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August 1986

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

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ABSTRACT

IRAS additional observations are presented which show that luminous ($\sim 10^5 L_\odot$) far-infrared sources are associated with supernova remnants N63A, N49, N49B, and N186D in the Large Magellanic Cloud. Comparison of the infrared and x-ray data show that a substantial fraction of the infrared emission from three of these remnants is due to collisionally heated dust. We conclude that the ratio of the dust-grain cooling to total atomic cooling by lines, recombination, and bremsstrahlung is ~ 10 in hot gas ($T \sim 10^6 K$). Consequently we infer that dust cooling must play an important role in the evolution of supernova remnants.

1 INTRODUCTION

It has been predicted for some time now that 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 to between a few tens to a few hundreds of kelvin, and so this energy is radiated at far-infrared wavelengths. Consequently, observational verification of grain cooling has proved difficult. Grain cooling is predicted to be an important energy sink when gas temperatures exceed $\sim 7 \times 10^5 K$. At temperatures characteristic of the x-ray emitting gas observed in supernova remnants (SNR) ($10^6 - 10^7 K$) the rate at which energy is lost to dust grains should exceed the normal cooling rate of a dust free plasma (Draine 1981, Dwek & Werner 1981). Therefore, a supernova remnant

should be an ideal astrophysical laboratory where grain cooling can be investigated.

Prior to the advent of the IRAS satellite infrared (IR) observations provided only very poor limits on the efficiency of dust cooling. Wright *et al.* (1980) have obtained far-infrared ($\lambda = 100\mu m$) upper limits for Cas A, Tycho, and Kepler. Unfortunately, these young (~ 300 years) remnants probably have not swept up much interstellar dust so the limits are not very severe. Dinerstein *et al.* (1982) claimed to have detected dust in the fast moving knots of Cas A. However, it seems that at least some of the flux is in fact due to emission lines of [NeII] (Dinerstein, private communication 1983). Before the launch of IRAS the only detection of far-infrared emission from a supernova remnant was the detection of DR4 (Campbell *et al.* 1981) and the Crab nebula (Wright *et al.* 1979). DR4 is associated with a complex of HII regions, and an unambiguous interpretation in terms of collisionally heated dust is difficult. The emission from the Crab found by Wright *et al.* (1979) was consistent with a non-thermal origin. The only other IR data are the $10\mu m$ observations of N63A and N49 in the Large Magellanic Cloud (LMC) by D'Odorico & Moorwood (1982). These place only very poor limits on the mass of cool dust. Recently Marley and Marsden (1985) have presented observations of Cas A, and interpreted the detected flux as due to collisionally heated dust grains.

We have obtained IRAS additional observations of supernova remnants in the Magellanic Clouds. Four remnants are detected with high signal to noise and excellent positional correspondence so that we are confident that the sources are associated with the remnants. We explore the possibility that these sources are powered radiatively by searching for luminous stars in the remnant's vicinity. We locate a candidate star in N186D, but find no luminous stars in the other remnants. By comparing the IRAS data with x-ray observations we can show that the most probable source of the infrared radiation for the other three cases is dust heated collisionally by the x-ray emitting plasma. We then consider the effects of grain cooling upon supernova remnant evolution.

It was decided to observe LMC remnants in preference to Galactic remnants for several

reasons. The pre-flight estimates of the IRAS confusion limit in the Galactic plane (Joseph & Robertson 1982) suggested that sensitive limits could only be achieved for a few high Galactic latitude SNR's. It was also not expected that the observatory would be able to observe large extended objects. Not only do the LMC remnants form an extremely well studied sample at x-ray, optical, and radio wavelengths, but they satisfy the observational constraints of typically having sizes of the order of the IRAS apertures, and they should be less confused than the Galactic remnants because in the LMC we are not looking through a galactic disc. The LMC remnants also have the unique property that they are at the same distance (in the following discussion we adopt 55 kpc). Unlike the Galactic remnants, for which the distances are uncertain, intrinsic properties such as size and luminosity can be derived.

This paper reports a detailed reduction and analysis of observations first described in Graham (1985) and Graham *et al.* (1985). These publications were based upon a provisional flux calibration and the data presented therein is therefore superseded by this work.

