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ANALYSIS OF THE INFRARED ECHO OF SUPERNOVA 1982e IN NGC1332

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SUMMARY

In a previous paper it was established that the infrared radiation observed from supernova 1982e originated from a pre-existing circumstellar dust cloud, and was produced by an echo of the radiation from the supernova. Here a model of the time dependent radiative transfer within a supernova dust cloud is developed to allow detailed comparison of the data and the model. This analysis further confirms the original conclusion that the infrared emission is due to an echo, and permits the self-consistent derivation of several cloud parameters including the optical depth of the dust cloud and the mass of dust in the cloud. A dusty stellar wind is the most likely source of this cloud. It is argued that an OH/IR star is the most plausible source of such a dusty wind, and a binary star model for the supernova explosion where a white dwarf near the Chandrasekhar limit accretes material from this wind is shown to be viable.

1 INTRODUCTION

The study of supernovae (SN) has remained principally the occupation of optical astronomers. A few supernovae have been studied at radio (Weiler *et al.* 1982), and UV wavelengths (e.g. Panagia *et al.* 1980), and one detected by its x-ray emission (Canizares *et al.* 1982). It has been suggested that supernovae could be targets for the more exotic new astronomies; γ-ray, neutrino, and gravitational wave. In spite of the potential benefits which the fairly well established techniques of infrared (IR) astronomy could bring to our understanding of supernovae, observations at these wavelengths are very sparse. Important contributions have been made by Dwek, Elias and their collaborators. The J, H, and K light curves of three type I supernovae have been reported by Elias *et al.* (1981, 1985) and Elias & Frogel (1983) and in Dwek *et al.* (1983) and Dwek (1983) observations of two type II supernovae are reported and discussed.

Two main themes of the IR study of supernovae are exploitation of infrared observations to give extragalactic distance measurements superior to those obtained through optical methods, and study of dust grains in the supernova environment and hence explore the nature of the supernova progenitor. Infrared data has great potential for distance studies but can not be used until many more supernovae have been observed, Elias *et al.* (1985). However, some supernovae have shown infrared properties which are worthy of detailed study. In particular there are those supernovae which have exhibited infrared emission in excess of the photospheric emission observed optically. Five infrared excess supernovae have been discovered: the type II SN (SNII) 1979*c* (Merrill 1980), the SNII 1980*k* (Telesco *et al.* 1981), the untyped supernova 1982*e* [2] (Graham *et al.* 1983, hereafter Paper I), SNII 1982*l* (Graham 1985), and the type I (SNI) 1982*r* (Graham 1985). In all these cases the authors (Bode & Evans 1980, Dwek *et al.* 1983, Dwek 1983, Graham *et al.* 1983, and Graham 1985) who have discussed the excess infrared emission concur that the infrared emission in excess of the photosphere is due to dust. In the case of SN1980k alternative models involving dust condensation in the ejecta (Dwek *et al.* 1983) or re–radiation by pre–existing circumstellar dust (Dwek 1983) have both been shown to be consistent with the observations. In the case of SN1979c, Bode and Evans (1980) suggested that the IR excess could have been due to pre–existing dust, and Dwek (1983) has pointed out that energy arguments very likely rule out the dust condensation hypothesis. However, observations of SN1982e (paper I) provided the most unambiguous demonstration to date that an IR echo was responsible for the IR excess in a supernova. Support for a pre-existing cloud was found by demonstrating that the temperature evolution of the emitting dust grains is exactly as one would expect from a pulse of radiation propagating outward at the speed of light into an extended dust cloud.

The infrared light curves of SN 1982*e* represent the most complete and accurate set of data relating to the development of thermal dust emission from a supernova. The light curves reported in Paper I at J (1.25μm), H (1.65μm), and K (2.2μm) cover the period from ~ 100-250 days after discovery with a typical photometric accuracy of 5%. The discovery that the emitting dust almost certainly pre-existed the supernova explosion, and lies within a dust shell of a radius of a few hundred light

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[2] In paper I 1982e was incorrectly designated SN1982g

days warrants further investigation. In this paper the details of time-varying dust temperatures in a circum-supernova dust shell, and the resultant infrared radiation are worked out, and compared with these observations so that the structure of the dust cloud around SN 1982*e* can be studied. In section 2) a circum-supernova dust cloud model is described which gives rise to an infrared echo, and in 2.1) the radiation balance is used to establish the grain temperature in terms of the supernova bolometric light curve and the nature, size and position of the grain. In 2.2) the total specific flux from the dust cloud and its temporal development is determined in terms of the grain temperature, nature and distribution. In 3) justifiable assumptions are made about the nature and distribution of the dust and about bolometric behaviour of the SN. In 4) the observed colour evolution of SN 1982e is used to find the temperature of dust grains at the vertex of the outermost parabola as a function of time and hence show that our use of the echo model is internally consistent. The shapes of the SN 1982e IR light curves are then used to show that a $1/r^2$ grain distribution provides a good fit to the data with very plausible cloud limits and grain nature. Finally it is shown that an optically thin dust cloud is able to reproduce the observed flux. In 5) the grain radius is determined, and then using the cloud parameters derived in 4) the cloud dust mass is found. In 6) our conclusion that the dust pre-dated the explosion is contrasted with post-explosion grain condensation in novae. A progenitor for SN 1982e is proposed and it is shown that such a star was probably obscured before the explosion. A stellar-wind trigger for SNI is suggested and in section 6.2) this mechanism is given quantitative support.

2 RADIATIVE TRANSFER IN A DUST SHELL

The problem of calculating the radiative transfer in a circumstellar dust cloud and the subsequent infrared radiation has been treated previously (e.g. Jones & Merrill 1976, Rowan-Robinson 1980). The additional difficulties which arise when the source of short wave radiation is variable have also been considered (Wright 1979, Bode & Evans 1979). Dwek (1983) has developed a model for calculating the IR emission from a supernova dust cloud for comparison with the IR light curves of SN 1979*c* and SN 1980*k*. The supernova 1982*e* in NGC1332 is the first infrared source which has been shown conclusively to be due to an echo from pre-existing dust grains. So for the first time there is the opportunity of using observations coupled with echo theory to yield information about the source of primary radiation and the dust cloud and its constituent grains. Here we incorporate the basic property of any echo model i.e. we take account of the finite light travel time across the dust cloud, but our approach is to tailor the model to describe the conditions in supernova dust clouds, whilst retaining as much simplicity as possible. We therefore consider a spherically symmetric dust cloud centred on the supernova composed of spherical dust grains of a unique size and composition. We assume that the cloud is optically thin to its own infrared ($\lambda > 1\mu m$) radiation, and is static on timescales ~ few hundred days.

2.1 DUST GRAIN TEMPERATURE

If the supernova is surrounded by a dust cloud of sufficiently great extent, there will be a significant time delay t, due to the finite velocity of light, between observation of the optical photons which set out from the supernova directly towards the earth, and those photons which were absorbed and re-radiated into the infrared by a dust grain at (r, θ). This delay is given by

$$t = (r/c)(1 - \cos\theta). \qquad (1)$$

See Figure 1 for an illustration of the coordinates used.

If a distant observer sets his clock, which reads t_0, to 0, when he sees the leading edge of the UV-optical light pulse, then grains at (r, θ) whose IR emission is due to absorption of radiation from the leading edge of the pulse is not observed until $t_0 = t$. So the observed grains heated by the leading edge of the pulse lie on a paraboloidal surface of revolution

$$r = ct_0/(1-\cos\theta), \tag{2}$$

where the supernova is located at the focus of the paraboloid. The time t at which the observer first receives IR radiation from a particular paraboloidal surface, i.e. when it is first observed to be heated by the leading edge of the pulse, is a useful co-ordinate which we will use later to identify any paraboloid within the cloud.

The consequence of the time delay is that according to a distant observer the temperature of a dust grain within the cloud is not only a function of its distance from the supernova and the time since the supernova explosion was observed, but also a function of the angle which the radius vector from the supernova to the dust grain makes with the line of sight.

If the observed UV-optical luminosity at time t_0 is denoted as $L(t_0)$, then the simultaneously observed IR emission from paraboloid t is caused by absorption and re-radiation of the UV-optical energy corresponding to the earlier epoch $t_0 - t$ when the observed UV-optical luminosity was $L(t_0 - t)$. The temperature of dust grains, T_g, on the paraboloidal surface t, as observed at t_0 is given by the radiation balance equation

$$\frac{L(t_0-t)\, e^{-\tau*}}{4\pi r^2}\pi a^2\overline{Q}(a, T_{SN}) = 4\pi a^2\overline{Q}(a, T_g)\sigma T_g^4 \tag{3}$$

τ^* is the optical depth from the supernova to a grain located at paraboloid t at optical-ultraviolet wavelengths. a is the grain radius, $\overline{Q}(a, T)$ is the Planck average emissivity, T_{SN} is the colour temperature of the supernova, and σ is Stefan's constant.

