THE ASTROPHYSICAL JOURNAL, 274:168–174, 1983 November 1
© 1983. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE EVOLUTION OF THE INFRARED EMISSION FROM THE TYPE II SUPERNOVA 1980k IN NGC 6946: THE DUST FORMATION MODEL

E. DWEK,[1] M. F. A'HEARN,[2] E. E. BECKLIN,[3] R. HAMILTON BROWN,[3] R. W. CAPPS,[3]
H. L. DINERSTEIN,[4] IAN GATLEY,[5] D. MORRISON,[3] C. M. TELESCO,[3]
A. T. TOKUNAGA,[3] M. W. WERNER,[6] AND C. G. WYNN-WILLIAMS[3]

Received 1982 December 27; accepted 1983 April 7

ABSTRACT

We present 1–4 μm photometry of supernova 1980k in NGC 6946 obtained over a period of 1 year following the outburst. During the period between 1980 November 1 and December 19, the infrared emission probably originated from the extended atmosphere of the expanding star. The *JHKL* colors and a 1.3–2.6 μm spectrum observed during this period correspond to those of a blackbody with an average temperature of ~5000 K. Observations around 1981 May 31 showed that the supernova developed an infrared excess after 1980 December. This infrared excess persisted through 1981 October and is consistent with the appearance of thermal emission from ~700 to 900 K dust in addition to a hotter photosphere. The similarity of this behavior to that of the infrared evolution of some novae suggests that dust formation may be occurring in the supernova ejecta. The hypothesis, that the emission arises from preexisting grains in a circumstellar shell which are heated by the supernova outburst, is also consistent with the data.

Subject headings: galaxies: individual — infrared: sources — nebulae: supernova remnants — stars: supernovae

I. INTRODUCTION

On 1980 October 28 a supernova was discovered in the spiral galaxy NGC 6946 (Wild 1980), the sixth reported occurrence of a supernova in that galaxy since 1917. Subsequent observations (summarized by Buta 1982 and Barbon, Ciatti, and Rosino 1982, hereafter BCR) indicated the event to be a Type II supernova with an apparent visual magnitude of ~11 near maximum light which occurred near 1980 October 30. Photometric observations of the supernova spanning the period between 1980 November 4 and 1981 May 5 were presented by Buta (1982) and spanning the period between 1980 October 29 and 1981 October 29 by BCR. The light curves show that the *U*, *B*, and *V* magnitudes declined almost linearly during the first ~60 days past maximum light at the respective rates of 0.100, 0.058, and 0.041 mag per day. In 1981 February the decline rate of the *B*, *V* magnitudes decreased to a constant rate of 0.01 mag per day. The supernova was no longer observable at *U* by BCR after 1980 December 29 but was detected by Buta with a magnitude of 19.03 on 1981 May 5.42. The color excess of NGC 6946 is given by $E(B-V) = 0.36$ and $E(U-B) = 0.27$ (Buta 1982) and is mostly due to reddening by dust in our own Galaxy. In addition Buta adopted a total extinction of $A_B = 1.5$ mag and estimated the distance to NGC 6946 to be 5.5 Mpc. For these parameters, the intrinsic UV-visual luminosity of the supernova around maximum light was about $1.5 \times 10^9\ L_\odot$.

This paper presents infrared observations of the supernova spanning a period of 1 year, starting within 2 days of maximum light. A dramatic change in the shape of the 1–4 μm spectrum was first observed around 1981 May 31 and reported by Telesco *et al.* (1981). The change in the spectrum is caused by the appearance of a thermal component with a temperature of ~920 K, which dominated the emission at the longer wavelengths. This component persisted at least through 1981 October. The origin of this thermal emission is a question of astrophysical importance. The emission could arise from preexisting dust present in a circumstellar shell heated up by the initial supernova outburst, or from dust that formed in the expanding supernova ejecta.

Dust formed in supernovae has been suggested by Clayton (1979) as the carrier of isotopic anomalies in meteorites. Furthermore, the balance between grain formation and destruction (Dwek and Scalo 1980) suggests that dust formation in supernovae is required to account for the observed gas-phase depletions of refractory elements in the interstellar medium. In addition, observational evidence for the formation of dust in supernovae may yield valuable information about the dust nucleation process in unusual astrophysical environments.

