SUPERNOVA BLAST WAVES IN LOW-DENSITY HOT MEDIA: 
A MECHANISM FOR SPATIALLY DISTRIBUTED HEATING

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Received 2004 December 17; accepted 2005 April 11

ABSTRACT

Most supernovae are expected to explode in low-density hot media, particularly in galactic bulges and elliptical galaxies. The remnants of such supernovae, although difficult to detect individually, can be profoundly important in heating the media on large scales. We characterize the evolution of this kind of supernova remnant, based on analytical approximations and hydrodynamic simulations. We generalize the standard Sedov solution to account for both temperature and density effects of the ambient media. Although cooling can be neglected, the expansion of such a remnant deviates quickly from the standard Sedov solution and asymptotically approaches the ambient sound speed as the swept-up thermal energy becomes important. The relatively steady and fast expansion of the remnants over large volumes provides an ideal mechanism for spatially distributed heating, which may help to alleviate the overcooling problem of hot gas in groups and clusters of galaxies, as well as in galaxies themselves. The simulations were performed with the FLASH code.

Subject headings: cooling flows — galaxies: clusters: general — galaxies: ISM — ISM: structure — supernova remnants

Online material: color figures

1. INTRODUCTION

Supernovae (SNe) are a major source of the mechanical energy input in galaxies and possibly in the intergalactic medium (IGM). On average, an SN releases about $10^{51}$ ergs of kinetic energy, which is carried by the ejecta that drives a blast wave into the ambient medium. How far this blast wave goes and how fast the energy is dissipated depend sensitively on the density and temperature of the medium. Core-collapsed SNe represent the end of massive stars, the bulk (if not all) of which form in OB associations. The energy release from such an association, highly correlated in space and time, has a great impact on the surrounding medium. Initially, the energy release from the OB association is primarily in the form of intense ionizing radiation from very massive stars, which tends to homogenize the surrounding medium (McKee et al. 1984). After several million years, fast stellar winds start to play a major role in heating and shaping the medium, creating a low-density hot bubble (Weaver et al. 1977), probably even before the explosion of the first SN in the association. Later, after about $5 \times 10^6$ yr of star formation (if more or less coeval), core-collapsed SNe become the dominant source of the mechanical energy input into the already hot surroundings (Monaco 2004). This combination of the concerted feedbacks, lasting for $\sim 5 \times 10^7$ yr—the lifetime of an 8 $M_\odot$ star—leads to the formation of a so-called superbubble of low-density hot gas enclosed by a supershell of swept-up cool gas (e.g., Mac Low & McCray 1988). The expansion of such a superbubble is expected to be substantially faster than typical OB association internal velocities of a few kilometers per second. Therefore, a majority of core-collapsed SNe ($\sim$90%) should occur inside their parent superbubbles (e.g., Higdon et al. 1998; Parizot et al. 2004 and references therein). SNe from lower mass stars (e.g., Type Ia; e.g., McMillan & Ciardullo 1996), particularly important in early-type galaxies and possibly in galactic bulges and halos, are also expected to occur mostly in low-density hot media. The interstellar remnants of such SNe are typically too faint to be well observed individually. But in terms of both heating and shaping the global interstellar medium (ISM)/IGM, such “missing” remnants are probably more important than those commonly known and well-studied supernova remnants (SNRs). Although spectacular looking, they are atypical products of SNe (e.g., from runaway massive stars), which happened to be in relatively dense media.