2.2 THE EMERGENT FLUX

In order to work out the IR flux at the earth resulting from a particular temperature structure in the cloud, we divide it into infinitesimal paraboloidal shells and calculate the contribution to the flux from each shell. Assuming the cloud to be optically thin to its own IR radiation and neglecting scattered supernova light, we then integrate over all shells and so obtain the total IR specific flux from the cloud at any time t_0. The IR specific flux dF_ν from one paraboloidal shell is

$$dF_\nu = \int_{ct/2}^{R_2} n\, Q_a\, \pi B_\nu(T_g)\, \frac{4\pi a^2}{4\pi d^2}\, dV, \tag{4}$$

where the integral extends over the spatial extent of the paraboloid, i.e. from the vertex ($r = ct/2$) to the outer radius ($r = R_2$) of the dust shell. n is the grain number density, Q_a is the absorption efficiency, $B_\nu(T_g)$ is the Planck function and dV is an infinitesimal volume element of the shell. The distance to the supernova is d. In polar co-ordinates the above integral can be re-written as

$$dF_\nu = \frac{cdt}{d^2} \int_{ct/2}^{R_2} n\, \pi a^2\, Q_a B_\nu(T_g)\, 2\pi r dr \tag{5}$$

by using Equ. 1. The total specific flux $F_\nu(t_0)$ from the cloud at time t_0 is obtained by integrating over all the paraboloidal shells, i.e. by integrating over the coordinate t.

$$F_\nu(t_0) = \int_0^{t_0} dt \int_{ct/2}^{R_2} \frac{c}{d^2}\, n\, \pi a^2\, Q_a\, B(T_g)\, 2\pi r dr \tag{6}$$

The limit $t = 0$ corresponds to dust along the line of sight to the supernova, and $t = t_0$ corresponds to the outermost heated paraboloid from which radiation is received at time t_0.

With our limited knowledge about the nature, size and distribution of the grains in the cloud, it is not possible to uniquely determine the temperature within the cloud (Equ. 3) or the total flux (Equ. 6). In order to make a start we have to make reasonable assumptions about the structure of the dust cloud, the nature of its constituent grains, and of course the supernova.

We will show in the following sections that the only assumptions which we need to make are that we a) know the functional dependence of supernova luminosity upon time, b) the wavelength dependence of the grain absorption efficiency, and c) that a power law grain density distribution can describe the dust cloud. If we adopt these assumptions then it is possible to reproduce the observed IR light curves accurately in a self-consistent manner. We will also find the optical depth of the dust cloud, the ratio of peak supernova luminosity to grain absorption efficiency, the grain evaporation temperature, and also the index of the dust cloud power law density distribution. Finally, by assuming the optical absorption efficiency per grain we can find the grain radius, and, if the density of the solid material which composes the grains is known, the total mass of dust in the cloud.

3 THE ASSUMPTIONS

3.1 DUST GRAIN OPTICAL PROPERTIES

For the first stage of the echo analysis it is only necessary to decide upon the wavelength dependence of the absorption efficiency because at first we only want to reproduce the IR colours and the shape of the IR light curves. The absolute value of the efficiency per grain is not required until we need to calculate the mass of dust in the cloud. The infrared colours are of the SN equally well fitted by a black-body, or by emission from grains with typical absorption laws which vary as $1/\lambda$, or $1/\lambda^2$. Consequently it is not possible to determine the emission law directly. Indeed this approach would be misleading because we are not observing dust at a single temperature. We must choose a form of efficiency which will be appropriate for either carbon or oxygen rich grain compositions. An absorption efficiency which varies as $1/\lambda$ in the near infrared ($1 < \lambda < 3\mu m$) seems reasonable for both cases. The most likely grain type in a carbon rich environment, amorphous carbon, exhibits this behaviour (Koike *et al.* 1980). Crystalline carbon, graphite, although a favoured grain type for some time, seems unlikely to form in astrophysical environments (Donn *et al.* 1981). The amorphous allotrope is also favoured by long wavelength IRAS observations of dusty carbon stars (Rowan-Robinson 1984). If the grain composition was oxygen rich, and consequently of a silicate type, then our choice of the near infrared wavelength dependence of Q_a would be the same. The type of silicate material which is thought to be found in astrophysical environments – dirty silicates (Jones and Merrill, 1976) – also have an absorption efficiency which varies as $1/\lambda$ in the wavelength interval 1–7 μm. The efficiency of these grains is high and comparable to that measured for amorphous carbon (Koike *et al.* 1980). In the range of temperatures of interest 800–1000 K; the temperature range which characterizes our observations, most of the grain radiation is emitted in the interval where $Q_a \propto 1/\lambda$ and so we expect that $\overline{Q} \propto T$ will be a good approximation. We have calculated Planck averaged emissivities for the dirty silicates of Jones and Merrill (1976), and the emissivity is proportional to T in the range $700 < T < 1000$ K, and the corresponding Planck average emissivity for amorphous carbon is given by $\overline{Q} \propto T$ as long as $T < 1000$ K (Draine, 1981).

When we need to know the absolute value of the absorption efficiency of an individual grain so that we can calculate the mass of dust we will use the optical properties of amorphous carbon, which have been measured by Koike *et al.* (1980), to typify all grain materials. We approximate their results for $1 < \lambda < 100\,\mu m$ for grains formed by burning xylene in air by $Q_a/a = 2.5/\lambda$. For the sake of simplicity we will assume that grains will absorb the radiation from the supernova efficiently, so that in the UV and optical $Q_a = 1$, and $\overline{Q}(T_{SN}) = 1$.

3.2 The Dust Grain Distribution

Only power-law grain distributions of the form $n \propto r^{\beta}$ will be considered. This choice covers most of the plausible possibilities, e.g., $\beta = 0$, represents a uniform grain distribution as might be expected if the supernova were embedded in a dusty ambient medium, or $\beta = -2$ if the grain distribution results from grain condensation in a stellar wind of constant $\dot{M}/V_{wind}$. The cloud is also chosen to have sharp inner and outer edges.

A grain with a sublimation temperature $\sim$ 1000 K will be destroyed out to distances of about 50 light days from the supernova. As grain condensation in winds is expected to occur within a few tens of stellar radii then the closest distance at which we will find dust depends upon whether or not pre-existing dust there has been destroyed. Survival of a particular type of grain depends upon the maximum grain temperature reached due to the supernova radiation field which, in turn, for a particular grain type, depends only upon its distance from the supernova. As the supernova radiation propagates outward into the dust cloud it will continue to evaporate dust until the radiation becomes so dilute that it can no longer raise grains above their evaporation temperature. Ignoring partially evaporated grains, we can define an evaporation temperature T_{evap}. Grains heated above T_{evap} are completely destroyed, but grains which do not exceed this temperature survive intact. T_{evap} corresponds to a radius R_{evap} (Equ. 3) within which grains are heated to destruction. From the observers viewpoint while $t_o < 2R_{evap}/c$ an evaporation wave propagates outward into the dust cloud creating a dust free cavity, leaving the radiating dust observed at the Earth contained between the outermost paraboloid ($t = t_0$) and the cavity – see Figure 2.

Grain destruction is almost instantaneous. The heating timescale $U/\dot{U} \sim 0.01s$ so the evaporation wave is very thin and contains only a very small mass of dust at any instant (Falk & Scalo 1975). The resultant infrared radiation from evaporating grains is therefore negligible.

The size of the cloud outer radius, R_2, determines the late time evolution of the IR light curve. Once the vertex of the outermost paraboloid passes beyond the edge of the cloud the flux falls rapidly. Initially we will assume that R_2 is practically infinite, i.e. $R_2 >> ct_0/2$ so that the dust at the outer edge of the cloud is cold, and makes no significant contribution to the flux. Then by examining the fit of the model to the late time data we will be able to test this assumption.

3.3 THE BOLOMETRIC LIGHT CURVE

The infrared radiation from a SN dust cloud depends on the input light curve, but the bolometric light curves of SNI's and SNII's are remarkably similar. The bolometric light curve can be characterized by a very rapid rise to maximum. The initial decline of the luminosity of a type I event has an e-folding time of ~ 20 days, and lasts about 50 days. This is followed by a final decline with an e-folding time of about 70 days (see following paragraph). The luminosity of a type II supernova shows an initial spike, and then it declines with an e-folding time of 40-50 days (Weaver and Woosley 1980) In either case most of the energy is radiated in the first 20-30 days. It is this highly peaked outburst combined with the echo geometry and the grain density distribution that primarily determines the development of the emergent infrared radiation.

As was argued in Paper I it is almost certain that SN 1982e was a type I event. This follows from: a) The early parent galaxy type (SO) – no type II has ever been observed in a galaxy of type SA or earlier (Kowal 1984), b) The large distance ($\sim$ 20 kpc for $H_0 = 75$ km/s/Mpc) of the supernova from the nucleus – well away from any region of recent star formation where the massive progenitors of type II SN are thought to be born (Maza and van den Bergh 1976). SNI optical light curves show a remarkably small scatter in peak brightness and evolution (Barbon *et al.* 1973). We can therefore use the bolometric light curve of other, better observed SNI's. We use the bolometric light curve of SN 1972*e* (Axelrod 1980). A least squares double exponential fit to the data gives

$$L = L_0 \begin{cases} 1.0e^{-t/22.8} & 0<t<54 \\ 0.181e^{-t/73.5} & t>54 \end{cases} \tag{7}$$

with t in days. Arnett *et al.* (1985) find that the best value for L_0 derived from a carefully selected sample of SNI that $L_0 = (0.9 \pm 0.2) \times 10^{43} (H_0/75kms^{-1}/\mathrm{Mpc})^{-2}$ erg/s

3.4 THE NATURE OF THE OBSERVED FLUX

We will assume that all the observed flux is due to thermal radiation from pre–existing dust which is heated by the SN. Comparison of the IR light curves of 82e and other type I's which have not developed an IR excess suggests the possibility that the SN itself makes a contribution to the flux observed on day 101. However this figure is sensitive to the distance and explosion date assumed. At J we estimate $\approx$ 20% could be due to the SN, with this figure falling at longer wavelengths.

