LUMINOSITY OF EVOLVING SUPERNOVA REMNANTS

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Abstract. We present an analytic kinematic model for the evolution of a supernova remnant beginning with the Sedov-Taylor adiabatic stage and continuing through the radiative stage. Using this model, we obtain the luminosity of the radiative shock and the hot interior.

I. Introduction

A strong explosion in a homogeneous uniform medium results in a blast wave whose adiabatic evolution is well-understood in terms of the classic Sedov-Taylor (ST) solution (Sedov 1959; Taylor 1950). We can model the early evolution of spherical supernova remnants (SNRs) with this solution, where the radius R_s grows with time t in a power law:

$$R_s = \left(\frac{\xi E}{\rho_o}\right)^{1/5} t^{2/5}, \tag{1}$$

where E is the energy of the explosion, ρ_o is the ambient density, and the numerical constant ξ is found to be 2.026 for $\gamma = 5/3$ (Ostriker and McKee 1987). As the hot gas begins to radiate, however, the evolution deviates from this solution, and, with less energy available to drive the remnant, the expansion rate slows. If one wishes to calculate analytically the continuous luminosity from an evolving SNR, one must possess both accurate kinematics and a sufficient knowledge of the distribution and thermal development of the hot gas. Although here we outline the methods and obtain the total SNR luminosity, in Cioffi and McKee (1987; [CM]) we obtain the broad-band spectrum and calculate the X-ray emission. These luminosities match those found in hydrodynamical simulations.

II. Kinematics, Cooling, and Radiation

Radiative losses in the SNR first set in near the edge and lead to the formation of a dense shell of gas which is driven into the ambient interstellar medium by the pressure of the hot interior gas – in other words, a ***pressure-driven snowplow*** (PDS). If the cooling function Λ (erg cm^3 s^{-1}) falls with the square root of the temperature T, then, as first realized by Kahn (1976), the entropy of a shocked parcel of gas is an explicit function of time alone. We can thus determine the time at which an element of gas first cools to zero temperature, t_{sf}. The discontinuity in the shock velocity seen in a numerical simulation (see Figure 1) confirms that a shell forms at this time, but since cooling has affected the evolution prior to t_{sf}, we begin the PDS stage a factor of e sooner at

$$t_{pds} \equiv \frac{t_{sf}}{e} = 1.33 \times 10^4 \, \frac{E_{51}^{3/14}}{\varsigma_m^{5/14} n_o^{4/7}} \text{ yr}. \tag{2}$$

Here we have used a cooling function $\Lambda = 1.6 \times 10^{-19} \varsigma_m T^{-1/2}$ erg cm^3 s^{-1}, where the metallicity $\varsigma_m = 1$ for cosmic abundances (Cioffi, McKee and Bertschinger 1987; [CMB]; also see Cox 1986).

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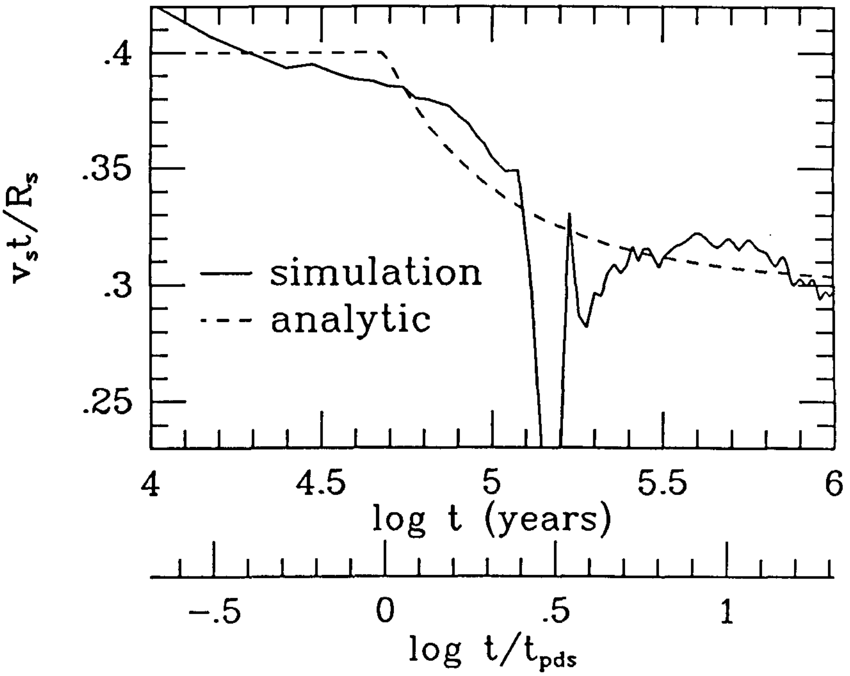

