X-RAY EMISSION FROM SUPERNOVA REMNANTS IN A CLOUDY MEDIUM

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ABSTRACT

Young SNRs expand to much larger radii in a cloudy ISM than in a homogeneous medium, and they can have large variations in the pressure. The collision between supernova ejecta and an ambient cloud can result in an expanding high pressure region (a "secondary blast wave"). Observations of MSH 15-52 can be accounted for in this manner. X-ray emission from both young and older SNRs can provide an important probe for inferring the structure of the ISM.

1. INTRODUCTION

The interstellar medium is observed to be quite inhomogeneous, with densities ranging from those in molecular clouds ($n \gtrsim 10^3$ cm^{-3}) to HI clouds and shells ($n \sim 10^{1-2}$ cm^{-3}) to warm medium ($n \sim 10^{-0.5}$ cm^{-3}, $T \sim 10^4$ K) to hot interstellar medium (HIM; $n \sim 10^{-2.5}$ cm^{-3}, $T \sim 10^{5.7}$ K). SNRs are thought to generate the HIM and pressurize the ISM (Cox and Smith 1974, McKee and Ostriker 1977), so to a significant extent SNRs govern the inhomogeneity of the ISM.

The cloudy structure of the ISM strongly influences the evolution and appearance of SNRs. The nature of the clouds encountered by the SNR depends on its age and type. Young SNRs, which are dominated by the ejecta, may have to contend with circumstellar material left by the pre-supernova star, as in the case of the quasi-stationary flocculi in Cas A (Peimbert and van den Bergh 1971) and possibly the "jet" in the Crab (Blandford et al. 1982). Massive type II SN may occur in a wind blown bubble (Castor, McCray, and Weaver 1975) such as those observed around Wolf-Rayet stars (Chu 1981); the low density in the bubble could allow the ejecta (plus shocked circumstellar gas) to penetrate to large radii, of order 20 pc. Outside the bubble, the strong ionizing radiation from the pre-supernova star tends to destroy the clouds and homogenize the medium out to the Stromgren radius. Massive type II SN tend to occur in stellar associations, where the combined effect of many

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stellar winds and SN is to produce a very large low density region, a "superbubble" (Bruhweiler et al. 1980). On the other hand Type I SN and relatively low mass or high velocity Type II's--which together probably comprise the majority of SN--are likely to occur in the typical ISM with the wide range of inhomogeneities described above.

2. YOUNG SNRs: THERMALIZATION OF THE ENERGY

Young SNRs are approximately in a state of free expansion and are characterized by having most of their energy in kinetic form. The conversion of a significant fraction of this energy into thermal energy is accomplished by shock waves, one propagating outward into the ambient medium and one (the reverse shock) propagating inward through the ejecta (Ardavan 1973, Kahn 1974, McKee 1974). If the ambient medium and/or the ejecta is cloudy, then the thermalization process and hence the onset of the Sedov-Taylor phase of blast wave evolution is delayed.

The evolution of a young SNR is particularly simple if both the ejecta and the ambient medium are homogeneous. Let

$$R_A = \left(\frac{3M_E}{4\pi\rho_A}\right)^{1/3} = 2.1\left(\frac{M_E/M_\odot}{n_A}\right)^{1/3} \text{ pc} \tag{1}$$

be the radius at which the swept up mass equals the ejected mass; ρ_A is the mass density, and n_A the baryon number density, in the ambient gas (for cosmic abundances, n_A is 1.4 times the hydrogen density). One can readily show that the reverse shock traverses much of the ejecta, thermalizing it in the process, by the time at which $R = R_A$. This is confirmed by numerical calculations (Gull 1975), which show that the thermal energy in the swept up gas has reached about half its final value of 0.71 E when $R = R_A$; the thermal energy of the ejecta never amounts to more than a few percent of E.

