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DUST FORMATION AROUND M-TYPE STARS

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IRAS LRS spectra (IRAS team, 1986) of M Mira variables have shown a large variation in the appearance of the 9.7 μm silicate feature, which is correlated with the shape of light curve (*cf.*, Vardya *et al.*, 1986). Onaka and de Jong (1987) and Onaka *et al.* (1988) have studied the LRS spectra of about 100 Mira variables by using simple dust shell models containing mixtures of silicate and aluminum oxide dust grains. They have shown that the aluminum oxide grains account for the observed broad feature around 12 μm and that the variation of the spectra can be interpreted in terms of the variation of the temperature at the inner boundary of silicate dust shell. They have proposed silicate mantle growth on aluminum oxide grains as a possible explanation for the results. In this report, we calculate model spectra taking account of silicate mantle growth and investigate the physical parameters which may determine the appearance of the 9.7 μm feature in M Mira variables.

In the model calculation it is assumed that aluminum oxide grains are already formed at the bottom of the circumstellar envelope because of their high condensation temperature (~ 1500 K). The growth of silicate mantle and the motion of gas and grains from $r=r_0$, where the mantle growth starts, are investigated. Sticking and sputtering processes due to the relative motion of grain to the ambient gas are taken into account. The thermal velocity is assumed to be negligible to the drift velocity. Acceleration by radiation pressure is considered in the gas motion equation. The formal solution is integrated to obtain the emergent spectra. Physical conditions inside r_0 are regarded as boundary conditions. Observed spectra are compared to model spectra to investigate the conditions at the bottom of circumstellar envelope. In modelling the envelope, a parameter C_l is introduced to take account of the density fluctuation of the envelope phenomenologically.

Silicate mantle growth on an aluminum oxide grain can be written as

$$\frac{dA}{d\bar{R}} = -\frac{F_R}{V(1+\bar{V}_d)}\left[1-\frac{A^3-1}{A_f^3-1}-\sum_i \frac{f_i}{f}S_i\right] \tag{1}$$

with $A=a/a_0$, $\bar{R}=r_0/r$, $V=v/v_0$, $\bar{V}_d=v/v_d$, and $A_f=a_f/a_0$. Here, a is the grain radius including core and mantle, a_0 the core radius, r the distance from the star, v the gas velocity, $v_0=v$ at $r=r_0$, and v_d the drift velocity of the grains relative to the ambient gas. The parameter a_f is determined by the abundance ratio of silicate to aluminum oxide, being about 3. The last term in the parentheses represents the erosion due to sputtering: f_i is the relative cosmic abundance of element i and S_i the sputtering yield taken from Kwok (1975). Sputtering is negligible unless v_d exceeds 20 km/sec. The parameter F_R describes the rate of mantle growth and is given by

$$F_R = \frac{\dot{M} f \Omega}{16\pi\, a_0\, r_0\, v \mu\, m_{\mathrm{H}}} \approx 1.35\left[\frac{\dot{M}}{10^{-6}\,\mathrm{M}_\odot/\mathrm{yr}}\right]\left[\frac{10\ \mathrm{nm}}{a_0}\right]\left[\frac{6\cdot 10^{14}\ \mathrm{cm}}{r_0}\right]\left[\frac{10\ \mathrm{km/sec}}{v_0}\right] C_l, \tag{2}$$

where $\dot{M}$ is the mass loss rate, f the fraction of the condensible material (~ $3\cdot10^{-5}$), Ω the volume of the monomer (~ $5\cdot10^{-23}$ cm^3), μ the molecular weight (~ 1.4), and m_{H} the hydrogen mass.

