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WILL DUST BLACK OUT SN 1987A?

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ABSTRACT

SN 1987A is the closest supernova ever to have occurred in the era of modern technology, providing astronomers with the unique opportunity to study in detail the various physical processes associated with the supernova phenomenon. Among these processes is that of dust formation in the cooling matter explosively ejected in the supernova event. This paper examines the prospects for the formation, survival, and detection of dust in the ejecta of SN 1987A. The formation of dust will have immediate implications on the spectral analysis of the ejecta, as the dust may obscure the visual and UV output of any pulsar that may have formed in the explosion. A $\sim 20\ M_\odot$ progenitor star can produce about $\sim 1\ M_\odot$ of supernova condensates. Supernovae will then constitute a major source of dust, equaling the combined output of all other sources. The detection of this dust in SN 1987A will be a significant addition to the incomplete picture we now have of the presence of isotopic anomalies in the solar system, and of the origin and evolution of dust in the interstellar medium.

Subject headings: interstellar: grains — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION

Dust formation is observed to take place in a variety of astrophysical environments including circumstellar shells around cool stars (Zuckerman and Dyck 1986), planetary nebulae, and novae (Gehrz *et al.* 1984). The presence of dust around cool stars is inferred from a number of phenomena, including: the presence of an infrared (IR) excess above the underlying stellar continuum; the extinction, scattering, or polarization of the stellar UV-visual photons; and the presence of reflection nebulae around the star. In novae, the formation of dust is inferred from the evolution of their radiative output at various wavelengths. The nova light curve may exhibit a dramatic rise in the IR, which is concurrent with a rapid drop in the UV-visual (see, e.g., Gehrz *et al.* 1984, and references therein). To date, there has been no conclusive evidence for the actual formation of dust grains in supernovae (SN). The evolution of the infrared light curves of SN 1979C, SN 1980K, and SN 1982E (Merrill 1980; Dwek *et al.* 1983; Graham *et al.* 1983) exhibited a behavior similar to that observed in novae. However, the most common explanation for this behavior is that the IR emission is an infrared echo of the initial UV-visual outburst of the supernovae caused by a preexisting circumstellar dust shell (Bode and Evans 1980; Dwek 1983; Graham and Meikle 1986).

The fact that dust must form in SN is implied by the presence of isotopic anomalies in the meteorites (Clayton 1982, and references therein). These anomalies strongly suggest that dust formed in the metal-rich layers of the ejecta. Following Clayton (1982), I will refer to these condensates as SUNOCONS (SUperNOva CONdensateS). A weaker argument for the existence of SUNOCONS suggests that they are needed to replenish the amount of interstellar dust that is continuously being destroyed by interstellar shocks (Draine and Salpeter 1979*a*; Dwek and Scalo 1980; Seab and Shull 1985). Theoretical models (e.g., Weaver and Woosley 1980) show that a typical massive star ($\sim 25\ M_\odot$) can produce $\sim 1\ M_\odot$ of SUNOCONS. Supernovae may therefore constitute a major source of dust, equaling the combined output of all other sources (Dwek and Scalo 1980).

The proximity of SN 1987A and its extensive coverage at various wavelengths provide astronomers with the rare opportunity to study the dust formation process in an unusual astronomical setting. The formation of dust in SN 1987A will have immediate implications on the spectral analysis of the ejecta, as the dust may obscure the UV-visual output of any pulsar that may have formed in the explosion (Gehrz and Ney 1987).

II. DUST ENERGETICS IN SUPERNOVAE

a) Radiation Sources

The continuous rise in the brightness of SN 1987A suggests that its light curve is powered by the radioactive decay of ^{56}Ni (Woosley *et al.* 1987; Woosley, Pinto, and Ensman 1988) or by a pulsar (Ostriker 1987). The energy released in the $^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$ decay chain ($\tau_{1/2} = 78$ days, $\langle E\gamma \rangle = 1.35$ MeV) is given by ($t \gg 7$ days):

$$L_n(\text{ergs s}^{-1}) = 5.1 \times 10^{42} M_{56}(M_\odot) \exp(-t/114\ \text{d}) , \quad (1)$$

where M_{56} is the mass of Ni produced in the core. If a pulsar is present, its luminosity will be (Ostriker and Gunn 1969):

$$L_p(\text{ergs s}^{-1}) = 4 \times 10^{43} B_{12}{}^2 P_0{}^{-4}(1 + t/\tau_0)^{-2} , \quad (2)$$

where B_{12} is the value of the pulsar's magnetic field in 10^{12} gauss, P_0 its period in ms, and $\tau_0(\text{yr}) = 16 P_0{}^2/B_{12}{}^2$ is its slowing down time. For a Crab-like pulsar, $P_0 = 17$ ms and $B_{12} \approx 4.3$ (Manchester and Taylor 1977) so that initially $L_p \approx 9 \times 10^{39}$ ergs s^{-1}. If the energy spectrum of the pulsar is proportional to E^{-1}, then about 5% of its total energy output will be emitted in the UV-visual band.

