THE ASTROPHYSICAL JOURNAL, 274:175–183, 1983 November 1

THE INFRARED ECHO OF A TYPE II SUPERNOVA WITH A CIRCUMSTELLAR DUST SHELL: APPLICATIONS TO SN 1979c AND SN 1980k

ELIAHU DWEK[1]
Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center
Received 1982 June 28; accepted 1983 April 7

ABSTRACT

A model for the infrared echo of a supernova with a circumstellar dust shell was constructed to examine the origin of the thermal infrared emission observed from the recent Type II supernovae 1979c and 1980k. The results show that the evolution of the infrared spectrum from both supernovae is consistent with a circumstellar shell origin model, in which the thermal infrared radiation arises from preexisting dust grains heated up by the UV-visual output of the supernova. The models suggest that both supernovae have circumstellar dust shells extending out to a distance of $\sim 6–8 \times 10^{17}$ cm from the star, with optical depths of ~ 0.3 and ~ 0.03 for SN 1979c and SN 1980k, respectively. A lower limit between $\sim 1–5$ and $\sim 0.1–0.4$ $M_\odot$ can be derived for their respective shell masses. However, more extensive observation (both in wavelengths and time) than those presently available are required to ascertain these results. Assuming a wind velocity of 10 km s^{-1}, the model also suggests that the progenitor star of SN 1979c had a mass loss rate $>(4–20) \times 10^{-5}$ $M_\odot$ yr^{-1}, and that of SN 1980k $>(0.4–2) \times 10^{-5}$ $M_\odot$ yr^{-1}, consistent with the rate required to interpret their radio emission and the X-ray luminosity from SN 1980k. A burst of soft X-rays and UV radiation with a luminosity $\gtrsim 10^{10}$ $L_\odot$ may have preceded the first observed visual light, lasting long enough to vaporize all the circumstellar dust out to a radius of $\sim 3 \times 10^{17}$ cm from the center of the explosion.

The above calculations show how combined optical and infrared observations of Type II supernovae can be used to estimate the masses and sizes of circumstellar shells around the progenitor stars. To illustrate this point, the paper depicts the time behavior of the infrared echo of a "typical" galactic supernova for various circumstellar shell masses.

Subject headings: infrared: sources — nebulae: individual — nebulae: supernova remnants — stars: circumstellar shells

I. INTRODUCTION

Recently, two supernovae, SN 1979c in NGC 4321 (Merrill 1980) and SN 1980k in NGC 6946 (Telesco *et al.* 1981; Dwek *et al.* 1983), have been observed to develop a thermal infrared excess about 7–9 months after visual maximum. The infrared behavior of these supernovae is almost identical to that observed in several novae, the classical one being Nova Serpentis 1970 (Hyland and Neugebauer 1970; Geisel, Kleinmann, and Low 1970), with Nova Vulpeculae 1976 (Ney and Hatfield 1978) being a more recent example. The novae observations have been interpreted as evidence for the rapid condensation of grains in the nova ejecta (e.g., Clayton and Wickramasinghe 1976; Ney and Hatfield 1978). The similarity between the nova and supernova phenomena therefore strongly suggests the same interpretation, namely, that the infrared emission from SN 1979c and SN 1980k arises from dust particles that formed in the expanding supernova ejecta.

However, a different explanation for the infrared behavior of novae was offered by Bode and Evans (1980*a*, 1981). According to their model, the thermal emission arises from circumstellar grains that existed *prior* to the eruption of the nova. This so-called infrared echo model was also suggested as a possible explanation for the infrared behavior of SN 1979c (Bode and Evans 1980*b*).

Dust of supernova origin plays an important role in the interpretation of isotopic anomalies found in meteorites (see review paper by Clayton 1982), and its formation is probably required to account for the typically observed gas-phase depletion of refractory elements in the interstellar medium (Dwek and Scalo 1980). Furthermore, observational evidence for the presence of dust in the supernova ejecta can yield valuable information about its nucleation process. The correct interpretation of the infrared behavior of the two supernovae is therefore a problem of considerable astrophysical interest.

In this paper I examine whether the thermal infrared radiation from SN 1979c and SN 1980k could have been emitted by dust particles that were present in a circumstellar shell prior to the supernova event. This circumstellar dust presumably formed in the expanding material ejected from the star during the red giant phase of its evolution.

The time behavior of the infrared echo depends on the detailed distribution of the dust around the super-

[1] National Research Council Resident Research Associate.

nova, and on the decay rate of its ultraviolet (UV) and visual output. The specialized case of a supernova flash going off in an extended, optically thick molecular cloud was studied by Wright (1980). However, the observations of the two supernovae show that the energy radiated in the infrared represents only a fraction of the total UV-visual output of the supernovae. Thus, the emission originates from an optically thin circumstellar dust shell, presumably the result of mass loss from the progenitor star.

The model for the infrared echo of a supernova with an optically thin circumstellar dust shell is described in § II, and analytical solutions are given for an exponentially-decaying supernova light curve. In § III the time behavior of the echo of a galactic supernova is studied for a variety of circumstellar shell sizes. The possibility that the infrared emission from SN 1979c and SN 1980k arises from a circumstellar dust shell is examined in § IV, and the results of the paper are briefly discussed in § V.

II. THE EVOLUTION OF AN ECHO FROM A CIRCUMSTELLAR DUST SHELL

a) *General Equations*

Morrison and Sartori (1969) suggested that the light of a supernova is not emitted from the star itself, but from the extended ambient gas excited by the UV outburst from the explosion. Their fluorescence model is modified here to calculate the infrared emission that arises from the ambient dust heated up by the UV-visual output of the star.

