IRAS OBSERVATIONS OF COLLISIONALLY HEATED DUST IN LARGE MAGELLANIC CLOUD SUPERNOVA REMNANTS

James R. Graham[1,2], A. Evans[3], J. S. Albinson[3], M. F. Bode[4] & W.P.S. Meikle[1]

[1]Imperial College, London, [2]Lawrence Berkeley Laboratory, University of California, [3]University of Keele, [4]Lancashire Polytechnic.

ABSTRACT

IRAS additional observations show that luminous (10^4-10^5 $L_\odot$) far-IR sources are associated with the Large Magellanic Cloud (LMC) supernova remnants N63A, N49, N49B, and N186D. Comparison of the IRAS and X-ray data shows that a substantial fraction of the IR emission from three of the SNRs can be accounted for by collisionally heated dust. The ratio of dust-grain cooling to total atomic cooling is ~10 in X-ray emitting gas (T~10^6 K). We show why dust cooling does not dominate, but probably speeds SNR evolution in an inhomogeneous interstellar medium.

INTRODUCTION

Dust grains may be an important coolant of astrophysical plasmas, because grains embedded in hot gas are heated by inelastic collisions with electrons and ions (Ostriker & Silk 1973). The energy deposited raises the grain temperature so this energy is radiated in the far-IR. Grain cooling should be important at temperatures characteristic of the X-ray emitting gas (~10^6K) in SNR's. Therefore, SNR's should be an ideal astrophysical laboratory where grain cooling can be investigated.

We observed LMC SNR's because they form a well studied sample at X-ray, optical, and radio wavelengths; they have sizes of the order of the IRAS apertures; they should be less confused than Galactic SNR's because we are not looking through a galactic disc; the LMC SNR's are all at the same distance (we adopt 55kpc).

RESULTS

Of 9 LMC SNR's for which IRAS AO data have been obtained, 4 are unambiguously associated with IR sources.The position of the IR source is shown on X-ray maps of the SNR's in Figure 1. The IR source is precisely coincident with the peak of the X-ray emission in the case of N63A, N49 and N49B. The IR source associated with N186D is offset from the X-ray peak by ~2' to the SW. There are upper limits for a further 3 SNR. The remaining 2 were too close to extended, bright sources to obtain useful limits.
The 8-120μm luminosity, the band III-IV temperature and the total luminosity, calculated assuming a black-body emission with a λ^{-1} grain emissivity law, for 55kpc, are presented in Table 1.

Table 1

SNR	T (K)	$L_{(8\text{-}120\mu m)}$ (10^5 $L_\odot$)	L_{tot} (10^5 $L_\odot$)	M_d/M_x	L_{IR}/L_x
N63A	30	1.1	1.8	0.03	12
N49	40	0.5	0.6	0.006	12
N49B	30	0.05	0.1	0.002	4
N186D	25	0.5	1.1	0.3	2100

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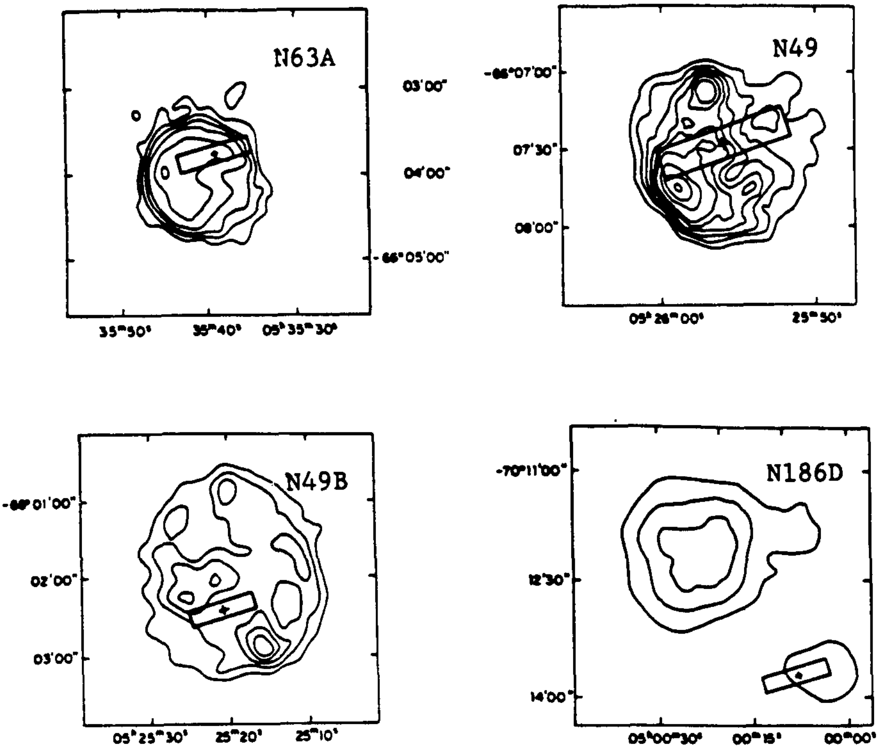