2 OBSERVATIONS

2.1 THE IRAS SATELLITE

The IRAS satellite consists of a spacecraft which accommodates a liquid helium cooled cryostat containing a cooled telescope. The telescope is a f/9.6 Ritchey-Chretien design with a 0.57m aperture. The optics are made of beryllium and cooled to < 10 K. The focal plane assembly is located at the Cassegrain focus of the telescope, and cooled to < 3 K. Sources are scanned, by a combination of orbital motion and rotation of the satellite, across the focal plane so that a source is seen consecutively by at least two detectors in any wavelength band, thus providing confirmation of a source on a timescale of seconds. (A detailed description of the mission can be found in Neugebauer *et al.* 1984).

2.2 ADDITIONAL OBSERVATION DATA

While the prime objective of the IRAS mission was to produce an all sky survey, part of the observing time was set aside so that IRAS could study particular objects in greater depth - so called additional observations (AO's). The IRAS AO is produced from a combination of the pointing history of the satellite, and the calibrated detector data.

After launch it became apparent that uncertainty in the baselines of the individual detectors introduced intensity stripes into the data which had not been through the point source filter. In addition, smooth intensity gradients were observed across many fields and are presumed to be due to variations in the zodiacal background. Stripe removal and flat-fielding is done in the post processing. The present IRAS AO data were reduced using standard STARLINK IRAS software (Abolins et al. 1985). These packages were used to co-add and rebin the data onto RA-DEC grids (I-COMBINE), and to extract positions of sources and to calculate in-band fluxes (I-CONTOUR). In view of the fact that the LMC remnants may have been slightly extended, particularly at the shorter IRAS wavelengths, the intensity maps were used in preference to the point source filtered data; however, this does not effect the discussion in this paper. Conversion from inband fluxes to color temperatures was done using tables in Young and Neugebauer (1984).

2.3 RESULTS

For the nine LMC remnants for which IRAS AO data has been obtained, there are four which are unambiguously associated with IR sources, i.e. the remnant falls within the IRAS positional uncertainty error box. The position of the peak IR emission is shown on the x-ray maps of the remnants in Figures 1 to 4. For a further three remnants there are upper limits. The remaining two were too close to extended bright sources to obtain useful limits. The positional data is summarised in Table 1 and the flux is presented in Table 2.

The fluxes derived from AO observations have been cross-checked with the IRAS survey

Point Source Catalogue. This can only be done for the brightest remnants because an AO consists of between 4 and 8 co-added survey-like scans. The correspondence in flux for N63A and N186D is to within a few percent. N49B is too faint to have been recorded, and in the case of N49 the value for the Band IV flux is very much higher than that derived from the AO. This discrepancy is almost certainly due to a nearby bright source which confuses the automatic source identification routine.

The total luminosity of each supernova remnant has been calculated from the 60 and 100 μm in-band fluxes assuming that the spectrum is Planckian. If F_ν is the flux density in Band IV, B_ν the Planck function, and T the grain temperature derived from the ratio of Bands III to IV then the total flux F is

$$F = \frac{F_\nu \sigma T^4}{\pi B_\nu} \quad (1)$$

where σ is Stephan's constant. The luminosities are calculated for a distance of 55kpc and presented in Table 3.

3 INTERPRETATION

The positional coincidence between the IR and the x-ray sources constitute *prima facie* evidence that the IR emission originates from the SNR. In some $2 \times 10^4 \square'$ (square minutes of arc) of the LMC scanned in these AO's, the density of sources detected at a level of significance $> 10\sigma$ (i.e. at a level comparable to the detections) is $0.002/\square'$ in band IV. Therefore, the probability of detecting an unassociated source at $100\mu m$ falling within a LMC SNR ($d \sim 1'$) is ~ 0.002 . The IR emission probably originates in the SNR and below we investigate the mechanisms which might possibly give rise to their luminosity.

3.1 ENERGY

3.1.1 RADIATIVE ENERGY SOURCES

Galactic far-infrared sources are usually interpreted as being due to dust grains re-radiating the light of luminous young stars. It would therefore be reasonable to look to radiative heating as the energy source. We consider direct heating of dust by luminous young stars and by resonantly trapped Lyman α photons.