An observer located at the center of the explosion will at any given time after the explosion see the infrared emission emerging from a spherically symmetric sphere of radius ct, centered on the supernova. A distant observer will at any given time t (measured since the arrival time of first visual light) see the infrared emission emerging from within a paraboloid of revolution with the supernova at its focus and its axis along the line of sight (Bode and Evans 1980*b*). The emitting volume is actually composed of an infinite number of paraboloid-shaped light fronts. The leading front defines the outer boundary of the infrared emission and consists of all the dust that was heated up by the initial supernova outburst at $t_0 \equiv 0$. Dust that was heated up by the supernova at any later time will lie on a trailing paraboloid of revolution. The situation is illustrated in Figure 1, showing several paraboloids of revolution that define the locus of the dust heated up by the supernova at successively later times: $t_2 > t_1 > t_0 = 0$. Since the supernova luminosity decays with time, "later" paraboloids are sequentially dimmer; that is, for any given radial distance from the supernova, the temperature of the dust on a given paraboloid is lower than that of the dust on the preceding paraboloid. If, for example, the source is turned off at t_2 then the respective paraboloid will actually represent a surface of zero light intensity.

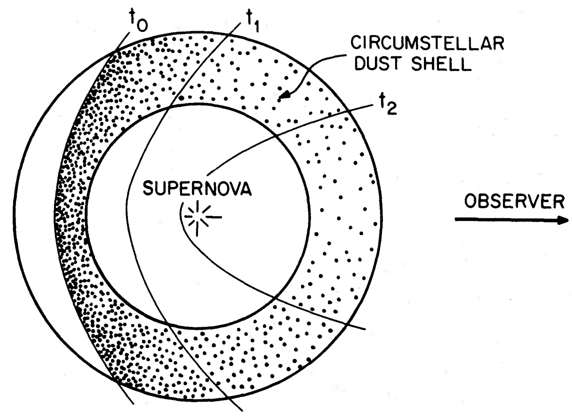

FIG. 1.—Schematic illustration of an infrared echo from a circumstellar dust shell surrounding a supernova. As viewed by a distant observer, the emitting volume is composed of a series of paraboloid shaped light fronts. Each paraboloid defines the locus of the dust heated up at a specific time since the supernova outburst, with the leading light front representing the dust heated up by the initial outburst. Most of the emission originates from the hottest dust located immediately behind the leading light front as suggested by the shading. For sake of clarity the radial variation of the dust temperature has been omitted in the figure.

Consider a circumstellar dust shell extending from R_0, the radius of the presupernova star, to a distance R_2 from 0, the center of the explosion (see Fig. 2). The initial outburst of the supernova will evaporate all the dust particles within a distance R_1, creating a dust-free cavity around 0. To a distant observer this cavity will initially appear as an extremely elongated paraboloid of revolution, slowly assuming a spherical shape as time goes on (Fig. 1). Let P designate the location of a dust particle of radius a that is located at a position (r, θ) from the supernova. Taking into account the light travel time r/c across the shell, dust particles that contribute to the infrared echo at "observer's time" t (measured since the arrival of first visual light) lie on a paraboloid of revolution defined by the relation:

$$t' = \tilde{t} \equiv t - \frac{r}{c}(1 - \cos\theta), \qquad (1)$$

where t' is the time (since the explosion) at which the visual light leaves its point of origin. The infrared

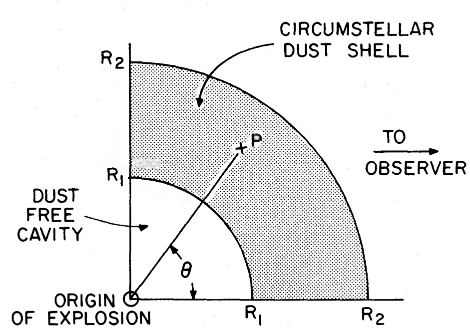

FIG. 2.—Schematic illustration of the geometry of the model

luminosity seen by a distant observer at time t is then given by:

$$L_{\rm IR}(t) = \pi a^2 \bar{Q}_v \int_{R_1}^{R_2} d^3 r n_d(r) e^{-\tau_d(r)} \int_0^\infty dt' \delta(t' - \tilde{t}) \frac{L_{\rm SN}(t')}{4\pi r^2}, \quad (2)$$

where $\bar{Q}_v$ is the UV-visual absorption efficiency of the dust averaged over the spectrum of the source, n_d is the number density of dust particles in the shell, $L_{\rm SN}$ the luminosity of the supernova, and $\tau_d(r)$ the UV-visual optical depth from R_1 to r given by:

$$\tau_d(r) = \pi a^2 \bar{Q}_v \int_{R_1}^{r} n_d(r') dr' . \quad (3)$$

The temperature, T_d, of the dust at (r, θ) and "observer's time" t can be determined from the equation:

$$\pi a^2 \bar{Q}_v e^{-\tau_d(r)} \int_0^\infty dt' \delta(t' - \tilde{t}) \frac{L_{\rm SN}(t')}{4\pi r^2} = 4\pi a^2 \int_0^\infty d\nu \pi B_\nu[T_d(r, \theta, t)] Q_\nu , \quad (4)$$

where Q_ν is the absorption/emission efficiency of the grain at frequency ν, and B_ν the Planck function. The observed flux at distance D can then be calculated from the following expression:

$$F_\nu(t) = \frac{a^2}{D^2} \int_{R_1}^{R_2} d^3 r n_d(r) \pi B_\nu[T_d(r, \theta, t)] Q_\nu . \quad (5)$$

The luminosity and flux of the shell can be represented by a sum of contributions from thin layers of radius $R_1 \leq r \leq R_2$ and width Δr ($\Delta r \ll r$) whose luminosity and flux are respectively given by:

$$L_{\rm IR}(r, t) = \tfrac{1}{2} \Delta\tau_d(r) e^{-\tau_d(r)} \int_0^{\theta_0} d\theta \sin\theta L_{\rm SN}(\tilde{t}) \quad (6)$$

and

$$F_\nu(r, t) = 2\left(\frac{r}{D}\right)^2 \frac{\Delta\tau_d(r)}{\bar{Q}_v} \int_0^{\theta_0} d\theta \sin\theta \pi B_\nu[T_d(r, \theta, t)] Q_\nu , \quad (7)$$

where $\Delta\tau_d(r) = \pi a^2 \bar{Q}_v n_d(r) \Delta r$ is the optical depth of the dust layer, and $\theta_0 \equiv \theta(r, t) = \cos^{-1}[\max(-1, 1 - ct/r)]$.

