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ARE THERE DETECTABLE INFRARED ARCS AROUND SUPERNOVA 1987A?

ELI DWEK
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center
AND
JAMES E. FELTEN
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, and Aspen Center for Physics
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ABSTRACT

We examine the possibility that the recently discovered arcs of reflected light in the Large Magellanic Cloud around SN 1987A may be accompanied by detectable arcs of thermal infrared emission from dust heated by the ultraviolet-visual output of the supernova. Detectability depends on the ratio $\zeta \equiv Q_a/Q_s P$, where Q_a and Q_s are the visual absorption and scattering efficiencies of the dust, and P is the small-angle scattering phase function. Detectability by the University of Texas infrared photometer ($F_{\rm IR} \gtrsim 1.2$ Jy at 100 μm) requires $\zeta \gtrsim 1$, but the high brightness of the observed visual echoes implies $\zeta \lesssim 2$. We present calculations for spherical grains of graphite and silicate. A Mathis-Rumpl-Nordsieck distribution of grain sizes has an effective $\zeta \approx 0.1$. Some grain-size distributions more heavily weighted toward small grains, similar to but more extreme than those proposed for reflection nebulae and high-latitude cirrus clouds in the Galaxy, have values of $\zeta \approx 1$–2. With current instrumentation, the flux is below or at best close to the detection limit. However, the echoes will remain accessible for many years, and future infrared, visible, and ultraviolet observations will provide more detailed information about the dust properties.

Subject headings: interstellar: grains — nebulae: general — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION

Recalling Nova Persei 1901 as a historical precedent, Schaefer (1987) and Chevalier (1987) suggested that light echoes could occur around Supernova (SN) 1987A as well. This prediction has been borne out by the recent discovery of light echoes around SN 1987A (Crotts 1988; Rosa 1988; Heathcote and Suntzeff 1988). The observations show two arc-shaped nebulae with radii of 33″ and 54″ around the supernova, and thicknesses between 5″ and 10″. The arcs have a knotty appearance, suggesting two cloudy scattering layers. The V band surface brightness of the brightest knots is $\sim$21 mag arcsec^{-2} (Suntzeff *et al.* 1988), and the spectrum of the inner ring, as observed on 1988 March 19, suggests that the reflected light emanated from the star during the epoch of peak SN luminosity, seen via the direct path during May 1987 (Heathcote and Suntzeff 1988; Suntzeff *et al.* 1988). The $\sim$300-day delay time suggests that the scattered light originates from sheets of dust located at distances of 120 and 330 pc in front of the supernova (Chevalier and Emmering 1988, hereafter CE; see also Crotts 1988, Suntzeff *et al.* 1988), so that the light scattering angle is very small ($\theta \approx 4°$ for the inner ring and 2° for the outer).

In this paper we examine the possibility that these sheets of scattering material will give rise to an observable infrared (IR) echo as well. The IR echo is the reradiated thermal emission from dust heated by the ultraviolet-visual output of the supernova. Its detectability is a sensitive function of the optical properties and size distribution of the emitting grains. If detected, the combined thermal and scattered echoes will provide detailed information on the properties of dust along the line of sight in the Large Magellanic Cloud (LMC).

II. THE DETECTABILITY OF THE INFRARED ARCS

Let $\mathscr{F}(\nu)$ be the flux density (ergs cm^{-2} s^{-1} Hz^{-1}) of a parallel beam incident on a spherical dust particle of radius a, and let $\mathscr{F} \equiv \int F(\nu)d\nu$. The flux density $F(\nu, \theta, a)$ scattered by a single grain to an observer at scattering angle θ and distance $D \gg a$ is $\mathscr{F}(\nu)S(\nu, \theta, a)/D^2$, where $S(\nu, \theta, a)$ is the differential scattering cross section per steradian. The total scattering cross section of the grain is

$$\sigma_s(\nu, a) = 2\pi \int S(\nu, \theta, a) d(\cos\theta) . \quad (1)$$

We write $\sigma_s(\nu, a) \equiv \pi a^2 Q_s(\nu, a)$ where $Q_s(\nu, a)$ is the dust scattering-efficiency factor. The dimensionless phase function $P(\nu, \theta, a)$ is defined by $P(\nu, \theta, a) \equiv 4\pi S(\nu, \theta, a)/\sigma_s(\nu, a)$ (Martin 1978, § 4.3). [This normalizes P so that $P(\nu, \theta, a) = 1$ for isotropic scattering]. The flux density scattered by the grain to the observer in direction θ can therefore be written as

$$F(\nu, \theta, a) = \mathscr{F}(\nu)\pi a^2 Q_S(\nu, a)P(\nu, \theta, a)/4\pi D^2 . \quad (2)$$

