THE COSMIC CRYSTALLINITY CONUNDRUM: CLUES FROM IRAS 17495−2534

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ABSTRACT

Since their discovery, cosmic crystalline silicates have presented several challenges to understanding dust formation and evolution. The mid-infrared spectrum of IRAS 17495−2534, a highly obscured oxygen-rich asymptotic giant branch (AGB) star, is the only source observed to date which exhibits a clear crystalline silicate absorption feature. This provides an unprecedented opportunity to test competing hypotheses for dust formation. Observed spectral features suggest that both amorphous and crystalline dust is dominated by forsterite (Mg₂SiO₄) rather than enstatite (MgSiO₃) or other silicate compositions. We confirm that high mass-loss rates should produce more crystalline material, and show why this should be dominated by forsterite. The presence of Mg₃SiO₄ glass suggests that another factor (possibly C/O) is critical in determining astromineralogy. Correlation between crystallinity, mass-loss rate, and initial stellar mass suggests that only the most massive AGB stars contribute significant quantities of crystalline material to the interstellar medium, resolving the conundrum of its low crystallinity.

Subject headings: circumstellar matter — dust, extinction — infrared: stars — stars: AGB and post-AGB —

1. INTRODUCTION

One of the most exciting recent developments in astronomy was the discovery of crystalline silicate stardust by the Infrared Space Observatory (ISO; de Graauw et al. 1996). Crystalline silicates were initially discovered around evolved intermediate mass stars at far-infrared (IR) wavelengths (Waters et al. 1996), but have since been detected in young stellar objects (Waelkens et al. 1996), comets (Crovisier et al. 1996), and ultraluminous infrared galaxies (Spoon et al. 2006). In the interstellar medium (ISM) silicate grains in crystalline form are rare (~1% crystalline by mass; Min et al. 2007; Kemper et al. 2004). However, asymptotic giant branch (AGB) stars and their successors (pre-planetary and planetary nebulae) are the major contributors of material to the ISM (Kwok 2004). It has been suggested that AGB stars could contain ~10% crystalline silicates (Kemper et al. 2004), so it is vital to understand the formation of dust around AGB stars to resolve this apparent discrepancy.

AGB stars are luminous cool giants, with high mass-loss rates ($10^{-7} M_\odot$ yr$^{-1} < M < 10^{-3} M_\odot$ yr$^{-1}$), which increase over time (van Loon et al. 2005). They are highly evolved descendants of low- to intermediate-mass ($0.8−8 M_\odot$) stars. Mass loss produces a circumstellar envelope, where dust forms. The order in which different species condense from the outflowing gas depends on the physical conditions within the envelope. Once $M$ is very high the circumstellar shell becomes optically thick, even at IR wavelengths, and the silicate emission features absorb themselves. The dust mineralogy is dictated by the dust condensation sequence and depends strongly on $M$ (Dijkstra et al. 2005). Blommaert et al. (2007) showed that the mineralogy depends only on the age of the star for a given initial stellar mass.

To date, crystalline silicate features have been seen clearly only in emission. It has been proposed that crystalline silicate absorption at 11 μm contributes to the broadening of the classic 10 μm amorphous silicate absorption feature associated with OH/IR stars (Sylvester et al. 1999; Vanhullebeke 2007). However, IRAS 17495−2534 (hereafter I17495) is the first object to show a distinct crystalline 11 μm absorption feature.

I17495 is located in the Galactic plane (Gal. coord. = 003.6844+00.3880) at a distance of ~4 kpc (Loup et al. 1993), about half way to the Galactic center. The IRAS LRS spectrum clearly exhibits an 11.1 μm absorption feature superposed on the classic 10 μm amorphous silicate feature (Fig. 1). This is the first clear crystalline silicate absorption feature seen to date in any object.

$M$ for this object is estimated to be $\sim 2 \times 10^{-4} M_\odot$ yr$^{-1} < M < 5 \times 10^{-4} M_\odot$ yr$^{-1}$ based on mid-IR ([25] − [12]) color (Loup et al. 1993) and the range of optical depths ($15 < \tau_{10\mu m} < 45$) consistent with our model results (see § 3). Both $M$ and expansion velocity ($v_{exp} = 16$ km s$^{-1}$; Loup et al. 1993) are at the high end of normal for AGB stars. Most extreme O-rich AGB stars are OH/IR stars, exhibiting OH-maser emission. I17495 is one of a handful of visibly obscured O-rich AGB stars not exhibiting OH-maser emission (dubbed color mimics; Lewis 1994). However, the spectra of other color mimics more closely resemble those of OH/IR stars; i.e., when observed, the putative 11 μm crystalline silicate feature is merely a hump superposed on the regular amorphous silicate absorption feature. This is also true for OH/IR stars with similar mass-loss rates in the Galactic bulge (GB). Even the GB source with the highest $M$ ($3 \times 10^{-4} M_\odot$ yr$^{-1}$; IRAS 17276−2846; Vanhullebeke 2007) shows the 11 μm feature as a hump, rather than the distinct 11 μm feature seen in Figure 1.

