A Model Analysis of the Infrared Data of Late Type Stars Surrounded by the Circumstellar Dust Envelopes

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A Model Analysis of the Infrared Data of Late Type Stars Surrounded by the Circumstellar Dust Envelopes

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Abstract
A lot of model infrared spectral energy distributions of the oxygen-rich late type stars surrounded by the circumstellar dust envelopes are calculated by solving the radiative transport equations in the spherical dust envelope with various model input parameters. Using IRAS photometric data at 12, 25 and 60µm and the strength of the silicate band feature at 10µm from LRS spectra the best fit model is searched for each IRAS oxygen-rich evolved star with the circumstellar dust envelope. It is found that those objects are divided into two groups which are clearly separated by the mass loss rate and the grain formation temperature.

1. Model of the circumstellar dust envelope
A model of the dust envelope of the mass losing late type stars is developed by solving the radiative transfer equations in the spherical envelope. A generalized two stream Eddington approximation which was recently improved by Unno (1989) for an optically thick gray spherical envelope is modified for non-gray case, and employed for the solution of the moment equations of the radiation transfer in the spherical envelope of non-gray dust grains. There are three input parameters in the model; the sizes of the inner and outer boundaries of the dust envelope and the number density parameter of the dust grains. The dust grains are formed at the inner boundary where \( r = r_i \). Because the envelope is expanding the grains at the outer boundary are the oldest ones, thus the size of the outer boundary \( r_o \) comes to indicate the time since the beginning of the dust formation or mass loss. Assuming steady mass flow with constant expansion velocity \( V_{exp} \) the duration time of the steady mass loss is estimated as \( t_{mass \ loss} \sim r_o/V_{exp} \), though this value largely depends on the optical properties of the dust grains in the far infrared wavelength region. Number distribution of the dust grains in the envelope of the steady mass flow can be represented as \( n(r) = n_0 (R_*/r)^2 \) for \( r_i < r < r_o \), where \( n_0 \) is the number density parameter and \( R_*/r \) is the radius of the central star. The dust number density parameter \( n_0 \) is proportional to the mass loss rate. Optical properties of amorphous silicate grain whose radius is 0.1µm by Rowan-Robinson (1986) are employed for the model. Temperature and dimension of the central star are set as \( T_* = 3000K \) and \( R_* = 400R_\odot \) respectively, which correspond to the luminosity about \( 10^4 L_\odot \).
2. Model analysis

A lot of infrared spectral energy distributions of the model of the oxygen-rich evolved stars surrounded by the circumstellar dust envelopes are obtained by varying the model input parameters as \( r_i = 7 \sim 300R_\star \), \( r_o = 10^{2.5} \sim 10^{5.5}R_\star \) and \( n_0 = 10^{-7} \sim 1 \text{ cm}^{-3} \). If expansion velocity of the envelope is assumed as \( V_{\text{exp}} = 15 \text{ km s}^{-1} \), density of the amorphous silicate grain as \( 3.5 \text{ g cm}^{-3} \) and the gas to dust ratio in mass as 200, those input parameters correspond to the dust temperature at the inner boundary of the envelope where dust grains are forming from 200 to 1500K, time scale of the continuous steady mass loss from about 200 to \( 1 \times 10^5 \) years and the mass loss rate from \( 10^{-8} \) to \( 5 \times 10^{-4} M_\odot \text{ yr}^{-1} \).

