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ON THE DETECTABILITY OF INFRARED ECHO ARCS AROUND SUPERNOVA 1987A

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ABSTRACT

The ring-like interstellar visual echoes of radii 33 and 54 arcsec detected around SN 1987A should coincide with infrared echoes (thermal reradiation) from dust at T ~ 15-30 K. We consider whether these infrared echoes are detectable at present. They will be brightest at ~100μm, the range of the Texas infrared photometer. Detectability depends on the ratio $\zeta \equiv \tau_a/\tau_s P(\theta)$, where τ_a and τ_s are the visual absorption and scattering optical thicknesses of the echo layer, and P is the phase function for small-angle scattering ($\theta \approx 2°$ to $4°$). We need $\zeta \gtrsim 1$ for a detectable signal (~0.3 Jy), but ζ cannot be >>1; otherwise the visual echoes could not be as bright as they are. Typical dust mixtures of Mathis-Rumpl-Nordsieck type have $\zeta \ll 1$. ζ remains small even if a population of very small grains with power-law index as steep as ~5.5 is added. A population with even more small grains and/or fewer large grains could have $\zeta \sim 1$ and be detectable at present, but this seems unlikely. The echoes will move, but should remain accessible for many years and should be detected eventually.

The detection of arcs or rings of visual echo light around Supernova (SN) 1987A (Crotts, 1988), similar to those seen around Nova Persei in 1901 (Felten, 1988), has introduced a new element into discussions of possible infrared echoes. These visual echoes (Suntzeff *et al.*, 1988; Gouiffes *et al.*, 1988; Chevalier and Emmering, 1988) consist of light emitted by the SN around its epoch of maximum visual light (observed via the direct path around May 1987), and scattered by dust clouds in the far foreground so as to reach us with a kinematical time delay of about a year. Two clouds or layers within the Large Magellanic Cloud (LMC) are identified, at distances z ≈ 123 and 330 pc in front of the SN. These dust clouds should absorb some of the SN light at the same time and reradiate the energy thermally. In principle this produces an infrared echo coincident with the visual echo.

We have heard rumors of attempts to detect this infrared echo. Therefore we have tried to predict its expected strength and infer whether it can be detected at present. A longer account of our work appears elsewhere (Dwek and Felten, 1988). Here we merely summarize the simple physical ideas involved and the results we obtain. Detection at present is unlikely, though not impossible.

Our approach is to make some simple estimates without worrying too much about the radiative-transfer complications which would ensue if any of the visual optical thicknesses τ_e which appear in the problem were large ($\tau_e \gtrsim 1$). It is generally believed that τ_e is not large, say not >1, along lines of sight to and near the SN, though this is not certain. A value of τ_e as large as ~2 could perhaps be permitted along the direct line to the SN without doing too much violence to theories of the outburst. Below we assume that $\tau_e \approx 0.5$, i.e., $A_V \approx 0.5$, in the numbers that we use. If τ_e were as large as 2, our numbers would have to be changed a bit, but the general features of the results would not change.

How bright could such an IR echo possibly be? In mid-May 1987, the dereddened bolometric luminosity of the SN was $L_{bol} \approx 6.4\times10^{41}$ erg s^{-1} (Hamuy *et al.*, 1988; Catchpole *et al.*, 1987). The outer echo arcs arise in a dust layer about z = 330 pc in front of the SN. If this layer is thick enough ($\tau_a \gtrsim 1$) to absorb and convert essentially all the incident radiation, we get the strongest possible IR signal. The equilibrium temperature of the dust will be roughly 15-30 K, and at this temperature roughly 1/3 of the reradiated energy will go into a bandwidth $\sim10^{12}$ Hz around wavelength 100μm. This is where the echo will be strongest, and this band is accessible to the Texas infrared photometer (Harvey, Lester and Joy, 1987). It is easy to show that under these circumstances the flux density received in this band would be

$$F_\nu \approx 1.3\times10^{-15} f_s\Omega_{IR} \text{ erg cm}^{-2}\text{s}^{-1}\text{Hz}^{-1}, \qquad (1)$$

where Ω_{IR} is the beam size (sr) of the photometer and f_s is the filling factor of the bright echo knots in this beam. The Texas photometer has a beam 8×15 arcsec^2. Inspection of photos and theoretical profiles of the echo shows that it can fill this beam pretty well: $f_s \approx 0.7$. Then we find $F_\nu \approx 0.3$ Jy. This is the maximum signal achievable for $\tau_a \gtrsim 1$; for $\tau_a < 1$, $F_\nu \tilde{\propto} \tau_a$. This is a marginal signal for the Texas photometer, which reaches 1 Jy in ~1 hour of integration time. Thus we need a thick layer ($\tau_a \sim 1$) to have hopes of seeing it.

