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THE INFRARED ECHO OF TYPE II SUPERNOVAE WITH CIRCUMSTELLAR DUST SHELLS. II. A PROBE INTO THE PRESUPERNOVA EVOLUTION OF THE PROGENITOR STAR

ELI DWEK
Laboratory for Extraterrestrial Physics, NASA/Goddard Space Flight Center
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ABSTRACT

This paper studies the spectral appearance and evolution of the infrared light curve, also referred to as the infrared echo, of Type II supernovae embedded in carbon- or oxygen-rich circumstellar dust shells. The distinct spectral signature of the echo and its temporal evolution can be used to estimate the mass of the shell and identify the composition of the dust. Since the shell mass and dust composition are determined by the combined effect of stellar mass loss and the dredging of newly synthesized heavy elements to the stellar surface, observations of the infrared echo may provide useful clues to the presupernova evolution of the progenitor star.

Subject headings: infrared: spectra — stars: abundances — stars: circumstellar shells — stars: supernovae

I. INTRODUCTION

The infrared light curve of several recently observed Type II supernovae has been attributed to thermal emission from circumstellar dust heated by the UV-visual output of the exploding star (SN 1979c, Bode and Evans 1980; SNs 1979c and 1980k, Dwek 1983; SN 1982g, Graham *et al.* 1983). The dust presumably formed in the outflowing matter ejected during the red giant phase of the evolution of the progenitor star. Note, however, that the observations of SN 1980k are also consistent with dust forming in the supernova ejecta (Dwek *et al.* 1983). For a given UV-visual light curve, the time behavior of the infrared emission, which I designate here as the infrared echo, is completely determined by the structure of the circumstellar dust shell. This structure is characterized by an inner radius R_1, the size of the dust-free cavity where all the dust was vaporized by the initial UV-visual outburst, and an outer radius R_2, determined by the physical extent of the shell. Echo models (Wright 1980; Dwek 1983) show that the infrared light curve rises rapidly to a plateau that lasts for a period of about $2R_1/c$. It thereafter decays at a rate which, for a given density structure and UV-visual light output, depends on R_2. From the observations of the infrared light curve and of its temporal behavior, lower limits to the mass of the circumstellar shell may be inferred (Dwek 1983). If outflow velocities are known, the mass loss rate from the progenitor star may be inferred as well.

In this paper I study the effect of the dust composition in the circumstellar shell on the spectral signature and temporal evolution of the infrared light curve. Two types of dust particles are considered in this paper: silicates, which are expected to form in oxygen-rich (C/O < 1) stellar outflows; and graphite particles, which form in carbon-rich (C/O > 1) ejecta (e.g., Huffman 1977). The dust composition affects the temporal behavior of the infrared light curve because of the different vaporization temperatures of the circumstellar dust particles. Graphite particles vaporize at higher temperatures than silicate particles of the same size, so that for a given UV-visual outburst a carbon-rich circumstellar shell will have a smaller dust-free cavity than an oxygen-rich circumstellar shell (§ II). The dust composition also determines the spectral signature of the infrared light curve. The temporal evolution of the infrared spectrum of identical supernovae embedded in carbon- and oxygen-rich circumstellar shells is described in § III.

The mass and composition of the circumstellar shell are determined by the history of the progenitor star. Section IV briefly describes evolutionary sequences in massive stars that can lead to the formation of carbon- or oxygen-rich circumstellar shells. Infrared observations of supernova light curves can therefore yield valuable information on the presupernova evolution of the progenitor stars.

II. THE VAPORIZATION TEMPERATURE OF THE DUST

The vaporization rate $R_{\rm evap}$ of a dust particle of radius a is given by (e.g., Friedlander 1977)

$$R_{\rm evap} = 4\pi a^2 F\ , \qquad (1)$$

where $F = P_0 \exp(2\omega m_A/a\rho kT)/(2\pi m_A kT)^{1/2}$, is the flux of particles of mass m_A leaving the surface, ω is the surface energy (in ergs cm^{-2}) of the dust, ρ the dust mass density, and T the dust temperature. P_0 is the vapor pressure over a flat surface of the same composition as the dust, and k is the Boltzmann constant.