Figure 1. The logarithmic derivative $v_s t/R_s$ versus time.

In Figure 1 we show the logarithmic derivative $v_s t/R_s$ from a hydrodynamical simulation of an SNR expanding into an interstellar medium of hydrogen density $n_o = 0.1\ \mathrm{cm}^{-3}$. The standard PDS power-law solution (McKee and Ostriker 1977) would show a straight horizontal line at $v_s t/R_s = 2/7$, which is discontinuous with the ST solution and, when compared to the hydrodynamical simulation, is too small after the formation of the shell. The SNR retains the "memory" of additional pressure from the ST stage, and cannot relax to a 2/7 index. We thus choose an *asymptotic* index of 3/10, and join the PDS solution to the ST solution by means of an "offset" power law (CMB):

$$R_s = R_{pds}\left[\frac{4}{3}\frac{t}{t_{pds}} - \frac{1}{3}\right]^{3/10}, \tag{3}$$

where R_{pds} is obtained from the ST solution at t_{pds}:

$$R_{pds} = 14.0\,\frac{E_{51}^{2/7}}{n_o^{3/7}\,\zeta_m^{1/7}}\ \mathrm{pc}. \tag{4}$$

Figure 1 shows how well the analytic logarithmic derivative agrees with that from the simulation through the transition across the formation of the shell. The luminosity of the radiative shock is $L = \frac{1}{2}\rho_o v_s^3\,(4\pi R_s^2)$ and we find that the product $R_s^2 v_s^3$ almost always agrees with the simulation to within 20% except near t_{sf}, where v_s falls too quickly. CMB show that this fit remains good so long as $t \lesssim 20\,t_{pds}$.

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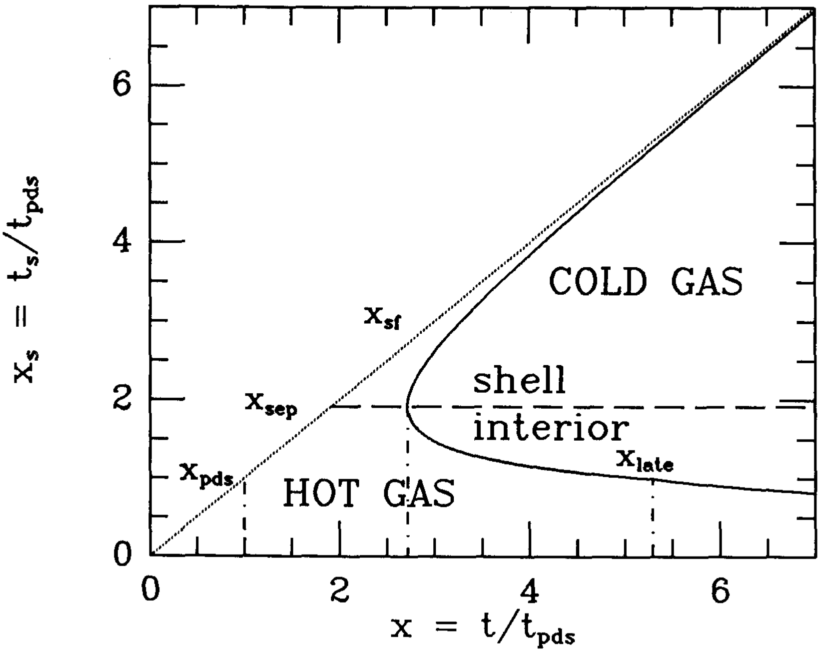

Figure 2. The thermal structure of an SNR.

