THE EVOLUTION OF YOUNG SUPERNOVA REMNANTS

A.C. Fabian*, W. Brinkmann†, G.C. Stewart*
*Institute of Astronomy, Madingley Road, Cambridge CB3 OHA, UK
†Max Planck Institut für Extraterrestrische Astrophysik,
8046 Garching bei München, F.D.R.

1. INTRODUCTION

Einstein X-ray observations of the young supernova remnants Cassiopeia A (Murray *et al.* 1980) and Tycho (Seward, Gorenstein and Tucker 1982) indicate that the swept-up mass does not much exceed that of the observed ejecta. The initial density distribution of the ejecta and surrounding material is then important in determining the X-ray structure and evolution. Some aspects of this behaviour have been dealt with in previous numerical (e.g. Gull 1973; Itoh 1977; Jones, Smith and Straka 1981) and analytical (e.g. Chevalier 1982a,b) studies. We present here results obtained from numerical models covering a wider range of initial conditions. In particular, we consider the effect of a constant stellar wind from the progenitor star on the expansion of the remnant. We have previously suggested that variable mass loss from SN1006 may explain its warm filled interior (Fabian, Stewart and Brinkmann 1982).

2. THE NUMERICAL MODELS

We have modelled the hydrodynamic evolution of our expanding supernova remnant using a simple one-dimensional Lagrangian programme following the prescription given in Richtemeyer and Morton (1967). Mass and energy are conserved to better than a few percent throughout the runs. The ejecta are distributed with a uniformly increasing velocity out to a radius of 5×10^{16} cm and the initial temperature is 2×10^4 K everywhere. The radii of the shells of surrounding matter increase in size logarithmically out to $\gtrsim 10^{20}$ cm. The count rate emissivity expected in the Einstein High Resolution Imager (HRI) has been computed for some and the ionization equilibrium of oxygen and sulphur have been calculated for a few others using the rates given by Shull and Van Steenberg (1982).

Fig. 1 shows the evolution of the inner and outer shocks from a 2.35×10^{33} gm, 7.673×10^{50} ergs explosion into either a constant

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 119–124.

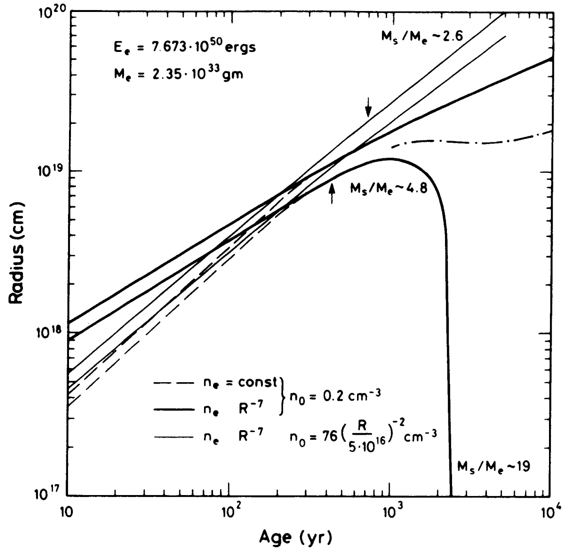

Fig. 1. Evolution of the inner and outer shocks from a low mass supernova of ejecta mass and energy M_e, E_e, into a surrounding medium of density n_0 which is either constant or representative of a wind. The solid curves are for an initial density distribution of ejecta, $n_e \propto R^{-7}$ over the outer $\sim$ 3/7 of the ejecta mass. Arrows indicate the point at which the reverse shock has reached the constant density interior. Note that the dashed and heavy solid pairs of lines merge at $\sim$ 200 yr. The contact discontinuity is indicated by the chain line.

density (0.2 particles cm^{-3}) or constant mass-flux wind. Two of the models have an outer density profile over the outer $\sim$ 3/7 of the mass proportional to (radius)$^{-7}$ to mimic the structure of a white dwarf (cf. Chevalier 1982b). The detailed behaviour of the most complex model is shown in fig. 2 and agrees with Chevalier's similarity solution (1982a). We note that the reverse shock reaches the centre of the remnant when the ratio of swept-up to ejecta mass (M_s/M_e) is $\sim$ 19, independent of the structure of the ejecta. This ratio is about twice the value inferred from Chevalier's analytical solution (1982b), which assumes that the ratio of the thermal pressures just behind the outer shock to that just within the inner one, α, is $\sim$ 0.3 - 0.4. The numerical results at both early and late (Sedov) stages (the central pressure in this last case) give α in this range but it is reduced to $\sim$ 0.1 as the reverse shock travels back toward the centre. No simple analytical result seems possible at this stage.

The almost free expansion of a constant density 15 $M_\odot$, 5.3 x 10^{51} ergs supernova into a wind of mass-loss rate 5 x 10^{-4} $M_\odot$ yr^{-1} and velocity of 10^8 cm s^{-1} is shown in fig. 3. The bubble blown by such a wind after 10^5 yr in a constant density interstellar medium would be $\sim$ 20 pc in size and its edge is reached by the remnant in $\sim 10^4$ yr. We note that the shock temperature is reduced by the effect of the wind velocity. The average mass loss rate (and thus total mass lost) from a star is likely to be much lower than that which we use here. Consequently the later expansion in a large bubble may be even more rapid than indicated in fig. 3.

