THE NATURE OF THE COMPACT SUPERNOVA REMNANTS IN STARBURST GALAXIES

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ABSTRACT

Radio observations of starburst regions in galaxies have revealed groups of compact nonthermal sources that may be radiative supernova remnants expanding in the interclump medium of molecular clouds. Because of the high pressure in starburst regions, the interclump medium may have a density $\sim 10^3$ H atoms cm^{-3} in a starburst nucleus like M82 and $\gtrsim 10^4$ H atoms cm^{-3} in an ultraluminous galaxy like Arp 220. In M82, our model can account for the sizes, the slow evolution, the high radio luminosities, and the low X-ray luminosities of the sources. We predict expansion velocities ~ 500 km s^{-1}, which is slower than the one case measured by VLBI techniques. Although we predict the remnants to be radiative, the expected radiation is difficult to detect because it is at infrared wavelengths and the starburst is itself very luminous; one detection possibility is broad [OI] 63 μm line emission at the positions of the radio remnants. The more luminous and compact remnants in Arp 220 can be accounted for by the higher molecular cloud density. In our model, the observed remnants lose most of the supernova energy to radiation. Other explosions in a lower density medium may directly heat a hot, low density interstellar component, leading to the superwinds that are associated with starburst regions.

Subject headings: galaxies: starburst — ISM: supernova remnants — shock waves

1. INTRODUCTION

Radio observations of starburst galaxies have revealed a population of compact supernova remnants that are more luminous than Cas A, the most luminous supernova remnant in our Galaxy. This population has been best studied in M82 (Kronberg, Biermann, & Schwab 1985), and similar populations have been found in NGC 253 (Antonucci & Ulvestad 1988), NGC 3448 (Noreau & Kronberg 1987), and Arp 220 (Smith et al. 1998). Although there is general agreement that these nonthermal radio sources are the result of supernovae, there has been no clear sense of their evolutionary status. One possibility is that they involve interaction with the winds from the progenitor massive star. The radio supernova phenomenon can be interpreted in terms of supernova interaction with the free wind of the progenitor (Chevalier 1982; Weiler et al. 1986). In this case, the radio properties do not depend on the interstellar environment. Alternatively, the remnants are interacting with interstellar material, in which case the starburst environment is likely to be important.

Recent observations of the compact remnants in M82 have yielded clues about their nature. Kronberg et al. (2000) found that 18 of the sources (75% of the sample) showed no discernible flux evolution over a 12 year period, which suggests a flux variability $< 0.1\%$ yr^{-1} (see also Ulvestad & Antonucci 1994). The evolution timescale is then $> 10^3|n|$ yr if the luminosity evolves as $L \propto t^n$. An estimate of n can be obtained from the radio $\Sigma - D$ (surface brightness – diameter) relation, assuming that it represents an evolutionary trend; for $\Sigma \propto D^{-3.5}$ (Huang et al. 1994), we have $|n| = 1.5$. Muxlow et al. (1994) resolved most the remnants in M82, finding diameters of $0.6 - 4$ pc, and suggested that they are supernova remnants rather than radio supernovae. In some cases, shell structure was observable, as expected for a supernova remnant. The combination of size and timescale yields a velocity $\lesssim 10^3$ km s^{-1}, which implies that these are evolved remnants. This forms the basis of our treatment of the compact remnants in M82 (§ 2) and in other galaxies (§ 3). We also briefly discuss supernova-driven superwinds in § 3. We take a distance to M82 of 3.63 Mpc (Freedman et al. 1994).

2. THE COMPACT REMNANTS IN M82

Of the 24 radio sources in M82 followed by Kronberg et al. (2000), two, 41.5+59.7 and 41.9+57.5, show especially rapid evolution. The first one was observed in 1981, but not in 1982. The rapid evolution was consistent with the radio emission from a Type Ib or Ic supernova (Kronberg et al. 2000), and we agree that this is a plausible interpretation. The emission is from a shock wave propagating in the free wind from the progenitor star. The other source, which has been the brightest of the compact sources, had an evolution that is compatible with that of a bright radio supernova like SN 1986J, but recent radio imaging shows that it has a bipolar structure (McDonald et al. 2001). We do not include 41.9+57.5 in our discussion.

