Variable Stars and the Asymptotic Giant Branch: Stellar Pulsations, Dust Production, and Mass Loss

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Abstract Low- and intermediate-mass stars (1–8 $M_{\odot}$; LIMS) are very important contributors of material to the interstellar medium (ISM), and yet the mechanisms by which this matter is expelled remain a mystery. In this paper we discuss how interferometry plays a role in studying the interplay between pulsation, mass loss, dust formation and evolution of these LIMS.

1. Introduction

1.1. The importance of cosmic dust

At the beginning of the Universe, all matter was in the form of hydrogen and helium: all elements heavier than helium form via nuclear fusion in stars. Newly-formed elements are ejected from stars either explosively (in the case of supernovae) or more gently over a few hundred thousand years for lower-mass stars like the Sun. These new elements then become part of the interstellar medium (ISM), from which new stars and their planets form.

With the emergence of infrared (IR) astronomy in the late 1960s, the importance of dust particles in the Universe began to be revealed. Dust is a vital ingredient in many astrophysical environments (Videen and Kocifaj 2002; Draine 2003; Krishna Swamy 2005). It plays an essential role in star formation processes, and contributes to several aspects of interstellar processes such as gas heating and molecule formation (Krügel 2008). In addition, since mass loss from evolved stars is driven by radiation pressure on dust grains, it is intimately linked to the precise nature of the circumstellar dust (Woitke 2006). Furthermore, dust has been observed at higher redshifts than expected, and understanding this phenomenon is vital to our understanding of the cosmos at large and its evolution (Sloan *et al.* 2009; Bussmann *et al.* 2009). Moreover, the detection of dust at high redshift raises concerns about the use of standard candles (for example, Type Ia Supernovae) as accurate distance indicators (Jain and Ralston 2006). Understanding the dust at high redshift is vital to cosmological models and dark energy studies (Corasaniti 2006; Jain and Ralston 2006). Dust needs to be well understood in its own right, if we are to understand how it contributes to many aspects of astrophysics.

1.2. Low- and intermediate-mass stars (LIMS)

The type of stars that produce the majority of the dust complement for the Galaxy start their lives as low- and intermediate-mass stars (0.8–8$M_\odot$; LIMS). Up to 95% of stars are LIMS (Kwok 2004). Studying the nature of dust around LIMS is important for three reasons: (1) this is where the dust originates, and thus knowing its initial state will allow us to predict more accurately its fate in and effect on the ISM and beyond; (2) the environment around most of these LIMS is relatively benign (little UV) and thus has simplified chemistry, which aids in our attempts to understand the processes in play and test current hypotheses of dust formation (which are also applied to many, more complex astrophysical environments); and (3) the evolution of LIMS is intimately linked to their dust production, and thus a feedback loop exists between dust production and stellar evolution. The precise nature of the dust grains must be assessed in order to understand this evolution. Since LIMS are major contributors of new elements to the ISM from which the next generation of stars and planets form, understanding their contribution to the ISM is crucial to our understanding of Galactic and Universal chemical evolution. In fact, mass loss is the main reason that LIMS do not explode as supernovae. We cannot understand mass loss fully until we understand the physical nature of the dust. As will be discussed below, interferometric techniques can provide data on evolved LIMS that are essential to understanding dust formation.

2. Stellar evolution

LIMS eventually evolve off the main-sequence to the red giant branch and subsequently become asymptotic giant branch (AGB) stars, ending their lives as cooling white dwarfs. Between the AGB phase and the white dwarf phase some of these stars may become planetary nebulae (PNe) as the previous AGB mass loss is illuminated by the shrinking, heating central core. However, precisely which AGB stars go through the PNe phase is not clear (see, for example, Sahai *et al.* 2010, and references therein).

