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Supernova propagation in the circumstellar and interstellar medium

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Abstract. We describe the propagation of supernova shocks within the surrounding medium, which may be due to mass-loss from the progenitor star. The structure and density profile of the ejected material and surrounding medium are considered. Shock wave interaction with clouds and wind-bubbles, and issues relevant to cosmic rays are briefly discussed.

Key words. shock waves – stars:massive – supernovae: general – stars: winds, outflows– ISM: supernova remnants

1. Introduction

The propagation of Supernova Remnants (SNRs) in the ambient medium has been studied for over 4 decades. Early work was reviewed by Woltjer (1972). Since then there have been several excellent reviews (Chevalier 1977; Ostriker & McKee 1988; Chevalier & Fransson 1994; Bisnovatyi-Kogan & Silich 1995). The high energy emission from SNRs was reviewed by Reynolds (2008). In this short presentation, our aim is to review the basic ideas of the propagation of SN shock waves into the ambient medium, and point out issues relevant to cosmic-ray acceleration. For further details we refer the reader to the excellent publications cited above.

2. Ejecta-dominated stage

The explosion of massive stars ($\gtrsim 8 M_{\odot}$), or the thermonuclear deflagration and detonation of white dwarfs, leads to the production of highly supersonic shocks waves that propagate into the ambient medium. In order to understand the evolution of these shock waves, one must know the density structure of the ejecta and the surrounding medium. The density structure of the ejecta in core-collapse SNe can be approximated by a decreasing power law (Chevalier & Soker 1989; Matzner & McKee 1999) with an index roughly between 9 and 11. Below a certain velocity the density is assumed roughly constant. The ambient medium in core-collapse SNe is much more complicated. Close to the star, the density can be approximated by a wind, whose density varies as r^{-2} if the wind parameters are constant (although there is no reason for them to be constant, see Dwarkadas & Gruszko 2011). The expansion of power-law ejecta decreasing as r^{-n} into a power-law circumstellar medium whose density decreases as r^{-s} can be described by a self-similar solution (Chevalier 1982; Truelove & McKee 1999), where the radius goes as $t^{(n-3)/(n-s)} \sim t^{m}$, where $m < 1$ is called the expansion parameter. For representative values $n = 9$ and $s = 2$ indicative

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Send offprint requests to: V. V. Dwarkadas of a wind, $m = 0.86$. Thus, the presence of a medium, however tenuous, restricts free expansion of the shock wave, whose velocity decreases as t^{m-1}. Further from the star, the density depends on the mass-loss from, and evolution of, the progenitor star, and may form a wind-blown bubble (Weaver et al. 1977, §5.2).

Type Ia SNe are assumed to arise from low mass stars, which don't suffer from considerable mass-loss and don't modify their ambient medium significantly (Badenes et al. 2007). A first assumption is to assume an unmodified constant density medium around Ia's. The ejecta profile is more complicated. By comparing density profiles obtained by hydrodynamical simulations of Type Ia explosions, Dwarkadas & Chevalier (1998, hereafter DC98) showed that an exponential profile is a better approximation for Type Ia ejecta profiles. The introduction of an exponential introduces one more variable, and therefore the solution is no longer self-similar, although it is still scalable, and can be expressed in terms of a single family of parameters.

The expansion of the SN ejecta into the ambient medium drives a shock into the medium. The material swept up by the shock is slower moving, and the ejecta need to be decelerated before they interact with this material. This leads to the formation of a reverse shock, that expands back into the ejecta in a Lagrangian sense. The two are separated by a contact discontinuity, which divides the region of shocked ejecta from the region of shocked ambient medium (Fig. 1). The shocks will accelerate particles to high energies due to a process that is generally thought to be some variant of Diffusive Shock Acceleration.

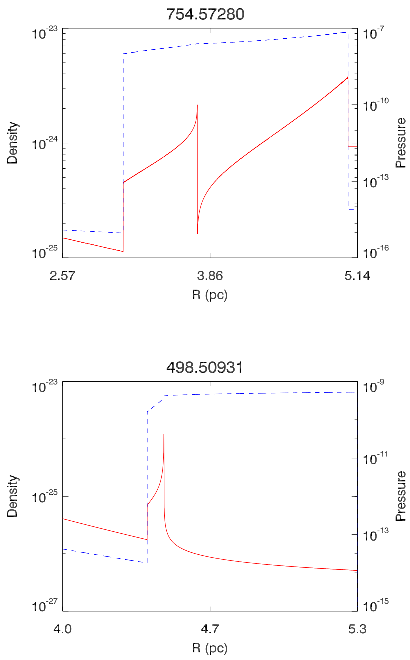

Fig. 1. The density (red) and pressure (purple) profiles of the shocked interaction region between the forward and reverse shocks, for [Top] a Type Ia SN with an exponential ejecta density profile interacting with a constant density medium and [Bottom] A core-collapse SN with a power-law density profile interacting with a wind with constant parameters. Time in years is given at the top. Note the variation in the profile between the two cases. An expanding grid is used to allow most of the computational domain to be occupied by the shocked region.

