Grain formation in Nova Envelopes

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(Received September 10, 1976)

Grain formation in ejected envelopes of novae is investigated. The solar abundance is assumed as one of the typical examples that C/O is smaller than unity. The magnesium silicate is proved to be the first main condensate. We estimate the monomer concentration \( c_1(t) \) at the onset of condensation to be about \( 10^5 \text{cm}^{-3} \) for \( \Delta M = 3 \times 10^{-4} M_\odot \) and \( V_{\text{exp}} = 1000 \text{km sec}^{-1} \). \( \Delta M \) is the ejected mass and \( V_{\text{exp}} \) is the expansion velocity. Then we calculate the time variation of the concentrations of magnesium-silicate grains on the basis of the nonsteady nucleation theory. The size distributions are found to be flat or diffuse and have no conspicuous peak. The boundary whether grains are formed or not is determined mainly by the amount of the ejected mass. The lower limit of the ejected mass for the grain formation is about \( 10^{-4} M_\odot \). The maximum radius of grains is estimated to be about \( 50 \text{Å} \) for \( c_1(t) = 5 \times 10^4 \text{cm}^{-3} \).

§ 1. Introduction

Recently, the development of infrared observations has revealed the existence of infrared excesses of some novae. Geisel et al.\(^{11}\) and Hyland and Neugebauer\(^{21}\) observed the infrared excess of Nova Serpentis 1970. Geisel et al. reported that in 50 days after its discovery the infrared luminosity started to increase and reached the peak after 90 days. They suggested that the infrared excess of Nova Serpentis 1970 was due to the thermal emission from grains formed in the ejected envelope. Westphal and Neugebauer\(^{29}\) observed the infrared excess of \( \eta \) Carinae. This object is said to be an old nova. On the other hand, Kawara et al.\(^{4}\) reported that Nova Cygni 1975 did not show the infrared excess within their observational accuracy.

Clayton and Wickramasinghe\(^{5}\) investigated the growth process of grains on the basis of a simple model and calculated the development of the infrared emission from these grains. They assumed the ejected gas is composed mainly of carbon and discussed the formation of graphite grains.

However, the chemical composition of the ejected gas has not been well known as yet. According to the theoretical work of Starrfield et al.\(^{6}\), the abundances of C, N and O are several times the solar abundance with some variety dependent on models. However, the abundance ratio C/O is smaller than unity according to their calculation. In this case, carbon atoms will be almost all depleted in CO molecules and cannot condense into graphite grains. The elemental
abundances heavier than C, N and O have not been studied. Thus, we assume the abundance of nova ejecta to be the solar abundance as one of the typical examples that C/O is smaller than unity, and investigate what grain materials will condense on the basis of the thermochemical calculations. Magnesium silicate is proved to be the first main condensate as described later.

Grain formation processes in various astrophysical environments have been studied based on the steady state nucleation theory, the chemical equilibrium calculations or the simple calculations of considering the sticking process alone. Taking into account the sticking process alone will give the most optimistic results. The steady state nucleation theory and the chemical equilibrium calculations are applicable so far as the time scales of variation of the temperature and density are long compared with the nucleation time lag such as in stellar atmospheres. In nova envelopes, however, the situation is quite different in that the time variation of temperature and density is so rapid that the steady state nucleation theory is unapplicable. In this paper, we derive the nonsteady nucleation formalism suitable for treating the present problem. On the basis of this formalism, we describe the grain formation process in nova envelopes and investigate the condition in which grains are formed.

In § 2, thermodynamical and chemical properties of ejected envelopes are described. Chemical species of condensates and the temperature and density at the beginning of condensation are estimated. The basic equations for nonsteady nucleation problem are given in § 3. In § 4, numerical results are presented with the estimate of maximum size of grains and of the lower limit of the ejected mass to form grains. Discussion is presented in § 5.

§ 2. Thermodynamical and chemical properties of ejected envelopes

The thermodynamical behavior of the ejected gas envelope is not established either theoretically or observationally. We assume a spherically symmetric expansion for simplicity. We also assume the uniformity of temperature $T$ and number density $n$ of the envelope. This assumption is enough for the limited purpose of a rough estimate of the number density at the onset of the condensation of grains. Since the optical depth of the envelope for UV and visible radiation is much larger than unity until the temperature of the envelope decreases to $\sim 10^4 \text{K}$, the energy balance $\Delta Q/\Delta t$ is given by

$$\Delta Q/\Delta t = L_\text{x} - 4\pi R^2 \sigma T^4.$$

In Eq. (2·1), $L_\text{x}$ is the luminosity of the central star, which is supposed to be several $10^4 L_\odot$. $R$ is the outer radius of the envelope, $T$ is the gas temperature, and $\sigma$ is the Stephan-Boltzmann constant. The condensation temperature is about 1000 K as shown later. The optical depth of visible radiation may be less than unity for this temperature. But Eq. (2·1) is still useful for the above-mentioned
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purpose.

