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DUST SHELL MODELS FOR LOW MASS-LOSS RATE OXYGEN-RICH AGB STARS

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ABSTRACT

We investigate the spectral energy distributions (SEDs) of low mass-loss rate O-rich asymptotic giant branch (AGB) stars using the infrared observational data including the Infrared Space Observatory (*ISO*) data. Comparing the results of detailed radiative transfer model calculations with observations, we find that the dust formation temperature is much lower than 1000 K for standard dust shell models. We find that the superwind model with a density-enhanced region can be a possible alternative dust shell model for LMOA stars.

Key words : stars: AGB and post-AGB — Circumstellar Matter — radiative transfer — infrared: stars

I. INTRODUCTION

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.

Comparing the detailed model results with observed SEDs of LMOA stars, Suh (2004) argued that the inner shell dust temperature is much lower than 1000 K and varies significantly during the pulsation phase (about 400 K at the minimum phase and about 600 K at the maximum phase). The dust formation temperatures for LMOA stars (420−654 K) derived by Suh (2004) may be too low and the dust shell inner radii (R_c= 27−41 R_*) could be too large. At this radius, especially given the low mass-loss rate, the gas could be too dilute to allow enough collisions to produce grain nucleation or growth on already existing nuclei.

The alternative dust envelope models for LMOA stars would be either non-continuous dust shell models or non-spherical dust envelope models. A possible non-continuous dust shell model for the LMOA stars could be that there is a density-enhanced region for the overall continuous dust shell (e.g., Suh & Jone 1997; Egan & Sloan 2001). Suh & Jone (1997) explored the effect of a superwind due to a helium shell flash by adding a density-enhanced region that proceeds outward. Depending on the position and the degree of the enhancement, the emergent model SEDs can be significantly different from the ones with the continuous density distributions.

In this paper, we investigate the SEDs of LMOA stars using various spherical dust shell models including the superwind models. We compare the results of radiative transfer model calculations with observed SEDs including the *Infrared Space Observatory* (*ISO*) Short Wavelength Spectrometer (SWS), *ISO* Long Wavelength Spectrometer (LWS), Infrared Astronomical Satellite (*IRAS*) Point Source Catalog (PSC), *IRAS* Low Resolution Spectrograph (LRS), and ground based observations. Based on possible dust models, we present detailed values of the global dust shell parameters and discuss possible explanations.

II. DUST ENVELOPE MODEL CALCULATIONS

We use the radiative transfer code developed by Egan, Leung & Spagna (1988) for spherically symmetric dust shells around AGB stars. A fixed model parameter for the dust shell is the wavelength dependence of the dust opacity. The adjustable input parameters are the dust optical depth at 10 μm (τ_{10}). We have performed the model calculations in the wavelength range 0.1 to 1300 μm.

(a) Central Stars

A change in the luminosity of the central star does not affect the shape of the output SED, it only affects the overall energy output. A change in the blackbody temperature does affect the output spectra especially for LMOA stars. For modeling LMOA stars, we use the luminosity (L_*) at maximum phase of $1 \times 10^4 L_\odot$ for the central star. We use the stellar black body temperature (T_*) of 2500−2900 K.

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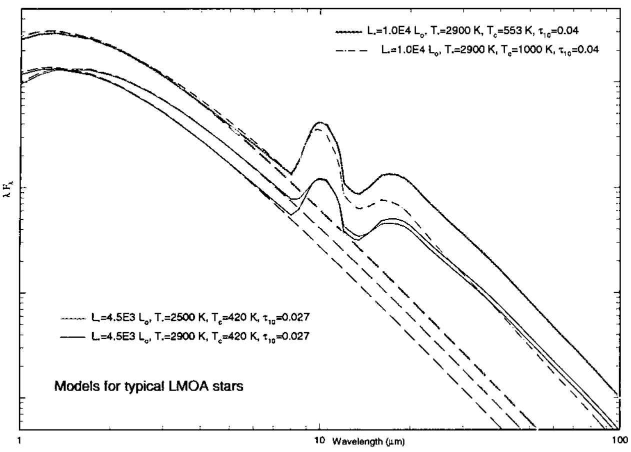

Fig.1.— Model SEDs for typical LMOA stars.

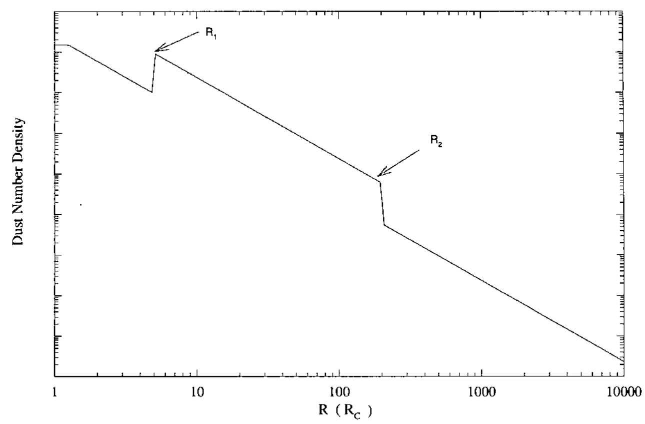

Fig.2.— The radial form of the dust density enhancement for a superwind Model.