The duration of the initial radio supernova phase is limited by the extent of the freely expanding progenitor wind. In the case of a starburst region, the wind expansion is likely to be limited by the high pressure of the interstellar medium. Based on energy input from supernovae, Chevalier & Clegg (1985) estimated a pressure in the central region of M82: $p/k \approx 10^7$ cm^{-3} K, where k is Boltzmann's constant. The ram pressure of a wind equals the external pressure at a radius $r_w = 0.2\dot{M}_{-4}^{1/2} v_{w1}^{1/2} p_7^{-1/2}$ pc, where $\dot{M}_{-4}$ is the mass loss rate in units of 10^{-4} $M_\odot$ yr^{-1}, v_{w1} is the wind velocity in units of 10 km s^{-1}, and p_7 is the external pressure in units of 10^7 cm^{-3} K. Except for 41.9+57.5, the radio remnants have $r \gtrsim 0.5$ pc (Muxlow et al. 1994), which is too large for interaction with a red supergiant wind. A Wolf-Rayet progenitor wind could expand to a larger radius because of the larger wind velocity ($v_{w1} \approx 100$), but the density is low, leading to a faint source. The majority of the compact sources in M82 cannot be interpreted as standard radio supernovae.

The interstellar medium in the center of M82 is believed to have a hot component that drives a galactic superwind (Chevalier & Clegg 1985; McCarthy, van Breugel, & Heckman 1987; Strickland & Stevens 2000). In the reference wind model of Chevalier & Clegg (1985) with a power of one 10^{51} erg supernova every $3-5$ years and a mass loss rate of 1 $M_\odot$ yr^{-1}, the central temperature is $T_c \approx 5 \times 10^8$ K and central H density is $n_H \approx 0.05$ cm^{-3}. The models of Strickland & Stevens (2000) are cooler, and appear to have $n_H \sim 0.1$ cm^{-3} in the central region. In *Chandra* observations, Griffiths et al. (2000) found an energetic X-ray component in the central kpc of M82 that is more luminous than predicted by the thermal emission in the wind models, but much of the emission could be from the inverse Compton mechanism. The radius at which a supernova has swept up its own mass is $R_s = 8.9(M/10\ M_\odot)^{1/3}(n_H/0.1\ \mathrm{cm}^{-3})^{-1/3}$ pc, where M is the ejecta mass, and the radius at which a 10^{51} erg supernova comes into pressure equilibrium with its surroundings is $R_p = 16p_7^{-1/3}$ pc. Under these conditions, the observed radio remnants, with diameters $\lesssim 4$ pc (Muxlow et al. 1994), would be primarily in free expansion, with characteristic velocities $\gtrsim 5,000$ km s^{-1}.

In view of the large evolutionary times for the compact remnants, we propose that most of the compact remnants are interacting with a dense, possibly molecular, interstellar medium. The analogy in our Galaxy would be remnants evolving in the interclump medium of molecular clouds (Chevalier 1999), which has a H density $n_H \approx 10$ cm^{-3}. Galactic remnants like IC 443 and W44, which have high radio surface brightnesses and radii ~ 10 pc, can be interpreted as recently having entered the radiative phase of evolution. The remnants in M82 can also be interpreted as recently having entered the radiative phase if the surrounding density is $n_H \approx 10^3$ cm^{-3}. This is a plausible density for the interclump medium of molecular clouds in M82 if the high pressure in the central region is taken into account. In our Galaxy, the pressure of the interclump medium of clouds is maintained at $\sim 10^5$ cm^{-3} K by nonthermal support, presumably related to magnetic fields. In M82, a similar situation is likely. Shen & Lo (1995) find a CO line width of 7 km s^{-1} and up in molecular clouds in M82. When this line width is combined with a density $n_H \approx 10^3$ cm^{-3}, the result is a nonthermal pressure $p/k \sim 10^7$ cm^{-3} K, as is inferred in the central region of M82. In addition, there is direct evidence for densities $\gtrsim 10^3$ H atoms cm^{-3} in the interclump medium of molecular clouds in starburst regions (Mao et al. 2000; Solomon 2001). The location of the radio remnants in M82 overlaps the regions of strong CO emission (e.g., Fig. 4 of Lord et al. 1996) and the gas column density to the remnants is high (Mattila & Meikle 2001), which is consistent with interaction with molecular gas.

