LA-UR -80-2756

TITLE: THE EFFECT OF STELLAR STRUCTURE ON SUPERNOVA REMNANT EVOLUTION

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SUBMITTED TO: Proceedings of International Astronomical Union Colloquium on Stellar Hydrodynamics, Los Alamos, NM, Aug. 12-15, 1980.

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The Effect of Stellar Structure on Supernova Remnant Evolution

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1. ABSTRACT

One-dimensional hydrodynamic calculations have been done of 1E51 erg explosions in $15M_\odot$ stars. We have appended a steep external density gradient to the pre-supernova model of Weaver et al and find: (1) the outer shock wave decelerates throughout the pre-Sedov phase, (2) the expanding stellar envelope and the shocked interstellar material are Rayleigh-Taylor stable until the Sedov phase, and (3) steep internal density gradients are R-T unstable during the early expansion and may be the source of high velocity knots seen in Cas A.

2. INTRODUCTION

Typically, numerical models of supernova remnants have been initialized by ignoring the stellar mass (Chevalier 1974, Straka 1974), assuming the star acts as a massive piston (Rosenberg and Scheuer 1973, Gull 1973, Mansfield and Salpeter 1974) or modelling the star with a shallow internal density gradient and a sharp contact surface (Chevalier and Klein 1978). These various calculations yield the following generalized statements.

(a) A shock wave expands into the interstellar medium entraining mass. Until the entrained mass become comparable with the ejecta mass, the expansion velocity is virtually constant.

(b) There is a Rayleigh-Taylor (R-T) unstable region due to the rarefaction propagating into the stellar material, which may produce R-T tongues on a time scale of days (Chevalier and Klein 1978).

(c) The contact surface becomes R-T unstable after about 0.3 x the ejecta mass has been entrained. The resultant turbulence is alleged to lead to sudden radio brightening (Gull 1973).

(d) After an ejecta mass has been entrained, the flow field is described by the blast wave solution (Sedov 1959)--at least until radiative cooling becomes significant.

We have done a preliminary study of the effect of pre-supernova stellar structure on development of the supernova remnant and find that the conventional description must be modified. Rayleigh-Taylor instabilities are expected to form at internal density discontinuities before the shock emerges from the photosphere, but the shock acceleration down any external density gradient (Falk 1978) produces a R-T stable expansion not encountered in previous calculations.

3. INITIAL CONDITIONS

We have appended an external density gradient ("ramp") to the density distribution of the $15M_\odot$ pre-supernova model of Weaver et al (1979). There is about $0.035M_\odot$ in the ramp (Fig. 1). The density distribution in the ramp and the temperature distribution in the star were calculated from hydrostatic equilibrium. The ramp temperature was assumed to be 10000°K.

We assumed the inner $1.5M_\odot$ formed a rigid object of 1.6E8 cm radius (Weaver 1980, private communication). The 1E51 erg explosion energy was deposited in the first cell outside the central object.

We used the one-dimensional hydrodynamics program RADFLO (Zinn 1973). We include self-gravity, radiation pressure in thick zones, time-dependent non-equilibrium ionization of helium in the equation of state (hydrogen is assumed completely ionized), and cooling from radiative recombination (χ + kT per recombination) in optically thin zones, but no radiation transport or magnetic fields.

The main features of the density distribution are the mantle, composed of processed stellar material, the mantle/envelope transition that has a steep gradient in the Weaver et al model, the envelope of low-density, normal composition material, and the previously described circumstellar ramp.

4. THE COLLAPSABLE PISTON

Most of the stellar mass ($10M_\odot$) is in the envelope so that the shock wave on reaching the photosphere has little memory of the internal density distribution. The shock in the envelope is described by Sedov (1959) and discussed by Chevalier (1976). However, on encountering the density ramp, the shock accelerates reaching particle velocities of order 1E8-1E9 cm/s (Falk 1978).

