Stellar dust production and composition in the Magellanic Clouds

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The dust reservoir in the interstellar medium of a galaxy is constantly being replenished by dust formed in the stellar winds of evolved stars. Due to their vicinity, nearby irregular dwarf galaxies the Magellanic Clouds provide an opportunity to obtain a global picture of the dust production in galaxies. The Small and Large Magellanic Clouds have been mapped with the *Spitzer* Space Telescope from 3.6 to 160 μm, and these wavelengths are especially suitable to study thermal dust emission. In addition, a large number of individual evolved stars have been targeted for 5–40 μm spectroscopy, revealing the mineralogy of these sources. Here I present an overview on the work done on determining the total dust production rate in the Large and Small Magellanic Clouds, as well as a first attempt at revealing the global composition of the freshly produced stardust.

Key words: Stars: AGB post-AGB stars, stars: mass loss, circumstellar matter, dust, Magellanic Clouds.

1. Introduction

Dust is a common ingredient of the interstellar medium (ISM) of galaxies. In the imaging obtained by optical observatories, such as the *Hubble Space Telescope*, dust manifests itself as dark lanes or patches that are obscuring the light from the stars. As such, dust was often seen as a nuisance, but with the advent of infrared astronomy, it has become obvious that the absorbed starlight is in fact re-emitted in the form of thermal emission from dust grains, thus altering the shape of galaxy spectral energy distributions (SEDs). The dust-to-gas ratio in the ISM of galaxies is usually $\lesssim$1% by mass for galaxies with Solar metallicities (e.g. Draine *et al.*, 2007), while typically about 30% of the energy emitted by such galaxies is in the form of thermal dust emission (e.g. Dale and Helou, 2002).

It is believed that dust in the interstellar medium is formed by generations of mass-losing evolved stars that gradually increase in metallicity with chemical galactic evolution (Morgan and Edmunds, 2003). Dust formation can occur in stars of all main-sequence masses, but the total dust budget is dominated by the more numerous Asymptotic Giant Branch (AGB) stars (with $M_{MS} < 8M_{\odot}$), although Red Supergiants (RSGs; originating from $M_{MS} > 8M_{\odot}$) are believed to be important contributors too, based on studies of stellar populations in the Solar neighbourhood (e.g., Whittet, 2003). AGB stars lose mass at a rate of 10^{-7}–10^{-6} $M_{\odot}$ yr^{-1}, and only for a short while, during the superwind phase, experience mass-loss rates of 10^{-4} $M_{\odot}$ yr^{-1} while RSGs can sustain mass loss at this high rate for longer (e.g. Habing and Olofsson, 2003; van Loon *et al.*, 2005).

2. The Magellanic Clouds

Due to our vantage point within the Milky Way, and the extinction in the Galactic plane it is not possible to obtain a full global picture of the dust production from evolved stars in our own Galaxy. Instead, a global picture may be obtained from nearby external galaxies, and the Magellanic Clouds are obvious candidates for such a study. The Large and Small Magellanic Clouds are irregular dwarf galaxies at a distance of 50 and 61 kpc respectively (Schaefer, 2008; Szewczyk *et al.*, 2009), and both are seen almost face-on, resulting in a low optical depth along the line-of-sight, and very little confusion and few chance superpositions. Unfortunately, due to their vicinity to the much more massive Milky Way Galaxy, both Magellanic Clouds are tidally disrupted. Their relatively low metallicities of $Z_{LMC} \sim 0.5\ Z_{\odot}$ (Dufour *et al.*, 1982) and $Z_{SMC} \sim 0.2\ Z_{\odot}$ (Bernard *et al.*, 2008) make the Magellanic Clouds analogues for Milky Way type galaxies at cosmic times of $\sim$2 and $\sim$0.7 Gyr after the formation of our own Milky Way (Naab and Ostriker, 2006). The nearest spiral galaxy M31 (Andromeda) is at 750 kpc significantly further away and to date, the Magellanic Clouds still provide the best compromise between distance and size to study the individual galaxy components, particularly stars.