The observations are described in § II, and the atmospheric emission phase is discussed in § III. We adopt here the model that the thermal infrared emission arises from dust condensed in supernova ejecta. The

---

[1] National Research Council Resident Research Associate, NASA Goddard Space Flight Center.
[2] Astronomy Program, University of Maryland.
[3] Institute for Astronomy, University of Hawaii.
[4] National Research Council Resident Research Associate, NASA Ames Research Center.
[5] United Kingdom Infrared Telescope Unit.
[6] Space Science Division, NASA Ames Research Center.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...274..168D

TABLE 1

BROAD-BAND PHOTOMETRY[a]

Date (UT)	*J* (1.25 μm)	*H* (1.65 μm)	*K* (2.2 μm)	*L* (3.4 μm)	*L′* (3.8 μm)	*M* (4.8 μm)
1980 Nov 1	10.46	10.23	10.07 ± 0.10	...	9.63 ± 0.15	...
1980 Nov 2	10.49	10.40	10.18	9.92 ± 0.15	10.01	$9.54^{+0.20}_{-0.34}$
1980 Nov 4	10.40	10.28	10.10	9.88 ± 0.06	9.87	...
1980 Nov 8	10.58	10.43	10.24	9.97	...	...
1980 Nov 9	10.55	10.42	10.22	9.89 ± 0.06	...	...
1980 Nov 14	10.71	10.56	10.35	10.05 ± 0.07	...	...
1980 Nov 15	10.60	10.53	10.33	10.00 ± 0.15	...	...
1980 Nov 16	10.78	10.64	10.40	10.14 ± 0.09	...	...
1980 Dec 3	11.13	10.93	10.64	10.35 ± 0.07	...	...
1980 Dec 19	11.48	11.30	10.97	10.55	...	...
1981 May 31	16.37 ± 0.10	15.85 ± 0.15	14.50 ± 0.15	12.60 ± 0.15	...	...
1981 Jun 19	16.37 ± 0.10	15.95 ± 0.10	14.72 ± 0.10	...	...	...
1981 Sep 16	17.70 ± 0.23	17.48 ± 0.23	16.71 ± 0.21	...	...	...
1981 Oct 3	17.66 ± 0.17	...	16.47 ± 0.13	...	...	...
1981 Oct 20	18.26 ± 0.15	17.63 ± 0.23	16.52 ± 0.15	...	13.40 ± 0.20	...

[a] All errors are 0.05 mag, unless given; calibration was with respect to the star θ Cep which was measured to have magnitudes of $J = 3.87$, $H = 3.85$, $K = 3.77$, $L = 3.76$, $L' = 3.76$, and $M = 3.75$, relative to the standards of Elias *et al.* 1982.

alternate possibility, that the emission is an infrared echo of the UV-visual output of the supernova, is discussed by Dwek (1983). Heating mechanisms for the newly formed dust and the physical properties of the dust shell are described in § IV. The results are discussed in § V and briefly summarized in § VI.

II. THE OBSERVATIONS

SN 1980k in NGC 6946 was observed with the NASA Infrared Telescope Facility (IRTF)[7] in the periods 1980 November 1 to December 19 and 1981 May 29 to October 21. The photometric data, which were obtained with a standard set of near-infrared filters using an InSb detector, are presented in Table 1. Table 2 lists the infrared fluxes in units of mJy (10^{-29} W m^{-2} Hz^{-1}). We adopted zero magnitude fluxes from Beckwith *et al.* (1976), taking the value 0 mag = 230 Jy at $\lambda = 3.8$ μm (*L′* filter). The fluxes in Table 2 are corrected for extinction assuming $E(B-V) = 0.36$, $E(U-B) = 0.27$, $A_B = 1.5$ mag (Buta 1982), and the interstellar reddening law derived by Schultz and Wiemer (1975).

