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DUST PRODUCTION BY EVOLVED STARS IN THE MAGELLANIC CLOUDS

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ABSTRACT

Within the context of the hugely successful SAGE-LMC and SAGE-SMC surveys, *Spitzer* photometry observations of the Large and Small Magellanic Clouds have revealed millions of infrared point sources in each galaxy. The brightest infrared sources are generally dust producing and mass-losing evolved stars, and several tens of thousands of such stars have been classified. After photometrically classifying these objects, the dust production by several kinds of evolved stars – such as Asymptotic Giant Branch stars and Red Supergiants – can be determined. SAGE-Spec is the spectroscopic follow-up to the SAGE-LMC survey, and it has obtained *Spitzer*-IRS 5–40 μm spectroscopy of about 200 sources in the LMC. Combined with archival data from other programs, observations at a total of $\sim$1000 pointings have been obtained in the LMC, while $\sim$250 IRS pointings were observed in the SMC. Of these, a few hundred pointings represent dust producing and mass-losing evolved stars, covering a range in colors, luminosities, and thus mass-loss rates. Red Supergiants and O-rich and C-rich AGB stars – the main dust producers – are well represented in the spectroscopic sample. This paper will summarize what we know about the mineralogy of dust producing evolved stars, and discuss their relative importance in the total dust budget.

Key words: dust, extinction; Magellanic Clouds; stars: late-type; stars: mass-loss

1. THE LIFE CYCLE OF DUST IN THE MAGELLANIC CLOUDS

The mass and composition of the interstellar dust reservoir is governed by dust consumption and dust production processes. Astration removes dust from the interstellar medium in the process of star formation. Towards the end of their lives, stars return dust to the interstellar medium, enriched with products of stellar nucleosynthesis. In particular, Asymptotic Giant Branch (AGB) stars, the evolutionary end point of low mass stars ($M < 8$ $M_{\odot}$), are effective dust producers, with a high dust-to-gas ratio in their winds. Indeed, it is thought that dust formation is a requirement to drive the dense winds that these objects often endure.

The Magellanic Clouds are excellent laboratories to study the life cycle of dust. The outside vantage point of these nearby galaxies gives us the opportunity to obtain a global picture, while the viewing angle is such that it is unlikely to see multiple objects along the same line of sight.

2. THE EVOLVED STELLAR POPULATION AS DUST FACTORIES

In order to study the occurence of dust in the Magellanic Clouds, we have conducted infrared surveys with the *Spitzer* Space Telescope using all IRAC and MIPS bands. The SAGE-LMC survey (Meixner et al., 2006) has identified 8.5 million infrared point sources in the Large Magellanic Cloud (LMC), while around 2 million infrared point sources are seen in the SAGE-SMC survey (Gordon et al., 2011) of the Small Magellanic Cloud (SMC). The catalogues have been cross-correlated with the 2MASS survey, to find near-infrared counterparts. The 2MASS bands (particulary the J vs. J-K diagram) can be used to classify the various populations. This was first done for the LMC by Blum et al. (2006), who identified several classes of evolved stars, e.g. M supergiants, O-rich AGB stars, C-rich AGB stars and extreme AGB stars. The latter category was separated from the AGB stars by the color cut $J - [3.6] > 3.1$. The infrared color classification of SAGE sources was further refined by Boyer et al. (2011) for the SMC. Using the mid-infrared excess measured in the IRAC-[8.0] and MIPS-[24] bands, Srinivasan et al. (2009) were able to estimate the total dust production rates in each of the evolved star categories. From this analysis, it became clear that the category of extreme AGB stars (referred to as FIR sources by Boyer et al. 2011) dominates the dust production.

3. DISSECTING THE COMPOSITION OF STARDUST

Srinivasan et al. (2009) show that C-rich and O-rich AGB stars produce roughly similar amounts of dust

(0.14 and 0.24 $\times 10^{-5}$ $M_\odot$ yr^{-1}, respectively), while the extreme AGB stars produce 2.36 $\times 10^{-5}$ $M_\odot$ yr^{-1} of dust, an order of magnitude more. Spectroscopic information will provide definite classifications of individual stars, and for this purpose we have performed a spectroscopic survey of targets in the LMC, using the low-resolution mode of the Infrared Spectrograph (IRS) on *Spitzer* (SAGE-spec Kemper et al., 2010). Around 200 point sources were targeted, and an additional ~800 further staring mode observations from other programs within the SAGE-LMC footprint were analyzed, yielding a total legacy of around 1,000 5–38 μm point source spectra in the LMC.

Srinivasan et al. (2010) selected a typical C-rich star for which IRS spectroscopy was available, and fitted the spectrum using the 2-DUST radiative transfer model (Ueta & Meixner, 2003). Two dust components were used, SiC and amorphous carbon, and the model results showed that a good fit was achieved for 10-16 wt.% of SiC, with the best fit for the composition with 12 wt.% SiC. Subsequently, Srinivasan et al. (2011) fixed the composition at 10 wt.% SiC and calculated a grid of radiative transfer models for varying physical parameters of the dust shell. This model grid, named GRAMS, is intended for use with photometric measurements of C-rich AGB stars, in order to determine the individual and overall dust production rate, while not aiming to fit variations in composition between individual sources.