Then we can calculate numerically the loci of expanding envelopes on the $n$-$T$ plane. Figure 1 shows that the nearly radiative equilibrium state is realized at the condensation temperature, irrespective of the choice of the parameters. The outer radius of the envelope $R$ and the number density of gas $n$ are related with the temperature $T$ as

$$R = \left( \frac{L_*}{4\pi\sigma T^4} \right)^{1/2}, \quad (2\cdot2)$$

and therefore,

$$n = \frac{\Delta M/m_H}{\frac{4\pi\eta}{3} (L_*/4\pi\sigma T^4)^{3/2}}, \quad (2\cdot3)$$

where $\Delta M$ and $m_H$ are the ejected mass and the mass of hydrogen atom, respectively. In Eq. $(2\cdot3)$, $\eta$ is the "geometrical factor" and is constant, if the envelope expands keeping its width proportional to the outer radius. (The width is $\eta R/3$ for the small width compared with the outer radius.) We adopt $\Delta M = 3 \times 10^{-4} M_\odot$, $\eta = 0.3$, $L_* = 5 \times 10^4 L_\odot$ as the standard values. Numerical expressions of Eqs. $(2\cdot2)$ and $(2\cdot3)$ are

$$R(T) = 4.3 \times 10^{14} \left( \frac{1100 K}{T} \right)^2 \left( \frac{L_*}{5 \times 10^4 L_\odot} \right)^{1/2} \text{ cm} \quad (2\cdot4)$$

and

$$n(T) = 3.5 \times 10^9 \left( \frac{T}{1100 K} \right)^6 \left( \frac{\Delta M}{3 \times 10^{-4} M_\odot} \right) \left( \frac{0.3}{\eta^2} \right) \left( \frac{5 \times 10^4 L_\odot}{L_*} \right)^{3/2} \text{ cm}^{-3}. \quad (2\cdot5)$$

Next, we investigate the condensation temperatures under the chemical equilibrium configuration. The method of the calculation is the same as those of Grossman, Salpeter and others. We are concerned with a lower pressure region ($P = 10^{-5} \sim 10^{-4} \text{ dyn cm}^{-2}$) than their cases. Thermochemical data on elements and compounds are from JANAF Tables.

For the standard parameters (the dash-dotted curve in Fig. 2), the condensation temperatures of $\text{Al}_2\text{O}_3$, $\text{Mg}_2\text{SiO}_4$, $\text{MgSiO}_3$, $\text{SiO}_2$ and Fe are found to be 1404 K, 1075 K, 1068 K, 1014 K and 988 K, respectively. An increase by one order of the gas pressure corresponds to an increase of only several tens of degrees for the condensation temperature of each condensate.

Corundum ($\text{Al}_2\text{O}_3$) is the first condensate, but the abundance of Al is lower than Si by about one order. Therefore we neglect $\text{Al}_2\text{O}_3$ grains. Magnesium
silicate (forsterite (Mg_2SiO_4) or enstatite (MgSiO_3)) is considered to be the first main condensate. In the following, the condensation process of magnesium-silicate grains is discussed in detail.

At the condensation temperature \( T_1 \) under the condition of chemical equilibrium, the nucleation process begins to work. At the onset of nucleation, the gas density and the outer radius of the envelope are given by \( n_1 = n(T_1) \) and \( R_1 = R(T_1) \), respectively. The time elapsing after the outburst is

\[ t_1 = \frac{R_1}{V_{\text{exp}}} \]

with a constant expansion velocity. We obtain \( n_1 = 3 \times 10^9 \text{ cm}^{-3} \), \( R_1 = 4 \times 10^{14} \text{ cm} \) and \( t_1 = 50 \text{ days} \) for the standard values of \( \Delta M \), \( \eta \) and \( L_\ast \), \( V_{\text{exp}} = 1000 \text{ km sec}^{-1} \) and \( T_1 = 1100 \text{ K} \).

§ 3. Kinetic equations of grain formation

The nucleation in nova envelopes is to be solved by considering that it is a nonsteady process and the temperature and the density decrease with time.