b) Dust Heating

A dust particle of radius a heats up at rate $H = \pi a^2 \epsilon S$, and radiates at a rate $L_{gr} = 4\pi a^2 \sigma T_d{}^4 \langle Q(T_d) \rangle$, where T_d is the dust temperature, $\langle Q(T) \rangle$ is the Planck-averaged value of the dust absorption efficiency at temperature T, S is the radiative flux incident on the dust, and ϵ is the spectrum-averaged efficiency at which the dust absorbs the incident radiation. If the incident flux is that of a blackbody at a photospheric temperature T_{ph}, then $\epsilon = \langle Q(T_{\mathrm{ph}})\rangle$. Adopting the optical properties of Draine and Lee (1984) and Draine (1987) for astrophysical silicates and graphite grains $\langle Q(T)\rangle/a$ can be written as:

$$\begin{aligned} \langle Q(T)\rangle/a\ (\mathrm{cm}^{-1}) &= 800 \qquad 100 < T_d(\mathrm{K}) < 300 \\ &= 0.28 T_d^{\,1.40} \qquad 300 < T_d(\mathrm{K}) < 10^4 \end{aligned} \tag{3a}$$

for graphite grains, and as

$$\langle Q(T)\rangle a\ (\mathrm{cm}^{-1}) \approx 2500 \quad 100 < T_d(\mathrm{K}) < 2000 \tag{3b}$$

for silicate grains. The latter expression is only accurate within a factor of 2. For incident hard photons of frequency ν ($h\nu > 60$ eV), $\epsilon_\nu = [1 - \exp(-3 \times 10^{-4} \kappa_\nu a(\mu\mathrm{m})]$, where κ_ν is the mass absorption coefficient of the dust at frequency ν, and where an effective mass column density of $4\rho_{\mathrm{gr}}/3a$ with $\rho_{\mathrm{gr}} = 3$ g cm^{-3} was adopted for the dust.

Initial grains are likely to be very small (< 10 Å), and their survival will depend on the time scales of the various processes for their growth and destruction in the hostile SN environment. The absorption of single photons (Draine and Anderson 1985) or particles (Dwek 1986) may raise the dust temperature to values sufficiently high to vaporize the dust. The heat capacity, $C(T_d)$, of silicate or graphite grains with temperatures above $\sim$1000 K is about equal to $1.6 \times 10^{-16} a^3(\text{Å})$ ergs K^{-1} (Draine and Anderson 1985; Dwek 1986). The deposition of 100 eV of energy in a dust particle will therefore raise its temperature to a value of

$$T_d(\mathrm{K}) = 1000E(100\ \mathrm{eV})/a^3(10\ \text{Å}) . \tag{4}$$

The dust will vaporize if its vaporization time, t_v, is smaller than its cooling time, t_{cool}, or smaller than its accretional time scale t_{accret}. The vaporization time is given by (e.g., Draine and Salpeter 1979*b*)

$$t_v(s) = 7.6 \times 10^{-13} a(\text{Å}) \exp[U_0/kT_d] , \tag{5}$$

where U_0 is the surface binding energy per atom, which is 7.35 and 5.7 eV for graphite and silicate grains, respectively (Draine and Salpeter 1979*b*). The dust cooling time is given by $|T_d^{-1} dT_d/dt|^{-1} = T_d^{-1} L_{\mathrm{gr}}/C(T_d)$, where L_{gr} is the grain evaporate or radiative energy loss rate. Using equations (3) and the value of $C(T_d)$, the dust cooling time (for $T_d > 1000$ K) by radiative emission is (see also Dwek 1986; Fig. 1):

$$\begin{aligned} t_{\mathrm{rad}}(s) &= 8.4 \times 10^{11} T_d^{\,-4.40} \quad \text{graphite} \\ &= 1.0 \times 10^{8} T_d^{\,-3.0} \quad \text{silicate} . \end{aligned} \tag{6}$$

To calculate the evaporative cooling time I assume that L_{gr} is given by the total binding energy of the dust ($\sim N \times U_0$, where N is the total number of atoms in the dust) divided by t_v. The cooling time due to evaporation is then given by

$$t_{\mathrm{evap}}(s) \approx 2 \times 10^{-12} a(\text{Å}) \exp(x)/x , \tag{7}$$

where $x = U_0/kT_d$.