3. Dust Factories

Thermal emission from dust, particularly warm ($\lesssim$1000 K) newly formed circumstellar dust, is most prominent in the near- and mid-infrared. Thus, surveying a galaxy in the infrared, and identifying the point sources, will give us a handle on the dust production by evolved stars. Such surveys have been done in the past (e.g. DENIS (Cioni *et al.*, 2000); MSX (Egan *et al.*, 2001)), but using IRAC (Fazio *et al.*, 2004) and MIPS (Rieke *et al.*, 2004), the first modern infrared surveys of the LMC (Meixner *et al.*, 2006) and SMC (Gordon *et al.*, 2011) have been done, cataloguing over 8 million and 2 million infrared

point sources in the LMC and SMC, respectively (Boyer *et al.*, 2011). The SAGE surveys can be supplemented with near-infrared surveys, such as 2MASS (Skrutskie *et al.*, 2006), the Vista Survey of Magellanic Clouds (VMC; Cioni *et al.*, 2011), or the AKARI survey of the LMC (Ita *et al.*, 2008).

3.1 Source classification

Blum *et al.* (2006) used the 2MASS data combined with the IRAC-[3.6] photometry to classify the dominant categories of dust producing evolved stars in the LMC. The first incarnation of the SAGE-LMC point source catalogue (Meixner *et al.*, 2006) contained about 4 million sources, of which ∼820,000 point sources have a J and [3.6] magnitude measurement, mostly consisting of Red Giant Branch (RGB) stars (∼650,000), which are not considered significant contributors of dust to the ISM. Only about 5% (∼43,000) of the sources with a reliable J and [3.6] magnitude are brighter than the tip of the RGB ([3.6] < 11.85) and thus potentially dust producing. These were subdivided using colour criteria, into carbon-rich AGB stars (∼7000), oxygen-rich AGB stars (∼18,000), (Red) Supergiants (∼1200) and *extreme* AGB stars (∼1200). Other, non-dust-producing sources identified include foreground (Galactic) and background (extragalactic) objects.

Recently, Boyer *et al.* (2011) extended this method of classification to the SMC by including the SAGE-SMC survey (Gordon *et al.*, 2011). They also revised the source counts for the LMC, using the most recent version of the SAGE-LMC point source catalogue, which now contains over 2 million sources with both J and [3.6] band magnitudes, due to improved extraction and calibration methods[1]. Nevertheless, the number of point sources brighter than the tip of the RGB has been revised upward by only ∼7% to 45,870, and the actual number of sources in each of the dust forming categories has changed at most by a similar percentage (see table 2 of Boyer *et al.*, 2011).

The classifications performed by Blum *et al.* (2006) and Boyer *et al.* (2011), but also those done by other teams (e.g. VMC; Cioni *et al.*, 2011) all work with sharply-defined colour and magnitude cuts to classify the point sources, while in reality the boundaries may not be that clear, and overlaps between the classes in colour-colour and colour-magnitude space may exist. Marengo and Sanchez (2009) have developed a more statistical approach to source classification using magnitudes and colours, based on a so-called *Nearest Neighbour* (k-NN) method. In this approach entries in a point source catalogue are assigned probabilities that they belong to a certain class of objects, based on their distance to, and the density (in colour-colour or colour-magnitude space) of a cloud of characteristic objects in that class. Thus, entries in the point source catalogue can have assigned probabilities to belonging to more than one object class, making this classification useful mostly in a statistical sense. The k-NN classification will be applied to all point sources in the SAGE-LMC and SAGE-SMC catalogues (Marengo *et al.*, in prep.).

3.2 Stellar dust production rates

From these classifications, it is possible to estimate the dust production per source category in the LMC. Srinivasan *et al.* (2009) focused on the carbon-rich, oxygen-rich and extreme AGB star classifications from Blum *et al.* (2006) and using the infrared excess measured at IRAC 8.0 and MIPS 24 μm found that the overall dust injection to the interstellar medium of the LMC is 2.74×10^{-5} $M_\odot$ yr^{-1}. The dust production is dominated by the category of extreme AGB stars, which are responsible for a dust production rate of 2.36×10^{-5} $M_\odot$ yr^{-1}, against 0.14 and 0.24×10^{-5} $M_\odot$ yr^{-1} for oxygen-rich and carbon-rich AGB stars respectively. An alternative estimate is presented by Matsuura *et al.* (2009) who used representative sources identified by their IRS (Houck *et al.*, 2004) spectra to carve out a classification scheme in the [8.0] vs. [3.6]−[8.0] colour-magnitude diagram, distinguishing between carbon-rich and oxygen-rich AGB stars. Using empirical mass-loss relations, they were able to estimate dust production rates of 4.3×10^{-5} $M_\odot$ yr^{-1} by carbon-rich AGB stars, and a lower limit of 4×10^{-6} $M_\odot$ yr^{-1} for the oxygen-rich AGB stars. RSGs were also included in their analysis and responsible for at least 2×10^{-6} $M_\odot$ yr^{-1} of dust production.