Most of the LMC remnants have been classified as type II supernova remnants, (Touhy *et al.* 1982), and therefore are extreme population I objects. N49, N49B, and N63A lie to the north of the LMC in a region rich in bright blue stars and neutral hydrogen. N63A is a member of an association of massive young stars, whereas N49 and N49B which lie 1 degree to the west of N63A, are not members of any association in the same obvious way. The nebula N49 is one of the most extensively studied SNR in the Magellanic Clouds, partly due to its high x-ray, radio, and optical surface brightness, and partly because of its position free from confusion away from the Bar and 30 Doradus. N186D is found in a local peak in the HI distribution (McGee & Milton 1966) to the SW of the bar, only 4' away from the supergiant star R67 which is thought to be similar to η Carina.

3.1.2 STELLAR CANDIDATES FROM CATALOGUES

Objective prism surveys of the LMC have been used to compile catalogues of emission line regions and early stars. There is a high probability that any star in these lists which is classified as *O* or *B* which is fainter than $m_{pg} = 10$ will be a cloud member (Sanduleak, 1970). As the deepest survey's limits are ~ 13.5 (Sanduleak, 1970) most cloud members earlier than *O9* ($L > 4 \times 10^4 L_{\odot}$) should be included.

Mezger (1983) estimates that the dust absorption cross-section per *H* atom in the UV is $\approx 10^{-21} \text{ cm}^2$, which gives an optical depth through a SNR shell of $\tau \approx 0.001nr$, where r is

the remnant radius in parsecs. Taking typical densities, $n \sim 1 \text{ cm}^{-3}$ (McGee & Milton 1966), we see that the efficiency of re-radiating starlight will be at most a few percent, and therefore, a star more luminous than O9 (Panagia 1973) would be required to account for the observed IR luminosity in all the remnants under consideration. Accordingly, if the energy source in any of these remnants is an early star, then it will have been catalogued.

The surveys of Henize (1956), Fehrenbach & Dulfot (1970), and Sanduleak (1970) have been searched for early stars within or around ($\sim 5'$) the SNR's which were detected. Only N186D contains a catalogued early star; S152 = Sand -77 30a ($m_{pg} = 12.4$, Spectral type = "OB", $\alpha = 05^{\text{h}}00^{\text{m}}19.65^{\text{s}}$, $\delta = -70^{\circ}12'27.2''$:1950). There is exact positional correspondence between this star and a source which is seen at $12\mu\text{m}$ (N186D#1). The source is "hot"; the temperature given by the ratio of 12 to $25\mu\text{m}$ flux is 350 K. This source is swamped at 60 and $100\mu\text{m}$ by the far brighter IR emission which peaks at the centre of the radio shell of N186D (designated N186D#2). There are two more notable stars within the vicinity of the SNR, although neither of these correspond to IRAS sources. The luminous supergiant R76 lies $4'$ to the SE of N186D, and DM-70 5006, spectral type BOI (Ardeberg *et al.* 1972) is a similar distance to the SW. R67 and DM-70 5006 are proven cloud members on the basis of radial velocity measurements (Ardeberg *et al.* 1972), but S152's association with the LMC is only based upon its faintness for its spectral type.

N63A contains no catalogued hot stars, but the remnant is embedded in the NE corner of an almost circular diffuse HII region some $4.3'$ in diameter. The HII region's exciting star can probably be identified with Sand -66 163 ($m_{pg} = 12.0$, Spectral type "OB", $\alpha = 05^{\text{h}}35^{\text{m}}37.1^{\text{s}}$, $\delta = -66^{\circ}04'21.3''$:1950) which is $1.3'$ SW of N63A. Any IR emission from the HII region must be very diffuse as the only observed emission peaks at the centre of N63A and is of comparable extent to the SNR. Baseline uncertainties make it difficult to determine whether or not there is any low surface brightness emission associated with the HII region. In any case the HII contribution to the flux can be no more than a few percent.

N49 and N49B are found in a much less densely populated region of the LMC and no early stars are found either in or around them.