The evolution of the energy distribution of SN 1980k is shown in Figure 1, which displays the dereddened *U*, *B*, *V*, and infrared data for several representative dates. *U*, *B*, and *V* magnitudes for the initial 2 months after the explosion were adopted from Buta (1982),

TABLE 2

INFRARED FUXES (mJy)[a]

Date (UT)	*J* (1.25 μm)	*H* (1.65 μm)	*K* (2.2 μm)	*L* (3.4 μm)	*L′* (3.8 μm)	*M* (4.8 μm)
A. Atmospheric Emission Phase						
1980 Nov 1	130	98	67	...	34 ± 5	...
1980 Nov 2	126	84	60	32 ± 5	24	23^{+5}_{-8}
1980 Nov 4	137	94	65	33 ± 2	27	...
1980 Nov 8	116	82	57	30	...	...
1980 Nov 9	119	83	58	33 ± 2	...	...
1980 Nov 14	103	73	52	28 ± 2	...	...
1980 Nov 15	114	75	53	30 ± 4	...	...
1980 Nov 16	96	67	49	26 ± 2	...	...
1980 Dec 3	70	52	40	21 ± 1	...	...
1980 Dec 19	51	37	29	18	...	...
B. Dust Emission Phase						
1981 May 31	0.56 ± 0.06	0.56 ± 0.09	1.13 ± 0.15	2.69 ± 0.40	...	...
1981 Jun 19	0.56 ± 0.06	0.51 ± 0.05	0.92 ± 0.10	...	...	...
1981 Sep 16	0.17 ± 0.03	0.12 ± 0.03	0.15 ± 0.03	...	...	...
1981 Oct 3	0.17 ± 0.03	...	0.18 ± 0.03	...	...	...
1981 Oct 20	0.10 ± 0.01	0.11 ± 0.02	0.18 ± 0.03	...	1.05 ± 0.22	...

[a] Fluxes are corrected for reddening assuming $E(B-V) = 0.36$, $E(U-B) = 0.27$, and $A_B = 1.50$ mag (Buta 1982). Errors in the fluxes are ~5% unless given.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1983ApJ...274..168D

whereas the *B* and *V* magnitudes given by BCR were used for the later phases of the evolution of the light curve. The *U* magnitude on 1981 May 31 was taken from Buta's observations on May 5.42, corrected for a decline rate of 0.01 mag per day. The figure clearly illustrates the existence of two distinct phases in the development of the infrared spectrum: (1) an initial phase during which the infrared emission is the long-wavelength extension of the hot photospheric component; and (2) a second phase during which the longer wavelength infrared emission is dominated by thermal radiation from a distinct cool component.

In addition, a spectrum was obtained on 1980 November 8 with a 1.3–2.6 μm circular variable filter (CVF) with 3% spectral resolution. This spectrum is shown in Figure 2, which represents the average of two scans in the 1.4–1.8 μm and 1.9–2.5 μm regions. Also plotted in the figure are the observed fluxes in the *JHKL* bands for the same night, and the spectrum of a 5200 K blackbody. The spectrum has no statistically significant features.

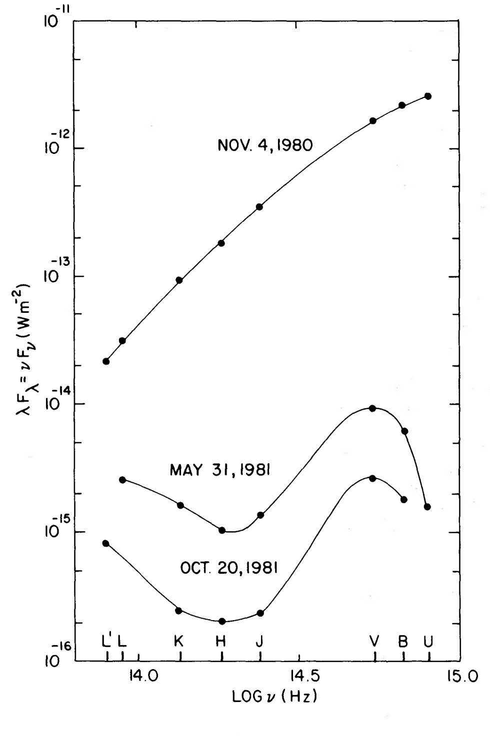

FIG. 1.—Evolution of the visible and infrared fluxes of supernova 1980k. *U*, *B*, and *V* fluxes for November 4 were determined from the observations of Buta (1982), and *B*, *V* fluxes for 1981 May 31 and October 20 were determined from the observations of Barbon, Ciatti, and Rosino (1982). The *U* flux on May 31 was taken from Buta's May 5.42 datum point and corrected for a decline rate of 0.01 mag per day. Fluxes were dereddened as explained in the text. The fluxes are plotted so that the area under the curve is proportional to the total energy emitted between the appropriate wavelengths.

