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SUDDEN GRAIN NUCLEATION AND GROWTH IN SUPERNOVA AND NOVA EJECTA*

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Abstract. The thermal conditions leading to the rapid nucleation and growth of dust in astronomical explosions are examined. The contribution herein to nucleation physics lies only in the clarification of the ambient conditions where it apparently occurs. In both nova and interior shells of supernovae, dust precipitates in gas densities of order of 10^{-14} g cm $^{-3}$ a few months after the explosion. The ambient conditions differ widely, however. Supernova condensation occurs in a thermal equilibrium, with photons, ions, electrons and grains having equal temperatures. In novae huge disequilibria exist, with photon and electron temperatures near 5×10^4 K, photon energy density near 750 K, and forming refractory grains near 1800 K. In neither type of explosion can the condensed matter easily maintain chemical equilibrium with the total system. Interesting isotopic anomalies are trapped in both types of refractory condensate in the interstellar medium. The nova provides the best astronomical laboratory for observing the condensation.

1. Introduction

First consider those events that have spotlighted the importance of dust nucleation and growth in astronomical explosions. Following the discovery (R. N. Clayton *et al.*, 1973) that carbonaceous meteorites contain ^{16}O -rich refractory minerals, the writer concluded that the ^{16}O -rich carriers in interstellar dust had most likely condensed during the thermal expansion and cooling of the supernova interior (Clayton, 1975a, b). R. N. Clayton *et al.* (1973) had suggested for the condensation site a ^{16}O -rich cloud that had been enriched in ^{16}O by an earlier ejection of ^{16}O from stars. However, Reeves (1972) had already shown that the supernova ejecta (regarded as gaseous) would mix with more than $10^5 M_{\odot}$ of interstellar gas before becoming ambient. Such a large dilution would result in ^{16}O excesses of only about 10^{-2} of the observed enrichments, which range up to 5%. The new argument was the utilization of an older idea (Cernuschi *et al.*, 1967; Hoyle and Wickramasinghe, 1970) that the expanding supernova could condense dust. This writer argued that the condensation of ^{16}O -rich minerals will occur when the remnant has a size comparable to the solar system, several months after the explosion, and before dilution with interstellar gas becomes possible. The observed dilution in meteorites occurs later on this picture, when very ^{16}O -rich grains are fused with other grains containing normal

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^{16}O during the formation of the carbonaceous-chondrite minerals. This very attractive picture seems likely to be correct, although the other ^{16}O -rich venues for dust formation envisioned by R. N. Clayton *et al.* (1973) may yet be found. Cameron and Truran (1977) have, for example, argued that the ^{16}O -rich gaseous ejecta is stopped, cooled and mixed with a dense molecular cloud, causing it to collapse and form the solar system. Whichever is correct, an interesting new astrophysical and astrochemical application of the formation of cosmic dust had been opened up.

Clayton (1975b) went on to apply this scenario of supernova condensation to the synthesis of other isotopically anomalous chemical carriers during the expansion of the several chemically distinct zones of the supernova. In particular, he proposed that condensation of Na-bearing dust in the helium zone would trap ^{22}Na , leading after a 2.6 yr half-life to ^{22}Ne trapped in those chemical carriers. This was advanced as an explanation of Ne-E, a very ^{22}Ne -rich gas found in carbonaceous meteorites by Black (1972), who called for the survival of some such presolar carrier for this purpose. This attractive idea too has not yet been proven correct, but it has many adherents. Clayton (1975b) went on to predict several other examples, the most important to date being very ^{26}Mg -rich magnesium in interstellar aluminum oxides (see also Clayton, 1977a, b). These predictions may already be largely confirmed, for such anomalies have been, in part, found; however, controversy exists concerning whether the anomalies observed are in fact due to the causes argued as grounds for the predictions. Very much more elaborate attempts at developing this condensation site now exist in the literature (Clayton, 1978a; Lattimer *et al.*, 1978).