The temperature structure throughout the circumstellar dust shell and its temporal evolution depend on the radius of the dust-free cavity, the dust emissivity, and the UV-visual emission from the exploding star. Let T_v be the initial dust temperature at the inner boundary of the dust shell, and $L_0 = L_{\rm SN}(t' = 0)$ the initial UV-visual output of the supernova. Taking the grain emissivity Q_ν to be equal to $(\lambda_0/\lambda)^n$ for $\lambda \geq \lambda_0$, and equal to unity at shorter wavelengths, the relation between the size of the cavity, and L_0, T_v, and λ_0 can be expressed as:

$$R_1({\rm pc}) = 23 \left[\frac{\bar{Q}_v L_0(L_\odot)}{\lambda_0(\mu{\rm m}) T_v^5}\right]^{0.5}$$

for $n = 1$, and as

$$R_1({\rm pc}) = 1250 \left[\frac{\bar{Q}_v L_0(L_\odot)}{\lambda_0^2(\mu{\rm m}) T_v^6}\right]^{0.5} , \quad (8)$$

for $n = 2$. The temperature T_v is equal to the vaporization temperature of the dust if the cavity was created by the initial outburst L_0. However, T_v may be lower than the vaporization temperature if a more luminous (than L_0) pulse of radiation preceeded the first visual output of the supernova and vaporized the dust in the cavity. The dust temperature at any position (r, θ) and time t can now be written as

$$T_d(r, \theta, t) = T_v \left(\frac{R_1}{r}\right)^2 \left[\frac{L_{\rm SN}(\tilde{t}) \times e^{-\tau_d(r)}}{L_0}\right]^{1/(4+n)} . \quad (9)$$

The outer radius, R_2, of the dust shell is related to the total mass (including the mass of the dust-free gas) of the circumstellar shell by:

$$M_s = 4\pi \left(\frac{4\rho_{\rm gr} a}{3\bar{Q}_v}\right) \frac{\tau_d}{Z_d} \times \frac{R_1 R_2^2}{R_2 - R_1} , \quad (10)$$

where I assumed an r^{-2} density distribution in the shell and $R_0 \ll R_2$. In equation (10) τ_d is the total UV-visual optical depth of the shell, $\rho_{\rm gr}$ the mass density of a grain, a the representative grain size in the shell, and Z_d the dust-to-gas mass ratio in the shell which is (prior to the supernova outburst) assumed to be constant throughout the circumstellar shell.

b) Analytical Solutions for an Exponentially Decaying Supernova Light Curve

In the following I will present analytical solutions for equations (6) and (7) for an exponentially decaying supernova light curve with a UV-visual luminosity given by:

$$L_{\rm SN}(t') = L_0 \exp(-t'/t_{\rm SN}) , \quad (11)$$

where $t_{\rm SN}$ is a characteristic decay time of the light curve. For the near-infrared ($\lambda \lesssim 5\ \mu$m) part of the spectrum, I can use Wien's approximation to the Planck function. The infrared luminosity and flux are then given by:

$$L_{\rm IR}(r, \xi) = \Delta\tau_d(r) e^{-\tau_d(r)} \frac{L_0}{\mu} \left[1 - \exp\left(-\frac{t}{t_{\rm SN}}\right)\right], \quad \xi < 1$$

$$= \Delta\tau_d(r) e^{-\tau_d(r)} \frac{L_0}{\mu} [\exp(\mu) - 1] \exp\left(-\frac{t}{t_{\rm SN}}\right), \quad \xi \geq 1 \quad (12)$$

and

$$F_\nu(r, \xi) = 2.50 \times 10^{11} \left(\frac{r_{\rm pc}}{D_{\rm Mpc}}\right)^2 \frac{\Delta\tau_d(r)}{\bar{Q}_v} \times \left(\frac{\lambda_0}{\lambda}\right)^n \lambda_{\mu{\rm m}}^{-3} G_\nu(\xi)\ {\rm mJy} \quad (13)$$

where

$$G_\nu(\xi) = \frac{2(4+n)}{\mu} [E_1(v) - E_1(u)] , \quad (14)$$

and $E_1(x)$ is the exponential integral:

$$E_1(x) = \int_x^\infty z^{-1} \exp(-z) dz \; .$$

In equations (12) and (13) ξ is the "observer's time" t given in units of the shell crossing time $2r/c$ ($\equiv t_s$), i.e.,

$$\xi = \frac{ct}{2r} = \frac{t}{t_s} \; . \tag{15}$$

Other symbols used in equations (12)–(14) are:

$$\mu = \frac{2r}{ct_{\rm SN}} = \frac{t_s}{t_{\rm SN}}$$

$$u = \frac{14{,}388}{\lambda_{\mu \rm m} T_v} \exp\left(\frac{\mu\xi}{4+n}\right)$$

and (16)

$$v = \frac{14{,}388}{\lambda_{\mu \rm m} T_v} \quad \text{for } \xi < 1$$

$$= u \exp\left(-\frac{\mu}{4+n}\right) \quad \text{for } \xi \geq 1 \; .$$

To accurately follow the distribution of the flux that emerges from the shell as a function of wavelength and time, a dust shell is divided into a large number of layers whose width is determined by the constraint that the initial dust temperature across the layer not change by more than 1%. A typical dust shell is composed of $\sim$30 layers.