Until we have early time IR data correcting for the photospheric contribution cannot be done sufficiently accurately to justify the procedure.

4 COMPARISON OF THE MODEL WITH THE DATA

Equations 3 and 6 are now combined to enable the calculation of the flux and colour evolution. To do this we adopt the emissivity wavelength dependence, the grain distribution, and the bolometric light curve described above. In order that the most important parameters in the problem can be identified, a few approximations will be made, and the integral will be re-expressed using substitutions. Our observations are made on the Wien slope. The hottest dust is at about 1200K, and the longest wavelength is $2.2\mu m$ so that we always have $h\nu/kT \geq 5.5$, so an error of only a few percent is introduced if the Wien approximation to the Planck function is used. The temporal dependence of grain temperature of SN 1982*e* demonstrated in Paper I requires that the dust cloud be optically thin to the radiation from the SN. We will assume that this is in fact true, but will show that this can be justified in a self-consistent manner.

If we parameterize the optical properties in the following dimensionless form

$$Q_a = Q_0(\nu/\nu_0)^\alpha, \tag{8}$$

and the dust grain number density is

$$n = n_0\,(r/r_0)^\beta, \tag{9}$$

then the specific flux at Earth is given by

$$F_\nu(t_0) = \frac{c}{d^2}\int_0^{t_0} dt \int_{R_1}^{R_2} \pi a^2\, Q_0(\nu/\nu_0)^\alpha\, \frac{2h\nu^3}{c^2}\, e^{-\frac{h\nu}{kT_g}}\, n_0\,(r/r_0)^\beta\, 2\pi r dr, \tag{10}$$

with $R_1 = ct/2$ or R_{evap}, whichever is the greater, and where

$$T_g(t_0,t,r) \; = \left[\frac{\pi^3\, L(t_0-t)\,(h\nu_0/k)^\alpha}{240\Gamma(4+\alpha)\,\varsigma(4+\alpha)\,Q_0\,\sigma\, r^2}\right]^{1/(4+\alpha)} . \tag{11}$$

Γ and ς are the gamma and Riemann zeta functions respectively. If we set $r = ct/2$ then $T_g(t_0, t, ct/2)$ is the observed grain temperature at the vertex of parabola t at t_0. This suggests a substitution which will combine all the unknowns which determine the temperature in the dust cloud into one function. If $q_\nu = (h\nu/kT_v)$ where $T_v{=}T_g(t_0,t,ct/2)$ is the temperature of dust grains at the vertex of parabola t, and $x = r/r_v$, where r_v is the vertex distance $ct/2$ of parabola t, then

$$F_\nu(t_0) = \frac{2\pi^2\, a^2\, n_0\, Q_0\; 2h\nu^{3+\alpha} c^{\beta+1}}{d^2\; 2^{\beta+2}\; r_0^\beta\; \nu_0^\alpha} \int_0^{t_0} t^{\beta+2} dt \int_{x_1}^{x_2} e^{-q_\nu(t_0,t)\, x^{2/(4+\alpha)}}\; x^{\beta+1} dx \tag{12}$$

An inspection of Equ. 12 reveals that for known α , β, and cloud limits, the temporal evolution of an echo from an optically thin dust cloud depends only upon $q_\nu(t_0,t)$. This function determines the dust temperature at every vertex point in the dust cloud, and is the key to untangling the IR light curves, and deducing the nature of the dust cloud. $q_\nu(t_0,t)$ contains information about the SN luminosity, its time dependence, and the absorption efficiency of the dust. As a first step towards extracting the dust cloud parametrs from the IR data, we consider the colour evolution. We note that the time dependence, if not the absolute value, of L is rather well known. Therefore, if we are prepared to assume cloud limits, and values of α and β, then, using observations at different wavelengths, we can solve for the combination of unknowns $L_0\nu_0^\alpha/Q_0$ as follows. If the specific flux at two different frequencies ν_i and ν_j are F_i, and F_j respectively, then the specific flux ratio can be written as

$$\frac{F_i}{F_j} = (\nu_i/\nu_j)^{3+\alpha}\; \frac{\int_0^{t_0} t^{\beta+2} dt \int_{x_1}^{x_2} e^{-q_i(t_0,t) x^{2/(4+\alpha)}}\, x^{\beta+1} dx}{\int_0^{t_0} t^{\beta+2} dt \int_{x_1}^{x_2} e^{-q_j(t_0,t) x^{2/(4+\alpha)}}\, x^{\beta+1} dx} \quad . \tag{13}$$

where $q_i = (\nu_i/\nu_j)q_j$, and

$$q_{\nu}(t_0, t) = \frac{h\nu}{k} \left[\frac{\pi^3 L(t_0 - t)(h\nu_0/k)^{\alpha}(2/ct)^2}{240\Gamma(4+\alpha)\,\varsigma(4+\alpha)\sigma Q_0} \right]^{-1/(4+\alpha)} \tag{14}$$

As we know the explicit time dependence of q_{ν} we can solve Equ. 13 for $L_0\nu_0^{\alpha}/Q_0$, and hence T_v^0, the temperature of dust grains at the vertex of the outermost parabola, can be found from our observations of SN 1982*e*. Equation 13 was solved iteratively by evaluating the double integral using the trapezoidal rule on Romberg's principle.

4.1 DETERMINATION VERTEX TEMPERATURES AND CLOUD STRUCTURE

If it can be demonstrated that $L_0\nu_0^{\alpha}/Q_0$ can be determined independently of the dust grain distribution, and so T_v^0 has been found in a self-consistent manner then we can test whether or not the fall in dust temperature is due only to geometric dilution of radiation from the supernova. Any deviation from the predicted behaviour could be due to the break down of one or both of the assumptions so that the optical depth to the SN radiation is not small, and the radiation is attenuated, or that the optical properties of the dust are not uniform throughout the cloud. However, if we are successful in showing that the change in dust temperature with time is consistent with the echo hypothesis, then we can present a rigorous form of the speed of light argument of Paper I.

We should recall at this stage why simple arguments were successful in demonstrating the presence of a light echo. In Paper I it was shown that the observed IR colour temperature $\propto t_0^{-2/5}$; the behaviour expected of T_v^0. This is because most of the radiation actually comes from the region around the vertex of the outermost paraboloid. This is where the combination of the pulse-like light curve and the echo geometry conspires to locate the hottest dust. We are observing at short wavelengths on the Wien slope, so that the contribution from dust which is anywhere else, and consequently cooler, is insignificant. The corollary of this is that we expect that the emergent near IR spectrum depends only upon the SN luminosity, the grain efficiency, and the time since the explosion. As far as the IR colours, and their time evolution are concerned, we expect that the global distribution of dust is unimportant because the IR emission arises only from a localized patch within the cloud. When Equ. 13 is solved for T_v^0 this expectation is confirmed. Using the bolometric light curve discussed above, the grain absorption efficiency given by $\alpha = 1$, and $x_{evap} << 1$, and $x_2 >> 1$, then the values of T_v^0 for $\beta = -1$ and -2 differ by less than 1%. Having determined $L_0 \nu_0^\alpha / Q_0$ and hence $q_\nu(t_0, t)$ we are in a position to use Equ. 12 together with the observed shapes of the IR light curve to determine the form of the grain distribution.

The assumption that the cloud is very large compared to $ct_0/2$ is fairly reasonable, but postulating that the inner radius is small is questionable. Dust grains can be destroyed out to $\sim$ 50 light days from the SN. However, if $L_0 \, \nu_0^\alpha / Q_0$ is known even approximately then R_{evap} can be found because the echo reaches maximum luminosity at $t_0 \approx 2R_{evap}/c$, which is about 100 days after the explosion, an epoch well covered by the IR light curves. By adjusting R_{evap} it should be possible to fit the early part of the IR light curves. Figure 3 shows the light curves calculated for models with different cloud limits, so that the effect on the shape of the light curve of changing these parameters can be illustrated. Fitting the data with the model and minimizing the residuals by eye yields $R_{evap} = 1.30 \pm 0.07 \times 10^{17}$ cm for $\beta = -2$, and 1.23×10^{17} cm with a similar uncertainty when $\beta = -1$. With a value of R_{evap} established $L_0 \nu_0^\alpha / Q_0$ was re-evaluated, and the temperatures thus derived changed by $< 0.5\%$, demonstrating, once again, the insensitivity of $L_0 \nu_0^\alpha / Q_0$ to the cloud structure and hence the correctness of our approach. We note one very important fact. The time evolution of the JHK fluxes for $t_0 > 127$ days (i.e. all but the first two points) is well fitted by the model in its simplest form; i.e. assuming $R_{evap} << ct_0/2 << R_2$, $Q \propto 1/\lambda$, and the exponential light curve *if the grain density distribution is given by* $\beta = -2$. In contrast, a flatter or steeper density law does not fit the late points at all well. Figure 4 illustrates the difference between the evolution of the IR echo from dust clouds with $1/r$ and $1/r^2$ distributions. Given that $\beta = -2$ would have been a plausible a priori choice it would seem most reasonable to deduce that the dust density does indeed follow an inverse square law. Adjusting R_{evap} in the manner outlined above allows the model to fit the first two observational points, yet setting R_{evap} to its optimum value does not prejudice the quality of the fit at later times. Finally, reducing the outer cloud limit only worsens the fit to the last observations. On this basis a lower limit, $R_2 > 5.0 \times 10^{17} cm (1\sigma)$, can be set on the outer cloud radius.