3.1.3 LYMAN ALPHA RADIATION

A possible alternative heating mechanism to direct absorption of starlight, is that dust absorbs resonantly trapped $Ly\alpha$. Short wavelength ionising photons originating either from a stellar surface, or from recombination behind the SNR shock are degraded by multiple absorption and subsequent recombination until they are converted into $Ly\alpha$ photons plus Balmer and higher series lines. These $Ly\alpha$ photons are scattered many times, until they either reach the edge of the nebula, or the absorbing H atom decays by 2 photon emission. The multiple scattering process increases the path length which photons must travel, and so the effective cross-section for absorption by dust can be very high. The $Ly\alpha$ luminosity of the remnant can be inferred from the $H\alpha$ flux measurements (Dopita, 1979) and hydrogen recombination theory. At high densities ($n_e \gg 2 \times 10^3 \text{ cm}^{-3}$) every effective recombination (all recombinations except those to the ground state) leads to the production of a $Ly\alpha$ photon, i.e. $\alpha_{Ly\alpha}^{eff}/\alpha_B = 1$ (Mezger *et al.* 1974). The spectra of the remnants show that the line emission arises from collisional excitation rather than photoionisation by a star, so shock conditions should be most appropriate. Optical emission lines indicate that the density is $\leq 10^2 \text{ cm}^{-3}$ in the recombination region (Dopita 1979), so the low density limit $\alpha_{Ly\alpha}^{eff}/\alpha_B = 0.64$ (Mezger *et al.* 1974) is adopted. Taking numerical values for the recombination coefficients from Osterbrock (1978) allows the $Ly\alpha$ flux to be related to the $H\alpha$ flux, giving

$$F_{H\alpha}/F_{Ly\alpha} = 0.13 \quad . \quad (2)$$

Dopita's (1979) measurements of the total $H\alpha$ flux have been used to calculate the $Ly\alpha$ luminosities. The infrared to $Ly\alpha$ luminosity ratio $L_{IR}/L_{Ly\alpha}$ is shown in Table 4. The remnants

N186D, N49, and N63A have an infrared luminosity greater than or comparable to that which could be provided by $Ly\alpha$ radiation. This demonstrates that absorption $Ly\alpha$ radiation from the shock could provide only a fraction of the observed IR luminosity. The only remnant where $Ly\alpha$ may be significant in the energy budget is N49, and even then we would require that the conversion efficiency was close to 100%.

A stellar energy source can be ruled out for N49, N49B, and N63A because the stellar luminosity required to account for the IR corresponds to stars which are brighter than the limiting magnitudes of the catalogues. The radiation from the shock itself has also been shown to be unimportant. In the absence of accurate spectroscopic classification of the star in N186D it is not possible to accurately estimate its luminosity and thus it is difficult to evaluate the contribution which it could make to the measured luminosity. Based on its magnitude, the star in N186D could be as early as O4. An O4 star is sufficiently luminous ($1.3 \times 10^6 L_{\odot}$, Panagia, 1973) to provide the power required, yet remain consistent with the dust temperature and the low expected optical depth, but many of the ionizing photons would have to escape to be compatible with the measured $H\alpha$ luminosity. It is possible that S-152 is the brightest member of a cluster of BO or O9.5 stars, whose integrated luminosity could produce the observed IR source. The presence of R67 and DM-70 5006 indicates that this region of the clouds is an active region of star formation.

We have found that a source of radiative heating probably cannot account for all the IR luminosity associated with N63A, N49, and N49B. Consequently, we assert that a strong case can be made for investigating alternative energy sources in these remnants. In the next section we investigate whether or not collisional heating of dust grains by hot x-ray emitting gas satisfies the energy requirements.

3.2 ENERGETICS OF COLLISIONAL HEATING

The respective masses of infrared (M_d) and x-ray (M_x) emitting material can be calculated. 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 x-ray emitting gas detected by the *Einstein* Observatory is at a temperature of $5.2 \times 10^6 K$ in N49 and, $6.2 \times 10^6 K$ in N63A (Clark *et al.* 1982). If we take a temperature of $6 \times 10^6 K$ to typify all the LMC remnants the corresponding emissivity in the *Einstein* energy band is $\Lambda_x = 3 \times 10^{-23} \text{ erg cm}^3 \text{ s}^{-1}$ for Galactic abundances (Raymond, Cox and Smith 1976). The cooling at this temperature is mainly due to heavy elements. The metallicity of the LMC is about 0.5 of that of the Galaxy (Lequeux *et al.* 1979), therefore assuming that Λ_x is proportional to Z we adopt $\Lambda_x = 1.5 \times 10^{-23} \text{ erg cm}^3 \text{ s}^{-1}$. X-ray emission from a Sedov blast wave with radius r_2 in a medium of number density n_0 will arise from the thin $\Delta r/r_2 \approx 1/12$ region with $n \approx 4n_0$ behind the shock, so that the x-ray luminosity of a Sedov remnant before shell formation can be related to the mass of hot gas by

$$M_x = \left[\frac{\pi L_x r_2^3}{3 \Lambda_x} \right]^{1/2} m \quad (3)$$

Where m is the mean atomic mass, and L_x is the x-ray luminosity from Mathewson *et al.* (1983), and r_2 is the shock radius.