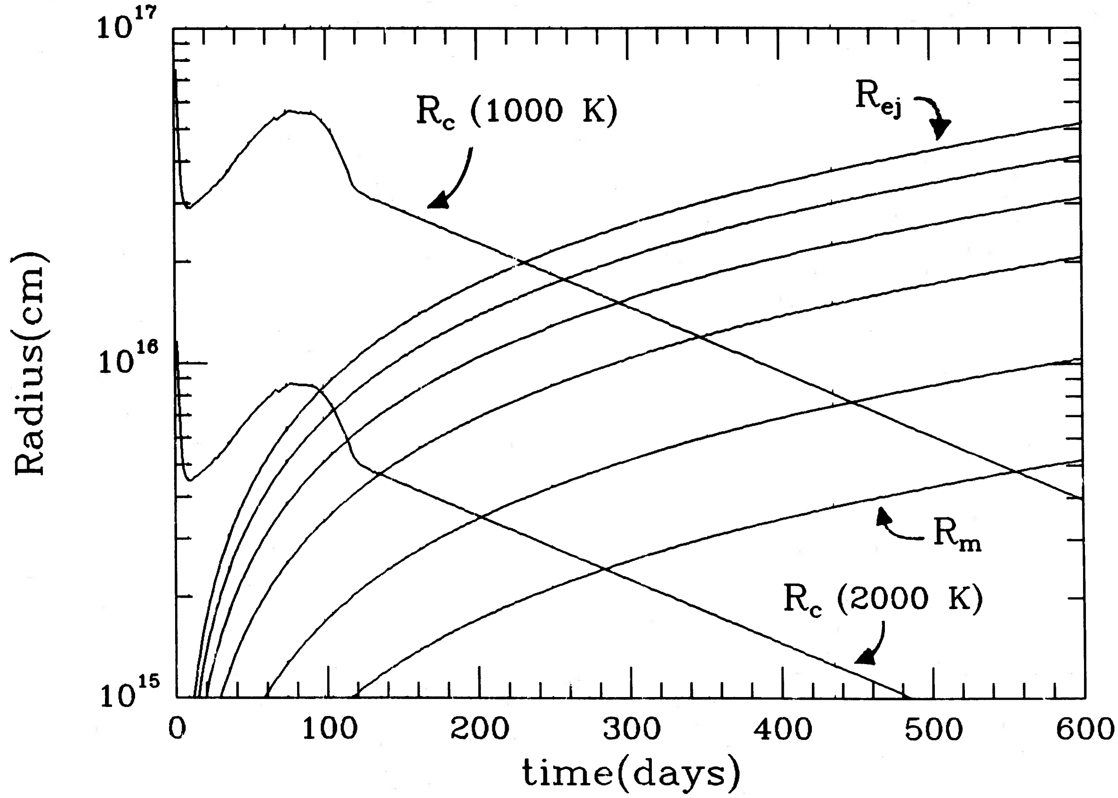

FIG. 1.—The condensation radius, R_c, defined as the distance from the photosphere above which dust can form, is depicted as a function of time since the supernova event for two values of the condensation temperature, T_c. Also shown in the figure are R_{ej}, the outer radius of the H-rich envelope, and R_m, the approximate position of the metal-rich ejecta. The evolution of R_{ej} and R_m assume expansion velocities of 10,000 and 1000 km s^{-1}, respectively. Curves between R_m and R_{ej} depict the positions of layers of the ejecta expanding at velocities of 2000, 4000, 6000, and 8000 km s^{-1}, respectively. Dust can form in a given layer as soon as $R_c < R$, but its formation may be delayed until conditions in that layer are more favorable for the nucleation of dust. The dust formation front sweeps through the expanding envelope and reaches the mantle when $R_c = R_m$.

The accretional time scale of a dust particle, defined by $[a^{-1}da/dt]^{-1}$, is given by

$$t_{\rm accret}(s) = 9 \times 10^3 a(10\ \text{Å})(n_c/10^7\ \text{cm}^{-3})(T/1000\ \text{K})^{-1/2}\ , \quad (8)$$

where T is the ambient gas temperature and n_c is the number density of condensable atoms. Equation (8) assumes that the sticking efficiency of the incident particles is unity, and that their average mass is 20 amu. Inspection of equations (5)–(8) shows, for example, that a 10 Å graphite particle heated to a temperature of 3000 K will evaporate in ~ 16 s, but that its radiative cooling time is only 4×10^{-4} s. A steady flux of energetic photons/particles (calculated in § III) is therefore needed to sustain the evaporation of the dust. A typical time scale for the accretional growth of a dust particle is $\sim 10^3$–10^4 s (calculated for about 1 yr after the explosion), significantly longer than the evaporation time of the particle if maintained at the constant temperature of 3000 K.

