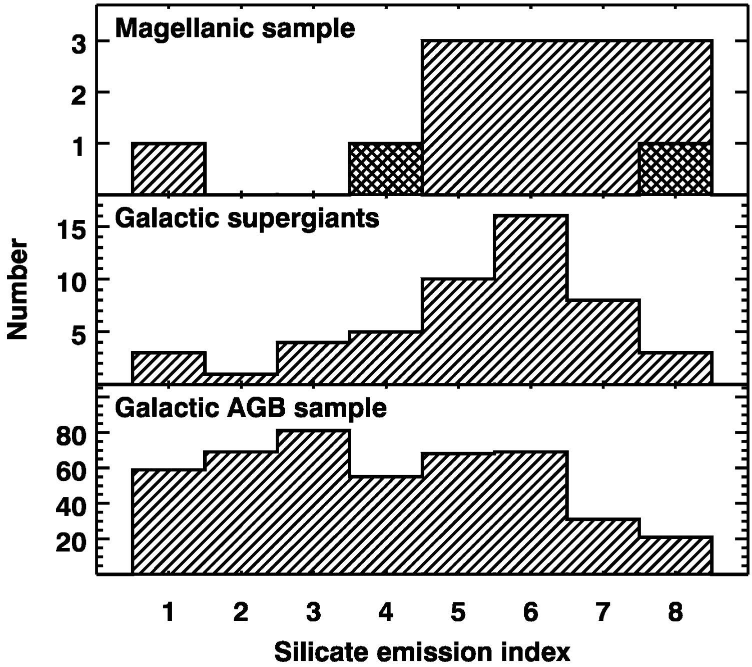

Figure 1. The distribution of the oxygen-rich dust chemistries in the MC_DUST sample, compared to Galactic supergiants and AGB stars. In the top panel, the two SMC sources are cross-hatched; the remainder are LMC sources. SE1–3 spectra arise from alumina-rich dust and are largely absent in the Magellanic sources considered here. (Adapted from Fig. 27 of Sloan *et al.* 2008a.)

subtracting an estimated stellar continuum and then quantifying the shape of the 10 μm feature with the remaining flux at 10, 11, and 12 μm. Spectra are classified as SE (for silicate emission) 1 through 8. Classifications of SE1–3 correspond to dust emission dominated by amorphous alumina grains (Al_2O_3), while the other end of the sequence (SE6–8) is dominated by amorphous silicates (Egan & Sloan 2001).

Figure 1 shows that amorphous alumina is largely absent from the Magellanic sample, while it is common in the Galactic AGB sample. The distribution of Magellanic SE indices looks much like the Galactic supergiant sample, even though the majority of the Magellanic sources are confirmed to be on the AGB.

Sloan & Price (1995) defined the dust emission contrast (DEC) in their oxygen-rich sample as the ratio of the dust excess to the stellar contribution integrated from 7.7 to 14.0 μm. This measure quickly assesses the amount of dust in the spectrum. Figure 2 plots the DEC for those oxygen-rich variables with known periods in the MC_DUST and Galactic samples. The amount of dust generally increases with increasing pulsation period in the Galactic sample, but the Magellanic samples lag behind. For periods < 500 days, most of the LMC and SMC sample are naked. From this point up to periods of 700 days, most LMC sources show some dust, but less than the Galactic sample, while the SMC sources are still naked. For periods < 700 days, the amount of dust clearly decreases with lower metallicity.