From the ratio of the IR in-band fluxes a dust temperature is derived. If the mass absorption coefficient κ is known, then the dust mass can be found. If the flux at the Earth from a SNR at distance d is F_ν , then the mass of dust M_d is given by

$$M_d = \frac{d^2 F_\nu}{\kappa B_\nu(T_d)} \quad (4)$$

The hot-dust to hot-gas ratio for a mass absorption coefficient of $\kappa = 250 \text{ g/cm}^2$ at $100 \mu m$ (Campbell *et al.* 1981) is shown in Table 4. The dust-to-gas ratio in the LMC, as measured by the ratio of HI column density to the color excess, is a factor of 4 lower than the Galactic value (Koorneef 1982). A dust-to-gas ratio of ~ 0.0015 is therefore probably representative of the LMC. The measured dust-to-gas ratios for N49 and N49B are close to this value, whereas in N63A it is closer to the Galactic value. Given the uncertainties in κ , Λ_x and variations in the local

dust-to-gas ratio, the inferred value for these three remnants are in reasonably good agreement with the hypothesis that this hot dust is embedded in, and heated by the x-ray emitting gas. N186D is clearly different as there must be a large fraction of the remnant's luminosity due to dust in cool gas ($T \ll 10^6 K$) which is unobservable by *Einstein*.

Given that it is reasonable to propose that the hot dust and x-ray emitting gas are mixed together, at least in N49, N49B, and N63A, we now investigate whether or not it is energetically feasible that collisional heating is responsible for maintaining the observed IR luminosities.

Gas grain impacts will deposit energy in dust grains contained within the plasma. This process heats the dust so that the plasma can cool by emission at IR wavelengths. If all the kinetic energy of an impinging particle of mass m is deposited in a grain of radius a , then the heating rate of the grain due to collisions will be

$$H = 4\pi a^2 \frac{1}{4} n \bar{v} \frac{1}{2} m v_{rms}^2 \quad (5)$$

Where $\bar{v}$ and v_{rms} are the mean and root mean square velocities respectively. Thus if gas grain impacts deposited energy with constant efficiency the dust cooling function would be $\propto T^{3/2}$, but at temperatures in excess of $10^7 K$ electrons begin to penetrate the dust grains and Λ_{dust} increases less rapidly than one might expect. The effect of collisional grain heating in hot gas has been investigated by Draine (1981), and Dwek & Werner (1981) using experimental energy loss rates for low energy ($\sim 10 eV$) electron and proton projectiles in intermediate Z targets which are characteristic of grain materials (e.g., C and Si). From these they have determined heating rates for interstellar grains in plasmas with temperatures from 10^5 to $10^9 K$. The functional form of the thermally averaged collisional energy deposition efficiency (Draine 1981), suggests the following approximation to the dust cooling function for a Galactic dust-to-gas ratio obtained by detailed calculation

$$\Lambda_{dust} = 6 \times 10^{-21} (1 + 26a_{-5}^2 T_7^{-3})^{-1/2} \text{ erg cm}^3 \text{ s}^{-1} \quad (6)$$

where a_{-5} is the grain radius in units of $0.1 \mu m$ and T_7 the temperature in units of $10^7 K$. This prescription reproduces Draine's (1981) and Dwek & Werner's (1981) calculations to about 20% over the temperature range $10^5 - 10^8 K$. In cool gas ($T < 10^7 K$) equation (5) is in fact quite accurate.

The ratio of IR luminosity to x-ray luminosity $L_{IR}/L_x = \Lambda_{dust}/\Lambda_x$ if collisional heating is invoked. At $6 \times 10^6 K$ we predict that 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 metallicity which is lower by a factor of 2 we expect $\Lambda_{dust}/\Lambda_x = 15$ for grains of Galactic composition and dimensions.

The infrared to x-ray luminosity ratio is presented in Table 4. 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. The upper limits do not provide very useful constraints on collisional heating.

Once again N186D is peculiar, with a very large "infrared excess" that can not 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, such as the star identified in section 3.1.2 must be important in the energy balance if the very high hot-dust to hot-gas ratio is to be explained.