III. DUST FORMATION AND SURVIVAL IN SUPERNOVAE

a) Dust Formation

i) *The Evolution of the "Dust-Formation" Front*

It is useful to define the *condensation radius*, hereafter R_c, as the distance from the underlying luminosity source where the temperature of a hypothetical dust particle in the ejecta is equal to its condensation temperature T_c. Dust can therefore only form at distances greater than R_c. In supernovae, unlike cool stars or novae, the condensation radius is not a fixed boundary in space, since the luminosity and effective temperature of the underlying photosphere vary with time. Initially R_c is larger than $R_{\rm ej}$, the outer radius of the ejecta. Dust formation can commence only when the "condensation front," defined by the position of R_c, moves into the ejecta (i.e., when R_c becomes smaller than $R_{\rm ej}$). However, this condition does not ensure that dust will actually form in the ejecta. Observations of mass-losing stars (see Draine 1985) and late-type Wolf-Rayet stars (Williams, van der Hucht, and Thé 1987) show that dust formation does not always take place as soon as the grains can survive. Dust formation can be delayed, presumably until a layer of the ejecta is encountered in which the conditions for the formation and kinetic growth of the particles are more favorable.

The flux incident on a hypothetical dust particle in the envelope is given by $S = L_{\rm SN}/4\pi R^2$, where $L_{\rm SN}$ is the total luminosity of the SN. The condensation radius during this period is then given by

$$R_c(t) = [L_{\rm SN}(t)/16\pi\sigma T_c^{\,4}]^{1/2}\zeta^{1/2}\ , \quad (9)$$

where $\zeta = [\langle Q(T_{\rm ph})\rangle/\langle Q(T_c)\rangle]$, and $T_{\rm ph}$ is the photospheric temperature. Figure 1 depicts the evolution of R_c and $R_{\rm ej}$ as a function of time for ζ appropriate for graphite particles (the essential results will not be significantly altered if silicates were adopted instead). Luminosities and effective photospheric temperatures used for calculating $R_c(t < 130$ days) were taken from the photometric observations of Catchpole *et al.* (1987). The results show that the luminosity of the supernova peaked on $\sim$May 19 (day 85) at a value of $\sim 8.5 \times 10^{41}$ ergs s^{-1}. An exponential decay with an *e*-folding time of 114 days was adopted for the evolution of $L_{\rm SN}$ after day 130 (Catchpole *et al.* 1987). Also shown in the figure is a family of curves describing the position of constant-velocity surfaces as a function of time. The curve marked $R_{\rm ej}$ describes the position of the outer boundary of the ejecta, taken to be expanding at a velocity of 10,000 km s^{-1}. The curve R_m represents the position of the mantle, taken to be expanding at 1000 km s^{-1}. Curves between $R_{\rm ej}$ and R_m depict the position of layers in the ejecta expanding at velocities of 8000, 6000, 4000, and 2000 km s^{-1}, respectively. The radius R_c was calculated for two values of the condensation temperature: 1000 K and 2000 K. The figure shows that, depending on the value of T_c, dust formation can commence between days 100 and 230, and that the dust formation front should reach the mantle between days 280 and 560 after the explosion. As pointed out earlier, dust formation may not take place as soon as the condensation front recedes into the ejecta (i.e., as soon as $R_c < R_{\rm ej}$), but may be delayed until conditions in the ejecta are favorable for the nucleation process. This may be especially relevant to the mantle which contains embedded radioactive heating sources. For this reason, and the fact that the density of condensable elements in the envelope is considerably different from that in the metal-rich mantle, the prospects for dust formation in these respective regions will be treated separately below.

ii) *Dust Formation in the Envelope*

Recent models calculated by Woosley (1987) show that 90% of the envelope's mass is expanding homologously with an outer velocity of 4000 km s^{-1}. This velocity will be subsequently adopted to calculate the density of condensable elements in the envelope, a critical quantity that determines the formation and ultimate size of the forming dust. All the calculations of R_c also assume that the γ-rays are absorbed in the ejecta throughout the entire period shown in the figure, and that the effective photospheric temperature after day 130 is $\sim$4700 K. If a significant fraction of the γ-rays are not thermalized, then the dust condensation radius will drop faster than indicated in the figure. This will mostly affect the calculations presented for $T_c = 1000$ K.

