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TIME-DEPENDENT DUST FORMATION IN NOVAE

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Abstract

The dust formation processes in novae are investigated with close attention to recent infrared observations. Using mainly the classical nucleation theory, we have calculated the time scales of dust formation and growth in the environments of novae. Those time scales roughly resemble the typical observations. We have classified the dust-forming novae into three classes according to their explosion properties and the thermodynamic properties of dust grains. Oxygen grains form much later than carbon grains because of their thermodynamic properties. The effect of grain formation to the efficiency of stellar winds to drive the material outward is tested with newly obtained Planck mean values of dust grains.

1. Introduction

The temporal infrared developments of about 13 novae have been reported as an evidence for dust formation in the white dwarf's atmosphere shortly after novae explosions. Dust grains are believed to form in about 40-250 days after the visual explosion and they keep showing their infrared appearence for about 50-200 days(*e.g.*, Gehrz 1988). Only medium speed novae are known to be related with the infrared developments, probably due to the fact that the fast novae accompany hot ionizing radiation which suppresses the dust formation and the slow novae do not provide enough material to produce notable dust grains(*e.g.*, Gallagher 1977, Mitchell and Evans 1984). Novae provide an unique opportunity to monitor the process of dust formation, even though their contribution to the content of dust grains in the Universe is minor. The major contributors, namely the red giants, show the continuous process of dust formation for a long time(about 10^7 years) but they hide the important information regarding dust formation in fresh(*i.e.* dust-free) environments. The purpose of this work is to investigate the processes of dust formation and growth in novae and the effect of dust formation on driving stellar winds.

We have examined the observational data of 13 novae which are believed to have formed dust grains, namely FH Ser 1970, V1229 Aql 1970, V1301 Aql 1975, V1500 Cygni 1975, NQ Vul 1975, V4021 Sgr 1977, LW Serpentis 1978, V1668 Cygni 1978, V1370 Aquilae 1982, GQ Mus 1983, PW Vulpeculae 1984, QU Vulpeculae 1984 #2, and Nova Hercules 1987. Among these 8 are positively identified as dust-forming novae.

2. Dust Formation and Growth Time Scales

Either graphite or silicate dust grains are believed to form at temperatures lower than about 1000K in circumstellar environments depending on chemical abundance of outflowing material. Dust-forming novae are characterized by their temporal infrared developments in about 40－250 days after their visible explosions depending on the physical properties of the explosion and dust grains. The material blown out from the white dwarf star gets cold enough to form notable dust grains at dust condensation radius. All dust-thick novae and many dust-thin novae are believed to have formed graphite grains whose main composition is carbon. Only one dust-thin nova, QU Vul 1984, has been identified to have formed oxygen dust grains, namely silicate. with their characteristic 10 μm and 20 μm emission features shown 250 days after the explosion (Gehrz *et al.* 1986). To understand the physics of dust formation, we need to know many physical parameters(luminosity, dust formation time, mass loss rate, and terminal velocity of the winds). Unfortunately, only 4 novae are well observed to meet our requirements. Table 1 lists the observational data of the four best observed novae. The meaning of t_{dust} is the time interval from the explosion until the maximum of infrared radiation is detected, V_t is teminal velocity of

Table 1. Physical properties of 4 well observed dust-forming novae

Nova	Luminosity ($\times 10^4 L_\odot$)	t_{dust} (days)	Dust	V_t (km/sec)	τ	Ref.
NQ Vul 1975	3	80	Graphite	750	1.0	1
LW Ser 1978	3－5	75	Graphite	1250	0.6	1
V1668 Cyg 1978	10	57	Graphite	1300	0.08	2
QU Vul 1984	10	240	Silicate	3000(±2000)	3×10^{-3}	3

References: 1:Gehrz *et al.* 1980a; 2: Gehrz *et al.* 1980b; 3:Gehrz *et al.* 1986.

the wind, and τ is the optical depth of the shell when infrared radiation is maximum. The strange thing is that the only one silicate nova from 8 positively identified dust-forming novae, namely QU Vul 1984, has the longest dust formation time and the gap from others is very noticeable.

