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Interaction of Supernova Remnants With the Ambient medium

VIKRAM V. DWARKADAS
Bartol Research Institute, Univ of Delaware, 217 Sharp Lab, Newark, DE 19716
E-mail: vikram@bartol.udel.edu
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ABSTRACT

We summarize various aspects of the interaction of supernova remnants (SNRs) with the ambient medium. We discuss the evolution of SNRs in environments sculpted by the progenitor star, and summarize the factors on which this evolution depends. As a specific example, we consider the evolution of the medium around a 35 $M_\odot$ star, and the interaction of the shock wave with this medium when the star explodes as a SN. We also discuss the interaction of Type Ia SNe with the ambient medium, especially the formation and growth of hydrodynamic instabilities.

Key Words : hydrodynamics; instabilities; shock waves; circumstellar matter; ISM: bubbles; supernova remnants

Most stars with an initial mass greater than about 8 $M_\odot$ will end their lives as core-collapse SN. The evolution of the resulting supernova remnants (SNRs) in the uniform interstellar medium has been well studied (Ostriker & McKee 1988). The evolution of SNRs in steady-state winds (density $\rho \propto r^{-2}$) has also been the subject of investigation (Chevalier 1982). An analytic study of SNRs evolving in circumstellar (CS) wind-blown bubbles was undertaken by Chevalier & Liang (1989). Numerical studies were carried out by Tenorio-Tagle et al. (1990, 1991) and Franco et al. (1991).

In this project we describe, using analytic models and high-resolution two-dimensional hydrodynamic simulations, the evolution of SNRs in the surrounding medium, especially inhomogeneous media. The simulations described herein were carried out with the VH-1 code, a 3-dimensional finite-difference hydrodynamics code based on the Piecewise Parabolic Method of Colella and Woodward (1984). The code uses a grid that tracks the shock and expands along with it, although no new zones are added. This is very useful in simulations where the dimensions change by many orders of magnitude over the course of a single run. However the grid expansion should be kept in mind when viewing images from the simulations, since the grid size is larger in each succeeding timeframe.

Three main topics are discussed:

- **The Evolution of SNRS in Circumstellar Wind-Blown Bubbles.** The general structure of a wind-blown nebula was first elucidated by Weaver et al. (1977). In the simplest, two-wind approximation, a fast wind from a star collides with slower material emitted during a previous epoch, driving a shock into the ambient medium. The pressure of the post-shock material causes the freely flowing fast wind to decelerate, driving a second shock that travels inwards towards the center. A complex double-shocked structure is formed. Figure 1 shows the density and pressure profiles from a simulation of a wind-blown bubble.

  Going outwards in radius from the central star we find the following regions delineated: freely flowing fast wind, inner or wind-termination shock (R_t), shocked fast wind, contact discontinuity (R_{cd}), shocked ambient medium, outer shock (R_o) and unshocked ambient medium.

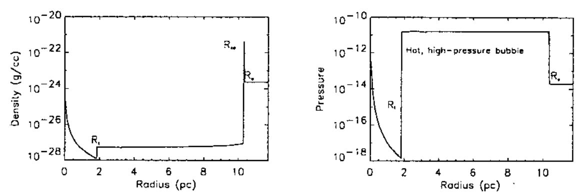

Fig. 1.— a) Density and b) Pressure profiles from a numerical simulation of a wind-blown bubble around a massive star.

  We consider SNe in the early free-expansion stage, before the swept-up mass substantially exceeds the ejecta mass and the SN enters the adiabatic stage. Therefore the density structure of the ejecta is important. Following Chevalier & Fransson 1994 we adopt a density profile, in the outer parts of the ejecta in the free-expansion phase, that varies approximately as a power-law with velocity, $\rho \propto v^{-n}$, where ρ is the ejecta density, v is the velocity, and $n > 5$.

  The interaction of the SN ejecta with the freely expanding wind gives rise to a double-shocked structure, consisting of a forward shock driven into the wind and a reverse shock moving into the ejecta. Given the low density interior of the wind-blown bubble, it is clear that in general most of the bubble mass is contained within the dense circumstellar (CS) shell. Thus the interaction of the ejecta with this shell is crucial to determining the evolution of the remnant. This interaction depends on a single parameter $\Lambda = \frac{M_{shell}}{M_{ejecta}}$, the ratio of the shell mass to the ejecta mass.