The purpose of this paper will be to examine the physical conditions surrounding dust precipitation in exploding objects in an attempt to aid further investigations of the physical efficiency of this process. Nucleation itself is not well understood, but we hope that our arguments that it has occurred in explosions will contribute to better defining the physics of nucleation. It will be argued that the more common nova explosion is a better observational laboratory than the supernova. They occur much more frequently and are transparent, so that the forming dust can actually be observed directly. Many of the same interesting isotopic anomalies (e.g. ^{22}Na and ^{26}Al) can be produced in nova dust as well, a fact that provided the motivation for Clayton and Hoyle (1976) to examine this isotopic aspect in nova dust. But the ambient conditions for nucleation in supernovae and novae differ in several important thermodynamic aspects, some of which are the topic of this paper. Because dust growth is observable in nova expansions, we call for an integrated attack on this problem to better define the actual conditions of observable nucleation in astronomy.

2. Supernova Condensates (SUNOCONS)

The core of a massive star evolves by thermonuclear evolution into a series of concentric zones, at the base of which thermonuclear burning is altering the composition (e.g., Arnett, 1978 and references quoted therein; Weaver *et al.*, 1978). At some point

in this process, the core collapses owing to loss of pressure support, and part of it is presumed to bounce off a much stiffer core at nuclear density, thereby sending a radial shock wave outward through the star. This shock wave compresses and heats the overlying mantle of fuels (Si, O, Ne, C, He, H in succession), causing them to burn more rapidly. This explosive burning adjusts the composition to produce the nuclei between Ne and Ni (Arnett and Clayton, 1970; Arnett, 1973; Clayton and Woosley, 1974). For example, the shock is believed to compress carbon to density between 10^4 and 10^5 g cm^{-3} and to heat it to near $2 \times 10^9 \text{ K}$. The important subsequent features for the present discussion are:

- (1) This matter is completely opaque to everything but neutrinos, so that electrons, ions and photons share the thermal temperature (i.e., equilibrate).
- (2) The photon pressure $P_r = \frac{1}{3}aT^4$ exceeds the gas pressure $p_g = nkT$ by a factor of order 10^2 . It is a radiation-dominated gas.
- (3) An overpressure exists. Following the shock dissipation and temperature increase, the radiation pressure exceeds that needed for hydrostatic equilibrium, so the zone expands.
- (4) The expansion rate is so great that the cooling due to the work of expansion $dU/dt = -P dV/dt$ greatly exceeds the cooling due to neutrino emission or due to photon diffusion along the temperature gradient. Therefore the expansion is approximately adiabatic.
- (5) In the adiabatic expansion, the entropy per gram of the photon gas, $S = 4aT^3/3\varrho$ (e.g., Clayton, 1968, p. 123) greatly exceeds that of ions plus electrons, so the adiabat is approximately $\varrho = CT^3$. With the characteristic explosive-shell conditions above, this is numerically $\varrho = 10^{-23}T^3 \text{ g cm}^{-3}$.
- (6) The expansion tends to preserve this condition of photon dominance for a very long time. If the expansion is homologous, then $\varrho \propto (1/R)^3$, so that the adiabat yields $R \propto 1/T$. The scale of expansion R/R_0 is then also the scale of cooling T_0/T , where R_0 , T_0 are the initial radius and temperature behind the shock. Radiation pressure continues to dominate because $P_r/P_g \propto T^4/\varrho T = T^3/\varrho \propto S_r$, which is constant by adiabaticity. It is only the slowly growing importance of the small terms that prevents the track from remaining $\varrho = 10^{-23}T^3$ down to very low temperatures. If the gas pressure P_g is actually a fraction β of the total pressure, the adiabatic expansion of the mix is characterized by $\varrho \propto T^n$, where (Clayton, 1968, p. 119) $n = 3(8 - 7\beta)(8 - 6\beta)^{-1}$. The pairs (β, n) have the following values for increasing gas pressure $P_g = \beta P$: (0, 3); (10^{-2} , 2.996); (0.1, 2.959); (0.5, 2.7); (1, 1.5). As long as $\beta < 0.1$, the relation $\varrho \propto T^3$ is very good. If the mantle interacts with the overlying giant envelope, this initial adiabat may be modified by the deceleration and consequent heating of the 'nucleosynthetic ejecta'.
- (7) Because refractory minerals begin condensing slightly below $T = 2000 \text{ K}$, the density for condensation to begin is, from the adiabat, $\varrho_{\text{cond}} \simeq 10^{-13} \text{ g cm}^{-3}$. In the carbon burning shell, this matter is about 70% oxygen, and about 10% MgNaAlSi,

so that a wide range of refractory minerals may precipitate. The same is true in the oxygen-burning shell.