Thermal radiation by the grain is emitted isotropically, and its frequency-integrated flux (ergs cm^{-2} s^{-1}) is given by $(a^2/4D^2) \int \mathscr{F}(\nu)Q_a(\nu, a)d\nu \equiv \pi a^2 \bar{Q}_a(a)\mathscr{F}/4\pi D^2$, where $\bar{Q}_a$ is the spectral-averaged value of the dust absorption efficiency, which for a thermal spectrum depends on the source temperature. In practice, most of the absorbed light is emitted at infrared wavelengths in some spectral band $\Delta\nu$(IR). The IR flux density can therefore be expressed in terms of the scattered one as

$$F_{\rm IR}(\nu, a) \approx \frac{F(\nu, \theta, a)}{\Delta\nu({\rm IR})}\left[\frac{\mathscr{F}}{\mathscr{F}(\nu)}\right]\left[\frac{\bar{Q}_a(a)}{Q_S(\nu, a)P(\nu, \theta, a)}\right] . \quad (3)$$

If a scattering cloud of particles of various sizes and compositions has a visual-extinction optical depth $\tau_e(=\tau_a + \tau_s)$ which is small ($\tau_e \ll 1$) along the line of sight, then multiple scattering can be neglected, and one can simply integrate the single-scattering contributions from the individual particles over their size distribution. The same ratios given by equation (3) can then be used to relate the flux densities or specific intensities in the two bands. We can then write the expected IR flux density in terms of the scattered visual surface brightness Σ (in mag arcsec^{-2}) and a dimensionless ratio $\zeta(\theta)$ as follows:

$$F_{\rm IR}(\nu) \approx f_s \Omega_{\rm IR} \zeta(\theta) F_0(\nu)[\text{dex}(-0.4\Sigma)] \times \left(\frac{\mathscr{F}}{\mathscr{F}(V)\Delta\nu(V)}\right)\left(\frac{\Delta\nu(V)}{\Delta\nu(\text{IR})}\right), \quad (4)$$

where $\Omega_{\rm IR}$ is the beam size of the IR detector in arcsec^2, f_s the filling factor of the bright knots in the beam, and $F_0(V)$ the zero-magnitude flux density in the V band. We have multiplied and divided equation (4) by the bandwidth $\Delta\nu(V)$ to make the last two factors dimensionless, and substituted V for the scattered frequency in the V band (λ = 5500 Å). The quantity $\zeta(\theta)$ is a weighted mean of the ratio in equation (3). The weighting is given by equation (2), and the result is (see Chevalier 1986):

$$\zeta(\theta) = \frac{\int \bar{Q}_a(a)a^2 n(a)da}{\int Q_s(V, a)P(V, \theta, a)a^2 n(a)da}, \quad (5)$$

where $n(a)da$ is the number density of grains with radii in da. If grains of two or more compositions are present, equation (5) should have two or more integrals in the numerator and in the denominator. If grains of only one size and composition are present, then $\zeta(\theta) = \bar{Q}_a(a)/Q_s(V, a)P(V, \theta, a)$. The effective blackbody temperature of the supernova during 1987 May was $\sim$5500 K, for which it is a good approximation to set $\bar{Q}_a(a) \approx Q_a(V, a)$, the absorption efficiency in the V band. Table 1 lists the values of $Q_a(V, a)/Q_s(V, a)$, and $P(V, \theta, a)$ and $\zeta(\theta)$ at $\theta = 2°$ and 6°, for graphite and silicate grains of various sizes. The values for the dust absorption and scattering efficiencies were calculated from Mie theory, using optical constants given by Draine and Lee (1984) and Draine (1987). A Henyey-Greenstein analytical form $P(\theta) = (1 - g^2)(1 + g^2 - 2g \cos \theta)^{-3/2}$ (Martin 1978) was adopted for calculating the phase function, and the asymmetry parameter g was taken from Mie calculations by Draine (1987). Except for grain sizes above 0.3 μm, $P(\theta)$ is nearly the same for graphite and silicate and varies for values of θ from 2° to 6° by less than 40%. The table illustrates the well known fact that, at any given wavelength λ, the absorbed fraction of the total extinction increases with diminishing grain size. Furthermore, the scattered light is more isotropically distributed as the grain size decreases. The function $\zeta(\theta)$ is therefore strongly dependent on grain size, ranging from $\sim 10^5$ for 10 Å size grains to $\sim 10^{-2}$ for 1.0 μm size particles.

