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Confirmation of dust condensation in the ejecta of supernova 1987a

(astronomy/infrared/supernova/pulsar)

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ABSTRACT **Shortly after its outburst, we suggested that supernova 1987a might condense a dust shell of substantial visual optical thickness as many classical novae do and predicted that dust might form within a year after the explosion. A critical examination of recent optical and infrared observations reported by others confirms that dust grains had begun to grow at a temperature of 1000 K after 300 days and that the dust shell had become optically thick by day 600. After day 600, the infrared luminosity closely followed the intrinsic luminosity expected for thermalized ^{56}Co γ rays, demonstrating that the luminosity is powered by radioactivity and that the dust is outside the radioactivity zone. The infrared luminosity sets an upper limit to the soft intrinsic bolometric luminosity of a pulsar central engine. This upper limit for the pulsar in supernova 1987a is the same luminosity as the Crab pulsar has today 936 years after its formation. It is unlikely that the rotation rate for a pulsar in supernova 1987a can be much higher than ≈30 revolutions per sec. The relatively long time required for the shell to grow to maximum optical depth as compared with the dust in nova shells may be related to the relatively low outflow velocity of the condensible ejecta.**

In Gehrz and Ney (ref. 1; hereafter called paper 1) we predicted that supernova 1987a (SN 1987a) might condense a dust shell of substantial visual optical depth. By analogy with the dust formation process in classical novae (2–4), we argued that the dust might form within a year of the explosion. In this paper we examine optical/infrared observations reported by others (ref. 5 and the references therein; refs. 6 and 7; N. Suntzeff, private communication), show that these observations indicate that dust grains had begun to grow at a temperature of 1000 K after 300 days, and argue that the dust shell had become optically thick by day 600. The dust hypothesis for SN 1987a has also been discussed in light of recent observations by several other investigators (5–10).

Dust Formation in Previous Novae and Supernovae

In paper 1 we reviewed evidence for dust formation in novae and type II supernovae before SN 1987a. Dust formation in the ejecta of classical novae has been well documented by infrared observations of >20 cases over the past two decades (3, 4). At least a third of all classical novae form optically thick dust shells that act as calorimeters for the luminosity of the central engine. An equal fraction form optically thin dust shells. Infrared measurements of the luminosities of optically thick nova shells have confirmed that novae have a constant luminosity phase. This constancy of the luminosity of the central engine facilitates the distinction between optically thick and optically thin dust shells in novae.

Dust formation was a plausible explanation for excess infrared radiation from two type II supernovae before SN 1987a. An infrared excess in SN 1980k after 257 days showed that dust may have formed (11), but the shell was probably optically thin because the short wavelength brightness of the supernova remained fairly high. A similar infrared excess combined with low luminosity at short wavelengths suggested the formation of an optically thick shell in SN 1979c (see paper 1). In neither case did the optical/infrared observations appear to cover the initial stages of dust formation; nor did they give any information on the extinction by the dust. Estimates of the dust shell optical depth in these supernovae are dependent entirely on assumptions about the temporal evolution of the luminosity of an unspecified central engine. Some investigators suggested that the infrared excesses in these cases might come from light echoes (12, 13).

SN 1987a presents a much more favorable opportunity to observe dust formation.

Review of Our Prediction of Dust Formation in SN 1987a

In paper 1, we argued that an optically thick dust shell could form in a time t_c:

$$t_c = \frac{R}{V_o} = \frac{1}{V_o}\left[\frac{L}{4\ \pi\sigma T_c^4}\right]^{1/2}, \qquad [1]$$

where L is the luminosity of the central engine, V_o is the outflow velocity of the condensible ejecta, T_c is condensation temperature, $R = [L/4\ \pi\sigma T^4]^{1/2}$ is the shell radius at the condensation point, and σ is the Stefan–Boltzman constant. The density ρ_c of a nova shell at the condensation radius was shown to be