2.1 Homogeneous Ejecta Expanding into a Cloudy Medium

In the more realistic situation of a cloudy ambient medium (but with uniform ejecta) we distinguish the cloud density ρ_{Ac} from the intercloud density ρ_{Ai}, etc. The radius R_{Ai} at which the swept-up intercloud mass equals the ejected mass is given by equation (1) with ρ_A replaced by ρ_{Ai}; for $n_{Ai} \sim 3 \times 10^{-3}$ cm^{-3} as in the HIM, this gives $R_{Ai} \simeq 13(M/M_\odot)^{1/3}$ pc. Usually the clouds, which occupy a fraction $f_{Ac} << 1$ of the volume, have most of the mass ($\rho_{Ac}f_{Ac} > \rho_{Ai}$), so that

$$R_{Ac} = (3\ M_E/4\pi\ \rho_{Ac}\ f_{Ac})^{1/3} \tag{2}$$

is smaller than R_{Ai}.

There will be an outgoing shock in the intercloud medium and a reverse shock in the ejecta. The energy of the ejecta can be thermalized by the reverse shock and by collisions with the ambient

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clouds. For the moment, assume that the intercloud medium is sufficiently tenuous that the ambient clouds dominate the thermalization process, and neglect evaporation and stripping of the clouds. Approximate the ejecta as being in a thin spherical shell with a column density of baryons N_E. (Chevalier 1982 has considered ejecta of variable density interacting with a uniform ambient medium.) Collision with a cloud of column density N_{Ac} results in a fraction $N_{Ac}/(N_{Ac} + N_E)$ of the initial kinetic energy being converted to heat. Now the probability of intersecting a cloud in an interval dR along a given line of sight is dR/λ_{Ac}, where λ_{Ac} = (density of ambient clouds x the cross section of clouds)$^{-1}$ is the cloud mean free path. In terms of λ_{Ac} the cloud column density is $N_{Ac} = n_{Ac} f_{Ac} \lambda_{Ac}$. Neglecting adiabatic expansion losses, we find that the increase in thermal energy E_{th} is

$$\frac{dE_{th}}{dR} \simeq \frac{E}{(R_{Ac}{}^3/3R^2) + \lambda_{Ac}} \tag{3}$$

with the aid of equation (2). Solution of equation (3) shows that the energy of the ejecta is entirely thermalized ($E_{th} = E$) at a radius $R_{Ac} + \lambda_{Ac}$ to within 20%. The intercloud medium will thermalize the ejecta via the reverse shock at R_{Ai}, so altogether the thermalization will be complete at

$$R_{therm} \simeq \min[(R_{Ac} + \lambda_{Ac}), R_{Ai}]. \tag{4}$$

This radius marks the end of the "young" stage of SNR evolution.

As an example, consider an SNR in a three phase ISM. For $M_E = 1.4\ M_\odot$, and with the ISM parameters given by McKee and Ostriker (1977), we find R_{Ac} = (2 pc, 5 pc) and λ_{Ac} = (88 pc, 12 pc) for the cold cloud cores and warm cloud envelopes, respectively. The mean free path of 88 pc for the cold cores is sufficiently large to ensure that they are ineffective at thermalizing the ejecta. Rather, it is the warm envelopes ($R_{Ac} + \lambda_{Ac}$ = 17 pc) together with the HIM (R_{Ai} = 15 pc) which thermalize the ejecta. For an ejected mass $M_E = 10\ M_\odot$, R_{Ac} and R_{Ai} are about twice as large but λ_{Ac} is unchanged; the warm clouds would thermalize the ejecta at $R_{therm} \simeq 22$ pc.

Evaporation (Cowie and McKee 1977, Balbus and McKee 1982) and/or hydrodynamic stripping (Nulsen 1982) of the clouds could accelerate the thermalization somewhat by increasing the intercloud density and thereby driving R_{Ai} closer to R_{Ac}. The dynamical effects of evaporation and stripping in young SNRs are limited by two factors, however: the short time available prevents a steady evaporative flow from being established, and the evaporated or stripped gas will tend to be blown behind the cloud, reducing its interaction with neighboring ejecta which did not hit the cloud. The evaporation will generally be suprathermal, with the hot electrons freely penetrating the surface of the evaporating cloud. The time to establish steady flow is of order $(a^2\mu/\Gamma)^{1/3}$, where Γ and μ are the heating rate and mass per particle (Balbus and McKee 1982); in the shocked HIM, this is 1700 $a_{pc}{}^{2/3} T_{i8}{}^{1/6}$ yr, where a_{pc} is