The change of the velocity due to the radiation pressure may be given by

$$\frac{dV}{d\bar{R}} = -\frac{F_V}{V}\left[\frac{g\,A^2 Q_p\,\bar{V}_d}{1+\bar{V}_d} - 1\right], \tag{3}$$

where Q_p is the radiation pressure coefficient of the grains and the parameters g and F_V are defined as

$$g = \frac{3\,L\,f_g}{16\pi\,c\;G\;M\;d\;a_0} \approx 9.0\left[\frac{10\text{ nm}}{a_0}\right] \tag{4}$$

and

$$F_V = \frac{G\;M}{r_0\,v_0^2} \approx 0.22\left[\frac{6\cdot 10^{14}\text{ cm}}{r_0}\right]\left[\frac{10\text{ km/sec}}{v_0}\right]^2. \tag{5}$$

Here L is the stellar luminosity (~ $2.5\cdot 10^{37}$ erg/sec), M the stellar mass (~ $2\cdot 10^{33}$ g), f_g the mass fraction of aluminum oxide (~ $9.6\cdot 10^{-5}$), d the density of aluminum oxide (~ 4 g/cm^3), c the light velocity, and G the gravity constant.

The drift velocity variable $\bar{V}_d$ is given, if the thermal velocity is much smaller than v_d, by

$$\bar{V}_d = \left[\frac{\dot{M}\;c\;v}{Q_p L}\right]^{1/2} \approx 0.276\left[\frac{\dot{M}}{10^{-6}\,M_\odot/\text{yr}}\right]^{1/2}\left[\frac{V}{Q_p}\right]^{1/2} C_l^{1/2}. \tag{6}$$

The emergent flux is obtained by the integration of the formal solution (Chandrasekhar, 1960):

$$F_\lambda = \pi\left[\frac{R_*}{D}\right]^2 \tag{7}$$

$$\times\left[B_\lambda(T_*)\,e^{-\tau_\lambda} + 2\int_0^{p_m} p^2\,dp \int_{\phi_1}^{\phi_2} B_\lambda(T_d(r))\,k(r)\,\text{cosec}^2\phi\;\exp(-p\int_{\phi_1}^{\phi} k(r)\,\text{cosec}^2\,\phi\,d\phi)\,d\phi\right].$$

Here T_* is the stellar temperature (~ 2500 K), R_* the stellar radius (~ $3\cdot 10^{13}$ cm), D the distance to the star, and τ_λ the extinction optical depth. The input parameter p is normalized by R_*. The dust temperature $T_d(r)$ is calculated from the energy balance:

$$\int \frac{F_*(\lambda)}{r^2}\,Q_{abs}(\lambda)\;e^{-\tau_\lambda}\,d\lambda = 4\int Q_{abs}(\lambda)\,B_\lambda(T_d(r))\,d\lambda \tag{8}$$

and the volume emission coefficient $k(r)$ is given by

$$k(r) = k_0\,A^2\,Q_{abs}\,\frac{(v+v_d)_0}{v+v_d}, \tag{9}$$

with

$$k_0 = \frac{3\,f_g\,R_*\,\dot{M}}{16\pi\,d\,r_1^2\,v_0\,a_0}\left[\frac{\bar{V}_d}{1+\bar{V}_d}\right]_0 \approx 1.91\left[\frac{10\text{ km/sec}}{v_0}\right]\left[\frac{10\text{ nm}}{a_0}\right]\left[\frac{\dot{M}}{10^{-6}\,M_\odot/\text{yr}}\right]\left[\frac{\bar{V}_d}{1+\bar{V}_d}\right]_0,$$

where r_1 is the inner boundary of the aluminum oxide dust shell (~ $3.8\cdot 10^{13}$ cm) and the suffix o represents the value at $r=r_0$. The optical constants for aluminum oxide are taken from Eriksson *et al.* (1981) and those for silicate referred to Day (1979).

In Figure 1, the radial variation of A, V, v_d, and T_d are shown for models with different a_0 and $\dot{M}$. As seen in Figure 1, the changes of V and v_d are small. The gas velocity decreases slightly at the beginning in order to adjust the boundary conditions ($v=v_0$) and the decrease is probably not realistic. However, it is small and does not make significant effects to calculated spectra. The temperature profile weakly depends on the model parameters. Thus, calculated spectra depends mostly on the parameter F_R and k_0. If the grain size is much smaller than the wavelength in question, Q_p and Q_{abs} are approximately proportinal to the size. Therefore, F_R is proportional to $\dot{M}/a_0$ and $k(r)$ to $\dot{M}$: a_0 and $\dot{M}$ are the major parameters in this model.