Courtney\(^{17}\) and Abraham\(^{18}\) studied a nucleation process in a nonsteady stage before the steady state is realized with initial conditions of given supersaturated states. They treated these transient phenomena by integrating numerically the master equations for each size of embryos under the condition of constant temperature. Feder et al.\(^{19}\) investigated a formation of water droplets in a cloud chamber assuming an expansion to be adiabatic. Since the nucleation time lag is much shorter than the expansion time scale of cloud chamber, however, they used
the steady state nucleation theory.

The reason why we should use the nonsteady theory for the nucleation in nova envelopes is that the nucleation time lag is about the same order as the expansion time scale (of the ejected envelope). The temperature decrease with time is also to be taken into account. Thus we use the master equations, in which the temperature-dependent coefficients are functions of time.

Clusters of condensate grow or decay by a set of monomer reactions,

\[ A_{g-1} + A \xrightarrow{r} A_g, \quad (g \geq 2) \]  

(3·1)

where \( A_g \) represents a cluster which contains \( g \) molecules of \( A \). Since the number density of monomers is much larger than that of the clusters with \( g \geq 2 \) in the early stage of the condensation process, and since the features of grain formation are almost determined in this stage as shown later, we can neglect the growth by cluster-cluster collisions.

For the formation of magnesium silicate, matters are rather complicated. The condensation process of magnesium silicate, for example, Mg\(_{2}\)SiO\(_4\) is not a set of simple monomer reactions as Eq. (3·1). Since the sticking of SiO molecules is essential for forming the solid silicate, however, we can simplify the problem without changing an essential feature as follows. Namely, we consider that the magnesium-silicate grains are formed through the set of reactions of Eq. (3·1), where the \( A \) means an SiO molecule and the \( A_g \), a cluster which consists of \( g \) Mg\(_2\)SiO\(_4\) (or MgSiO\(_3\)) molecules.

We denote the concentration of \( A_g \) clusters by \( c_g \) and the specific volume by \( E \). The specific volume means the volume of the envelope divided by the volume of the envelope at time \( t_1 \) (at the onset of condensation). The master equations are given by

\[ \frac{df_g}{dt} = p_{g-1}f_{g-1} - q_gf_g + r_{g+1}f_{g+1}, \quad (g \geq 2) \]  

(3·2)

where \( f_g = Ec_g(t)/c_1(t) \). The coefficients \( p_g \), \( r_g \) and \( q_g \) are the sticking rate, the evaporation rate and their sum, respectively. The sticking rate \( p_g \) is given by

\[ p_g = \alpha_g c_1(t) \sigma_g \langle v \rangle, \]  

(3·3)

where \( \alpha_g \), \( c_1(t) \), \( \sigma_g \) and \( \langle v \rangle \) are the sticking probability, the number density of monomers, a surface area of an \( A_g \) cluster and the mean thermal velocity of monomers respectively. Here we take \( \alpha_g \) to be unity for any \( g \). If \( \alpha_g \neq 1 \), the grain formation time scale just increases by \( 1/\alpha_g \) times on the assumption that \( \alpha_g \) is independent of \( g \). With the aid of the principle of detailed balance, the evaporation rate \( r_g \) is related to the sticking rate as

\[ r_g = p_{g-1} \exp[\frac{\alpha_g}{\alpha_g} - (g-1)z] - \ln S], \]  

(3·4)

where

\[ \tau = 4\pi \sigma_0 a_0^2/kT. \]  

(3·5)
In Eq. (3.5), $a_0$ is the radius of a monomer, and $\sigma_s$ is the surface tension of the condensate. For magnesium silicate, we put $a_0 = 1.5\,\text{Å}$ and $\sigma_s = 400\,\text{erg}\,\text{cm}^{-2}$. 

The vapor pressure of the condensable matter at temperature $T$ is approximated as

$$\log P_v(T) = -\frac{a_v}{T} + b_v.$$  \hspace{1cm} (3.6)

In this problem, $P_v(T)$ is taken to be the SiO partial vapor pressure over magnesium-silicate condensate. From Fig. 2, we have $a_v = 2.77 \times 10^4\,\text{K}$ and $b_v = 17.98$, where $P_v$ is in dyn cm$^{-2}$.

The equation of mass conservation is practically written as

$$f_1(t) = f_1(t_1) - \sum_{g \geq 2} g f_g(t),$$ \hspace{1cm} (3.7)

because the $c_p(t_1)'s$ for $g \geq 2$ are much less than the monomer concentration $c_1(t_1)$ at $t = t_1$.