In this work, we have used the classical nucleation theory. The theory had been applied to red giant stars by many authors(*e.g.*, Kozasa *et al.* 1984, Suh *et al.* 1990). In novae, dust grains are believed to form in originally dust-free environments. We can measure the time scales of dust formation only from the observations of novae. Adopting the notations of Yamamoto and Hasegawa(1977), the grain growth and vapor consumption equations are given by:

$$da/dt = \alpha_s \Omega \langle v \rangle C_1(t) \quad \cdots\cdots (2\text{-}1)$$

$$C_1(t) = C_1(0) - \int_0^t J(t')\ (4\pi/3\Omega)\ a^3(t, t')dt' \quad \cdots\cdots (2\text{-}2)$$

where a, t, α_s, Ω, $\langle v \rangle$, $C_1(t)$ are the grain radius, the time, sticking probability, the volume of vapor molecule, the mean speed at which the vapor molecules collide with a grain, and the concentration of vapor molecules. And J(t) is the steady state nucleation rate. J(t) is a function of $C_1(t)$, μ, and the supersaturation ratio S(t). The value of μ is dependent on thermodynamical properties of the grain material. The important scale parameter (Λ) which characterizes the dust formation process is defined as τ_{sat}/τ_{col} where τ_{sat} is the saturation time and τ_{col} is the mean collision time. The values of Λ, τ_{sat}, and τ_{col} at dust condensation radius are dependent on mass loss rate and luminosity. The value of Λ is about $10^4 - 10^5$ and the saturation time is about $1-2$ weeks based on the luminosity of $10^4 - 10^5$ solar luminosity and the mass loss rate of 10^{-5} solar mass per years for typical novae. Then the nucleation and grain growth equations are solved by using standard Runge-Kutta method.

Figure 1 shows the results of calculation of nucleation rate and grain growth as a function of X for graphite($\mu=10$) in the environment of luminous novae($\Lambda=10^5$). The value of X is defined as $(t-t_e)/\tau_{sat}$ where t is given time and t_e is the time when the temperature becomes the equilibrium temperature which is 1000 K. The value of t_e measured from the visual explosion is about $4-6$ weeks for typical novae. Dust formation begins about $2-4$ weeks after t_e, the nucleation rate is maximum at X_1 which is 2.10, and the grain grows very quickly within one week to its final radius 0.4 μm. So the theoretical dust formation time scale(about 8 weeks) is very simi-

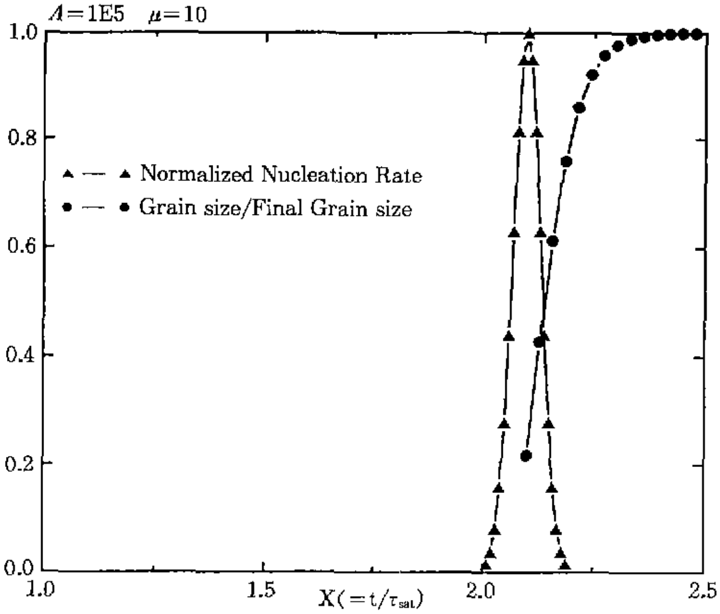

Fig. 1. Dust formation and growth time scales for luminous carbon novae

lar to that of V1668 Cyg 1978 in Table 1. We have done similar calculations for different dust grains and environments.