The ramp material quickly goes into free expansion. In the ramp the density and particle velocity are related by a power law:

$$\rho t^3 = (U/U_0)^{-a} \quad , \qquad (1)$$

where $U_0 \sim 3.5E8$ cm/s and a $\approx$ 13.

The high velocity ramp material collides with the interstellar medium (ISM) creating two shock waves: one expanding outward into the ISM and the other moving inward (in a Lagrangian sense) into the ramp material. The distribution of density, pressure, and velocity at the foot of the collapsing ramp is illustrated in Fig. 2. Solution of the jump equations (Harlow and Amsden 1971) reveals that the density at the foot of the ramp is equal the interstellar density ($\rho_1 = \rho_0$) and that v_s, the shock speed, and U_1, the particle velocity at the

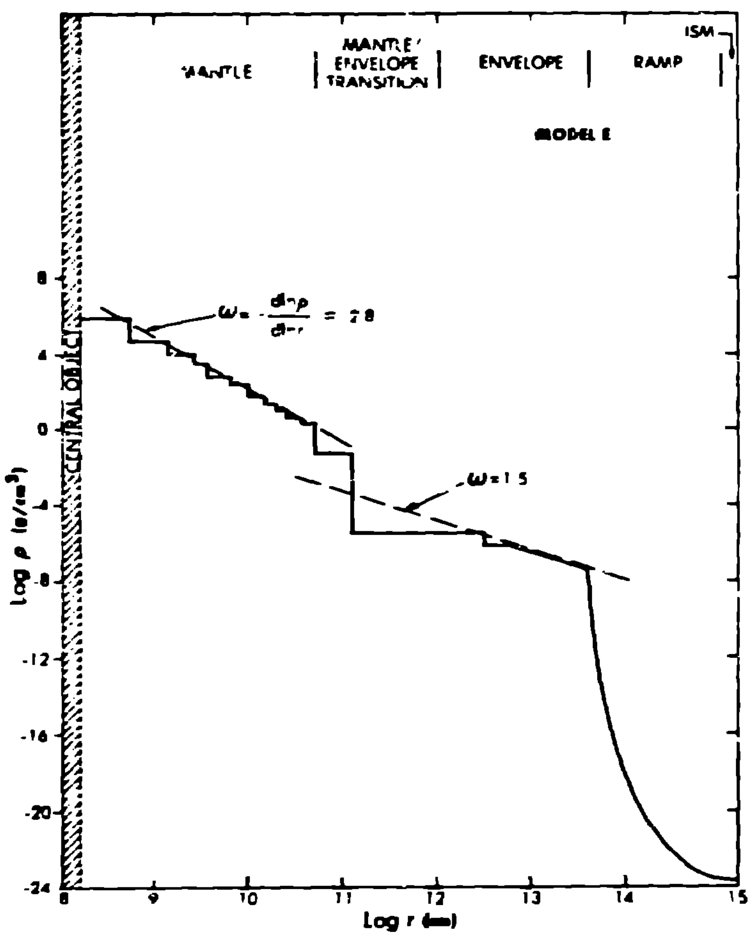

Fig. 1. Initial density distribution adapted from Weaver et al (1979) with a density gradient "ramp" at 10000°K added to the outside.