To estimate the dust injection in the SMC, the analysis performed by Srinivasan *et al.* (2009) for the LMC can be repeated. The colour cuts lead to the classification of almost 500,000 point sources in the SMC, with detections in J and [3.6]. Of these, ∼19,000 objects are brighter than the tip of the RGB. About 1700 stars are classified as carbon-rich AGB stars; about 4000 stars as oxygen-rich AGB stars, of which 227 as *bright* oxygen-rich AGB stars; a further 349 stars are *extreme* AGB stars; and around 3300 objects are thought to be RSGs. Thus, using the [8.0] and [24] μm excess, the overall dust production rate is thought to be an order of magnitude lower for the SMC, compared to the LMC (Boyer *et al.*, 2012).

An important potential source of dust is ignored for both the LMC and the SMC: the dust production by supernova. This contribution is harder to estimate due to the incidental occurrence of supernovae, and the difficulties in establishing the dust production per supernova. Recently, Matsuura *et al.* (2011) provided a measurement of the dust mass associated with SN 1987A in the LMC, of 0.4–0.7 $M_\odot$, implying that supernovae can indeed be important dust producers, and providing an important step forward in establishing the dust contribution due to supernovae in the ISM of galaxies in the local universe.

4. Mineralogy of Stardust

The mineralogical make-up of the freshly formed stellar dust can be derived from infrared spectroscopy, as many common dust species have spectral resonances in the mid-infrared, that can relatively easily be distinguished from each other.

Prior to *Spitzer*, a rare mineralogical analysis of dust produced by an LMC star was presented by Voors *et al.* (1999), who detected the presence of crystalline silicates in the luminous blue variable R71, observed with the Infrared Space Observatory (ISO; Kessler *et al.*, 1996), using the Short Wavelength Spectrometer (SWS; de Graauw *et al.*,

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[1]Both the SAGE-LMC and SAGE-SMC point source catalogues are available through the NASA/IPAC Infrared Science Archive http://irsa.ipac.caltech.edu/applications/Gator/.

1996). Trams *et al.* (1999) reported the presence of a silicate feature around a carbon-star in an observation with limited spectral range, but with a more extensive spectral range it was later shown that the 'emission feature' was really a lack of molecular absorption (Speck *et al.*, 2006). Further ISO studies focused on the 10 μm emission features in M-stars (Dijkstra *et al.*, 2005), showing the presence of alumina and amorphous silicates, with the fraction of silicates increasing as the star evolves to higher mass loss rates.

With *Spitzer* it became possible to obtain 5–40 μm spectroscopy of many point sources in the LMC and SMC. Indeed, many observing programs were proposed, some targeting just a single or a few point sources, while other PIs observed a few hundred point sources with the IRS instrument. At several points during and after the mission, overviews of the spectral inventory of point sources in the Magellanic Clouds were given (Kastner *et al.*, 2008; Sloan *et al.*, 2008; Buchanan *et al.*, 2009; Kemper *et al.*, 2010). In total ∼1000 point sources were observed in the LMC, and another ∼300 in the SMC, covering a wide range of colours and magnitudes, and thus physical environments. The spectroscopic information can help to test the photometric classification schemes discussed in Subsection 3.1. The 297 staring mode observations performed in the context of the SAGE-Spec program (Kemper *et al.*, 2010), were classified with the help of a decision tree (Woods *et al.*, 2011). The result of this classification was complementary to and in agreement with the analysis done by Buchanan *et al.* (2009) and Kastner *et al.* (2008). A full spectral classification of the IRS staring mode observations in the LMC (Woods *et al.*, in prep.) and SMC (Ruffle *et al.*, in prep.) is in preparation, the results of which will be used to test the *k*-NN photometric classification (Marengo *et al.*, in prep.).

4.1 Oxygen-rich stars

Silicates dominate the spectra of both RSGs and oxygen-rich AGB stars in the LMC. Dijkstra *et al.* (2005) studied a sample of M stars (of AGB and RSG origin) showing the 10 μm silicate feature in emission or self-absorption in the ISO spectroscopy, and found that, while the spectra all show amorphous silicates, some of them also show the spectral signature of Al_2O_3 (alumina). The relative strength of the alumina signature to the spectrum decreases with increasing mass-loss rate, suggestive of a covering of the alumina grains by silicate mantles. At the highest mass-loss rates, the spectra are entirely dominated by silicate features.