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the cloud radius in parsecs and T_{i8} is the intercloud temperature normalized to 10^8 K. A freely expanding SNR would reach a radius of order 10 pc in this time. The heated cloud material will emit X-rays at a temperature $8 \times 10^5\ t_y n_i/T_{i8}^{1/2}$ K, where t_y is the heating time in years. The numerical simulations of SNR evolution in a cloudy medium by Cowie, McKee, and Ostriker (1981) focussed on the later stages of the evolution and did not include these effects.

2.2 Cloudy Ejecta

Young SNRs like Cas A are considerably more complicated than the model above because the ejecta are also inhomogeneous. SN ejecta can fragment in several ways: (1) Due to Rayleigh-Taylor instability at the interface between the core and envelope of the exploding star (Falk and Arnett 1973, Chevalier 1975, 1976). The resulting clumps should have anomalous abundances. A significant fraction of the mass of the ejecta should remain in an intercloud medium. (2) Due to Rayleigh-Taylor instability at the interface between the ejecta and the swept up ISM (Gull 1973). If the development of this instability is limited by viscosity (Cowie 1975) only a small fraction of the mass of the ejecta may be involved. (3) Due to interaction with an embedded pulsar. We shall not consider this case here.

How is the thermalization radius R_{therm} estimated in equation (4) altered by clumping of the ejecta? The analysis proceeds exactly as in §2.1 except that the column density of the ejecta N_E may be increased by the clumping. Define the ejecta covering factor C_E as the fraction of the sky covered by ejecta as seen from the site of the explosion. If ω_{Ec} is the density of ejecta clouds and σ_{Ec} their cross section, and if the clouds are randomly distributed in direction, then the "optical depth" of the clouds is $\tilde{\tau}_E = \int \omega_{Ec}\, \sigma_{Ec}\, dR$ and $C_E = 1 - \exp(-\tilde{\tau}_E)$. The mean value of the ejecta column density is

$$N_E = \frac{M_E}{4\pi R^2 m_p C_E} = \frac{1}{3}\,\frac{n_{Ac} f_{Ac} R_{Ac}{}^3}{R^2 C_E} \quad . \tag{5}$$

We then recover equation (3) with R_{Ac} replaced by $R_{Ac}C_E^{-1/3}$. A similar argument shows that R_{Ai} in equation (4) should be increased by the same factor, so that altogether

$$R_{therm} \simeq \min[(\lambda_{Ac} + R_{Ac}C_E^{-1/3}),\ R_{Ai}C_E^{-1/3}]. \tag{6}$$

This result will differ significantly from that for homogeneous ejecta, equation (4), only if $C_E << 1$. It is difficult to estimate C_E theoretically, but it is unlikely to be very small. Once the clouds are pressurized by the reverse shock, it is possible that σ_{Ac} will remain about constant and $\tilde{\tau}_E$ will fall off as R^{-2}; however, this occurs at $R \sim O(R_{Ai})$ and cannot have a large effect by R_{therm}. If the shocks which compress the clouds are radiative, very high cloud densities can be attained, but the compression will be primarily one dimensional and will not significantly decrease $\tilde{\tau}$.

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2.3 Comparison with Observation

A number of techniques have been developed to differentiate young SNRs from those in the Sedov phase, in which the dynamics are governed by the swept up ISM. Several observations suggest the young stage lasts well beyond the canonical estimate of $2(M_E/M_\odot)^{1/3}$ pc appropriate for a uniform ISM. By measuring the pressure in optical filaments in a number of SNRs in the LMC, Dopita (1979) inferred that the thermal energy E_{th} increased rapidly with SNR radius for $R \lesssim 15$ pc. This effect has been confirmed in a broader sample by Blair, Kirshner, and Chevalier (1981), but they pointed out that this procedure would underestimate E_{th} if the optical filaments were supported by magnetic pressure. A further complication in the interpretation is introduced by the fact that young SNRs are far from isobaric (see §3): the optical filaments may be shocked clouds in low pressure regions of the remnant, whereas the same clouds exposed to the mean SNR pressure would be heated to X-ray temperatures. In fact X-ray observations provide a better indication of the mean pressure, but their interpretation is complicated by the effects of the enhanced emissivity of the ejecta. Bearing these problems in mind, note that an approximate integration of equation (3) (which is more illuminating than the exact expression) gives