The supersaturation ratio $S$ is defined by

$$S = \frac{f_1(t)}{S_n},$$ \hspace{1cm} (3.8)

where $S_n = c_1(t_1)kT/EP_v(T)$, which is called the nominal supersaturation ratio. The quantity $\sum_{g \geq 2} g f_g(t)$ in Eq. (3.7) indicates the degree of the exhaustion of monomers, and so the ratio $S/S_n$ is a measure of grain formation.

If we know a time-dependent form of the specific volume $E$ and a volume-dependence of the temperature $T$, we can calculate, from Eq. (3.2), the time variation of the concentrations of clusters of various sizes as functions of $E$.

§ 4. Results of calculations

4.1. Numerical results

We define here the expansion time scale $\tau_1$ of the envelope at the onset of condensation by

$$\tau_1 = \frac{R_1}{3V_{\text{exp}}} = 1.44 \times 10^6 \left( \frac{1000\,\text{km}\,\text{sec}^{-1}}{V_{\text{exp}}} \right) \left( \frac{L_\odot}{5 \times 10^4 L_\odot} \right)^{1/2} \left( \frac{1100\,\text{K}}{T_1} \right)^2 \text{sec}.$$ \hspace{1cm} (4.1)

As already assumed, the expansion velocity $V_{\text{exp}}$ is constant, and the width of the envelope increases in proportion to the outer radius $R$. Then the time dependence of $E$ is given by

$$E = (t/3\tau_1)^2.$$ \hspace{1cm} (4.2)

Here we take $\tau_1$ to be $10^8\,\text{sec}$ as a standard value (Eq. (4.1)). From Eq. (2.4), the temperature $T$ is expressed as

$$T = T_1 E^{-1/4}.$$ \hspace{1cm} (4.3)
At the onset of condensation process, the hydrogen number density \( n_1 \) is several \( \times 10^9 \) cm\(^{-3}\). Since the solar abundance of Si is about four orders of magnitude smaller than that of hydrogen, the number density of monomers \( c_1 \) at \( t = t_1 \) is about \( 10^5 \) cm\(^{-3}\). On account of ambiguities of \( \Delta M, \eta \) and \( L_\eta \) as well as the actual abundance of Si, we consider the following three cases representatively:

Case A: \( c_1(t_1) = 5 \times 10^5 \) cm\(^{-3}\), 
Case B: \( c_1(t_1) = 5 \times 10^5 \) cm\(^{-3}\), 
Case C: \( c_1(t_1) = 5 \times 10^5 \) cm\(^{-3}\).

The condensation temperatures for the three cases are 1061 K, 1104 K and 1151 K respectively.

The supersaturation ratio \( S \) and the size of the critical cluster \( g^* \) are shown in Fig. 3, where \( g^* \) is given by

\[
g^* = \left( \frac{2r}{3 \ln S} \right)^3. \tag{4.4}
\]

The behavior of \( S \), compared with the nominal supersaturation ratio \( S_n \), indicates the degree of the depletion of monomers. In Case A (very tenuous gas), there is a little difference between the actual \( S \) and the \( S_n \), which means that the growth of clusters is very slow. In Cases B and C, \( S \) deviates remarkably from \( S_n \) beyond \( E \approx 1.4 \), because the clusters grow rapidly in the small time interval just after the onset of condensation.

Figure 4 shows the growth curves of the concentrations \( c_g \) of clusters with sizes \( g = 10, 50 \) and 95. For large clusters, their concentrations increase rapidly in the early stage of the condensation. The larger the size is, the more rapidly the clusters grow, because the larger clusters have larger sticking cross sections and are more stable energetically. The growth curve for each cluster size reaches a plateau in a short time. At about \( E = 2 \), the grain formation comes practically to the end by the monomer consumption into grains as well as by the density dilution with volume expansion. The concentration of monomers is still larger than that of the clusters with \( g \geq 2 \) at \( E = 2 \) for all cases. Therefore the growth by cluster-cluster collisions is considered to be ineffective practically in all stages.

The fraction of monomers which survive without condensing into grains is less than one-tenth at \( E = 2 \) in Cases B and C. In Case A, large clusters \( (g \geq 100) \) are hardly formed. Even in this tenuous case, monomers are consumed for making small clusters. Only one-third of them survives at \( E = 2 \), and the further consumption of monomers continues.