When the IRS spectra of two typical AGB stars in the LMC, one of low and one of high mass-loss rate, are fitted with the same dust composition (Sargent *et al.*, 2010), it is found that the best fit is produced by oxygen-deficient amorphous silicates (Ossenkopf *et al.*, 1992), although other amorphous silicate profiles give good results too.

Some oxygen-rich stars show the sharp spectral resonances due to crystalline silicates. In addition to the presence of crystalline forsterite (Mg_2SiO_4) around LBV R71 (Voors *et al.*, 1999), Zijlstra *et al.* (2006) showed that oxygen-rich AGB star IRAS 05003−6712 also contains crystalline forsterite and enstatite ($MgSiO_3$) in its circumstellar shell. Low mass-loss rate LMC AGB star HV 2310 also shows crystalline silicates, particularly around 11.2 μm, and the crystalline fraction of the silicates is around 7%

by mass (Sloan *et al.*, 2006a). A comprehensive study of all oxygen-rich AGB stars and RSG in the LMC and SMC for which IRS spectroscopy is available, shows that most objects do not show significant crystallinity in their silicates, although in some cases, the strength of the crystalline silicate features due to enstatite and forsterite at 23, 28 and 33 μm can be up to 10% above the continuum level (Jones *et al.*, in prep.). Given that at the wavelengths of the crystalline silicates resonances the intrinsic opacities of these crystalline silicates is much stronger than their amorphous counterparts, these measurements correspond to crystalline fractions of a few percent, at most. It needs to be emphasised however, that the lack of crystalline silicate features in the infrared spectrum does not mean that the crystalline silicates are absent; in particular in optically thin dust shells, they may simply be colder than the amorphous silicates (Kemper *et al.*, 2001). Thus, I conclude for the purposes of this paper, that oxygen-rich AGB stars and RSGs in the LMC and SMC predominantly produce silicates, of an unspecified composition, but that a small fraction of these silicates may actually be due to crystalline enstatite and forsterite at the ∼5% level by mass.

4.2 Carbon-rich stars

The mineralogy of carbon-rich AGB stars in the Magellanic Clouds has been the subject of several studies. Silicon carbide (SiC), amorphous or graphitic carbon (C) and, in some cases, a solid-state feature at 30 μm, previously thought to be due to magnesium sulfide (MgS; Hony *et al.*, 2002; Zhang *et al.*, 2009), are seen in the IRS spectra of carbon-rich AGB stars in the LMC (Zijlstra *et al.*, 2006) and the SMC (Sloan *et al.*, 2006b). The 30 μm feature is found to be present only in the redder, and hence colder, dust shells, where the dust temperature drops below 600 K (Zijlstra *et al.*, 2006). In the low metallicity environments of the LMC and the SMC the mass balance between SiC and C in carbon stars will differ from those found in Galactic carbon stars (e.g. Sloan *et al.*, 2006b), as the required carbon is produced by the star itself, but the silicon abundance reflects the composition of the natal cloud. Therefore, less silicon is available with lower metallicities. Indeed, Lagadec *et al.* (2007) confirmed that the SiC-feature-to-C-continuum ratio in the SMC is lower than in the LMC, but they also see an evolution with temperature ([6.4] − [9.3] colour) of the dust shells. While initially the SiC feature strength increases, with decreasing temperature, the SiC feature strength eventually drops. This is also seen by Leisenring *et al.* (2008), who study the strength of the 30 μm emission feature in the same sequence, and extend the sample to bluer colours, indicative of lower mass-loss rates, particularly for the Milky Way comparison sample. While Lagadec *et al.* (2007) argue that SiC condenses first, followed by the condensation of C on top of the SiC, Leisenring *et al.* (2008) show that it is not possible with the LMC or SMC data set to establish the condensation sequence for SiC and C. Both studies agree, however, that MgS condenses after SiC and C (Lagadec *et al.*, 2007; Leisenring *et al.*, 2008). Srinivasan *et al.* (2010) has determined the composition of the dust shell of a typical, albeit only one, C-rich AGB star, without the MgS emission feature at 30 μm, and finds that about 12% (in a range of 10–16%) of the dust by mass is contained in SiC, and that

Table 1. Dust production in the LMC by various types of evolved stars, along with the adopted mineralogy in each source category. The bottom row summarises the total dust production rate and the mineralogy of the stellar dust production for the LMC. Dust production rates are taken from Matsuura *et al.* (2009) and Srinivasan *et al.* (2009). The typical compositions are discussed in Section 4 of the main text.