A possible complication is that the analysis of the dense gas emission in terms of photodissociation regions implies that the gas has a filling factor $\sim 0.05 - 0.1$ and is in many clouds with radii $\lesssim 1$ pc (Lord et al. 1996; Mao et al. 2000). If this were the case, the observed radio emission is presumably from shock fronts in the dense gas, but some of the expansion is in a lower density medium. However, an LVG (large velocity gradient) analysis of the CO data yields cloud radii of $\sim$ 150 pc (Mao et al. 2000) and Shen & Lo (1995) identify $\sim$ 60 CO "clouds" with half-power diameters of $10 - 100$ pc. In any case, the dense gas is likely to have complex structure. The radio images of the remnant do show considerable structure in the nonthermal emission (Muxlow et al. 1994).

An upper limit on the filling factor f of 10^3 cm^{-3} gas can be obtained by assuming that all of the central gas is at this density. Assuming a disk of diameter 600 pc, a total height of 100 pc, and an interclump density of $n_H = 10^3$ cm^{-3}, the gas mass is $9.8 \times 10^8 f\ M_\odot$. The total gas mass within a radius of 400 pc, including H_2, HI, and HII, is $\sim 1.3 \times 10^8\ M_\odot$ (Götz et al. 1990), yielding $f \lesssim 0.13$. The filling factor appears to be low, but we expect the supernovae to come from massive stars that are born in the molecular gas, so that the supernovae are correlated with the presence of molecular gas.

Although a late red supergiant phase is unlikely to significantly affect the surrounding medium, as discussed above, photoionization and a wind during the main sequence phase could have an effect on the surroundings. Draine & Woods (1991) considered these effects and found that for a surrounding density of 10^3 cm^{-3}, stars with an initial mass of 25 $M_\odot$ or less have supernovae that enter the radiative blast wave phase in that medium. This should apply to most of the massive star supernovae in M82.

Wheeler, Mazurek, & Sivaramakrishnan (1980) find that a remnant in a medium with $n_H = 10^3$ cm^{-3} becomes radiative at a radius $R_c = 0.78$ pc for a 10^{51} erg explosion. For the same parameters, Draine & Woods (1991) find $R_c = 1.37$ pc; the difference can be attributed to the fact that their cooling function is a factor $\sim$ 2 smaller than that used by Wheeler et al. (1980). Except for the sources 41.9+57.5 and 44.0+59.6, which may be an active galactic nucleus (Seaquist, Frayer, & Frail 1997), Muxlow et al. (1994) find that the diameters of the compact remnants in M82 are in the range 1.1 to 4 pc. We suggest that the remnants in M82 have recently entered the radiative phase of evolution. The evidence in our Galaxy is that remnants which have recently become radiative (e.g., W28, W44) have higher radio surface brightnesses for a given diameter than those that are non-radiative with a similar diameter (e.g., SN 1006).