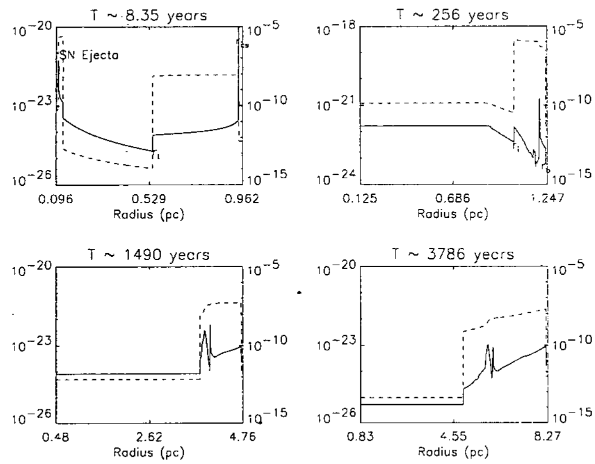

Fig. 2.— Snapshots in time from a simulation of SN ejecta interacting with a CS bubble. The mass in the circumstellar shell is 14% of that in the ejecta. The solid lines display density, with the scale given on the LHS. The dashed lines displays the pressure, with the scale given on the RHS. All units are CGS. The time is given at the top of each figure in years. The labels (a) to (d) in the text go in order of increasing time, from top to bottom and left to right.

An exploration of the interaction of SN shock waves with CS bubbles described by the Weaver et al. (1977) model shows (eg. Dwarkadas 2001), that for small values of the parameter $\Lambda \leq 1$, the structure of the density profile is important (Figure 2a-d). Just after the shock-shell interaction has taken place, the density *decreases* outwards from the reflected shock to the contact discontinuity. However as the evolution proceeds, the supernova remnant begins to "forget" the existence of the shell, and loses memory of the interaction. The density structure changes to reflect this, and begins to *increase* from the reflected shock to the contact discontinuity. In this case it takes about 15 doubling times of the radius for the remnant to forget the interaction with the shell (Fig 2d). In another few doubling times, the remnant density profile will resemble that of a SNR evolving directly in the ambient medium. It is important to take this changing density profile into account when computing the emission, such as in the X-ray and optical regime, which depends on the value of the density.

As the value of the parameter Λ increases, i.e. the mass of the wind-blown shell increases compared to the ejecta mass, the energy transmitted by the remnant to the shell also increases. Energy transfer to the shell becomes dynamically important, and the remnant evolution is speeded up. The reflected shock moves rapidly through the ejecta, and complete thermalization of the ejecta is achieved in a shorter time as compared to the SN reverse shock thermalizing the ejecta. If the value of Λ is large, the SN shock may become radiative, and the kinetic energy is converted to thermal energy. In extreme cases, the remnant may then go directly from the free-expansion stage to the radiative stage, by-passing the classical adiabatic or "Sedov" stage.

- **The case of a 35 $M_\odot$ star.** Using mass-loss data kindly provided to us by Norbert Langer, we have modelled the evolution of the medium around a 35 $M_\odot$ star, and the further interaction of the shock wave with this medium once the star explodes as a SN. The star goes through the sequence O-Star, Red-Supergiant Star (RSG) and Wolf-Rayet (WR) star. Below we describe, mainly through images of the fluid density, the subsequent evolution of the CSM around the star.

MAIN SEQUENCE (MS) STAGE

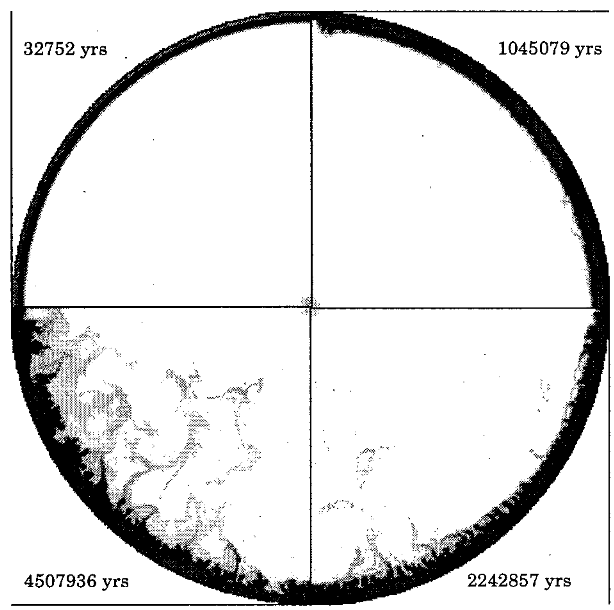

Fig. 3.— Time-sequence of images of the formation of the CSM around a 35 $M_\odot$ O-Star during the main sequence.

The wind from the star, with velocity of a few (3-4) thousand km/s and mass loss rate on the order of $10^{-7} M_\odot$/yr expands into a medium with density of about 1 particle/cc. The MS bubble grows to a radius of about 74pc. Fig 3 shows (clockwise from top left) a time-sequence of density images of the formation of the MS bubble. Note that the main-sequence shell is unstable to a Vishniac-type thin-shell instability. Perturbations arise from small numerical errors in finite differentiation near the boundary and propagate throughout the swept-up shell. The density inhomogeneities lead to pressure fluctuations which propagate within the interior, which soon develops into a turbulent state. The evolution of these perturbations distinguishes our results from those of Garcia-Segura et al. (1996), who considered the MS shell to be stable and modelled it only in 1D. However the 2D structure is quite different, and has significant implications for the succeeding evolution of the bubble.