We have found a self-consistent scheme for determining the temperatures, and distribution of dust within the cloud. With this knowledge, we can adjust the optical depth of the model, and compare the observed and predicted fluxes, checking the assumption of low optical depth. With a knowledge of the absorption efficiency per unit mass we can express this optical depth in terms of a dust mass, and grain number density.

4.2 OPTICAL DEPTH OF THE CLOUD

The flux from the dust cloud described above was calculated and the optical depth required to reproduce the observed fluxes from SN 1982e was found to be $\tau^* = 0.15$, independent of Hubble's constant. To check the accuracy of the optically thin approximation all the dust cloud parameters determined with the optically thin model were included in a re-calculation of the flux in which the attenuating effect of the dust was treated, and the Wien law was replaced by the Planck function. This accurate calculation produced IR light curves which are almost identical to the results of the approximate model. This calculation and the IR data are compared in Figure 5. The only significant difference was that the flux generated at late times was a little lower than the flux predicted by the optically thin approximation, with the result that the fit to the last two observations was enhanced. So the total optical depth of the cloud calculated from the full model is the same as yielded by the approximation.

The grain temperatures at the vertex of the outermost paraboloid found by solving Equ. 13 for $L_0\ \nu_0^{\alpha}/Q_0$ using the dust cloud described above (i.e. $\alpha = 1$, $\beta = -2$, $R_{evap} = 1.3 \times 10^{17} cm$, and $R_2 = 5.0 \times 10^{17} cm$) are shown in Table 1. These temperatures can be used in the speed of light argument of Paper I to identify an echo. According to Equ. 3, $T_v^{o\,-5/2}$ plotted against time should be a straight line intercepting the origin. Figure 6 shows this graph and demonstrates the high degree of linearity.

5 DERIVED DUST CLOUD PROPERTIES

During the process of fitting the IR observations our assumptions have been justified, and the values of several vital parameters have been determined. Although these quantities have particular relevance to our interpretation of the IR emission of SN 1982*e* as an echo, they can be used to provide key astrophysical insight to the SN dust cloud and its constituent grains. Of particular interest is the quantity $L_0 \nu_0^a / Q_0$. For $L_0 = (0.9 \pm 0.2) \times 10^{43} (H_0/75 \text{ kms}^{-1}/\text{Mpc})^{-2}$ erg/s, and carbon grains with $Q_a = 2.5a/\lambda$ the grain radius $a = (0.07 \pm 0.02)$ $(H_0/75\text{kms}^{-1}/\text{Mpc})^{-2}$ μm. The evaporation temperature can be found from the evaporation radius and $L_0 \nu_0^a / Q_0$, independently of the distance. R_{evap} corresponds to $T_{evap} = 1320 \ \pm 30K$, a temperature which is more representative of oxygen rather than carbon rich refractory condensates, and is in fact the sublimation temperature of magnesium silicate (Salpeter 1974). This identification should be treated with some caution because, in novae, where the condensate is thought to be carbon derived sublimation temperatures vary between 1300-2000 K from nova to nova (Bode & Evans 1983). A further note of caution should also be added. Some models of type II supernovae predict that there will be a burst of UV and soft x-rays when the shock driven by core collapse breaks through the photosphere (Colgate 1975). If the peak luminosity of this burst is sufficiently high then the evaporation radius will be determined by this radiation, and the evaporation temperature which is derived by assuming that the grains are destroyed by the light curve described by Equ. 7 will be incorrect. As we derive a plausible value for the evaporation temperature we find no evidnce for such a precursor.

The extent and optical depth of the dust cloud has been found. Dust with the properties of amorphous carbon grains ($\rho = 2.0 g/cm^3$) is distributed according to an inverse square law, so that the cloud can be described by

$$\rho_{dust} \approx 5 \times 10^{-23}(r/10^{17}cm)^{-2}(H_0/75 \text{ km/s/Mpc})^{-2} \text{ g cm}^{-3} \tag{15}$$

which when integrated between the cloud limits gives a total mass of dust

$$M_{dust} \approx 0.001(H_0/75 \text{ km/s/Mpc})^{-2}M_{\odot} \tag{16}$$

The parameters for the model dust cloud are summarized in Table 2. It would seem extremely unlikely that the dust cloud is part of the local interstellar medium. The dust distribution follows an inverse square law with the SN at its centre, and the density of dust is also high, presumably implying a high gas density. For a gas to dust ratio by mass of 100, the hydrogen number density is ≈ 2800 cm^{-3} at 10^{17} cm from the SN, which is more typical of a molecular cloud than the ISM expected in the halo of an early galaxy. Furthermore, the possibility that NGC 1332 is a hydrogen rich early type galaxy is ruled out by 21 cm HI measurement (P. Appleton, private communication) which imply $M_{HI} < 1.3 \times 10^8 M\odot$ $(3\sigma, H_0 = 75 \text{ kms}^{-1}/\text{Mpc})$. For a uniform distribution out to 20 kpc this gives $n_{HI} < 2 \times 10^{-4}cm^{-3}$. The dust cloud was almost certainly produced by the pre-SN star during a phase of dusty mass loss.

5.1 ALTERNATIVE DUST DISTRIBUTIONS

We mentioned earlier that it is possible to reproduce the light curves by assuming a different dust distribution and adjusting the dimensions of the dust cloud. For the purpose of illustration we will use a $1/r$ density distribution of dust. Unlike an inverse square law cloud the infrared light curves predicted by a $1/r$ cloud cannot fit the light curves unless *both* R_2 and R_{evap} are specially chosen. As before, adjusting R_{evap} allows fitting of the early points. The resultant R_{evap} is not significantly different from that for the inverse square distribution. If the $1/r$ cloud is truncated by imposing an outer radius upon it, it is possible to reduce the flux at times $t_0 > 2R_2/c$, until the latter part off the K light curve (which extends to the latest epoch) is reproduced by the model. However, justification of this drastic cut-off is difficult. The flux drops very rapidly after time $t_2 = 2R_2/c$ as the echo runs out of dust. Observations of a continued rapid decline after t_2 would be required to fully justify imposing this outer radius. The parameters in Table 2 describe the $1/r$ model which best reproduces the light curves. Despite the fact that the dust distribution has been changed substantially the derived dust mass has changed much less than the factor which any distance uncertainty would introduce.

6 DISCUSSION

6.1 Dust Condensation

The undoubted conclusion of the preceding section is that the IR emission from SN 1982*e* was due to dust grains which formed long before the explosion. These dust grains are found at distances >50 light days from the SN, and are heated by radiation which left the SN during its most luminous phase.

As yet no evidence has been found for dust condensing in supernovae. One of the principal pieces of evidence adduced to support the hypothesis that dust condenses in nova ejecta is the observation of the simultaneous rapid rise and fall of the IR and optical fluxes respectively (e.g. Ney and Hatfield 1978). This behaviour is interpreted as being due to dust forming in the ejecta above the photosphere, absorbing optical radiation and re-radiating it in the IR. Should dust condensation be expected in a SN? Novae and SN are quite different systems. While expansion velocities are comparable, the luminosity of a nova is only $\sim 10^{-4}$ of that of a SN at maximum (Bath and Shaviv 1976), and the nova photosphere is some 100 times smaller. Nova ejecta also suffer severe adiabatic losses because the material expands from an originally compact configuration, whereas a SNII is thought to originate from an explosion within a red supergiant, with an initial radius $\sim 10^{14}$cm and consequently is much less affected by adiabatic cooling. A SNI ejecta contains decaying radioactive nuclides (Colgate and McKee 1969) which supply a continuing source of energy. Thus in either case high temperatures ($> 10^3$K) are maintained for $\sim 10^3$ days. All these factors will conspire so that dust condensation in SN must lag behind condensation in novae. The presence of non-thermal particles (gamma rays and relativistic positrons) in a SNI complicate any consideration of condensation so the following discussion will be confined to SNII. When numerical models of SNII are calculated they are found to be in good agreement with observations (Falk and Arnett 1977). Therefore these models can probably be used to predict the conditions in the ejecta. In their model only a small fraction of the hydrogen rich envelope cools below 2000K before 200 days. Therefore, condensation can only occur before this date, if, as in novae, the expansion can carry material sufficiently far above the photosphere so that radiative heating does not destroy any grains which do form. In a nova ($L \approx 5 \times 10^{38} erg/s$) after only 30 days the expansion has carried the ejecta far enough away so that dust grains can survive, i.e. Tg<2000K. Similar consideration for a SNII (based on the extensive bolometric light curve of SNII 1969*l*, Weaver and Woosley; 1980) indicates that dust cannot condense until after 200 days.