To estimate the observed X-ray fluxes, we use an analytical model for the evolution of the supernova remnants, as in Draine & Woods (1991), for different values of the ambient density, n_H. From the shock temperature and density we calculate the cooling rate and luminosity of the remnant as function of time. Using a simple bremsstrahlung form for the spectrum and including the absorption by the interstellar medium, we estimate the resulting X-ray luminosity in the $0.1 - 2$ keV and $2 - 10$ keV bands. In the upper panels of Fig. 1 we show the unabsorbed luminosities in the two bands, while the lower panels show the observed luminosities for a column density of 4.3×10^{22}cm^{-2} (solid lines), and for a lower column density of 2×10^{22}cm^{-2} (dashed lines). Mattila & Meikle (2001) find that the average H column density to the remnants, including atomic and molecular H, is 4.3×10^{22} cm^{-2} ($\sigma \approx 1.7 \times 10^{22}$ cm^{-2}). We terminate the calculations at the point when the internal pressure of the remnant is equal to the external pressure of the interstellar medium, here taken to be $p/k = 10^7$ K cm^{-3}. This mainly affects the cases with $n_H \lesssim 10^2$ cm^{-3}. The peaks in the unabsorbed X-ray luminosity, especially apparent in the light curves of the 0.1 – 2 keV band, occur at the time of the transition from the adiabatic to the radiative phase.

It is seen that in the 0.1 – 2 keV band the observed luminosities are $\sim 3 \times 10^{37}$ erg s^{-1} for $n_H = 10^3$cm^{-3}, and considerably below this for lower densities. For the low value of the column density the luminosity approaches $\sim 1 \times 10^{38}$ erg s^{-1}. The observed luminosities in the 2 – 10 keV band are basically unaffected by the interstellar medium absorption. For $n_H = 10^3$cm^{-3}, the peak luminosity is $\sim 3 \times 10^{38}$ erg s^{-1}, scaling roughly with the ambient density.

A *Chandra* image of M82 (Griffiths et al. 2000) shows many compact X-ray sources, but their positions are $> 1''$ from the positions of the compact radio remnants, except in one case. Most of the sources are likely to be X-ray binaries, or supernova remnants that are not strong radio emitters. The luminosity limit of the image is $\sim 10^{37}$ erg s^{-1}. While especially the 2 – 10 keV luminosities would be observable with *Chandra* and in possible conflict with the small number of X-ray sources coinciding with the compact radio sources, we note that the peak of the X-ray flux occurs considerably before the radiative transition when we expect an enhanced radio flux. The radio and X-ray bright remnants may therefore represent two different populations, with the former more numerous because of their greater ages. An uncertainty in the predicted X-ray emission is that it is strongest at a small radius when the effects of winds from the progenitor may be a factor in the surrounding density distribution.

There are possible problems with our picture. VLBI observations by Pedlar et al. (1999) show that the remnant 43.3+59.2 is expanding at 9850 ± 1500 km s^{-1}, as opposed to the ~ 500 km s^{-1} that we expect. This remnant shows a relatively constant flux (Kronberg et al. 2000), so it belongs to the main class of remnant. If further VLBI measurements confirm the initial result, and find similar rapid expansion in other remnants, our model will have to be abandoned. Also, Muxlow et al. (1994) find the number – diameter relation for the remnants to be consistent with free expansion; the number of remnants with size less than diameter D increases linearly with D. However, the relation may be due to decelerating remnants evolving in an interstellar medium with density variations (Berkhuijsen 1987). In our model, the remnants would be brightest when they first become radiative, which is a function of density.

There are arguments, in addition to the expected rapid evolution, against free expansion for the remnants at a velocity $\sim 10^4$ km s^{-1}. The high radio luminosities of the remnants suggests substantial thermalization and deceleration of the ejecta. Huang et al. (1994) argued that the surface brightness – diameter relation that applies to the M82, LMC, and Galactic remnants could be approximately understood by assuming that some constant fraction of the supernova energy goes into relativistic particles and magnetic fields. The small diameter remnants are not observable in the Galaxy and LMC because they have not interacted with a sufficiently dense medium to thermalize the ejecta energy.

