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DUST GRAINS IN AGB STARS AS SOURCES OF INTERSTELLAR DUST

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ABSTRACT

The main sources of interstellar dust are believed to be dust envelopes around AGB stars. The outflowing envelopes around the long period pulsating variables are very suitable place for massive dust formation. Oxygen-rich silicate dust grains or carbon-rich dust grains form in the envelopes around AGB stars depending on the chemical composition of the stellar surface. The dust grains expelled from AGB stars get mixed up and go through some physical and chemical changes in interstellar medium. There are similarities and differences between interstellar dust and dust grains in AGB stars. The mass cycle in the Galaxy may be best manifested by the fact that the dust grains at various regions have many similarities and understandable differences.

Key words : stars: AGB and post-AGB – Circumstellar Matter – dust, extinction – infrared: stars – infrared: ISM

I. INTRODUCTION

The main sources of dust grains in the Galaxy are believed to be the dust envelopes around asymptotic giant branch (AGB) stars before leaving the red giant branch and rapidly evolving into a planetary nebula (e.g., Gehrz 1989). This phase of the Mira variable is characterized by the long period, large amplitude pulsation and dusty stellar winds with high mass-loss rates (10^{-8} - 10^{-4} $M_{\odot}/yr$).

Oxygen-rich AGB stars (M-type Miras and OH/IR stars) typically show the 10 μm and 18 μm features in emission or absorption. They suggest the presence of silicate dust grains in the outer envelopes around them (e.g., Suh 1999). Low mass-loss rate O-rich AGB (LMOA) stars with thin dust envelopes show the 10 μm and 18 μm emission features. And high mass-loss rate O-rich AGB (HMOA) stars with thicker dust envelopes show the absorbing features at the same wavelengths.

Carbon stars are generally believed to be the evolutionary successors of M-type Mira variables that have thin O-rich dust envelopes. When AGB stars of intermediate mass range go through carbon dredge-up process and thus the abundance of carbon is larger than that of oxygen, O-rich dust grain formation ceases, and the stars become visual carbon stars (Iben 1981). After that phase, C-rich dust grains start forming and the stars evolve into infrared carbon stars with thick C-rich dust envelopes and very high mass-loss rates. Infrared observations of C-rich AGB stars have revealed some types of carbon dust grains in the envelopes around them. They are amorphous carbon (AMC), silicon carbide (SiC) and magnesium sulfide (MgS). AMC dust grains play major role in producing the overall shape of the spectral energy distributions (SEDs) of C-rich AGB stars (e.g., Suh 2000).

Interstellar dust and dust grains in young stellar objects (YSOs) are known to be closely related with those in AGB stars. In this paper, we investigate the similarities and the differences between interstellar dust and the dust grains in the envelopes around AGB stars.

II. DUST GRAINS IN AGB STARS

Dust grains in the outer envelopes of AGB stars absorb and scatter the stellar radiation and re-emit the radiation at longer wavelengths. For given characteristics of the central star and the dust envelope around it, the emergent SED can be found by analyzing the radiative transport processes. Comparison of these results with observations can be used to make adjustments and improvements in the model input parameters. To clarify the SED evolution of AGB stars, we need to use the opacity functions of the dust grains that are consistent with observations and physics.

Because of the strong binding energy of the CO molecule, there is a clear separation between O-rich dust envelopes and C-rich dust envelopes around AGB stars except for a transitional case of silicate carbon stars. Therefore, the chemistry of dust grains in AGB stars is relatively simple and the modeling is easier.

(a) Optical properties

For given characteristics of the dust material (the optical constants, the size, and the shape) the absorption and scattering efficiency factors can be calculated at any given wavelength (e.g., Bohren & Huffman 1983). Figure 1 shows the opacity functions for

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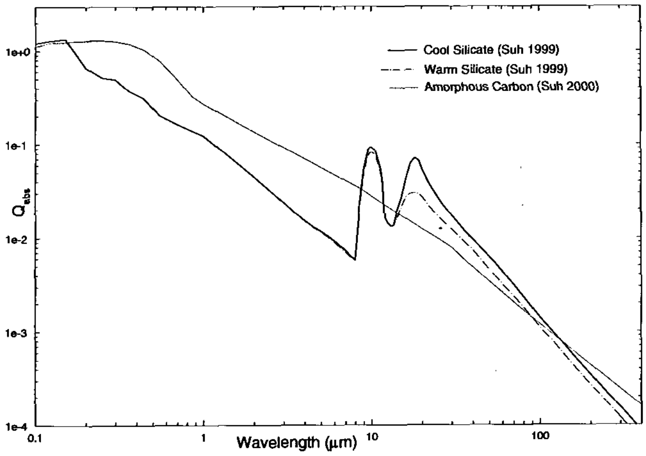

Fig.1.— The opacity functions for the dust grains in AGB stars.