The density of condensable elements is given by

$$\rho_c(\text{g cm}^{-3}) \approx 7.4 \times 10^{-9}(M_d/0.01\ M_\odot)(v_8\, t_{\rm cond})^{-3}\ , \quad (10)$$

where M_d is the mass of condensable matter, v_8 the velocity of the ejecta in 10^8 km s^{-1}, and $t_{\rm cond}$ is the time when the dust temperature in the envelope falls below the condensation temperature. The quantity M_d is normalized to a mass of 0.01 $M_\odot$, since an envelope with a mass of $\approx 10\ M_\odot$ (Woosley 1987) and a metallicity of $Z_\odot/4$ would contain approximately that amount of condensable elements. An important parameter that examines the likelihood of nucleation as a function of density and time is a dimensionless quantity, η, that measures the number of times a given surface site is hit by impinging monomers during a supersaturation *e*-folding time (Draine 1979). Values of η that are larger than unity suggest that nucleation will take place without the need for high supersaturation. Assuming that all impinging carbon atoms stick to the surface, η becomes

$$\eta = 3 \times 10^{16}(T/2000\ \text{K})^{1/2}\rho_c\, t(\text{days})\ . \quad (11)$$

The dust will typically have η monolayers corresponding to radii of $\sim 1.3\eta$ Å. An alternative criterion for judging the likelihood of dust formation is to compare the density of the condensable elements in the ejecta to that around objects where dust formation was observed to have taken place. Observations of novae show that dust can form when the density of condensable elements is $\sim 10^{-16}$ g cm^{-3} (Ney and Hatfield 1978). Dust has been observed to form in cooling stellar atmospheres at densities of $\sim 10^{-18}$ g cm^{-3} (Draine 1985), and around Wolf-Rayet stars at densities as low as $\sim 10^{-19}$ g cm^{-3} (Williams, van der Hucht, and Thé 1987). First, consider the case where $T_c = 2000$ K. At the onset of dust formation [when $R_c = R(4000 \text{ km s}^{-1})$; ~day 140) the density will be $\sim 4 \times 10^{-17}$ g cm^{-3}, dropping to a value of $\rho_c \approx 5 \times 10^{-18}$ g cm^{-3} when the dust formation front reaches the inner boundary of the H envelope (~day 280). Values of η at these epochs are 170 and 40, respectively. This suggests that dust will form throughout the whole envelope with grain sizes in the ~50 to 200 Å range. If T_c is as low as 1000 K, dust formation will be delayed to day 340 when $\rho_c \approx 3 \times 10^{-18}$ g cm^{-3}, at which point $\eta \approx 20$. When the inner boundary of the H envelope is reached (~day 560), ρ_c is $\sim 7 \times 10^{-19}$ g cm^{-3} and $\eta \sim 10$. Typical grain sizes will therefore be between ~10 and 30 Å.

iii) *Dust Formation in the Mantle*

Following the passage of the shock, the mantle expands at such a rapid rate that the expansion is essentially adiabatic; Clayton (1979) developed a simple model to calculate the time when condensation is likely to take place. The gas follows a $\rho = CT^n$ adiabat, where C is a proportionality constant determined by the initial conditions of the gas. The index n is equal to 3 for a radiation dominated gas, and equal to 3/2 for gas that is dominated by gas pressure. Applying Clayton's model to a region of enhanced density in the expanding mantle of SN 1987A (see Woosley 1987), I find that dust formation will take place about 430 days after the explosion. The density of condensable elements is then $\sim 5 \times 10^{-14}$ g cm^{-3}, creating more favorable conditions for nucleation than those in the envelope. If the density spike expands with constant thickness, the condensation will be delayed to ~8 yr, but will take place at the same density.