There is also the rate of formation of the radio remnants. If the remnants expand at 10^4 km s^{-1} and there are 28 with diameters < 3 pc (Huang et al. 1994), the formation rate is 1/(5 yr) (see also Muxlow et al. 1994). In our model, the remnants have mean expansion velocities about an order of magnitude smaller and a correspondingly lower formation rate. No new remnants have been found above the flux level observed by Kronberg et al. (1985) in the past 20 years, so the observations are more consistent with the slow expansion model.

An individual radiative remnant is expected to have a peak total luminosity $\sim 10^{40}$ erg s^{-1}, most of which is expected to be at infrared wavelengths (Wheeler et al. 1980; Draine & Woods 1991). The problem with observing this emission is that the starburst nucleus of M82 has an infrared luminosity $\sim 10^{44}$ erg s^{-1}. For the high absorption toward the compact remnants, the observable emission is likely due to dust continuum emission and infrared fine structure lines. The [OI] 63μm line dominates the postshock cooling below 5,000 K and should be prominent (Hollenbach & McKee 1989). For a newly cooling remnant in a medium with $n_H = 10^3$ cm^{-3} and shock velocity $v_{sh} = 426$ km s^{-1} and $R = 1.37$ pc (Draine & Woods 1991), the expected [OI] 63 μm luminosity is 1×10^{37} erg s^{-1} (Chevalier 1999). The total observed [OI] 63 μm luminosity from the starburst region of M82 is $\sim 1 \times 10^{41}$ erg s^{-1}, most of which is thought to arise from warm neutral gas photodissociated by radiation from OB stars (Lord et al. 1996). The expected line emission is faint, but might be observable because the line is broad and is expected in localized regions. However, we estimate that the line is somewhat below the expected detection limit of the *AIRES* echelle spectrograph on *SOFIA*.

Greenhouse et al. (1997) have detected 6 sources of [Fe II] 1.2 and 1.6 μm line emission that they identify as shock emission from supernova remnants. The emission does not coincide with that from the radio remnants. We attribute this partially to the high extinction to the radio supernova remnants. Mattila & Meikle (2001) find an average $A_V \approx 24$ to the radio remnants, while Greenhouse et al. (1997) find $A_V = 6-9$ to the [Fe II] remnants. Taking $A_V = 7.5$ to the [Fe II] remnants and the extinction curve of Fitzpatrick (1999), the additional extinction would reduce the observed flux of the radio remnants by a factor of 13 compared to the [Fe II] remnants. In addition, both theoretical shock models (Hollenbach & McKee 1989) and observations of a Galactic remnant (Oliva et al. 1999) indicate that the luminosity ratio L([FeII] 1.65μm)/L([OI] 63μm) < 1, leading to a low expected [Fe II] 1.65 μm line luminosity. The same considerations indicate that the [Fe II] remnants should be strong [O I] 63 μm line sources, easily detectable with *SOFIA*. The uncertainties in this argument are that the expected shock velocities in the radio remnants are higher than have been modeled or observed, and the shock velocities in the [Fe II] remnants are unknown.

Three of the [Fe II] remnants are resolved with diameters of ~ 40 pc and the remainder are unresolved at a diameter of 22 pc (Greenhouse et al. 1997), an order of magnitude larger than the radio remnants. Expansion in a 10^3 cm^{-3} medium would lead to substantial energy loss and a lower [Fe II] luminosity, yet the observed high luminosity requires interaction with relatively dense gas. We suspect that the remnants are primarily interacting with a low density gas, and the [Fe II] emission is from radiative shock waves in clouds. The positions of the remnants extend to a larger distance from the center of M82 than do the radio remnants (Greenhouse et al. 1997). The [Fe II] remnants should be weak nonthermal radio sources; based on the surface brightness – diameter relation approximately followed by radio remnants (Huang et al. 1994), we estimate radio fluxes of $\sim 0.01 - 0.04$ mJy. As noted by Greenhouse et al. (1997), the high radio background in M82 makes faint sources difficult to detect.