(8) Different shells tend to lie on the same adiabatic path of expansion, because the initial configuration of the star is similar to the $\rho \propto T^3$ relationship. Thus each and every interior shell tends to pass through condensation temperatures at a density of refractory metals near $10^{-14} \text{ g cm}^{-3}$, bathed in an order of magnitude more oxygen.

(9) The oxidizing bath becomes instead sulfurous ($\text{S/O} \gg 1$) in zones where oxygen is largely consumed. This is potentially important for expectations of interstellar sulfides (Clayton and Ramadurai, 1977).

(10) The interior shells decelerate to $10^{2-3} \text{ km s}^{-1}$ by virtue of this mantle-envelope 'collision' in the expansion, although the surface layers are accelerated to the observed 10^4 km s^{-1} . Therefore, at long times $R \approx 10^8 t$ in c.g.s units. The burning shell was initially near $R_0 = 10^9 \text{ cm}$, so the reduction in temperature by the factor 10^6 corresponds to an expansion of the shell to $R \simeq 10^{15} \text{ cm}$, or about 100 AU. This condensation size is much too small to sweep up substantial circumstellar matter, so these condensates are pure SUNOCONS (supernova condensates).

(11) If the expansion speed is 10^8 cm s^{-1} , expansion to 10^{15} cm requires about 3 months time. A year may be more appropriate if the deceleration via envelope collision is severe. This is when the burst of dust precipitation is expected. It was the realization of this short time that led the writer (Clayton, 1975b) to advance an enlarged interpretation of extinct radioactivities (see also Clayton, 1978b). Should these be confirmed, they will provide the best proof of rapid supernova condensation. Many interesting radioactive species of appropriate half-life are ejected from explosive burning, where they condense chemically as the parent and later transmute to the daughter.

Now consider the thermal environment for the supernova condensation under the conditions outlined. When $T = 2000 \text{ K}$ and $\rho = 10^{-13} \text{ g cm}^{-3}$ the interior is still optically thick. Even if only one solar mass of matter were distributed through a ten-times-larger sphere ($R = 10^{16} \text{ cm}$) surrounding this shell, the column thickness would still be 5 g cm^{-2} . Because this is a conservative estimate, and because 5 g cm^{-2} is quite opaque, it is correct to regard the internal radiation field as being still trapped when chemical condensation commences. This means that the thermal equilibrium is complete in a kinetic sense (ions, electrons, photons). To good approximation it will remain so as the temperature falls to 1000 K , by which time the very refractory condensates have already precipitated (e.g., Grossman and Larimer, 1974). It would, however, be incorrect to assume that the condensed matter remains in equilibrium either with itself or with the gas. This is because the chemistry may be dominated by the time scales for the reaction dynamics that occur. The temperature decline from 2000 K to 1000 K occurs, in the example given, over a three-month time interval (from three to six months following the explosion). It is not at all clear that the condensed and gaseous phases can find in that time the chemical-exchange routes needed to preserve chemical equilibrium. But *thermal equilibrium*, in the sense of

temperature equality, *is* preserved. The forming grains are at the same temperature as both the photon and particle baths. This equality will break down only when the infrared emission of the grains (which will radiate more efficiently than the gas) become able to penetrate the thinning overlying atmosphere to free space. This breakdown of equilibrium will not be estimated here because it is so sensitive to the uncertain amount of overlying envelope, its rate of expansion, and on infrared opacity. The problem is fairly well solvable for a specific model (Falk and Arnett, 1977), however, so no fundamental problem exists here. But it does seem likely that the refractory SUNOCONS will already have been precipitated before thermal equilibrium breaks down. This stands in contrast to the nova conditions to be discussed in Section 3.

A preliminary survey of the time-scale problems for the chemistry seems to emphasize three physically different bottlenecks: (1) nucleation of chemical clusters of critical size and stability, (2) kinetics of growth, and (3) chemical rearrangement of condensates. The first is by far the most severe, because so little is known. One might attempt to use homogeneous nucleation theory (e.g., Salpeter, 1977), usually with equilibrium concepts as aids. Draine and Salpeter (1977) discuss a time-dependent form of this. But a worrisome uncertainty remains concerning how the nucleation begins in the first place. For example, if Al_2O_3 is to be a first condensate, from what gaseous particles do the critical clusters grow? By what reaction channels do they grow? What is the time for growing them? Multi-ion reactions can be very slow. Donn (1976) has pointed out for this example that the gaseous molecule Al_2O_3 is not likely to exist, so it cannot serve as a monomer for the growth of Al_2O_3 . What then? Many possibilities can be envisioned, but estimating their effective rates for forming critical clusters is unclear.