4 DISCUSSION

We have identified three supernova remnants where a substantial fraction of the associated IR luminosity is most plausibly ascribed to warm dust which is heated by gas-grain collisions. As predicted an impinging gas particle must transfer a substantial fraction of its kinetic energy to the dust grain, and consequently grain cooling of a hot plasma is very efficient.

At the temperature in these SNR ($\sim 6 \times 10^6 K$) grain cooling exceeds atomic processes (free-free, bound-free, and bound-bound transitions) by an order of magnitude. We estimate that $\Lambda_{dust} \sim 2 \times 10^{-22} \text{ erg cm}^3 \text{ s}^{-1}$ under the conditions prevailing in these remnants. A value of $\Lambda_{dust} \sim 8 \times 10^{-22} \text{ erg cm}^3 \text{ s}^{-1}$ at $6 \times 10^6 K$ is expected in the Galaxy where the dust-to-gas ratio which is 4 times higher than in the LMC. Grain cooling will therefore be significant in determining the evolution of supernova remnants.

The structure of a young supernova remnant is usually treated as an adiabatic blast wave propagating into the interstellar medium. In an adiabatic shock the shock temperature drops at a rate which is faster than the rate at which freshly shocked material cools by adiabatic expansion so maintaining the positive temperature gradient into the SNR. Cox (1972) argues that if there is cooling in addition to adiabatic cooling then the temperature gradient will be flattened out and the post-shock temperature will eventually fall below the shock temperature. Radiative cooling triggers an instability which will eventually destroy the adiabatic shock structure. If material entering the shock cools below the shock temperature, then it will find itself sandwiched between older hot shocked gas, which has not cooled appreciably, and freshly shocked gas which has not had time to cool. Consequently, once the shock temperature has dropped sufficiently to allow cooling, shocked gas is compressed and swept up to form a dense cool shell. With the onset of shell formation the expansion law changes from $r \propto t^{2/5}$, which is appropriate for adiabatic expansion to $r_2 \propto t^{2/7}$.

Shell formation starts when the temperature gradient behind the shock becomes flat, i.e. when the rate of cooling due to the expansion and radiative cooling equals the rate at which the shock temperature drops. Following Cox (1972), but taking into account the detailed structure of the shock, the "sag time" t_{sg} is

$$t_{sg} = \frac{9}{8\mu} \frac{3kT_2}{20n_0\Lambda} \quad (7)$$

T_2 is the shock temperature, n_0 is the pre-shock gas number density, Λ is the cooling function, k is the Boltzman constant, and μ is the mean particle mass (see Appendix for details).

Substituting Λ_{dust} in eq. (7) and taking the time evolution of T_2 from the Sedov solution yields

$$t_{sg}^{dust} = 3000 \epsilon_{51}^{2/11} n_0^{-7/11} \text{ yr.} \quad (8)$$

Where ϵ_{51} is the SN energy in units of 10^{51} erg, and n_0 is the pre-shock gas number density in units of cm^{-3} . The sag time of a shock is greatly advanced by dust cooling, and is only $1/7$ of the sag time calculated if atomic cooling alone is considered. The effects of dust cooling means that the adiabatic expansion phase must be very brief. The remnant will have hardly had time to relax to Sedov expansion before radiative effects have profoundly modified the shock structure and altered the ensuing evolution.

Despite the simplicity of the above estimate of t_{sg} it is comparable to the results of Dwek's (1981) numerical investigation of grains in an adiabatic blast wave. In particular Dwek (1981) included the effects of grain destruction by sputtering. Erosion of grains in the hot, dense, post-shock gas could reduce the importance of grain cooling to such an extent that it may be rendered negligible. However, this does not appear to be the case. For a SNR with $\epsilon_{51} = 1$, $n_0 = 1$ Dwek (1981) shows that the temperature behind the shock should begin to sag by the second time step of his calculation at 4700 years. Unfortunately, Dwek's (1981) investigation of the evolution of adiabatic blast waves in dusty gas is unsuited to establishing the evolutionary influence of dust. This is because an adiabatic shock structure was enforced, whereas the shock was in fact becoming radiative very soon after the start of the calculation. Consequently, in this calculation dust cooling did not greatly accelerate the evolution of the remnant. A self-consistent treatment of the evolution of a SNR in a dusty medium is clearly called for so that the effect on the dynamics of grain cooling can be studied in detail.