2.1. Asymptotic giant branch stars

As LIMS evolve they become asymptotic giant branch (Iben and Renzini 1983) stars: luminous ($L_\star \approx 10^4 L_\odot$), cool ($T_{eff} \approx 3000$ K) giants ($R_\star \approx 1$ AU), which lose mass at high rates (10^{-7} to a few times $10^{-4} M_\odot$/yr). AGB stars pulsate due to dynamical instabilities, leading to intensive mass loss and the formation of a circumstellar shell of gas. Pulsations levitate atmospheric material, allowing it to achieve an altitude where temperatures permit molecules to form, followed by the formation of small particles (dust grains). The dust grains tap into the tremendous luminosity power of the star and drive a radiation-pressured wind (see, for example, Höfner and Dorfi 1997), leading to a circumstellar outflow of dust and gas. This outflow (wind) causes AGB stars to lose mass at such

tremendous rates that they wither into white dwarfs rather than explode as supernovae. Generally, the mass-loss rate, $\dot{M}$, increases over time as an AGB star evolves, and ends in an episode of extremely high mass loss, the superwind (SW) phase (Iben and Renzini 1983; Bowen 1988; Bowen and Willson 1991; Blöcker and Schönberner 1991; Vassiliadis and Wood 1993; Willson 2000). During the SW phase $\dot{M}$ exceeds $10^{-5}\,M_{\odot}/yr^{-1}$. Continued AGB star mass loss causes the dust shell to increase in depth both optically and geometrically as mass-loss rate increases, shown schematically in Figure 1. As these stars approach the SW phase they become invisible at optical wavelengths and very IR-bright. During this SW stage, intense mass loss depletes the remaining hydrogen in the star's outer envelope, and terminates the AGB phase. The rapid depletion of material from the outer envelope of the star means that while AGB mass loss may last for > 10^5 yrs, this extremely high mass-loss SW phase must have a relatively short duration (a few × 10^4 years; Volk *et al.* 2000).

During their ascent of the AGB, these stars also evolve chemically, starting with oxygen-rich atmospheres. Helium burning forms ^{12}C, which is dredged up to the stellar surface by strong convection currents in the mantle. Thus, carbon is injected into the stellar atmosphere. The stability of the CO molecule in the stellar atmosphere means that the carbon-to-oxygen ratio (C/O) controls the chemistry around the star: whichever element is less abundant will be entirely locked into CO molecules, leaving the more abundant element to control dust formation. Therefore, AGB stars can be either oxygen-rich or carbon-rich. For the O-rich AGB stars C/O can vary from approximately cosmic C/O ≈ 0.4) to just less than unity. Once C/O is greater than unity these stars become C-rich. Other nuclear processes (for example, the *s-process*) also occur in the He- and H-burning shells of AGB stars and thus other new elements are also dredged up and enrich the dust formation region. For a more detailed description of AGB stars we refer to Habing (1996) and Habing and Olofsson (2004).

2.2. Post-AGB stars

Once the AGB star has exhausted its outer envelope, the AGB phase ends. At this stage the mass loss virtually stops, and the circumstellar gas and dust shell begin to drift away from the star. At the same time, the central star begins to shrink and heat up from ~3000 K until it is hot enough to ionize the surrounding gas, at which point the object becomes a planetary nebula (PN). The short-lived post-AGB phase, as the star evolves toward to the PN phase, is also known as the proto- or pre-planetary nebula (PPN) phase. However, not all post-AGB stars will become PNe; for some post-AGB objects the expansion speed of the circumstellar shell, combined with its density, will preclude a visible nebula of ionized gas. (Indeed, the term pre-PN was adopted to replace proto-PN to reflect the idea that not all PPNe will end up as PNe.)

As the detached dust shell drifts away from the central star, the dust cools, causing a PPN to have cool IR colors. Meanwhile, the dust shell spreads out,

becoming less dense and optically thinner, leading to changes in its spectral characteristics that may also be related to an evolution in the intrinsic nature of the dust grains (that is, composition, crystal structure, grain size, and grain shape, not just optical depth and temperature). This structural evolution of the dust shell is illustrated schematically in the upper panel of Figure 1. This post-AGB evolution of the circumstellar envelope changes its appearance, revealing features that were hidden during the AGB phase.