$$\rho_c = 1.2 \times 10^{-4}\left[\frac{M}{M_\odot}\right]\left[\frac{L_\odot}{L}\right]^{3/2} g{\cdot}cm^{-3}, \qquad [2]$$

where M is the mass of the ejected shell. Novae that condense optically thick dust shells were found to have $\rho_c \geq 3 \times 10^{-16}$ g·cm^{-3}. If $L \leq 5 \times 10^5 - 5 \times 10^6\ L_\odot$ and $M \geq 0.1\ M_\odot$, we predicted that the condensation of an optically thick dust shell was probable for SN 1987a. We further predicted that the central source would be obscured when the dust condensed, resulting in an abrupt drop in the visible light.

Early spectra showed that the envelope appeared to be expanding at velocities between 6000 and 8000 km·sec^{-1}. We argued that if the central engine maintained the luminosity observed at outburst throughout the dust production process, the maximum dust shell optical depth should have been reached sometime between 240 and 330 days after the outburst. In fact, the dust began to form ≈300 days after the outburst and did not reach maximum optical depth until ≈day 600. We show that the actual time scale is consistent with a much slower outflow velocity of ≈2000 km·sec^{-1} and an exponentially declining radioactive central engine.

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Abbreviations: SN 1987a, supernova 1987a; SIBL, soft intrinsic bolometric luminosity.

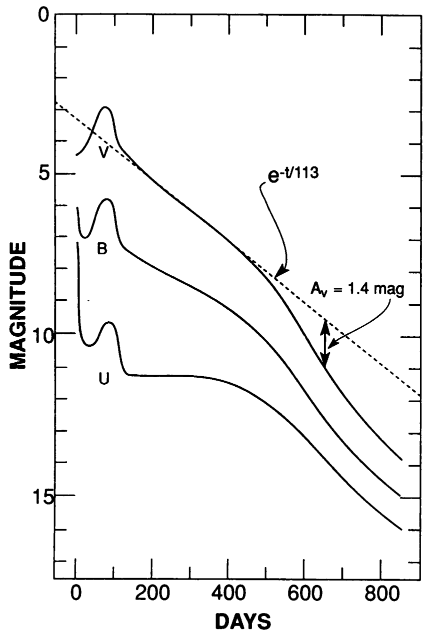

FIG. 1. The ultraviolet (U), blue (B), and visual (V) (UBV) light curves for SN 1987a (after ref. 5) show evidence for obscuration by dust beginning around day 400 at U and by day 600 at V.

A crucial test of dust condensation as compared to light echoes is the angular size of the shell; light echo shells are 10–30 times larger than dust condensation shells. The angular size of the dust shell is determined by the velocity of the ejecta, the time since outburst, and the known distance to the Large Magellanic Cloud.

Evidence for Dust Formation in SN 1987a

Recent optical/infrared observations of SN 1987a (refs. 5 and the references therein, refs. 6 and 7) appear to provide at least three independent indications that an optically thick shell of cool material had formed in the ejecta by ≈600 days after the eruption and was still dominating the luminosity on day 1050:

(*i*) Danziger *et al.* (14) found that the red wings of the emission lines in the ejecta became strongly obscured by ≈650 days after the eruption as if an optically thick cloud of dust had formed that obscured the far side of the expanding ejecta and estimated that ≈1 magnitude of visible extinction to the center of the shell was required to model the observed obscuration in the red wings of the line profiles.* This is consistent with the extinction that is implied by extrapolating the early exponential visible decline rate to day 650 (see Fig. 1).