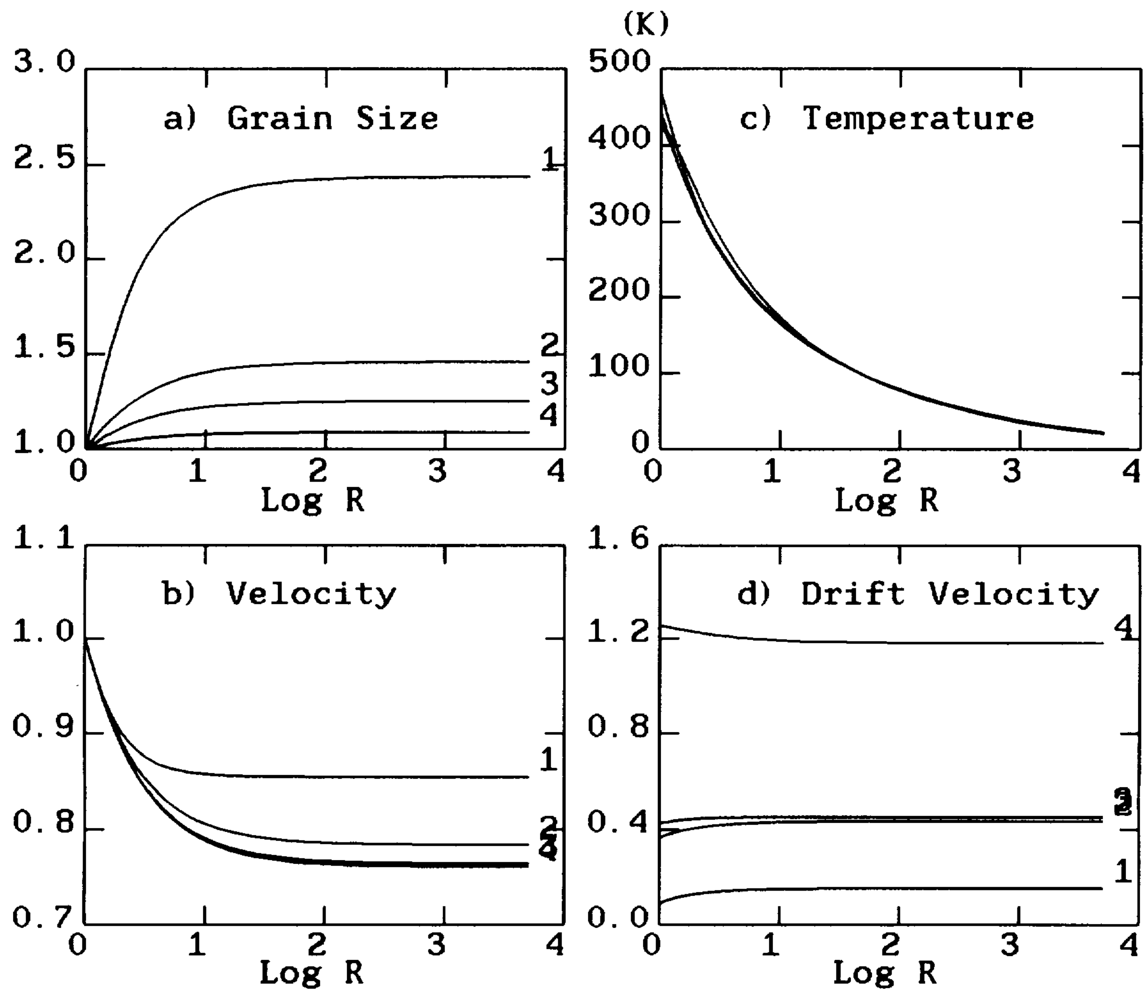

Figure 1. a) Radial distribution of grain radius normalized by core radius. b) Normalized velocity. c) Dust temperature (in K). d) Drift velocity normalized by initial gas velocity. All models are calculated with v_0=10 km/sec, C_l=1, and r_0=6·10^{14} cm. Model numbers are indicated on each curve; 1: a_0=10 nm, $\dot{M}$=10^{-5} M$_\odot$/yr, 2: a_0=100 nm, $\dot{M}$=10^{-5} M$_\odot$/yr, 3: a_0=20 nm, $\dot{M}$=10^{-6} M$_\odot$/yr, and 4: a_0=100 nm, $\dot{M}$=10^{-6} M$_\odot$/yr. The abscissa is the normalized distance (r/r_0).