The analysis above ignored the energy input in the gas by the radioactive decay of ^{56}Co, which may delay the onset of condensation (Lattimer, Schramm, and Grossman 1978). Assuming that the radioactive material is mixed in the dust-forming region, the results of Lattimer *et al.* show that if ~5% of the material is initially ^{56}Ni, then condensation temperatures are reached at densities that may be lower by a factor of $\sim 10^{-3}$. In SN 1987A the initial mass of ^{56}Ni is about 1% of the mass of the mantle (Woosley 1987). Dust formation may still take place, but significantly later than day 430. However, dust may form sooner if the density spikes containing the condensable elements become Rayleigh-Taylor unstable and break up into clumps. Calculations by Woosley (1987) show that the radioactive decay of ^{56}Co creates a bubble that accelerates the overlying shell with $g \approx 1$–10 cm s^{-2}. The bubble has a thickness of $l \approx 10^{14}$ cm, so that Rayleigh-Taylor instabilities may develop in a time scale of $\sim (l/g)^{1/2} \sim 40$–120 days. The resulting clumps may have a high optical depth for soft X-ray and EUV photons, and if their volume filling factor is less than unity, the trapped radiation will escape through the interclump medium, which may have a significantly reduced opacity. The early formation of dust in the mantle is therefore linked to the early escape of the UV and soft X-rays from the SN. The dust shell will then never completely obscure the underlying energy sources. The location of the dust in clumps will also shield them from future destruction (~few hundred years) by reverse shocks that will expand into the ejecta (McKee 1974).

b) Dust Survival

Some novae or Wolf-Rayet stars do not form dust, a condition which suggests the existence of some grain suppression mechanisms in these objects. Various mechanisms may prevent the formation of critical-size clusters in SN 1987A even if it is thermodynamically feasible. It is beyond the scope of this paper to speculate whether such grain suppression mechanisms exist in SN 1987A, as these mechanisms are not well understood. Instead, I will examine if any dust that may have formed will survive. High-energy photons or particles emitted by a pulsar that may have been left behind in the explosion may destroy the newly formed dust. To estimate the likelihood of grain survival, I will adopt a dust vaporization temperature of 2000 K, and an average dust size of 10 Å. The following conclusions will not be changed if a vaporization temperature of 1000 K is used instead. From the analysis of § II I find that an energy deposition of 200 eV is required to raise the dust temperature to 2000 K. After absorbing this quanta of energy, a dust particle will radiatively cool in 1.25×10^{-3} s. This time is significantly shorter than the evaporation time of the dust at that temperature. A steady flux of particles with an energy deposition rate of $\sim 200 \text{ eV}/t_{\text{cool}} = 2.6 \times 10^{-7}$ ergs s^{-1} is therefore required to vaporize the dust. Photons with energies of ~200 eV are absorbed in the dust with an efficiency of $Q \sim 10^{-3}$. The required photon flux is therefore $\sim 4 \times 10^9$ ergs cm^{-2} s^{-1}. The average distance to the dust-forming region is $\sim 10^{15.4-16}$ cm, so that the minimum luminosity required to vaporize the dust is $\sim 10^{40-42}$ ergs s^{-1}. The near exponential decay of the SN luminosity after day 130 constrains the pulsar's contribution to the total energy output to be less than $\sim 10^{40}$ ergs s^{-1}. A significantly more energetic pulsar radiating a large fraction of its energy output at UV wavelengths is required to vaporize the dust. Similar arguments rule out the likelihood of grain destruction by energetic particles. I therefore conclude that if dust forms in the supernova it will likely survive any subsequent destruction.

IV. OBSERVATIONAL CONSEQUENCES

SN 1987A offers the first opportunity to observe the dust formation process in a supernova, and to discriminate between it and the echo model for the evolution of the infrared light curve. In the echo model the emission originates from a preexisting stationary dust shell that reprocesses the UV-visual output from the underlying photosphere to infrared wavelengths. Assuming spherical symmetry, the IR luminosity, L_{IR}, should remain approximately constant for a period of $t_d \approx 2R_d/c$, where R_d is the distance of the dust shell from the supernova. The quantity $L_{\text{IR}} \approx \Delta t/t_d \tau_d L_{\max}$, where τ_d is the optical depth of the circumstellar dust shell, $L_{\max}$ is the peak SN luminosity, and Δt is an effective duration period of the visual light curve. For SN 1987A, $L_{\max} \approx 8.5 \times 10^{41}$ ergs s^{-1}, and $\Delta t \approx 60$ days. Given the distance of the shell (and hence the delay time in the IR signal), the spectral evolution of the IR echo can be fairly well determined given the extensive UV-optical coverage of the central heating source. In contrast to the echo model, the IR light curve in the dust formation model reflects the instantaneous behavior of the UV-visual light curve, and the IR luminosity and temperature are determined by the available dust heating sources. The onset of dust formation and subsequent changes in the optical depth of the newly formed dust shell will be accompanied by corresponding increases and decreases in the observed UV-visual light curve (see *Note added in manuscript*).