Defining the evaporative lifetime of the dust as

$$t_{\rm evap} = (1/a\ da/dt)^{-1}\ , \qquad (2)$$

yields

$$t_{\rm evap}^{-1} = (P_0/\rho a)(m_A/2\pi kT)^{1/2} \exp(2\omega m_A/\rho akT)\ . \qquad (3)$$

The grain lifetime given by equation (3) is a rapidly decreasing function of temperature. I will define the evaporation temperature of the dust as the temperature at which $t_{\rm evap} = t_{\rm SN}$, the decay time of the supernova light curve, since dust that evaporates in a time much less than $t_{\rm SN}$ ($\sim$25 days) will have a negligible contribution to the infrared emission. To calculate the grain lifetime I adopted a grain size of 0.1 μm. Values for the vapor pressure and surface energy of the dust used in equation (3) were equal to those used by Lefèvre (1979). The mass density of the dust was taken to be 2.2 g cm^{-3} for graphite and 3.3 g cm^{-3} for the silicate particles. Finally, I assumed that the evaporating graphite and silicate "atoms" are individual carbon atoms and SiO molecules respectively. The resulting evaporation temperatures T_v, were found to be 1900 K for the graphite particles and 1500 K for the silicate grains.

To calculate the spectral evolution of the infrared echo of a supernova embedded in an oxygen- or carbon-rich circumstellar shell, I adopted the following "typical" supernova and dust parameters: a supernova UV-visual luminosity L_{SN} equal to $1 \times 10^{10}\ L_{\odot}$, which decays exponentially with an e-folding time of 25 days; a distance from the observer to the remnant of 1 Mpc; dust optical properties for 0.1 μm particles from Draine and Lee (1984); a visual optical depth in the shell τ_{vis} of 0.1; and an r^{-2} power-law behavior to characterize the density distribution of the gas (or dust) in the shell.

The radius of the dust-free cavity is given by

$$R_1 = (L_{SN}/16\pi\sigma T_v^4 \langle Q \rangle)^{1/2}\ , \tag{4}$$

where σ is the Stefan-Boltzmann constant and $\langle Q \rangle$ the Planck-averaged value of the dust emissivity. I assumed that the UV-visual output is absorbed with unit efficiency by the dust. The outer radius of the shell is a free parameter, chosen so that the shell comprises 10 zones across which the initial dust temperature does not change by more than 10%.

The results of the calculations show that for the above parameters, the inner radius of the carbon-rich shell is 0.02 pc, giving a plateau period of about 48 days. The inner radius of the oxygen-rich shell is 0.10 pc, resulting in an extended plateau period of 247 days. The outer radii of the shells were found to be 0.082 and 0.42 pc respectively. The evolution of the infrared luminosity and spectrum is shown in Figures 1–4 and is briefly described below.

III. THE SPECTRAL EVOLUTION OF THE INFRARED ECHO

a) *The Evolution of the Infrared Luminosity Curve*

Figure 1 depicts the evolution of the infrared light curve of a supernova embedded in a carbon- or oxygen-rich circumstellar shell as a function of time. Model parameters were chosen so that the fraction of the total energy output of the supernova that is radiated in the infrared is about equal in both cases. The rate at which this energy is radiated away is quite different and is determined by the size of the dust-free cavity around the remnant. The infrared luminosity during the plateau period is approximately given by (Wright 1980; Dwek 1983)

$$L_{IR} = \tau_{vis}(ct_{SN}/2R_1)L_{SN} \tag{5}$$

and lasts for about $2R_1/c$. The infrared luminosity of a supernova embedded in a carbon-rich shell is therefore higher and lasts for a shorter period of time than that of a supernova embedded in an oxygen-rich shell.

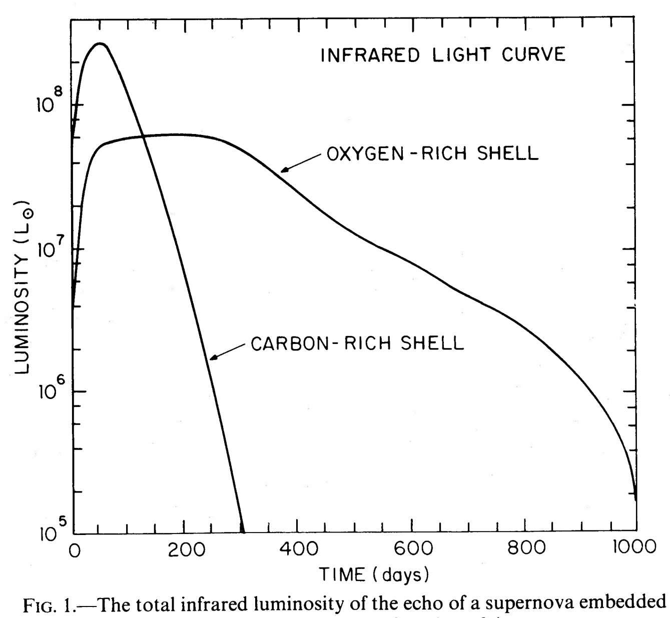


FIG. 1.—The total infrared luminosity of the echo of a supernova embedded in a carbon- or oxygen-rich shell is shown as a function of time.