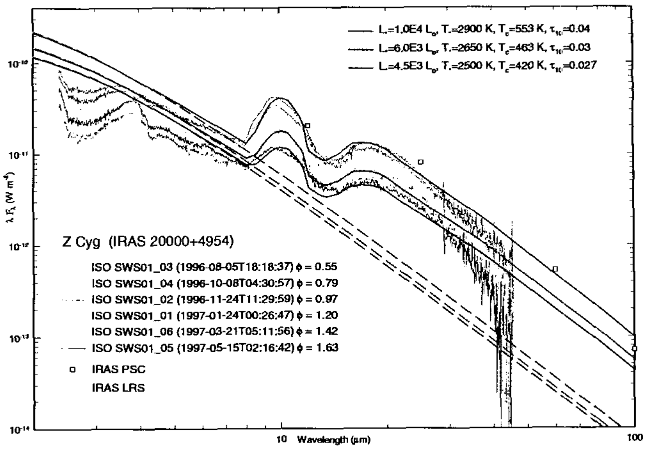

Fig.2.— The SEDs of Z Cyg.

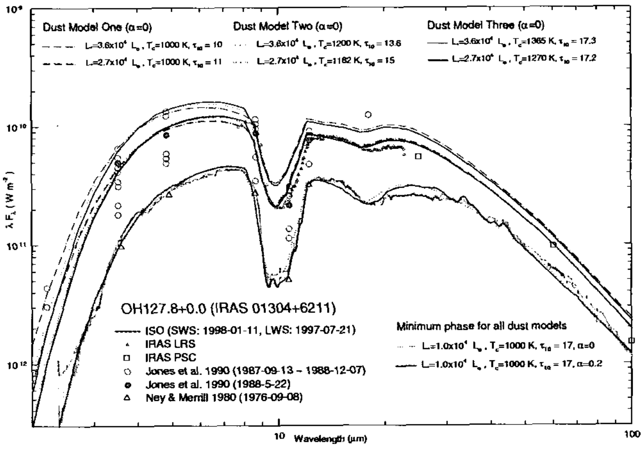

Fig.3.— The SEDs of OH127.8+0.0.

important dust grains in AGB stars. The absorption efficiency factors are calculated for a spherical dust grain with the radius of 0.1 μm. Using the deduced opacity, we may derive the complex dielectric function $\varepsilon(\lambda) = \varepsilon_1 + i\varepsilon_2$ when we consider further physical constraints: a dispersion model given by Clausius-Mosotti law for dielectrics or Kramers-Kronig relations (Bohren & Huffman 1983). The complex dielectric function may be expressed by the complex index of refraction, $m(\lambda) = n + ik$, where $\varepsilon = m^2$.

Derivation of two functions of complex dielectric constants, $\varepsilon_1(\lambda)$ and $\varepsilon_2(\lambda)$, from the deduced function $Q_{ext}(\lambda)$ requires additional information. The supplementary physical constraint that the dielectric constants should satisfy is the Kramers-Kronig relation (Bohren & Huffman 1983). Practically, we use the following procedure, analogous to that used in Draine & Lee (1984), to obtain the complex dielectric functions:

(i) $\varepsilon_2(\lambda)$ was chosen over the whole electromagnetic spectrum to agree with the existing laboratory data.

(ii) $\varepsilon_1(\lambda)$ was obtained using the Kramers-Kronig relation

$$\varepsilon_1(\lambda) = 1 + \frac{2}{\pi} P \int_0^\infty \frac{x\varepsilon_2(x)}{x^2 - \lambda^2} dx \qquad (1)$$

where P indicates that the Cauchy principal value is to be taken. The integral is computed numerically.

(iii) From the complex dielectric function we calculate $Q_{ext}(\lambda)$ for a spherical dust grain with radius of 0.1 μm using Mie theory. $Q_{ext}(\lambda)$ was compared with the deduced opacity for AGB stars.

(iv) Where disagreements were found, the choice of $\varepsilon_2(\lambda)$ was modified, and steps (ii) - (iv) were repeated.

From the satisfactory sets of complex dielectric constants, we find the optical constants ($m(\lambda) = n + ik$). The derived optical constants for the dust grains in AGB stars are slightly different from those obtained from laboratory measurements of terrestrial or meteoritic materials. It is also clear that interstellar dust grains might be strongly modified by chemical and physical processing after their expulsion from AGB stars.