We have not yet corrected equation (4) for differential extinction of the visual and infrared. The reradiated IR suffers negligible extinction between the absorbing layer and the observer. We can correct for the visual extinction by dereddening the observed surface brightness $\Sigma_{\rm obs}$ back to a mean particle in the scattering layer, using an appropriate extinction A_V. The total extinction along lines of sight to and near the SN is not well known. Guesses for the total reddening $E(B-V)$ range from 0.25 (Panagia *et al.* 1987) down to 0.15 (Hamuy *et al.* 1988). The latter authors divide their reddening into $E(B-V) = 0.06$ due to the Galaxy and $E(B-V) = 0.09$ due to the 30 Dor region in the LMC. Using $R \equiv A_V/E(B-V) = 3.17$, we would conclude that the total visual extinction is 0.19 mag in the Galaxy plus 0.29 mag in the LMC. If the latter figure applies also to a particular line of sight through one of the echo layers, a portion of it presumably belongs to the echo layer itself, and other portions lie in front of and behind the echo layer. On the other hand, a line of sight passing through a bright (observed) echo might have an extinction higher than the area mean. (We will return to this below.) Assuming the larger reddening figure $E(B-V) = 0.25$ would also allow a larger extinction. Provisionally we apply an extinction A_V = 0.5 mag to deredden the observed visual surface brightness back to the scattering layer. The observed brightnesses $\Sigma_{\rm obs}$ for the bright parts of the arcs are 21.28 mag arcsec^{-2} on the outer arc and 20.84 on the inner (Suntzeff *et al.* 1988). Correcting these by 0.5 mag, we obtain Σ = 20.78 mag arcsec^{-2} on the outer arc and 20.34 on the inner. Taking $F_0(V)$ = 3843 Jy (Allen 1973, p. 202), we find $F_0(V)$ dex $(-0.4\Sigma) = 1.9 \times 10^{-5}$ Jy arcsec^{-2} on the outer arc and 2.8×10^{-5} Jy arcsec^{-2} on the inner. These values are to be used in equation (4).

The dust is heated by the SN output around 1987 May, at which time the dereddened bolometric luminosity and temperature were $\approx 6.4 \times 10^{41}$ ergs s^{-1} and $\approx$5500 K, respectively (Hamuy *et al.* 1988; Catchpole *et al.* 1987). The fraction

TABLE 1

SELECTED OPTICAL PROPERTIES OF GRAPHITE AND SILICATE DUST[a]

Optical Properties	Grain Size (μm) 0.0010	0.0030	0.01	0.03	0.1	0.3	1.0
$Q_a(V)/Q_s(V)$	2.65(5)	9.87(3)	2.70(2)	1.16(1)	8.75(−1)	8.58(−1)	6.66(−1)
	8.00(4)	2.97(3)	8.05(1)	3.15	1.63(−1)	1.43(−1)	5.37(−1)
$P_V(\theta = 2°)$	1.00	1.00	1.01	1.10	2.66	17.6	32.4
	1.00	1.00	1.01	1.08	2.77	14.3	51.9
$\zeta_V(\theta = 2°)$	2.65(5)	9.85(3)	2.67(2)	1.05(1)	3.29(−1)	4.87(−2)	2.06(−2)
	8.00(4)	2.97(3)	7.98(1)	2.92	5.89(−2)	9.98(−3)	1.03(−2)
$P_V(\theta = 6°)$	1.00	1.00	1.01	1.10	2.56	12.1	16.4
	1.00	1.00	1.01	1.08	2.67	10.6	18.7
$\zeta_V(\theta = 6°)$	2.65(5)	9.85(3)	2.67(2)	1.06(1)	3.41(−1)	7.11(−2)	4.05(−2)
	8.00(4)	2.97(3)	7.99(1)	2.92	6.12(−2)	1.35(−2)	2.87(−2)
$Q_a(\text{UV})/Q_a(V)$[b]	5.67	5.29	4.05	2.03	5.14(−1)	6.59(−1)	7.52(−1)
	1.37(2)	1.27(2)	9.15(1)	4.35(1)	8.24	1.88	9.51(−1)

[a] Double rows correspond to entries for graphite and silicate grains, respectively. Numbers in parentheses represent powers of 10.

[b] UV properties calculated at wavelength of 300 Å.

of the total luminosity emitted at that time in the V band $[\Delta\nu(V) = 8.8 \times 10^{13}$ Hz] is $[\mathscr{F}/\mathscr{F}(V)\Delta\nu(V)]^{-1} \approx 0.12$. Dust temperatures depend on grain size and composition, with composition being the dominant factor. At a distance of 120 pc dust temperatures will be ≈ 30 and 20 K for, respectively, graphite, and silicate particles, decreasing to ≈ 25 and 15 K at a distance of 330 pc. Grain-size variations from 50 Å to 0.3 μm will change these temperatures by only a few degrees. The IR emission is therefore most readily observable at ≈ 100 μm. The only instrument operating in this spectral range and actively observing the supernova is the University of Texas photometer (Harvey, Lester, and Joy 1987; Harvey 1988). The instrument has a 100 μm beam size $\Omega_{\rm IR} \approx 20'' \times 33'' = 660$ arcsec^2. Elsewhere (Felten and Dwek 1989*a*), we have incorrectly given this beam size as $8'' \times 15''$, which is the 50 μm beam size of the instrument. Under good conditions the instrument has a 1 σ sensitivity of 0.2 to 0.3 Jy achieved in 2 hr of integration time [roughly the total time available for target observation during one flight of the Kuiper Airborne Observatory (KAO)]. For dust temperatures between 15 and 30 K, roughly one third of the dust thermal emission goes into the detector bandwidth $\Delta\nu \approx 1 \times 10^{12}$ Hz around 100 μm. (This fraction is of course a function of T, but for purposes of this paper a rough approximation is adequate.) For these instrument characteristics, with the surface brightness derived above, the expected value of $F_{\rm IR}$ on the outer arc is given by

$$F_{\rm IR}({\rm Jy}) \approx 1.6 \times 10^{-4} f_s \Omega_{\rm IR} \zeta[\Delta\nu(V)/3\Delta\nu({\rm IR})] \approx 3.1 f_s \zeta\ . \quad (6)$$