A model grid was constructed for various sets of a_0 and $\dot{M}$. The *best fit* model parameters were obtained for each observed spectrum. The samples of LRS spectra are the same as in Onaka *et al.* (1988). The parameter r_0 was set to be 6·10^{14} cm since it was found to give the best fit of models to most observed spectra. Effects of v_0 and C_l were also examined. Examples of fitted spectra with LRS spectra are shown in Figure 2. Most LRS spectra of M Mira variables in the present sample are reproduced satisfactorily by the models with parameter range $10^{-6} < \dot{M} < 10^{-5}$ M$_\odot$/yr and $5 < a_0 < 400$ nm). However, in some cases, *e.g.*, RR Aql, a much larger F_R is reqiured to reproduce a *strong* silicate feature. Unless we assume a very fine core radius (~ 0.5 nm) it is difficult to have a good fit.

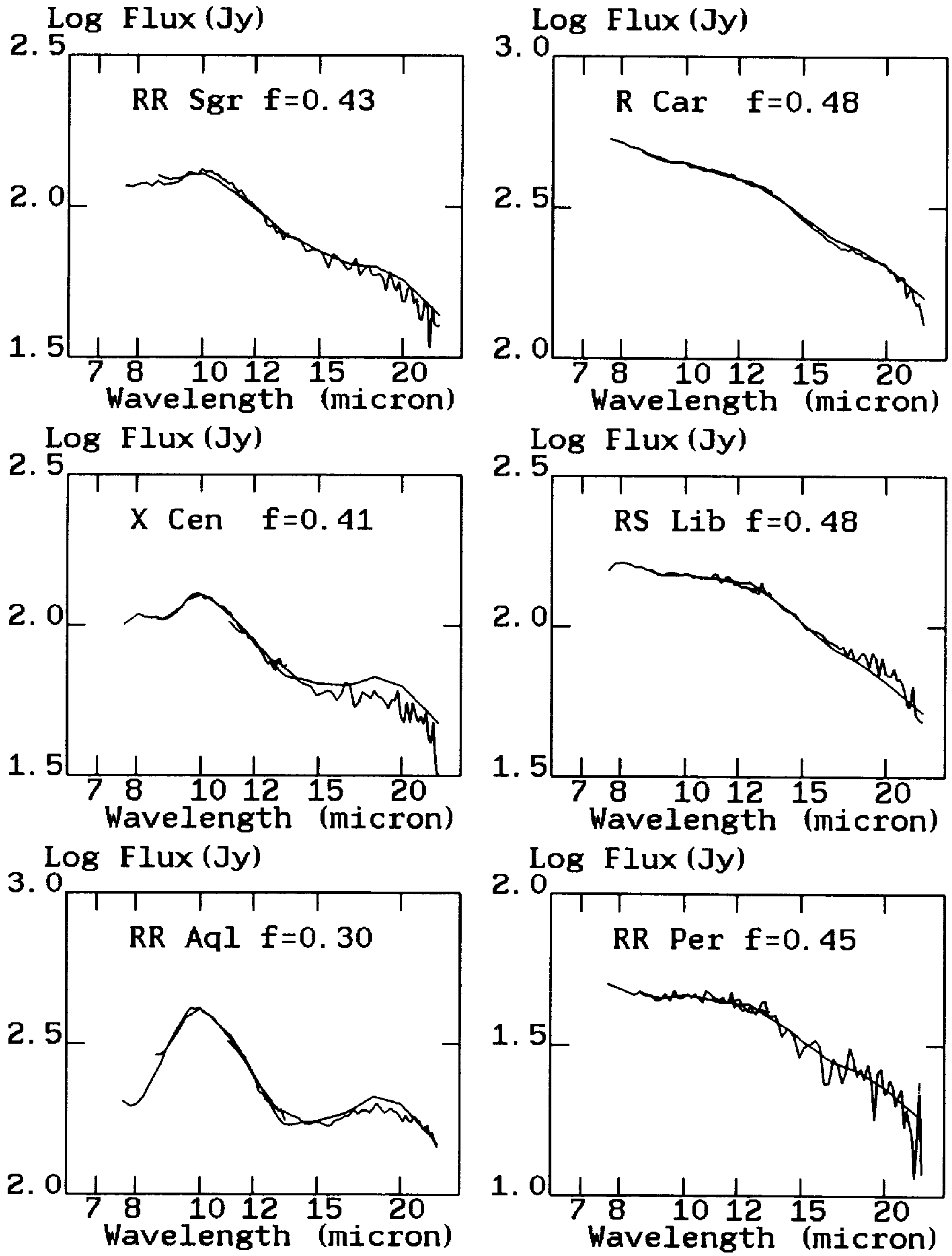

Figure 2. Examples of model spectra together with LRS spectra of M-type Mira variables. They are shown in the order of light curve asymmetry index f (*cf.* Vardya *et al.*, 1986). Model parameters are: (a_0 (nm), $\dot{M}$ (10^{-6} $M_\odot$/yr), v_0 (km/sec), and C_l) = (5, 2, 10, 10) for RR Aql, (5, 2, 7, 1) for X Cen, (10, 2, 7, 1) for RR Sgr, (200, 10, 7, 1) for RR Per, (100, 10, 10, 1) for RS Lib, and (400, 10, 7, 5) for R Car.