$$E_{th}/E \simeq R^3/(R_{Ac}{}^3 + R^2\lambda_{Ac}) \qquad (R < R_{therm}) \qquad (7)$$

to within 30%. For the values of R_{Ac} and λ_{Ac} in a three phase ISM quoted in §2.1, this is qualitatively consistent with the observed trend, although the predicted range of variation of E_{th}/E for $R > 5$ pc is smaller than the observed range.

With a complete sample of SNRs, it is possible to determine their dynamics statistically. If SNRs occur at a rate $\dot{N}$, then the number of SNRs smaller than R is $N(<R) = \dot{N}t(R)$, where $t(R)$ is the remnant age. If $R \propto t^m$, then $N(<R) \propto R^{1/m}$. Applying this technique to radio-selected SNRs in the LMC, Clarke (1976) found $N(<R) \propto R$ for $R < 25$ pc, which implied that either the remnants were freely expanding or the sample was incomplete; he favored the latter. Mathewson (1983) and Mills (1983), using SNR samples based on recent radio, optical, and X-ray observations, have substantiated the result that the LMC SNRs are freely expanding for $R \lesssim 20$ pc. This is consistent with equations (4) or (6) provided most of these SNRs are expanding in a very low density medium. This result is remarkable because $N(<R)$ tends to be dominated by the oldest SNRs, which are in the densest surroundings and are most luminous.

3. X-RAY EMISSION FROM YOUNG SNRS

3.1 Pressure Variations and Emissivity

Density variations in the ejecta and the ISM lead to large pressure variations in young SNRs, and these density and pressure variations strongly affect the appearance of the SNR. To emit X-rays, shocked gas in an SNR must be in the correct temperature range. Describe the pressure p of the radiating gas by the characteristic density $\rho_p \equiv p/v_E^2$; then the temperature of the radiating gas is

$$T = 260\ (\rho_p/\rho_o)(v_{E9}^2/x_t)\ \text{keV} \tag{8}$$

where ρ_o is the preshock density, x_t is the number of particles per baryon (= 1.64 for a fully ionized gas of cosmic abundances), and $v_{E9} = v_E/(10^9\ \text{cm s}^{-1})$. The lowest pressure in the SNR is in the unshocked ejecta, where $p \simeq 0$. In the shocked intercloud gas between the outgoing and reverse shocks, the pressure is about $\rho_{Ai}v_E^2 = 7 \times 10^{-9}$ $(n_{Ai}/0.003\ \text{cm}^{-3})\ v_{E9}^2$ dyne cm^{-2}; a gas of cosmic abundances must be initially less dense than $0.5(n_{Ai}/0.003\ \text{cm}^{-3})\ v_{E9}^2\ \text{cm}^{-3}$ in order to be shocked to a temperature above 1 keV by this pressure. Ejecta clouds interacting with the ambient intercloud medium are subjected to this pressure also, but ambient clouds of density ρ_{Ac} overtaken by ejecta of density ρ_E are subjected to a greater pressure, amounting to $\rho_E v_E^2$ for $\rho_E << \rho_{Ac}$.