While forsterite (crystalline Mg₂SiO₄) is expected to have a peak near 11.3 μm (e.g., Koike et al. 2003), the peak can shift to shorter wavelengths. In the laboratory, Jäger et al. (1998) found that synthetic forsterite peaks closer to 11.2 μm, and matches the position of the hump observed in GB OH/IR stars (Vanhullebeke 2007). Fabian et al. (2001) investigated grain shape effects. Their mass absorption coefficients for ellipsoidal forsterite grains are included in Figure 1, and demonstrate that the crystalline forsterite feature can peak at 11.1 μm. Boersma et al. (2008) attributed an 11.1 μm emission feature in the spectrum of a Herbig Ae/Be star to forsterite. Tamanai et al. (2006) found that, for non-embedded free-flying particles of forsterite, the feature actually peaks at 11.06 μm. Composition,
forming below will be amorphous, while grains forming
diagnostic infrared features of crystalline grains can remain
requires such conditions (e.g., Cami et al. 1998). However, the
talline silicates should be more common in high N stars and
with very high T, leading to the inference that crystal formation
for annealing and crystallization. This suggests that crys-
taline MgSiO₃ should be more common in high N stars and
(see § 4).

2. CRYSTALLINITY AND MASS-LOSS RATES

Crystalline silicates were first observed around evolved stars
with very high N, leading to the inference that crystal formation
requires such conditions (e.g., Cami et al. 1998). However, the
diagnostic infrared features of crystalline grains can remain
hidden by the strong amorphous silicate features until M \( \approx 10^{-3} \) M\(_{\odot}\) yr\(^{-1}\) (Kemper et al. 2001).

Dust condensation temperatures (T\(_{\text{dust}}\)) are depressed at low
gas pressures (Lodders & Fegley 1999; Gail & Sedlmayr 1999).
Figure 2 shows the calculated pressure-temperature (P-T) con-
ditions in the dust-forming zone around O-rich AGB stars (see
Dijkstra et al. 2005 for method), compared to thermodynamic
equilibrium dust condensation models (Lodders & Fegley
1999), and the glass-transition temperatures (T\(_{\text{g}}\)) for MgSiO₃
(Richet et al. 1993) and MgSiO₃ (Wilding et al. 2004). Grains
forming below T\(_{\text{g}}\) will be amorphous, while grains forming
much above this temperature should crystallize rapidly (Sogawa & Kosasa 1999). In addition, for stars with \( M \gtrsim 10^{-5} \) M\(_{\odot}\) yr\(^{-1}\)
forsterite forms at a higher temperature than enstatite (crys-
talline MgSiO₃), and the difference in T\(_{\text{dust}}\) for these two species
increases with M (see § 4).

3. RADIATIVE TRANSFER MODELING

We used the 1D radiative transfer (RT) program DUSTY
(Ivezić & Elitzur 1995), to determine the gross mineralogy
associated with the mid-IR absorption features. RT modeling
is inherently degenerate (Ivezić & Elitzur 1997) and hence
models are not unique. Consequently, we use the modeling
only to constrain \( n_{\text{dust}} \), and to determine which minerals are
inconsistent with the observed spectral features. A detailed
analysis of the model results will be presented elsewhere.