The growth timescale, once critical clusters exist, is much easier to estimate and is seen to provide little impediment to grain growth. Suppose, for example, that Al and O are able to nucleate critical clusters of radius 3×10^{-7} cm, say, at a temperature of 1800 K where corundum condensation becomes thermodynamically favored. A geometric calculation shows that if all Al atoms stick to these clusters when they strike them, the initial timescale for the depletion of Al is $\tau \approx 1/N_c$ (cm^{-3}) years, where N_c is the c.g.s. number density of critical clusters. This number is hard to estimate *a priori*. Each critical cluster has a mass (3×10^{-19} g) that is about 0.1% of the total Al mass density at the time condensation begins. Thus if 1% of Al is in critical clusters, even the initial growth rate is as rapid as $(0.1 \text{ yr})^{-1}$. If the initial density of critical clusters is smaller, the growth equations must be integrated to take account of the growing area of the grains being struck by gas particles. Clayton and Wickramasinghe (1976) have done this in the case of little monomer depletion from the gas. The Al-bearing-grain radius a grows according to the equation

$$\frac{da}{dt} = \frac{\alpha m^* n(\text{Al})}{s} \sqrt{\frac{kT}{2\pi m(\text{Al})}} = \frac{\alpha m^* n_0}{s} \sqrt{\frac{kT_0}{2\pi m(\text{Al})}} \left(\frac{t}{t_0}\right)^{-7/2},$$

where $\alpha =$ sticking coefficient $\simeq \frac{1}{2}$, $m^* = m(\text{Al}_2\text{O}_3)$, $s =$ corundum density and, in the second equation, the density $n(\text{Al})$ and the temperature are scaled for expansion according to $n = n_0(t/t_0)^{-3}$ and $T = T_0(t/t_0)^{-1}$, with $t_0 \simeq 10^7$ s being the time when condensation begins. This equation assumes that oxygen, being 10^2 times more abundant, is always available for Al_2O_3 growth, and the scaling $n \propto t^{-3}$ is only valid over times short enough that most Al remains gaseous. For the numerical example given, $da/dt = 1.5 \times 10^{-11}(t/t_0)^{-7/2} \text{ cm s}^{-1}$ integrates easily to $a = a_0 + 0.6 \times 10^{-11}t_0[1 - (t/t_0)^{-5/2}] \text{ cm}$. If $t_0 = 10^7$ s marks the onset of condensation (otherwise $t_0 \simeq 10^{15} \text{ cm/v}$), the asymptotic grain size $a_\infty = 0.6 \mu\text{m}$ is large, confirming that there is no obstacle to condensing much of the Al if the critical clusters can form. Since this integral is only valid while most Al remains gaseous, however, it is valid only for a low density of critical clusters. A better idea of the condensation rate inquires how much corundum condenses as the temperature drops by 10% (about 200 K), which requires $t/t_0 = 1.1$, at which time $a(1.1) = 0.12 \mu\text{m}$. Such a corundum grain contains a mass of Al equal to that contained in 3 cm^3 of gas at t_0 . It follows that a single critical cluster per cm^3 will deplete the gaseous Al at a rate of order 10^{-6} s^{-1} during the roughly 10^6 s accompanying the first 10% drop in temperature. Thus the kinetic factors are themselves adequate to grow the dust, and, more to the specific point, to grow Al_2O_3 before the temperature has fallen below the condensation temperature for common less refractory chemical forms, specifically spinel, MgAl_2O_4 . The crucial physical question falls back on the nucleation – will $10^{-15} \text{ g cm}^{-3}$ of Al bathed in $10^{-13} \text{ g cm}^{-3}$ of O nucleate at least one critical cluster for Al_2O_3 per cm^3 during a 10^6 s interval? If a density N_g of critical clusters significantly greater than unity forms, the gaseous Al will be quickly depleted, so that the asymptotic grain size will be determined by the number density of grains rather than by the integral described above – of order $a_\infty \simeq (0.1 \mu\text{m})N_g^{-1}$. That is, *nucleation will determine the final grain size* (cf. Falk *et al.*, 1977).