b) *The Evolution of the Infrared Spectrum*

Figures 2 and 3 show the evolution of the infrared spectra of supernovae with, respectively, carbon- or oxygen-rich circumstellar shells as a function of time. The spectra are depicted for three different time periods, representing the initial rise to the plateau, the plateau period, and the subsequent declining phase of the infrared light curve.

The difference in the spectral evolution of the echo between the carbon- and oxygen-rich cases is as pronounced as the difference between their light curves. The spectrum of the echo in the carbon-rich case retains its general shape, whereas that in the oxygen-rich case changes substantially.

One noticeable change in the spectrum is its reddening, which results from the fact that at later times increasingly colder dust, previously "invisible" to the observer (see Fig. 1 in Dwek 1983), contributes to the emission. Figure 4 shows the evolution of the "color" of the spectrum, defined here as the L (3.4 μm) to K (2.2 μm) flux ratio, as a function of time. The "color" of the spectrum remains constant during the plateau period of the evolution of the light curve. The L-to-K flux ratio is then about 0.6 and 1.6 for the carbon-rich and oxygen-rich cases respectively, reflecting the different vaporization temperatures of the dust particles of the shell. After the plateau period, the flux ratios increase by about factors of 2 and 3 respectively by the time the light curves decline to about 10% of their peak value.

The 9.7 and 18 μm silicate features dominate the spectrum in the oxygen-rich case. The reddening of the spectrum results in significant changes in their relative sizes and in their position relative to the peak of the underlying blackbody curve. The graphite spectrum is featureless except for a pronounced, but narrow, resonance at 11.52 μm, which was suggested on theoretical grounds by Draine (1984). The resonance feature becomes more pronounced, relative to the underlying continuum emission, as a function of time. Otherwise, the graphite spectrum retains its general shape.

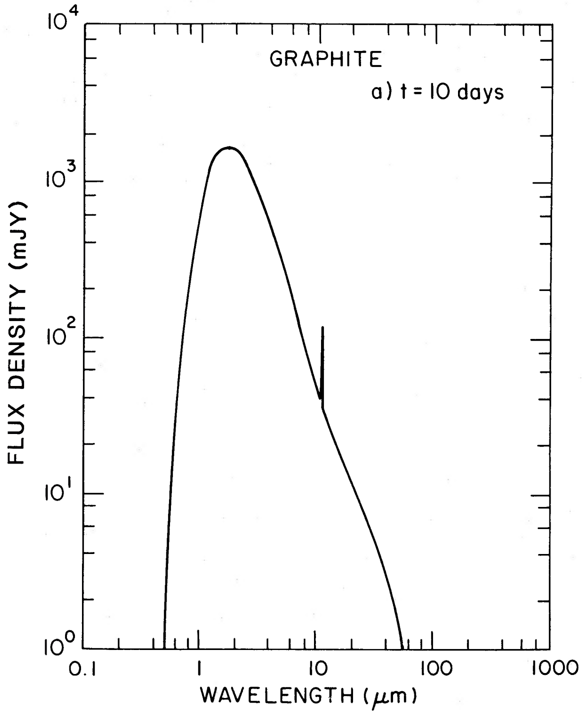
IV. DISCUSSION

It is interesting to compare these theoretical predictions with the observations of the two recent Type II supernovae SN 1979c and SN 1980k. Both supernovae were first observed at the end of the "plateau" phase of the evolution of their light curve (Dwek 1983) with an L-to-K flux ratio of ~ 1.7 and $\sim 2.4 \pm 0.6$ respectively. These "color" temperatures are consistent with those expected from dust in an oxygen-rich shell. However, a compositional determination based on the color of the spectrum may be complicated by the fact that a short burst of soft X-rays may have preceded the first observed UV-visual output from the supernovae. An X-ray precursor can vaporize the dust to a distance R_x that is larger than R_1, so that the subsequent UV-visual flux will heat the dust to a temperature of only $\sim (R_1/R_x)^{2/5} T_v$ (Wright 1980). The observations of SNs 1979c and 1980k can therefore also be interpreted as an echo from a supernova embedded in a carbon-rich shell which had a radiative precursor. This ambiguity can only be resolved with more extensive wavelength coverage of the infrared spectrum.