At pressures relevant to I17495, T\(_{\text{dust}}\) \approx 1200 K for MgSiO₃
and MgSiO₃. Models with T\(_{\text{dust}}\) < 800 K could not match the
observations because the near-IR becomes too bright, and in
the mid-IR the spectrum slopes the wrong way. One important
result of the modeling is that pyroxenes can be excluded from
the mineralogy in I17495. The underlying amorphous silicate
feature is unusually narrow and peaks closer to 10 μm rather
than 9.7 μm, consistent with MgSiO₃ glass (Ossenkopf et al.
1992 and references therein). Models incorporating amorphous
silicate of pyroxene composition (e.g., Jäger et al. 1994) or
other more silica-rich compositions (e.g., Ossenkopf et al.
1992) are inconsistent with the observed spectrum, as the peak
position of the feature gets too blue, and the FWHM gets too
wide. Increasing the iron content in olivine has a similar effect
on the peak position (Ossenkopf et al. 1992). Our models sug-
gest that the crystalline component is also dominated by for-
sterite with enstatite and other crystalline compositions limited
to less than a few percent of the dust mass. Therefore, both
amorphous and crystalline dust is dominated by MgSiO₃. This
observed forsteritic mineralogy needs to be understood in terms
of dust formation mechanisms.
4. COMPETING DUST FORMATION MECHANISMS

There are effectively three competing dust formation mechanisms for circumstellar environments: (1) thermodynamic equilibrium condensation (Lodders & Fegley 1999); (2) formation of chaotic solids in a supersaturated gas followed by annealing (Stencel et al. 1990); (3) formation of seed nuclei in a supersaturated gas, followed by mantle growth (Gail & 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 (Dijkstra et al. 2005; Blommaert et al. 2007), which is consistent with both mechanisms 1 and 3. In 2, 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).

In the seed-mantle model, Mg$_2$SiO$_4$ is expected to use more refractory condensates as nucleation centers (e.g., Al$_2$O$_3$; see Fig. 2). Whether the transformation into Mg$_2$SiO$_4$ by gas-grain reaction occurs is then dependent on gas density. Condensation and annealing experiments show that the resulting dust is dominated by forsterite; enstatite is present only in trace amounts (e.g., Day & Donn 1978; Nuth & Donn 1982; Hallenbeck et al. 1998). In laboratory experiments, the density is always high compared to circumstellar shells, so they may only be relevant to the highest $M$.

The modeled mineralogy is consistent with an abrupt decrease in density between the formation temperatures for forsterite and enstatite. Once $\sim$20% of the Si atoms are incorporated into dust, the opacity is such that radiation pressure accelerates the circumstellar material, resulting in a precipitous density decrease, and inhibiting further gas-grain reactions (Gail & Sedlmayr 1999). At high $M$, forsterite is stable at a higher temperature than enstatite. Formation of forsterite grains provides the impetus for radiation-driven acceleration and thus reduces the efficacy of enstatite formation, leaving gas that is depleted in Mg and thus more silica-rich. Without a surface on which to nucleate, silicates will tend to form amorphous solids rather than crystals (Tsukamoto et al. 2001), thus the seed nuclei are of the utmost importance to forming crystalline grains. Moreover, the dispersion due to radiation pressure may lead to seedless amorphous dust formation in the low-density gas, which should be slightly more silica-rich than Mg$_2$SiO$_4$ due to the depletion of Mg into forsterite grains. The glass composition should tend toward Mg$_2$Si$_3$O$_8$, which is one of the metastable compositions predicted by Rietmeijer et al. (1999).

It is possible that the appearance of the clear crystalline absorption feature in 117495 is related not to increased crystallinity, but rather to less masking of the feature as a result of similar crystalline and amorphous silicate compositions (see Kemper et al. 2001). This still leaves the question of why this source is different—how can this source have both its crystalline and amorphous dust components dominated by Mg$_2$SiO$_4$, given that the bulk composition of the gas is closer to Mg$_2$SiO$_4$?

5. FACTORS INFLUENCING CRYSTALLINITY AND MINERALOGY

The physical factors which could give rise to the extremely high crystal content include: (1) $M$; (2) $v_{\exp}$; (3) metallicity; (4) C/O ratio. $M$ for 117495 is high, but similar to OH/IR stars and other color mimics, suggesting that $M$ alone cannot explain the high degree of crystallinity exhibited by this source. A low $v_{\exp}$ would increase the pressure at a given temperature and thus promote grain formation/growth at higher temperatures. However, $v_{\exp}$ for 117495 is relatively high. Increasing metallicity increases the partial pressure of the dust forming elements, and thus increases the dust formation temperature at a given total gas pressure. The metallicity of the source is unknown, although its location in the Galactic plane suggests that it may have higher than solar metallicity. If metallicity were the determining cause, we would expect to see similar spectra in the GB OH/IR stars. The fact that even the high $M$ GB stars do not exhibit such a distinct crystalline silicate feature suggests that a combination of $M$ and metallicity would also fail to increase the crystal fraction.