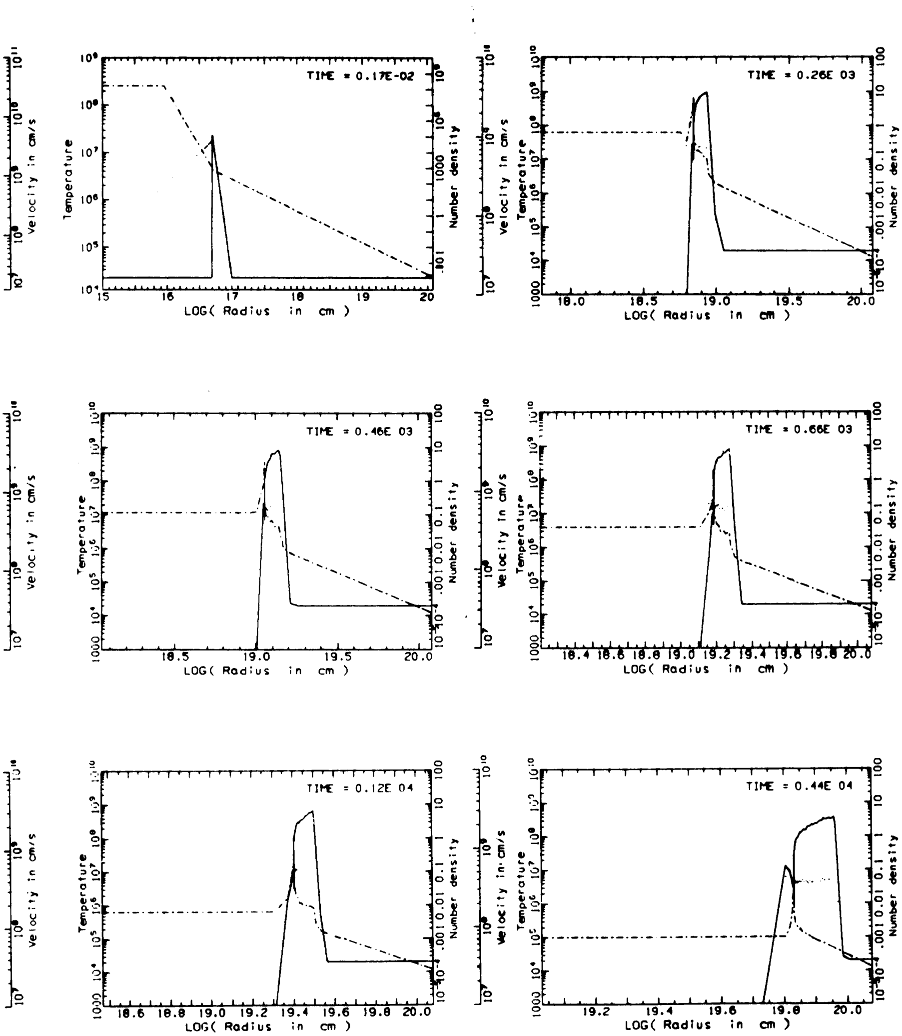

Fig. 2. Velocity (dots), density (chain) and temperature (solid) evolution of the model shown as a fine solid line in fig. 1. The time is given in yr.

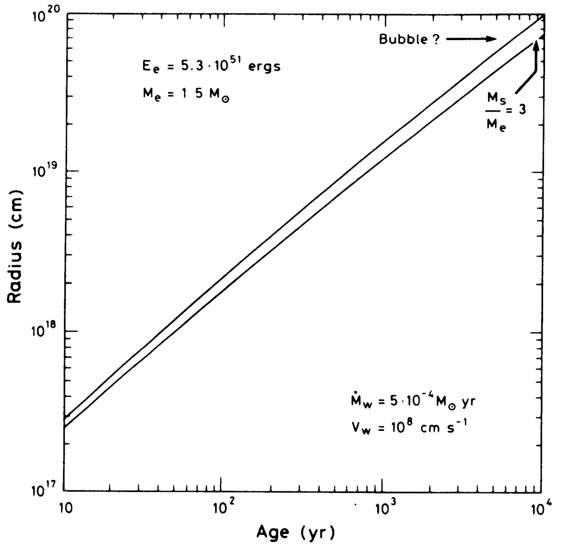

Fig. 3. Evolution of a 15 $M_\odot$, 5.3 x 10^{51} erg supernova in a stellar wind. About 45 $M_\odot$ have been swept up in $\sim 10^4$ yr. A possible size of bubble blown by such a wind is indicated

We show the HRI emissivity of a 1 $M_\odot$, 10^{51} erg explosion in a constant density surrounding medium of density 20 cm^{-3} in fig. 4. The outer blast wave dominates the X-ray appearance of the remnant after a few hundred years; the reverse shock only seriously contributes well before that time and becomes 'invisible' as it parts company with the contact discontinuity (which continues to be 'visible', although it is mainly an artefact of the initial steep density discontinuity).