Surprisingly, there has been little work toward the understanding of the SNR evolution in hot media with relatively high pressure. Almost all the existing studies assume an ambient medium with both low temperature and low pressure (e.g., $T \lesssim 10^4$ K, $nT \lesssim 10^4$ cm$^{-3}$ K; Chevalier 1974; Cioffi et al. 1988; Shelton 1999) or relatively high in temperature but still low in pressure (e.g., $T \sim 10^6$–$10^7$ K, $nT \sim 10^4$–$10^5$ cm$^{-3}$ K; Dorfi & Volk 1996). If both the ambient gas temperature and pressure are low (e.g., $T \lesssim 10^4$ K, $nT \lesssim 10^4$ cm$^{-3}$ K), much of the SNR evolution may then be described by the self-similar Sedov solution (Sedov 1959), which assumes that both the thermal energy and radiative cooling of swept-up gas are negligible. The ambient gas with both high temperature and high pressure makes two differences: (1) the shock is weak due to the high sound speed, and (2) the thermal energy of the swept-up gas is not negligible. Sedov (1959, p. 238–251) made a linear approximation to the pressure effect but did not account for the high-temperature effect (Gaffet 1978). Dorfi & Volk (1996) briefly mentioned the behavior of an SNR shock asymptotically reaching the sound speed but primarily studied the cosmic-ray acceleration. McKee & Ostriker (1977) considered the SNR evolution in a cloudy medium, including thermal evaporation. Although the intercloud medium in this case is hot ($T \sim 10^6$ K), the average ambient pressure is still low ($nT \sim 10^5$ cm$^{-3}$ K). The characteristic temperature and pressure inside galactic bulges and elliptical galaxies are about $\sim$2–3 orders of magnitude higher than the values used in these SNR studies (Spergel & Blitz 1992; Morris & Serabyn 1996 and references therein). Shigeyama & Fujita (1997) simulated an SNR in a hot medium with relative high
pressure \( (n = 0.1 \text{ cm}^{-3} \text{ and } T \approx 10^7 \text{ K}) \) but focused only on the ejecta. In short, we are not aware of any simple description or simulation of the SNR evolution in the hot media typical in galactic bulges and elliptical galaxies.

We have closely examined the SNR evolution in the relatively low-density and high-pressure hot media. The evolution of such an SNR is significantly different from those in a relatively dense and cold environment. While the low density means that the SN energy loss rate is slow, the high pressure makes the swept-up thermal energy dynamically important. Furthermore, the expansion speed of the blast wave is always above the sound speed of the hot ambient medium with the value of a few hundred kilometers per second. Therefore, the SNR can expand to a large volume and distribute its energy in a rather uniform fashion. In the following, we demonstrate these effects, based chiefly on one-dimensional high-resolution hydrodynamic simulations.

2. SIMULATION SETUP

Our simulations use the newly released FLASH code (ver. 2.4), which allows for modular, adaptive mesh, and parallel simulations and solves the hydrodynamic equation explicitly (Fryxell et al. 2000 and references therein). To accurately capture a shock front, we use a uniformly spaced grid with a spatial resolution of about 0.01 pc. We assume that the SN explosion is spherically symmetric and that the ambient medium is uniformly distributed with identical temperature \( (T_0) \) and density \( (\rho_0 = n_0 m_p) \). The number density of particles is \( n = n_0/\mu \), where \( \mu \approx 0.6 \) for fully ionized gas with the solar abundance. An SN energy \( E_{SN} \) is deposited inside a small radius \( r_{inital} \).

The ambient gas is assumed to be mostly ionized. The cooling is neglected in the simulations (further discussion in § 4). Table 1 lists the setup parameters \( (T_0, n_0, \rho_{inital}) \) of a few representative cases, which are characteristic of the Galactic bulge (A), giant elliptical galaxies (B), and rich clusters of galaxies (C). The table also lists various inferred parameters to be discussed in § 3.

We have experimented with various energy deposition schemes (Cioffi et al. 1988; Chevalier 1974). If the explosion energy is initially deposited as heat uniformly in a small volume, a Sedov solution can be quickly reached. On the other hand, depositing the initial energy in the form of kinetic energy leads to many small-scale structures due to various internal shocks especially inside the ejecta. Exploding SNe with or without ejecta (assumed to have a total mass of \( 1.4 M_{\odot} \)) do affect the evolution before the swept-up mass becomes dominant compared with the ejecta. However, a specific choice of the initial conditions does not significantly affect our conclusion on the overall structure and evolution of the SNRs.

We output simulation results every 100 yr. The radius of the outer shock front \( R_c(t) \) corresponds to the position where the gradients of the pressure and velocity are the largest. The shock front velocity \( V_c(t) \) is estimated from the \( R_c \) difference between two consecutive steps. Therefore, the accuracy of the local \( R_c \) and \( V_c \) estimates is limited by the finite resolution in both time and spatial step sizes. An adaptive smoothing of the \( V_c \) evolution is performed to reduce the step-by-step fluctuations. The uncertainties in these calculations in individual steps do not affect the actual evolution of these parameters, which are determined by the internal hydrodynamic solutions in the simulations.

