THE ASTROPHYSICAL JOURNAL, 319:126–135, 1987 August 1

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

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Received 1986 August 12; accepted 1987 January 26

ABSTRACT

IRAS additional observations are presented which show that luminous (10^4–10^5 $L_\odot$) far-infrared sources are associated with the Large Magellanic Cloud supernova remnants N63A, N49, N49B, and N186D. Comparison of the infrared and X-ray data shows that a substantial fraction of the infrared emission from three of the remnants can be accounted for by collisionally heated dust. The ratio of dust-grain cooling to total atomic cooling by lines, recombination, and bremsstrahlung is ~ 10 in X-ray emitting gas ($T \approx 10^6$ K). The evolution of a supernova remnant in a two-phase interstellar medium is considered, and it is concluded that dust cooling will not dominate supernova remnant evolution, but it probably accelerates the process.

Subject headings: galaxies: Magellanic Clouds — infrared: sources — interstellar: grains — nebulae: supernova remnants — radiation mechanism

I. 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 and Silk 1973). The energy deposited raises the grain temperature to between a few tens to a few hundred K, 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 be an order of magnitude greater than the normal cooling rate of a dust free plasma (Draine 1981; Dwek and 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 could only provide poor limits on the efficiency of dust cooling. Wright *et al.* (1980) have obtained far-infrared ($\lambda = 100$ μm) upper limits for Cas A, Tycho, and Kepler, Unfortunately, these young (~ 300 yr) 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. But some of the flux is due to emission lines (Dinerstein *et al.* 1987). Before the launch of *IRAS* the only observation of far-infrared emission from a supernova remnant was the detection of DR 4 (Campbell, Hoffmann, and Thronson 1981) and the Crab Nebula (Wright *et al.* 1979). DR 4 is associated with a complex of H II 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 nonthermal origin. The only other IR data are the 10 μm observations of N63A and N49 in the Large Magellanic Cloud (LMC) by D'Odorico and Moorwood (1982). These place only very poor limits on the mass of cool dust. Recently Marley and Marsden (1985) have presented *IRAS* observations of Cas A and interpreted the detected flux as due to collisionally heated dust grains.

We decided to observe LMC remnants in preference to Galactic remnants for several reasons. The preflight estimates of the *IRAS* confusion limit in the Galactic plane (Joseph and Robertson 1982) suggested that sensitive limits could only be achieved for a few high Galactic latitude SNRs. It was also not expected that the observatory would be able to observe large low surface brightness extended objects. (This, of course, turned out not to be the case.) Not only do the LMC remnants form an extremely well-studied sample at X-ray, optical, and radio wavelengths, but they also 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 SNRs also have the unique property among well-studied remnants that they are at the same distance (in the following discussion we adopt 55 kpc). Unlike the Galactic remnants, for which distances are often uncertain, intrinsic properties such as size and luminosity can be derived.

Four Magellanic Cloud remnants are detected in the additional observation data which we have obtained. The signal-to-noise ratio is high, and the positional correspondence is excellent, so 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 we find no luminous stars in the other remnants. A comparison of the *IRAS* data and X-ray observations shows that the most probable source of the infrared radiation from N63A, N49, and N49B is dust heated collisionally by the X-ray emitting plasma. We then consider the effects of grain cooling upon supernova remnant evolution.

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

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II. OBSERVATIONS

a) The IRAS Satellite

The *IRAS* satellite consists of a spacecraft which accomodates a liquid helium–cooled cryostat containing a cooled telescope. The telescope is a f/9.6 Ritchey-Chrétien design with a 0.57 m 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 time scale of seconds. (A detailed description of the mission can be found in Neugebauer *et al.* 1984).

b) 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 (AOs). 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 R.A.-decl. 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).

c) Results

Of the nine LMC remnants for which *IRAS* AO data have been obtained, four are unambiguously associated with IR sources, i.e., the remnant falls within the *IRAS* positional uncertainty error box. The position of the IR source is shown on X-ray maps of the remnants in Figures 1–4. From these figures it can be seen that 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 (radius $\sim 1'$) is offset from the X-ray peak by $\sim 2'$ to the SW.

There are upper limits for a further three remnants. The remaining two were too close to complexes of extended bright sources to obtain useful limits. The positional data are summarized in Table 1, and the observed fluxes are presented in Table 2.

The fluxes derived from AO observations have been cross-checked with the *IRAS* survey *Point Source Catalog*. This can