The self-similar, or scalable solutions, provide the ratio of radii of the reverse shock, contact discontinuity (CD) and forward shock. These ratios are fixed for purely non-radiative hydrodynamical evolution, but may be modified if significant energy (> 10%) is expended in accelerating particles to relativistic speeds (Caprioli 2011). Large modification of these ratios is often taken as evidence of cosmic-ray acceleration, which would tend to narrow the distance between the CD and forward shock for instance (Warren et al. 2005; Kosenko et al. 2011). However this presumes that the ejecta profiles, and especially the smooth, homogeneous ambient medium profiles, are exact representations. For Type Ia's, DC98 showed that while the exponential is a good and convenient approximation to the ejecta profiles, deviations from this are important, especially for low-energy explosions. One would also expect inhomogeneities in the ambient medium over large scales, especially for core-collapse SNe, whose effect may remain imprinted in the profile over several doubling times, and thus modify the ratio. Other factors, including the growth of R-T instabilities (Orlando, these proceedings), could alter the distance between CD and forward shock (Kosenko et al. 2011).

Since the reverse shock is generally expanding into a higher density than the forward shock, it's velocity is lower. If particles are accelerated by the reverse shock, as suggested for Cas A (Helder & Vink 2008), they would be expected to have a lower maximum energy than those at the forward shock. If core-collapse SNe expand in winds whose density decreases as r^{-2}, whereas Type Ia SNe expand into a constant density medium, then the ratio of the density ahead of the reverse shock to that ahead of the forward shock falls more rapidly in Type Ia's then in core-collapse SNe, suggesting that the reverse shock's effects are felt longer in core-collapse SNe than in Ia's.

During the early stages of the evolution, both the forward and reverse shocks expand outwards in radius. The decelerating contact discontinuity is Rayleigh-Taylor (R-T) unstable, and R-T fingers will mix shocked ejecta material with the shocked ambient medium (Chevalier et al. 1992; Dwarkadas 2000). At a later time, depending on the ejecta profile (Dwarkadas & Chevalier 1998), the ejecta density becomes low enough that the reverse shock will "turn over" and actually begin to move inwards in radius, towards the explosion center. It is only after the reverse shock reaches the center that the SNR can be thought of as entering the Sedov-Taylor phase.

3. Sedov-Taylor stage

In this adiabatic stage the remnant expansion depends mainly on two parameters, the energy of the explosion E and the ambient medium density ρ. The shock front travels as $R_{sh} \propto (E/\rho)^{1/5}\, t^{2/5}$ when expanding into a constant density medium, or $R_{sh} \propto t^{2/3}$ in the less likely case of the stage being reached while the SN is expanding in a wind medium with $\rho \propto r^{-2}$. This expression was first derived for a point explosion in a uniform medium (Taylor 1950).

In order for the remnant to reach the Sedov stage, several things must happen (1) The reverse shock must reach the center and effectively cease to exist, since the Sedov-Taylor solution is a single-shock solution, as opposed to the double-shocked solutions earlier (Fig. 1). In multi-dimensional simulations, the reverse shock generally does not remain spherical as it moves back, and eventually tends to dissipate. (2) The expansion parameter m discussed earlier must decrease from its larger value till it reaches the Sedov value of 0.4 (0.67) in a constant density medium (wind) (3) The density profiles must change from those of the ejecta-dominated stage (Fig. 1) to those of the Sedov stage. Although traditionally the Sedov stage is assumed to be reached when the swept-up mass is just larger than the ejecta mass, this does not hold in practice, as first shown almost 4 decades ago (Gull 1973). DC98 showed that the swept-up mass must be about 20-30 times the ejecta mass (depending on the ejecta profile) when the reverse shock reaches the center.