The position of the moving echo can be predicted easily (e.g., CE). Careful positioning of the aperture in a direction tangential to the arc will maximize the beam filling factor f_s and hence the detectability of the IR echo. Inspection of the surface-brightness results (Suntzeff *et al.* 1988) and photographs, and of model profiles (CE), suggests that the effective f_s on the outer arc can be made as large as 0.4. (On the inner arc, the peak surface brightness is higher, but f_s will be smaller.)

Assuming $f_s = 0.4$ on the outer arc, we see from equation (6) that the IR echo reaches a flux density $F_{\rm IR} \approx 1.2$ Jy if $\zeta \approx 1$. This flux density at 100 μm represents a 4 σ–6 σ detection for the instrument. Bearing in mind the need to spend time mapping surrounding areas to verify that one is detecting the arc and not something else (Harvey 1988), one sees that this value of $F_{\rm IR}$ is near the practical limit for detection. Thus we require $\zeta \gtrsim 1$ for detection; $\zeta \ll 1$ would not be sufficient.

It might appear from Table 1 that this is easily achievable if the grain sizes are sufficiently small. There is evidence (e.g., Witt, Bohlin, and Stecher 1986; Witt *et al.* 1987; Weiland *et al.* 1986) for a variety of grain-size distributions in different clouds in the Galaxy. However, we are not entirely free to assume a large number of arbitrarily small grains in the case at hand. To see this, note that the scattering optical depth τ_s must not be negligible, because the scattered visual echo is seen. For small grains, Table 1 shows that the albedo $\omega \equiv (1 + Q_a/Q_s)^{-1}$ is very small, $\sim 10^{-3}$ or 10^{-5}. Assuming a size distribution confined to small grains therefore may involve assuming a *large absorption optical depth* τ_a.

To be more specific, we first follow CE in assuming a modified MRN grain model (Mathis, Rumpl, and Nordsieck 1977) characterized by an $a^{-3.5}$ power law in the size distribution, and sizes in the ranges ($a_{\rm min}$–$a_{\rm max}$) of (0.005–0.25 μm) and (0.01–0.25 μm) for, respectively, graphite and silicate spheres. The number ratio of graphite and silicate spheres in the common size range is assumed to be 1 : 3 (thought appropriate for LMC abundances; Nandy 1984). We refer to this dust mixture as "CE dust." We have calculated in Table 2 the optical properties of CE dust integrated over the size distribution. To determine the normalized quantities on the right-hand side of the table, we need to determine the optical thickness of the echo layer along the line of sight. The observed surface brightness, compared to the peak direct magnitude of the SN ($m_V \approx 3.0$), does not constrain τ_s directly. What it constrains (provided τ_s is small, so that multiple scatterings can be neglected) is the product $\tau_s P = \tau_e \omega P$. Applying Chevalier's (1987) equation for the surface brightness Σ to the outer arc, we set $\Sigma = 21.28$, $m_{\rm SN} = 3.0$, $R = 330$ pc, and $\tau = \tau_{\rm SN}$, and find

$$\tau_s P = \tau_e \omega P \approx 1.11 \quad (7)$$

as the constraint that must be satisfied by the layer producing the outer echo. [Chevalier's equation contains an error, inconsequential here: his coefficient 0.434 should be $(\ln {\rm dex}\ 0.4)^{-1} \approx 1.086 \approx 0.434 \times 5/2$.] From Table 2, CE dust has $\omega \approx 0.66$ and $P \approx 7.9$, so we conclude that the layer must have $\tau_e \approx 0.21$, close to the value found by CE.