It is therefore not surprising that the dust seen in SN 1982*e* has been attributed to a pre-existing shell in view of the fact that the observations were made up to only day 272. However, it is conceivable that the dust seen in SN1979*c* and SN1980*k*, which were observed at much later epochs, might have condensed within the ejecta. The problem of identifying this dust would seem to be that of distinguishing it against a background of IR emission from pre-existing grains. Freshly condensed dust will presumably be most readily detectable when it has just condensed and is consequently at its hottest. When a pre-existing dust shell is present the way to discover condensing dust is to search for an additional hot component in the IR spectrum which emerges after ~200 days. Thus we must observe the onset of IR emission due to pre-existing dust, follow the IR light curves, and look for a departure from the echo cooling law. It will then be possible to determine whether or not subsequent observations made after ~200 days include an extra hot component. Dust producing such a component can only be hotter than pre-existing dust if it lies within the volume where the pre-existing grains were destroyed by the SN at maximum, and therefore a hot dust component constitutes evidence for condensation within the ejecta.

6.2 THE SUPERNOVA PROGENITOR

Mass loss is observed during many phases of stellar evolution. During the post-main sequence evolution of nearly all stars, a considerable fraction of the initial stellar mass is returned to the ISM. Many, if not all, late-type giant star winds are both cool and dense enough to form dust (Zuckerman 1980). It will therefore be difficult to unambiguously identify the SN progenitor solely from the presence of a circumstellar shell.

It is interesting to calculate the mass loss rate in steady state required to produce the observed dust distribution. For steady mass loss

$$\dot{M} = 4\pi r^2 \rho v, \tag{17}$$

where v is the wind velocity. Therefore knowing the density distribution from the echo the mass loss rate required is

$$\dot{M} \approx 0.9 \times 10^{-5}\ (a/0.01)^{-1}\ (v/10\ \mathrm{km/s})(H_0/75\ \ \mathrm{km/s/Mpc})^{-2}\ M_\odot/\mathrm{yr}. \tag{18}$$

a is the dust-to-gas ratio by mass. A value typical for the ISM has been inserted however, Werner *et al.* (1980) found that a varies between 0.018 and 0.004 in a sample of circumstellar dust shells. Winds from late type stars are typically $\sim$ 10km/s and so a mass loss rate $\sim 10^{-5} M \odot$ /yr is inferred. This is comparable to the rate inferred by Dwek (1983) for SN1979c and SN1980k. Mass loss rates of this order are observed from the most luminous K and M supergiants (Cassinelli 1975). The mass flows from sources with circumstellar molecular emission (e.g. OH or CO) involve some of the largest mass loss rates observed with M up to $10^{-4} M_\odot$/yr (Knapp *et al.*

1982).

6.2.1 LOW MASS STARS - EVOLUTION AND MASS LOSS

This SN arose from the old stellar population of an SO galaxy, and well away from the nucleus, far from any likely site of recent star formation. This requires that the star which produced the circumstellar shell was $\lesssim 1 M\odot$. This evolutionary constraint allows us to discard the massive supergiant stars as possible progenitors. However, the Mira/Long Period Variables are excellent prospective candidates, with masses which satisfy the age criterion.

The maximum mass loss from a Mira/Long Period Variable (an asymptotic giant branch [AGB] star on the Mira instability strip) as a first overtone pulsator is $\dot{M} = 7.6 \times 10^{-6} M \odot /\mathrm{yr}$ (Cahn and Wyatt 1978). This occurs when $M_{core} = 1.4 M\odot$. This is barely sufficient to produce the inferred circumstellar cloud. However, only stars much more massive than 1.4 M⊙ build up such large cores. Studies of white dwarfs (WD) suggest that the initial mass which leaves a such a massive WD is between 3-7 M⊙ (van den Heuvel 1975; Romanishin and Angel 1980). These stars are too massive to be the source of the wind. However, mass loss rates greatly in excess of the above limit are observed from lower mass AGB stars. These stars are obscured by optically thick dust shells, and are often associated with luminous molecular emission, hence the designation OH/IR star. Knapp *et al.* (1982) has observed molecular mass flows up to $10^{-4} M \odot /\mathrm{yr}$ from AGB CO sources. Werner estimates $\dot{M}$ to be between 5×10^{-6} and $7 \times 10^{-5} M \odot /\mathrm{yr}$ for OH/IR sources, which are either Mira type stars or M supergiants. But of special interest, Jones *et al.* (1983) found that there is a class of low luminosity OH/IR sources with $L < 10^4 L\odot$, with very long periods. The luminosity of these sources is very much less than an extrapolation of the Mira period-luminosity relation would imply, so it is suggested that these sources are fundamental mode pulsators $\sim 1 M\odot$ on the asymptotic giant branch. Jones *et al.* (1983) propose that at some stage of Mira evolution on the AGB the star switches to fundamental mode as the result of some unknown instability, and mass loss increases dramatically. The star develops a very massive circumstellar shell, an extreme IR excess is produced, and it becomes a radio luminous OH/IR source.

6.2.2 PRE-SUPERNOVA EVOLUTION AND THE DUST SHELL

We argue that the supernova dust cloud was produced by a low mass AGB star in the final stages of its evolution. The mass loss needed to produce the cloud requires that about $0.1 M_\odot$ of gas must be ejected from the star. Fundamental mode mass loss is so intense that the star will sustain a mass loss rate of $\sim 10^{-5} M_\odot$/yr until it completely ejects its envelope. The lifetime in the fundamental mode is $\sim 10^4$ years (Jones *et al.* 1983), leading to a cloud mass estimate which is comparable to that for the supernova cloud.

We call upon two more important facts to substantiate this proposition. Firstly we note that the SN dust cloud has been greatly modified by the SN explosion. We have demonstrated that dust is evaporated by the SN out to 1.3×10^{17} cm, but the outer cloud radius is $> 5 \times 10^{17}$ cm, implying that less than 25% of the cloud dust mass has been evaporated. However, dust close to the SN must have originally represented a significant opacity because of the inverse square density distribution. If we replace this evaporated dust we find that there was a very large optical depth, τ^*, through the pre-SN dust cloud.

$$\tau^* = 26[R_0^{-1} - R_2^{-1}] \tag{19}$$

where R_0 is the original inner cloud radius, and both radii are in units of 10^{15} cm. Unless R_0 was atypically large, i.e. $\gg 5 \times 10^{14}$cm (Jones and Merril, 1976), then the pre-SN would have been completely obscured.

It seems paradoxical that the progenitor of SN 1982*e* was probably obscured by a few tens of magnitudes yet the supernova was discovered optically. In fact, under most circumstances when the pre-SN is heavily obscured the SN will be visible. Grains near the SN evaporate before they have time to radiate a substantial amount of energy. Grain destruction does not represent a significant energy sink either (Falk & Scalo 1975), so only dust grains which are not destroyed attenuate the optical radiation. If the optical depth between R_{evap} and R_2 is small, i.e. $\tau^*(R_{evap}, R_2) \ll 1$, grains which survive the explosion will not significantly absorb or redden the primary SN radiation. This condition is satisfied by the dust cloud deduced in the previous section. In fact SN are so efficient at destroying dust that only an extremely massive star's dust cloud could present enough extinction to render it invisible. A dust cloud of similar structure to SN 1982*e*'s, but with a mass 100 times greater, $\approx 0.1 M\odot$, and presumably accompanied by $\approx 10 M\odot$ of circumstellar gas would provide about 10 magnitudes of extinction after the explosion.

Secondly, it is very tempting to point out that the fundamental mode pulsation lifetime is very short lived when compared to the timescales of most stages of stellar evolution, and that this phase immediately preceded the SN explosion. The possibility that the SN explosion and the switch to fundamental mode are causally connected must be investigated. The mass loss might be symptomatic of some instability which eventually disrupted the star. This would be a rather *ad hoc* postulate as possible mechanisms are unknown. The currently favoured models for SNI are based upon accreting WD's (see Wheeler, 1981). If the pre-SN system consisted of a WD and an evolved star in the process of ejecting its envelope, then the WD might accrete enough matter from this wind to exceed some critical mass $\sim$ Chandrasekhar mass. A WD above this limit may collapse violently to a neutron star and/or suffer degenerate thermonuclear ignition releasing sufficient energy to power a SN outburst.

6.2.3 STELLAR WIND ACCRETION IN A BINARY SYSTEM

We can check whether or not a WD could capture enough material from a stellar wind to drive it over the Chandrasehkar limit and thus trigger a supernova explosion. If the mass accretion rate is $\dot{m}_a$ then the efficiency of mass loss capture for a system of two stars of equal mass m in circular orbits of radius r with velocity v is

$$\dot{m}_a/\dot{M} \approx \frac{(Gm)^2}{4r^2v^4} \tag{20}$$

(Shapiro & Lightman, 1976). The accretion efficiency for 1M⊙ stars is

$$\dot{m}_a/\dot{M} \approx 0.4\, r_{14}^{-2}\ v_6^{-4} \tag{21}$$

where r_{14} and v_6 are the orbital radius in units of 10^{14} cm and the wind velocity in units of 10 km/s respectively. Therefore, it is not unreasonable to consider the SN progenitor as a binary system where the WD could intercept a substantial fraction of the mass lost by its companion. We might expect, given the mass loss rate derived at the beginning of this section, that the WD will grow at a rate of $10^{-5} - 10^{-6}\ M\odot$/year. More rapid growth of the dwarf is not possible because this is close to the Eddington limited accretion rate. For a WD this is $\dot{m}_a \sim 1.5\times10^{-5}\ M\odot$ /yr. And so even at the maximum accretion rate the brief period ($\sim 10^4$ years) of intense mass loss from the companion star must be thought of as only finally "tipping the scales". Under the circumstances where a WD is just less than the critical mass the ejection of its companion's envelope at the end of its evolution on the asymptotic giant branch could trigger a supernova explosion within a dusty shell. One might predict that dusty type I's should not be very common since rather special conditions must obtain to produce an IR excess. It is certainly clear from present data that not all SNI have dust clouds as massive as that around SN 1982*e*. One might suspect that dusty SNI occur in systems where the WD's companion is of a relatively low mass. The lower the mass of the companion, the lower the pre–OH/IR phase mass loss rate. Consequently a sufficiently low mass companion might evolve to the dusty OH/IR phase without triggering a SN explosion. On reaching the fundamental mode phase ejection of a massive dusty shell might provide enough material to drive the WD over the Chandrasekhar limit. Such supernovae may be more prevalent in low mass stellar populations. Whereas, for example, if the donor star were much more massive, and consequently losing mass at a greater rate for a longer period, a degenerate companion could accrete enough mass to explode before the giant has produced a substantial dusty envelope.