(*ii*) There was a marked downturn in the ultraviolet, blue, and visual light curves (Fig. 1) between days 400 and 600 (earlier at the shorter wavelengths) that represented a significant increase in the rate of decay compared with the 78-day half-life (113-day mean-life) that the visible light displayed from day 125 to day 450. The 78-day decline is believed to provide evidence that the ejecta are powered by the absorption of γ rays emitted during the $^{56}Co \rightarrow ^{56}Fe$ decay process.† One of two explanations might be offered for the accelerated decline after day 450. First, as proposed by Michel *et al.* (18), the ejecta may be going optically thin to γ rays so that radioactivity can no longer heat the ejecta. Second, a shell of obscuring material that is optically thick along the line of sight may have condensed in the outflowing ejecta. We believe that obscuration was a major effect because the extinction implied by the disappearance of the red wings is compatible with the magnitude of the deviation of the light curve from the 78-day half-life. As shown in Fig. 2, the infrared dominated the bolometric luminosity on day 640.

*It is now well known from the infrared signatures of novae that dust forms in the ejecta (2, 3), but before the birth of infrared astronomy McLaughlin (15) originated the dust condensation hypothesis for DQ Her novae by recognizing that "The relative fading of the longward emission (line) maxima stands out alone as distinctly favorable to the hypothesis of obscuration, whether by molecules or by dust."

†The first suggestion that radioactivity determined the decline rate of supernova light curves was by Fowler (16), who proposed that the isotope was ^{254}Cf. Truran (17) later attributed the decay to ^{56}Co.

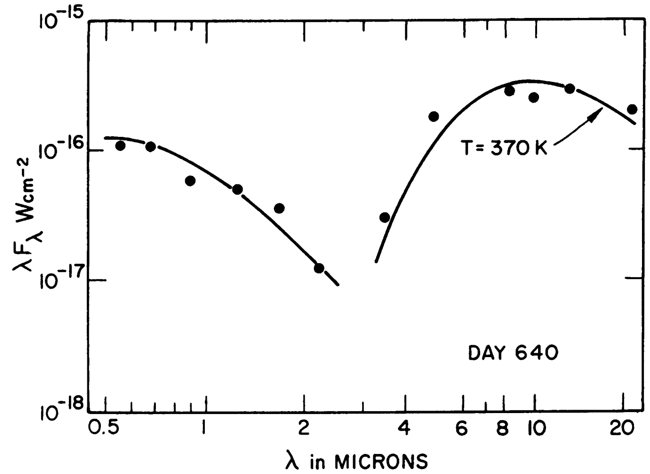

FIG. 2. Energy distribution of SN 1987a on day 640 when 72% of the luminosity was contributed by the 370 K black body (data from ref. 5; N. Suntzeff, private communication). Plot shows λF_λ versus λ; luminosity of a black body is $1.35(\lambda F_\lambda)_{max}$.

(*iii*) The decline in visible light was accompanied by a steady rise in the thermal infrared intensity (see data in ref. 5), as would be expected for a shell of growing grains reradiating absorbed short wavelength energy from a central luminosity source. By day 640, the infrared luminosity was 1.36×10^{39} erg·sec^{-1} and the shell had a temperature of 370 K (Fig. 2). Between days 300 and 900, the shell temperature, determined from plots like Fig. 2, dropped from 1000 K to 150 K (Fig. 3). The infrared luminosity continued to decline until day 1050 (Fig. 4).

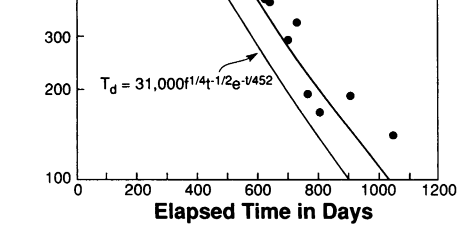

FIG. 3. Temporal evolution of the dust temperature in SN 1987a. Black circles are based on our analysis of the infrared data (ref. 5 and the references therein; N. Suntzeff, private communication). The upper curve is the temperature dependence for a shell that is optically thick in the infrared; the lower curve is for an optically thin shell of black grains.