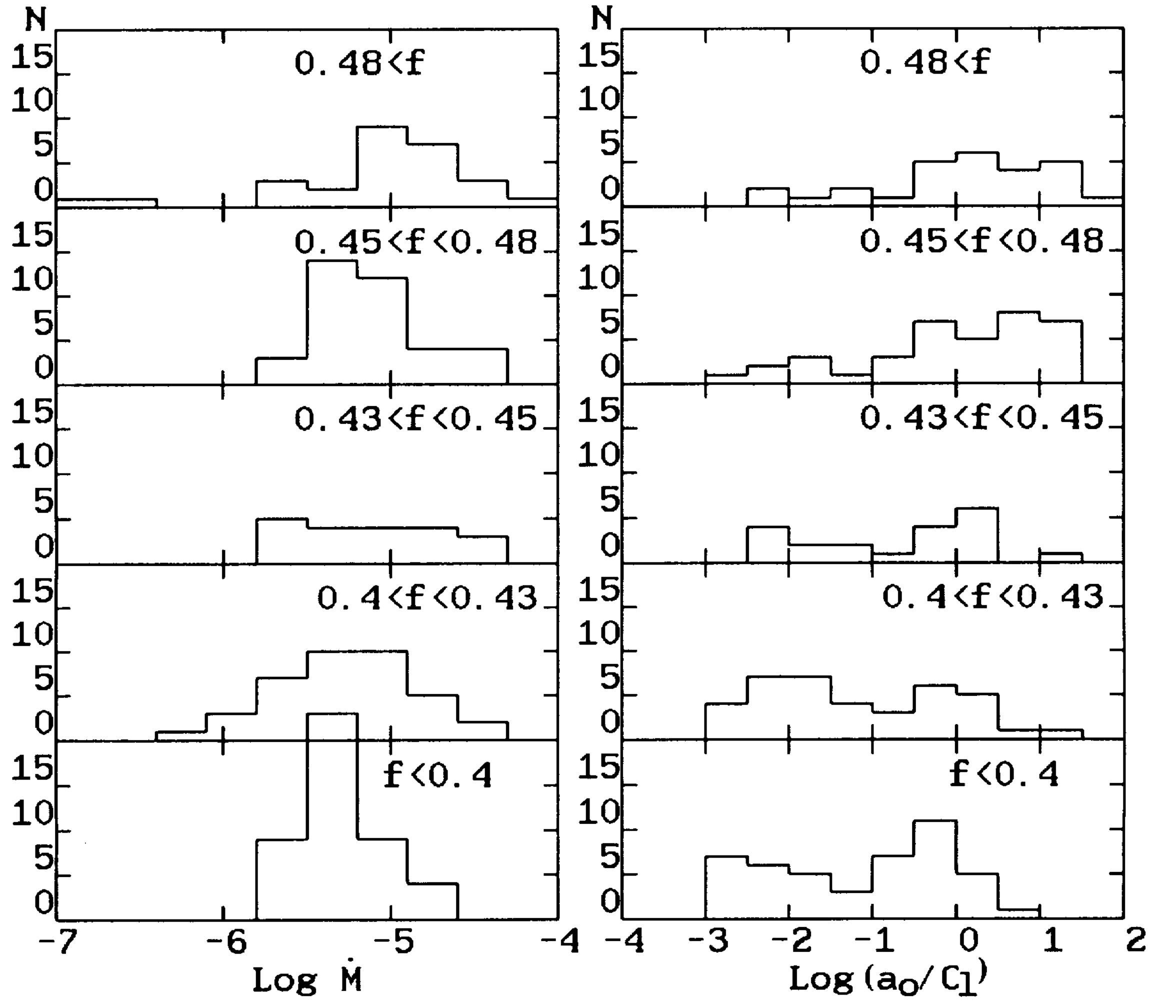

Figure 3. Distributions of model parameters Log($\dot{M}$) ($\dot{M}$ in $M_{\odot}$/yr) and Log(a_0 / C_l) (a_0 in nm) for stars with different light curve asymmetry index f.

Thus, we introduce a *clumpiness* parameter C_l as described in equations (2) and (6). We assume that in these stars a density fluctuation occurs and accelerates the mantle growth. It also affects the drag force (equation (6)). However, owing to the optically-thin nature of the present models, effects to the transfer equation (7) can be neglected. If we introduce C_l, the model fit becomes much improved (*e.g.*, RR Aql in Figure 2). As inferred from equations (2) and (6) it is difficult to separate the effects of C_l from those of a_0 a priori. The change of v_0 also improves the model fit. However, its effects are small since observed terminal velocities are in a small range.

The distribution of model parameters a_0 divided by C_l and $\dot{M}$ are shown in Figure 3 for five groups of stars with different light curve asymmetry index f. It is clear that for stars with small f index (asymmetric light curve) a small core radius or a large clump is required. For models of stars with large f index (symmetric light curve), somewhat larger $\dot{M}$ is obtained compared to stars with small f index. This is consistent with the observed trend of the 9.7 μm feature with f: Only stars with f <0.43 show the 9.7 μm feature and those with f >0.43 do not. If a_0 is small or C_l is large, F_R becomes large and silicate mantle grows quickly; emergent spectra show the silicate feature clearly. If a_0 is large, on the other hand, mantle growth is suppressed and the aluminum oxide feature at 12 μm is observed.