Having eliminated $M$, $v_{\exp}$, and metallicity as likely causes of higher crystallinity, we are left with C/O ratio as the most likely culprit. The condensation scheme suggested in § 4 is relevant to solar C/O ($\approx$0.48). Oxygen-rich AGB stars have C/O ratios between 0.4 and 0.8, where the exact value depends on both the initial mass and age of the star; increasing this ratio decreases the availability of oxygen atoms with which to make dust.

The Mg/Si ratio in the circumstellar outflow from which the dust forms is close to unity. The silica-poor composition of the amorphous dust requires sequestration of some silicon into a non-silicate phase to increase the Mg/Si ratio (cf. Ferrarotti & Gail 2001). While the formation of gehlenite (Ca$_2$Al$_2$SiO$_7$) before the Mg-rich silicates is predicted in many condensation models (e.g., Lodders & Fegley 1999; Gail & Sedlmayr 1999; Tielens 1990 and references therein), Si/Ca $\approx$16, and thus gehlenite is not an effective sink for silicon atoms.

Other options would be keeping the Si in gas-phase SiO$_2$ or condensation of Si into a metallic (or other featureless) phase (e.g., FeSi). The predicted path by which Mg$_2$SiO$_4$ forms is a reaction of Mg$_2$SiO$_4$ with SiO gas, requiring an additional oxygen atom. Consequently, high C/O may limit the conversion of Mg$_2$SiO$_4$ into Mg$_2$SiO$_4$ and preserve a silica-poor mineralogy. The condensation of FeSi is predicted for C/O ratios $\gtrsim$0.65 (Ferrarotti & Gail 2002; Lodders & Fegley 1999). As C/O approaches unity, $T_{\text{dust}}$ for the Mg-silicates decreases rapidly (Lodders & Fegley 1997) and Si is more apt to be incorporated into FeSi (Ferrarotti & Gail 2002). For C/O $\gtrsim$ 0.85, the Mg-silicate dust formation temperature drops to below that of FeSi (Ferrarotti & Gail 2002), which results in sequestration of Si and increases the Mg/Si ratio of the gas from which the silicates form. Therefore, there are at least two mechanisms by which higher C/O ratios may be able to explain the composition of 117495.

Based on the preceding arguments we suggest that a high C/O ratio is the cause of the unusual mineralogy of 117495. Our hypothesis predicts several observable correlations: (1) between the strength of SiO absorption and C/O ratio in low $M$ stars; (2) between SiO absorption and the relative abundances of crystalline forsterite and enstatite in high $M$ stars; and (3) between C/O and the peak positions/FWHM of the classic 10 $\mu$m (emission) feature. As discussed in § 3 the peak position and FWHM of the 10$\mu$m feature depend on the composition of the amorphous silicate.
Molster et al. (1999, 2002) found a correlation between AGB/post-AGB star crystallinity and source morphology, with “disklike” sources having a higher degree of crystallinity than spherical sources. Molster et al. (1999) suggested that this correlation is due to low-temperature crystallization in a long-lived disk. However, the inference of a disk around highly crystalline sources comes from imaging and the general shape of the SED, which cannot distinguish between a Keplerian disk and a toroidal disk. There is evidence that the last stages of mass loss from AGB stars become increasingly toroidal, and that this effect is stronger the more massive the progenitor star (Dijkstra & Speck 2006 and references therein). In this case, the density and pressure in the dust-forming regions would be enhanced further by the concentration of material into the star’s equatorial region, leading to conditions more apt to form crystalline structures. This in turn would correlate degree of crystallinity with initial mass of the star. Only massive AGB stars would produce significant amounts of crystalline material, and these are significantly rarer than low-mass AGB stars. This resolves the conundrum of the ISM (having low crystallinity) being enriched by high-crystallinity sources (see § 1).

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We have presented the first crystalline silicate absorption feature observed to date. The spectrum of I17495 is enigmatic and suggests that its dust is dominated by Mg2SiO4 in both the crystalline and amorphous phases. We have confirmed that high mass-loss rates should produce more crystalline material than low mass-loss rates; and that the crystalline mineralogy should be increasingly dominated by forsterite as mass-loss rates increase. The most likely factor controlling both crystallinity and mineralogy is the C/O ratio. We suggest that the correlation between crystallinity, mass-loss rate, and initial stellar mass mitigates the problem of the very different crystal fractions observed in some AGB stars and in the ISM. Only the rarer, higher mass AGB stars contribute a significant amount of crystalline material to the ISM.

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