Figure 1
The mean IR position from IRAS is indicated by a cross along with the X-ray contours (reproduced with permission) from Mathewson et al. (1983). The positional uncertainty (1σ) is represented by the rectangle.

INTERPRETATION

The positional coincidence between the IR and the X-ray sources constitute *prima facie* evidence that the IR emission originates from the SNR; from LMC source counts the chance of detecting an unassociated source at 100μm is ~ 0.002.

The IR sources are thermal in nature. Although these SNR's are bright radio objects, extrapolation to 100μm indicates that the non-thermal contribution to the IRAS fluxes is 0.02-0.4%. A significant contribution by IR fine structure lines of [O III], [NII] and [NIII] can be ruled out, but, if any of these SNR's are interacting with dense molecular material, like IC443, then [O I] 63μm may contribute to the band III flux.

Galactic far-IR sources are usually due to dust grains re-radiating the light of luminous young stars. We have considered direct heating of dust by luminous young stars and by resonantly trapped Lyman α and been able to show that radiative heating cannot account for the IR luminosity associated with N63A, N49, and N49B, but not N186D (Graham et al. 1987). Consequently, a strong case can be made for investigating alternative energy sources in these remnants.

The respective masses of IR (M_d) and X-ray (M_x) emitting material can be calculated (Table 1). If the X-ray emitting gas heats the dust, then the ratio of these masses, in the absence of grain destruction, should just be the dust-to-gas ratio in front of the shock. The mass of hot gas for the LMC SNR's has been calculated from the X-ray luminosity and the shock radius assuming a Sedov blast wave and emissivity in the *Einstein* energy band $\Lambda_x = 1.5 \times 10^{-23}$ erg cm^3 s^{-1} appropriate for T= 6×10^6 K and LMC abundances (0.5 of Galactic; Lequeux et al. 1979, Raymond, et al. 1976). The mass of radiating dust M_d is calculated assuming mass absorption coefficient of κ=250 cm^2/g at 100µm (Gatley et al 1977; Harvey, Hoffmann, and Campbell 1979; Harvey, Campbell, and Hoffmann 1979; Harvey, Thronson, and Gatley 1979)

A dust-to-gas ratio of ~0.0015 is representative of the LMC. The measured dust-to-gas ratios for N49B is close to this value, the value for N49 is comparable to the Galactic value. In N63A the dust-to-gas ratio is substantially higher than either the typical LMC or Galactic values. The N186D IR source is clearly not due to dust heated by X-ray emitting gas because a large fraction of the SNR's luminosity is due to dust in cool gas (T«10^6K) which is unobservable by *Einstein*. This may explain why the N186D IR source does not coincide precisely with the peak of the X-ray emission.

It is important to emphasize that there are uncertainties in the determination of the dust-to-gas ratio because of uncertainties in κ, Λ_x, L_x. Nevertheless, the inferred dust-to-gas ratios for N63A, N49, and N49B are in reasonably good agreement with the hypothesis that this hot dust is embedded in, and heated by the X-ray emitting gas.

The ratio of IR luminosity to X-ray luminosity $L_{IR}/L_x = \Lambda_{dust}/\Lambda_x$ if collisional heating is invoked. At 6×10^6K this ratio should be ≈30 for Galactic metallicity and dust-to-gas ratio. For a dust-to-gas ratio which is a factor of 4 lower, and a LMC metallicity which is lower by a factor of 2 we predict $\Lambda_{dust}/\Lambda_x = 15$.