The geometry of the dust shell also changes. Whereas observations suggest that the AGB phase has mostly spherically-symmetric mass loss, there is clearly a deviation from spherical symmetry somewhere in the evolution of these stars and their mass loss, since PNe are rarely spherical. It has been suggested that mass loss can explain the structural changes alone (Dijkstra and Speck 2006). By studying the distribution of matter in these AGB and post-AGB circumstellar shells we can gain a better understanding of the mass-loss processes involved in the evolution of these stars and test hypotheses for the effect of dust. However, the observations needed require high angular resolution, and thus interferometric techniques are vital to these studies.

3. Astromineralogy

Astromineralogy is the study of the precise nature (that is, the composition, crystal structure, size, and shape) of dust grains in space. This field has developed rapidly over the last decade or so (see reviews in Speck *et al.* 1997; Speck 1998; Speck *et al.* 2000; Molster 2000; Waters and Molster 1999; Henning 2003; Kwok 2004; Pitman *et al.* 2010; Guha Niyogi *et al.* 2011a, and references therein).

The major factors that determine the astromineralogy of dust grains are the chemistry, density, and temperature of the gas from which the dust forms. The chemistry determines the type of atoms available to form dust particles, whereas the density determines how likely these atoms are to come into contact and make dust particles. The temperature determines which solid state materials will be stable. For AGB stars the chemistry and density of the dust-forming region are in turn determined by the nature of the central star, including its metallicity and its initial mass, and by the evolution of the star. Stellar changes may lead to a transformation in the nature of the dust that is produced, which may in turn influence stellar evolution, indicating a feedback relationship between the changes in the star and dust formation in its circumstellar envelope. For instance, if mass loss is radiation-driven, the opacity of the dust grains affects the force of the radiation and thus mass-loss rate. Opacity is determined by the astromineralogy of the dust grains. Therefore, the nature of the dust grains affects mass-loss rates (and changes therein) which, in turn, affects stellar evolution. Stellar evolution cannot be fully understood until we determine the nature of the dust in the circumstellar region.

Typically, astromineralogy is studied by means of IR spectroscopy; dust in a circumstellar envelope absorbs visible light from the central star and re-radiates it at IR wavelengths. Dust particles of a given size, shape, temperature, structure, and composition have their own signature IR spectra. We can thus use the IR spectra of candidate dust species studied in the laboratory to identify IR spectral features observed in astronomical environments. However, many astromineralogical studies have yielded contradictory results. For instance, a spectral feature at ~13μm has been attributed to a variety of minerals including corundum, spinel, and silica (see Sloan *et al.* 2003, and references therein) and its true identity remains a mystery. The shapes and positions of the spectral features have sometimes been used to make attributions without thorough consideration of the nature of the dust-forming environments in which they occur (see, for example, Zhang *et al.* 2008). There are other constraints or lines of evidence that can be used to aid our studies of dust in space, including spatial distributions of materials, theoretical models for dust formation and evidence from meteoritic studies of presolar grains (see section 4).

4. Dust Formation

4.1. Competing dust formation mechanisms

There are effectively three competing dust formation mechanisms for circumstellar environments: (i) thermodynamic equilibrium condensation (see, for example, Lodders and Fegley 1999); (ii) formation of chaotic solids in a supersaturated gas followed by annealing (see, for example, Stencel *et al.* 1990); (iii) formation of seed nuclei in a supersaturated gas, followed by mantle growth (see, for example, Gail and Sedlmayr 1999). The latter should follow thermodynamic equilibrium as long as density is high enough for gas-grain reactions to occur.

Several observational studies support the thermodynamic condensation sequence (see, for example, Dijkstra *et al.* 2005; Blommaert *et al.* 2007), which is consistent with both (i) and (iii). In mechanism (ii), chaotic grains form with the bulk composition of the gas, and then anneal if the temperature is high enough (Stencel *et al.* 1990). This mechanism predicts that at low C/O ratios, the dust grains would comprise a mixture of olivine, pyroxene, and silica, rather than be dominated by olivine alone. At high C/O ratios, Al-O bonds are predicted to form preferentially, leading to dust dominated by oxides rather than silicates. These predictions are inconsistent with observations (Dijkstra *et al.* 2005; Blommaert *et al.* 2007).

If we assume that dust formation follows either (i) or (iii) we expect to see a condensation sequence shown schematically in the left panel of Figure 2.