The highest pressures in the remnant occur in the collision between an ejecta cloud and an ambient cloud. Shocks are driven into the two clouds at velocities v_{Ecs} and v_{Acs}, respectively, such that $v_{Acs} + v_{Ecs} \simeq v_E$ and $p \simeq \rho_{Ac}v_{Acs}^2 \simeq \rho_{Ec}v_{Ecs}^2$. The pressure is $\rho_p v_E^2$ (see eq. 8), where

$$\rho_p^{-1/2} \simeq \rho_{Ac}^{-1/2} + \rho_{Ec}^{-1/2}\ ; \tag{9}$$

more crudely, we have $p \simeq \min(\rho_{Ac},\rho_{Ec})\ v_E^2$. Both clouds will emit X-rays, provided the density ratio is not too large. The luminosity of the shocked region in each cloud is governed by the abundances (McKee 1974; Long, Dopita, and Tuohy 1982), temperature, and volume emission measure,

$$\text{VEM} = \int n_e^2\ dV \propto \rho^2 v_s \propto \rho^{3/2}p^{1/2}\ , \tag{10}$$

where we have assumed the shock has not crossed the cloud and that the shock is fast enough ($v_s \gtrsim$ few hundred km s^{-1}) that it is non-radiative. Note that the initially denser gas strongly dominates the volume emission measure and, being cooler, is a stronger source of soft X-rays.

3.2 Secondary Blast Waves

The impact of ejecta, whether homogeneous or cloudy, upon an ambient cloud creates a localized region of high pressure which expands outward. In some cases the expansion is analogous to a blast wave, and we term it a secondary blast wave; it will manifest itself as an X-ray bright spot. Consider an ejecta cloud which is small compared to the ambient cloud it strikes. The energy $(1/2)M_{Ec}v_E^2$ of the ejecta cloud is dissipated in a time of order $t_d = m_p N_{Ec} v_E/\rho_p v_E^2$, where ρ_p is given by

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equation (9). This corresponds to a column of shocked ambient cloud $N_{Acs} = n_{Ac} v_{Acs} t_d$, or

$$N_{Acs} = [1 + (\rho_{Ac}/\rho_{Ec})^{1/2}] N_{Ec} \quad . \tag{11}$$

If the stopping length N_{Acs}/n_{Ac} is large compared to the size a_{Ec} of the ejecta cloud (which requires $\rho_{Ec} >> \rho_{Ac}$), then this energy is distributed in the wake of the decelerating ejecta cloud. On the other hand, if the stopping length is $\lesssim a_{Ec}$, then the energy is initially confined to a volume of order $a_{Ec}{}^3$ and a secondary blast wave is produced. The evolution of the blast wave is complicated by the fact it occurs near the interface between the ambient cloud and the adjacent intercloud medium, but it passes through the same stages as a standard blast wave. Energy injection, corresponding to the SN explosion, occurs during the deceleration of the ejecta cloud. Next comes the free expansion phase, which lasts much longer in the intercloud medium than in the ambient cloud. Once the ejecta are thermalized in the cloud, mass and energy are blown from the cloud into the surrounding intercloud medium until the pressures are balanced. If the sound speed in the intercloud medium is small compared to v_E, then the pressure in the blast wave when the swept up intercloud mass equals the ejecta mass will be large compared to the intercloud pressure, and the blast wave will enter the Sedov-Taylor phase. The shocked cloud has a disk-like shape in this phase: the area corresponds to the radius of the blast wave in the intercloud medium, but the depth is smaller by $(\rho_i/\rho_{Ac})^{1/2}$. The non-equilibrium X-ray luminosity (Hamilton, Sarazin, and Chevalier 1982) is reduced from that due to a spherical blast wave in a medium of density ρ_{Ac} by $(\rho_i/\rho_{Ac})^{1/4}$.

3.3 MSH 15-52

The SNR MSH 15-52 appears to be a middle-aged remnant with a radius of 17 pc at a distance of 4.2 kpc. However, it was recently discovered to contain a pulsar with a spin down age of only 1600 yr (Seward and Harnden 1982). If this is the true age of the SNR, a possibility discussed by Seward et al. (1982), then it must still be in the free expansion phase: 17 pc/1600 yr = 10^4 km s^{-1}. As discussed in §2 above, this is possible provided the density of the interstellar medium is low, particularly if the ejecta are clumped so that their covering factor C_E is less than unity.

