Supernova Remnant Evolution: from explosion to dissipation

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Abstract

Here is considered the full evolution of a spherical supernova remnant. We start by calculating the early time ejecta-dominated stage and continue through the different phases of interaction with the circumstellar medium, and end with the dissipation and merger phase. The physical connection between the phases reveals new results. One is that the blast wave radius during the adiabatic phase is significantly smaller than it would be, if one does not account for the blast wave interaction with the ejecta.

1 Introduction

A supernova remnant (SNR), the aftermath of a supernova explosion, is an important phenomenon of study in astrophysics. The typical $10^{51}$ erg of energy released in the explosion is transferred primarily into the interstellar medium during the course of evolution of a SNR. SNR are also valuable as tools to study the evolution of star, the evolution of the Galaxy, and the evolution of the interstellar medium. A SNR emits in X-rays from its hot shocked gas, in infrared from heated dust, and in radio continuum. The latter is via synchrotron emission from relativistic electrons accelerated at the SNR shock.

The evolution of a single SNR can be studied and calculated using a hydrodynamics code. However to study the physical conditions of large numbers of SNR, it is desirable to have analytic methods to obtain input parameters needed to run a detailed hydrodynamic simulation. The short paper describes the basic ideas behind the analytic methods, the creation of software to carry out the calculations and some new results of the calculations.

2 Theory and calculation methods

The general time sequence of events that occur after a supernova explosion, which comprise the supernova remnant can be divided into a number of phases of evolution (Chevalier, 1977). These are summarized as follows.
The ejecta dominated (ED) phase is the earliest phase when the ejecta from the explosion are not yet strongly decelerated by interaction. Self-similar solutions were found for the ejecta phase for the case of a supernova with ejecta with a power-law density profile occurring in a circumstellar medium with a power-law density profile (Chevalier, 1982). Solutions were given for ejecta power-law indices of 7 and 12, and circumstellar medium power-law indices of 0 and 2. The latter correspond to uniform a circumstellar medium and one caused by a stellar wind with constant mass-loss rate.

The non-self similar evolution between ED to the Sedov-Taylor (ST) self-similar phase was treated by Truelove and McKee (1999). They found the so-called unified solution for the evolution of the forward and reverse shock waves during this phase.

The Sedov-Taylor (ST) self-similar phase is that for which the shocked ISM mass dominates over the shocked ejecta mass and for which radiative energy losses from the hot interior supernova remnant gas remain negligible. These solutions are reviewed in numerous works, and are based on the original work on blast waves initiated by instantaneous point energy injection in a uniform medium (Taylor, 1946; Sedov, 1946).

The next stage occurs when radiative losses from the post-shock gas become important enough to affect the post-shock pressure and the dynamics of expansion of the supernova remnant. This phase is called the pressure-driven snowplow phase (PDS phase). Cooling sets in most rapidly for the interior gas closest to the outer shock front, so that a thin cold shell forms behind the shock. Interior to the thin shell, the interior remains hot and has significant pressure, so it continues to expand the shell. The shell decelerates because it is gaining mass continually while being acted upon by the interior pressure. Here we refer the review of this phase of evolution by Cioffi, McKee and Bertschinger (1988). This work also compares the analytic solutions to numerical hydrodynamic solutions for verification.

When the interior pressure has dropped enough, it no longer influences the evolution of the massive cool shell. After this time, the supernova remnant is in the momentum conserving shell (MCS phase). The shell slows down according to the increase in swept up mass from the interstellar medium. The final fate of a supernova remnant is merger with the interstellar medium, when the shock velocity drops low enough the the expanding shell is no longer distinguishable from random motions in the interstellar medium.

To create an analytic model, or its realization in software, the different phases of evolution were joined. This problem is not simple, as pointed out in the work of Truelove and McKee (1999). The evolution of the SNR is determined by the distribution of mass, pressure and velocity within the SNR and the shock jump conditions where there are any shocks. We follow similar methods to those in Truelove and McKee (1999), to ensure that the SNR evolution has continuous shock velocity and radius with time and closely follows that of more detailed hydrodynamic calculations.

3 Results

Analytic solutions have been created which cover the evolution of the SNR from early ED phase through ED-ST transition, ST phase, ST to PDS transition and final dissolution of
Figure 1: Left panel: forward and reverse shock radius vs. time for a SNR with energy \( E = 10^{51}\text{erg} \), ejected mass \( 2M_\odot \), in a uniform circumstellar medium \((s = 0)\) with density \( 1\text{ cm}^{-3} \) and temperature 100 K. The ejecta density power-law index is \( n = 7 \). Right panel: forward and reverse shock velocity vs. time.

One of the new results from the analytic calculations is that the shock radius at any given time during the ST phase is significantly less than it is for the standard analytic ST solution. The reduced shock radius is a real physical effect and is understood as caused by interaction of the reverse shock wave with the (initially unshocked) ejecta. This result has not been pointed out previously, and will change SNR parameter estimates that have been made with the standard ST solution.

Results of some of the calculations with the full-evolution model are shown in Figures 1 and 2. Figure 1 shows the forward and reverse shock radii and velocities for the ED phase, ED to ST phase and ST phase, for a SNR in a uniform circumstellar medium, and the parameters listed in the figure caption. Figure 2 shows similar plots for a SNR in a stellar wind circumstellar medium.
Figure 2: Left panel: forward and reverse shock radius vs. time for a SNR with energy \( E = 10^{51}\) erg, ejected mass \( 2M_\odot \), in a stellar wind \( s = 2 \) with wind velocity 30 km/s and mass loss rate \( 10^{-6}M_\odot/\text{yr} \). The ejecta density power-law index is \( n = 7 \). Right panel: forward and reverse shock velocity vs. time.

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References

Chevalier, R., 1977, ARAA, 15, 175
Chevalier, R., 1982, ApJ, 258, 790
Truelove, K., & McKee, C., 1999, ApJSup, 120, 299
Taylor, G.I., 1946, Proc.R.Soc.London A, 186, 273
Sedov, L., 1946, Dokl.Akad.Nauk SSSR, 42, 17
Cioffi, D., McKee, C., & Bertschinger, E., 1988, ApJ, 334, 252