If a different dust-size distribution is now chosen, the

TABLE 2

Selected Optical Properties of Dust Models Considered in This Paper[a]

Dust Model	ω	$P(\theta = 2°)$	$\zeta(\theta = 2°)$	$\tau_e \omega P$	$\tau_e(V)$	$\tau_a(V)$	$\tau_s(V)$	$\tau_a({\rm UV})/\tau_a(V)$
CE	0.665	7.93	6.34(−2)	1.11	2.10(−1)	7.04(−2)	1.40(−1)	3.93
DLMRN	5.53(−1)	6.79	1.19(−1)	1.11	2.96(−1)	1.32(−1)	1.63(−1)	2.72
ECE	6.38(−1)	7.86	7.22(−2)	1.11	2.21(−1)	8.01(−2)	1.41(−1)	6.25
A30	6.13(−1)	7.86	8.03(−2)	1.11	2.30(−1)	8.92(−2)	1.41(−1)	8.51
B30	5.04(−1)	7.86	1.25(−1)	1.11	2.80(−1)	1.39(−1)	1.41(−1)	1.57(1)
C30	2.33(−1)	7.86	4.19(−1)	1.11	6.07(−1)	4.66(−1)	1.41(−1)	2.50(1)
D30	4.67(−2)	7.86	2.60	1.11	3.02	2.88	1.41(−1)	2.83(1)
E30	6.38(−3)	7.86	1.98(1)	1.11	2.21(1)	2.20(1)	1.41(−1)	2.88(1)
A50	5.89(−1)	7.86	8.87(−2)	1.11	2.40(−1)	9.85(−2)	1.41(−1)	1.04(1)
B50	3.60(−1)	7.86	2.27(−1)	1.11	3.93(−1)	2.51(−1)	1.41(−1)	2.17(1)
C50	6.98(−2)	7.86	1.70	1.11	2.02	1.88	1.41(−1)	2.79(1)
D50	6.46(−3)	7.86	1.96(1)	1.11	2.19(1)	2.17(1)	1.41(−1)	2.90(1)
E50	5.01(−4)	7.86	2.54(2)	1.11	2.82(2)	2.82(2)	1.41(−1)	2.90(1)
DA	3.13(−1)	1.81	1.21	1.11	1.96	1.35	6.14(−1)	1.72(1)

[a] Model details are given in Table 3. Numbers in parentheses represent powers of 10.

product $\tau_e \omega P$, being fixed by observations, must still satisfy equation (7). If we choose grains of a single small size, say silicate grains with $a = 0.01$ μm, then Table 1 shows that $\omega \approx (80 + 1)^{-1}$ and $P \approx 1.09$, so we have $\tau_e \approx 1.11(\omega P)^{-1} \approx 82$. Since $\tau_a = (1 - \omega)\tau_e$, this translates to $\tau_a \approx \tau_e \approx 82$. Note that $\zeta = (1 - \omega)(\omega P)^{-1} \approx \tau_a/1.11$. This large τ_a is not acceptable. If a large τ_a is present in the echo layer and also extends across the direct line of sight to the SN, then, as pointed out by CE, it does not affect the calculation of the relative echo brightness in the visual, but the large extinction correction would upset all existing theories of the SN explosion. One cannot choose an arbitrarily large value for τ_a in order to increase ζ even if it does not extend to the SN line of sight. Most of the visual luminosity is absorbed by the scattering layer when $\tau_a \approx 2$. So from energy considerations we can gain nothing by taking a value of $\tau_a > 2$. Another way of looking at this is that a large τ_a would weaken the visual echo by a factor $\sim \exp(\tau_a)$ and render it invisible. Any value of τ_a above a limit, conservatively taken as 2, is therefore ruled out. With this assumption, $\zeta < 2/1.11 \approx 2$. The high relative brightness of the visual echo prohibits large ζ, i.e., prohibits effective grain sizes smaller than ~ 0.03 μm.

Detectability of the IR echo is therefore marginal at best. Indeed, for typical grain-size mixtures, ζ may be much smaller. Table 2 shows that $\zeta \approx 0.063$ for CE dust. We show also in Table 2 the optical properties for 13 additional models. In all models, the phase function was calculated for a scattering angle of $\theta = 2°$, applicable to scattered light from the outer ring. The parameters of these models are listed in Table 3. Model DLMRN is an MRN model as modified by Draine and Lee (1984). For this model, the graphite/silicate number ratio was set by them at 0.93 to optimize the fit of their synthetic extinction curve to the observed Galactic one. Differences between the CE and DLMRN models arise mainly from the higher abundance of graphite in the latter. The remaining models in the table preserve the graphite/silicate mass ratio (0.241) inferred from the CE dust model for the LMC, but differ from it by introducing a population of very small dust grains. Model ECE simply extends the CE distribution to smaller sizes. The models farther down the table are characterized by a steeper power law extending from $a_{\rm min}$ to a size a_b, where it is smoothly joined to the large-grain size distribution. The models are labeled A-E, in order of increasing value of the power law of the size distribution of small grains. Two sets of models were calculated, characterized by a_b values of 30 and 50 Å. Models A and B are similar to those proposed by Draine and Anderson (1985) and Weiland *et al.* (1986), respectively, to fit the IR emission by high-latitude Galactic cirrus. The other models are significantly more weighted toward small grains. Finally, we add to the table model DA, similar to a model adopted by Draine and Anderson (1985) for one abnormal high-latitude Galactic cloud. This has both an augmentation at small grain sizes and a lower truncation ($a_{\rm max} = 0.1$ μm) at large sizes. The truncation at 0.1 μm reduces P. As Draine and Anderson point out, such a model would have an abnormal UV-visual extinction curve.