The above discussion of grain cooling effects has assumed that the SNR expands into a uniform homogeneous medium. This is clearly far from the case. According to McKee and Ostriker (1977) a number of different shock systems are present. Fast shocks in the inter-cloud medium give rise to x-ray emission, while slower shocks in denser clouds results in optical emission. As grain destruction is a strong function of temperature, and hence shock speed (Draine and Salpeter 1979), it is not immediately clear how dust cooling affects the evolution of a SNR in a non-uniform medium. Any future calculations should take account of this extra complexity.

5 CONCLUSION

We have discovered four luminous ($10^4 - 10^5 L_{\odot}$) infrared sources associated with Large Magellanic Cloud supernova remnants. In three cases out of four the evidence based on consideration of the energetics and dust-to-gas ratio indicates that a considerable fraction of the observed infrared luminosity is due to dust grains heated by inelastic collisions with gas particles. These sources are therefore predominantly powered by the store of thermal energy of the hot x-ray emitting plasma contained within the supernova remnant.

The fourth source, N186D, is clearly powered by starlight from nearby luminous star(s). The IR/x-ray properties of N186D are so different from those of the other remnants that we assert that a comparison of the IR and x-ray data allows us to distinguish clearly between collisional and radiative dust heating as the dominant energy source.

We confirm, that as predicted, cooling by collisionally heated dust grains at $T \sim 10^6 K$ is an order of magnitude greater than atomic cooling processes. In the light of this result the evolution of supernova remnants must be reconsidered.

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7 APPENDIX

Once the supernova has swept up a few times its own mass of interstellar gas the SNR stage will have begun, and, if the expansion is adiabatic then the subsequent evolution can be described by the Sedov blast wave solution (Sedov 1959). The characteristics of the SNR shock can then be described in terms of the initial energy ϵ_0 , the density of the interstellar medium ρ_0 , and the time t since the explosion. For example, the position of the shock r_2 is given by

$$r_2 = \xi(\epsilon_0/\rho_0)^{1/5} t^{2/5} \quad (A1)$$

Where ξ is a dimensionless constant of the motion, ~ 1 . Taylor (1950) who independently found Sedov's results numerically, presents useful numerical approximations in terms of the dimensionless distance $\lambda = r/r_2$. The temperature, T , and density, ρ , structure described by Taylor's approximation to Sedov's solution is

$$T(\lambda, t) = T_2 \lambda^{-9/2} [1 + 3/5(1 - \lambda^5)]^{-1/6} \quad (A2)$$

and

$$\rho(\lambda, t) = 4\rho_0 \lambda^{9/2} [1 + 3/5(1 - \lambda^5)]^{-5/2} \quad (A3)$$

T_2 is the shock temperature. Just behind the shock $T \propto \lambda^{-9/2}$, so there is a very steep

temperature gradient behind the shock. Using the adiabatic invariant $T_2(t_0)\rho_2^{1-\gamma}$ to identify an element of gas within the shock which was shocked at time t_0 , we find that its present position is now given by

$$\lambda = \left[\frac{5\tau^{4/5} + 3}{8} \right]^{-1/5} \quad (A4)$$

where $\tau = t/t_0$, and $\gamma = 5/3$. The temperature history of an element of gas just entering the shock is therefore, to a very good approximation

$$T = T_2 \left[\frac{5\tau^{4/5} + 3}{8} \right]^{9/10} \quad (A5)$$

In an adiabatic shock the shock temperature drops at a rate

$$\frac{dT_2}{dt} = -\frac{6}{5} \frac{T_2}{t} \quad (A6)$$

which is faster than the rate at which freshly shocked material ($\tau \approx 1$) cools by adiabatic expansion

$$\frac{dT}{dt} = -\frac{3}{4} \frac{T_2}{t} \quad (A7)$$

so maintaining the positive temperature gradient into the SNR.