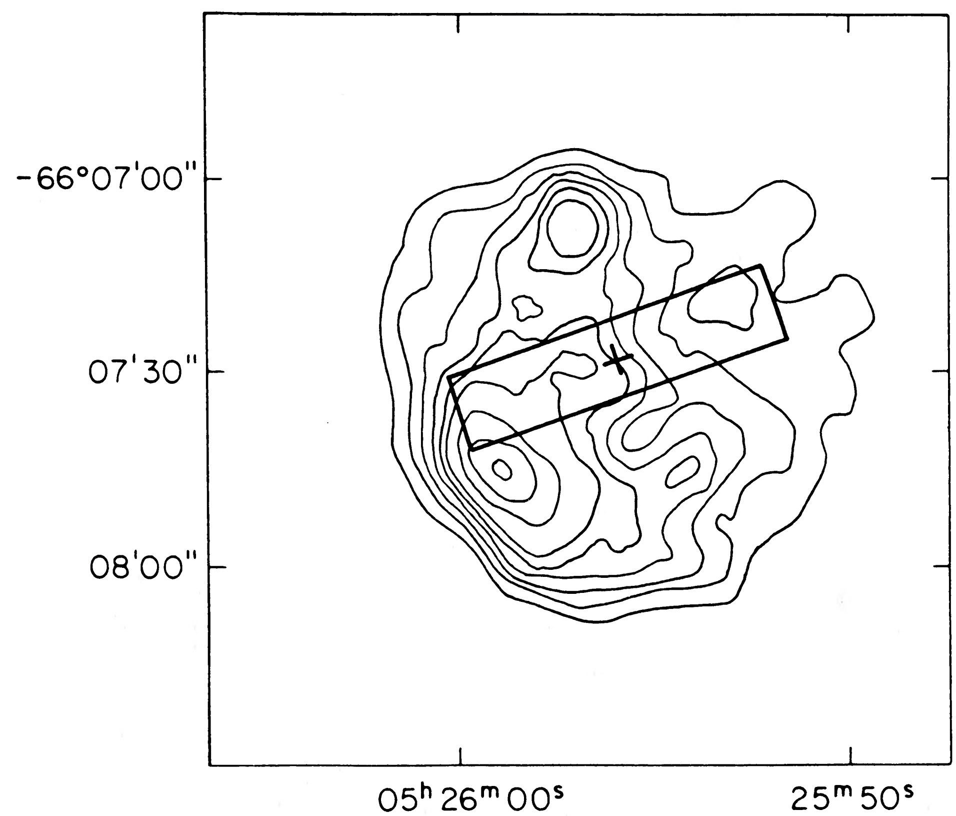

FIG. 1.—The mean IR position of N49 is indicated by a cross along with the X-ray contours (reproduced with permission) from Mathewson *et al.* (1983). The positional uncertainty (1 σ) is represented by the rectangle.

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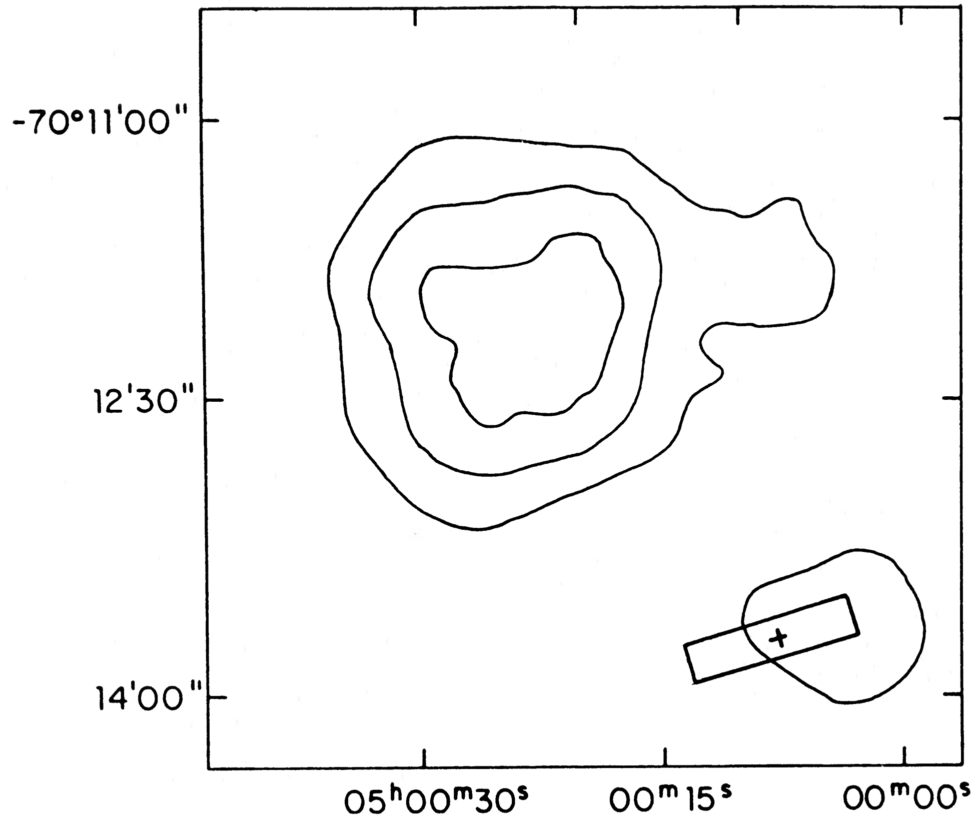

FIG. 2.—The mean IR position of N186D is indicated by a cross, along with the X-ray contours from Mathewson *et al.* (1983). The positional uncertainty (1 σ) is represented by the rectangle.