Direct evidence for the effect of cloudy ejecta may be provided by the two small bright X-ray sources near the rim of the SNR (Seward et al. 1982). The brighter one has a radius of 0.1 pc, a temperature of about 1 keV, an X-ray luminosity of 2 x 10^{34} erg s^{-1}, and a pressure estimated as (3 x 10^{-7}, 1.5 x 10^{-8}, 1.5 x 10^{-7}) dyne cm^{-2} based on (X-ray, optical, IR) observations. Since the IR and optical filaments may be supported by magnetic pressure (Hollenbach and McKee 1979, Blair et al. 1981), the pressure in the X-ray filament is more indicative of the total pressure in the region. This pressure is $400/E_{51}$ times greater than the mean pressure in an SNR with R = 17 pc and

$E = 10^{51}\ E_{51}$ erg. If we neglect the possibility of energy transport by jets such as those in SS433 (Begelman et al. 1980), such a localized region of high pressure in the remnant can be accounted for only by the impact of highly clumped ejecta upon an ambient cloud. For example, if we are viewing the collision just after the ejecta has been decelerated so that the column density of shocked gas in the ambient cloud is given by equation (11), then the observations can be accounted for by an ejecta cloud of radius 0.1 pc and density 0.33 cm^{-3} striking a larger ambient cloud of density 60 cm^{-3} at 10^4 km s^{-1}. The ejecta will be shocked to T > 100 keV and will be effectively invisible; the integrated effect of many such collisions might produce a detectable hard X-ray source, however. Pressure balance ensures that the ambient cloud will be shocked to $T \sim 1$ keV; its X-ray luminosity will agree with the observed value if the non-equilibrium emissivity of Hamilton et al. (1982) is used [$\Lambda(0.2\text{-}2\ \text{keV}) \simeq 1.5 \times 10^{-22}$ erg cm^3 s^{-1}]. An ejecta cloud with these properties would have decelerated significantly in passing through an intercloud medium with $n_{Ai} \gtrsim 3 \times 10^{-3}$ cm^{-3}, and it would have evaporated relatively quickly (Balbus and McKee 1982). Both problems would be alleviated if the ejecta cloud had a comparable mass to that assumed above, but 10 times the density, and if we were observing the collision after a blast wave had developed in the ambient cloud. Note that the time scale for variability could be as short as 0.1 pc/10^4 km s^{-1} $\sim$ 10 yr. Diffuse X-ray emission from this region of the SNR could be the result of many smaller or older impacts such as this.

4. MIDDLE AGED SNRs

When the swept up interstellar mass exceeds the ejected mass, then the dynamics and appearance of the SNR are governed by the shocked ISM, and, as for young SNRs, are strongly affected by the inhomogeneity of the ISM. The structure of the ISM may in turn be determined by SNRs to a large extent (Cox and Smith 1974, McKee and Ostriker 1977). Here we shall briefly discuss the effect of an inhomogeneous ISM on the X-ray emission of SNRs.

In a two-phase ISM (Field, Goldsmith and Habing 1969), cold clouds ($T \sim 10^2$ K, $n_H \sim 10^{1.5}$ cm^{-3}) are embedded in a warm intercloud medium ($T \sim 10^4$ K, $n_H \sim 10^{-0.5}$ cm^{-3}). The filling factor of the clouds is small ($\sim$ few percent), so SNRs evolve as Sedov-Taylor blast waves in the warm medium. Clouds shocked to the mean pressure of the blast wave reach a temperature

$$T_c \simeq 2.2 \times 10^6\ E_{51}\ [n_H(R/20\ \text{pc})^3]^{-1}\ \text{K}. \qquad (12)$$

For $n_H \gg 1$ cm^{-1}, the shocked clouds emit X-rays only in the early stages, $R \lesssim 15$ pc. Once T_c drops to about 5×10^5 K, the shocked clouds cool and produce optical emission lines, as in the case of the Cygnus Loop. X-ray emission from the shocked intercloud medium follows the normal result for Sedov blast waves (e.g., Hamilton et al. 1982) and dominates the X-ray luminosity once the shocked clouds are too cool to emit X-rays. The SNR becomes radiative and forms a dense shell at $R_c \simeq 20\ E_{51}^{0.29}\ n_o^{-0.41}$ pc, where n_o is the intercloud density; very few such shells have been seen, which argues against the pervasiveness of the two phase ISM.