RED-SUPERGIANT (RSG) STAGE

In the RSG stage the wind velocity falls to a low value of about 75 km/s, whereas the mass loss rate jumps up to a few times $10^{-5} M_\odot$/yr. A new pressure equilibrium is established, and a RSG shell is formed in the interior, which is also unstable to thin-shell instabilities. Fig 4 shows 2 images of the density during the RSG evolution.

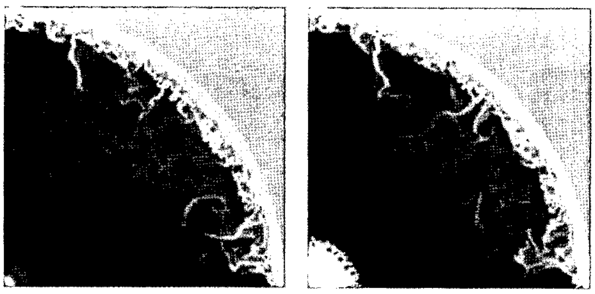

Fig. 4.— Two density images showing the formation of the inner RSG shell, which is unstable to thin-shell perturbations.

WOLF-RAYET (WR) PHASE

The wind velocity in the WR phase climbs back up to almost 3000 km/s, whereas the mass loss rate drops by only a factor of a few from the RSG stage. The momentum of the WR wind is then about an order of magnitude larger than that of the RSG wind, and the wind pushes the RSG shell outwards, simultaneously causing it to fragment (Fig 5, LHS). The RSG wind material is mixed in with the rest of the MS material (Fig 5, RHS), a key result since the RSG wind velocity was so low that the material by itself could not have gone very far. Out of $\sim 26 M_\odot$ of material lost in the wind, about 19 $M_\odot$ is lost in the RSG stage, so much of the material within the nebula is composed of matter lost in the RSG phase.

SN-CSM INTERACTION

At the end of the WR phase the stellar mass is about 9.1 $M_\odot$. We assume that about 1.4 $M_\odot$ remains as a neutron star, and the remaining mass is ejected in a supernova explosion, with a density profile that goes as a power-law in the outer parts, with a power-law index of 7. The interaction soon forms the usual double-shocked structure. In Figure 5 we show images of the fluid pressure. This variable is chosen as the shocked region between the inner and outer shocks clearly stands out. The shock starts off as a spherical

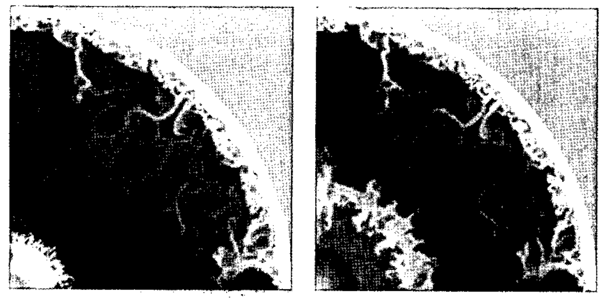

Fig. 5.— The onset of the WR wind (LHS) and its collision with the RSG shell (RHS), causing it to fragment and the RSG material to be mixed in with the rest of the nebula.

shock (Fig 6a), but the pressure within the turbulent interior soon makes the shock rippled (Fig 6b). The corrugated shock structure collides with the inner boundary of the bubble in a piecemeal fashion, and as each small part collides with the outer boundary, a reflected shock arises in that region. Thus there exist many pieces of reflected shock that arise from various interactions, have different velocities, and consequently reach the inner boundary at different times. The thermalization of the material then occurs in different stages, and X-ray images will reveal a very complicated structure which will differ considerably on scales of tens to hundreds of years.

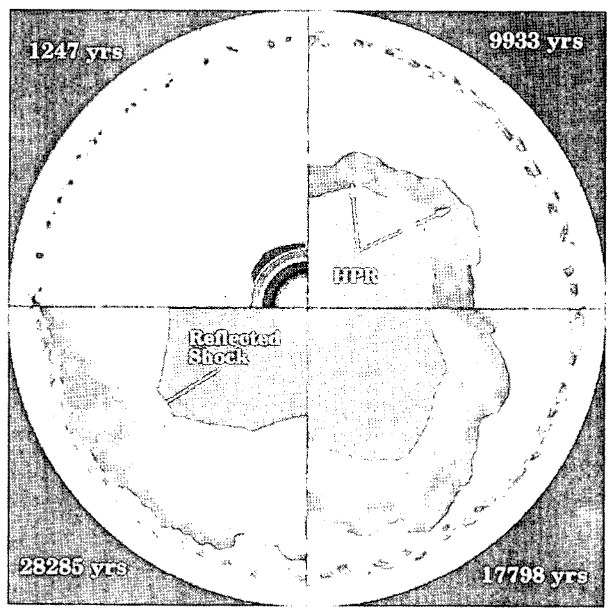

Fig. 6.— Time-sequence of pressure images of the interaction of the SNR shock with the WR bubble. HPR represents the high-pressure region between the inner and outer shocks of the SNR. Note the rippled structure of the outer shock from frame 2 onwards.