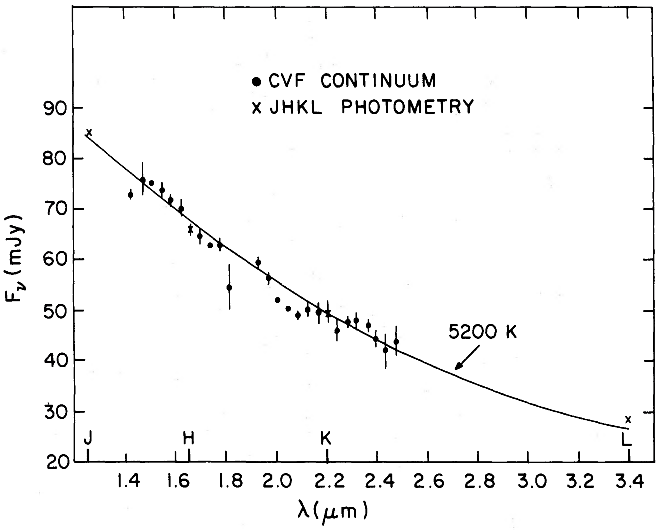

FIG. 2.—CVF spectrum of supernova 1980k (uncorrected for reddening) obtained on 1980 November 1. The data points (*solid circles*) represent the average of two scans in the 1.4–1.8 μm and 1.9–2.6 μm regions that were taken during the observing run. Also shown in the figure are the observed fluxes (for the same night) in the *JHKL* bands (**X**). The solid line is the spectrum of a 5200 K blackbody.

III. ATMOSPHERIC EMISSION PHASE

The infrared fluxes observed during the period 1980 November 1 to December 19 originate from the atmosphere of the expanding star. The time behavior of the energy distribution shows a gradual decrease in the color temperature of the ejecta, presumably due to the cooling of the expanding material. Table 3 lists the mean dereddened colors of the supernova during this phase. We interpolated within the data given by Buta (1982) to obtain the *UBV* magnitudes at some selected dates on which the infrared observations were made. The table shows that in the initial phases of the expansion the $B-V$, $V-J$, and $V-K$ colors of the supernova are similar to those of a main-sequence A5 star (Johnson 1966), with the $U-V$ and $V-L$ colors suggesting both a *U* and *L* excess. These colors gradually change to the colors of a main-sequence F5 star. The initial ultraviolet and infrared excesses are probably the result of extended atmosphere effects which give rise to large temperature variations in the expanding stellar ejecta. The combined optical and infrared observations should therefore be useful in constraining the temperature gradients and opacities in the supernova envelope and in estimating its physical extent. The structure of the supernova envelope is of considerable interest, since Type II supernovae have been suggested as cosmological distance indicators (e.g., Kirshner and Kwan 1974).

The flux emitted at 1.25 μm (*J* filter) can be taken as a rough measure of the total infrared flux emitted from the photosphere. During the first 2 months of observations this flux declined at an average rate of 0.021 mag per day, corresponding to an *e*-folding time of ~50 days. This is slower than the average decline rate

---

[7] The IRTF is operated by the University of Hawaii for the National Aeronautics and Space Administration.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

TABLE 3

MEAN COLORS OF THE EXPANDING SUPERNOVA EJECTA[a]

Date (1980)/Standard	$U-V$	$B-V$	$V-J$	$V-K$	$V-L$	$J-L$
A. Observations						
Nov 4	−0.80	−0.04	0.19	0.30	0.43	0.24
Nov 9	−0.63	0.10	0.19	0.33	0.57	0.38
Dec 3	0.77	0.50	0.67	0.97	1.17	0.50
B. Main-Sequence Stars[b]						
A5	0.25	0.14	0.27	0.36	0.40	0.13
F5	0.43	0.43	0.79	1.07	1.25	0.46

[a] Corrected for reddening as explained for Table 2.