4.2. P-T space in the condensation zone around AGB stars

The composition of AGB star dust depends upon pressure and temperature

(P-T) in the dust-formation zone around the star. The precise astrominerals that can form depend on various parameters, most notably C/O ratio and gas pressure (Lodders and Fegley 1999; Gail and Sedlmayr 1999). Gas pressure is a measure of the mass-loss rate ($\dot{M}$) convolved with the photospheric temperature ($T_\star$) and outflow velocity (v_{exp}). Detailed calculations of the outflow structure (and its temporal variations) require the stellar temperature, radius, and luminosity. These can be provided using interferometric methods.

Applying the method from Speck *et al.* (2008, 2009) we can estimate the P–T space around a mass-losing star and compare with theoretical models for dust compositions forming under various P–T conditions. For a star with a mass-loss rate $\dot{M}$ and an expansion velocity of v_{exp}, the density ρ of the circumstellar shell at a radius *r* is given by:

$$\rho = \frac{\dot{M}}{4\pi r^2 v_{exp}} \tag{1}$$

If we know the temperature and luminosity of the star and the composition of the outflowing material we can combine this information with the Ideal Gas Law and a $T(r) \propto 1/\sqrt{r}$ temperature distribution to determine the gas pressure at the condensation radius, which is the distance from the star where the gas has the condensation temperature.

For simplicity, the solid and gas phases are assumed to be at the same temperature. While this is clearly a simplification (Chigai and Yamamoto 2003), the temperature difference is small compared to the difference needed to significantly affect dust formation. We assume that most of the outflowing material is atomic hydrogen. In fact it will probably be a mixture of atomic and molecular hydrogen (H_2) since H_2 forms around 2000 K and the temperature in the outflow is decreasing from the stellar surface temperature of ~3000 K to the dust condensation temperature in the 1000–1800 K range. An entirely molecular hydrogen gas would halve the gas pressure compared to the the atomic gas. However, we also assume an outflow velocity of 10 km/s, which reflects the speed of the outflowing material after radiation pressure acceleration. Adopting the pre-dust-formation outflow speed ($\lesssim$5km/s) would increase the pressure. Thus we can estimate where dust condensation zones fall in P–T space as a function of mass-loss rate, as shown in Figure 3. For C-rich environments we expect to form carbon before SiC in most cases, but the order is sensitve to mass-loss rate, C/O ratio, and metallicity (Speck *et al.* 2006). For O-rich environments, the condensation sequence is essentially the classic condensation sequence and is similar to that shown schematically in the left panel of Figure 2.

4.3. Presolar grains

The isotopic compositions of certain grains found in primitive meteorites indicate that they originated outside the solar system and are thus dubbed

"presolar". The majority (~99%) of the "presolar" dust grains emanated from AGB stars based on their isotopic compositions and the nuclear processes expected to occur in those stars. Presolar grains demonstrate that the AGB dust grains become part of the next generation of stars and planets (Clayton and Nittler 2004, and references therein). This also means that we have real samples of the circumstellar dust that we can observe spectroscopically around evolved stars. The precise physical characteristics of these meteoritic dust grains (for example, sizes, crystal structures, and compositions) can be used to help constrain the nature of the dust we see in our astronomical observations.

Silicon carbide was the first presolar grain to be found in meteorites (Bernatowicz *et al.* 1987) and remains the best studied (see Bernatowicz *et al.* 2006, and reference therein). Other carbon-rich grains, such as graphitic onions and seed-core grains of various refractory carbides, have also been well studied (see Bernatowicz *et al.* 2006, and reference therein). Presolar examples of refractory oxides, spinel and alumina, have been found in meteorites. Detailed studies of the nature of these grains (especially crystal structure) are in their infancy, but can be used to constrain candidates for the 13μm feature. For example, Stroud *et al.* (2004) have analyzed the crystal structure of two presolar alumina grains and found that one is indeed a crystalline form (corundum), while the other is amorphous. Many astronomical studies have falsely assumed that the use of the word "corundum" in the meteoritics literature refers to this particular crystal structure, when it actually refers only to the composition of the presolar grains.