- **The Evolution of Type Ia SNe in the Ambient Medium** We discuss the evolution of Type Ia supernovae in the surroundings using 2-dimensional numerical hydrodynamic simulations. The ejecta are assumed to be described by an exponential density profile, following the work of Dwarkadas & Chevalier (1998). The case of a circumstellar region formed by mass loss from the progenitor or a companion star is also considered. The decelerating contact discontinuity is found to be Rayleigh-Taylor (R-T) unstable, as expected, and the nature of the instability is studied in detail for 2 cases: 1) a constant density ambient medium, and 2) a circumstellar medium whose density goes as r^{-2}. The nature of the instability is found to be different in both cases. In the case of a circumstellar medium the instability is much better resolved, and a fractal-like structure is seen (Fig 7). In the case of a constant density medium the extent of growth is less, and the R-T fingers are found to be limited by the presence of Kelvin-Helmholtz mushroom caps at the tips of the fingers (Fig 8). The unstable region is far enough away from the reverse shock that the latter is not affected by the mixing taking place in the interaction region. In contrast the reverse shock in the case of a circumstellar medium is found to be rippled due to the formation of instabilities. In neither case is the outer shock front affected. Further details of this work can be obtained from Dwarkadas (2000).

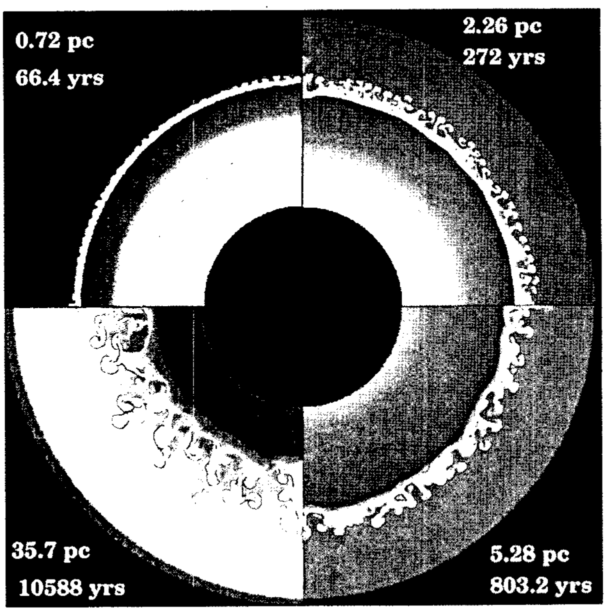

Fig. 7.— Time-sequence of images showing the formation of the Rayleigh-Taylor instability for a SNR with an exponential density profile expanding into a steady wind. As the shock moves outwards, the grid size increases. The size of the grid and the age of the remnant is listed on each figure.

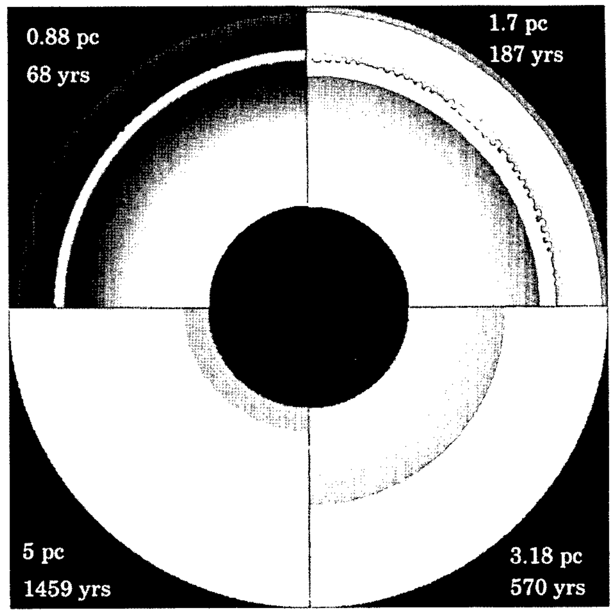

Fig. 8.— Time-sequence of images showing the formation of the Rayleigh-Taylor instability for a SNR with an exponential density profile expanding into a constant density medium. Note the more wispy nature of the filaments and their smaller size.

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