III. THE INFRARED ECHO OF A GALACTIC SUPERNOVA

Before attempting to fit the observations of SN 1979c and SN 1980k with the echo model, I will briefly describe the general characteristics of the model, and particularly examine the effect of the size of the circumstellar dust shell on the evolution of the infrared light curve. For the purpose of these calculations I adopted a λ^{-1} emissivity law for the dust and the following dust and supernova parameters: $\rho_{\rm gr} = 3$ g cm^{-3}, $a = 0.1$ μm, $\bar{Q}_v = 1$, $Z_d = 0.006$, $\lambda_0 = 0.2$ μm, $T_v = 10^3$ K, $L_0 = 1 \times 10^{10}$ $L_\odot$, and $t_{\rm SN} = 25$ days. The optical depth, τ_d, of the dust shell was taken to be 0.01, and the distance to the supernova was 10 kpc. For these parameters the radius R_1 of the dust-free cavity is 5.1×10^{17} cm, and $t_1 = 2R_1/c = 390.6$ days. The outer radius, R_2, of the circumstellar shell is a free parameter, and four models characterized by the following respective values of t_2 ($=2R_2/c$) and M_s are presented here: (A) 4819d, 1.44 $M_\odot$; (B) 2916d, 0.93 $M_\odot$; (C) 1764d, 0.62 $M_\odot$; and (D) 646d, 0.45 $M_\odot$. The L ($\lambda = 3.4$ μm) flux, and the total infrared luminosity of the supernova are plotted in Figures 3a and 3b, respectively, as a function of time, for the various circumstellar shell models described above. Figure 4 shows the time evolution of the 1–12 μm spectrum of model B. For $\tau_d \ll 1$, fluxes, luminosities, and shell masses are linearly proportional to the optical depth, and can therefore be scaled for any other value of τ_d.

The results show that the infrared light curve has a plateau that lasts for a period of $t_1 \approx 390$ days. The

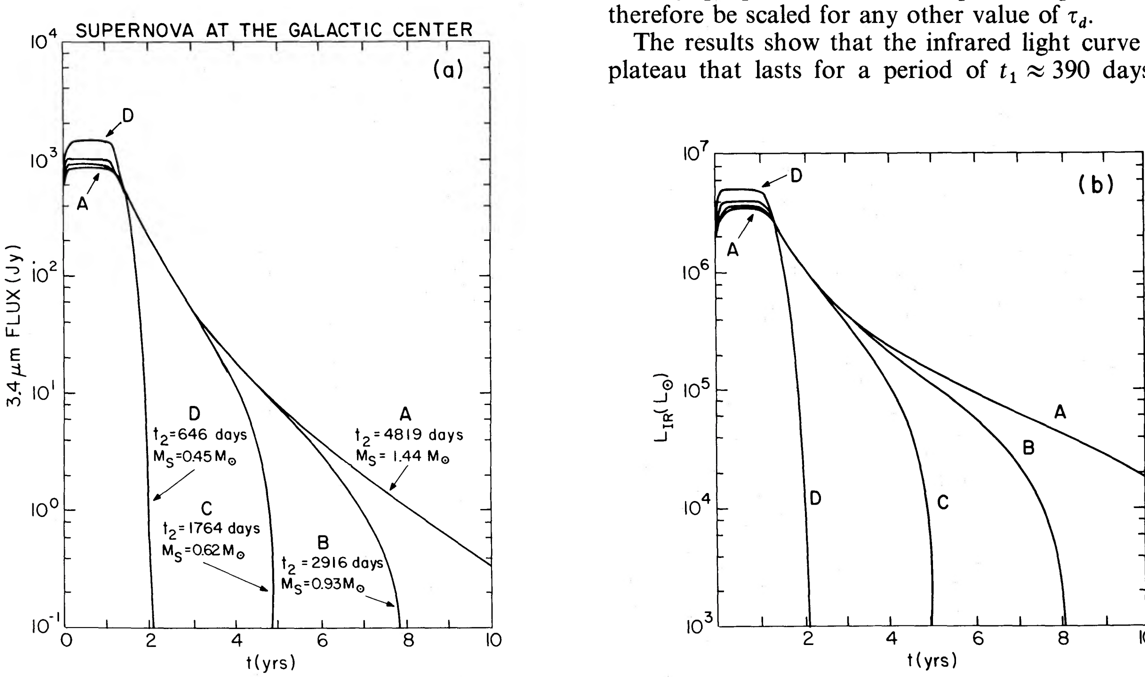

FIG. 3a FIG. 3b

FIG. 3.—(a) The 3.4 μm flux of a supernova exploding at a distance of 10 kpc is given as a function of time for various circumstellar shell models characterized by the extent of their outer radius R_2 (given in the figure in units of $2R_2/c$ days) and their mass. Supernova parameters are: $L_0 = 1 \times 10^{10}$ $L_\odot$, $t_{\rm SN} = 25$ days; and the dust parameters are: $\lambda_0 = 0.2$ μm, $T_v = 10^3$ K. For further explanation, see text. (b) The total infrared luminosity of a supernova exploding at a distance of 10 kpc is given as a function of time for the same circumstellar shell models and the same supernova and dust parameters as in Fig. 3a.

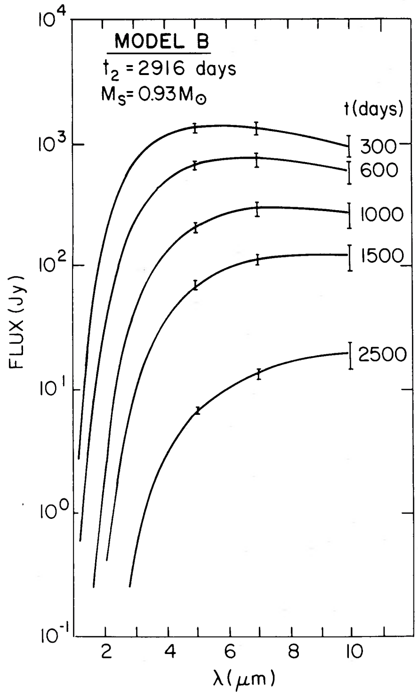

FIG. 4.—The 1–12 μm spectrum of model B is plotted as a function of wavelength for selected epochs of time (days) given along the curves.