The extinction in each model was normalized to satisfy the observational constraint $\tau_e \omega P = 1.11$, set in equation (7).

TABLE 3

CHARACTERISTICS OF DUST MODELS USED IN THE PAPER

Dust Model	Graphite $a_{\rm min}$ (μm)	Graphite $a_{\rm max}$ (μm)	Graphite Index	Silicate $a_{\rm min}$ (μm)	Silicate $a_{\rm max}$ (μm)	Silicate Index	Graphite-to-Silicate Mass Ratio
CE	0.005	0.25	3.5	0.01	0.25	3.5	0.241
DLMRN	0.005	0.25	3.5	0.005	0.25	3.5	0.631
ECE	0.0003	0.25	3.5	0.0003	0.25	3.5	0.241
A30	0.0003	0.0030	4.5	0.0003	0.0030	4.5	0.241
	0.0030	0.25	3.5	0.0030	0.25	3.5	
B30	0.0003	0.0030	5.5	0.0003	0.0030	5.5	0.241
	0.0030	0.25	3.5	0.0030	0.25	3.5	
C30	0.0003	0.0030	6.5	0.0003	0.0030	6.5	0.241
	0.0030	0.25	3.5	0.0030	0.25	3.5	
D30	0.0003	0.0030	7.5	0.0003	0.0030	7.5	0.241
	0.0030	0.25	3.5	0.0030	0.25	3.5	
E30	0.0003	0.0030	8.5	0.0003	0.0030	8.5	0.241
	0.0030	0.25	3.5	0.0030	0.25	3.5	
A50	0.0003	0.0050	4.5	0.0003	0.0050	4.5	0.241
	0.0050	0.25	3.5	0.0050	0.25	3.5	
B50	0.0003	0.0050	5.5	0.0003	0.0050	5.5	0.241
	0.0050	0.25	3.5	0.0050	0.25	3.5	
C50	0.0003	0.0050	6.5	0.0003	0.0050	6.5	0.241
	0.0050	0.25	3.5	0.0050	0.25	3.5	
D50	0.0003	0.0050	7.5	0.0003	0.0050	7.5	0.241
	0.0050	0.25	3.5	0.0050	0.25	3.5	
E50	0.0003	0.0050	8.5	0.0003	0.0050	8.5	0.241
	0.0050	0.25	3.5	0.0050	0.25	3.5	
DA	0.0003	0.01	4.0	0.0003	0.01	4.0	0.241
	0.01	0.1	3.5	0.01	0.1	3.5	

From the results in Table 2, we see that ζ remains small unless the power law for the smallest grains is made very steep, greater than 6. Models E30, D50, and E50 have $\zeta \gg 1$ and can, in light of the discussion above, be rejected for these echo layers in the LMC because of the observed visual echo. (Some of these could be rejected on other grounds as well. For example, model E50 has $\tau_e \approx 282$, and for a normal dust-to-gas mass ratio it would have an extremely large column density of hydrogen, of order 10^{24} cm^{-2}.) Models not too different from models D30 and C50 have $\zeta \approx 1$–2 and would produce a detectable IR echo. The same is true of model DA. All other models listed in Table 3 are viable but produce weak echoes, $\lesssim 0.5$ Jy at ~ 100 μm. In particular, with the exception of model DA, all models with small-particle power law of 5.5 or flatter range downward from 0.3 Jy. The "conventional" models CE, DLMRN, and ECE produce fluxes $F_{\rm IR} \approx 0.08$ Jy, 0.15 Jy, and 0.09 Jy, respectively. Detection of the echo is not impossible but appears unlikely at current sensitivity levels.

III. INFRARED ECHOES FROM THE UV BURST

It is interesting to examine whether the UV burst associated with the breakout of the shock through the stellar surface (e.g., Woosley 1988) can result in an observable IR echo. The UV echo region on the outer arc is expected to be a narrow ring lying $\sim 6''$ outside the visual echo peak (CE) and might be spatially resolvable from it in the IR. We might try to express the IR flux density originating in the UV echo in terms of that originating in the neighboring visual light echo. If the beam size includes the whole width of the ring in each case, then we can write

$$F_{\rm IR}({\rm UV}) \approx F_{\rm IR}({\rm vis})\left[\frac{\Delta\nu_{\rm IR}({\rm vis})}{\Delta\nu_{\rm IR}({\rm UV})}\right]\left[\frac{\tau_a({\rm UV})}{\tau_a({\rm vis})}\right]\left[\frac{E({\rm UV})}{E({\rm vis})}\right], \quad (8)$$