(b) The SEDs

Using the opacity functions derived from the observations of a large sample of AGB stars and other information about the central stars and the dust envelopes, we may perform the radiative transfer model calculations. Figure 2 shows the Infrared Space Observatory (*ISO*) Short Wavelength Spectrometer (SWS; λ = 2.4–45.2 μm) SEDs at different pulsation phases for a LMOA star, Z Cyg, and the model SEDs. Figure 3 shows the *ISO* SWS and Long Wavelength Spectrometer (LWS; λ = 43–197 μm) and *IRAS* data at different pulsation phases for a HMOA star, OH127.8+0.0, and the model SEDs. See Suh (2004) for details of the model parameters.

IRAS four-colour photometric data are available for more than 2000 objects identified as AGB stars (Suh,

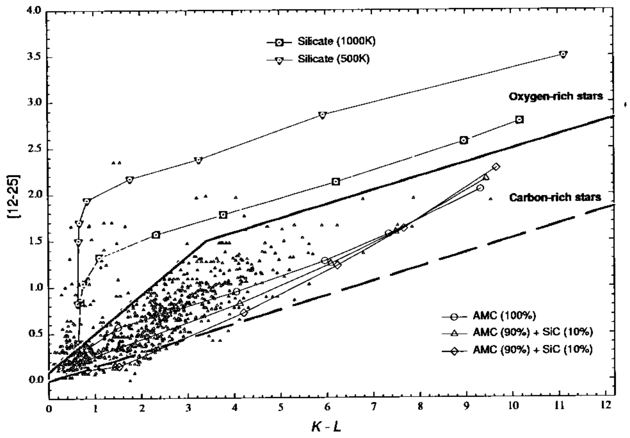

Fig.4.— The infrared two-color diagram for AGB stars.

Lee, & Kim 2000). The photometric data at K and L bands are available for 1234 AGB stars. Figure 3 plots the 504 O-rich AGB stars and 730 C-rich AGB stars in an *IRAS* two-colour diagram using [25−60] versus $K - L$. In the diagram, the small symbols are the observational data and the lines with large symbols are the model results. The stars in the upper-right region of the diagram have thicker dust envelopes with larger optical depths. The IR two-color diagram is useful in discriminating between O-rich and C-rich AGB stars

(c) Dust formation in AGB stars

One of the most controversial parameters for modeling the dust shells is the dust formation temperature. Most of the previous authors assumed a single dust formation temperature (1000 K - 1500 K) for modeling O-rich AGB stars. Detailed investigations about dust formation processes suggested that the dust formation temperature is higher for the stars with stronger stellar winds (e.g., Kozasa, Hasegawa & Seki 1984; Gail & Sedlmayr 1999; Sogawa & Kozasa 1999). According to Sogawa & Kozasa (1999), dust grains condense at different gas temperatures depending on the characteristics (density, pressure etc.) of the stellar winds. Sogawa & Kozasa (1999) suggest that once formed, silicate dust grains rapidly radiatively cool to temperatures between 900 K for $\dot{M} = 4 \times 10^{-5} M_{\odot}/yr$ to lower than 500 K if $\dot{M} = 5 \times 10^{-6} M_{\odot}/yr$.

The dust evaporation temperature is not well known. The destruction of dust grains requires sputtering or grain collision processes. The radiation and the stellar winds from AGB stars even at the maximum phase may not be able to destroy the dust grains in the inner shells of the dust envelopes. Then the inner shell dust temperature (T_c) may easily rise higher than the dust formation temperature.

(d) Crystalline Dust grains

Fabian et al. (2000) investigated the thermal evolution of amorphous silicates. They found that annealing at temperature 1000 K transformed amorphous silicates to crystalline ones in relatively short time scales. The crystallization took place within one day for the smoke materials and several days for the glass materials. Hallenbeck, Nuth & Nelson (2000) also investigated the thermal evolution of amorphous silicates. They obtained similar results. If the dust formation temperature is much lower than 1000 K for low mass-loss rate O-rich AGB stars, the annealing would not be effective for those stars. This may be the reason why we find virtually no evidence of crystalline silicates for LMOA stars. If $T_c \geq 1000$ K for HMOA stars, the annealing process could be effective in crystallizing amorphous silicates.