plateau value of the infrared flux and luminosity depend on the extent of the shell, but can to within a factor of 2 be respectively given by:

$$F_\nu(\mathrm{Jy}) \approx 2 \times 10^{10} \frac{R_1(\mathrm{pc})^2}{D(\mathrm{kpc})} \frac{\tau_d}{\bar{Q}_v} (4 + n) \times \left(\frac{\lambda_0}{\lambda}\right)^n \frac{T_v}{\lambda_{\mu\mathrm{m}}{}^2} \left(\frac{t_{\mathrm{SN}}}{t_1}\right) \exp\left(-\frac{14{,}388}{\lambda_{\mu\mathrm{m}} T_v}\right) \quad (17)$$

and

$$L_{\mathrm{IR}}(L_\odot) \approx \tau_d \left(\frac{t_{\mathrm{SN}}}{t_1}\right) L_0 \,. \quad (18)$$

Following the plateau period, the infrared light curve may exhibit an extended tail whose existence and decay time depend, for a given decay time of the UV-visual light, on the value of t_2. The time behavior of the tail approximately follows an e^{-x}/x law, which describes the asymptotic behavior of $E_1(x)$ for sufficiently large values of x. At $t \approx t_2$ the gradual decay of the tail is followed by a very rapid decline.

A stellar wind expanding freely into the ambient medium for a period of $\sim 10^5$ yr at a velocity of 10 km s^{-1} will reach a distance of 3×10^{18} cm from the star. A progenitor star with a mass loss rate of $\sim 10^{-5}$ $M_\odot$ yr^{-1} will then have the characteristics of the circumstellar dust shell of model B. With current ground-based telescopes, the L-flux of the supernova will be detectable for ~ 7 yr. With a supernova rate of about one per decade, a search for such an event may therefore be worthwhile.

The evolution of the spectrum of the infrared radiation of model B is given in Figure 4 for several selected dates. Since Wien's approximation introduces large errors in the long wavelength regime, fluxes beyond 10 μm were calculated by the numerical integration of equation (5). The figure shows that the spectrum is broader than that of a single blackbody. This is because the emission originates from a range of shell radii and dust temperatures. As the supernova light front propagates farther into the shell, increasingly cooler dust contributes to the emission, and the maximum of the spectrum shifts at later times to longer wavelengths. On day 300, about 10% of the total infrared luminosity is emitted at wavelengths longer than 10 μm, a fraction which increases to $\sim 35\%$ on day 2000.

IV. COMPARISON WITH OBSERVATIONS OF SN 1979c AND SN 1980k

a) Model Parameters and Circumstellar Shell Masses

Since the model involves a number of adjustable parameters, it is useful to summarize their effect on the evolution of the infrared echo. I have assumed that the relevant supernova parameters (i.e., the initial UV-visual luminosity outburst L_0, and its subsequent decay time t_{SN}) are known from optical observations. The dust and circumstellar shell parameters are then chosen to give the best fit to the infrared observations.

For a given value of n, the spectral index of the dust emissivity law, the temperature T_v is chosen to give the best fit to the observed spectra. For a given optical depth, the geometry of the shell (i.e., the values of R_1 and R_2) is determined by the duration of the plateau period, and the subsequent decline rate of the flux. Once R_1 is determined, the value of $\lambda_0{}^n/\bar{Q}_v$ is calculated from equation (8). The optical depth of the shell is then chosen to fit the observed magnitude of the fluxes for the given source distance. The resulting fits are, however, not unique as shown in more detail in § IV*d*.

The mass of the circumstellar shell is given by equation (10), which represents the total mass of the shell, including that of the dust-free cavity gas. For given values of R_1, R_2, and optical depth, the shell mass depends on unknown parameters such as the value of $(3\bar{Q}_v/4\rho_{\mathrm{gr}}\, a)$ and the dust-to-gas mass ratio in the shell. The latter quantity is constrained by cosmic abundance considerations to be less than 0.006, giving a lower bound on the mass of the shell. The former quantity is equal to $\bar{K}_v$, the spectrum-averaged mass absorption coefficient of the dust at UV-visual wavelengths. For a λ^{-1} emissivity law, the value of $\bar{K}_v$ can be determined from the model-derived quantity $\lambda_0/\bar{Q}_v$ and the near-infrared properties of the dust particles. A compilation of various astronomical observations and laboratory measurements (Draine 1981) shows that for small particles composed either of silicates or amorphous carbon, $\lambda Q/a = 2$ in the 1–10 μm wavelength region. This behavior suggests a λ^{-1} emissivity law with $\lambda_0 = 2a$ so that, assuming a similar behavior for the dust in the shell, $\bar{K}_v$ is given by $3\bar{Q}_v/2\rho_{\mathrm{gr}}\, \lambda_0$. Infrared observations of the ionization front in the Orion nebula (Becklin *et al.* 1976) show the presence of a population of hot dust particles that can be modeled by a λ^{-2} emissivity law and $\lambda_0 = 2\pi a$ (Dwek *et al.* 1980). However, for a λ^{-2} emissivity law, the model-derived quantity is $\lambda_0{}^2/\bar{Q}_v$, and an additional assumption is needed to determine the ratio of $\bar{Q}_v/a$. For this purpose I will assume that $\bar{Q}_v = 1$, giving $\bar{K}_v = 3\pi/2\rho_{gr}\lambda_0$. As we will see later (Table 2), the resulting grain size is 0.1 μm, large enough to be consistent with the assumption that it absorbs with an efficiency of unity at UV-visual wavelengths.