Isolating the C-rich grains can be achieved chemically, whereas presolar silicates can not be separated chemically from their terrestrial/solar system brethren. However, *in situ* techniques have been developed which led to the discovery and analysis of presolar silicate grains. Recent work on these presolar silicate grains suggests that there is more iron in silicate grains around AGB stars than our current models allow (see, for example, Stroud *et al.* 2008; Bose *et al.* 2010).

5. Astronomical observations of AGB circumstellar dust

For carbon stars the dominant dust formed is amorphous or graphitic carbon which does not have diagnostic spectral features, merely contributing to the IR continuum. SiC exhibits a spectral feature at ~ 11.3μm which has been used extensively to diagnose the physical parameters of carbon star dust shells (see reviews in Speck *et al.* 2005, 2009; Thompson *et al.* 2006).

The spectra of O-rich AGB stars exhibit a diverse range of IR dust spectral features. The spectra of AGB stars are generally classified according to the gross shape of the silicate emission feature at ~10μm. Various attempts have been made to classify these mid-IR features according to their shapes and positions, which reflects a progression from a broad feature to the classic narrow 10μm

silicate feature (see, for example, Little-Marenin *et al.* 1990; Sloan and Price 1995; Speck *et al.* 2000; Sloan *et al.* 2003; see Figure 4). This progression of the spectral features can be interpreted in terms of a dust condensation sequence (see, for example, Grossman 1972; Tielens 1990; shown schematically in Figure 2) and expected to represent evolution of the dust from the early forming refractory amorphous oxides to the dominance of amorphous silicates (the classic 10μm feature; see SE 8 in Figure 4).

The most recent version of this IR spectral classification scheme divides the observed AGB spectra into eight groups based on the silicate emission (SE) feature from SE1 to SE8 (Sloan and Price 1995; Sloan *et al.* 2003). Classes SE1–SE3 are expected to correspond to low-contrast alumina-rich amorphous dust seen in evolved stars losing mass at low rates and have optically thinner shells. Moving up the sequence, classes SE3–SE6 show structured silicate emission, with features at 10 and 11μm. The upper end of the silicate dust sequences (SE6–SE8) consist of sources with the classic silicate emission feature believed to be produced by amorphous silicate grains. These sources have optically thicker shells and higher mass-loss rates than sources at the other end of the sequence. However, recent findings (for example, Pitman *et al.* 2010; Guha Niyogi *et al.* 2011a) show the evidence for Fe-rich crystalline silicates on some of the stars from SE1 class (for example, T Cep, RX Lac, T Cet), which calls the classic dust condensation sequence into question. The new condensation sequence is shown schematically in the right panel of Figure 2. These empirical observational results cannot easily be reconciled with the classic conception of dust formation as shown in the left panel of Figure 2. In order to understand these new findings we need interferometry measurements of closeby AGB stars to provide stellar radii for input into models of dust formation. In particular the variations in dust formation as a result of stellar pulsation require precise information on how the stars change in radius, temperature, and luminosity with time.

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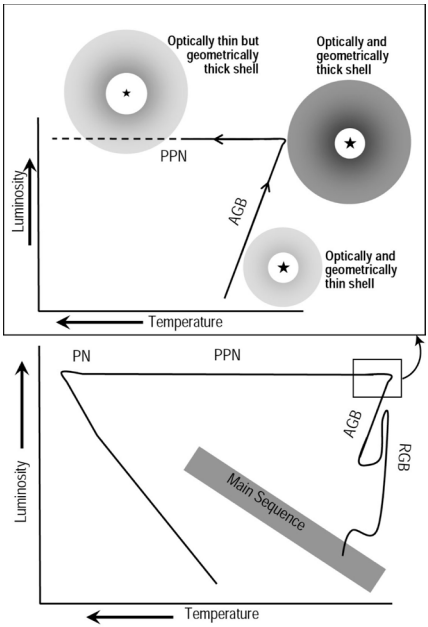

Figure 1. Schematic H-R diagram showing post-main-sequence evolution of LIMS. RGB = Red Giant Branch; AGB = Asymptotic Giant Branch; PPN = pre- or proto-planetary nebula; PN = planetary nebula; *upper panel* shows close up on AGB and PPNe phases and cartoons the changes in dust shell densities.