[b] Johnson 1966.

of 0.054 mag per day (e-folding time of ~ 20 days) of the U, B, and V light curves during this period (Buta 1982; BCR). This is consistent with the general decrease in the color temperatures seen at all wavelengths (see Table 3).

IV. DUST EMISSION PHASE

After 1981 May 29, the infrared flux was dominated by the emission from the longest observed wavelengths. The color temperature between 2.2 and 3.5 μm is 1100 K, corresponding to a photospheric radius of $\sim 3 \times 10^{15}$ cm for an assumed distance of 5.5 Mpc. An unreasonably large amount of dust-free gas would be needed to produce a substantial opacity at this wavelength. Thermal radiation from dust is therefore the most probable source of the emission. We will assume that the dust formed in the supernova ejecta, and in the following, consider possible heating mechanisms of the newly formed dust, and derive the physical properties of the dust shell.

a) Heating Mechanisms of the Newly Formed Dust

The dust in the supernova ejecta can be heated in several different ways (Dwek and Werner 1981), including collisions with the ambient gas, absorption of X-rays emitted from the supernova cavity, and the absorption of UV-visual radiation from the underlying photosphere of the expanding star. In the following we discuss each of these possibilities in more detail.

i) *Collisional Heating*

We first examine the possibility that the dust may be heated up by collisions with the ambient gas out of which it condensed. The observations suggest (see below) that the mass of the emitting dust is $\sim 1 \times 10^{-5}$ $M_\odot$. Typical masses of supernova ejecta are ~ 10 $M_\odot$ (e.g., Weaver and Woosley 1980). At a temperature of ~ 2000 K, the condensation temperature of the dust, the total thermal energy content of the ejected gas is $\sim 10^{45}$ ergs. Radiated at a rate of $\sim 1 \times 10^6$ $L_\odot$, as implied from the infrared observations, this gas will cool in about 10^5 s. This is in contrast to the slow decay time of ~ 130 days ($\sim 10^7$ s) of the infrared luminosity. Clearly collision with the ambient gas is an inadequate energy source for the dust, unless the gas itself is heated up by some other mechanism. This "solution" merely substitutes the original problem of heating the dust with that of finding a heating mechanism for the gas, which also has no obvious solution.

ii) *Radiative Heating*

The dust may be heated up by X-rays resulting from the interaction of the expanding shock wave with circumstellar material. In the case of the Cas A remnant, Dwek and Werner (1981) showed that the resulting X-ray luminosity is sufficiently high to heat up any supernova condensates to temperatures of ~ 20–30 K, producing a detectable infrared flux at the wavelength of maximum emission. Observations of the supernova 1980k (Canizares, Kriss, and Feigelson 1981) show that the 0.2–4 keV X-ray luminosity on day 42 was only $\sim 1.6 \times 10^5$ $L_\odot$, declining to one-half this value in a period of 50 days. It is therefore unlikely that this X-ray luminosity could be responsible for the observed ($\sim 10^6$ $L_\odot$) infrared emission between day 215 and day 357 after the outburst.

The only possibility left is that the dust is radiatively heated by the UV and visual luminosity emitted from the supernova. The energy distribution on May 31 and October 20 (Fig. 1) shows that the luminosity emitted in the B and V bands is comparable to the total infrared luminosity radiated by the dust at that time, suggesting that the dust shell absorbed about half of the UV-visual energy available at that time. The visual light curve of the supernova shows no evidence for a transition phase associated with the formation of the dust shell. This same behavior was seen in Nova Cygni 1978 (Gehrz *et al.* 1978) and may be typical of objects that form optically thin dust shells. The small optical depth may suggest a clumpy shell, or a low efficiency for dust formation in the ejecta.

b) Physical Properties of the Dust Shell

In the following we derive the physical properties of the dust shell from the combined infrared and UV-visual data. A distance of 5.5 Mpc to NGC 6946 is adopted whenever necessary in our calculations.

