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Infrared emission by dust grains near variable primary sources – III. Type II supernovae

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Summary. We consider the radiative heating of an extensive pre-existing circumstellar dust shell surrounding the recent supernova in M100. The results are consistent with observations of Merrill (IAUC 3444) of a thermal infrared excess in this object after ~ 260 days. We also examine emission by interstellar dust grains in the galactic plane of M100. Although the derived fluxes are too low by $\sim 10^3$, re-emission by interstellar dust heated by supernovae in Local Group galaxies should be detectable for a long time after outburst.

1 Introduction

Recent infrared observations by Merrill (1980) of the supernova in M100 (NGC 4321) have revealed excess emission in the *HKL* bands, which he suggested is consistent with the formation of grains in the ejecta. However, as Type II supernova progenitors are generally believed to be late-type supergiants (e.g. Falk & Arnett 1977), it is not unlikely that such a progenitor might already possess an extensive circumstellar envelope (*cf*. Palumbo 1980), in which dust could be a major component. The heating of such grains by the supernova could account for the Merrill observations. We have considered the possibility that the infrared emission arose from such a circumstellar shell, and alternatively that it might have arisen from interstellar grains in the galactic plane of M100.

2 Source configuration

Unlike the case of novae, in which the grains responsible for the infrared emission are heated by a source of constant bolometric luminosity with increasing effective temperature (Bode & Evans 1980), the bolometric luminosity of Type II supernovae decays like the visual light curve (Falk & Arnett 1977). We shall assume here that the grains' response at short wavelengths is flat, so that the grain 'heating function' H (Bode & Evans 1980) is simply given by the bolometric luminosity L of the central object, i.e.

$$H = L\langle Q_{\text{abs}}\rangle,$$

where the Planck mean of the grain absorption efficiency $\langle Q_{\text{abs}}\rangle$ is taken to be independent of time. For the supernova in M100, the peak luminosity was 2.7×10^{43} erg s^{-1} (Panagia

1979) and we assume thereafter an exponential decay with an *e*-folding time of 50 days (Falk & Arnett 1977). The distance D of M100 is taken to be 20.5 Mpc.

We assume a spherical dust envelope centred on the supernova progenitor, and that the dust grains are graphite-like with radius 0.2 μm and absorbing efficiency in the infrared $Q_{\rm abs} \propto \nu^2$. For such grains, any variations in the effective temperature of the supernova photosphere (Falk & Arnett 1977; de Vaucouleurs & de Vaucouleurs 1979) will have negligible effect on the grain heating function; such changes are therefore neglected. Before outburst, the innermost regions of the dust shell are likely to lie within a few stellar radii of the central star. At outburst, however, grains will evaporate to such an extent that a spherical cavity will be swept out by the erupting supernova. Although we have examined the evaporation of grains surrounding an erupting (supernova-like) source in detail, this work is to be elaborated on elsewhere; nevertheless we may note here that grains of radius a having $Q_{\rm abs} \propto \nu^2$ evaporate in a time

$$t_{\rm ev} \approx (6sa/p_0)\left(\frac{2\pi kT_1}{m}\right)^{1/2} \exp(T_0/T_1)\cdot(T_1/T_0)$$

when exposed to a source of luminosity L. Here T_0 and p_0 characterize the vapour pressure of the grain material as a function of temperature, T_1 ($\propto (L/r^2a)^{1/6}$) is the initial grain temperature, s is the grain density, m the atomic weight of the grain material and k is Boltzmann's constant. Thus for 0.2-μm graphite grains to exist for significant times during the period of interest, they must lie at distance $R_1 \approx 8 \times 10^{16}$ cm. We accordingly suppose that, at the time of the Merrill (1980) observation, the dust envelope possessed a cavity of this size.

3 Results

When the supernova erupts, the infrared emission seen by a distant observer lies within a paraboloid of revolution with focus at the supernova and axis along the line of sight (*cf.* Fig. 1 of Bode & Evans 1979; hereafter Paper I). We have integrated equations (8) and (9) of Paper I, taking into account the light travel-time across the dust shell in the usual way. We suppose that the supernova progenitor had a circumstellar dust envelope of outer radius $R = 0.5$ pc and mass $M_{\rm gr} = 0.06\,M_\odot$. The latter is not unreasonable, as the masses of Type II supernova progenitors are believed to be $\sim 10\,M_\odot$ (Falk & Arnett 1977); while observations described by Palumbo (1980) suggest that the M100 supernova progenitor possessed a circumstellar gas envelope of $\gtrsim 0.2 M_\odot$, probably arising from a stellar wind. For the parameters assumed, the extinction optical depth at short wavelengths $\tau^* \approx 0.18$ and at 3.4 μm is $\tau \approx 0.01$, values that are only weakly dependent on the grain density law assumed (see below).

Assuming that the grains also originated in the neighbourhood of the progenitor, we would expect the grain number density $N(r)$ to vary with distance r from the central star as r^{-2}, a result that applies only for uniform ejection rate and constant outflow velocity from the star. In the more realistic case of variable outflow velocity, for example, due to gas drag, or non-uniform (decreasing) ejection rate, then a flatter dependence of N on r would be appropriate. The assumption of uniform grain number density reproduces the Merrill (1980) observation well, as illustrated in Fig. 1; for $N(r) \propto r^{-2}$, equivalent agreement has been obtained with similar values of R and $M_{\rm gr}$ (note that the flux at 1.2-μm wavelength comes almost entirely from the supernova photosphere).