3. RESULTS: OUTER BLAST WAVE EVOLUTION

Figure 1 shows the evolution of \( R_c \) and \( V_c \) for the three cases listed in Table 1. In all cases, the initial free-expansion stage is short and ends when the swept-up mass roughly equals that of the ejecta. The expansion then more or less follows the self-similar Sedov solution:

\[
V_{Sedov} = \frac{2}{5} \xi \left( E_{SN} / \rho_0 r^2 \right)^{1/5},
\]

where \( \xi = 1.14 \) for gas with \( \gamma = 5/3 \). But the Sedov phase does not last long if the ambient medium has a high temperature. The evolution gradually deviates from the Sedov solution, as the blast wave expansion asymptotically approaches the sound speed of the ambient medium. Based on these asymptotic behaviors (neglecting the brief free-expansion phase), we find that the following expression gives a simple generalization of the Sedov solution, approximately characterizing the blast wave evolution in a low-density hot medium (to an accuracy of \( \lesssim 3\% \); see the bottom panels of Fig. 1):

\[
V_s = c_s \left( \frac{t_c}{t} + 1 \right)^{3/5},
\]

where \( c_s \) is the sound speed of the ambient medium and \( t_c \) is a characteristic time that can be obtained from the Sedov solution by equating \( V_{Sedov} \) and \( V_s \) when \( t \ll t_c \):

\[
t_c = \left[ \frac{2}{5} \xi \right]^{5} \left( \frac{E_{SN}}{\rho_0 r_s^5} \right)^{1/3}.
\]

From equation (2), one can easily estimate the Mach number \( M = V_c/c_s \) of the blast wave as a function of time, e.g., \( M \approx 1.5 \) at \( t = t_c \) and a strong shock (i.e., \( M > 2 \) for \( t < 0.46 t_c \), or about a few times \( 10^4 \) yr. For ease of reference, Table 1 also lists the time and the swept-up ambient mass when \( M = 2 \). Note that equation (1) is not valid even before \( t = t_c \). Subsequently, the blast wave expands with a low Mach number and will eventually be dissipated by radiative cooling and turbulent motion, which cannot be accounted for here in one-dimensional simulations, however. But the expansion speed would not fall below the sound speed.

By integrating equation (2), we further derive the blast wave radius,

\[
R_s(t) = \int_0^t c_s \left( \frac{t_c}{t'} + 1 \right)^{3/5} dt' = \frac{5}{2} c_s t_c \left( \frac{t_c}{t} \right)^{2/5} \frac{F}{\left( \frac{3}{5} \frac{2}{5} \right) \left( \frac{7}{5} \frac{1}{5} - \frac{t}{t_c} \right)},
\]

where \( F \) is the generalized hypergeometric function.

| Table 1 |
| --- |
| **Parameter** | **Case A** | **Case B** | **Case C** |
| \( n_0 \text{ (cm}^{-3} \text{)} \) | 0.2 | 0.01 | 0.002 |
| \( T_0 \text{ (K)} \) | \( 5 \times 10^6 \) | \( 10^7 \) | \( 5 \times 10^7 \) |
| \( r_{inital} \text{ (pc)} \) | 1.0 | 5.0 | 2.0 |
| \( c_s \text{ (km s}^{-1} \text{)} \) | 339 | 479 | 1071 |
| \( t_c \text{ (Myr)} \) | 0.035 | 0.053 | 0.024 |
| \( M_{swept} \text{ (M}_{\odot}) \) | 874 | 437 | 87 |
| \( t_m = 2 \text{ (Myr)} \) | 0.016 | 0.024 | 0.011 |
The characteristic parameter $t_e$ has a clear physical meaning. Within the radius $R_e \equiv R_e(t_e) \approx 2.89 c_s t_e$, the ambient thermal energy swept up by the blast wave is

$$\frac{4}{3} \pi R_e^3 \frac{\rho_0 T_0}{\mu (\gamma - 1)} \approx 2.47 \times 10^5 \frac{E_{SN}}{\gamma (\gamma - 1)} \approx 1.8 E_{SN},$$

where $\mu = 0.6$. Therefore, $t_e$ characterizes the time when the swept-up thermal energy is about twice the explosion energy. Note that for a given $E_{SN}$, $R_e$ depends only on the ambient pressure, but $t_e$ depends on both the density and the temperature.

Equations (2) and (4) generalize the Sedov solution, by accounting for both temperature and density effects of the ambient medium. The temperature effect is reflected in the explicit dependence of the SNR evolution on $c_s$. When $c_s \to 0$ (thus $t_e \to \infty$), equations (2) and (4) become the Sedov solution. In general, $R_s$ is determined by $M$, which depends only on $t/t_e$ (eq. [2]), and $R_e$. In other words, $M$ is uniquely determined by $R_s$ for a given $R_e$. Equations (2) and (4) show that both $V_s$ and $R_e$ could have substantially larger values than what are predicted by the Sedov solution, while $M$ is generally low. Therefore, the SNR blast wave heating is locally gentle and is over a large volume in the low-density hot medium.