The third timescale has to do with the transmutation of the chemical forms of the condensed matter. This is an important problem for SUNOCON identity. The Al emerges, for example, primarily from a supernova shell that has just burned carbon, wherein Mg is an even more abundant product ($\sim 10^{-14} \text{ g cm}^{-3}$ at t_0). Chemical equilibrium (e.g., Grossman and Larimer, 1974) would require that Al_2O_3 be converted to MgAl_2O_4 (spinel) by the time that the temperature has fallen by $\Delta T \simeq -200$ K. The time required in the example for that temperature drop, $\Delta t/t_0 = \Delta T/T$, is about 10^6 s, and the question arises whether the Mg will be depleted fast enough, and even more importantly if it can, does the Mg and O deposited on the surface of Al_2O_3 grains, which are believed solid rather than liquid, diffuse sufficiently rapidly into the Al_2O_3 ? Chemical literature related to this latter problem is unknown to this writer. There are similarities to diffusion in solids, except that the diffusion is a wave of chemical reorganization. In this particular case the gaseous Mg is more abundant than the Al_2O_3 grains it must infiltrate, but that is not generally true of the equilibrium-SUNOCON transmutations. Therefore, a good general theory

will be needed unless it can be shown that these transmutations can occur as rapidly as the deposition, in which case the latter becomes rate-determining. The question bears on significant issues, such as whether Al_2O_3 will be ejected at all or whether it will be converted entirely to MgAl_2O_4 . If the Al_2O_3 does in part survive, the writer has shown (Clayton, 1975b; 1977a, b) that the ^{26}Mg spike carried within it from ^{26}Al decay may generate the linear correlation found between $^{26}\text{Mg}/^{24}\text{Mg}$ and Al/Mg in the CaAl-rich inclusions of C3 meteorites.

A very significant astronomical question impacted by research on supernova condensation is the extra depletion of Ca, Al and Ti from the interstellar gas in comparison with other refractory elements (e.g., Field, 1974). Field interpreted these gas depletions as evidence for thermally condensed dust, but he found within that picture no explanation for the very large depletions of these three elements (and probably also Fe) when compared to Mg and Si. An explanation of that fact in terms of SUNOCONS has been provided by the writer (Clayton, 1977a, b, c; 1978a), who observed that it is the abundance ratios in the supernova shells that conspire to make these three elements much more easy than others to condense completely. Al is, for example, bathed in much more abundant Mg and O, as described above, and should therefore condense totally if it condenses at all, whereas Mg could be condensed only by C and O, leaving MgO and MgCO_3 as the candidates. Because these two minerals are thermally less favored, a significant amount of gaseous Mg or gaseous MgO will probably escape. Similarly Ca condenses much more totally than Si in the oxygen-burning zones. Fe will condense as metal droplets. The point is that *this adiabatic expansion is the first event in the lives of these newly-synthesized nuclei!* Therefore, the physical conditions and relative abundances that apply there will determine the chemical form of this matter as it is injected into the interstellar medium. It already seems clear that if dust can nucleate at all during this expansion, Ca and Al will be much more thoroughly condensed than will Mg and Si upon ejection. This explanation of a major astronomical mystery must be regarded as a big plus for the SUNOCON theory, but it awaits more complete knowledge for its unequivocal establishment.

3. Nova Condensates

A second and more direct evidence of explosive condensation comes from the common nova, where the dust formation and the thermodynamic conditions are astronomically observable. The astonishingly rapid rise of the infrared luminosity observed (Geisel *et al.*, 1970) in Nova Serpentis 1970 stimulated us (Clayton and Hoyle, 1976; Clayton and Wickramasinghe, 1976) to formulate numerical models of the dust growth required to account for this infrared emission. The physical setting of these models is interestingly different from that of the supernova, as the following features of our models illustrate:

(1) The geometry is thin to radiation because even the central star can be seen, as can the dust when it forms 2 months (for Nova Serpentis) later. The Nova phenom-

enon is believed to be a thermonuclear explosion on the skin of a white dwarf. The hydrogen involved in this hot-CNO process is believed accreted from a companion star of a binary pair, because hydrogen cannot exist stably on a white dwarf. There do exist interesting opacity problems, even though the system is partially transparent, as evidenced by a blueward shift of the central-star light in time, radiating mostly in the ultraviolet after about 3 to 4 weeks (Gallagher and Code, 1974). Apparently the luminosity source appears hotter and hotter as the overlying shells thin out owing to the expansion. One may regard the central source as one of almost constant luminosity (probably near $2 \times 10^4 L_\odot$) that grows hotter as one sees the white-dwarf surface more directly. Nonetheless, the total system is approximately transparent.