Object type	Mineralogy (mass)	Dust production rate ($M_\odot$ yr^{-1})
O-rich AGB	95% am. sil.; 5% cryst. sil.	$0.14 - > 0.4 \times 10^{-5}$
C-rich AGB	88% am. carbon.; 12% SiC; var. % MgS	0.24×10^{-5}
extreme AGB	88% am. carbon; 12% SiC; var. % MgS	$2.36 - \lesssim 4.3 \times 10^{-5}$
RSG	95% am. sil.; 5% cryst. sil.	0.2×10^{-5}
Total	77% am. carbon; 11% SiC 12% am. sil.; <1% cryst. sil.; var. MgS	$(4 \pm 1) \times 10^{-5}$

the remainder is in the form of amorphous carbon.

The class of *extreme* AGB stars is shown by Gruendl *et al.* (2008) to be made up of carbon-rich objects. In their sample of 13 objects, the SiC feature is actually seen in absorption, due to the high optical depth. Only two of the objects studied show the MgS silicate feature, casting doubt on how common this dust component really is in more evolved AGB stars. The mass fractions taken up by SiC, C and possibly MgS in *extreme* AGB stars are not yet determined, but the subject of a future study (Speck *et al.*, in prep.), and for the purpose of this work I will assume they are similar to what is derived for lower mass-loss rate C-rich AGB stars by Srinivasan *et al.* (2010).

5. Results and Outlook

The dust production rates and typical mineralogies for the dust factories in the LMC are summarised in Table 1. With the analysis so far, it is possible to derive the mineralogy of the stellar dust production input into the ISM for the LMC. I find that the majority ($\sim$77%) of the freshly produced stardust is in the form of amorphous or possibly graphitic carbon. Roughly equal amounts of stardust are taken up by SiC ($\sim$11%) and amorphous silicates ($\sim$12%). Crystalline silicates, e.g. enstatite and forsterite, make up less than 1% of the dust production by evolved stars. An unspecified amount of MgS may also be produced by evolved stars. Apart from the fact that the 30 μm feature is only seen in a subset of all C-rich AGB stars, and therefore hard to include in the analysis of a typical spectrum, it is also difficult to determine the dust mass contained in MgS in radiative transfer calculations, because of the lack of optical and near-infrared optical constants of MgS (Hony *et al.*, 2002).

Another caveat is the absence of dust production by supernovae in Table 1. Although a reliable measurement of the dust mass associated with SN 1987A now exists (Matsuura *et al.*, 2011), it is difficult to assess what fraction of that dust is produced by the supernova, and what fraction is simply processed or heated interstellar dust. In addition, we need to know how typical this supernova is in terms of dust production, and what the overall supernova rate is for the LMC and the SMC, to establish the dust production by supernovae. Finally, the mineralogy of supernova dust is not well known, with the mineralogy of supernova ejecta determined by interpreting single spectral features (Arendt *et al.*, 1999; Rho *et al.*, 2009).

Within the SAGE collaboration, we will continue to improve on the numbers presented in Table 1, as establishing the integrated composition of freshly produced stardust is indeed one of the goals of the SAGE-Spec project (Kemper *et al.*, 2010). The typical compositions derived by Srinivasan *et al.* (2010) and Sargent *et al.* (2010) have been used to calculate a grid of SEDs, as a function of dust shell parameters (GRAMS; Srinivasan *et al.* (2011) and Sargent *et al.* (2011)). The SEDs in this grid will be fitted to the relevant photometric data in the SAGE-LMC catalogue, which will then allow us to update in particular the third column of Table 1, and calculate the total dust production accordingly.

In an alternative approach, the *k*-NN colour classification will allow for a statistical determination of the numbers in each source category (Marengo *et al.*, in prep.). Along with a more detailed study of the mineralogy of a range of objects within source categories (e.g. Jones *et al.*, in prep.; Speck *et al.*, in prep.), the overall mineralogy will be better established as well. This procedure will also be carried out for the SMC.

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