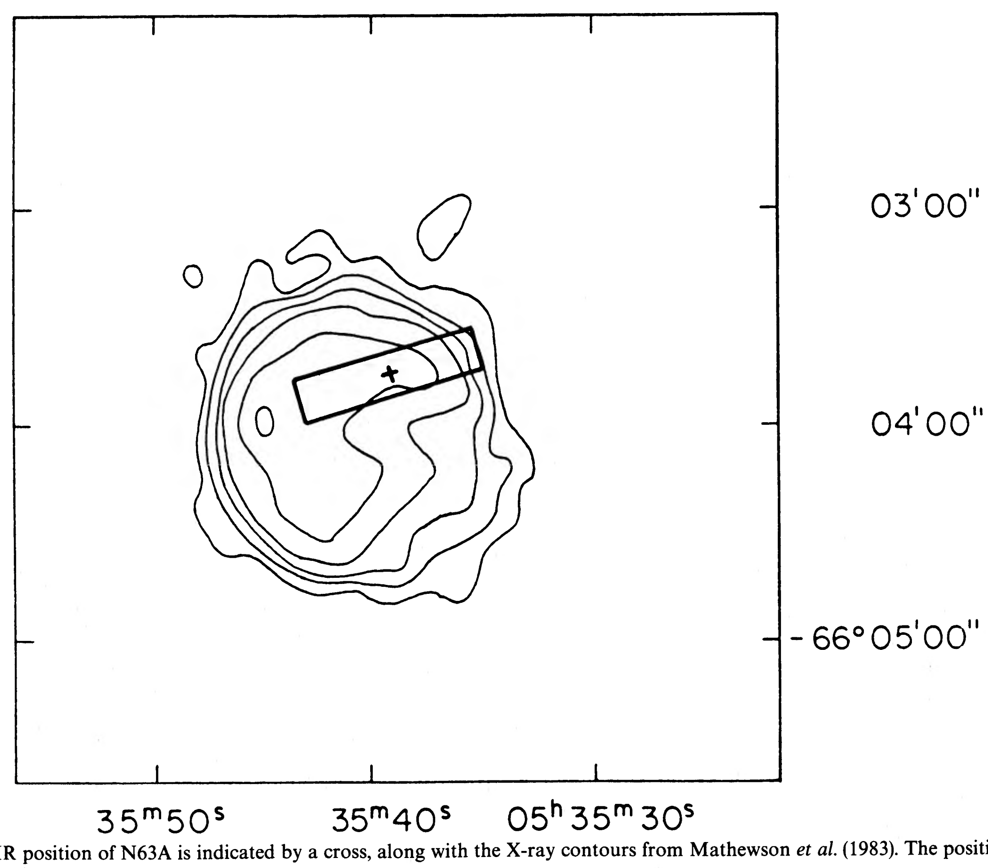

FIG. 3.—The mean IR position of N63A is indicated by a cross, along with the X-ray contours from Mathewson *et al.* (1983). The positional uncertainty (1 σ) is represented by the rectangle.

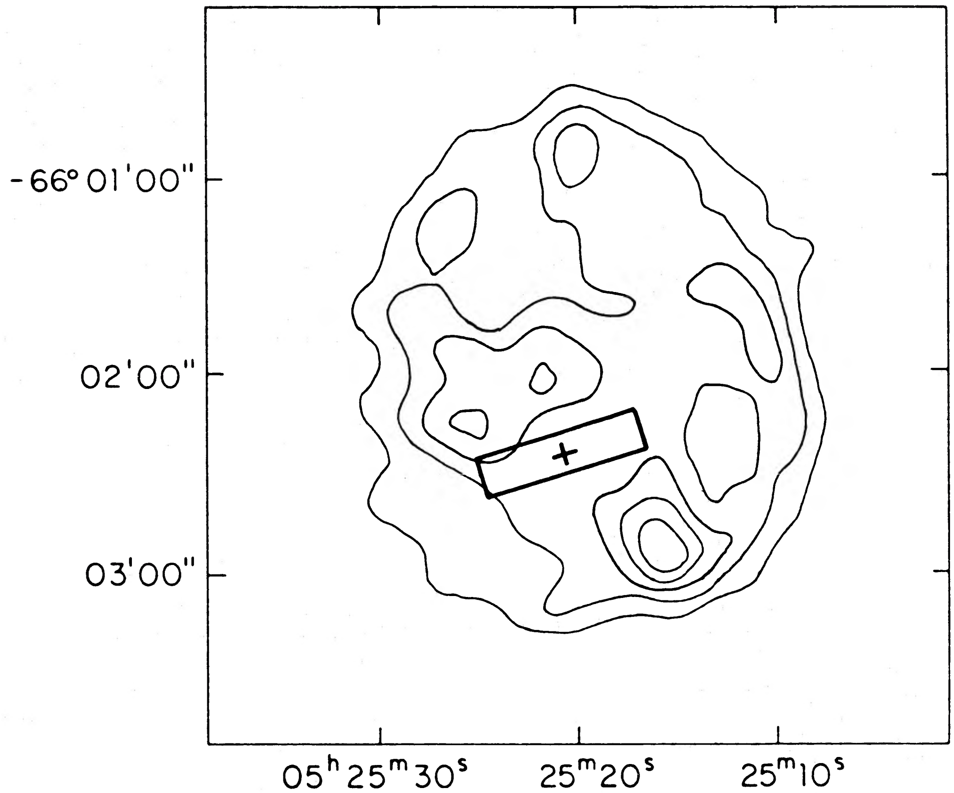

FIG. 4.—The mean IR position of N49B is indicated by a cross, along with the X-ray contours from Mathewson *et al.* (1983). The positional uncertainty (1 σ) is represented by the rectangle.

only be done for the brightest remnants because an AO consists of between four and eight 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.