The observational consequences of the dust depend on the optical depth of the dust shell, the nature of the energy sources that powered the rise in the light curve of SN 1987A, and on the details of the dynamic and radiative transfer phenomena in the ejecta. It will therefore be quite premature to present a detailed prediction of the IR behavior of SN 1987A. The expected behavior of the IR emission can, however, be described in a general way for various plausible scenarios.

a) Obscuration of the UV-visual Output of SN 1987A

First, I will consider the possibility that the dust shell that may form in the envelope of SN 1987A will be optically thick, as is the case for dust shells around many novae. If M_d is the mass of dust formed in the H-rich envelope, then the mass column density of the dust is $M_d/4\pi R^2$. The envelope will therefore remain optically thick for a period of

$$t_{\rm thick}({\rm months}) \approx 50[\kappa_\nu M_d(M_\odot)]^{1/2}/v_8 \; . \qquad (12)$$

Graphite and silicate particles with sizes below ∼100 Å have an average opacity in the 3650 to 5500 Å wavelength region of $\kappa = 4 \times 10^4$ and 2×10^3 cm^2 gr^{-1}, respectively. This opacity is independent of their grain size (Draine 1987). If 0.01 $M_\odot$ of silicates or graphite dust formed in the envelope, then any UV-visual output from the pulsar will be blocked for a period of about 5–20 yr, depending on the dust composition. Using equation (12) with the above value of κ (graphite) shows that a typical nova, for which $M_d \approx 10^{-7}$ $M_\odot$ and $v_8 \approx 1$ (e.g., Gehrz *et al.* 1980), should remain opaque for a period of about 3 months, consistent with observations. The 5–20 yr period of obscuration derived here for SN 1987A is therefore consistent with the observed obscurations in novae, if the difference in dust mass and ejecta dynamics is taken into account.

b) Infrared Emission from SN Condensed Dust

An optically thick dust shell will reprocess any UV-visual radiation emitted by the central energy source(s) to IR emission. The late-time evolution of the IR spectrum is therefore determined by the still unknown evolution of the UV-visual output from the energy sources in SN 1987A. At present, the existence of a pulsar (let alone its period or energy distribution) has not yet been firmly established. Any detailed prediction regarding the IR evolution of SN 1987A is therefore premature. Nonetheless, general conclusions can be drawn about the intensity and evolution of the IR flux. If dust forms in the ejecta, then the supernova will be brightest in the IR between the onset of dust formation (∼day 140–340) and the time when a significant fraction of the γ-ray lines will start to emerge from the ejecta (∼day 600). After γ-ray transparency the only remaining heating source will be the compact remnant left in the explosion, which will be significantly less effective in heating the dust.

For simplicity I will assume that the dust absorbs a fraction ϵ of the total luminosity of the central energy source. Assuming a λ^{-1} wavelength dependence of the dust emissivity, the IR flux (in Jy) at any wavelength λ can be written as

$$F_\lambda({\rm Jy}) = 67 L_{{\rm IR},\,38}\, G(x)/T_d \; ,$$

where

$$G(x) = x^4/[\exp(x) - 1] \; . \qquad (13)$$

$L_{{\rm IR},\,38}$ is the total IR luminosity emitted by the dust in units of 10^{38} ergs s^{-1}, $x = 14388.3/[\lambda(\mu{\rm m})T_d]$, and the distance to the LMC was taken to be 50 kpc. The dust temperature is approximately (accuracy of ∼20%) given by

$$\begin{aligned} T_d(K) &\approx 24[\epsilon L_{S,\,38}/a(\mu m) R_{\rm pc}{}^2]^{0.2} \\ &\approx 10^3[\epsilon L_{S,\,38}/a(\mu m) v_8{}^2]^{0.2} t^{-0.4}({\rm months}) \; , \qquad (14) \end{aligned}$$

where $L_{S,38}$ is the source (nuclear + pulsar) luminosity in units of 10^{38} ergs s^{-1}, v_8 is the expansion velocity (in 10^8 cm s^{-1}) of the dust layer: $v_8 \approx 4$ for dust in the envelope, and ∼1 for the dust in the mantle.

First, consider the case in which the SN light curve is powered only by the radioactive decay of ^{56}Ni. For $t > 130$ days L_n (ergs s^{-1}) $\approx 3.1 \times 10^{41}$ exp $[-(t - 130)/114]$ (Catchpole *et al.* 1987). As long as the mantle is opaque to the γ-rays, most of this luminosity will be reprocessed to visual wavelengths where $\epsilon/a(\mu{\rm m}) \approx 4.2$. Without an underlying pulsar, the dust temperature will rapidly decrease due to the combined effect of the decrease in the nuclear energy output, and the fact that less γ-rays are downscattered to lower energies where they are more efficiently absorbed by the dust. For example, at $t \approx 300$ days the mantle is still opaque to γ-rays. If the dust shell is optically thick, then the total IR luminosity will be 7×10^{40} ergs s^{-1}, the dust temperature will be ∼1000 K, and the 4 μm IR flux will be ∼200 Jy. As the mantle becomes more transparent to the γ-rays, the dust will absorb less of the underlying energy and will rapidly become undetectable at IR wavelengths.