The K and L light curves for the case of the uniform grain density are shown in Fig. 2, in which the time of the Merrill observation is indicated. Note that these light curves peak at

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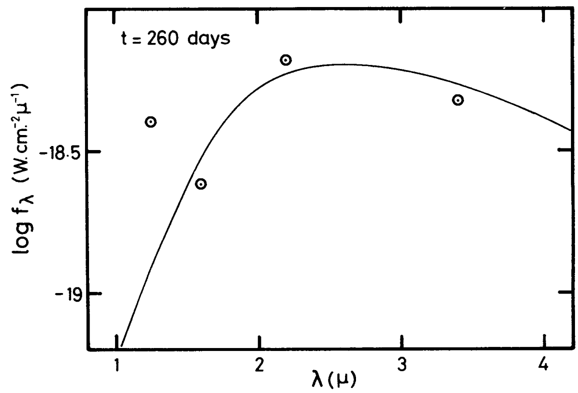

Figure 1. Observed (Merrill 1980) and theoretical (solid curve) near infrared spectrum of M100 supernova. See text for details.

~100 days from outburst and that from this time the infrared colours would suggest a cooling shell. It is of interest to note that, at ~400 days from outburst (i.e. ~1980 July), the flux at 3.4 μm should be $\gtrsim 3 \times 10^{-19}$ W cm^{-2} μm^{-1}, and may well still be detectable. A steeper grain density distribution leads to somewhat steeper light curves after maximum, as illustrated in Fig. 9 of Paper I. Further data on the infrared behaviour of the M100 supernova would enable us to refine our model by detailed fitting of individual light curves, as we have already done for the classical novae FH Ser and V1301 Aql (Bode & Evans 1980). To the best of our knowledge, the supernova has not been observed in the infrared since the time of the Merrill observation.

We also note that, at earlier times, the emission from the dust envelope would have been overwhelmed by the supernova photospheric contribution. Thus although, on this model, the dust contribution would have been present since the earliest times, its *detectability* as a measurable excess would be precluded until the photospheric flux at these wavelengths declined to a sufficient degree. This effect would give rise to an apparent developing excess and would simulate grain formation.

4 Heating of interstellar grains

As an alternative interpretation, we have considered heating by the erupting supernova of the interstellar grains of M100. For simplicity, we have approximated the galactic plane of

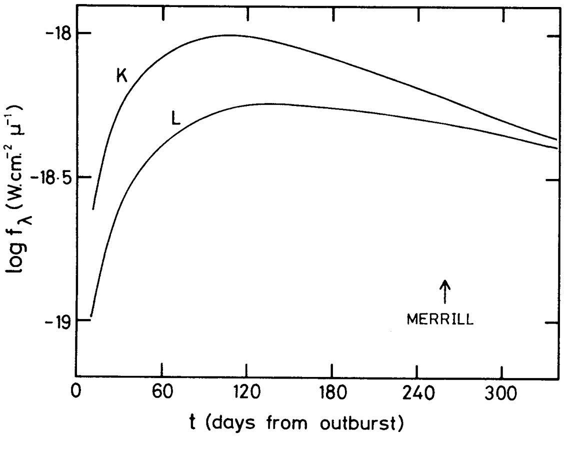

Figure 2. Theoretical *K* and *L* light curves for M100 supernova. The time of the Merrill (1980) observation is indicated.

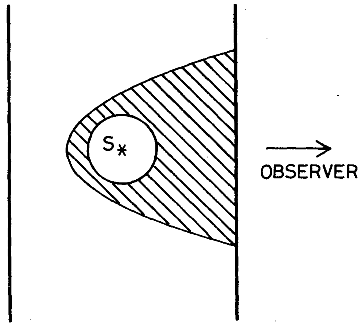

Figure 3. Heating of interstelar grains by erupting supernova S. Emission detected by a distant observer comes from grains in shaded region.

M100 by a plane parallel slab in the plane of the sky (the slight inclination of M100, ~ 25°, does not affect our qualitative conclusions). A distant observer again sees emission from grains bounded by a paraboloid of revolution with focus on the supernova and axis along the line-of-sight (*cf*. Fig. 3). In this case we assume a grain number density $5 \times 10^{-13}\,\mathrm{cm}^{-3}$ – similar to that in our own Galaxy (Allen 1973) – and a half-thickness for the dust plane of 100 pc (FitzGerald 1967; Allen 1973); otherwise all relevant parameters are the same as in the previous section. For this configuration, the infrared fluxes for the M100 supernova are three orders of magnitude too low compared to the Merrill observation, even if peak supernova luminosity is maintained throughout the outburst. However, similar heating of interstellar grains in Local Group galaxies ($D \sim 1$ Mpc) could well be detectable ($K \sim 12$, $L \sim 9$) and may be so even some years after outburst.

5 Concluding remarks

Merrill's (1980) observation of the infrared excess in the M100 supernova may be explained by emission of circumstellar material heated by the erupting supernova – the grains need not be formed in the ejecta but could exist prior to eruption. Further observations of the supernova at infrared wavelengths, even at this stage, could well prove useful. Also, infrared observations of supernovae in Local Group galaxies could reveal the heating of their interstellar grains. Such observations, if successfully modelled, could help in the determination of interstellar grain type and distribution in these galaxies.

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