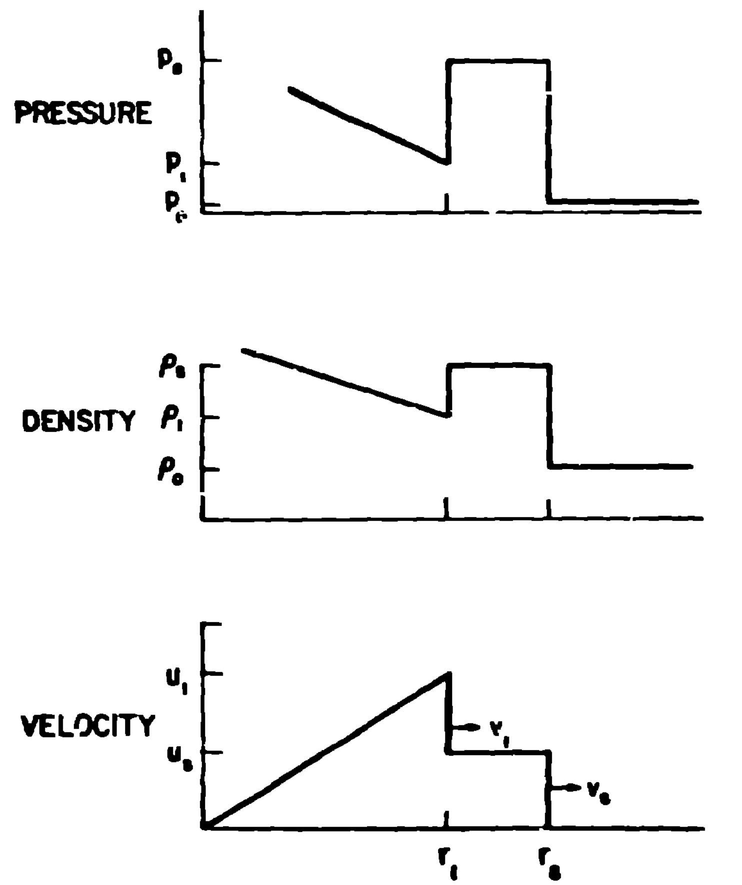

Fig. 2. Flow structure at the foot of the ramp after the interstellar shock (s) is formed. Another shock (l) is collapsing the ramp/piston.

foot of the ramp, are proportional. Combining these pieces of information, we find

$$r_s \alpha\ t^{(a-3)/a} \quad , \tag{2}$$

The computed shock radius is shown in Fig. 3 (Model E: filled circles). We can see the shock acceleration as it runs down the ramp in the interval 5<log t<5.5. By 1E6 seconds the expansion agrees well with Eq. (2) with a ≈ 13. As a check of RADFLO, we ran calculations with an unresolved star (Model B: triangles) and a resolved uniform star (Model C: filled squares) and found linear expansion until the Sedov phase--as expected. One additional calculation was done of the Weaver et al configuration, but with no central object. Other than a time scale shift, related to energy losses as the shock climbs out of the potential well, the solution is similar to the calculation with the central object.

Clearly, the expansion is decelerated. If supernova progenitors have relatively shallow ramps, perhaps created during mass loss, the deceleration may be detectable. However, as we shall see below, the shocked material at the foot of the ramp is R-T stable and may be detectable only as an extended x-ray shell, not as a radio source.