Relations between observation values and the model input parameters are examined. For example the relation between IRAS color \( \log(S_{25}/S_{12}) \) and \( n_0 \) for various \( r_i \) and \( r_o \) is presented in Figs.1 and 2, where \( S_\lambda \) is the flux density at wavelength \( \lambda \mu m \). In Fig.1 the inner radius is fixed as \( r_i = 10R_\star \) for various outer radii from \( 10^{2.5} \) to \( 10^{5.5} R_\star \), while the outer radius is fixed as \( r_o = 10^4 R_\star \) for \( r_i = 7 \sim 300R_\star \) in Fig.2. These figures indicate that the IRAS color \( \log(S_{25}/S_{12}) \) does not depend only on the number density parameter \( n_0 \) but sensitively on the size of the inner radius \( r_i \), though the size of the outer boundary has very small effect on this value. Strength of the silicate band feature at \( 10\mu m \ln(F_{\text{sil.}}/F_{\text{cont.}}) \) and near infrared colors such as \( K - L \) as well as IRAS colors are examined in the figures similar to Figs.2 and 3 and the results are summarized in Table 1.

3. Results of the model analysis of IRAS data

Using IRAS photometric data at 12, 25 and 60\( \mu \)m and the strength of the silicate band feature at 10\( \mu \)m measured from IRAS LRS spectra, the best fit model is searched for each IRAS evolved star. Only three observation values \( \log(S_{25}/S_{12}) \), \( \log(S_{60}/S_{25}) \) and \( \ln(F_{\text{sil.}}/F_{\text{cont.}}) \) are used for this fitting, however the relations shown in Table 1 indicate that those three observation values can determine the model parameters with satisfaction; \( \log(S_{25}/S_{12}) \) and \( \ln(F_{\text{sil.}}/F_{\text{cont.}}) \) mainly determine \( r_i \) and \( n_0 \) and with these two values \( \log(S_{60}/S_{25}) \) plays an important role for determination of \( r_o \).

Results of the model fitting for the IRAS objects which show the 10\( \mu \)m silicate feature in their LRS spectra in emission or absorption are presented by the number distributions of the best fit parameters in Figs.3-5. For this analysis only objects whose flux densities at 12, 25 and 60\( \mu \)m are all of good quality and scarcely polluted by the infrared cirrus ( FQUAL=3, CIRR1\leq3, CIRR2\leq5) are selected.

The distribution of the number density parameter of the dust grains is presented in Fig.3. Hatched part corresponds to the objects which show the absorption band feature at 10\( \mu \)m. Two peaks at \( \log n_0 \sim -3.3 \) and \( \log n_0 \sim -1.7 \) are seen in the histogram, and they are clearly separated by the border at \( \log n_0 \sim -2.5 \). The mass loss rates for the two peaks are estimated about
$\dot{M} \sim 3 \cdot 10^{-7} M_\odot yr^{-1}$ and $\dot{M} \sim 1.2 \cdot 10^{-5} M_\odot yr^{-1}$ respectively. This distribution indicates that the IRAS cool stars surrounded by the oxygen-rich dust envelopes are divided into two distinctly separate groups.

Figure 4 shows the number distribution of the temperature of the dust grains at the inner boundary of the envelope where the grains are forming. Hatched part correspond to the object which are fitted by the number density parameter $\log n_0 > -2.5$, or the members of the group of the larger mass loss rate. It is found that the grain formation temperature is also different among the two groups distinguished by the grain number density parameter. The typical grain temperature at $r = r_i$ for the group of the larger $n_0$ is about 1100K, which is compatible with theoretical grain formation temperature of the silicate grain (Kozasa et al., 1984), while that for the other group distributes around 500K, which is too low to be explained by the ordinary nucleation theories. However, such low dust formation temperature is consistent with the results obtained by Onaka et al. (1989a, 1989b) from analyses of the IRAS LRS spectra of Mira variable stars.

The number distribution of the outer radius of the dust envelope presented in Fig.5 does not indicate any clear differences between the two groups separated by their grain number density parameters.