Ultraviolet, radio, and infrared observations of early-type stars (Hutchings 1976; Barlow and Cohen 1977), show that they undergo mass loss at rates ranging from $\sim 10^{-7}$ to $\sim 10^{-4}$ $M_{\odot}$ yr^{-1}. Mass loss rates of these magnitudes can significantly affect the evolution, nucleosynthesis yield, and spectral appearance of a star (e.g. Maeder 1984, and references therein).

A star with an initial mass below ~ 25 $M_{\odot}$ may not lose mass at a sufficiently high rate to significantly alter its evolution (Dearborn *et al.* 1978; Brunish and Truran 1982). The star retains a fraction of its hydrogen-rich envelope, the fraction depending on its initial mass and mass loss rate. Convection during the red giant phase will bring CNO processed material to the surface of the star (Brunish and Truran 1982), altering the chemical composition of the wind. The only factor that governs the type of dust particles that will from in the outflow is the C/O ratio, which is decreased by the CNO process below its solar value of 0.55. The dust that will form during this phase will therefore consist of silicate-type particles. A star in this phase of evolution may be the highly reddened star IRC + 60 375, which was identified by Fawley and Cohen (1974) as an M7 supergiant, a possible precursor of Type II supernovae. They presented the 0.8–22 μm energy distribution from the star, which showed emission features at 10 and 18 μm in excess of the extrapolated free-free emission. The signature of the excess suggests the presence of silicate dust grains in the circumstellar material.

Higher mass stars can lose mass at a rate of $\sim 10^{-5}$ $M_{\odot}$ yr^{-1}, which will have significant effects on their structure and evolution (e.g., Maeder 1984). Stars losing mass above a given critical rate will strip their hydrogen-rich envelope to reveal their underlying layer of ^{14}N-rich material (Dearborn *et al.* 1978). Such stripped cores will appear as Wolf-Rayet stars of type WN. If the star continues to lose mass during the helium-burning phase of its evolution, it will be stripped of its ^{14}N-rich envelope and expose a ^{12}C-rich layer, the product of the 3-alpha process. Such a star will appear as a Wolf-Rayet star of type WC. Wolf-Rayet stars are known to exhibit an infrared excess emission (e.g., Cohen, Barlow, and Kuhi 1975) which