A possible objection to the above scenario is the characteristic lack of hydrogen in SNI spectra which might not be expected when the SN engulfs the hydrogen rich envelope of its companion. We do not know how to meet this objection, but note that Branch (cited by Sutherland & Wheeler, 1984) has pointed out that the lack of hydrogen in SNI spectra may not constrain severely the mass of hydrogen present if it is ejected at a single velocity in a restricted solid angle.

As a more general point it is very surprising that SNI, which appear so similar from event to event at optical wavelengths, should show such a profound variety of IR behaviour. SN 1982*e* (probably type I) and SN 1982*r* (confirmed type I) had strong IR excesses, but these SN were quite unlike type I's 1980*n*, 81*n*, and 81*d* (Elias *et al.* 1981) or the peculiar Type I's 1983*n* and 1984*l* (Meikle *et al.* in preparation), which showed no evidence for such a component. Does this mean that there are several types of SNI? This would seem difficult to accept given the optical homogeneity of SNI. It seems much more likely that all SNI are due to exploding WD's, and the different IR behaviour is due to various types of donor star. A good way to test such a hypothesis would be to study the variation of IR emission from SNI with morphological class of parent galaxy, and hence with stellar population. It may be that both high and low mass donor stars could cause a companion WD to explode, thus reconciling the current dispute regarding the origin of SNI.

7 CONCLUSIONS

We have:

1) Shown that the temperature evolution of infrared emission from SN 1982e follows the behaviour predicted by the echo model, and that the flux evolution can also be reproduced by a simple form of the model.

2) Determined the structure and optical depth of the dust cloud which gave rise to the infrared

echo from SN 1982*e*. By adopting a value for the optical efficiency of the dust grains we have been able to calculate the mass of the dust cloud.

3) Discussed the possibility of finding evidence for grain condensation in supernovae. Only observations which begin at the onset of infrared emission around day 100 and continue for several hundred days will be able to distinguish between an initial infrared echo and any subsequent emission from condensing dust.

4) Inferred that the progenitor system experienced a period of intense dusty mass loss before the supernova explosion. Any plausible hypothesis attempting to explain this which is consistent with the system being of low mass, requires that this mass loss phase must be due to the final stages of AGB star evolution. A white dwarf companion of such a star could accrete enough material from this wind to cause an explosion. Therefore the accreting white dwarf model for SN 1982*e* fits well.

5) Suggested that the difference between those type I supernovae which produce infrared echoes and those which do not can be explained by differences in the mass of the donor star in the progenitor's binary system.

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Day	T_v^0 (K)
101	1320 ± 30
127	1134 ± 20
191	990 ± 50

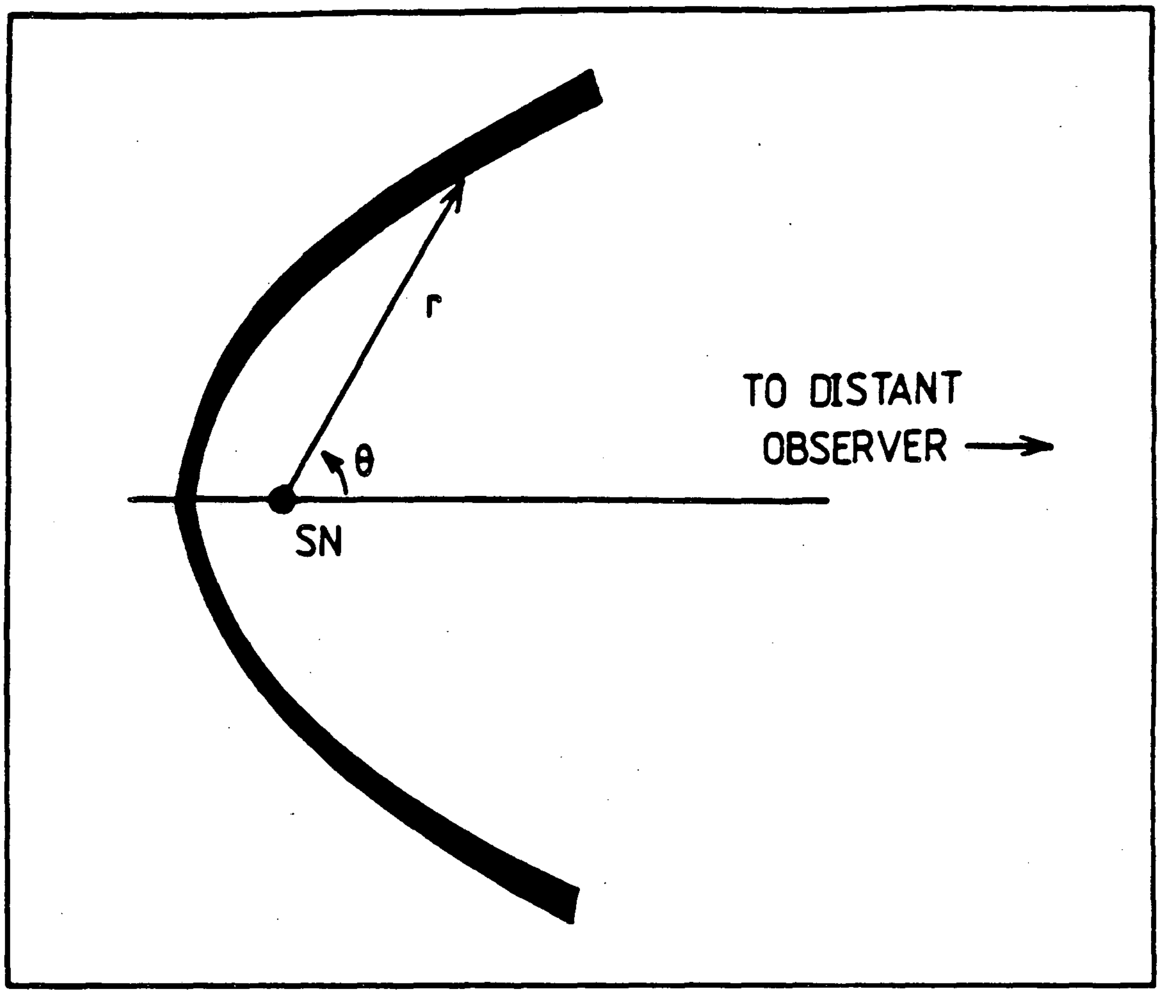
Table 1

The Evolution of Vertex Temperatures

Dust Distribution	τ^*	$R_{evap}(10^{17}cm)$	$R_2(10^{17}cm)$	$M_{dust}(M_\odot)H_0 = 75kms^{-1}/Mpc$
$1/r^2$	0.15	1.30	$> 5(1\sigma)$	1.1×10^{-3}
$1/r$	0.14	1.23	3.0	0.7×10^{-3}

Table 2

Dust Cloud Model Parameters.



XBL 859-3903

Figure 1: Dust cloud geometry; a paraboloidal shell of dust surrounding the SN is shown, and the cloud co-ordinate system is illustrated.