(b) Dust Opacity

Silicates are believed to be a major component of the dust grains in the envelopes around O-rich AGB stars. The SEDs of them are usually well fitted with amorphous (or dirty) 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; Suh 2002).

For simplicity, we assume that all silicate dust grains are spherical with a uniform radius of 0.1 μm and the bulk density is 3.0 g cm^{-3}. For amorphous silicates, we use the warm dust opacity functions derived by Suh (1999) for LMOA stars.

(c) Dust Shell Parameters

We assume that the dust shell density distribution is continuous ($\rho \propto r^{-2}$) in large scale from the inner radius of the dust shell (R_c) to the outer radius which is always taken to be 10000 R_c. See Suh (1999) and Suh & Kim (2002) for detailed discussion about this assumption.

After a few trials, we find the dust shell inner radius (R_c) at which the dust temperature (the inner shell dust temperature; T_c) becomes the desired one. The model SEDs sensitively dependen on T_c. The temperature is not necessarily the same as the dust formation temperature depending on the physical situations. And for the same reason, the dust shell inner radius is not necessarily the same as the dust formation (or condensation) radius. In this paper, we assume different T_c depending on the physical conditions of the objects and the fitting of the resulting SEDs with the observations.

The basic model results are displayed in Figure 1. The dashed lines represent the radiation from the central stars. A change in the blackbody temperature of the central star significantly affects the output spectra for LMOA stars. This is because in optically thin dust shells the underlying energy distribution of the star strongly influences the emergent near infrared continuum, and the model SEDs sensitively depend on the inner shell dust temperature (T_c). For LMOA stars, the lower T_c produces much more radiation at wavelengths longer than 10 μm.

(d) Superwind Models

If a thermal pulse strongly effects the mass loss rate from the star, the dust density distribution will be different from a smooth radial distribution. Figure 2 illustrates a description of the hypothesized density discontinuity we will use in the models. The radial density distribution is still a r^{-2} power law, except for an abrupt elevation of the density in the region of the superwind. The controlling parameters for this enhancement are its inner and outer radii R_1 and R_2 and the factor by which the density is enhanced over the distribution for the rest of the shell (i.e., 10x, 20x, etc.). Initially, a 10 times enhancement of the mass loss rate will produce a narrow region of enhanced density at the inner boundary of the shell. See Suh & Jones (1997) for detailed discussion of the assumptions.

III. THE SED COMPARISON

To compare our model results with the observed SEDs, we choose two LMOA stars for which good spectral data are available at two or more separate phases of pulsation. The spectral data include *ISO* SWS and LWS data as well as the *IRAS* PSC, *IRAS* LRS, airborne and ground based observational data. Table 1 lists the two selected stars. For each star, the table lists the pulsation period, the expansion velocity of the outer shell (v_{exp}), the blackbody temperature of the central star (T_*), the dust grain opacity, the number of available *ISO* SWS (λ = 2.4−45.2 μm) and LWS (λ = 43−197 μm) data sets, and the *ISO* data reduction information. The number of the good data sets that are

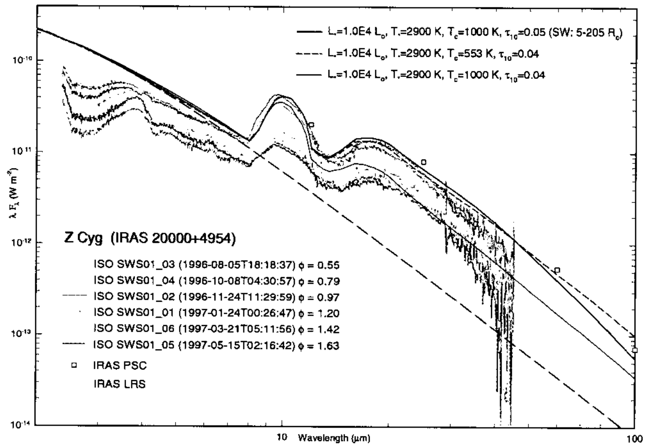

Fig.3.— The SEDs of Z Cyg.

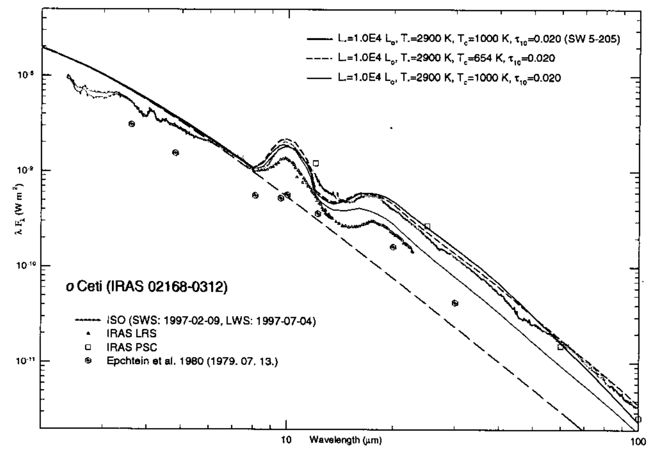

Fig.4.— The SEDs of o Ceti.

used for SED comparison is presented in the parenthesis of the SWS or LWS column. We have used the *ISO* spectral data reduced by previous authors (Sylvester et al. 1999; Onaka et al. 2002). The details of the data and reduction processes are described in the references.