Shell formation starts when the temperature gradient behind the shock becomes flat, i.e. when the rate of cooling due to expansion and radiative cooling equals the rate at which the shock temperature drops. Cox (1972), who first carried this type of analysis, approximated the adiabatic cooling rate by T_2/t , determined from Heiles' (1964) graphs illustrating Sedov's exact solutions. But here, using the analytic result above, we find a slower rate yielding a longer (44%) time to reach temperature sag

$$t_{sg} = \frac{9}{8\mu} \frac{3kT_2}{20n_0\Lambda} \quad (A8)$$

μ is the mean particle mass in a.m.u., n_0 is the pre-shock number density and Λ is the cooling function for hot gas, defined so that the luminosity per unit volume = $n_e n_i \Lambda$, where n_e , and n_i are the electron and hydrogen ion number densities respectively.

TABLE 1

Positional Information

SNR	Band	Position (Epoch 1950.0)					
		α			δ		
		H	M	S	°	'	"
N63A	I	05	35	42	-66	03	54
	II	05	35	39	-66	03	47
	III	05	35	35	-66	03	39
	IV	05	35	30	-66	03	45
	Mean IR	05	35	39	-66	03	46
X-Ray		05	35	41	-66	04	03
N49	I	05	25	58	-66	07	30
	II	05	25	57	-66	07	34
	III	05	25	56	-66	07	34
	IV	05	25	41	-66	07	17
	Mean IR	05	25	56	-66	07	28
X-Ray		05	25	56	-66	07	31

TABLE 1 continued

SNR	Band	Position (Epoch 1950.0)					
		α			δ		
		H	M	S	°	'	"
N49B	I	...	...	...	...	...	...
	II	...	...	...	...	...	...
	III	05	25	20	-66	02	13
	IV	05	25	06	-66	02	34
Mean IR		05	25	21	-66	02	24
X-Ray		05	25	19	-66	01	54
N186D #1	I	05	00	20	-70	12	27
	II	...	...	...	...	...	...
	III	...	...	...	...	...	...
	IV	...	...	...	...	...	...
N186D #2	I	05	00	12	-70	13	42
	II	05	00	03	-70	13	43
	III	05	00	03	-70	13	43
	IV	04	59	53	-70	13	45
Mean IR		05	00	08	-70	13	42
X-Ray		05	00	20	-70	12	13

TABLE 2
IRAS IN BAND FLUXES^{1,2}

SNR	I	II	III	IV
N63A	0.42	1.0	4.66	5.47
N49	0.22	0.54	2.4	1.7
N49B	...	...	0.26(10)	0.31(8)
N186D#2	0.23(8)	0.21	1.39	3.34
N103B	...	...	<0.2	<0.6
N135	...	...	<2.0	<0.7
N206	...	...	<0.8	<5.0

¹ In units of $10^{-13} \text{ W m}^{-2}$

² All limits are 3σ . Where the statistical uncertainty is more than 5%, it is shown as a percentage in brackets following the flux entry.

TABLE 3

Source Luminosity and Temperature

SNR	T(K)	$L(10^5 L_{\odot}, d = 55\text{kpc})$
N63A	35	2.0
N49	50	0.7
N493	35	0.13
N186D#2	30	1.3
N103B	35 ¹	<1.7
N135	35 ¹	<1.2
N206	35 ¹	<1.9

¹ Assumed temperature

TABLE 4

Infrared to Lyman α and x-ray luminosity ratios, and dust-to-gas ratio.

SNR	$L_{IR}/L_{Ly\alpha}$	M_d/M_x	L_{IR}/L_x
N63A	14	0.02	14.0
N49	2.9	0.003	13.9
N49B	... ¹	0.001	5.7
N186D#2	25	0.1	2500
N103B	... ¹	<0.2	<40
N135	<2	<0.04	<600
N206	<8	<0.05	<1000

¹ No optical observations are available for these remnants

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FIGURE CAPTIONS

Figure 1.

X-ray contours of N49 (reproduced with permission) from Mathewson *et al.* (1983) are shown along with the mean IR position indicated by a cross. The positional uncertainty (1σ) is represented by the rectangle

Figure 2.

X-ray contours of N186D from Mathewson *et al.* (1983) are shown along with the mean IR position indicated by a cross. The positional uncertainty (1σ) is represented by the rectangle

Figure 3.

X-ray contours of N63A from Mathewson *et al.* (1983) are shown along with the mean IR position indicated by a cross. The positional uncertainty (1σ) is represented by the rectangle

Figure 4.

X-ray contours of N49B from Mathewson *et al.* (1983) are shown along with the mean IR position indicated by a cross. The positional uncertainty (1σ) is represented by the rectangle

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Figure 1

Figure 2

Figure 3

Figure 4

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