The high resolution *ISO* spectroscopic observations detected prominent emission from crystalline silicates in the far infrared spectra of HMOA stars but not from the spectra of LMOA stars (Sylvester et al. 1999). Using the averaged single grain population model for mixed amorphous and crystalline silicates, Suh (2002) found that spherical envelope models with about 10 % to 20 % of crystalline silicates produce the observed crystalline emission features for HMOA stars and virtually no evidence of the existence of crystalline silicates for LMOA stars. We find that the environments for the HMOA stars are suitable for the dust grains to be crystallized by annealing because of the hot dust temperature at the inner shell and the slow velocity of the stellar winds. Crystalline silicates are known to exist in Solar system comets and in interplanetary dust grains (Molster et al. 1999).

III. INTERSTELLAR DUST

The dust grains produced in many type of stellar objects (AGB stars, Supernovae, Wolf-Rayet stars, Planetary Nebulae, and Novae) contribute to the interstellar dust in galaxies. In Galactic ecology, Gehrz (1989) pointed out that AGB stars produce overwhelming portion (more than 90 %) of the interstellar dust grains supplied from all stellar objects.

When the dust grains formed in AGB stars enter the interstellar medium, they get mixed up and go through some physical and chemical changes. There are similarities and differences between interstellar dust and dust grains in AGB stars. In interstellar medium or in YSOs, both O-rich and C-rich dust grains can exist together and the sizes of the dust grains are usually much smaller than found in AGB stars probably because of the erosion processes in interstellar medium. Silicate materials in interstellar medium are similar to those in AGB stars. But for C-rich dust grains, the crystallization of AMC material to graphite or the significant chemical changes including hydrogenation can occur just after AGB phase or in interstellar medium.

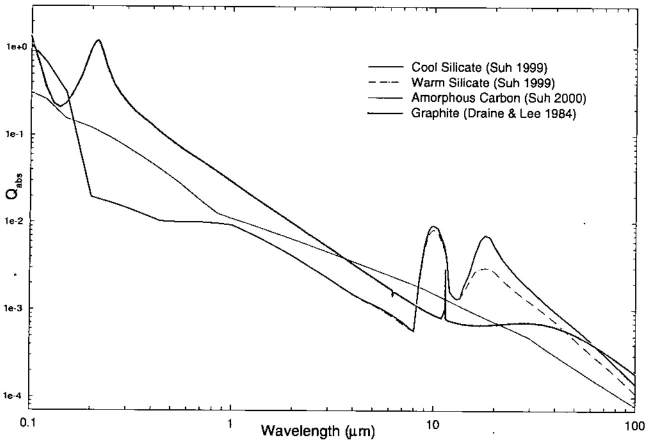

Fig.5.— The opacity functions for interstellar dust.

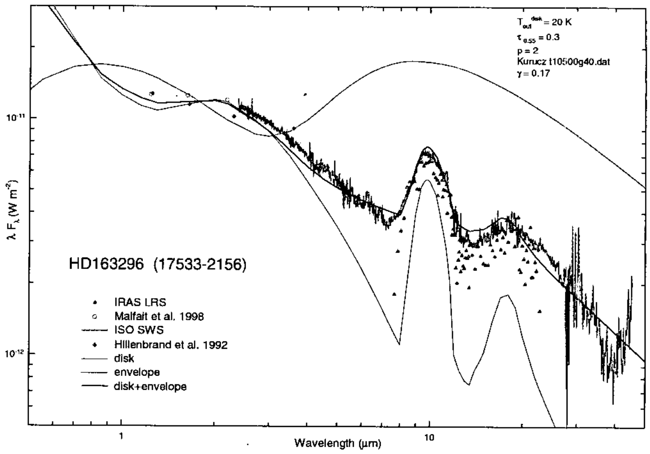

Fig.6.— The SEDs of a HAEBE star (HD163296).

Table 1 summarizes the comparison of dust grains at different regions of the Galaxy.

(a) The Galactic extinction curve

Figure 5 shows the opacity functions for important dust grain materials in interstellar medium. The absorption efficiency factors are calculated for a spherical dust grain with the radius of 0.01 μm which is smaller than the one for AGB stars. Graphite grains are believed to be originated from AMC through crystallization processes. The conspicuous 0.2175 μm graphite feature is well known in the Galactic extinction curve (e.g., Draine 2003). The ratio of silicate and graphite depends on the metallicity. Although Pei (1992) suggested that 57.73 % of silicate dust grains and 42.27 % of graphite dust grains by number would be appropriate, the actual mixture would be more complicated with another materials having minor contributions.