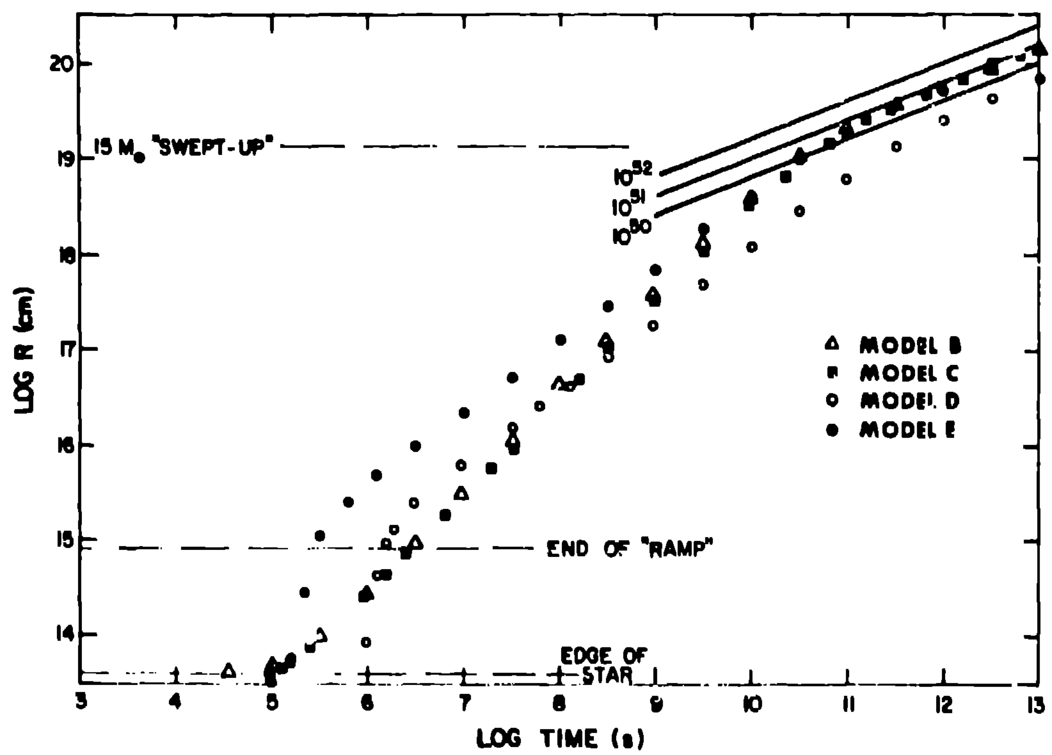

Fig. 3. R(t) of the interstellar shock wave. Sedov solutions for three energies are shown as solid lines. Both calculations using the ramp (Models D and E) have log R α 0.75 log t in the pre-Sedov phase.

5. FORMATION OF THE SUPERNOVA REMNANT

The mantle mass ($3.5M_\odot$) is about one third the envelope mass ($10M_\odot$) so that by the time the shock reaches the photosphere (1E5 seconds) the mantle/envelope interface behaves as a R-T unstable contact surface with growth times of order 1E4 seconds. The interface becomes stable again after the rarefaction propagating inward from the surface reaches the interface at about 3E5 seconds. The interface may be the site of large amplitude instabilities

The shock reaches the bottom of the ramp at about 2.5E5 seconds. During subsequent expansion the material in the ramp is formally unstable (Schwarzschild criterion), but the growth times are of order 1E8 seconds. The ramp material is effectively stable.

The flow at 3E8 seconds is typical of the remainder of the pre-Sedov phase. The ramp and stellar materials are in free expansion and virtually stable. The shocked gas at the foot of the ramp is a high temperature and gradually engulfs more interstellar material and collapses the ramp. Ramp collapse is complete by 3E9 seconds. Thereafter the envelope/ramp interface is unstable with growth times are of order 1E9 seconds. We basically confirm Gull's (1973) result that radio brightening is delayed until a significant mass (here, equal the ramp mass) is entrained.

Finally, at about 3E11 seconds the shock has entrained a stellar mass and the flow rapidly approaches the blast wave solution, with the exception that internally density structures are present. These may have been destroyed or drastically altered during the instability episodes. Between 3E11 and 6E11 seconds, the reverse shock (McKee 1974) traverses the stellar material heats it to a few hundred electron volts, and effectively completes the transition to the Sedov phase.

6. OBSERVATIONAL CONSEQUENCES

We believe that the following general statements can be made about the calculation.

(a) Steep gradients lead to R-T unstable contact surfaces only after an equivalent mass has been entrained.

(b) The mantle/envelope interface is unstable early and may well be the source of high-density, enriched "clumps". If these clumps were to decouple from the general flow, they might be expected to move outward unimpeded at about 1E8 cm/s. These clumps may be related to the fast knots in Cas A.

(c) The outer gradient is R-T stable until just before the Sedov phase. The shocked material outside the free expansion region may be observable only as 1- to 100-keV x rays depending on age. During ramp collapse the shock strength decreases, producing a temperature decrease and a continuum luminosity increase proportional to time to the 2.5 power. Radio brightening occurs fairly late in the pre-Sedov phase.

(d) The external density gradient can play a key role in the development and observability of a young supernova remnant.

7. ACKNOWLEDGEMENTS

This work was supported by the Los Alamos Scientific Laboratory which is operated by the University of California for the U. S. Dept. of Energy. One of us (W.C.S.) was supported in part by NSF Grant RIM 7-8-16987.

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