Thus the idealistic representation of the Sedov stage is reached later in time, and SN radius, than when the swept-up mass equals the ejecta mass. The simple reason is that a SNR is not a point explosion, and the Sedov stage arises from the ejecta-dominated stage, when the remnant is already light-years across in radius. Major galactic remnants, such as Tycho, Cas A, Kepler, and even the 1000-year old SN 1006 are currently in the ejecta-dominated stage, with a double-shocked structure.

Some calculations suggest that the transformation of SNR energy to cosmic-rays is most efficient at the beginning of the Sedov stage (Berezhko & Völk 1997; Ptuskin & Zirakashvili 2005; Ptuskin et al. 2010). This has prompted many investigations into the acceleration of particles in the Sedov stage (Kang 2006, 2010; Castro et al. 2011). The transition into the Sedov stage however may occupy a significant amount of the lifetime of this stage, and must be taken into account in computations of the accelerated particle spectrum. In some cases, the Sedov stage may be shortened, or even completely eliminated (§5.2).

4. Radiative stage

When the shock slows down sufficiently that the cooling time of the material behind the shock becomes smaller than the flow time, the SNR enters the radiative phase. This phase is not generally of much interest in cosmic-ray physics because the slow shock is inefficient at accelerating particles to relativistic energies (Berezhko & Völk 1997). The evolution can be approximated by a momentum-driven flow, where $R_{sh} \propto t^{1/4}$. Ostriker & McKee (1988) prefer a pressure-driven snowplow model ($R_{sh} \propto t^{2/7}$), while Cioffi et al. (1988) suggest an offset solution $R_{sh} \propto t^{0.3}$. In any case the SNR has decelerated considerably from the initial stages. Eventually, it will merge with the ISM, finally mixing all the constituents of the explosion back into the ISM.

A radiative shock though can form at any time depending on the density of the ambient medium, if the cooling time $t_{cool} \propto kT_s/(n\Lambda)$ becomes smaller than the flow time. Here $T_s \propto v_s^2$ is the postshock temperature, n the density of the ambient medium, and Λ the cooling function. This can happen for young SNe expanding into a high density medium, as has been postulated for SN 1993J (Nymark et al. 2009; Chandra et al. 2009). SNRs impacting with clouds or driven into clumps may also form radiative shocks. For some SNe, modelling of the X-ray and optical emission indicates a radiative shock impacting clumps while an adiabatic shock expands into the interclump medium (Chugai 1993; Chugai & Danziger 1994; Chugai et al. 1995).

5. Some special case studies

5.1. SNR-molecular cloud interaction

This is an interesting case for cosmic ray physicists, because many SNRs discovered in γ-rays are found to be interacting with molecular clouds, suggesting a hadronic origin for the emission. There are various possibilities, depending on whether the SNR shock is actually interacting with the cloud or not. (1) Shock-cloud interaction has not occurred. The escaped particles from the SNR have interacted with the dense cloud material, leading to broadband non-thermal emission (Gabici et al. 2009). The hydrodynamical evolution of the SNR is not yet affected by the presence of the cloud. (2) The SN shock has impacted the cloud. The impact of SNR shocks with clouds was discussed by Klein et al. (1994), and resulting γ-ray emission by Uchiyama et al. (2010). Fig 2 shows results from a simulation of a SNR interacting with a cloud of density ρ_{cl}. The impact drives a shock into the cloud, and a reflected shock back into the intercloud medium with density ρ_{ic}. The velocity of the cloud shock $v_{cl} \propto v_{ic}\ \sqrt{(\rho_{ic}/\rho_{cl})}$ can be much smaller than the inter-cloud shock velocity. In case of a dense cloud, the cloud shock can become radiative if it cools faster than the flow time through the cloud. The impact of the shock on the cloud, and the shear flow on the front and sides, leads to the formation of Richtmeyer-Meshkov and Kelvin-Helmholtz instabilities, which will eventually lead to the destruction of the cloud. On a smaller scale, these types of interactions are seen in SNRs interacting with a clumpy medium.

5.2. SNRs in wind-blown bubbles

Many massive stars will form large, and some not-so-large, wind bubbles around the star. Wind bubbles are regularly seen around main-sequence and Wolf-Rayet (W-R) stars (Chu 2008). The basic structure (Fig 3) comprises of an inner and outer shock separated by a contact discontinuity (CD). The shocked wind between the inner shock and CD usually has a low density and high pressure, and thus high temperature. The outer shock is usually radiative, and the material between the outer shock and CD forms a thin, dense shell. Ionization from the star may result in the formation of an ionized region around the wind-blown shell.