The unidentified infrared (UIR) features at 3.3, 6.2, 7.7, 8.6, and 11.3 μm were noticed for compact HII regions, Planetary Nebulae, YSOs, and galactic disks. The spectrum as a whole is confidently assigned to poly cyclic aromatic hydrocarbons (PAHs) or to small grains containing PAHs. PAHs are certain component of the carbonaceous material in the galaxy probably originated from hydrogenated amorphous carbon (e.g., Chiar et al. 2000). Because the carbon skeleton of PAH molecules resembles a portion of a graphite sheet, PAH molecules also tend to have strong electronic transitions at about 0.2175 μm (Draine 2003).

The SED of a galaxy reveals the extinction and re-emission processes in the interstellar medium as well as the radiation from many types of stars. A theoretical population synthesis model is sensitively influenced by the property of the radiative processes and completeness of the spectral library of stars. The population synthesis model calculation combines several factors as the initial mass function, star formation rate, libraries of evolutionary tracks and model atmospheres which give an effect to the evolution of galaxies. The radiative transfer model for the interstellar medium of a galaxy requires opacity functions of the dust grains. We find that the opacity functions for silicate dust grains derived from AGB stars are useful (Suh & Kim 2003). The contribution of dusty AGB stars to the SEDs of galaxies or stellar clusters is believed to be significant (e.g., Bressan, Granato, & Silva 1998; Piovan, Tantalo, & Chiosi 2003).

(b) Dust grains in YSOs and meteorites

YSOs are surrounded by a gas and dust envelope and/or disk (e.g., Waters & Waelkens 1998). As YSOs evolve into main sequence, the structure of dust envelope changes. The dust envelopes become thinner, and the accretion disks become more prominent. Unlike AGB stars, YSOs have the dust grains that are much more complicated in chemical and physical properties. Silicates (amorphous, crystalline, and hydrous silicates), carbon grains (amorphous grains, smaller graphite grains, and PAH), and water ice grains are believed to be the major components in the envelopes or disks around YSOs. The SEDs of them are usually difficultly fitted with any mixture of candidate dust grains with various grain size distributions.

Herbig Ae/Be (HAEBE) stars are believed to be intermediate-mass pre-main-sequence (PMS) stars (~ 2-10 $M_\odot$). To understand the physical and chemical properties of the envelope and/or the disk, the detailed spectral observations at IR are required. The recent *ISO* mission has provided the essential data. We have modeled HAEBE stars using the radiative transfer code developed by Miroshnichenko et al. (1999). In Figure 6 displays the model SED for a dusty disk and shell model and the observations including *IRAS* and *ISO* data for a HAEBE star: HD163296. Suh, Kim, & Baek (2002) found that most HAEBE stars show the amorphous silicate features at 10 and 18 μm in emission. In our Galaxy, silicates are most widely spread in inter-

TABLE 1
DUST GRAINS AT DIFFERENT REGIONS

	AGB stars	Interstellar Dust	YSOs
large dust grains	[O]>[C] → O-rich (silicate,...)	well mixed	well mixed
(0.01-0.5 μm)	[O]<[C] → C-rich (AMC,...)		
	larger size (~ 0.1 μm)	smaller size (~ 0.01 μm)	mixed size
	systematic crystallization	random crystallization(?)	random crystallization(?)
small graphite grains	almost none	abundant	abundant
PAH	almost none	abundant	abundant

stellar medium because of abundant O-rich AGB stars. Only a few HAEBE stars show evident crystalline silicate features. This is in contrast to the fact that all the HMOA stars that are observed by *ISO* show prominent crystalline silicate features. The size distribution of the dust grains in YSO's is that small size (~ 0.01 μm) grains are mixed up with very large grains (~ 1 μm) probably formed in the disk through coagulation of smaller grains (see Table 1).

The most common meteoritic minerals are silicate materials including pyroxenes and olivines. Primitive chondritic meteorites contain the material that predates the formation of our Solar System. Astronomical observations suggest that silicates must have been the dominant solids in the protoplanetary disk from which the planets of the Solar System formed, but no presolar silicates had been identified in chondrites. Recently, Nagashima, Krot, & Yurimoto (2004) reported that the discovery of presolar silicate grains 0.1-1 μm in size in the matrices of two primitive carbonaceous chondrites. These grains suggest an origin in an O-rich AGB star. Their result is best explained by the destruction of silicates during high-temperature processing in the solar nebula.

IV. CONCLUSIONS

When the dust grains formed in AGB stars enter in interstellar medium, they get mixed up, go through some physical and chemical changes, and become important components of star formation. The mass cycle in the Galaxy may be best manifested by the fact that the dust grains at various regions in the Galaxy have many similarities and understandable differences. The traces of the dust grains in AGB stars are commonly found in interstellar medium, YSOs, meteorites, the Galactic extinction curve, and the SEDs of galaxies.

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