Since the *IRAS* bands do not overlap appreciably, the total observed (i.e., 8–120 μm) luminosity can be found simply by summing the measured in-band fluxes. A significant fraction of the luminosity of these sources is unobserved because the 60–100 μm flux ratios indicate temperatures of 30–40 K. To estimate the total luminosity we have fitted a blackbody with a λ^{-1} grain emissivity law (Gatley *et al.* 1977; Gatley *et al.* 1979) to the band III and band IV data and integrated the emission longward of 120 μm. This contribution is then added to the observed luminosity to obtain an estimate of the total luminosity. The observed 8–120 μm luminosity, the band III–IV temperature, and the total luminosity, calculated for a distance of 55 kpc, are presented in Table 3.

III. 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 2×10^4 square arc minutes of the LMC scanned in these AOs, the density of sources detected at a level of significance $> 10\ \sigma$ (i.e., at a level comparable to the SNRs) is 0.002 per square arc minute in band IV. Therefore, the probability of detecting an unassociated source at 100 μm falling within a LMC SNR ($d \approx 1'$) is $\sim$0.002. The IR emission probably originates in the SNR, and below we investigate the mechanisms which might possibly give rise to their luminosity.

The IR sources considered here are thermal in nature. Although these SNRs are conspicuous objects at radio frequencies, extrapolation of measured fluxes (taken from Mathewson *et al.* 1983) to 100 μm indicates that the nonthermal contribution to the *IRAS* fluxes is 0.02%–0.4%. We have also considered the contribution made by the IR fine-structure lines [O III] 51.7 and 88.4 μm, [N II] 76.3 and 121.7 μm, and [N III] 57.3 μm. We estimate that, for normal abundances, a band IV flux of $< 2 \times 10^{-17}$ W m^{-2} in these lines so a significant contribution can be ruled out. If any of the remnants are interacting with dense molecular material, like IC 443, then [O I] 63.1 μm may contribute to the band III flux.

a) Energetics

i) *Radiative Energy Sources*

Galactic far-infrared sources are usually interpreted as due to dust grains reradiating 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 (Tuohy *et al.* 1982), and therefore they 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° to the west of N63A, are not members of any association in the same obvious way. The nebula N49 is one of the most exten-

TABLE 1

POSITIONAL INFORMATION

SNR	BAND	POSITION (Epoch 1950.0) α	δ
N63A	I	$05^h35^m42^s$	−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
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 no. 1	I	05 00 20	−70 12 27
	II	...	...
	III	...	...
	IV	...	...
N186D no. 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

sively studied SNRs, in the Magellanic Clouds, partly due to its high X-ray, radio, and optical surface brightness, and partly because of its position away from the Bar and 30 Doradus which ensures that it is free from confusion. N186D is found in a local peak in the H I distribution (McGee and 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.

ii) *Stellar Candidates from Catalogs*

Objective prism surveys of the LMC have been used to compile catalogs 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 and 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 ($L > 4 \times 10^4\ L_\odot$; Panagia 1973) should be included.

Mezger, Mathis, and Panagia (1982) estimate that the dust absorption cross section per H atom in the UV is $\approx 10^{-21}$ 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, $n \approx 1$ cm^{-3} (McGee and Milton 1966), we see that the efficiency of reradiating starlight will be at most a few percent, and therefore, a star more luminous than O9 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 cataloged.

The surveys of Henize (1956), Fehrenbach and Dulfot (1970), and Sanduleak (1970) have been searched for early stars within or around (~5′) the SNRs which were detected. Only N186D contains a cataloged early star; S152 = Sand −77 30a (m_{pg} = 12.4, spectral type = "OB," $\alpha = 05^h00^m19^s.65$, δ = −70°12′27″.2:1950). There is exact positional correspondence between this star and a source which is seen at 12 μm (N186D no. 1). The source is "hot"; the temperature given by the ratio of 12 to 25 μm flux is 350 K. This source is swamped at 60 and 100 μm by the far brighter IR emission which peaks at the center of the radio shell of N186D (designated N186D no. 2). There are two more notable stars within the vicinity of this SNR, although neither of these correspond to *IRAS* sources. The luminous supergiant R67 lies 4′ to the SE of N186D, DM-70 5006, spectral type B0 I (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 cataloged hot stars, but the remnant is embedded in the NE corner of an almost circular diffuse H II region some 4′.3 in diameter. The H II region's exciting star can probably be identified with Sand −66 163 (m_{pg} = 12.0, spectral type "OB," $\alpha = 05^h35^m37^s.1$ δ = −66°04′21″.3:1950) which is 1′.3 SW of N63A. Any IR emission from the H II region powered by this star must be very diffuse as the only observed emission peaks at the center 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 H II region. In any case the H II region's 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.

TABLE 2

IRAS IN BAND FLUXES[a,b]

SNR	I	II	III	IV
N63A	0.42	1.0	4.66	5.47
N49	0.22	0.54	2.4	1.7
N49B	<0.1	<0.1	0.26 (10)	0.31 (8)
N186D no. 2	0.23 (8)	0.21	1.39	3.34
N103B	...	...	<5	<2
N135	...	...	<2	<7
N206	...	...	<1	<5

[a] In units of 10^{-13} W m^{-2}.