3. CONCLUSIONS

We emphasise (see Chevalier 1982b) that observed deceleration (e.g. from proper-motions) need not mean that the remnant is close to any Sedov-phase (fig. 1). The ejecta may instead have a steep outer density profile. Successive mass elements of the ejecta suffer a deceleration on being 'reverse'-shocked, but are then carried along by inner (and more massive) neighbours.

Thick reverse-shocked regions ($\Delta R/R >> 0.1$) should be difficult to observe. When the reverse-shock starts to travel inward relative to the centre of explosion, the low inner density and tendency for pressure equilibrium mean that it does so rapidly. The shock temperature then varies roughly as (time)$^{9/5}$ and reaches $\sim 10^9$ K at the centre of our models. A Sedov phase begins when $M_s/M_e > 5$ and is only firmly established when the centre has been reached by the reverse shock ($M_s/M_e > 19$).

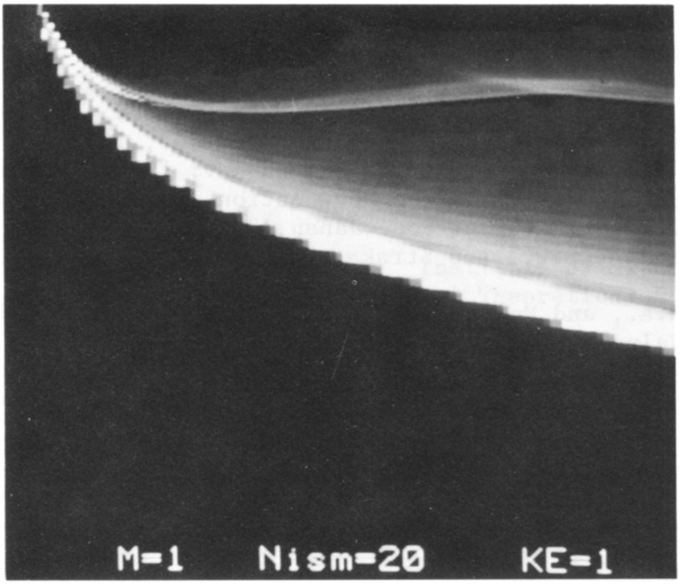

Fig. 4. HRI X-ray count-rate emissivity of a 1 $M_{\odot}$, 10^{51} erg explosion in a high density surrounding medium (N_{ism} = 20 cm^{-3}). Radius and time increase linearly downward and to the right up to $\sim$ 5 pc and $\sim$ 1000 yr, respectively. The dynamic range of features shown is a factor of 256. The broad structure lies just behind the outer shock; the inner thinner line is the contact discontinuity. The effects on this of a central bounce (at $\sim$ 300 yr) and of the coarse binning are evident.

We note that the ratio of swept-up mass to shocked ejecta (M_s/M_r) is always near unity in the early phases. Measurements of $M_s/M_r \sim 1$ do not indicate that free expansion will soon end. We confirm that X-ray bright reverse-shocked matter is likely to be close to ionization equilibrium (Itoh 1977). Simple checks may be made by comparing the ionization/recombination time (given a deduced density) with the remnant age.

Finally we note that winds from massive stars may prevent a simple Sedov phase from occurring.

ACKNOWLEDGEMENTS

ACF thanks the Royal Society for financial support.

REFERENCES

Chevalier, R.A.: 1982a, Astrophys.J., 258, 790.
Chevalier, R.A.: 1982b, Astrophys.J., 259, L59.
Fabian, A.C., Willingale, R., Pye, J.P., Murray, S.S. and Fabbiano, G.: 1980, Monthly Notices Roy. Astron. Soc., 193, 175.
Fabian, A.C., Stewart, G.C., and Brinkmann, W.: 1982, Nature, 295, 508.
Gull, S.F.: 1975, Monthly Notices Roy. Astron. Soc., 171, 263.
Itoh, H.: 1977, Publ. Astron. Soc. Japan, 29, 813.
Jones, E.M., Smith, B.W., and Straka, W.C.: 1981, Astrophys. J., 249, 185.
Richtemeyer, R.A., and Morton, K.W.: 1967, Difference Methods for Initial Value Problems, Interscience, New York.
Seward, F.D., Gorenstein, P., and Tucker, W.: 1982, preprint.
Shull, J.M., and Van Steenberg, M.: 1982, Astrophys. J. Suppl., 48.

DISCUSSION

Winkler: You mentioned that material behind the reverse shock is in or very near ionization equilibrium. Why is that; is it due to high density?

Fabian: Yes.

Hamilton: Would you not expect the X-ray emission from the reverse shock to be greatly enhanced by the enhanced heavy element abundances?

Fabian: Only when the thickness of the reverse-shocked material is small, such that the temperature is low and line emission important.

Dickel: Is there enough density to see γ-rays from the super-hot reverse shock?

Fabian: No - pressure equilibrium gives very small density.