It would be meaningful to classify the dust-forming novae according to the chemical structure of dust grains and the environment in which dust formation proceeds. Table 2 lists our tentative classification. The value of μ which is dependent on thermodynamical properties of the grain material, the scale parameter A which characterizes the environment of novae, and X_j at which the nucleation rate is maximum, and R_f which is the final grain radius are listed. Type 1 is for *the fastest dust-forming carbon novae. Type 2 is for the intermediate-speed carbon novae* but this type produce the largest amount of dust grains. Type 3 is for the slowest-speed oxygen novae.

Figure 2 shows the grain growth for different types of novae. We may explain Table 1 for dust formation time. For silicate dust grains, dust formation time scale measured from the equilibrium time is about 3 times longer than graphite grains. Silicate grains need more supercooling time, so the dust formation is late. The oxgen novae should be much more difficult to identify because the dust condensation radius is much bigger, so the dust shell is much thiner than normal dust-forming novae.

Table 2. Classification of dust-forming novae

Type	Characteristics	μ	Λ	X_j	R_f	Examples
1	Luminous Carbon Nova	10	10^5	2.10	0.4 (μm)	V1668 Cyg 1978
2	Carbon Nova	10	10^4	2.41	0.05 (μm)	NQ Vul 1975 LW Ser 1978
3	Oxygen Nova	20	10^4	6.44	0.1 (μm)	QU Vul 1984

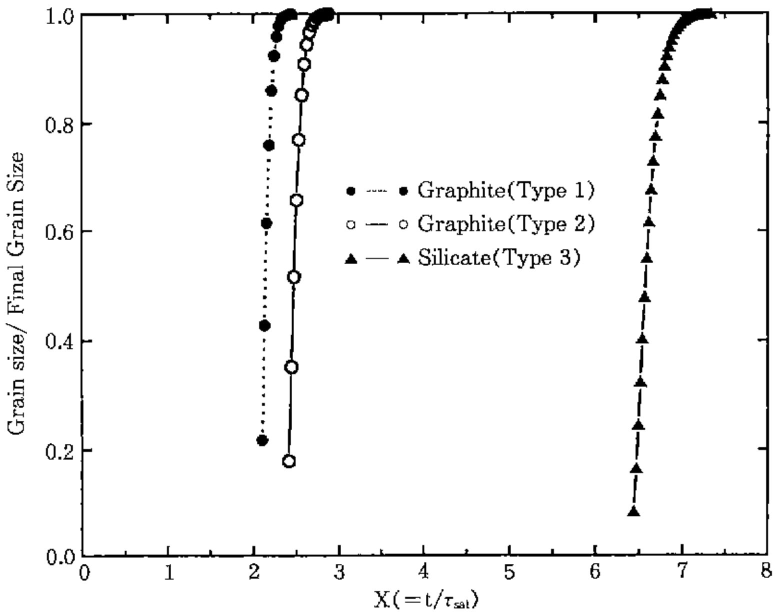

Fig. 2. Dust growth times scales for different types of dust-forming novae

3. Stellar Winds

Dust formation in a circumstellar shell changes not only the chemical structure but also dynamical structure of the shell because of the significantly increased opacity. The following equation determine the flow of dust grains outside the dust condensation radius:

$$\frac{dV}{dt} = -\frac{G'M}{r^2} \qquad (3.1)$$

where r, V(r), G′, M are the distance from the center of the star, the flow velocity, effective gravitational constant, and mass of the star. The effective gravitational constant is given by:

$$G' = G - (\kappa L)/(4\pi MC) \qquad (3.2)$$

where G, κ, L, C are the gravitational constant, radiation pressure opacity, luminosity of the star, and velocity of light. The radiation pressure opacity is given by:

$$\kappa = (N < Q_{pr} > \pi a^2)/\rho \qquad (3.3)$$

where N, a, ρ are number of dust grains, radius of dust grain, mass densty of dust grains. And $<Q_{pr}>$ is the Planck mean value of radiaton pressure efficiency factor which is defined as: $Q_{pr} = Q_{ext} - g \cdot Q_{sca}$, where Q_{ext}, Q_{sca} are the extinction and scattering efficiency factors. And $g = <\cos\theta>$ is the anisotropy factor where θ is the angle between the incident wave and the scattered wave. The radiation pressure efficiency factors are calculated using Mie theory. The optical constants from Draine(1985) for graphite and the ones from Suh(1991) for silicate are used for our calculations.

Figure 3 shows the Planck mean values of radiation pressure efficiency factors for various grain sizes of graphite and silicate. And Figure 4 shows the radiation pressure opacities for various grain sizes of graphite and silicate. Our result is qualitatively similar to Gilman(1974)'s, but the values are significantly different at low temperatures. At low temperatures, our values are bigger than Gilman's. That is because we have used the optical constants which includes the substantial absorption in the far infrared. But at high temperatures they are not very different.

The effective graivitational constant(G′) in equation(3.2) has a negative value when outward acceleration due to radiation pressure is higher than inward gravitational attraction. For normal white dwarf stars, outward radiation pressure is almost negligible(less than 1% of gravitational attraction) therefore the material cannot escape from the central star's atmosphere. But for novae which have much higher luminosity, the value of G′ is about negative $10^4 - 10^5$ times G. That means overwhelming outward acceleration. So dust grains can escape from a nova very efficiently.