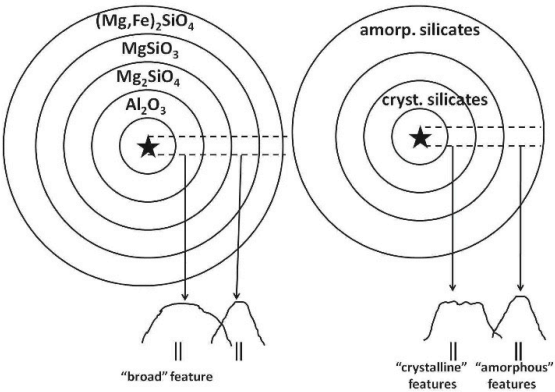

Figure 2. Schematic structure of dust shells. *Left*: Classic condensation sequence from, for example, Grossman (1972), Tielens (1990); see also thermodynamic equilibrium sequence in Figure 3; *Right*: New sequence suggested by the study of low mass-loss rate stars (for example, T Cep) as shown in Guha Niyogi *et al.* (2011a, 2011b) and Guha Niyogi (2011).

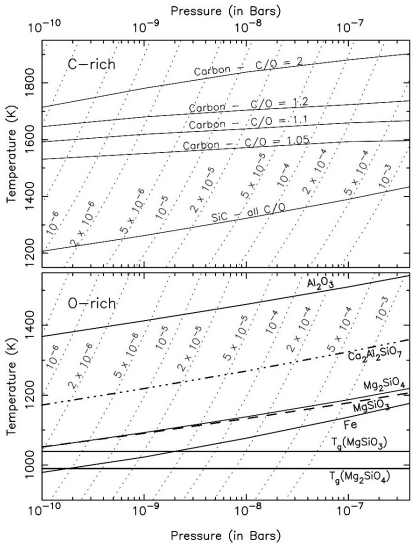

Figure 3. Pressure-temperature space in dust-condensation zone around AGB stars. *Top panel* is for C-rich stars; *bottom panel* is for O-rich stars. *x*-axis is outflow gas pressure in bars, *y*-axis is outflow gas temperature in Kelvin. Solid and dashed lines indicate T_{dust} for a given pressure from thermodynamic equilibrium calculations (relevant compositions are labeled; from Lodders and Fegley 1995, 1999). For all $\dot{M}$ values, Al_2O_3 forms at a significantly higher temperature than the silicates, and thus can form a seed nucleus. Light grey dotted lines indicate the P–T paths for the outflowing gas for a range of $\dot{M}$ (indicated in $M_\odot$/yr) as calculated from equation 1 and described in the text. Thick dark grey horizontal lines indicate glass transition temperatures (T_g) for Mg_2SiO_4 and $MgSiO_3$.

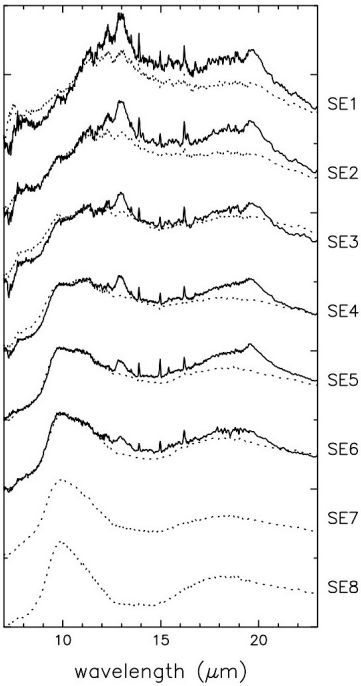

Figure 4. Continuum-subtracted ISO SWS spectra of O-rich AGB stars. Spectra are divided into classes according to the shape/strength of their silicate feature (designated by SE#, where #=1 to 8; SE8 has the strongest classic silicate feature, SE1, the weakest). Solid lines: spectra which exhibit the 13μm feature. Dotted lines: spectra which do not exhibit a 13μm feature. From data presented in Sloan *et al.* (2003).