In our model, \( E = 2 \) corresponds to 10 days after the onset of condensation. The results suggest that almost all the monomers of condensable elements condense into grains within several tens of days after the explosion when \( c_1(t_1) \) is larger than \( 5 \times 10^5 \) cm\(^{-3}\). The total mass of grains \( M_g \) is about \( 1.5 \times 10^{-6} M_\odot (Z_g/5 \times 10^{-3}) \cdot (\Delta M/3 \times 10^{-4} M_\odot) \), where \( Z_g \) is the mass abundance of condensable elements.
In order to illustrate the feature of grain formation in nova envelopes, we refer to the condensation process in stellar atmospheres. In the latter case, the monomer concentration is so high that the steady state nucleation theory has been applied. In our case, the supersaturation ratio $S$ is about 10 at $E = 1.4$. This value is larger than the corresponding values in stellar atmospheres like carbon stars.\textsuperscript{80~103} Moreover, in the stellar atmospheres, a sudden drop of the supersaturation ratio is expected because of the rapid consumption of monomers.\textsuperscript{8} However such a sudden drop cannot be found in our case, because even in Cases B and C the monomer density is not so high as in the stellar atmospheres that the collision frequency of monomers with clusters is relatively low.

Though the steady state may not be realized in nova envelopes, a consideration of the steady state nucleation rate may serve to clarify the feature of grain formation. The steady state nucleation rate $J_s$ is given by

\[ J_s = K c_1(t)^2 \exp(-\Delta G^*/kT), \]  

(4.5)
where $K$ is a constant determined by the grain material and $\Delta G^*$ is the free energy of formation of the critical cluster. Figure 5 shows that $J_1$ increases rapidly after the onset of condensation, takes a maximum at $E=1.9$ (Case A), 1.6 (Case B) and 1.4 (Case C), respectively and decreases slowly after the maximum. In each case, the critical size $g_m^*$ at the maximum of $J_1$ is below 10, although these values may be beyond the limit of applicability of the capillarity approximation. On the other hand, the nucleation rate in the dense gas drops off suddenly after its maximum and the critical size is relatively large. Thus the slow decrease of $J_1$ and the smallness of $g_m^*$ are considered to be a general feature in low density and rapid cooling environments.

The size distributions of clusters in Case B at several values of $E$ (several $t$'s) are shown in Fig. 6. The nonsteady effect is seen from this figure. Whereas the concentrations of small clusters reach the equilibrium values immediately, the concentrations of large clusters with $g \geq g^*$ are considerably smaller than those expected from the steady state theory. For example, $c_{95}(t)$ at $E=1.10$ is only about $10^{-20}$ times the value expected from the steady state theory.

In Fig. 7, the size distributions at $E=2.25$ for the three cases are shown. These are regarded as the final distributions. To form many large clusters, the
monomer concentration at the onset of condensation $c_1(t_1)$ should be about $5 \times 10^5 \text{cm}^{-3}$ or more, corresponding to the ejected mass $\Delta M$ of $1 \times 10^{-5} M_\odot$ for the abundance adopted here. It is noted that the size distributions in our case are flat or diffuse, extending to very small clusters ($g \leq 10$) compared with those in stellar atmospheres.\(^8\)

4.2. Maximum size of grains

We have solved numerically the master equations of the $f_i$'s with $g \leq 100$. For large clusters of $g$ appreciably larger than the critical size $g^*$, the sticking rate is much larger than the evaporation rate. The growth of such clusters can be described by the equation

$$\frac{d}{dt} \left( \frac{4}{3} \pi a^3 \right) = \mathcal{Q} c_1(t) 4\pi a^2 \langle v \rangle,$$  \hspace{1cm} (4.6)

where $a$ and $\mathcal{Q}$ are the radius of the cluster and the molecular volume of the condensate, respectively. As was already shown in § 4.1, the critical size $g^*$ is a small number except for a very small time interval just after the onset of condensation. Therefore we obtain the maximum radius of clusters $a_{\text{max}}$ approximately by integrating Eq. (4.6) from $t = t_1$ to $t = \infty$. The result is

$$a_{\text{max}} = \frac{4}{3} c_1(t_1) \mathcal{Q} \tau_1 \left( \frac{kT_1}{2\pi m} \right)^{1/2},$$  \hspace{1cm} (4.7)

if the effect of monomer depletion is neglected.