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

TABLE 3

SOURCE LUMINOSITY AND TEMPERATURE

SNR	T[a] (K)	L(8–120 μm)[b] ($10^5\ L_\odot$)	L_{tot}[b] ($10^5\ L_\odot$)
N63A	30	1.1	1.8
N49	40	0.46	0.61
N49B	30	0.054	0.094
N186D no. 2	25	0.49	1.1
N103B	35	<0.6	<0.6
N135	35	<0.8	<3.0
N206	35	<0.6	<2.0

[a] Temperature derived assuming a λ^{-1} grain emissivity law. Upper limits were derived assuming a grain temperature of 35 K.

[b] A distance of 55 kpc was assumed.

iii) *Lyman-Alpha Radiation*

An alternative heating mechanism to direct absorption of starlight is that dust absorbs resonantly trapped Lyα. Short wavelength ionizing 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 Lyα photons plus Balmer and higher series lines. In a pure hydrogen H II region Lyα photons are scattered many times, until they either reach the edge of the nebula, or the absorbing H atom decays by two-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 Lyα luminosity of the remnant can be inferred from the Hα flux measurements (Dopita 1979) and hydrogen recombination theory. At high densities ($n_e \gg 2 \times 10^3$ cm^{-3}) every effective recombination (all recombinations except those to the ground state) leads to the production of a Lyα photon, i.e., $\alpha^{\rm eff}_{\rm Ly\alpha}/\alpha_B = 1$ (Mezger, Smith, and Churchwell 1974). Optical emission lines indicate that the density is $\leq 10^2$ cm^{-3} in the recombination region (Dopita 1979), so the low density limit $\alpha^{\rm eff}_{\rm Ly\alpha}/\alpha_B = 0.64$ (Mezger, Smith, and Churchwell 1974) is adopted. Taking numerical values for the recombination coefficients from Osterbrock (1978) allows the Lyα flux to be related to the Hα flux, giving

$$F_{\rm H\alpha}/F_{\rm Ly\alpha} = 0.13 \; . \qquad (1)$$

Dopita's (1979) measurements of the total Hα flux have been used to calculate the Lyα luminosities. The infrared to Lyα luminosity ratio $L_{\rm IR}/L_{\rm Ly\alpha}$ 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 Lyα radiation. This demonstrates that absorption of Lyα radiation from the shock could provide only a fraction of the observed IR luminosity. The only remnant where Lyα 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 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 (1.3×10^6 $L_\odot$; 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 Hα luminosity. It is possible that S152 is the brightest member of a cluster of B0 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.

TABLE 4

INFRARED TO LYMAN-α AND X-RAY LUMINOSITY RATIOS AND DUST-TO-GAS RATIO

SNR	$L_{\rm IR}/L_{\rm Ly\alpha}$[a]	M_d/M_x	$L_{\rm IR}/L_x$
N63A	12	0.03	12
N49	2.4	0.006	12
N49B	...	0.002	4
N186D no. 2	20	0.3	2100
N103B	...	<0.03	<12
N135	<30	<0.03	<1200
N206	<10	<0.03	<1000

[a] No optical observations are available for N49B of N103B.

b) 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 5.2×10^6 K in N49 and, 6.2×10^6 K in N63A (Clark *et al.* 1982). If we take a temperature of 6×10^6 K to typify all the LMC remnants, the corresponding emissivity in the *Einstein* energy band is $\Lambda_x = 3 \times 10^{-23}$ ergs cm^3 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 $\Lambda_x = 1.5 \times 10^{-23}$ ergs cm^3 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 can be related to the mass of hot gas by

$$M_x = \left(\frac{\pi L_x r_2^3}{3\Lambda_x}\right)^{1/2} m \; . \qquad (2)$$

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

If the IR flux at Earth from a SNR at distance d is F_ν, then the mass of radiating dust M_d is given by

$$M_d = \frac{d^2 F_\nu}{\kappa B_\nu(T_g)} \; . \qquad (3)$$

Where, as in § IIc, the grain temperature has been determined assuming a λ^{-1} emissivity law. The hot-dust to hot-gas ratio calculated for a mass absorption coefficient of $\kappa = 250$ cm^2 g^{-1} at 100 μm (Gatley *et al.* 1977; Harvey, Hoffmann, and Campbell 1979; Harvey, Campbell, and Hoffmann 1979; Harvey, Thronson, and Gatley 1979) is shown in Table 4. The dust-to-gas ratio in the LMC, as measured by the ratio of H I 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 N49B is close to this value, the value for N49 is comparable to the Galactic value, and 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 remnant's luminosity is due to dust in cool gas ($T \ll 10^6$ K) which is unobservable by *Einstein*. This may explain why the IR source associated with N186D does not coincide precisely with the peak of the X-ray emission as does the emission from N63A, N49, and N49B.

It is important to emphasize that there are several uncertainties in our determination of the dust-to-gas ratio. There are uncertainties in κ, Λ_x, L_x, and undoubtedly there are variations in local abundances and dust-to-gas ratio. 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.