Figures 3 and 4 show the SED comparison of observations and model results at the maximum phase for the two LMOA stars. The figures show the superwind model results compared with continuous dust shell models. With T_c=1000 K, the 10 times density-enhanced region from 5 to 205 R_c produces a SED similar to the *ISO* spectra of the both stars. Namely, the superwind dust shell with the density enhancement mimics a continuous shell with a lower inner shell dust temperature. If the superwind model is right, the dust formation temperature can be as high as 1000 K for LMOA stars.

Table 2 lists the best SED model fitting parameters for the two LMOA stars. For each star, the table lists the optical depth, the central luminosity, the stellar temperature, the inner shell dust temperature (T_c), the dust shell inner radius (R_c) in parsecs and stellar radius (R_*), R_1 (R_c) and R_2 (R_c).

IV. DISCUSSION AND CONCLUSIONS

The dust formation temperatures for LMOA stars derived for continuous dust shell models (420−654 K) may be too low and the dust shell inner radii (R_c= 27−41; see Table 2) could be too large. It is difficult to understand how this can be correct in view of the several interferometric measurements which have been made and show dust formed much closer to the star and at a higher temperature (e.g., Lopez et al. 1997). As we discussed in section III, the superwind dust shell with the density enhancement mimics a continuous dust shell with a lower inner shell dust temperature. If a LMOA star has the superwind dust shell, the dust formation temperature can be as high as 1000 K and R_c= 10.8 R_*. If the dust formation temperature for a LMOA star is as high as 1000 K, the dust grains in LMOA stars may be crystallized by annealing.

One of the most controversial parameters for modeling the dust shells is the dust formation temperature. 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; 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 $\dot{M}$ = $5 \times 10^{-6} M_\odot/yr$. Therefore, even if the dust formation temperature is as high as 1000 K for LMOA stars, the annealing may not be as effective as for HMOA stars. When we compare the detailed SEDs for a larger sample of LMOA stars, we may be able to get better conclusions on the dust formation temperature.

The presence of distinct shells of material around planetary nebulae suggests these thermal pulse episodes strongly modulate the mass-loss rate from the star. In order to explain the very thick dust shells and high mass loss rates seen in the more extreme OH/IR stars, the mass-loss rate from an AGB star must increase by at least factor of 10 for the duration of the superwind. We expect one thermal pulse about every 10^4 - 10^5 years which endures for a few hundred years (Iben 1975; Vassiladis & Wood 1993). Although the superwind is not expected to be exactly in phase with the thermal pulse, the duration is predicted to be comparable (Vassiladis & Wood 1993).

Interferometric measurements of LMOA stars (e.g., Lopez et al. 1997) suggest that the shapes of the dust envelopes around LMOA stars are not spherically symmetric and the density distribution is not continuous. A more detailed study on the superwind models and

TABLE 1.
TWO SELECTED STARS FOR SED COMPARISON

Class	Name	P[a] (days)	v^a_{exp} (km/sec)	T_* (K)	τ_{10}	Dust[b]	*ISO*[c] SWS; LWS	*ISO* data reduction
LMOA	Z Cyg	264	4.3	2500-2900 K	0.02-0.04	warm	7(6); 2(0)	Onaka et al. 2002
	o Ceti	332	16.9	2500-2900 K	0.01-0.02	warm	2(1); 4(1)	Sylvester et al. 1999

[a] The values were taken from Groenewegen et al. (1999). [b] The optical properties of the amorphous silicate dust grains as presented in Suh (1999). [c] The number of the good data sets that are used for SED comparison is presented in the parenthesis.

TABLE 2.
THE BEST FITTING DUST SHELL MODEL PARAMETERS AT THE MAXIMUM PHASE

Name	Model	$\tau_{10\mu m}$	L_* $L_\odot$	T_* (K)	T_c (K)	R_c (pc)	R_c (R_*)	R_1 (R_c)	R_2 (R_c)
Z Cyg	Continuous	0.04	1.0E+04	2900	553	3.30E-04	36.8	-	-
	Superwind	0.05	1.0E+04	2900	1000	9.69E-05	10.8	5	205
o Ceti	Continuous	0.02	1.0E+04	2900	654	2.40E-04	26.8	-	-
	Superwind	0.02	1.0E+04	2900	1000	9.67E-05	10.8	5	205

the non-spherical dust envelope models (e.g., the axi-symmetric dust envelope model by Ueta & Meixner 2003) could explain the SEDs of LMOA stars better.

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