For magnesium silicate (forsterite), $\mathcal{Q} = 7.2 \times 10^{-20} \text{cm}^4 \text{cm}^{-3}$ and $m = 7.4 \times 10^{-23} \text{g}$. Then Eq. (4.7) can be written as

$$a_{\text{max}} = 87 \left( \frac{c_1(t_1)}{5 \times 10^5 \text{cm}^{-3}} \right) \left( \frac{\tau_1}{10^8 \text{sec}} \right) \left( \frac{T_1}{1100 \text{K}} \right)^{1/2} \text{Å}.$$  \hspace{1cm} (4.8)

Considering the monomer depletion by grain formation, the numerical factor in Eq. (4.8) turns out to be about 50 instead of 87, and afterwards the new value 50 is used. For the typical envelope conditions such as $\tau_1 = 10^8 \text{sec}$, $T_1 = 1100 \text{K}$ and $c_1(t_1) = 5 \times 10^4 \text{cm}^{-3}$, $5 \times 10^5 \text{cm}^{-3}$ and $5 \times 10^6 \text{cm}^{-3}$, the maximum size $a_{\text{max}}$ is $5 \text{Å}$, $50 \text{Å}$ and $500 \text{Å}$, respectively.

For $c_1(t_1) < 5 \times 10^4 \text{cm}^{-3}$, $a_{\text{max}}$ becomes smaller than $5 \text{Å}$ and loses its physical meaning. Thus, it is necessary for $c_1(t_1)$ to be larger than $5 \times 10^4 \text{cm}^{-3}$, at least, corresponding to $\Delta M$ of $1 \times 10^{-4} M_\odot$ for the abundance adopted here.

It is noted that the maximum size $a_{\text{max}}$ is several hundred Å or less. Novae will not be able to supply micron or submicron grains into the interstellar space,
unless the secondary process such as the condensation of less refractory materials (for example, iron) on the primary grains takes place.

§ 5. Discussion

(1) The boundary whether the grains are formed or not in nova envelopes is determined mainly by the amount of the ejected mass. From Fig. 7 and the estimate of \( a_{\text{max}} \), \( c_1(t_1) \) should be larger than \( 5 \times 10^4 \text{ cm}^{-3} \) to form grains. Therefore, the ejected mass \( \Delta M \) should be larger than about \( 10^{-4} \text{M}_\odot \) for the abundance adopted here, assuming the expansion velocity \( V_{\text{exp}} = 1000 \text{ km sec}^{-1} \). In view of this criterion, the infrared excess novae such as Nova Serpentis 1970 seem to have \( \Delta M \) larger than this critical mass. On the other hand, Nova Cygni 1975 does not.

It is noted that if the ejected mass is larger than this critical mass, we can expect that almost all the condensable elements condense into grains within several tens of days after the explosion (within about ten days after the onset of condensation). According to Starrfield et al., the CNO abundances in their nova ejecta models are several times enhanced. If the abundances of Si and Mg are also enhanced, the critical mass will become smaller in proportion to the degree of the enhancement.

(2) It is characteristic that the size distributions are flat or diffuse and have no such peak as those in cool stellar atmospheres. The particle sizes are widely distributed from, say, several hundred \( \AA \) to the order of \( \AA \). This tendency is considered to be general in which the gas density is low and the expansion time scale is short. Therefore, a number of very small grains are formed in these environments. Nova envelopes may be the sources of very small grains which are demanded from the discussions on the interstellar far UV extinction and the interstellar condensation nuclei.

(3) The chemical composition of the ejected gas is not well known, especially for the elements heavier than CNO. We have assumed here the solar abundance as one of the typical examples that C/O is less than unity. Then, the first main condensate is magnesium silicate. Unfortunately, however, we have no observations as yet which indicate the 10\( \mu \) feature that is characteristic to silicate grains. Further observations are needed for the future novae.

If C/O is larger than unity as in the atmospheres of carbon stars, graphite grains will be formed. For graphite grains, the condition for the formation will be satisfied more easily than silicate because of the higher abundance of carbon and of the higher condensation temperature. However, it is not assured that C/O is larger than unity.

Anyway, the abundances of the ejected gas should be studied further as well as the future observations of novae to investigate the composition of grains formed in nova envelopes.
Acknowledgements

We are grateful to Professor H. Hasegawa for reading the manuscript and continuous encouragement. We wish to thank Professor C. Hayashi for helpful suggestions. We also express our gratitude to Dr. T. Mukai of Kanazawa Institute of Technology for the aid in numerical calculations. One of us (S.N.) would like to acknowledge continuous support of Professor C. Tatsumi and Professor T. Matsuda of Setsunan University.

Numerical calculations have been performed by FACOM 230-75 of the Data Processing Center of Kyoto University.

References