As an example of the large uncertainties involved, consider the value of the grain opacity which we have adopted. The value of κ is derived from the correlation between the H I column density and color excess $E(B-V)$, and measurements of $\tau_V/\tau_{100\,\mu m}$ in Galactic H II regions and toward the Galactic center. Our value of 250 $cm^2\ g^{-1}$ is consistent with the interstellar extinction curve of Mezger, Mathis, and Panagia (1982). However, more recent work on the optical properties of grains by Draine and Lee (1984) suggests a much lower value of the grain opacity at 100 μm. A value of $\kappa \approx 50\ cm^2\ g^{-1}$, derived from the studies of the reflection nebula NGC 7023 (Whitcomb *et al.* 1981) and *IRAS* observations of the Galactic cirrus (Low *et al.* 1984), is compatible with the work of Draine and Lee. Adoption of a lower value of the grain opacity would increase our estimate of the dust-to-gas ratio. However, the dust-to-gas ratios presented in Table 4 are probably underestimates because the mass of X-ray emitting gas was determined using simple conversion from instrumental counts to flux which probably tends to systematically underestimate SNR luminosities by up to a factor of 2 (Long, Helfand, and Grabelsky 1981). Thus if we adopted a lower value of κ we could still argue strongly that the hot dust and X-ray emitting gas are mixed together. And so despite these difficulties it is unreasonable to invoke collisional heating, 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 gas particle of mass m is deposited in a grain of radius a, then the heating rate of the grain due to collisions in gas of temperature T will be (Draine 1981)

$$H = \pi a^2 n \left(\frac{8kT}{\pi m}\right)^{1/2} 2kT\ . \quad (4)$$

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 and Werner (1981) using experimental energy loss rates for low energy ($\sim$100–1000 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

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

where a_{-5} is the grain radius in units of 0.1 μm and T_7 the temperature in units of 10^7 K. This prescription reproduces Draine's (1981) and Dwek and Werner's (1981) calculations to about 20% over the temperature range 10^5–10^8 K. In cool gas ($T < 10^7$ K), equation (4) 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 6×10^6 K we predict that this ratio should be $\sim$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 observed infrared to X-ray luminosity ratio is presented in Table 4. 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). The total IR luminosity is probably known to better than 25%. However, as noted above the X-ray luminosity 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. The upper limits do not provide very useful constrains 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 § IIIa(ii) must be important in the energy balance if the very high hot-dust to hot-gas ratio is to be explained.

IV. 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 temperatures 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 $\Lambda_{dust} \approx 2 \times 10^{-22}$ ergs $cm^3\ s^{-1}$ under the conditions prevailing in these remnants. A value of $\Lambda_{dust} \approx 8 \times 10^{-22}$ ergs $cm^3\ s^{-1}$ at 6×10^6 K is expected in the Galaxy where the dust-to-gas ratio which is 4 times higher than in the LMC. Grain cooling could 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 postshock 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

$$t_{sg} = \frac{2}{5}\left(\frac{n_i + n_e}{n_i n_e}\right)\frac{3kT_2}{8\Lambda}, \tag{6}$$

where n_e and n_i are the preshock electron and ion number densities, T_2 is the shock temperature, Λ is the cooling function, and k is the Boltzmann constant (see the Appendix for details).

Our estimate of $\Lambda_{dust} = 8 \times 10^{-22}$ ergs cm^3 s^{-1}, for a Galactic dust-to-gas ratio, yields

$$t_{sg}^{dust} = 7000\epsilon_{51}^{2/11} n_0^{-7/11} \text{ yr}, \tag{7}$$

where the time evolution of T_2 substituted in equation (6) comes from the Sedov solution, ϵ_{51} is the supernova energy in units of 10^{51} ergs, and n_0 is the preshock gas number density in units of cm^{-3}. The sag time indicates when cooling starts to modify the structure of the remnant. However, cooling does not begin to dominate the dynamics of the supernova remnant until $t \approx t_{dyn} = 2^{5/11} t_{sg}$ (see the Appendix).

Our observations indicate that dust cooling exceeds atomic cooling processes by an order of magnitude. Consequently, departures from adiabaticity occur sooner than predicted by calculations which only included atomic processes. If t_{sg} and t_{dyn} signpost important events in the evolution of SNRs, then we might expect that dust cooling speeds the evolution by a factor of ~ 3.

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, postshock 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 yr.

We note that our estimate of t_{sg} is conservative since we have used the measured value of Λ_{dust} for $T = 6 \times 10^6$ K, and not allowed for the fact that equation (4) indicates that Λ_{dust} rises with temperature. If equation (5) is used to extrapolate Λ_{dust} to higher temperatures, then t_{sg} could be as short as $3000\epsilon_{51}^{2/11} n_0^{-7/11}$ yr.