where E(UV) and E(vis) are the total energy emitted, respectively, in the UV burst and during the ≈ 60 days around the peak of the optical light curve; τ_a(UV) and τ_a(vis) are the dust absorption optical depths at, respectively, UV and visual wavelengths; and $\Delta\nu_{\rm IR}$(vis) and $\Delta\nu_{\rm IR}$(UV) are the approximate bandwidths of the thermal IR emission in the two echoes. The UV burst, which can be characterized by a blackbody temperature of $\sim 10^5$ K, has a peak luminosity ~ 50 times greater than the peak visual luminosity of 1987 May, but it is much shorter and contains less energy. The absorption efficiency for UV photons is higher than that for visual light, the exact ratio depending on grain size and composition. Table 1 presents the ratio of the dust absorption efficiency at $\lambda = 300$ Å, which is about equal to the wavelength of maximum photon emission in the UV pulse, to that in the visual band. The table shows that this ratio may vary from ~ 100 to ~ 1, depending on grain size and composition. One can therefore construct dust models with arbitrarily large $\tau_a({\rm UV})/\tau_a({\rm vis})$ ratios by weighting the grain-size distribution more heavily toward smaller grain sizes. The larger τ-ratios thus obtained cannot, however, be used in equation (8), for the following reason: equation (8) assumes that all optical thicknesses are small. But we saw above that the brightness of the visual echo suggests that τ_e may already be sizable in the V band. The layer echoing the UV burst cannot reradiate more IR than the total UV energy which strikes it. Therefore, if $\tau_a({\rm UV}) > 1$, then the $\tau_a({\rm UV})/\tau_a({\rm vis})$ ratio in equation (8) must be replaced by $1/\tau_a$(vis) if $\tau_a(V) < 1$, and by 1 if $\tau_a({\rm vis}) > 1$. Table 2 shows that for small silicate grains we expect this situation; i.e., we expect $\tau_a({\rm UV}) > 1$ at 300 Å. In particular, for CE dust (Table 2), the value of $\tau_a({\rm UV}) = 0.277$, so that $\tau_a({\rm UV})/\tau_a({\rm vis})$ in equation (8) is ≈ 4. However, model B30 has $\tau_a({\rm UV}) = 2.2 > 1$, so we replace the term $\tau_a({\rm UV})/\tau_a({\rm vis})$ in equation (8) by $1/\tau_a({\rm vis}) \approx 7$.

Effective dust temperatures in the UV echo will be significantly higher than those (15–30 K) resulting from the optical SN light curve: ≈ 70 and 60 K for, respectively, graphite and silicate dust grains located at 120 pc; and ≈ 60 and 50 K for, respectively, graphite and silicate dust grains located at 330 pc. The ratio of bandwidths in equation (8) is therefore $\sim 20/60 = 1/3$. The IR emission in the UV echo will be most readily observable around 50 μm. The total energy emitted in hard UV photons during the first day after the explosion is $E({\rm UV}) \approx 10^{47}$ ergs (Woosley 1988), and $E({\rm vis}) \approx 3 \times 10^{48}$ ergs (e.g., Catchpole *et al.* 1987). Then we find, for CE dust, $F_{\rm IR}({\rm UV})/F_{\rm IR}({\rm vis}) \approx 0.04$. This means that the UV pulse will give rise to a much weaker IR echo than that arising from the visual SN light curve. If we insert small grains with the maximum ζ permitted by the visual echo, $\zeta \sim \tau_a({\rm vis})/1.11 \sim 2$, then the factor $\tau_a({\rm UV})/\tau_a({\rm vis})$ must be replaced by unity, and the ratio $F_{\rm IR}({\rm UV})/F_{\rm IR}({\rm vis})$ grows even smaller. Prospects for the detection of the IR echo from the UV burst with present detectors at 50–100 μm are not good.

Very small particles (< 30 Å in radius), stochastically heated by the UV burst, transfer some of the reradiated flux to shorter wavelengths (e.g., Dwek 1986), accessible to sensitive ground-based detectors. This effect could be significant for those models in Table 3 which are heavily weighted toward small grains (index > 4.5). Nevertheless, detection of such a weak signal ($\lesssim 10^{-2}$ Jy) is unlikely with currently available instruments.

IV. CONCLUSIONS

The calculations presented here suggest that the visual arcs around SN 1987A are accompanied by thermal infrared echoes, which in principle are or will be detectable. Dust heated by the visible output of the SN will radiate around 100 μm, but in a $20'' \times 33''$ beam it will achieve a presently detectable flux level (~ 1 Jy) only if the grain-size distribution is heavily weighted toward small sizes, more so than distributions proposed for some reflection nebulae and high-latitude cirrus clouds in the Galaxy. A grain-size distribution even more heavily weighted toward small sizes could formally produce a much stronger IR echo (~ 100 Jy). But in practice such a size distribution is ruled out for these echo layers in the LMC by the visual observations, because it implies a high absorption optical depth $\tau_a(V)$. This would either (*a*) introduce an implausibly high extinction on the SN line of sight or (*b*) snuff out the observed visual echo. A more conventional MRN distribution is compatible with the visual observations but would produce a much weaker IR echo (~ 0.1 Jy).