An additional quantity of astrophysical interest that can be inferred from the echo model is the mass loss rate from the presupernova star. The mass loss rate $\dot{M}$ is equal to $4\pi\rho r^2 v$, where v is the presupernova wind velocity. The product $\dot{M}v^{-1}$ can therefore readily be expressed as

$$\dot{M}v_{10}{}^{-1} = 3.15 \times 10^{13} \frac{M_s(M_\odot)}{R_2} M_\odot \text{ yr}^{-1} , \quad (19)$$

where v_{10} is the wind velocity in units of 10 km s^{-1}.

b) Supernova 1979c

Optical and ultraviolet observations of SN 1979c in NGC 4321 (M100) made during the first 6 weeks after its discovery on 1979 April 19 were presented by Panagia *et al.* (1980). For an assumed distance of 16 Mpc the initial reddening free UV-visual luminosity was found to be 6.3×10^9 $L_\odot$. The luminosity decayed exponentially with a time scale of 23 days. The B light curve did not follow the usual SN-II light curve, characterized by a plateau phase which develops shortly after maximum light. Instead, it resembled the average light curve of a subgroup L (Barbon, Ciatti, and Rosino 1979) which exhibit an almost linear decline with a characteristic *e*-folding time of $\sim$22 days. The $B-V$ excess toward NGC 4321 was estimated independently by Panagia *et al.* and by Penston and Blades (1980), giving, respectively, values of 0.10 ± 0.03 and $0.13^{+0.06}_{-0.02}$. Of this number, 0.072 ± 0.006 can be attributed to absorption in our Galaxy. The optical depth of the circumstellar dust shell is therefore bound by $\tau_d \lesssim 0.1$–0.3, with 0.3 being a generous upper limit. Table 1 summarizes the observable quantities of SN 1979c.

The dust emission phase in the evolution of the infrared light curve of SN 1979c was first observed by Merrill (1980) on 1980 January 3, 259 days after the first visual detection of the supernova. Additional observations made on days 282 and 440 (K. M. Merrill 1982, private communication) show the persistence of this phase throughout this period. The infrared fluxes at K (2.2 μm) and L (3.4 μm) decreased, respectively, from 7.1 and 14.4 mJy on day 259, to 5.9 and 8.2 mJy on day 282, and to 1.1 and 2.6 mJy on day 440. The total infrared luminosity is $\sim 10^8$ $L_\odot$ on day 259, and has a characteristic *e*-folding time of $\sim$100 days. Taking into account the emission during the plateau period of $\sim$200 days, the total energy radiated in the infrared amounts to a significant fraction of $\sim$30% of the total UV-visual output of the supernova. Such large absorption suggests the presence of an extensive and massive circumstellar shell.

In Figure 5, the infrared fluxes predicted by the model are plotted versus wavelength and compared with the observations on the various days. The fluxes shown in the figure are plotted for $n = 2$. An equally good fit to the observations can be obtained with a λ^{-1} wavelength dependence of the dust emissivity. The fit requires the optical depth of the dust to be $\sim$0.3 and suggests a lower limit of 5 $M_\odot$ for the mass of the circumstellar shell. Compared to the $n = 2$ case, a λ^{-1} emissivity law requires a higher dust temperature

TABLE 1

SUMMARY OF OBSERVABLE SUPERNOVA PARAMETERS[a]

Parameter	SN 1979c	SN 1980k
$L_0(L_\odot)$	6.3×10^9	1.5×10^9
t_{SN}(days)	23	20
D(Mpc)	16	5.5
τ_d	$\lesssim 0.3$	< 0.1

[a] References and details are given in text.

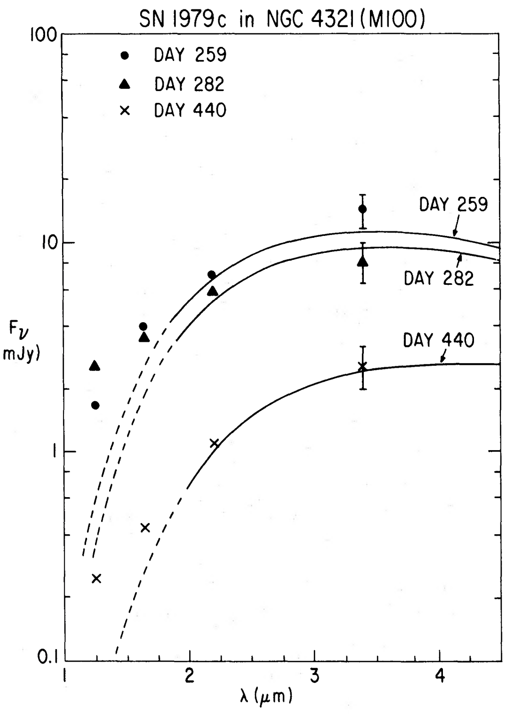

FIG. 5.—The fluxes predicted by the echo model for SN 1979c are plotted as a function of wavelength for various time epochs and compared with the observations. The emissivity law of the dust in the plotted model is given by $Q \propto \lambda^{-2}$. A similar fit to the observations was obtained with an emissivity index of $n = 1$. Excess fluxes at 1.25 and 1.65 μm are attributed to emission from the photosphere of the expanding star, and model fluxes in this wavelength region are given by a dashed curve. A summary of the model parameters is given in Table 2.

TABLE 2

SUMMARY OF ECHO MODEL PARAMETERS[a]

PARAMETER	SN 1979c		SN 1980k	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$
Dust parameters:				
T_v(K)	1600	1200	1150	900
$\lambda_0{}^n(\mu m)/Q_v$	0.035	0.379	0.053	0.49
Shell parameters:				
R_1(cm)	3.0×10^{17}	2.9×10^{17}	2.7×10^{17}	3.0×10^{17}
t_1(days)	229	224	207	228
R_2(cm)	8.1×10^{17}	8.3×10^{17}	8.3×10^{17}	6.3×10^{17}
t_2(days)	625	643	642	484
τ_d	0.33	0.30	0.032	0.027
$M_s(M_\odot)$[b]	1.0	4.6	0.12	0.45
$\dot{M}(M_\odot\ \mathrm{yr}^{-1})$[c]	3.8×10^{-5}	1.8×10^{-4}	4.5×10^{-6}	2.3×10^{-5}

[a] Symbols are explained in text.

[b] The mass of the shell *includes* the mass of the gas inside the dust-free cavity, and is calculated from eq. (10) with $\rho_{gr} = 3$ g cm^{-3}, $Z_d = 0.006$, and $\bar{K}_v$ $(=3\bar{Q}_v/4\rho_{gr}a)$ which is equal to $\bar{Q}_v/2\lambda_0$ for $n = 1$, and equal to $\pi/2\lambda_0$ for $n = 2$.