In order to establish under what conditions grain cooling modifies SNR evolution, it is important to investigate the effects of grain destruction. The thermal grain sputtering rate calculations of Draine and Salpeter (1979) can be summarized as

$$\frac{da}{dt} = 9 \times 10^{-7} n(1 + 0.002T_7^{-3})^{-1} \ \mu\text{m yr}^{-1}. \tag{8}$$

If we define the lifetime of a grain, t_g of radius a as $a(da/dt)^{-1}$, then taking the temperature and density from the Sedov solution, we find that on entering the shock the ratio of grain lifetime to the time for grains to affect the dynamics is

$$\frac{t_g}{t_{dyn}^{dust}} \approx 3a_{-5}(\epsilon_{51} n_0^2)^{-2/11}. \tag{9}$$

Thus, if $\epsilon_{51} = 1$ the lifetime of a 0.1 μm grain always exceeds t_{dyn}^{dust} so long as $n_0 < 20$ cm^{-3}. Equation (9) assumes complete coupling between grain and gas motions, and therefore it is probably only correct to a factor of 2 because it neglects effects which might enhance grain destruction behind the shock such as betatron acceleration.

Accordingly, if the ISM were uniform and homogeneous with a mean density of ~ 1 cm^{-3} then it seems most likely that SNR lifetime would be very short, and the remnant would hardly have time to relax to Sedov expansion before radiative effects modified the shock structure and the dynamics. Any structure in the ISM profoundly changes this conclusion.

Consider a simple two-phase model for the ISM consisting of diffuse clouds with $n = 20$ cm^{-3} and an intercloud medium of $n = 0.1$ cm^{-3} (cf. Spitzer 1978). The grain lifetime in the intercloud medium is 3×10^5 yr and exceeds even the time for atomic cooling processes to affect the dynamics. In the low-density medium, which supports the X-ray emitting blast wave, $t_{dyn}^{dust} = 4 \times 10^4$ yr. By this time the shock temperature has dropped to 1×10^6 K, equation (7) is no longer valid, and dust and atomic cooling rates are approximately equal. Consequently, the remnant remains adiabatic while dust cooling dominates, and although dust cooling will speed the onset shell formation after t_{dyn}, dust and atomic cooling will be equally important in this process.

The shocks driven into the clouds will probably 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 IC 443 where $\sim 30\%$ of the iron-bearing grains are destroyed in shocks propagating into clouds with $n_0 \approx 10$–20 cm^{-3} (Graham, Wright, and Longmore 1987).

V. 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 $T \approx 10^6$ K is an order of magnitude greater than atomic cooling processes. Dust cooling will probably accelerate SNR evolution, but not dominate it. Since the effects of dust cooling are a strong function of the preshock density, any further theoretical investigations of the role of dust should take into account the inhomogeneity of the ISM.

These observations were obtained as part of the UK Science and Engineering Research Council collaboration in the *IRAS* project, which was developed and operated by the Netherlands Agency for Aerospace Programs, the US National Aeronautics and Space Administration, and the UK Science and Engineering Research Council. We are particularly indebted to the software support provided by Drs. Abolins and Fairclough as part of the Rutherford-Appleton Laboratories Starlink *IRAS* data reduction project.

M. F. B. acknowledges the receipt of an SERC Advanced Fellowship, and J. R. G. is supported by a Royal Commission for the Exhibition of 1851 Fellowship, and a NATO/SERC Fellowship. This work was supported in part by US Department of Energy contract DE-AC03-76SF00098.

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

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

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

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

and

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

T_2 is the shock temperature. Just behind the shock $T \propto \lambda^{-4}$, 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

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

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,

$$T = T_2\left(\frac{5\tau^{4/5} + 3}{8}\right)^{4/5} . \tag{A5}$$

In an adiabatic shock the shock temperature drops at a rate

$$\frac{dT_2}{dt} = -\frac{6T_2}{5t} , \tag{A6}$$

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

$$\frac{dT}{dt} = -\frac{4T_2}{5t} , \tag{A7}$$

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 out this type of analysis, approximated the adiabatic cooling rate by T_2/t, determined from Heiles's (1964) graphs illustrating Sedov's exact solutions. Using the analytic result above, we find a slower rate yielding a longer (40%) time to reach temperature sag

$$t_{sg} = \frac{2}{5}\left(\frac{n_i + n_e}{n_i n_e}\right)\frac{3kT_2}{8\Lambda} , \tag{A8}$$

where n_e and n_i are the preshock electron and ion number densities, and Λ is the cooling function for hot gas, defined so that the luminosity per unit volume $= n_e n_i \Lambda$.

Remnant dynamics are affected by cooling when the temperature of a mass element drops faster from radiation than from expansion (Cox 1972). This time denoted as t_{dyn} is given by

$$t_{dyn} = \frac{4}{5}\left(\frac{n_i + n_e}{n_i n_e}\right)\frac{3kT_2}{8\Lambda} . \tag{A9}$$