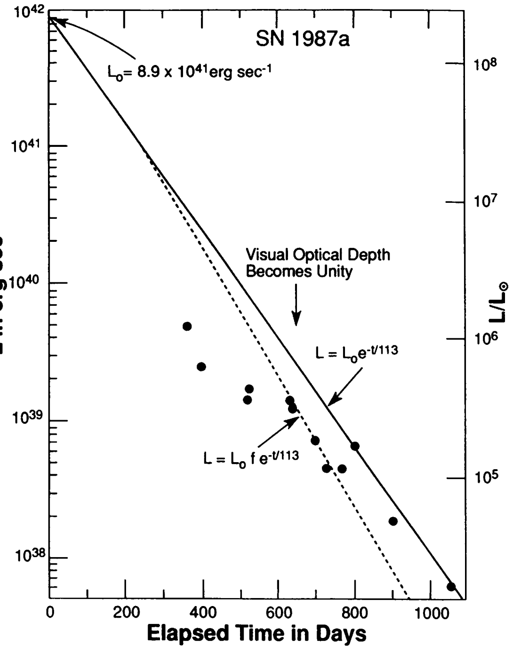

FIG. 4. Temporal evolution of the infrared luminosity of SN 1987a. Closed circles are based on our analysis of the infrared data (ref. 5 and the references therein; N. Suntzeff, private communication). —, Decay of the radioactive central engine due to ^{56}Co; ---, SIBL derived by correcting for escaping γ rays by using the model proposed by Woosley *et al.* (19).

The variations of the infrared color temperature and luminosity (Figs. 3 and 4) are consistent with the hypothesis that an optically thick shell of material had obscured a central engine powered by γ rays from the radioactive decay of ^{56}Co to ^{56}Fe, with a mean-life of 113 days. Cosmic rays emitted directly by the central engine might not couple efficiently to small dust grains. Therefore, the radiation from the dust must be a measure of the lower energy emissions that contribute to what we term the soft intrinsic bolometric luminosity (SIBL), L, of the central engine. γ rays that are thermalized within the central engine are the primary source of the SIBL for a radioactive central engine. L as a function of time t after outburst is as follows:

$$L(t) = L_o f(t)(2)^{-t/78} = L_o f(t) e^{-t/113} \quad [3]$$

where L_o is the SIBL extrapolated to $t = 0$, and $f(t)$ is the fraction of the γ ray energy that can be thermalized in the ejecta; f is unity at outburst and decreases later as the ejecta become optically thin to γ rays (20). The obscuring dust directly affects the UBV decline rates (Fig. 1) while simultaneously blocking the far side of the shell and reradiating the SIBL (see Fig. 4). This result implies that the dust lies mainly outside the region containing the radioactive ejecta. For the case of an exponentially decaying central engine, Eq. **1** for the time t_c for the ejecta to reach the condensation radius becomes

$$t_c = \frac{1}{V_o}\left[\frac{L_o f(t_c) e^{-t/113}}{16\,\pi\sigma T_c^4}\right]^{1/2}, \quad [4]$$

and an optically thick dust shell will have a temperature T_g:

$$T_g(t) = \left[\frac{L_o f(t) e^{-t/113}}{4\,\pi\sigma V_o^2 t^2}\right]^{1/4} \quad [5]$$

where $T_c = 1000$ K is the condensation temperature. $T_g(t)$ will be 2 1/2 times lower for a shell of black grains that is optically thin in the thermal infrared. The evolution of the temperature of the SN 1987a dust shell (Fig. 3) suggests that the shell eventually became optically thick in the thermal infrared region. It seems possible that the condensation of water ice onto the grains could have accelerated their growth after day 700. Woosley *et al.* (20) have shown that mixing in the outer ejecta should produce an oxygen-rich mixture where the condensation of water might be expected.