A similar approach was taken by Sargent et al. (2010, 2011), who found that amorphous silicates provided a good fit to the IRS spectra of two typical O-rich AGB stars (Sargent et al., 2010), and constructed the oxygen-rich component to the GRAMS model grid by varying the dust shell parameters to represent the spectral energy distributions (SEDs) of the O-rich AGB stars (Sargent et al., 2011).

Riebel et al. (2012) applied the GRAMS model grid to the entire evolved star population in the LMC identified by Boyer et al. (2011) from the SAGE-LMC point source catalogue. They also included 12 extremely red point sources, described by Gruendl et al. (2008), which turn out to be C-rich AGB stars. These 12 sources were not identified by Boyer et al. (2011) as evolved stars, because they did not have IRAC-[3.6] or IRAC-[8.0] detections to allow for classification, and were only picked up in MIPS-[24]; or they were not identified as point sources by the SAGE-LMC team at all (Meixner et al., 2006), having only been extracted as such in the alternative pipeline developed by Gruendl & Chu (2009). Riebel et al. (2012) determine the dust production rate and chemistry of this sample of evolved stars by fitting the SED to the GRAMS model grid, and find that overall, in terms of chemistry the fit results agree well with the infrared color classification done by Boyer et al. (2011). The 12 extreme carbon stars from Gruendl et al. (2008) were also correctly classified as carbon stars. Moreover, Riebel et al. (2012) estimate the dust production to be predominantly carbon-rich, and it is dominated by the extreme AGB stars (~1300 sources; 74% of the total dust production rate), as defined by Blum et al. (2006) and Boyer et al. (2011). Within this class, the 12 sources described by Gruendl et al. (2008), not identified by Boyer et al. (2011), account for 29% of the total dust production rate in the LMC (D. Riebel, *priv. comm.*). Srinivasan et al. (*in prep.*) are preparing a similar study for the SMC.

In this context it should be noted that for amorphous carbon more than one set of optical constants exists and is in common use. The difference in mass-loss rate determined by using different sets of optical constants can be as large as a factor of four. Notably, the work by Groenewegen et al. (2009) finds higher mass-loss rates, inflating the contribution from (extreme) C-rich AGB stars even further.

4. FURTHER INSIGHTS IN THE DUST MINERALOGY FROM *SPITZER* IRS OBSERVATIONS

To determine the dust production rate by dust species using the GRAMS model grid is rather simplistic; it only uses the photometry to distinguish between O-rich and C-rich, and determine the dust mass loss rate. Within the O-rich and C-rich categories, only one composition has been modeled (pure amorphous silicates in the case of the O-rich dust, and 10 wt.% SiC / 90 wt.% amorphous carbon in the case of the C-rich case).

Infrared spectroscopy in the 5-38 μm wavelength range, obtained with *Spitzer*-IRS allows for a more detailed analysis of the mineralogical composition of the dust produced. The SAGE-Spec *Spitzer* legacy survey (Kemper et al., 2010) aims to do exactly that, in addition to a first goal which is to verify the photometric classification. Woods et al. (2011) have applied a decision tree to the ~200 point sources targeted in the LMC in the SAGE-Spec program, while the classification of all IRS targets in the LMC is currently underway (Woods et al. *in prep.*), as well as a classification effort of all IRS staring mode targets in the SMC (Ruffle et al. *in prep.*).

4.1. Carbon-Rich AGB Stars

Inspection of the IRS spectra of carbon stars in the Magellanic Clouds reveals two obvious solid state features, the SiC feature at 11 μm, and the so-called "30 μm" feature (Zijlstra et al., 2006; Lagadec et al., 2007). The "30 μm" feature is generally identified with MgS (Hony et al., 2002), and it only seems to occur in higher mass-loss rate objects (Lagadec et al., 2007). Its occurrence seems to coincide with a diminishing peak strength of the SiC feature, leading to the conclusion that the MgS is deposited *on top of* the SiC, thus weakening the SiC feature strength (Leisenring et al., 2008). Not all high mass loss rate stars show the "30 μm" feature, but for those stars that do, Groenewegen et al. (2009) derive a typical mass fraction of 6% of the total dust mass. However, the discovery of the SiC feature in absorption towards very red stars (Gruendl et al., 2008) suggests that rather than being coated by MgS, the diminishing of the SiC feature is due to an optical depth effect: the SiC feature appears in self-absorption, and then fully in absorption, as the total optical depth increases.

As for the "30 μm" feature, doubt has been cast on the identification with MgS (Zhang et al., 2009), and indeed Otsuka et al. (2014) demonstrate that it could be due to the same carrier as the underlying continuum. The continuum could be (partially) due to graphite, rather than amorphous carbon, and graphite has a resonance at approximately the right wavelength (Draine & Lee, 1984; Jiang et al., 2013). Thus, a separate dust component to explain the "30 μm" feature may no longer be needed.