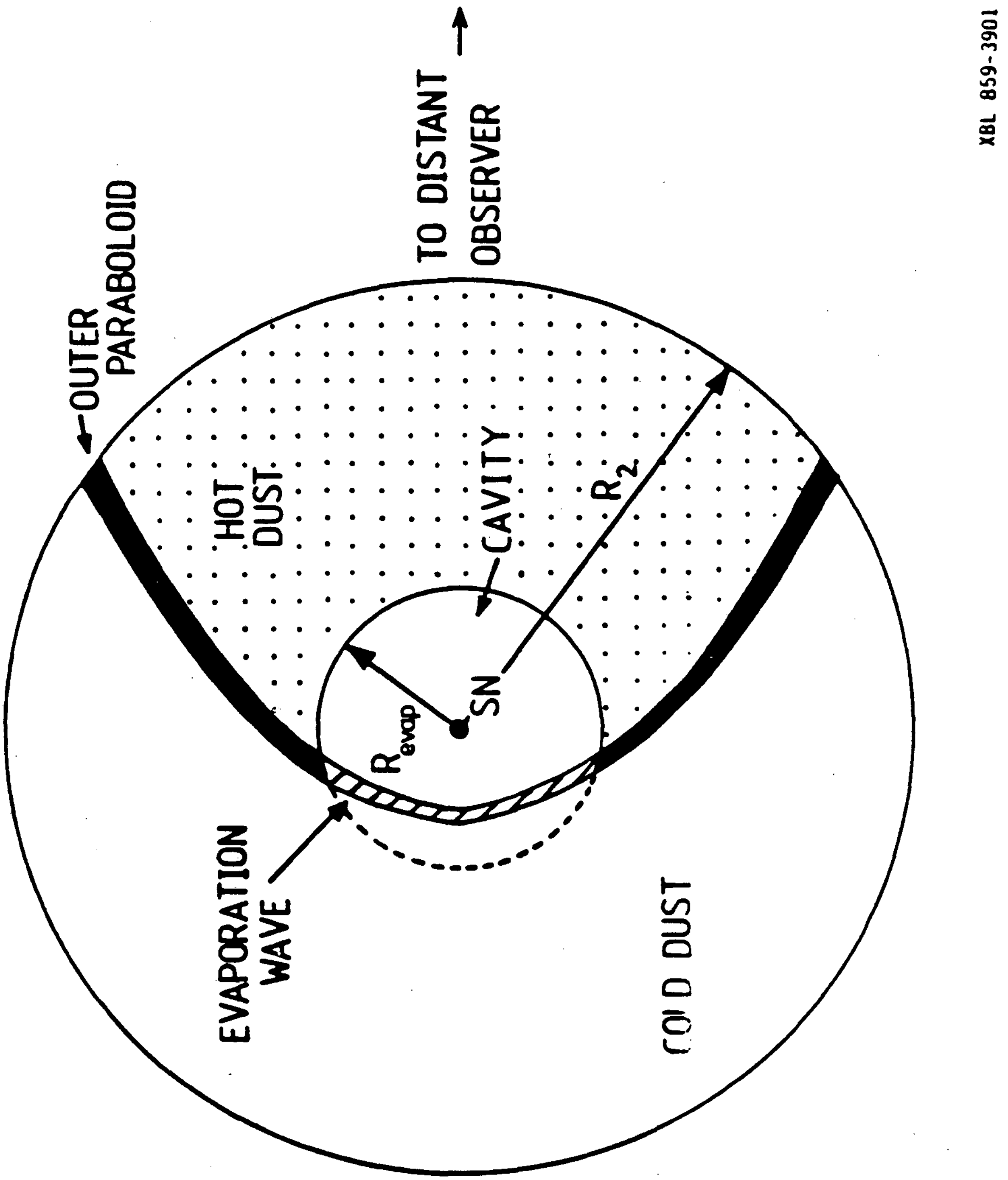
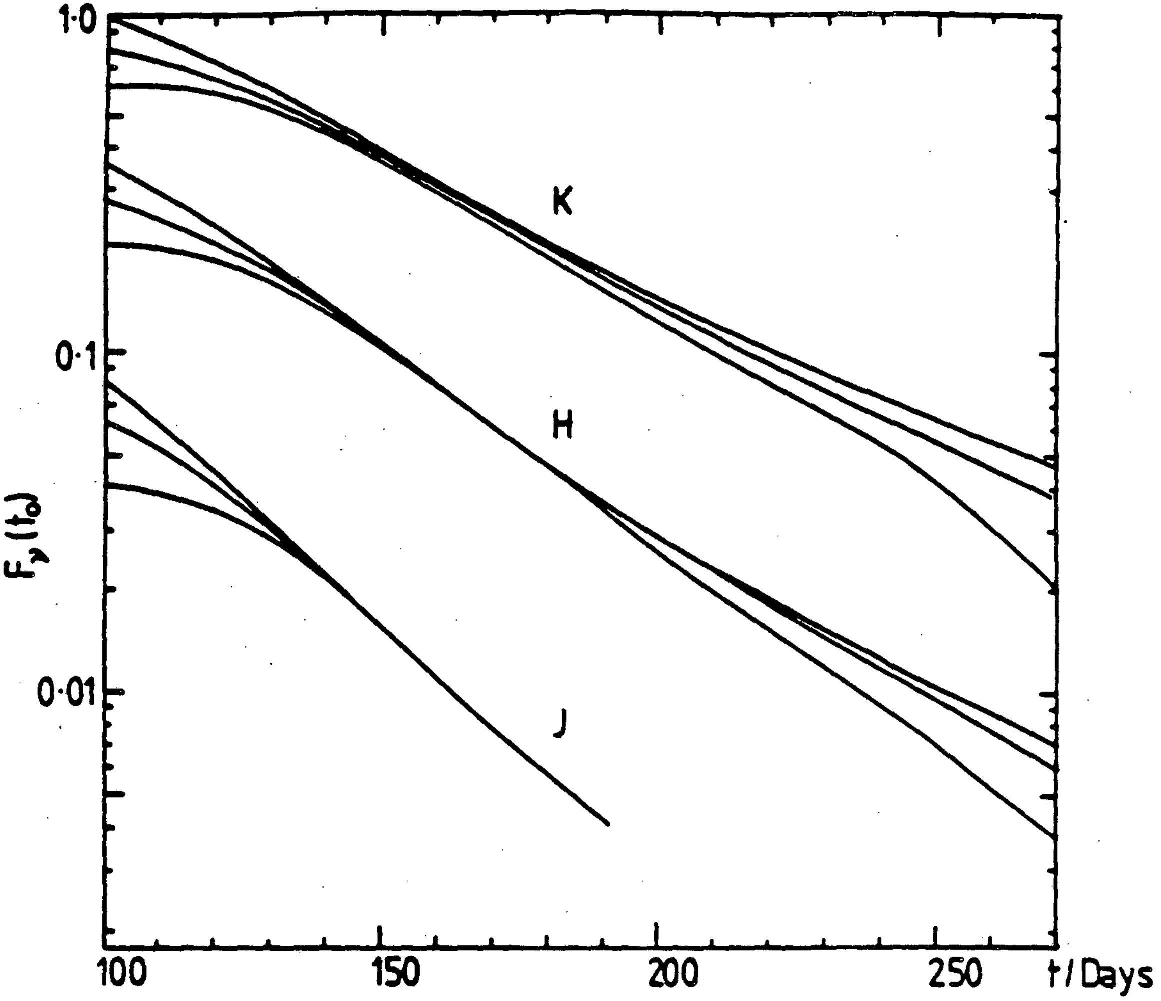


Figure 2: The SN dust cloud after the explosion. An evaporation wave (diagonal hatching) is illustrated in the process of creating a spherical dust free cavity around the SN radius R_{evap}. Dust heated by the SN is confined within the outermost paraboloid and the cloud limit R_2.



XBL 859-3904

Figure 3: An illustration of the IR echo (flux in arbitrary units) from a $1/r^2$ opticaly thin dust cloud with varying limits. The J, H, and K light curves for the following limits are shown. Top curve of the family R_{evap} = 90 l.d. (light days), R_2 = 230 l.d., middle curve R_{evap} = 100 l.d., R_2 = 190 l.d., and the bottom curve is R_{evap} = 110 l.d., R_2 = 150 l.d.. The other parameters are those adopted in the text.