[c] Calculated for a wind velocity of 10 km s^{-1}.

to fit the observed spectrum. As a result, a smaller amount of dust is needed to supply the same amount of power at the elevated dust temperature. The lower limit on the circumstellar shell mass is consequently smaller and equal to about 1 $M_\odot$. Additional results of the models are summarized in Table 2.

c) *Supernova 1980k*

Photometric observations of the supernova between 1980 November 4 and 1981 May 5 were presented by Buta (1982). The data shows that the UV-visual luminosity declined almost linearly during the first 57 days past maximum light with an *e*-folding time of 20 days. The $B-V$ excess toward NGC 6946 was estimated to be 0.36, of which 0.33 ± 0.16 can be attributed to absorption in our own Galaxy. The optical depth of the circumstellar shell is therefore loosely constrained by $\tau_d \lesssim 0.1$. In addition, Buta estimated a distance of 5.5 Mpc to NGC 6946. At this distance the intrinsic UV-visual luminosity of the supernova around maximum light was about 1.5×10^9 $L_\odot$. The observable quantities of SN 1980k are summarized in Table 1.

The change in the 1–4 μm spectrum of SN 1980k was first observed by Telesco *et al.* (1981), 215 days after its first optical discovery. Subsequent observations, summarized by Dwek *et al.* (1983), show the persistence of the thermal emission phase at least through 1981 October 21. Average *K*, *L* fluxes on day 215 were, respectively, 1.1 and 2.7 mJy, and average *K*, *L′* (3.8 μm) fluxes on day 357 were, respectively, 0.18 and 1.05 mJy. The total infrared luminosity on day 215 was $\sim 2.7 \times 10^6$ $L_\odot$, and had a characteristic *e*-folding time of ~ 130 days. Including the emission during the plateau period, the total energy radiated in the infrared is only about 3% of the total UV-visual output of the supernova.

In Figure 6, the infrared fluxes predicted by the echo model are plotted versus wavelength, for the various days of observations, and for a dust emissivity model with $n = 2$. The model requires a dust optical depth of 0.027 and a circumstellar shell with a mass larger than 0.45 $M_\odot$. Results for $n = 1$ and other model parameters are given in Table 2.

d) *The Uniqueness of the Models*

The model fluxes presented here give, in general, an excellent fit to the observations. This should not be surprising due to the large number of parameters

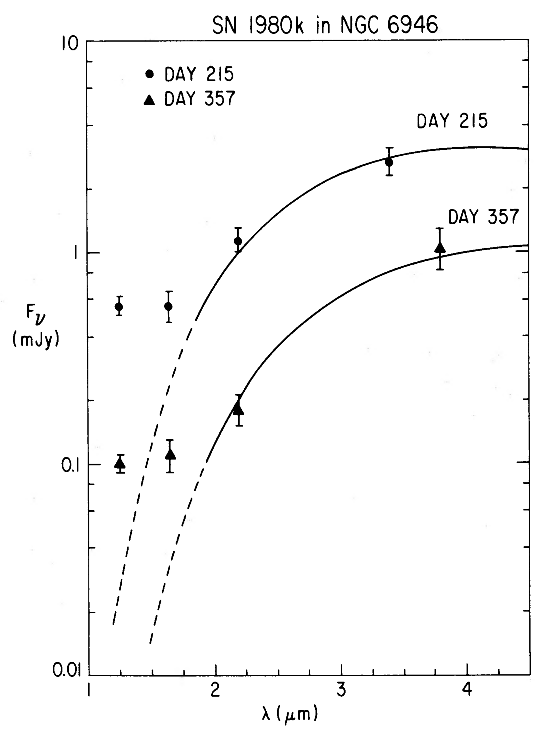

FIG. 6.—Same as Fig. 5 for SN 1980k

involved in the model, and the relatively few data available. As a result of the latter factor, different combinations of circumstellar shell masses and optical depths are able to yield the same observational constraints. To demonstrate this point I constructed an additional model for SN 1980k with a dust emissivity $\propto \lambda^{-1}$, which has a more extended shell with an outer radius of 3.3×10^{18} cm ($t_2 = 7.0$ yr). Keeping all other input parameters equal to those presented in Table 2, the observed fluxes could be reproduced if the optical depth of the shell was increased to 0.040. As a result, the mass of the shell increased to 0.43 $M_\odot$, but the inferred mass loss rate remained almost unchanged at a value of 3.3×10^{-7} $M_\odot$ yr^{-1}. The model produced a significantly broader spectrum due to the participation of colder dust in the emission, and exhibited a slower decline rate of the flux; both effects resulting from the increased size of the dust shell. This example demonstrates the need for more extended observations, both in wavelengths and in time, to determine the physical properties of the circumstellar dust shell.

V. DISCUSSION

The results of this paper confirm the suggestion of Bode and Evans (1980b) that the thermal emission from SN 1979c may have originated from preexisting dust present in a circumstellar shell and heated up by the UV-visual output of the supernova. This possibility has also been suggested by Chevalier (1982). In addition, the results suggest that the thermal infrared emission from SN 1980k may have a similar origin. This infrared echo model requires a fraction ($\sim$0.3 for SN 1979c and $\sim$0.03 for SN 1980k) of the total UV-visual energy emitted by the supernova during the first few weeks after the outburst to be converted to infrared radiation. In the dust-formation model the energy emitted in the infrared reqpresents the UV-visual energy actually available at the time of dust formation (7–9 months after the outburst). While this energy constraint is met by SN 1980k (Dwek *et al.* 1983), it very likely rules out the dust-formation interpretation for SN 1979c. If the echo model for the thermal emission applies to both supernovae, then their infrared light curves can be used to estimate the extent and mass of the circumstellar shells around their progenitor stars and, assuming a wind velocity, to estimate the rate of mass loss during the presupernova phase of their evolution. The models suggest a lower limit of 1–5 $M_\odot$ for the circumstellar shell around SN 1979c, and of 0.1–0.5 $M_\odot$ for that of SN 1980k. The range in values reflect the uncertainties in the wavelength dependence of the dust emissivity. The inferred mass loss rates from the presupernova stars are about (4–20) $\times 10^{-5}$ $M_\odot$ yr^{-1} for SN 1979c, and about (0.4–2) $\times 10^{-5}$ $M_\odot$ yr^{-1} for SN 1980k, assuming a wind velocity of 10 km s^{-1}. Furthermore, as shown below, the models suggest that the luminosity of the initial UV-visual outburst was higher than that inferred from the first visual detection. The details of the shell and dust properties presented here for SN 1979c differ from those given by Bode and Evans. Their attempt to deduce these properties on the basis of one observation appears premature, since the time behavior of the infrared emission plays an important role in determining the detailed structure of the shell. Even the models presented here are not unique. As shown in the previous section, more extended coverage in wavelengths and time is needed to ascertain the properties of the circumstellar shell.