According to the present model, the observed variation in appearance of the 9.7μm feature is ascribed to the variation of grain size of core aluminum oxide grains or to the degree of density fluctuation in the circumstellar envelope. Some degree of density fluctuation is necessary unless very fine grains are assumed, although in the present analysis it is difficult to separate the effects of C_l from those of a_0. The size of aluminum oxide grains is considered to be determined by the nucleation process at the bottom of the circumstellar envelope. According to Yamamoto and Hasegawa (1977) and Draine and Salpeter (1977) the particle size in the homogeneous nucleation process is determined by the ratio of the cooling time scale of the system to the collision time scale of the condensible gas particles. In stars with small f index the shock propagates strongly and the cooling occurs rapidly, thus, small aluminum oxide grains may be formed. It may be also possible that further mutual collisions occur frequently in circumstellar envelopes of these stars and that grains are broken into small pieces (Biermann and Harwit 1980). Strong shocks may also produce a large density fluctuation. The observed variation of LRS spectra, thus, can be ascribed to the difference of the physical conditions at the bottom of the circumstellar envelope and should provide important information on the acceleration mechanism of mass loss process.

The increment at 18μm for some stars (*e.g.*, R Car in figure 2) may not be well reproduced by the present model. The dependence of silicate band strength on the temperature, which has been indicated experimentally by Day (1976) and suggested from the dust shell model analysis by Bedijn (1987), may have to be taken into account.

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