In a three-phase ISM the warm medium is itself clumped and most of space is occupied by the hot interstellar medium ($T \sim 10^{5.7}$ K, $n_H \sim 10^{-2.5}$ cm^{-3}). SNRs expand to large radii in this medium, $R \gtrsim 100$ pc. Warm clouds are shocked to X-ray temperatures ($T \gtrsim 2 \times 10^6$ K) only for $R \lesssim 30\ E_{51}^{1/3}$ pc. Two different three phase models have been proposed. In one, there is little mass transfer between warm or cold clouds and the HIM (Cox 1979). SNRs expand as Sedov-Taylor blast waves until they are slowed by cloud drag at large radii. The expansion velocities are extremely large, $v \simeq 4000\ E_{51}^{1/2}(R/20\ \mathrm{pc})^{-3/2}$ km s^{-1}, which should be readily observable in galactic SNRs. The age of an SNR is correspondingly short, $t \sim 5000$ yr at $R \sim 30$ pc. The shocked HIM is ineffective at radiating X-rays because of its low density, so X-ray emission from an SNR essentially ceases for $R \gtrsim 30\ E_{51}^{1/3}$ pc. It is difficult to construct a self-consistent, steady-state model for the ISM of this type (McKee 1982).

On the other hand, in the three phase model proposed by McKee and Ostriker (1977) mass transfer between the clouds and the HIM is assumed to be efficient. They focussed on thermal evaporation of clouds, but turbulent stripping of the clouds (Nulsen 1982) may also contribute to the mass transfer. Under typical conditions, the model predicts that an SNR at $R = 20$ pc in a three phase ISM should be similar in mean density and age to a Sedov SNR in a medium with $n \simeq 0.2$ cm^{-3}. Thereafter the density of evaporated gas declines as $R^{-5/3}$. X-ray emission is produced by evaporated cloud gas as well as by shocked clouds, and it should be observable out to radii well in excess of 30 pc. The temperature of the evaporated gas decreases slowly, $T \propto R^{-4/3}$, whereas that of the shocked cloud drops as R^{-3}. The resulting spectrum has been calculated by Cowie et al. (1981) with the crude approximation of ionization equilibrium. Observational tests of the model have been discussed by McKee (1982).

5. CONCLUSIONS

Young SNRs are often observed to have clumpy ejecta and to be expanding into an inhomogeneous medium. There are two major effects of this inhomogeneity: the transition from a young SNR, dominated by the ejecta, to a middle-aged SNR, dominated by swept up ISM, occurs at a much greater radius than in the homogeneous case; and there can be large deviations from pressure equilibrium. The relative importance of clouds and intercloud medium in thermalizing the ejecta and thereby terminating the young stage was analyzed in §2. The observation that SNRs in the LMC follow an approximately linear number-radius relation for $R \lesssim 20$ pc implies that either (1) virtually all SNRs in the LMC occur in localized regions of low density, such as wind-blown bubbles, or (2) most of the volume of the LMC is filled by very low density gas, as in three phase models of the ISM. The second possibility is more likely.

In contrast to middle-aged SNRs, which are approximately isobaric, young SNRs have shock-heated gas ranging in pressure from (intercloud density) x v_E^2 to (cloud density) x v_E^2. There are correspondingly large spatial variations in the X-ray emissivity. The collision of an ejecta cloud with an ambient cloud can result in a secondary blast wave, a remote, miniature version of the original explosion. MSH 15-52, a relatively large SNR with a young pulsar, can be accounted for by highly clumped ejecta expanding into a low density medium and producing X-ray hot spots upon collision with ambient clouds.

The observational problem of determining the evolution of SNRs in later stages, when the swept up ISM is dominant, is to a large extent equivalent to determining which of the various ISM models--two phase, three phase with or without evaporation, or other--is correct. Studies of young SNRs may provide a valuable new tool in this effort.