If a pulsar is present, then the IR luminosity will be a measure of the UV-visual output of the pulsar that breaks out through any intervening ejecta. The average value of $\epsilon/a(\mu{\rm m})$ in the 100–5000 Å range is ∼1 for silicates, and ∼10 for graphite. If the UV-visual output of the pulsar is $\sim 5 \times 10^{38}$ ergs s^{-1}, then typical graphite temperatures will be ∼360 K on day 300, decreasing to ∼280 K on day 700. The average IR flux during this period will be ∼4 Jy at 10 μm. The temperature of the SUNOCONS may be higher than that of the dust in the envelope because of their proximity to the pulsar. However, if the clumps are dense enough, the UV-visual may be significantly attenuated. Furthermore, if the volume filling factor of the clumps is significantly less than unity, only a fraction of the pulsar's radiative output will be intercepted. Thus, even though dust may have formed in the mantle, it may remain undetectable in the infrared.

V. CONCLUSIONS

In this paper I examined the prospects for the formation and detection of dust in the cooling ejecta of SN 1987A. The formation of dust will have immediate implications on the spectral analysis of the ejecta since, as originally suggested by Gehrz and Ney (1987), the dust may obscure the visual and UV output of any pulsar that may have formed in the explosion. The results of this paper are briefly summarized below.

Grains may form in the expanding ejecta as soon as they can survive the heating by the ambient radiation field, which may be as early as 3 to 8 months after the explosion. In practice, dust formation may be delayed. Typical densities of condensable elements in the H-rich layers of the ejecta at the time when dust is likely to form are between 10^{-18} to 10^{-17} g cm^{-3}. These values are comparable to those found in some novae or Wolf-Rayet stars, where dust formation has been observed to take place. Higher densities of condensable elements will exist in the metal-rich layers (mantle) of the ejecta. However, for reasons that are still not well understood, some objects do not form dust even if it is thermodynamically feasible. Such dust suppression mechanisms may prevent the formation of dust in SN 1987A as well. If dust forms, then a mass of 0.01 $M_\odot$ of dust will obstruct the UV-visual output of the pulsar for ∼5–20 yr, depending on dust composition. The supernova will be brightest in the infrared between the onset of dust formation and the time of maximum γ-ray transparency ($\sim$day 600). If the dust shell is optically thick, the infrared luminosity will be larger than $\sim 10^{40}$ ergs s^{-1}. Thereafter, all the infrared luminosity will be provided by the UV-visual output of the pulsar. If the pulsar has an initial luminosity and energy distribution like those of the Crab, then typical infrared luminosities will be $\sim 5 \times 10^{38}$ ergs s^{-1}.

The formation of dust in a uniformly expanding mantle may be suppressed for a few years by the presence of radioactively decaying matter. The mantle may, however, become Rayleigh-Taylor unstable and form high-density clumps in which dust may form as early as 1 yr after the explosion. Since the clumps do not fill the entire volume of the ejecta, only a fraction of the visual, UV, and soft X-ray output of the pulsar will be reprocessed to infrared wavelengths. In this scenario, the formation and detection of dust in the mantle are closely linked to the early breakout of the UV and soft X-rays.

Once formed, the dust will likely survive any subsequent destruction by energetic particles or photons. Theoretical models suggest that a $\sim 20\ M_\odot$ progenitor can produce about $\sim 1\ M_\odot$ of supernova condensates. Supernovae will then consitute a major source of dust, equaling the combined output of all other sources. The detection of this dust in SN 1987A will be a significant addition to the complete picture we now have of the presence of isotopic anomalies in the solar system, and of the origin and evolution of dust in the interstellar medium.

Note added in manuscript.—Since this paper was written, the CO vibration line at 4.6 μm, and its 2.3 μm overtone have been detected in the spectrum of SN 1987A (e.g., McGregor and Hyland 1987). In at least two novae the dust formation period was preceded by the appearance of a pronounced excess, above the free-free spectrum, of infrared emission at 5 μm. This excess radiation is now widely interpreted as emission from CO that formed in the novae ejecta (Gehrz *et al.* 1980). If the CO lines detected from SN 1987A are emerging from the outflowing material, their appearance may be signaling the imminent onset of dust formation.

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