The total infrared luminosity emitted by the dust shell is given by

$$L_{\rm IR} = N_{\rm gr} 4\pi a^2 \sigma T_d^4 \bar{Q} \ , \qquad (1)$$

where $N_{\rm gr}$ is the total number of dust particles in the shell, a and T_d their radius and temperature, $\bar{Q}$ the Planck averaged absorption efficiency of the dust, and σ the Stefan-Boltzmann constant. For an absorption efficiency Q equal to $2\pi a/\lambda$ at infrared wavelengths, $L_{\rm IR}$ can be written as (Dwek *et al.* 1980):

$$L_{\rm IR} = 1.2 \times 10^{-2} N_{\rm gr} a^3 T_d^5 \ {\rm ergs\ s^{-1}} \ , \qquad (2)$$

where the radius a is in cm. The total mass of dust in the shell is

$$M_d = N_{\rm gr} \frac{4\pi}{3} \rho_{\rm gr} a^3 \ , \qquad (3)$$

where $\rho_{\rm gr}$ (≈ 3 g cm^{-3}) is the mass density of a dust particle. From equations (2) and (3) we derive the mass of the emitting dust which is independent of grain size and given by:

$$M_d(M_\odot) = 2 \times 10^{-12} \left(\frac{L_{\rm IR}}{L_\odot}\right) \times \left(\frac{T_d}{10^3\ {\rm K}}\right)^{-5} . \qquad (4)$$

The UV-visual luminosity emitted by the supernova originates in part from the photosphere of the expanding star, and in part from the optically thin line-emitting regions in the expanding ejecta. Assuming that the infrared-emitting grains are heated by this UV-visual luminosity, the UV-visual optical depth of the shell is determined observationally as

$$\tau_d = \ln\left(\frac{L_{\rm vis} + L_{\rm IR}}{L_{\rm vis}}\right) = \pi a^2 n_{\rm gr} \Delta R \ . \qquad (5)$$

$L_{\rm vis}$ is the observed visual luminosity, corrected for the reddening to the galaxy, and unit absorption efficiency is assumed for the grains at UV-optical wavelengths. The shell thickness, ΔR, is related to the shell mass using equation (3), because $N_{\rm gr} = 4\pi R_d^2 n_{\rm gr} \Delta R$. Here R_d is the shell radius, which can thus be estimated as

$$R_d = \left(\frac{3 M_d}{16\pi \rho_{\rm gr} \tau_d a}\right)^{1/2} . \qquad (6)$$

Assuming a λ^{-1} grain emissivity behavior, the dust temperature was determined from a least squares fit of the dust emission spectrum to the observations. The resulting dust temperature, T_d, for days 215 (1981 May 31) and 357 (1981 October 20) was 920 and 720 K, respectively. The infrared luminosity was obtained by integrating the emission spectrum at the given dust temperature over wavelengths. The value of $L_{\rm IR}$ was $2.7 \times 10^6\ L_\odot$ on day 215 and $0.9 \times 10^6\ L_\odot$ on day 357. The luminosity emitted in the visual can be estimated from the observations of BCR, giving $L_{\rm vis} \approx 6 \times 10^6$ and $2 \times 10^6\ L_\odot$ for days 215 and 357, respectively. Combined with the infrared fluxes on these days we find $\tau_d \approx 0.4$ for both days. These values have been used with equations (4) and (6) to calculate the dust shell parameters given in Table 4 for days 215 and 357. A value of 0.1 μm is assumed for the grain radius for calculating R_d.

Table 4 shows that the parameters derived for the dust shell do not vary greatly between days 215 and 357. The mass of dust is estimated to be about $10^{-5}\ M_\odot$, and the shell radius is about 1×10^{16} cm. The blackbody radius, computed by assuming that the shell radiates as a blackbody, represents a strict lower limit to the dimension of the radiating region and lies about a factor of 3 below the value derived from the more detailed procedure.

V. DISCUSSION

The observed evolution of the infrared spectrum closely resembles that seen in several novae, including Nova Serpentis 1970 (Hyland and Neugebauer 1970; Geisel, Kleinmann, and Low 1970), Nova Vulpeculae (Ney and Hatfield 1978), and Nova Cygni 1978 (Gehrz *et al.* 1980). The infrared excesses observed in these novae have been interpreted as thermal emission from dust that formed in the expanding nova shell. The phenomenological similarity in the infrared behavior of SN 1980k and these novae strongly suggests that the present observations can be simply interpreted as evidence for the formation of dust in the expanding supernova ejecta. The same interpretation was offered by Merrill (1980) for the infrared observations of the 1979c supernova in NGC 4321 (M100).