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REFERENCES

Ardavan, H.: 1973, Ap.J. 184, p. 435.
Balbus, S.A., and McKee, C.F.: 1982, Ap.J. 252, p. 529.
Begelman, M., Sarazin, C., Hatchett, S., McKee, C., and Arons, J.: 1980, Ap.J. 238, p. 722.
Blair, W.P., Kirshner, R.P., and Chevalier, R.A.: 1981, Ap.J. 247, p. 879.
Blandford, R., Kennel, C., McKee, C.F., and Ostriker, J.P.: 1982, Nature (in press).
Bruhweiler, F.C., Gull, T.R., Kafatos, M., and Sofia, S.: 1980, Ap.J. (Letters) 238, p. L27.
Castor, J., McCray, R., and Weaver, R.: 1975, Ap.J. (Letters) 200, p. L107.
Chevalier, R.A.: 1975, Ap.J. 200, p. 698.
Chevalier, R.A.: 1976, Ap.J. 207, p. 872.
Chevalier, R.A.: 1982, Ap.J. 258, p. 790.
Chu, Y.H.: 1981, Ph.D. Thesis, U.C. Berkeley.
Clarke, J.N.: 1976, M.N.R.A.S. 174, p. 393.
Cox, D.P.: 1979, Ap.J. 234, 863.

Cox, D.P., and Smith, B.W.: 1974, Ap.J. (Letters) 189, p. L105.
Cowie, L.L.: 1975, M.N.R.A.S. 173, p. 429.
Cowie, L.L., and McKee, C.F.: 1977, Ap.J. 211, p. 135.
Cowie, L.L., McKee, C.F., and Ostriker, J.P.: 1981, Ap.J. 247, p. 908.
Dopita, M.A.: 1979, Ap.J. Suppl. 40, p. 455.
Falk, S.W., and Arnett, W.D.: 1973, Ap.J. (Letters) 180, p. L65.
Field, G.B., Goldsmith, D.W., and Habing, H.J.: 1969, Ap.J. (Letters) 155, p. L149.
Gull, S.F.: 1973, M.N.R.A.S. 161, p. 47.
Gull, S.F.: 1975, M.N.R.A.S. 171, p. 263.
Hamilton, A., Sarazin, C., and Chevalier, R.: 1982, Ap.J. (in press).
Hollenbach, D., and McKee, C.F.: 1979, Ap.J. Suppl. 41, p. 555.
Kahn, F.D.: 1974, in "The Interstellar Medium," ed. K. Pinkau (Dordrecht:Reidel), p. 235.
Long, K., Dopita, M., and Tuohy, I.: 1982, Ap.J. 260, p. 202.
Mathewson, D.S.: 1983, this volume, p. 553.
McKee, C.F.: 1974, Ap.J. 188, p. 335.
McKee, C.F.: 1982, in "Supernovae: A Survey of Current Research," M. Rees and R. Stoneham, eds. (Dordrecht: Reidel), p. 433.
McKee, C.F., and Ostriker, J.P.: 1977, Ap.J. 218, p. 148.
Mills, B.Y.: 1983, this volume, p. 563.
Nulsen, P.E.J.: 1982, M.N.R.A.S. 198, p. 1007.
Peimbert, M., and van den Bergh, S.: 1971, Ap.J. 167, p. 223.
Seward, F.D., and Harnden, F.R.: 1982, Ap.J. (Letters) 256, p. L45.
Seward, F.D., Harnden, F.R., Murdin, P., and Clark, D.H.: 1983, Ap.J. (in press).

DISCUSSION

RADHAKRISHNAN: Would you comment on the high ambient densities for the historical SNRs which were mentioned this morning?

MCKEE: For SNRs high above the plane, such as Tycho, a circumstellar rather than interstellar origin for this gas appears more reasonable. Chevalier has argued against this possibility by showing that the observed evolution is more consistent with a uniform ambient medium than a wind. Perhaps this problem could be overcome if the wind, which would come from the red giant precusor of the SN, were confined by the pressure of the ambient medium.

FEDORENKO: Is it possible to associate the observed turbulence in Cas A with multiple shocks produced by propagation of the expanding envelope in a cloudy medium?

MCKEE: Such shocks undoubtedly contribute to the turbulence, as do the Rayleigh-Taylor instability in the ejecta (Gull 1973) and cloud-cloud collisions.