3. OTHER GALAXIES AND SUPERWINDS

Ulvestad & Antonucci (1997) have studied compact radio sources in NGC 253 with a resolution of 1 pc. They find that both HII regions and supernova remnants are present (based on their spectral indices), that some of the sources are resolved, and that there is little evidence for flux variation over a timespan of 8 yr. The upper limits on the rate of flux decrease of the strongest sources are $1 - 2\%$ yr^{-1}. These properties indicate that the remnants are quite similar to those in M82.

The sources found by Smith et al. (1998) in the NW nucleus of the Arp 220 merging system have somewhat different properties: they are unresolved with a 1.1×2.9 pc beam and they are more luminous than the M82 sources. Their luminosities are comparable to that of the luminous radio supernova SN 1986J and Smith et al. (1998) identify the objects with this class of radio source. This requires that essentially all of the supernovae in the nuclear region of Arp 220 produce very luminous radio supernovae. Events like SN 1986J are thought to involve interaction with an especially dense wind and are rare among supernova explosions. However, the interstellar conditions in the nuclear region of Arp 220 are probably more extreme than those in M82 and may account for the difference in the radio source properties. The projected area covered by the radio sources is more compact: 75×150 pc in Arp 220 as compared to 100×600 pc in M82. The infrared luminosity in Arp 220 is $\sim 10^{12} L_\odot$ as compared to $\sim 4 \times 10^{10} L_\odot$ in M82, which suggests that the supernova rate is correspondingly higher in Arp 220. In the spherically symmetric galactic wind theory of Chevalier & Clegg (1985), the central pressure is $p_c \propto \dot{E}^{1/2} \dot{M}_w^{1/2} R^{-2}$, where $\dot{E}$ is the total power input from supernova, $\dot{M}_w$ is the mass loss rate in the galactic wind, and R is the radius of the region of power input. The pressure in the starburst region of Arp 220 is plausibly $\gtrsim 10$ greater than that in M82 and the density in the interclump region of molecular clouds may have a correspondingly higher density. Solomon (2001) in fact finds that the mean density in the starburst region of Arp 220 is $\sim 10^4$ cm^{-3}. For $n_H = 10^4$ cm^{-3}, the cooling radius for a supernova remnant is 0.5 pc when its age is ~ 100 yr (Draine & Woods 1991). We thus predict that the remnants are only somewhat smaller than the current size limits and that they evolve more rapidly than the remnants in M82.

In our model for the compact remnants, they are radiative and thus do not efficiently provide mechanical energy to heat gas in the starburst region. In addition, our estimate of ages of the objects is larger than in models where they expand at a high constant velocity (e.g., Muxlow et al. 1994) and the rate of supernova explosions is correspondingly lower. We hypothesize that there is a population of massive star supernovae that are able to escape from their parent molecular cloud and explode in a low density, hot medium ($n_H \lesssim 1$ cm^{-3}). These supernovae are responsible for driving the galactic winds from M82 and other starburst galaxies (Chevalier & Clegg 1985; Heckman, Armus, & Miley 1990). Unfortunately, the remnants of these supernovae are difficult to observe; Fig. 1 shows that remnants occurring in the low density component should have luminosities $< 10^{36}$ erg s^{-1} and are not detectable with *Chandra*. However, the initial supernovae may be directly observable (e.g., Bregman, Temi, & Rank 2000). Supernovae in the low density medium may have smaller line-sight column densities that the ones in molecular clouds.