The luminosity L_o is $3.5 \times 10^{42} M_{Co} \Delta E$ erg·sec^{-1}, where M_{Co} is the initial mass in solar masses of ^{56}Co available from the decay of the ^{56}Ni produced in the outburst, and ΔE in Mev is the γ ray energy per ^{56}Co decay that can be absorbed in the ejecta. Assuming that $M_{Co} = 0.075\, M_\odot$ (20) and $\Delta E = 3.59$ Mev (19), we find $L_o = 9 \times 10^{41}$ erg·sec^{-1} for SN 1987a. The expansion velocity V_o can be determined by the expansion rate of the black body angular radius of the optically thick shell, as shown by Gallagher and Ney (21). Assuming a distance of 50 kiloparsec to the Large Magellanic Cloud (5), we derive an expansion velocity of 2140 km·sec^{-1} by this method (Fig. 5). It follows from Eqs. **4** and **5** that refractory dust grains should have condensed at 1000 K $\approx$300 days after the explosion. This result is consistent with the evolution of the shell temperature from infrared measurements (Fig. 4). This condensation process was substantially the one we originally predicted in paper 1, except that the process occurred at a much lower expansion velocity than we had assumed and with an exponentially declining central engine. These competing effects, nonetheless, conspired to produce dust on the time scale we had predicted. The relatively low expansion velocity of the condensible ejecta has been confirmed spectroscopically (22).

The energy now observed in the infrared sets some upper limits on the luminosity of an embedded pulsar if one assumes that the pulsar luminosity is comparable to the luminosity due to radioactivity. Although high-energy electrons and cosmic rays emitted by a pulsar may not couple efficiently to a dust shell, it is likely that most of the pulsar's magnetic dipole radiation will be converted to SIBL (see ref. 23). Presumably, only a small fraction of the pulsar's luminosity will be in high-energy cosmic rays that penetrate the dust layer. The day-1050 luminosity of SN 1987a of 2×10^{38} erg·sec^{-1} is about equal to the present total power radiated by the Crab Nebula, which is presumed to come from the time rate of change of the kinetic energy of the Crab pulsar. If the bolometric output of SN 1987a is now due to a pulsar central engine, to supply

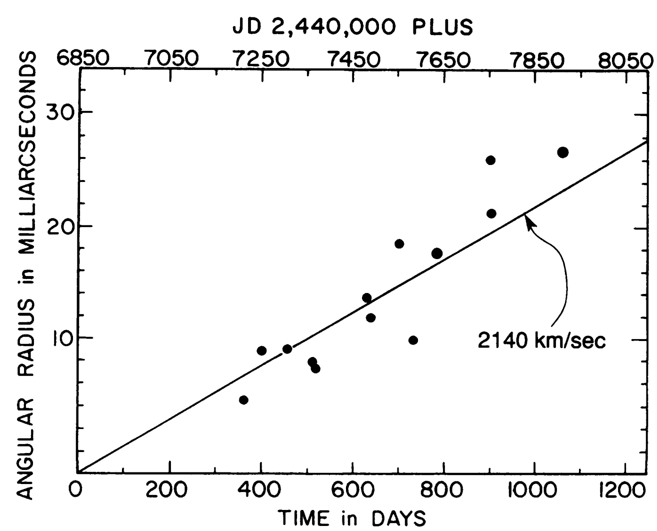

FIG. 5. Temporal evolution of the angular diameter of the dust shell of SN 1987a. Black circles are based on our analysis of the infrared data (ref. 5 and the references therein; N. Suntzeff, private communication), JD, Julian day.

this power would demand that $B^2\Omega^4R^6$ for the central engine of SN 1987a be the same as the present value for the Crab Nebula. Because R is determined by a neutron star model (for example, $R = 10$ km), Ω^4 must be the same as the present value for the Crab Nebula pulsar if both pulsars have the same magnetic field strength (i.e., 3×10^{12} gauss). Thus, the SN 1987a pulsar would have a period of ≈30 msec, much longer than the 0.5-msec period reported by Kristian *et al.* (24).[‡] If the current luminosity of SN 1987a is still dominated by radioactivity, then the argument above gives a lower limit to the period of the central pulsar.

‡As of February 23, 1990, Kristian *et al.* (25) have retracted this result and attributed it to an experimental error.

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