(2) The transparent geometry produces large disequilibria among the various temperatures. The spectrum of photons is hot (10^4 to 5×10^4 K) but their energy density at dust-forming distances is cool (~ 2000 K). Therefore, forming dust will be much cooler than the Wien peak of the source photons. The dust is also cooler than ambient gas; but it is hotter than a black body would be. Assuming that the central luminosity L radiates a photon spectrum of temperature T_* , dust grains cannot form too near the object; otherwise they would quickly vaporize by heating to that grain temperature T_g which balances absorption and emission from the grain – i.e.,

$$\pi a_0^2 (L/4\pi r_0^2) \bar{Q}(T_*, a_0) = 4\pi a_0^2 T \bar{Q}_g^4(T_g, a_0);$$

where a_0 is the initial grain size (critical clusters) a distance r_0 from the central object and $\bar{Q}$ is the absorption (or emission) efficiency. Because of the energetic-photon spectrum near $T_* = 5 \times 10^4$ K when dust forms, the absorption efficiency will be near unity when particles have grown to $a = 10^{-6}$ cm, but the emission $\bar{Q}$ remains below unity because its thermal wavelengths are much longer. Because the absorption $\bar{Q}$ exceeds the emission $\bar{Q}$, the grain temperature will be greater than that of a black sphere, T_{rad} – i.e.,

$$4\sigma T_{\text{rad}}^4 \equiv L/4\pi r_0^2.$$

(3) For grains having radius a of order 10^{-6} cm to exist at a grain temperature $T_g < 2000$ K requires that r_0 be great enough that the black-sphere temperature has fallen to

$$T_{\text{rad}} \simeq 750 \text{ K} \left(\frac{a}{10^{-6} \text{ cm}} \right)^{1/4} \left(\frac{T_g}{2000} \right)^{1.41},$$

where the approximations $\bar{Q}(T_*) = 1$ and $\bar{Q}(T_g, a) = 3.22a(T_g/10)^{1.65}$ have been adopted (Clayton and Wickramasinghe, 1976). This interesting equation requires $T_{\text{rad}} < 750$ K in order that a 10^{-6} cm grain have $T_g < 2000$ K, where solids can reasonably exist. The definition of T_{rad} shows that, for $L = 2 \times 10^4 L_\odot$,

$$r^2(\text{cm}) = 2.6 \times 10^{-40} T_{\text{rad}}^{-4},$$

so that $T_{\text{rad}} < 750$ K implies $r_0 > 2.8 \times 10^{14}$ cm. The expansion must carry the

ejecta at least that far from the star before grains become stable. Note that the 10^{-6} cm grains are at that time almost three times hotter than a black sphere.

(4) Photons, rather than particle collisions, are the main heat source for the grains. Even if the free-electron density were as great as 10^8 cm^{-3} , roughly the expected order of the particle density, and even if each electron deposits 20 eV into the grain, the radiant energy flux on the grain still exceeds the particle energy flux by 10^2 . Since these assumptions are liberal ones, we may consider that radiation dominates the grain heating (and, of course, also the cooling), as assumed above.

(5) Taking an expansion speed $v = 700 \text{ km s}^{-1}$ for the nova ejecta shows that grains will not be stable prior to $t_0 = r_0/v = 4 \times 10^6 \text{ s} = 46$ days. This delay is almost exactly what was observed for Nova Serpentis 1970. Between days 55 and 60 after the outburst a hot infrared source began a rapid growth, after which the color temperature of the growing grains slowly declines. The infrared luminosity increases thereafter at the rapid rate of about 10% per day, which reflects the growing surface area of the grains as they deplete the condensible matter. Clayton and Wickramasinghe (1976) generated a good characterization of this behavior with their grain-growth models dominated by efficient sticking. The declining grain temperature between day 50 ($T_g \simeq 1500 \text{ K}$) and day 90 ($T_g \simeq 900 \text{ K}$), when L_{IR} reaches its peak value ($\sim 2 = 10^4 L_\odot$), follows naturally from the increasing distance from the central object.