REFERENCES

Abolins, J. A., Fairclough, J. H., Richards, P. J., and Stewart, B. C. 1985, Starlink Users Note, **83**, 1.
Ardeberg, A., Brunet, J.-P., Maurice, E., and Prevot, L. 1972, *Astr. Ap.*, **6**, 249.
Campbell, M. F., Hoffmann, W. F., and Thronson, H. A. 1981, *Ap. J.*, **247**, 530.
Clark, D. H., Tuohy, I. R., Syzmkowiak, A. E., Dopita, M. A., Mathewson, D. S., and Culhane, J. L. 1982, *Ap. J.*, **255**, 440.
Cox, D. P. 1972, *Ap. J.*, **178**, 159.
Dinerstein, H. L., Lester, D. F., Rank, D. M., Werner, M. W., and Wooden, D. H. 1987, *Ap. J.*, **312**, 314.
Dinerstein, H. L., Werner, M. W., Dwek, E., and Capps, R. C. 1982, *Ap. J.*, **255**, 552.
D'Odorico, S., and Moorwood, A. F. M. 1982, *ESO Messenger*, **28**, 29.
Dopita, M. A. 1979, *Ap. J. Suppl.*, **40**, 455.
Draine, B. T. 1981, *Ap. J.*, **245**, 880.
Draine, B. T., and Lee, M. L. 1984, *Ap. J.*, **285**, 89.
Draine, B. T., and Salpeter, E. E. 1979, *Ap. J.*, **231**, 77.
Dwek, E. 1981, *Ap. J.*, **247**, 614.
Dwek, E., and Werner, M. W. 1981, *Ap. J.*, **248**, 138.
Feherenbach, C., and Duflot, M. 1970, *Astr. Ap. Special Suppl.*, **1**, 1.
Gatley, I., Becklin, E. E., Sellgren, K., and Werner, M. W. 1979, *Ap. J.*, **233**, 575.
Gatley, I., Becklin, E. E., Werner, M. W., and Wynn-Williams, C. G. 1977, *Ap. J.*, **216**, 277.
Graham, J. R. 1985, Ph.D. thesis, University of London.
Graham, J. R., Meikle, W. P. S., Evans, A., Bode, M. F., and Albinson, J. S. 1985, in *Proc. First International IRAS Symposium*, ed. F. P. Israel (Dordrecht: Reidel), p. 397.
Graham, J. R., Wright, G. S., and Longmore, A. J. 1987, *Ap. J.*, **313**, 847.
Harvey, P. M., Campbell, M. F., and Hoffmann, W. F. 1979, *Ap. J.*, **228**, 445.
Harvey, P. M., Hoffmann, W. F., and Campbell, M. F. 1979, *Ap. J.*, **227**, 114.
Harvey, P. M., Thronson, H. A., and Gatley, I. 1979, *Ap. J.*, **231**, 115.
Heiles, C. 1964, *Ap. J.*, **140**, 470.
Henize, K. G. 1956, *Ap. J. Suppl.*, **2**, 315.
Joseph, R. D., and Robertson, N. A. 1982, in *Proc. E.S.O. Second Infrared Workshop*, ed. A. F. M. Moorwood and K. Kjär (Garching: ESO), p. 391.
Koorneef, J. 1982, *Astr. Ap.*, **107**, 247.
Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., and Torres-Peimbert, S. 1979, *Astr. Ap.*, **80**, 155.
Long, K. S., Helfand, D. J., and Grabelsky, D. A. 1981, *Ap. J.*, **248**, 925.
Low, F. J., *et al.* 1979, *Ap. J.* (*Letters*), **278**, L19.
Marley, S. R., and Marsden, P. L. 1985, in *RS Oph and the Recurrent Nova Phenomenon*, ed. M. F. Bode (Utrecht: U.N.U. Science Press), p. 59.
Mathewson, D. S., Ford, V. L., Doptia, M. A., Tuohy, I. R., Long, K. S., and Helfand, D. J. 1983, *Ap. J. Suppl.*, **51**, 345.
McGee, R. X., and Milton, J. A. 1966, *Australian J. Phys.*, **19**, 343.
Mezger, P. G., Mathis, J. S., and Panagia, N. 1982, *Astr. Ap.*, **105**, 372.
Mezger, P. G., Smith, L. F., and Churchwell, E. 1974, *Astr. Ap.*, **32**, 269.
Neugebauer, G., *et al.* 1984, *Ap. J.* (*Letters*), **278**, L1.
Osterbrock, D. E. 1978, *Astrophysics of Gaseous Nebulae* (San Francisco: W. H. Freeman).
Ostriker, J. P., and Silk, J. 1973, *Ap. J.* (*Letters*), **184**, L113.
Panagia, N. 1973, *A.J.*, **78**, 929.
Raymond, J. C., Cox, D. P., and Smith, B. W. 1976, *Ap. J.*, **204**, 290.
Sanduleak, N. 1970, *Contr. of Cerro Tololo Inter-American Obs.*, No. 89.
Sedov, L. I. 1959, *Similarity and Dimensional Methods in Mechanics* (New York: Academic Press).
Spitzer, L. 1978, *Physical Processes in the Interstellar Medium* (New York: Wiley).
Taylor, G. 1950, *Proc. Roy. Soc. London A*, **201**, 159.
Tuohy, I. R., Dopita, M. A., Mathewson, D. S., Long, K. S., and Helfand, D. J. 1982, *Ap. J.*, **261**, 473.
Whitcomb, S. E., Gatley, I., Hildebrand, R. H., Keene, J., Sellgren, K., and Werner, M. W. 1981, *Ap. J.*, **246**, 416.
Wright, E. L., Harper, D. A., Hildebrand, R. H., Keene, J., and Whitcomb, S. E. 1979, *Nature*, **279**, 703.
Wright, E. L., Harper, D. A., Loewenstein, R. F., Keene, J., and Whitcomb, S. E. 1980, *Ap. J.* (*Letters*), **240**, L157.
Young, E., and Neugebauer, G. 1984, Guide to *IRAS* AO's.

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