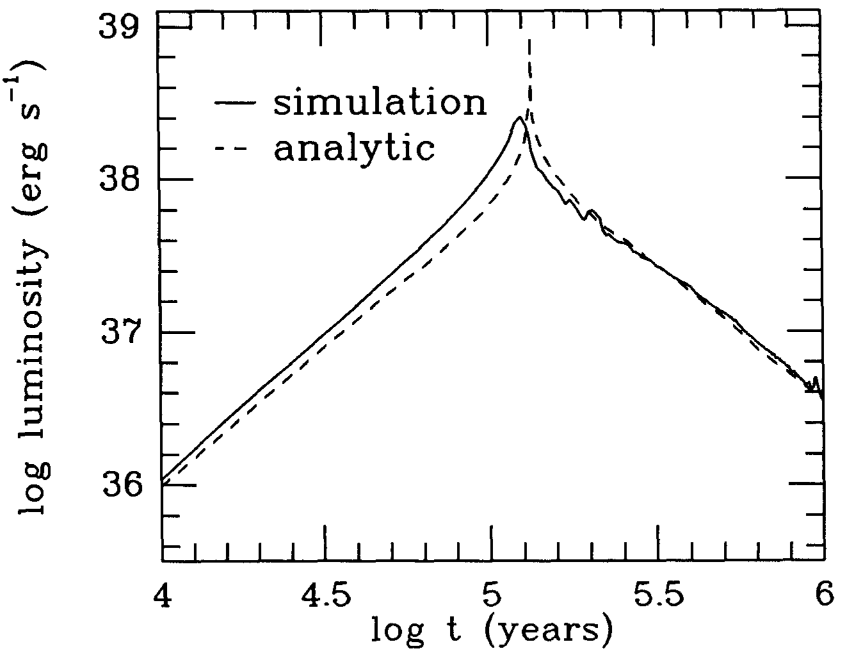

Figure 3. Total luminosity versus time.

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We need to integrate through the hot gas to calculate the radiation from the interior. If we again use the $T^{-1/2}$ cooling law, and the solutions (3), we can construct Figure 2, which shows the cooling of an SNR in terms of the normalized times at which a gas element was shocked, $x_s \equiv t_s/t_{pds}$ (CM). At any fixed time $x \equiv t/t_{pds}$, one proceeds vertically along the x_s axis to ascertain the thermal structure of the remnant. At the separation time, $x_{sep} = 1.92$, we "flag" the gas element which will be the first to cool completely. At the shell formation time, $x_{sf} = 2.72$, this element cools to zero temperature and separates the SNR into three zones: i) an extremely narrow, hot region behind the shock; ii) a cold shell and iii) the hot interior, which consists of material shocked prior to x_{sep}. The cold shell grows from both sides as the interior cools and the material behind the now-radiative shock also cools. One other time of interest is $x_{late} = 5.29$; after this time any hot gas remaining in the interior of the SNR was shocked during the remnant's ST expansion.

At a given time t we can sum the emission from all elements which were shocked at prior times t_s, where we again assume a $T^{-1/2}$ cooling law. We fully explain the methods in CM. Figure 3 shows the excellent results from this approach.

III. Summary

Lack of space prevents consideration of two additional contributions to the luminosity (see CM): We can calculate the emission at early times from the reverse-shocked ejecta (e.g., McKee 1974) in a manner similar to that just outlined for the interior gas. Secondly, we note that for a real SNR in interstellar space, dust grains may supply a large luminosity during part of the evolution (e.g., Graham *et al.* 1987). This additional energy loss will shorten the PDS onset time somewhat (Dwek 1981), modifying our results slightly, but not strongly affecting the X-ray emission.

To achieve an accurate ($\lesssim 20\%$) analytic luminosity from SNRs in all stages of evolution, the overall kinematics, $R_s(t)$ and $v_s(t)$, must be very accurate ($\lesssim 5\%$) to obtain the correct radiative shock luminosity $L \sim R_s^2 v_s^3$, and the thermal history of the shocked gas must be calculated. Through understanding the dynamics of SNR expansion and the use of offset power laws, we have obtained a simple expression for accurate kinematics. The assumption of a $T^{-1/2}$ cooling law then allows a determination of the thermal structure and luminosity of a post Sedov-Taylor SNR.

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