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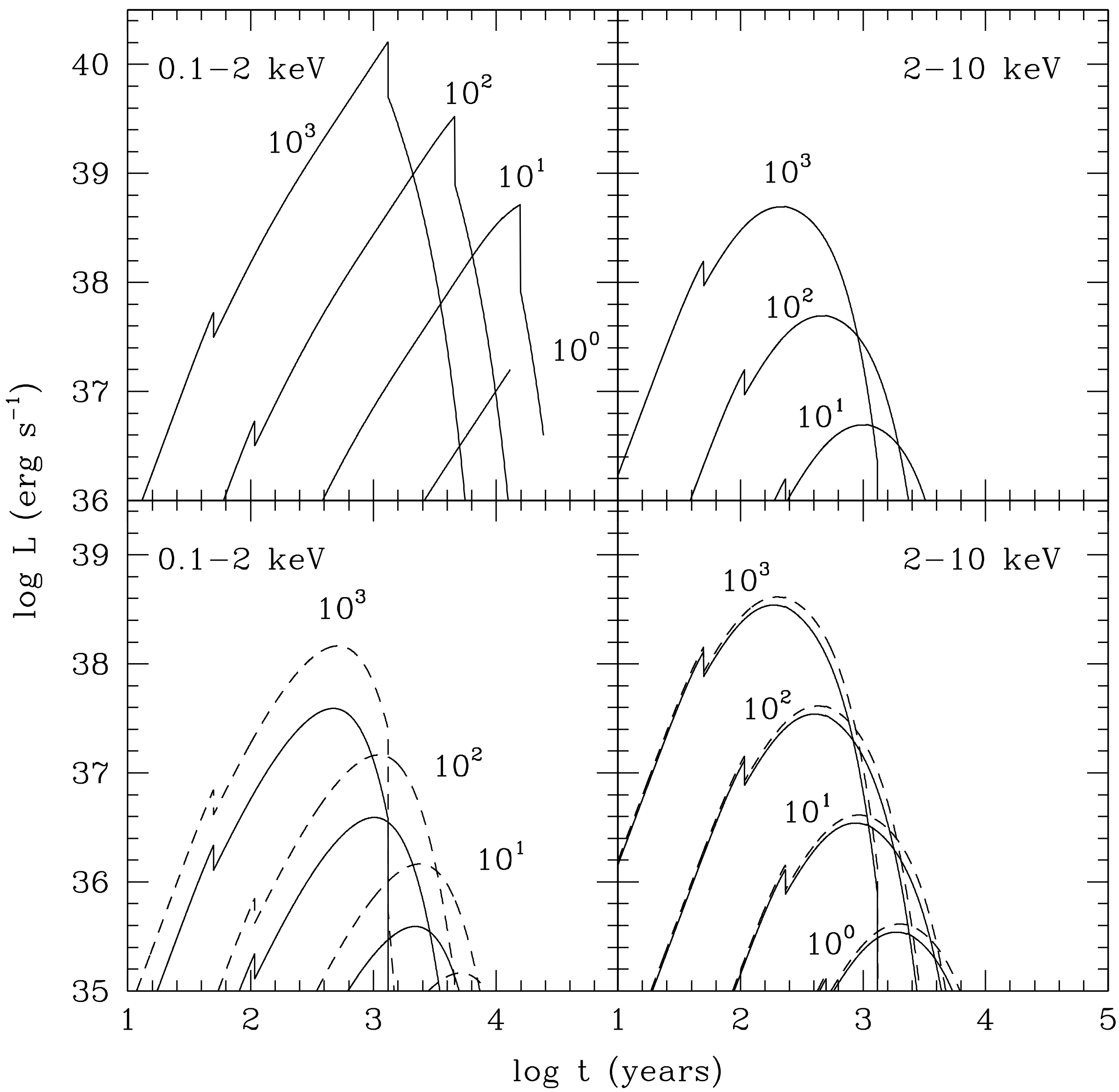

Fig. 1.— X-ray luminosities in the 0.1 – 2 keV and 2 – 10 keV bands as a function of time. The upper panel gives the emitted total luminosities in the two bands for different densities. The curves for $n_0 = 1$ cm^{-3} and $n_0 = 10$ cm^{-3} are truncated at the point where the pressure of the interstellar medium stalls the expansion of the remnant. The lower panel shows the observed luminosity in the two bands corrected for interstellar absorption. The solid lines show the results) for $N_H = 4.3 \times 10^{22}$ cm^{-2}, while the dashed lines show the luminosities for $N_H = 2 \times 10^{22}$ cm^{-2}.