Many IRAS objects which show the silicate absorption feature at 10$\mu$m are OH/IR objects and located near the Galactic plane. The cirrus emission around those objects are often so strong that very few are selected in the analysis by the selection criteria on the cirrus pollution. Because these objects are very red ones, however, fraction of the flux from the infrared cirrus in the observed IRAS flux density at 60$\mu$m is thought to be smaller than that for the objects which show the silicate feature in emission. IRAS objects with the silicate absorption feature at $\lambda = 10 \mu$m and good quality flux densities at 12, 25 and 60$\mu$m are studied by the dust envelope model. From this analysis it is found that these objects all show very large values of $n_0$ which correspond to the mass loss rate larger than $10^{-5} M_\odot yr^{-1}$. It is also noted that those $n_0$ values distribute continuously from the group of the IRAS objects with the larger grain number density parameter in the model analysis discussed above. Although the grain temperature at the inner radius widely distributes from 200K to 1500K, significant fraction of objects are concentrated around 1300K, which is also similar to or slightly higher than that of the group with the larger mass loss rate. In respect of the mass loss and grain formation the objects in the group with $\log n_0 > -2.5$ are statistically very similar to the OH/IR objects which show the silicate absorption feature. Some OH/IR objects which show the grain temperature much lower than 1000K may be the evolved stars whose mass loss have been stopped as Bedijn (1987) has indicated.

Hashimoto et al. (1990) have shown that some M stars without any spectral features in their LRS spectra show very red IRAS color of $\log(S_{25}/S_{12})$ which is
red enough for showing the strong silicate emission feature at $\lambda = 10\mu m$ by the model if the grain formation temperature is higher than 500K. Such M stars with no features in LRS spectra are also studied by the model, setting the strength of the band feature at 10$\mu$m as $\ln(F_{sil.}/F_{cont.}) \sim 0$. The result of this analysis indicates that the grain density parameter of all these M stars are similar to that of objects with the 10$\mu$m feature in the group of the smaller mass loss rate, while the grain temperature at the inner edge of the envelope is lower than 300K, which is too low for the formation of the silicate grains by the ordinary nucleation. For these M stars the mass loss may be stopped for longer than a hundred years, though their original mass loss rate is similar to that for the objects which show the silicate feature at 10$\mu$m and belong to the group with the smaller $n_0$.

4. Conclusions

It is concluded that the oxygen-rich late type stars surrounded by the dust envelopes are essentially divided into two groups which are clearly distinguished by the mass loss rate and the grain formation temperature. One is the group of the ordinary late type giant stars and the other is that of OH/IR star type objects. The grain temperature at the inner boundary for the former group distributes around 500K, which is too low to be explained by the ordinary nucleation theories, although that for the latter group is about 1100K which is comparable with prediction by the theories.

References

Figure captions

Fig.1 Relation between the IRAS color $\log(S_{25}/S_{12})$ and the grain number density parameter $n_o$ for the model with fixed inner boundary $r_i = 10R_*$ and various outer radii $r_o = 10^{2.5} \sim 10^{5.5}R_*$. 

Fig.2 Relation between the IRAS color $\log(S_{25}/S_{12})$ and the grain number density parameter $n_o$ for the model with fixed outer boundary $r_o = 10^4R_*$ and various inner radii $r_i = 7, 10, 15, 20, 30, 40, 60, 100$ and $300R_*$. 

Fig.3 Number distribution of $n_o$ for the IRAS objects which show the silicate feature at $10\mu$m in their LRS spectra. Hatched part corresponds to the objects which show the silicate feature in absorption. The mass loss rate can be estimated as $\dot{M} \sim 7 \cdot 10^{-4} \cdot n_o \ M_\odot yr^{-1}$. 

Fig.4 Number distribution of the dust temperatuer at $r = r_i$ for IRAS objects with the $10\mu$m silicate feature. Hatched part corresponds to the objects with $\log n_o > -2.5$. 

Fig.5 Number distribution of the size of the outer radius for IRAS objects with the $10\mu$m silicate feature. Hatched part corresponds to the objects with $\log n_o > -2.5$. 
Table 1. Relation between observation values and the model input parameters.

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<th>$r_i$</th>
<th>$r_o$</th>
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○ : sensitive  
× : not or very weakly sensitive  
△ : weakly sensitive  
□ : sensitive only when $r_i$ is extremely small