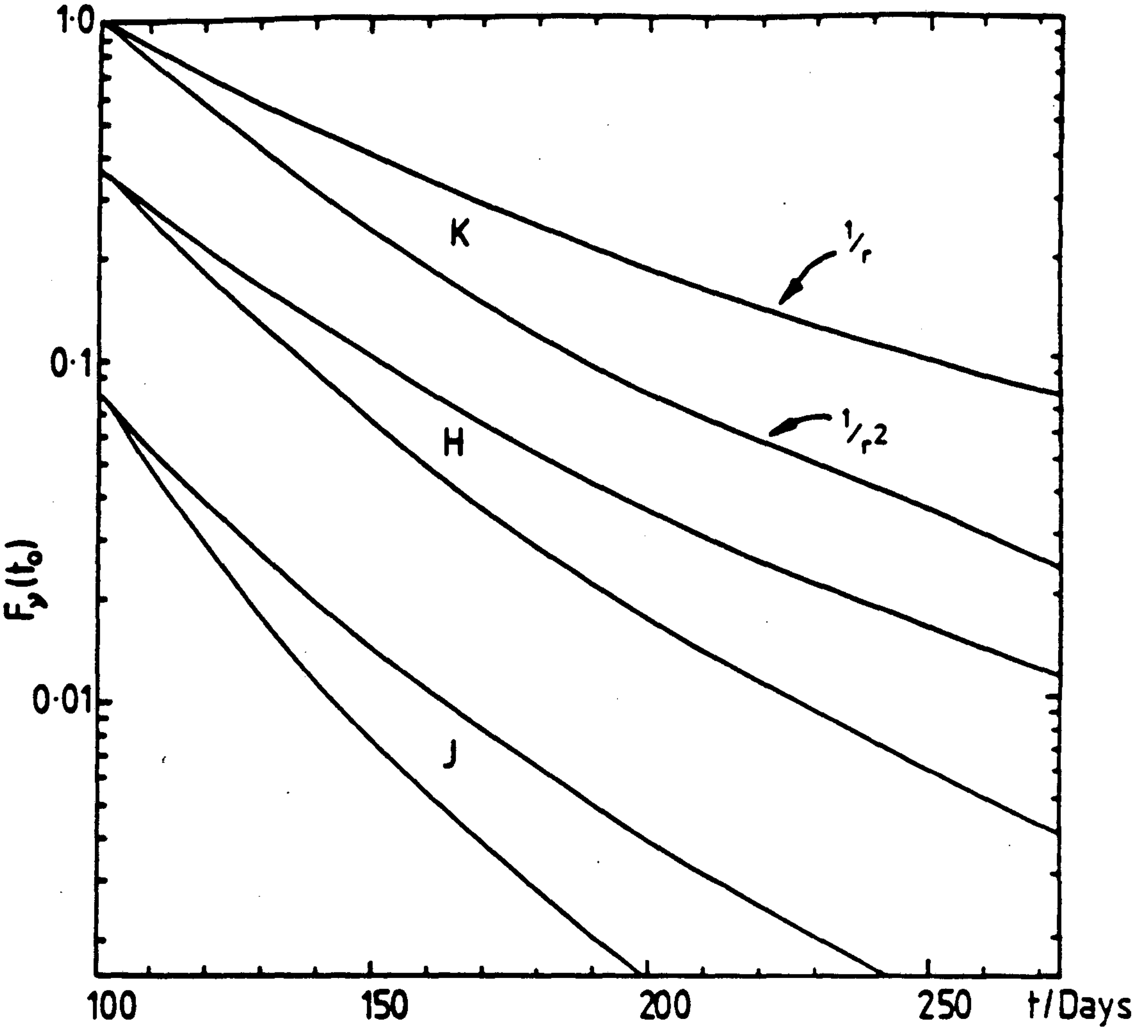


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Figure 4: An illustration of the development of the IR echo from optically thin dust clouds with different density distributions. The light curves for the three IR filters are shown. The upper light curve of the pair is the echo due to a $1/r$ distribution, and the lower curve is the echo from a $1/r^2$ law. The cloud limits are such that $R_{evap} << 2t_0/c << R_2$ at all times. The other parameters are those adopted in the text.

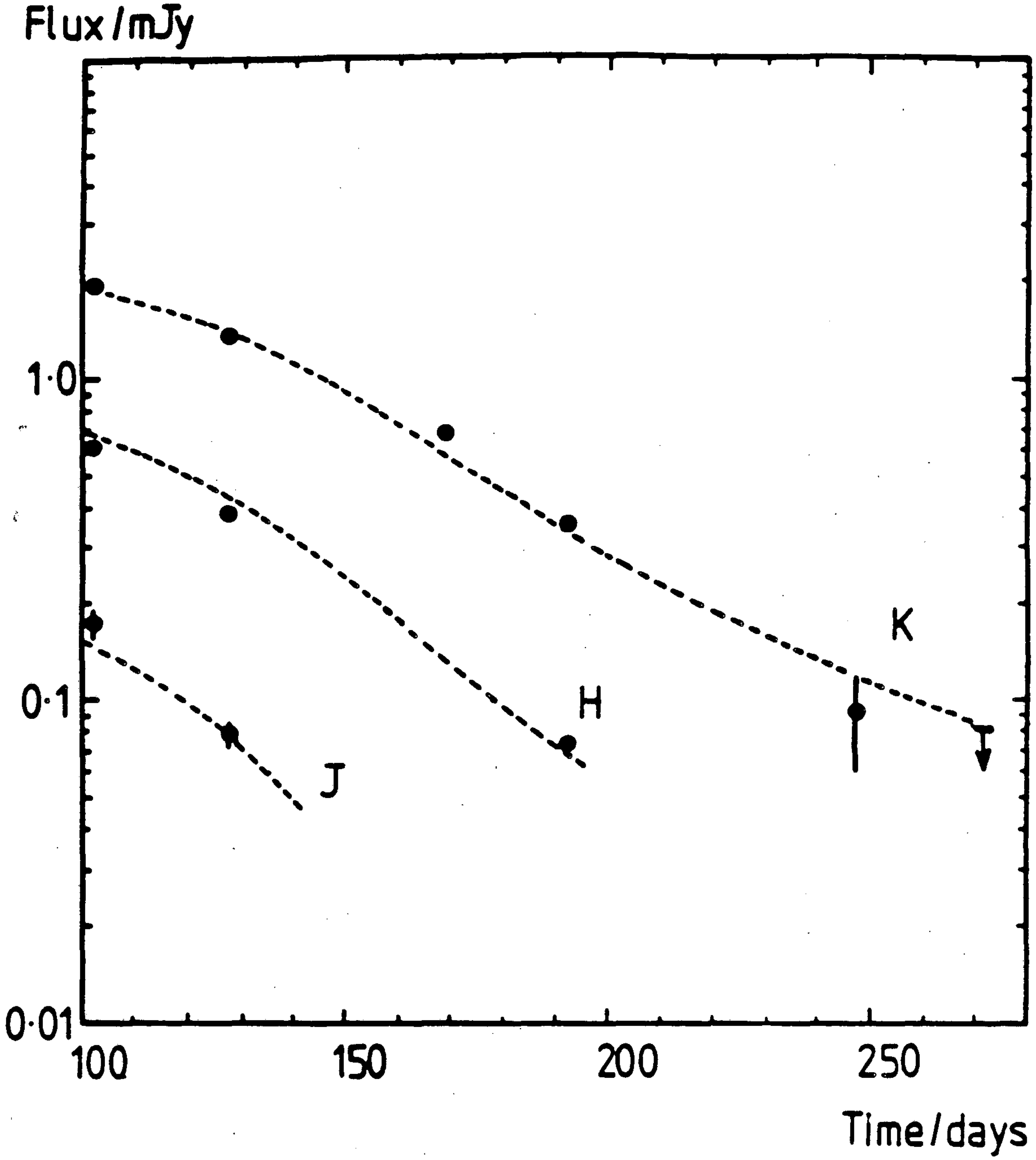

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Figure 5: A comparison of the IR observations of SN 1982e with the dust cloud model with the final derived parameters $\alpha = 1, \beta = -2, R_{evap} = 1.30 \times 10^{17}$ cm, $R_2 = 5.0 \times 10^{17}$cm, and $\tau^* = 0.15$.

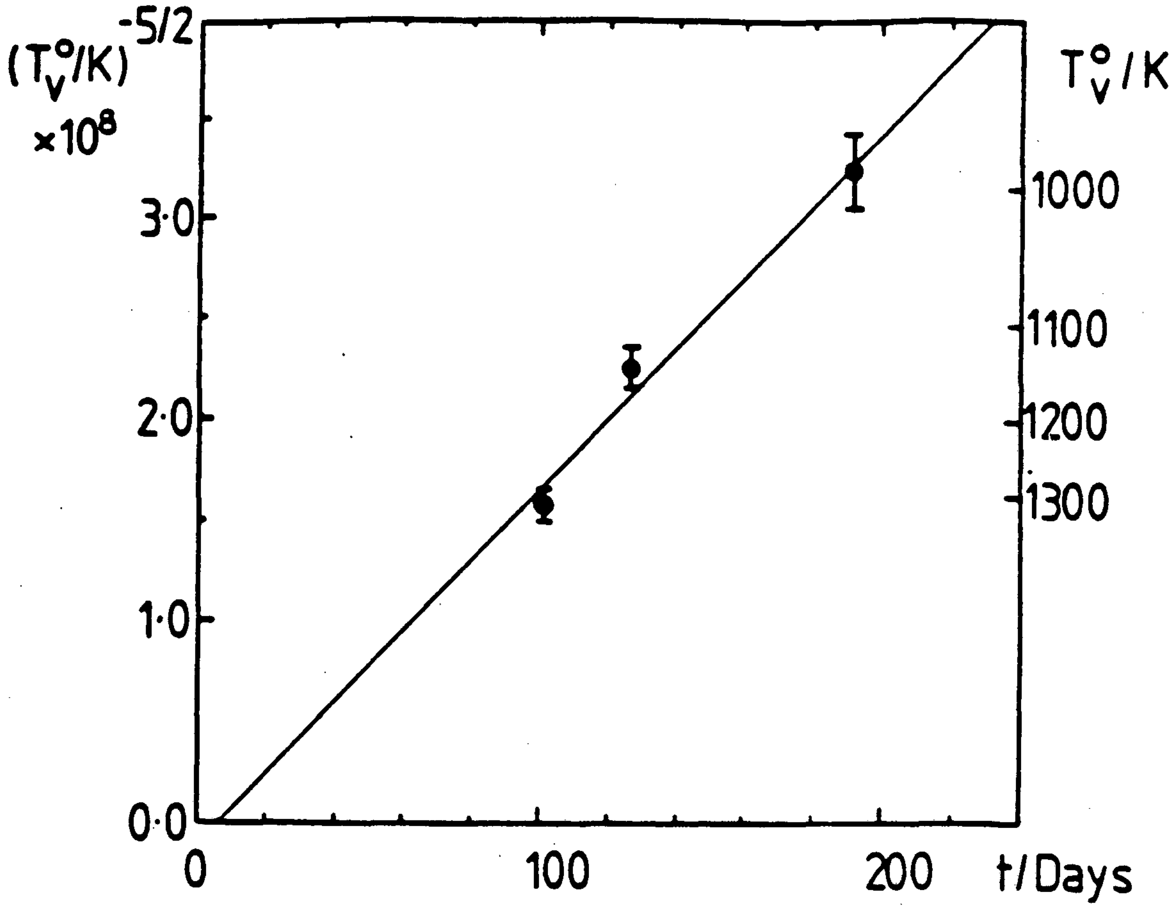

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Figure 6: The vertex temperature of the outermost paraboloid T_v^0, plotted against time. The solid line is the best fit straight line.

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