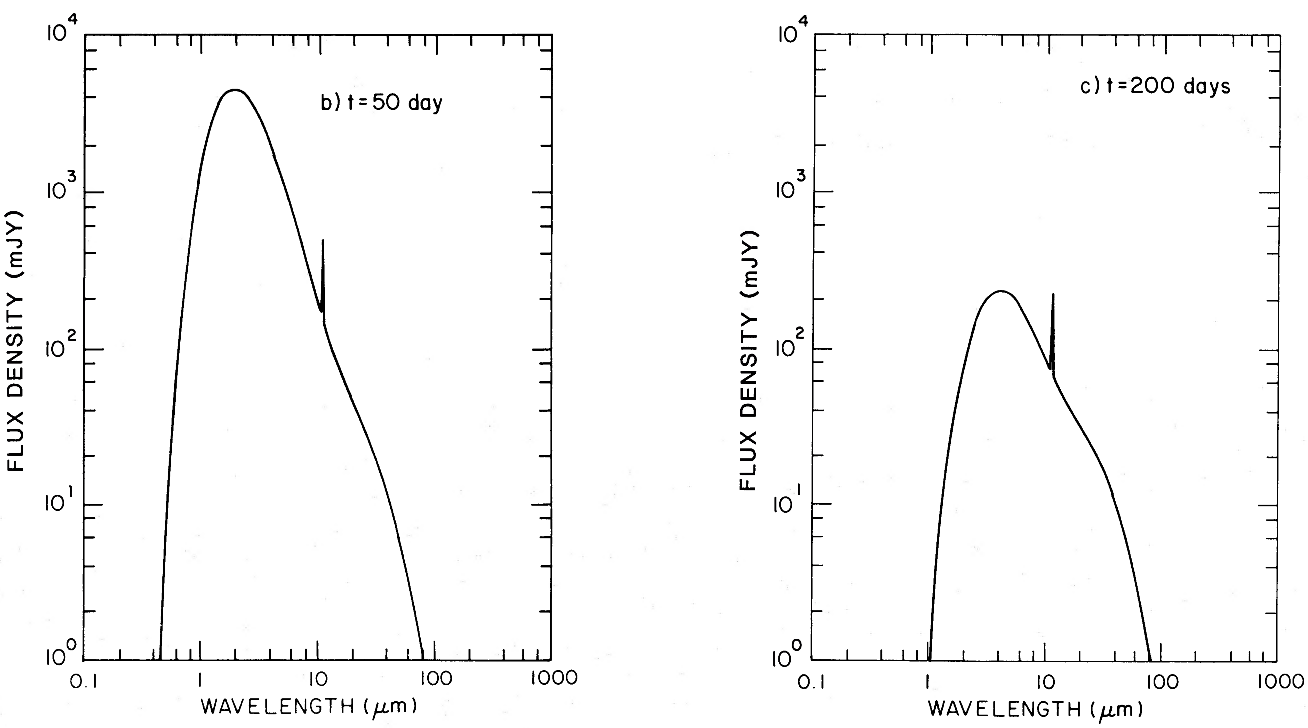
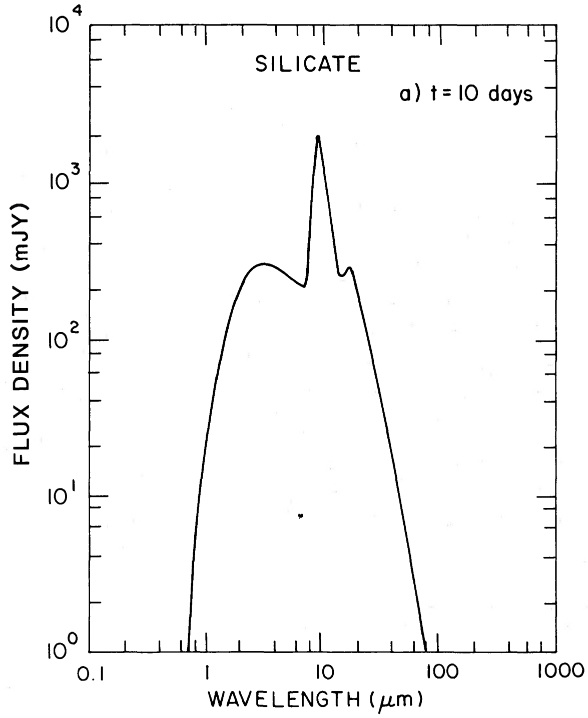


FIG. 2.—The evolution of the infrared spectrum of a supernova embedded in a carbon-rich shell is shown here for three different epochs: (*a*) $t = 10$ days, (*b*) $t = 50$ days, and (*c*) $t = 200$ days. The spectral feature corresponds to the 11.52 μm resonance feature in graphite.

can be attributed to thermal emission by dust grains only in the late-type (mostly WC9 and some WC8) and coolest WC stars (Cohen 1975; Cohen and Kuhi 1977; Cohen and Vogel 1978). The infrared excess is featureless, suggesting graphite as a likely condensate, consistent with the enrichment of carbon in the stellar winds.

To summarize, observational evidence suggests that precursors of Type II supernovae may develop circumstellar dust



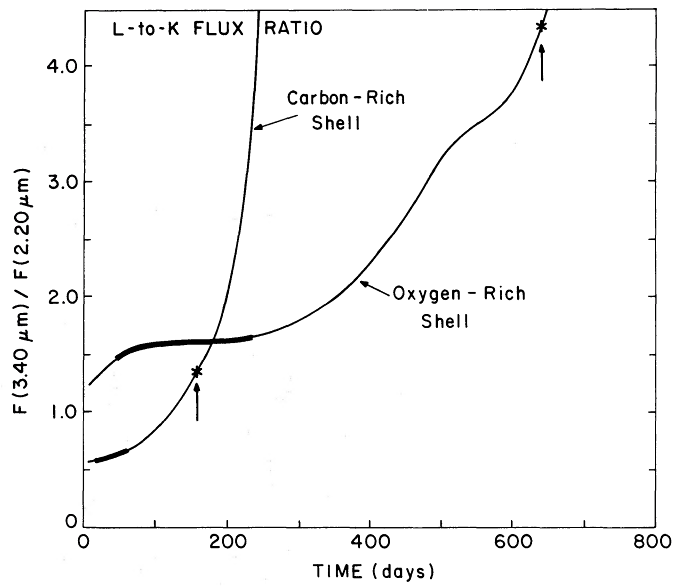


FIG. 4.—The evolution of the "color" of the infrared spectrum, defined here as the L (3.4 μm)-to-K (2.2 μm) flux ratio, is shown as a function of time for a supernova embedded in a carbon-rich and an oxygen-rich circumstellar shell. The arrows in the figure depict the time at which the infrared luminosity decreased to 10% of its value during the plateau phase (boldly marked along the curve).