Radio observations of the two supernovae (Weiler *et al.* 1981) and the X-ray observations of SN 1980k (Canizares, Kriss, and Feigelson 1982) can yield additional information on the structure and mass of the circumstellar shells (Chevalier 1981 and 1982). The observations show that SN 1979c became thin at 20 cm considerably later than SN 1980k. In Chevalier's model, the radio emission results from the interaction of the expanding supernova envelope with the circumstellar shell. If the low frequency opacity is due to free-free absorption in the cool circumstellar shell, then his model suggests that the progenitor of SN 1979c had a mass loss rate of about 5×10^{-5} $M_\odot$ yr^{-1}, and that of SN 1980k had a mass loss rate of about 1×10^{-5} $M_\odot$ yr^{-1}. These mass loss rates are consistent with the lower limits suggested in this paper. The inferred density structure of the circumstellar shell around SN 1980k is also consistent with that required to produce the observed X-ray luminosity in Chevalier's model, if allowance is made for the difference in the assumed distance to the supernova.

The value of $\sim$1100 K found for T_v, the initial dust temperature at R_1, is significantly lower (at least for the λ^{-2} emissivity law) than the typical value of $\sim$1700 K calculated by Grossman (1972) for refractory minerals, or than that suggested by laboratory experience with amorphous silicates (B. Donn and J. A. Nuth 1982, private communications). Given that the dust vaporizes at 1700 K, an initial luminosity $\gtrsim 10 L_0$ is needed to create a dust-free cavity of the same size R_1. This luminosity may be associated with the $\sim$2000 s long pulse of soft X-ray and UV radiation suggested by theoretical models to occur as the shock breaks through the surface of the star (e.g., Falk 1980). Infrared observations can therefore suggest the occurrence and put constraints on this early event in the evolution of Type II supernova outbursts.

I would like to thank Mike Merrill for providing observational material in advance of publication, Mike Werner for his comments on an earlier version of this paper, and Phyllis Bayne for patiently typing this manuscript.

REFERENCES

Barbon, R., Ciatti, F., and Rosino, L. 1979, *Astr. Ap.*, **72**, 287.
Becklin, E. E., Beckwith, S., Gatley, I., Matthews, K., Neugebauer, G., Sarazin, C., and Werner, M. W. 1976, *Ap. J.*, **207**, 770.
Bode, M. F., and Evans, A. 1980*a*, *Astr. Ap.*, **89**, 158.
Bode, M. F., and Evans, A. 1980*b*, *M.N.R.A.S.*, **193**, 21P.
———. 1981, *M.N.R.A.S.*, **197**, 1055.
Buta, R. J. 1980, *IAU Circ.*, No. 3554.
———. 1982, *Pub. A.S.P.*, **94**, 578.

Canizares, C. R., Kriss, G. A., and Feigelson, E. D. 1982, *Ap. J.* (*Letters*), **253**, L17.
Chevalier, R. A. 1981, *Ap. J.*, **251**, 259.
———. 1982, *Ap. J.*, **259**, 302.
Clayton, D. D. 1982, "The 1981 George Darwin Lecture of the Royal Astronomical Society", *Quart. J.R.A.S.*, **23**, 174.
Clayton, D. D., and Wickramasinghe, N. C. 1976, *Astr. Space Sci.*, **42**, 463.
Draine, B. T. 1981, *Ap. J.*, **245**, 880.
Dwek, E., *et al.* 1983, *Ap. J.*, **274**, 168.
Dwek, E., and Scalo, J. M. 1980, *Ap. J.*, **239**, 193.
Dwek, E., Sellgren, K., Soifer, B. T., and Werner, M. W. 1980, *Ap. J.*, **238**, 140.
Falk, S. W. 1980, *Space Sci. Rev.*, **27**, 545.
Geisel, S. L., Kleinmann, D. E., and Low, F. J. 1970, *Ap. J.* (*Letters*), **161**, L101.
Grossman, L. 1972, *Geochim. Cosmochim. Acta*, **36**, 597.
Hyland, A. R., and Neugebauer, G. 1970, *Ap. J.* (*Letters*), **160**, L177.
Merrill, K. M. 1980, *IAU Circ.*, No. 3444.
Morrison, P., and Sartori, L. 1969, *Ap. J.*, **158**, 541.
Ney, E. P., and Hatfield, B. F. 1978, *Ap. J.* (*Letters*), **219**, L111.
Panagia, N., *et al.* 1980, *M.N.R.A.S.*, **192**, 861.
Penston, M. V., and Blades, J. C. 1980, *M.N.R.A.S.*, **190**, 51P.
Telesco, C., Becklin, E., Koehler, R., and Gatley, I. 1981, *IAU Circ.*, No. 3613.
Wright, E. L. 1980, *Ap. J.* (*Letters*), **242**, L23.
Weiler, K. W., van der Hulst, J. M., Sramek, R. A., and Panagia, N. 1981, *Ap. J.* (*Letters*), **243**, L151.

Note added in proof.—Recently, James R. Graham *et al.* (1983, preprint) obtained infrared light curves for SN 1982g in NGC 1332, covering 100–250 days after its discovery. From the analysis of their data, they conclude that the infrared emission is an echo of the UV-visual output of the supernova.

ELIAHU DWEK: NASA Goddard Space Flight Center, Code 693.2, Greenbelt, MD 20771