The observed IR to X-ray luminosity ratio is presented in Table 1. To calculate this ratio we have used our estimate of the total IR luminosity and the 0.14-4.5 keV X-ray luminosity from Mathewson et al (1983). L_{IR} is probably known to ~ 25%. However, L_x may have been underestimated by a factor of up to 2. We see that it is energetically feasible that the IR radiation from N63A, N49, and N49B could be due to collisional heating. In fact the IR luminosity is at a level remarkably close to the predicted value.

N186D is peculiar, with a large "IR excess" that cannot be accounted for by collisional heating. It is clear from a comparison of the X-ray and IR data that the dust heating is of a completely different character in N186D. An additional source of heating, must be important in the energy balance if the very high hot-dust to hot-gas ratio is to be explained.

SNR Evolution

We have identified three SNR's where a substantial fraction of the IR luminosity is most plausibly ascribed to dust which is heated by gas-grain collisions. In these SNR grain cooling exceeds atomic processes by an order of magnitude and we estimate that $\Lambda_{dust} \sim 2 \times 10^{-22}$ erg cm^3 s^{-1} under the conditions prevailing in these SNR's. For the Galaxy $\Lambda_{dust} \sim 8 \times 10^{-22}$ erg cm^3 s^{-1} at 6×10^6K since the dust-to-gas ratio which is 4 times higher than in the LMC.

Our estimate of Λ_{dust}, for a Galactic dust-to-gas ratio, implies that the dynamics of a Galactic remnant will be affected by cooling at a time-scale

$$t_{dyn} = 9000\, \varepsilon_{51}^{2/11}\, n_o^{-7/11} \quad \text{yr.}$$

where ε_{51} is the supernova energy in units of 10^{51} erg, and n_o is the pre-shock gas number density in units of cm^{-3}. Departure from adiabaticity occurs sooner than predicted by calculations which only included atomic processes and we might expect that dust cooling speeds the evolution by a factor of ~3.

In order to establish under what conditions grain cooling modifies SNR evolution it is important to investigate grain destruction. Using the thermal grain sputtering rate calculations of Draine and Salpeter (1979) we find that on entering the shock the ratio of grain lifetime t_g to the time for grains to affect the dynamics is

$$t_g / t_{dyn} \approx 3a\,(\varepsilon_{51}\, n_o^2\, t)^{-2/11},$$

where a is the grain radius in units of 0.1μm. Thus, if $\varepsilon_{51}=1$, the lifetime of a 0.1μm grain always exceeds t_{dyn} so long as $n_o < 20\text{cm}^{-3}$. Accordingly, if the ISM were homogeneous with a mean density of ~ 1 cm^{-3} then the SNR lifetime would be very short, and the SNR would hardly have time to relax to Sedov expansion before radiative effects modified the dynamics. Any structure in the ISM profoundly changes this conclusion.

Consider a two phase model for the ISM consisting of diffuse clouds with $n=20\text{cm}^{-3}$ and an intercloud medium of $n=0.1\ \text{cm}^{-3}$ (c.f. Spitzer 1978). The grain lifetime in the intercloud medium is $3\text{x}10^5$ yr and exceeds even the time for atomic cooling to affect the dynamics. In the low density medium, which supports the X-ray emitting blast wave, $t_{dyn}=4\text{x}10^4$ yr. By this time the shock temperature has dropped to $1\text{x}10^6$ K, and dust and atomic cooling rates are approximately equal. Consequently, the SNR remains adiabatic while dust cooling dominates, and although dust cooling will speed shell formation after t_{dyn}, dust and atomic cooling will be equally important in this process.

The shocks driven into the clouds will not be significantly modified by grain cooling since the grain lifetime is short at high density. This conclusion is supported by IR spectroscopy of the SNR IC443 where ~ 30% of the iron bearing grains are destroyed in shocks propagating into clouds with n_o~10-20 cm^{-3} (Wright *et al.* in this volume, and Graham, Wright & Longmore, 1987)

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