shells that consist of either oxygen- or carbon-rich material. Normal O stars will be enshrouded in an oxygen-rich circumstellar shell that will produce a spectrum characterized by the 9.7 and 18 μm silicate emission features. O stars that undergo more extensive mass loss will evolve into WN- and subsequently WC-type stars before they become supernovae. The radiative output from a supernova produced by a WC star

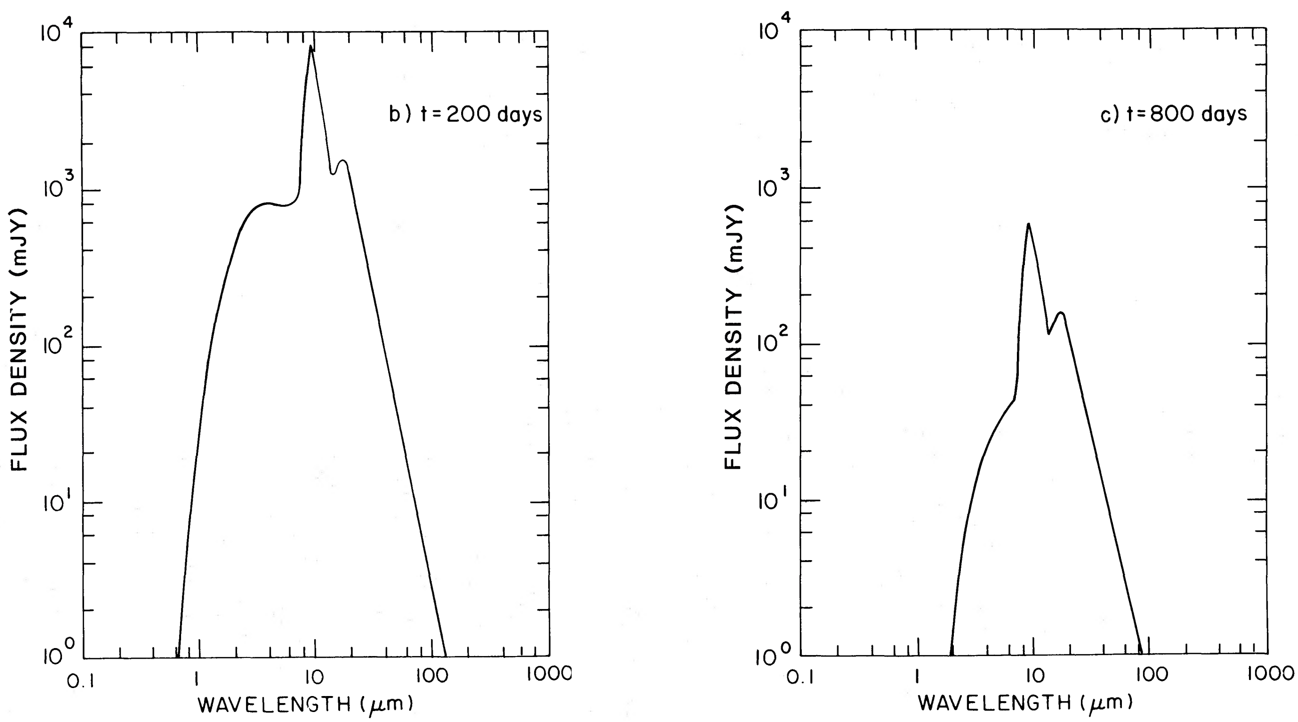


FIG. 3.—The evolution of the infrared spectrum of a supernova embedded in an oxygen-rich shell is shown here for three different epochs: (*a*) $t = 10$ days, (*b*) $t = 200$ days, and (*c*) $t = 800$ days. The spectral features correspond to the 9.7 and 18 μm features of the silicate grains.

may be quite different from that of a "typical" Type II event. Without an extensive envelope to filter its energy release (Falk and Arnett 1974), the star may produce an X-ray or UV supernova. The infrared echo of this outburst will be characterized by a featureless graphite spectrum.

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ELI DWEK: Code 697, NASA/Goddard Space Flight Center, Greenbelt, MD 20771