At longer periods, the situation is complicated by the presence of younger, more massive stars which may not reflect the average metallicity of their host galaxy. In Figure 2, most of the longer-period variables in the LMC show strong dust emission. Of the four

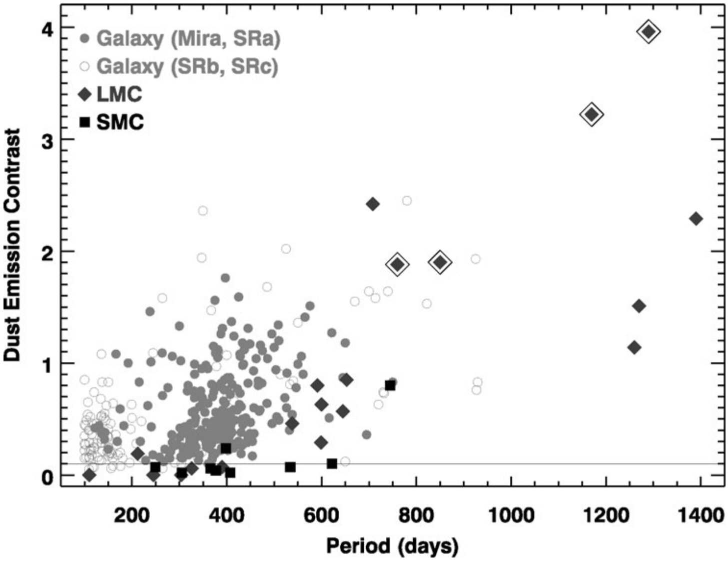

Figure 2. Dust emission contrast as a function of pulsation period for the MC_DUST sample of Magellanic stars and a Galactic sample observed by the LRS. The horizontal line separates naked from dusty stars. The four outlined LMC sources are known or suspected supergiants. (Based on Fig. 26 of Sloan *et al.* 2008a.)

outlined in Figure 2, the two with periods close to 800 days are certain supergiants, and the two with DEC > 3 are probably super-AGB sources.

4. Carbon stars

The key measure used in the study of Magellanic carbon stars is the [6.4]−[9.3] color, which is defined in the Manchester method to measure the amount of amorphous carbon in the spectra. Amorphous carbon shows no obvious spectral structure in the infrared; instead, its opacity drops steadily with wavelength in the infrared, falling as λ^{-2}. The [6.4]−[9.3] color measures the contribution of amorphous carbon in two narrow wavelength ranges which are mostly free of molecular absorption bands or dust emission features. Groenewegen *et al.* (2007) applied radiative transfer models to all of the Magellanic carbon stars in the samples published through 2007 and showed that the [6.4]−[9.3] color is closely correlated with the mass-loss rate. More significantly, they noted that there was little evidence that the mass-loss rate from carbon stars changed with metallicity.

Sloan *et al.* (2008a) examined the dust properties of the carbon stars in the Galactic and Magellanic samples as a function of pulsation period. Figure 3 shows that there is no apparent difference between these samples, All trace the same relation of increasing [6.4]−[9.3] color, and thus mass-loss rate, with increasing period, no matter the initial metallicity of the sample.

5. Discussion

Infrared spectroscopy from *Spitzer* reveals an important difference in how the production of oxygen-rich and carbon-rich dust depends on metallicity in nearby Local Group galaxies. While the production of oxygen-rich dust declines in more metal-poor environments, no change in carbon-rich dust is detected. Observations of the Magellanic Clouds