The infrared observations of SN 1980k are consistent with the formation of an optically-thin dust shell that is heated by the UV-visual radiation emitted from the underlying photosphere of the expanding star. The approximate constancy of the radius of the dust shell

TABLE 4

PHYSICAL PROPERTIES OF THE DUST SHELL OF SN 1980k[a]

Date (1981)	Day Number	T_d (K)	$L_{\rm IR}$ ($10^6\ L_\odot$)	τ_d	M_d ($10^{-5}\ M_\odot$)	R_d (10^{16} cm)
May 31	215	920 ± 70	2.7 ± 1.2	~0.4	~0.8	~1
Oct 20	357	720 ± 50	0.9 ± 0.4	~0.4	~1.0	~1

[a] Error bars reflect 1 σ scatter of the data. The derived quantities M_d and R_d are accurate to no better than a factor of 2. The calculations were made assuming a distance of 5.5 Mpc to NGC 6946, and a λ^{-1} emissivity law for the dust.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

suggests that it is not associated with the physical shell, which is expanding in time, but with the position of the dust forming zone. The distance of the zone from the center of explosion indicates that material is being injected into the zone at velocities of ~ 5000 km s^{-1} on day 215, and ~ 3000 km s^{-1} on day 357. These velocities are lower than the typical expansion velocities of $\sim 10,000$ km s^{-1} observed for the outer layers of supernova ejecta. This suggests that the material injected into the dust formation zone originates from deeper, perhaps metal-enriched, layers of the expanding star. However, given the uncertainties involved, an expanding shell is not ruled out, although the present analysis suggests a constant radius. Furthermore, the distance estimate is quite uncertain, and the shell radius depends on the assumed grain properties.

Finally, it should be noted that although the present observations are suggestive and are consistent with dust formation in the ejected material, they do not rule out the possibility that the emission originates from preexisting circumstellar dust, heated by the initial outburst of the supernova. This "infrared echo" model, suggested by Bode and Evans (1980) as an explanation for the origin of the thermal emission from SN 1979c, is also consistent with the infrared behavior of SN 1980k (Dwek 1983). For SN 1979c the echo model is preferred based on energy considerations.

VI. CONCLUSIONS

The infrared emission of SN 1980k in NGC 6946 was observed over a period of 1 year after the supernova outburst. The evolution of the emission can be briefly summarized as follows:

1. During an initial phase from day 2 to day 50, the infrared emission originated from the atmosphere of the expanding star. The time behavior of the infrared fluxes shows a gradual decrease in the color temperature of the ejecta, an effect also seen at visual wavelengths. The 1–4 μm luminosity declined with an *e*-folding time of 50 days, which is slower than the *e*-folding time of 20 days for the UV-visual luminosity. The observed colors of the supernova during the initial phases of the expansion showed both a *U* and *L* excess, probably due to extended atmosphere effects in the ejecta. A 1.4–2.6 μm spectrum of the supernova showed no significant features.

2. On day 215 (1981 May 31), after a gap in the observations, the 1–4 μm spectrum was seen to have an additional component, consistent with the appearance of dust emitting at a temperature of $T_d \sim 920$ K. These observations resemble that observed of several novae, in particular Nova Cygni 1978, and are suggestive of dust formation in the expanding supernova ejecta. From day 215 to day 357 (1981 October 20) the dust temperature decreased to ~ 720 K, and the dust luminosity decreased from 2.7 to $0.90 \times 10^6 \ L_\odot$ (for $D = 5.5$ Mpc), in both cases corresponding to $\sim 1 \times 10^{-5} \ M_\odot$ of material at the characteristic temperature of the emission. The radius of the dust shell remained approximately constant at $\sim 1 \times 10^{16}$ cm. This behavior is consistent with the formation of an optically-thin dust shell, created by the continuous injection of material into a dust-formation zone that maintained approximately the same spatial position during this period. *B* and *V* photometry taken during this period suggest that the dust shell absorbed about one-third of the visual luminosity emitted on days 215 and 357.