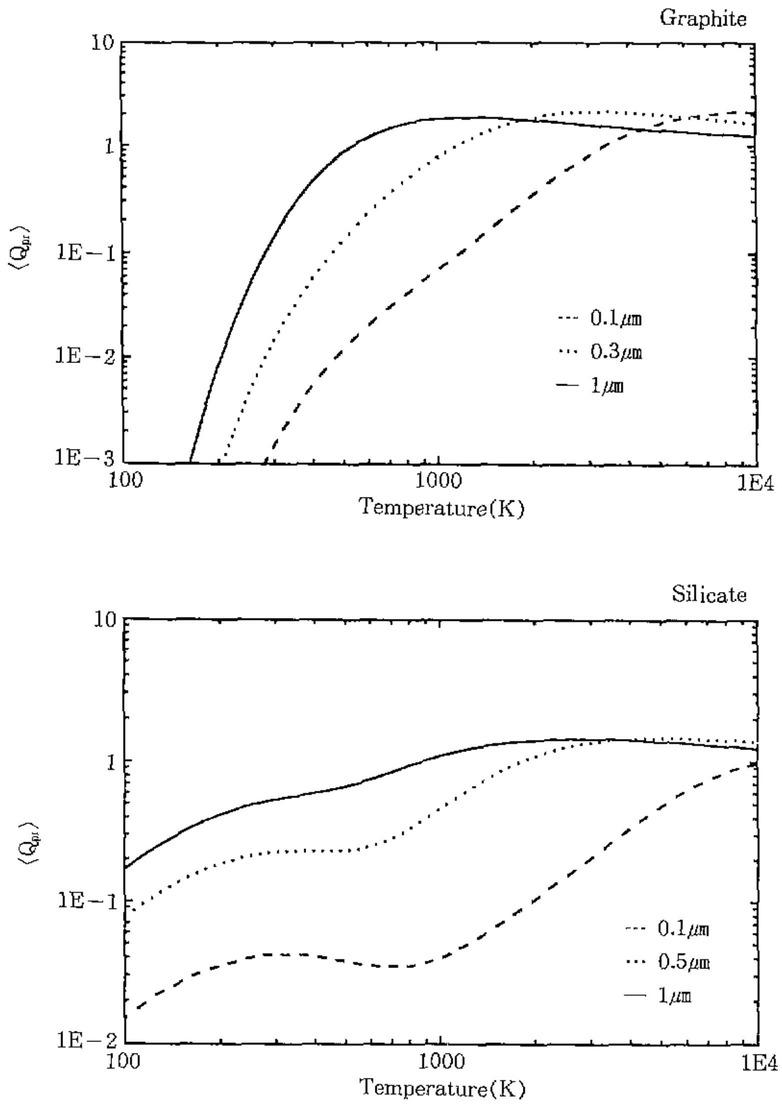

Fig. 3. Radiation pressure efficiency factors for various grain sizes

For a typical carbon nova, the dust condensation radius(R_c) is about 2×10^{14} cm which means that the expansion velocity is about 200−600 km/sec before the material reaches R_c. Then the expansion velocity gets much higher to reach its terminal velocity about 1000−2000 km/sec

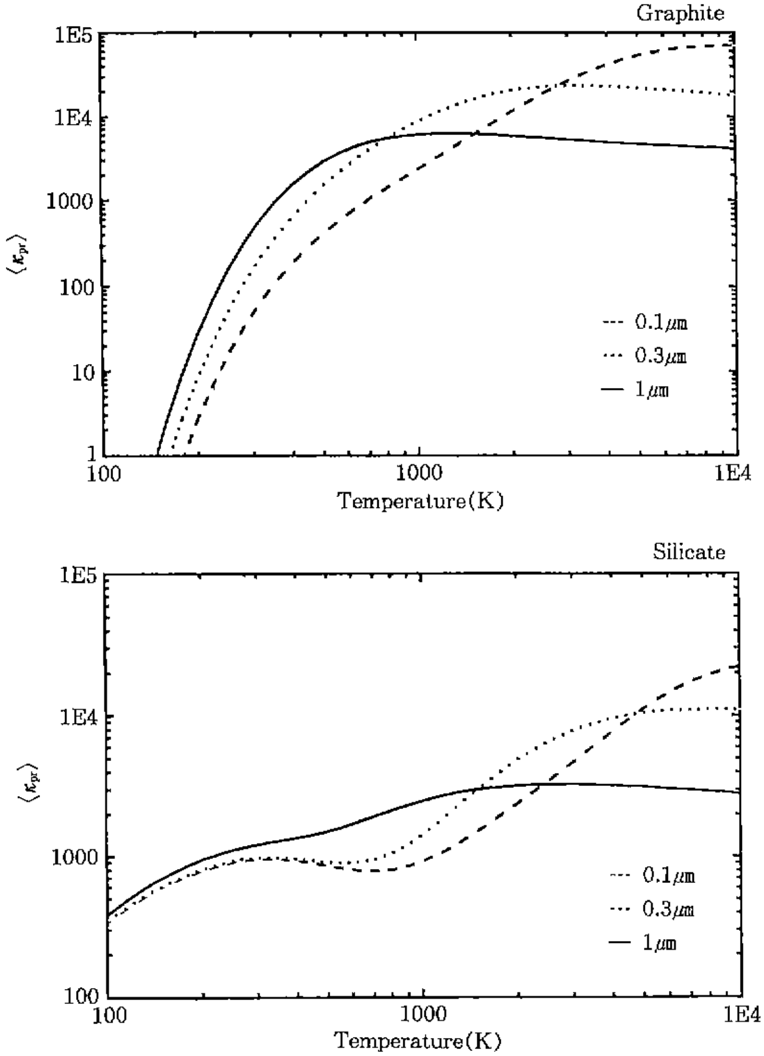

Fig. 4. Radiation pressure opacities for various grain sizes

because of the increased opacity due to dust formation.

Figure 5 shows the expansion velocity of dust grains(0.1 μm graphite) outside R_c and escape velocity from the star for two possible initial velocities(V_i) at dust condensation radius. The velocity is much higher than escape velocity and reaches terminal on which is 1000 km/sec within about 5 R_c.