How thick is the actual dust layer? From the observed surface brightness of the visual echo relative to the SN, it is easy to show (Dwek and Felten, 1988; Chevalier, 1987) that $\tau_s P(\theta) \equiv \tau_e \omega P(\theta) \approx 1.1$. Here τ_s and τ_e are the visual scattering and extinction optical thicknesses of the layer, ω is the dust albedo, and $P(\theta)$ is the visual scattering phase function at scattering angle θ, where $\theta \approx 2°$ for the outer echo ring. (This expression is rigorous for small optical depths but will remain approximately correct for $\tau_e \sim 1$. It holds even if there is heavy additional absorption, equal along the direct path to the SN and along the path through the echo layer. The only assumption is that τ_s for the echo layer itself is small, so that multiple scattering can be neglected.) This implies that, if we are to detect the infrared echo, we have to assume that

$$\zeta(\theta) \equiv \tau_a/\tau_s P(\theta) \gtrsim 1 . \tag{2}$$

We could also write ζ as $\bar{Q}_a/\bar{Q}_s P$, where $\bar{Q}_a$ and $\bar{Q}_s$ are the effective mean efficiencies for absorption and scattering for the dust grains which are present.

The problem is that for typical interstellar dust mixtures ζ is small (<<1), because τ_a/τ_s is <1 and P(2°) is large. Very small grains have large ζ, but large grains have small ζ, particularly at small forward angles $\theta \approx 2°$, because they scatter strongly forward. For a typical MRN mixture (Mathis, Rumpl and Nordsieck, 1977) of graphite and silicate spheres, with a power law $dn/da \propto a^{-3.5}$ in grain sizes and an upper size cutoff at $a_{max} = 0.25\mu m$, P(2°) is about 8 and $\zeta(2°) \lesssim 0.1$. We have calculated ensemble properties for 14 different dust mixtures (Dwek and Felten, 1988). We took Q_a, Q_s and the asymmetry parameter g for individual spherical grains from Mie-theory calculations by Draine and Lee (1984) and Draine (1987), and assumed a Henyey-Greenstein form for the individual-grain phase function: $P(\theta)=(1-g^2)(1+g^2-2g\cos\theta)^{-3/2}$. We can increase ζ somewhat by taking an MRN mixture and adding an extra population of very small grains, but the power-law index for these small grains must be made very steep, >5.5, before ζ reaches unity. Such a dust distribution would contain more small grains than any previously suggested (e.g., Weiland *et al.*, 1986). Another way to obtain $\zeta \sim 1$ is to truncate the large-grain size distribution at a lower value a_{max}, say $0.1\mu m$ instead of 0.25. Draine and Anderson (1985) suggested such a distribution for one abnormal high-latitude Galactic cloud. The phase function then drops from $P \approx 8$ to $P \approx 2$, being strongly determined by the largest grains present. This, however, is an abnormal distribution, and the scattering by normal interstellar matter is expected to be more strongly peaked forward.

In summary, we must expect that these infrared echoes in the LMC, unless they issue from abnormal dust populations, will be one to two orders of magnitude below the present detection threshold, because the absorption optical thickness in the visual is expected to be small. The reradiated infrared echo produced at these layers by the initial ultraviolet burst from the SN should be even weaker (Dwek and Felten, 1988). It is of some interest that the visual echoes already rule out values of ζ >> 1 for these layers, because such dust would have $\tau_a >> 1$ and would attenuate either the SN itself, or the observed visual echoes, by an additional factor $\sim \exp \tau_a$, which is not acceptable.

Finally we note that, while the infrared echoes may not be detectable at present, they are expected to remain accessible for many years at roughly the same flux level (though they move on the planes of dust). Detection should eventually be possible and should give additional information about the dust properties. We are preparing a longer paper (Felten and Dwek, 1988) on more general aspects of these echoes.

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