Nevertheless, we wish to emphasize that these IR echoes will probably remain accessible to observations for many years, at roughly a constant flux level, and should eventually be detected. The rings grow in a predictable manner, and the scattering angles (presently quite small, 2° and 4°) increase slowly. Additional echoes closer to the SN may also be detected as the SN continues to dim down. Observations of the visual (scattered) echoes already constrain properties of the dust in these LMC clouds, and future observations of the thermal and scattered echoes will yield much more information on properties of dust in the LMC.

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Note added in manuscript, 1989 February 13.—A third foreground echo ring, with radius $\approx 9''.5$, is reported as of 1989 January 24, and preliminary data are given by Bond *et al.* (1989). This echo is no brighter than the large echo rings discussed above, although the dust involved is much closer to the SN ($R \approx 5.4$ pc instead of 120 or 330 pc). The scattering angle is $\theta = 25°$. The expected surface brightness goes as $\tau_s P(\theta) R^{-2}$ (Chevalier 1987; Felten and Dwek 1989*b*), so we conclude that the optical thickness of this cloud must be very small ($\tau_s \ll 0.1$). At small R, this dust will radiate at higher temperature, $T \approx 65$ K for silicates and ≈ 115 K for graphite. Using the methods above, we estimate that the corresponding infrared echo ring occupies ~ 100 arcsec^2 or a little more, and that, if the dust is CE dust, then $\zeta(\theta) \approx 0.36$ and the 30 μm surface brightness is $\sim 4 \times 10^{-4}$ Jy arcsec^{-2}. The detection of this flux is beyond the capabilities of currently available detectors. As in the case of the large rings, very small grains could have larger ζ and produce a stronger IR echo.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (London: Athlone).
Bond, H. E., Panagia, N., Gilmozzi, R., and Meakes, M. 1989, *IAU Circ.*, No. 4733.
Chevalier, R. A. 1986, *Ap. J.*, **308**, 225.
———. 1987, in *Proc. ESO Workshop on SN 1987A*, ed. I. J. Danziger (Garching: ESO), p. 481.
Chevalier, R. A., and Emmering, R. T. 1988, *Ap. J. (Letters)*, **331**, L105 (CE).
Crotts, A. 1988, *Ap. J. (Letters)*, **333**, L51.
Catchpole, R. M., *et al.* 1987, *M.N.R.A.S.*, **229**, 15p.
Draine, B. T. 1987, *Princeton Obs. Preprint*, No. 213.
Draine, B. T., and Anderson, N. 1985, *Ap. J.*, **292**, 494.
Draine, B. T., and Lee, H. M. 1984, *Ap. J.*, **285**, 89.
Dwek, E. 1986, *Ap. J.*, **302**, 363.
Felten, J. E., and Dwek, E. 1989*a*, in *IAU Symposium 135, Interstellar Dust: Contributed Papers*, ed. L. J. Allamandola and A. G. G. M. Tielens (Washington: NASA), in press.
———. 1989*b*, preprint.
Hamuy, M., Suntzeff, N. B., Gonzalez, R., and Martin, G. 1988, *A.J.*, **95**, 63.
Harvey, P., Lester, D., and Joy, M. 1987, *IAU Circ.*, No. 4518.
Harvey, P. M. 1988, private communication.
Heathcote, S., and Suntzeff, N. 1988, *IAU Circ.*, No. 4567.
Martin, P. G. 1978, *Cosmic Dust* (Oxford: Clarendon).
Mathis, J. S., Rumpl, W., and Nordsieck, K. H. 1977, *Ap. J.*, **217**, 425 (MRN).
Nandy, K. 1984, in *IAU Symposium 108, Structure and Evolution of the Magellanic Clouds*, ed. S. van den Bergh and K. S. de Boer (Dordrecht: Reidel), p. 341.
Panagia, N., *et al.* 1987, *Astr. Ap.*, **177**, L25.
Rosa, M. 1988, *IAU Circ.*, No. 4564.
Schaefer, B. E. 1987, *Ap. J. (Letters)*, **323**, L47.
Suntzeff, N. B., Heathcote, S., Weller, W. G., Caldwell, N., Huchra, J. P., Olowin, R. P., and Chambers, K. C. 1988, *Nature*, **334**, 135.
Weiland, J. L., Blitz, L., Dwek, E., Hauser, M. G., Magnani, L., and Rickard, L. J. 1986, *Ap. J. (Letters)*, **306**, L101.
Witt, A. N., Bohlin, R. C., and Stecher, T. P. 1986, *Ap. J.*, **302**, 421.
Witt, A. N., Bohlin, R. C., Stecher, T. P., and Graff, S. M. 1987, *Ap. J.*, **321**, 912.
Woosley, S. E. 1988, *Ap. J.*, **330**, 218.

ELI DWEK and JAMES E. FELTEN: Code 685, NASA Goddard Space Flight Center, Greenbelt, MD 20771