The post-main-sequence phases occupy a small fraction of the total stellar lifetime, but may result in substantial mass-loss and modification of the ambient medium (van Marle et al. 2005; Freyer et al. 2006; Dwarkadas 2007b; Toalá & Arthur 2011). Stellar evolution theory suggests that single stars $< 30\ M_\odot$ will end their lives as RSGs to form Type IIP SNe. Stars with higher initial mass will become W-R stars, with perhaps an intermediate Luminous Blue Variable phase, and explode as Type Ib/c SNe. RSGs have slow dense winds. W-R stars have fast winds with a lower mass-loss rate (Puls, these proceedings), resulting in a lower den-

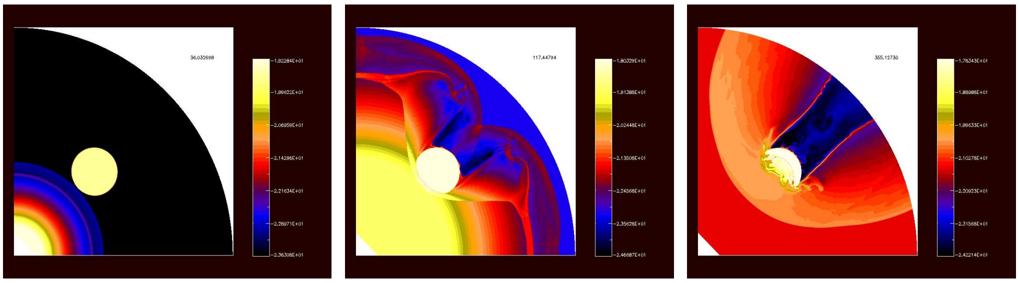

Fig. 2. Snapshots from a simulation of the interaction of a SNR with a dense cloud, carried out using the VH-1 code in spherical symmetry. (a) A SNR with a spherical double-shocked structure approaches the cloud. Time in years is at top of picture. (b) The impact drives a shock into the cloud, and a reflected shock back into the inter-cloud medium. A complicated hydrodynamic structure is seen. (c) The rest of the intercloud shock has swept past, while the reflected shock can be clearly seen. Meanwhile, the shock crossing the cloud results in the formation of instabilities that will ultimately destroy the cloud.

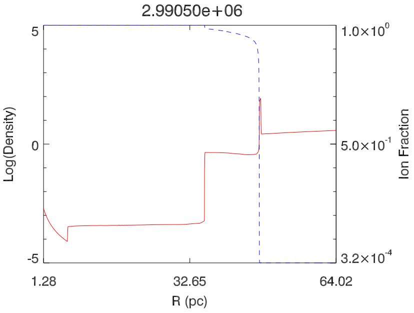

Fig. 3. The basic structure of a wind-blown bubble around a main-sequence 40 $M_\odot$ star, carried out using the ionization-gasdynamics code AVATAR (Dwarkadas & Rosenberg 2011). Density in red (scale on left), ionization fraction in blue (scale on right). Radius in parsecs on X-axis. From left, we see the freely expanding wind, the wind termination shock, a shocked wind region, an ionized HII region, and the dense shell. The structure upto the HII region is fully ionized. The ionization front is trapped within the shell, and the ionization fraction can be seen to drop very sharply within the shell.

sity in the ambient medium into which the SN will expand. A binary companion can alter the stellar evolution and structure of the ambient medium, as postulated for SN 1987A (Morris & Podsiadlowski 2007).

The evolution of SN shock waves within these bubbles has been studied by Chevalier & Liang (1989); Tenorio-Tagle et al. (1990, 1991); Dwarkadas (2005, 2007a,b); Dwarkadas et al. (2010). The collision of a SN shock with a shock or CD results in a transmitted shock expanding outwards, and a reflected shock expanding back into the ejecta. Thus expansion within a bubble results in several shocks bouncing around in the remnant cavity. Many of these shocks can accelerate particles to high energies, at least for short periods of time. Accelerated particles that escape from the SNR and interact with this shell may give rise to γ-ray emission (Ellison & Bykov 2011). When the SN shock collides with the dense shell, it can result in significant deceleration of the shock, and an increase in the optical and X-ray emission, as seen in SN 1987A (Park et al. 2006) and SN 1996cr (Bauer et al. 2008). The shock will traverse the shell with a low velocity (see 5.1) until it emerges. In extreme cases, the shell density may be so high that the shock will be trapped in the shell, and the kinetic energy may be radiated away. The SN will then go directly to the radiative phase, avoiding the Sedov phase.

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