(6) In such a rapidly expanding condition, grain growth ceases even without depletion of monomers. If we assume that $n(t) = n_0(t_0/t)^2$, as if undepleted monomers are confined to a spherical shell moving outward with constant thickness, the grain growth equation integrates (cf. Clayton and Wickramasinghe, 1976) to

$$a = a_0 + 4 \times 10^{-20} t_0 [1 - (t_0/t)^{5/4}] n_0 \text{ c.g.s.}$$

The radius a grows from the assumed critical radius $a_0 \simeq 3 \times 10^{-7} \text{ cm}$ to an asymptotic value $a_\infty = 4 \times 10^{-20} t_0 n_0 = 1.6 \times 10^{-13} n_0$ for $t_0 = 46$ days. If the condensible mass ejecta has a typical value of $3 \times 10^{-4} M_\odot$ and if the shell thickness at t_0 is of order $10^{-2} v t_0$, then $n_0 = 1.4 \times 10^9 \text{ cm}^{-3}$, yielding an asymptotic size $a_\infty = 2.2 \mu\text{m}$. These choices agree well with observation, causing the infrared luminosity L_{IR} to achieve maximum at $t_{\text{max}} = 1.91 t_0$, which evaluates as 88 days, just as observed. If this grain growth occurs with a number of critical clusters sufficient to deplete the gas, the asymptotic size will instead be determined by the ratio of the condensible mass to the number of grains. That is, nucleation determines the final grain size. Theoretical models offer the change of relating these nucleation properties to the growth of the infrared luminosity through the grain size and growth rate.

(7) The agreement with the observations seems to imply that nucleation has occurred at the earliest moment allowed by the radiation field. These nuclei grow quickly to account for the rapid luminosity rise. The doubling time for a near 10^{-6} cm is less than 10^5 s , so that if critical clusters had existed prior to t_0 , the heat prevents them from growing. Otherwise there would have been a more gradual infrared growth. It

seems likely that nucleation occurs over a less-than-10-day interval following the drop of T_g to a sufficient level, whereafter grain growth occurs as rapidly as conditions permit. The physics of the nucleation itself is once again the big problem.

(8) Although the densities and timescales for nova and supernova nucleation may be comparable, the chemistry may differ greatly, partly for differences in ambient conditions, but partly also because the composition may be so very much different. Most importantly, the nova contains hydrogen. It is not derived from the white dwarf, but rather from the accreted hydrogen-rich envelope that causes the explosion. The white dwarf itself could be very carbon-rich, as an example, so that hydrocarbons could conceivably play a role. Graphite may form in novae but be unable to form in supernovae owing to CO locking up the carbon. An observational problem here is that it has traditionally been hard to understand white-dwarf spectra and compositions.

(9) A review of dust formation in Novae (Gallagher, 1977) shows that some form dust and some do not. Therefore they represent a common but variable event that can, with enough data, provide the nearest thing to an observable experiment in explosive dust nucleation. Their borderline behavior increases their value as an experiment. The observed trend is what one would expect on this model; viz. the roughly ten-times-more-luminous 'rapid novae' are not dust producers, probably because their higher luminosity reduces n_0 by increasing r_0 proportionally to $\sqrt{L}$ and because a more rapid expansion allows less time for growth. Gallagher (1977) has speculated that nucleation may be suppressed by ionization, also causing differences between novae of differing energy.

In light of the far ranging astronomical importance of dust formation in novae and supernovae, it seems reasonable to pursue an astronomical attack on this aspect of the nova. Good observations at all wavelengths plus elaborate hydrodynamic models (e.g. Starrfield *et al.*, 1978, and references therein) may ultimately define the circumstances of nucleation rather well. Perhaps some precursors to grains can even be seen spectroscopically. Clayton and Wickramasinghe (1976) were tempted in this regard to attribute a $5\ \mu$ excess at day 19 to stretching bands of $C\equiv C$, $C=C$, and a corresponding $10\ \mu$ feature to stretching bands of the $C-C$ linkages in molecular clusters involving carbon atoms. Since nucleation of solid graphite is expected to pass through a phase of such molecular aggregates, they expected those features to diminish or disappear when nucleation is complete. They did disappear by day 36, before the dust was observed to grow (Geisel *et al.*, 1970). One may well wonder what the limits of infrared spectroscopy may provide for this interesting problem.

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