Another feature seen in some Magellanic carbon-rich objects is the "21 μm" feature. An identification is still lacking (Volk et al., 2011).

4.2. *Oxygen-Rich AGB Stars*

Less work has been done on the O-rich AGB stars, after the initial study by Sargent et al. (2010), who established that typical O-rich AGB stars contain only amorphous silicates. Notable exceptions are the studies by Jones et al. (2012, 2014). In their first work, Jones et al. (2012) investigated the onset of crystallization of the silicates in AGB stars and red supergiants in the SMC, LMC and Milky Way, representing three different metallicities, and thus dust-to-gas ratios. The goal of this study was to establish whether the crystallization is due to annealing of amorphous silicates (in case the crystallization is correlated with dust mass loss rate), or whether crystalline silicates directly condense from the gas phase (in case the crystalline fraction is correlated with the gas mass loss rate). They showed that annealing is the most likely formation mechanism of crystalline silicates, but they also noticed that the fraction of crystalline silicates is low (of the order of 10%, in line with the results by Kemper et al. 2001).

Furthermore, Jones et al. (2014) have extended the GRAMS grid with an alumina (Al_2O_3) component, which is often seen in low-mass loss rate AGB stars. Jones et al. (2014) notice that the amount of alumina decreases with increasing mass-loss rate, to typical values of $\sim$20% at 10^{-6} M$_\odot$ yr^{-1}. It is therefore not a significant component in the dust injected into the ISM.

5. COMPARISON WITH INTERSTELLAR DUST

The observationally derived total dust production rate in the LMC by AGB stars is (2–4) $\times 10^{-5}$ M$_\odot$ yr^{-1} (Riebel et al., 2012; Kemper, 2013). This can be compared with the total dust reservoir in the interstellar medium of the LMC, $(7.3 \pm 1.7) \times 10^5$ M$_\odot$ (Skibba et al., 2012; Gordon et al., 2014), to derive a replenishment time scale of the order of 10^{10} year, comparable to the age of the LMC. So, in principle, AGB ejecta could build up a sufficient amount of dust to explain the interstellar dust reservoir. This observational conclusion is confirmed by Schneider et al. (2014), who use the LMC's star formation history (Harris & Zaritsky, 2009) and theoretical AGB dust yields to find that there is sufficient dust production over the history of the LMC to explain the present day dust reservoir.

However, the present day star formation rate in the LMC is around 0.38 M$_\odot$ yr^{-1} (e.g. Skibba et al., 2012), which, with an assumed dust-to-gas ratio of 1/200, yields a dust astration time scale of 10^8 years, much faster than the dust replenishment time scale estimated above. Furthermore, dust destruction by supernova shocks is also not taken into account in the comparison between AGB ejecta and interstellar dust masses above.

The composition of the dust injected into the ISM by AGB stars is $\sim$77% (amorphous) carbon; $\sim$11% SiC; $\sim$12% amorphous silicates, and $\lesssim$1% crystalline silicates and oxides (Kemper, 2013), assuming the "30 μm" feature is not due to MgS. Unfortunately, the composition of the ISM dust in the LMC is not well known, but since the interstellar extinction curve is very similar to that of the Milky Way (Gordon et al., 2003), we assume that the interstellar dust compositions are also very similar between those two galaxies. However, the composition of interstellar dust is dominated by amorphous silicates (Tielens et al., 2005), with amorphous carbon only a minor component ($\sim$20%), and SiC, oxides and crystalline silicates all around the 1% level or less. This difference in composition confirms that the majority of interstellar dust is not of AGB origin.

6. ADDITIONAL SOURCES OF DUST

Additional sources of dust are needed to explain the present day dust reservoir in the LMC, both in terms of composition, as it does not match the composition of the AGB ejecta, and in terms of amount, as dust destruction by supernova shocks and astration effectively removes dust from the ISM.

A number of possibilities suggest themselves. First, the dust production by AGB stars is dominated by a handful of the reddest objects (Riebel et al., 2012), but as the SED peaks at longer wavelengths, it is more difficult to detect it as a point source against the extended emission of interstellar dust (Boyer et al., 2010), due to confusion and spatial resolution issues. It may be necessary to use a high-resolution submm facility, such as ALMA, to detect such sources, but doing a dedicated search over the SAGE-LMC footprint will be prohibitively expensive. Second, supernovae could provide a reasonable source of interstellar dust (e.g. Matsuura et al., 2011), although supernovae are small in number. Kemper et al. (2011) show that the dust production rate by supernovae on a galactic scale is only important if the dust formation efficiency is comparable to that in AGB stars. Generally this is not expected to be the case. Finally, dust may form in the denser parts of the ISM directly (Jones, 2005; Zhukovska et al., 2008), but it is hard to conceive the formation of reasonably well-defined minerals at the very low temperatures prevalent in such environments.

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