4. RESULTS: INTERIOR STRUCTURE OF THE SUPERNOVA REMNANTS

Figure 2 illustrates the radial structure of our simulated SNRs (case A as an example). In the early stages (before time $a$) the SNR maintains a strong shock, and the postshock gas moves forward at a speed greater than the sound speed of the ambient gas. A low-pressure region gradually develops inside the SNR due to the adiabatic expansion, as shown in the pressure panel. Remarkably, both densities and temperatures can fall below the ambient values. Therefore, the cooling rate, and hence the X-ray emission, of this region can be very low. The pressure at the SNR center reaches the minimum at time $b$. Later, the postshock gas starts to flow back, and the central pressure increases, gradually approaching the value of the ambient medium (time $c-d$). But the underpressure region behind the widening blast wave front remains. Figure 3 shows the conversion of the explosion energy to the thermal and kinetic energy of the swept-up medium as a function of time, which depends weakly on the specific initial conditions except for the first several thousand years ($\lesssim 2$). In addition to the explosion energy, the blast wave also redistributes the thermal energy of the swept-up ambient medium.

While the energies are redistributed widely, the ejecta are confined within relatively small regions. Figure 1 (left) includes the evolution of the contact discontinuity between the ejecta and the swept-up ambient medium of case A with $1.4 M_\odot$ ejecta. The discontinuity reaches a maximum of only $\sim 10$ pc, consistent with the result of Shigeyama & Fujita (1997). Therefore, the metal enrichment of an SNR may still be localized even in a low-density medium, unless an interaction with another SNR or a global flow such as a galactic wind redistributes the ejecta.

We have neglected the cooling effect. Using the collisional ionization equilibrium (CIE) cooling rate, we estimate the total radiative energy loss to be less than 5% up to 0.2 Myr. The undisturbed ambient gas itself radiates even more efficiently than the gas swept up by the SN blast wave. The potential deviation from the assumed CIE should be small, because the ambient medium considered here is already highly ionized.

5. DISCUSSIONS

The above results show that the evolution of an SNR in a low-density hot medium has several distinct properties: (1) the blast wave always moves at a speed greater than, or comparable to, the sound wave and can thus reach a much larger radius than that...
predicted by the Sedov solution; (2) because the remnant never gets into a snowplow radiative phase, the radiative cooling is typically negligible; (3) the swept-up thermal energy is important, affecting the evolution of both the blast wave and the interior structure; and (4) because the Mach number of the blast wave is typically small, its heating is subtle and over a large volume.

The large-scale distributed heating by such SNRs may have strong implications for solving the energy balance problems in studying diffuse hot gas. The most notable problem is perhaps the apparent lack of predicted cooling flows in groups and clusters of galaxies (Mathews & Brighenti 2003; Peterson et al. 2003). Various existing proposals for the solution (e.g., AGN heating and thermal conduction) have only limited success and many uncertainties. Fundamentally, a distributed heating mechanism is required to balance the cooling (e.g., Roychowdhury et al. 2004). Indeed, heating due to sound waves generated by buoyant bubbles from AGN energy injections has recently been proposed as a solution (Ruszkowski et al. 2004a, 2004b). But none of these proposals are likely to explain the more acute overcooling problem in individual galaxies, where the cooling timescale of hot gas is even shorter. As shown above, blast waves produced by SNe, Type Ia in particular, may provide a natural mechanism for the heating required to balance, or at least alleviate, the cooling of the diffuse hot gas around individual galaxies, possibly even in the IGM (Domainko et al. 2004).

Clearly, the above discussion is very much limited by our one-dimensional simulations of individual SNRs. We are
currently carrying out three-dimensional simulations to study the evolution of hot gas in galactic bulges. These simulations will account for the cooling, as well as the spatial inhomogeneity generated by the global galactic gravity and by the interaction among multiple SNRs. The spatial distribution and physical properties of the gas will then be determined self-consistently.

We thank R. A. Chevalier, J. Slavin, R. Shelton, and the anonymous referee for useful comments on the work, which is supported by NASA through grant GO3-4111X. The software used in this work was in part developed by the Department of Energy–supported Advanced Simulation and Computing/Alliance Center for Astrophysical Thermonuclear Flashes at the University of Chicago.

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