3. The infrared behavior is also consistent with an infrared echo model in which the dust emission is from preexisting circumstellar grains, heated by the UV-visual output of the supernova. A similar behavior is seen in SN 1979c (Merrill 1980, and 1982, private communications), consistent with a circumstellar origin for the infrared excess emission. This model, with applications to SN 1980k and SN 1979c, is discussed by Dwek (1983).

We encourage more coordinated optical and infrared observations of future supernovae. The current ambiguity over the origin of the thermal infrared emission from SN 1980k can be avoided in future supernovae with more extensive time and spectral coverage of their emission.

For a galactic supernova the origin of the emission can be readily established with sufficiently high ($<3''$ at $\lambda = 3.4$ μm) spatial resolution since in the echo model the infrared emission originates from a circumstellar shell of radius $\gtrsim 4 \times 10^{17}$ cm, whereas in the dust formation model the emission originates from a $\lesssim 10^{16}$ cm region around the center of the explosion.

We thank the IRTF staff, in particular the telescope operators Ron Koehler, Charlie Kaminski, and Barbara Schaefer for assistance with the observations. We acknowledge helpful conversations with D. Branch and would like to thank Mike Merrill for many helpful suggestions. E. Dwek acknowledges the financial support of the Center for Theoretical Physics at the University of Maryland during the initial stages of this research.

REFERENCES

Barbon, R., Ciatti, F., and Rosino, L. 1982, *Astr. Ap.*, **116**, 35 (BCR).
Beckwith, S., Evans N. J., II, Becklin, E. E., and Neugebauer, G. 1976, *Ap. J.*, **208**, 390.
Bode, M. F., and Evans, A. 1980, *M.N.R.A.S.*, **193**, 21p.
Buta, R. J. 1982, *Pub. A.S.P.*, **94**, 578.
Canizares, C. R., Kriss, G. A., and Feigelson, E. D. 1981, *Ap. J. (Letters)*, **253**, L17.
Clayton, D. D. 1979, *Space Sci. Rev.*, **24**, 147.
Dwek, E. 1983, *Ap. J.*, **274**, 175.
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.
Dwek, E., and Werner, M. W. 1981, *Ap. J.*, **248**, 138.
Elias, J. H., Frogel, J. A., Matthews, K., and Neugebauer, G. 1982, *A.J.*, **87**, 1029.
Gehrz, R. D., Hackwell, J. A., Grasdalen, G. L., Ney, E. P., Neugebauer, G., and Sellgren, K. 1980, *Ap. J.*, **239**, 570.
Geisel, S. L., Kleinmann, D. E., and Low, F. J. 1970, *Ap. J. (Letters)*, **161**, L101.
Hyland, A. R., and Neugebauer, G. 1970, *Ap. J. (Letters)*, **160**, L177.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
Kirshner, R., and Kwan, J. 1974, *Ap. J.*, **193**, 27.
Merrill, K. M. 1980, *IAU Circ.*, No. 3444.
Ney, E. P., and Hatfield, B. F. 1978, *Ap. J.* (*Letters*), **219**, L111.
Schultz, G. V., and Wiemer, W. 1975, *Astr. Ap.*, **43**, 133.
Telesco, C. M., Becklin, E. E., Koehler, R., and Gatley, I. 1981, *IAU Circ.*, No. 3613.
Weaver, T. A., and Woosley, S. E. 1980, *Ann. N.Y. Acad. Sci.*, **336**, 335.
Wild, P. 1980, *IAU Circ.*, No. 3532.

M. F. A'HEARN: Astronomy Program, University of Maryland, College Park, MD 20742

E. E. BECKLIN, R. HAMILTON BROWN, R. W. CAPPS, D. MORRISON, C. M. TELESCO, A. T. TOKUNAGA, and C. G. WYNN-WILLIAMS: Institute for Astronomy, University of Hawaii, Honolulu, HI 96822

H. L. DINERSTEIN: Astronomy Department, University of Texas, Austin, TX 78712

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

IAN GATLEY: UKIRT, 900 Leilani Street, Hilo, HI 96720

M. W. WERNER: NASA Ames Research Center, MS-245-6, Moffett Field, CA 94035

© American Astronomical Society • Provided by the NASA Astrophysics Data System