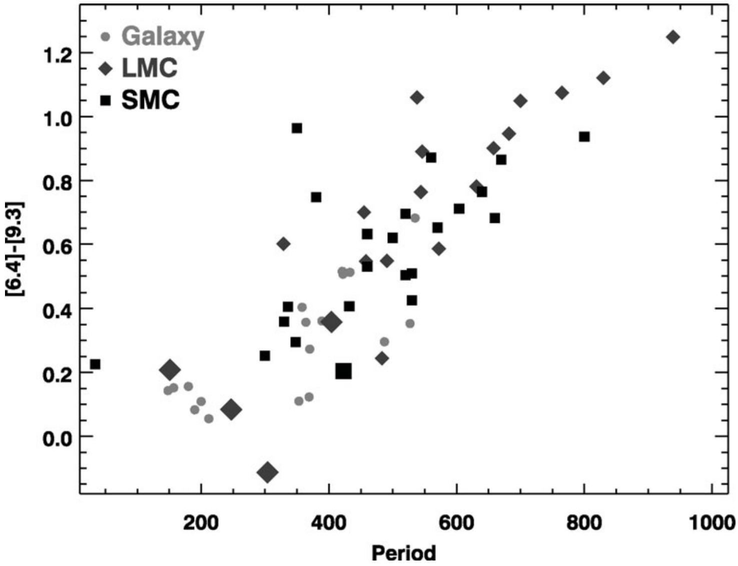

Figure 3. The [6.4]–[9.3] color as a function of pulsation period for Magellanic and Galactic carbon stars. The [6.4]–[9.3] color traces mass-loss rate. No difference in mass-loss rate as a function of period is apparent in the samples. (Based on Fig. 29 of Sloan *et al.* 2008a).

show that the fraction of AGB stars which are carbon rich increases at lower metallicities (Blanco *et al.* 1978, 1980). This increase results from a drop in the lower mass limit for carbon stars with lower initial metallicities (Renzini & Voli 1981). These trends lead to the conclusion that more metal-poor galaxies will produce less oxygen-rich dust and more carbon-rich dust.

The observed trends are relevant to the question of how to power the mass loss from oxygen-rich AGB stars. Woitke (2006) modeled the process in both oxygen-rich and carbon-rich stars, and he found that while the opacity of carbon-rich dust can drive the mass loss, oxygen-rich dust is too transparent to transfer sufficient radiation pressure outward to the gas. Lagadec & Zijlstra (2008) have recently examined observations of evolved stars in the Magellanic Clouds and other Local Group galaxies. They find that the final phase of high mass loss on the AGB, the superwind, has different triggers in the carbon-rich and oxygen-rich environments. For carbon stars, the superwind begins when the C/O ratio crosses a metallicity-dependent threshhold, while for oxygen-rich sources, the superwind begins at a critical luminosity which grows higher as the metallicity decreases. This conclusion still does not answer the question of what drives the mass loss from the oxygen-rich stars. In metal-poor stars, the lack of Si should limit the production of silicate grains, making a solution even more difficult than in the Milky Way. Perhaps some combination of pulsation velocity, molecular opacity, and grain opacity is sufficient to drive the gas over the escape velocity.

The mass-loss rate from carbon stars does not depend on metallicity in any obvious way. This observation helps address the question of why emission from polycyclic aromatic hydrocarbons (PAHs) is weak in metal-poor galaxies (e.g., Engelbracht *et al.* 2005; Wu *et al.* 2006). Either the PAHS are destroyed more efficiently by the harsher interstellar radiation in these systems (Galliano *et al.* 2005; Madden *et al.* 2006) or the precursors to PAHs are not forming (Galliano *et al.* 2008). If anything, the results from Magellanic carbon stars suggest the injection of *more* carbon-rich grains into the interstellar medium, not less. The evidence is growing linking PAHs to the amorphous carbon produced by carbon stars, which is a fragile mixture of aliphatic and aromatic hydrocarbons (e.g., Sloan *et al.* 2007; Pino *et al.* 2008). Thus, plenty of PAH precursors are being produced in metal-poor galaxies. Their absence must be due to their destruction, as supported by recent work showing that the PAH emission strength is related more to the harshness of the radiation field than to the metallicity in M 101 (Gordon *et al.* 2008) and within extended H II regions in the Galaxy and Magellanic Clouds (Lebouteiller *et al.* 2008).

The spectroscopic surveys of mass-losing stars in the Large and Small Magellanic Clouds with *Spitzer* have allowed us to study how the mass-loss and dust formation processes depend on metallicity. Not only are these investigations helping us understand the evolution of these two galaxies, but they are providing insight into the fundamentally important questions of what drives the mass loss from evolved stars and how this process seeds more distant galaxies with dust.

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