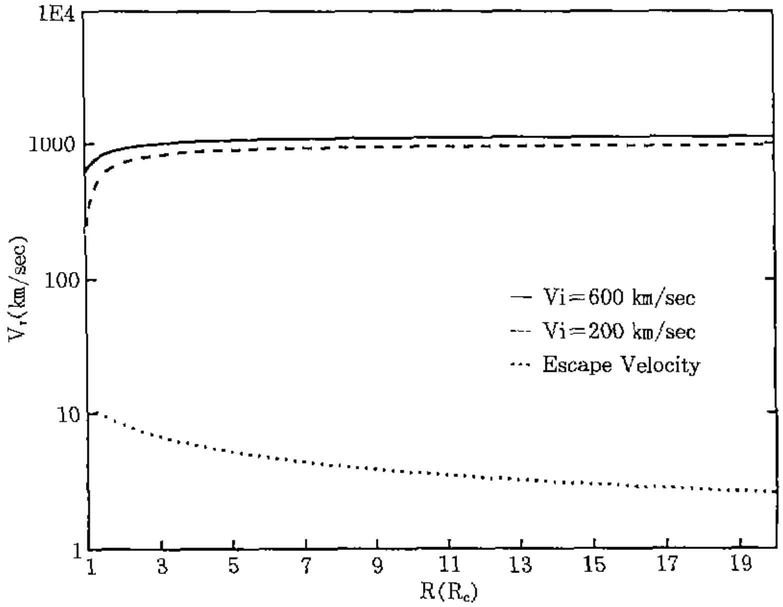

Fig. 5. Dust grain velocity distribution as a function of distance from the star for different initial velocities (V_i) at dust condensation radius

4. Conclusions and Discussion

Dust formation time scales in novae resemble the results of theoretical calculations based on classical nucleation theory. Oxygen grains form much later than carbon grains because of their thermodynamic properties. White dwarfs cannot drive dust grains out, but novae explosions drive them out very efficiently. So the infrared decay may be due to the fact that dust grains already have been driven out of the system.

Our work is based on the assumption that there were no dust grains in the pre-nova. But Jenkins and Evans(1988) suggested a physically reasonable scenario that small dust grains or nucleation centers could have been formed in the white dwarf's accretion disc before the nova explosion and the explosion enhances the process of dust formation and growth significantly and drives the material outward very efficiently. That possibility should be closely examined. So we plan to work on other possible dust formation processes in the near future.

References

Draine, B. T. 1985, *Ap. J.* Suppl., **57**, 587.

Gallagher, J. S. 1977, *A. J.*, **82**, 209.

Gallagher, J. S., and Starrfield, S. 1978, *Ann. Rev. Astr. Ap.* **16**, 171.

Gehrz, R. D. 1988, *Ann. Rev. Astr. Ap.* **26**, 377.

Gehrz, R. D., Grasdalen, G. L., Greenhouse, M., Hackwell, J. A., Hayward, T., and Bentley, A. F. 1986, *Ap. J.* (*Letters*), **308**, L63.

Gehrz, R. D., Grasdalen, G. L., Hackwell, J. A., and Ney, E. P. 1980a, *Ap. J.*, **237**, 855.

Gehrz, R. D., Hackwell, J. A., Grasdalen, G. L., Ney, E. P., Neugebauer, G., and Sellgren, K. 1980b, *Ap. J.*, **239**, 570.

Gilman, R. C. 1974, *Ap. J.* Suppl., **28**, 397.

Jenkins, R. N., and Evans, A. 1988, *Dust in the Universe*, ed. Bailey, M. E. and Williams, D. A. (Cambridge University Press: Cambridge), p. 373.

Kozasa, T., Hasegawa, H., and Seki, J. 1984, *Astrophy. Space Sci.*, **98**, 61.

Mitchell, R. M., and Evans, A. 1984, *M. N. R. A. S.*, **209**, 945.

Suh, K. W. 1991, *Astrophy. Space Sci.*(In press).

Suh, K. W., Jones, T. J., and Bowen, G. H. 1990, *Ap. J.*, **358**, 588.

Yamamoto, T., and Hasegawa, H. 1977, *Progr. Theoret. Phys.*, **58**, 816.