THE EVOLUTION OF YOUNG SUPERNOVA REMNANTS

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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
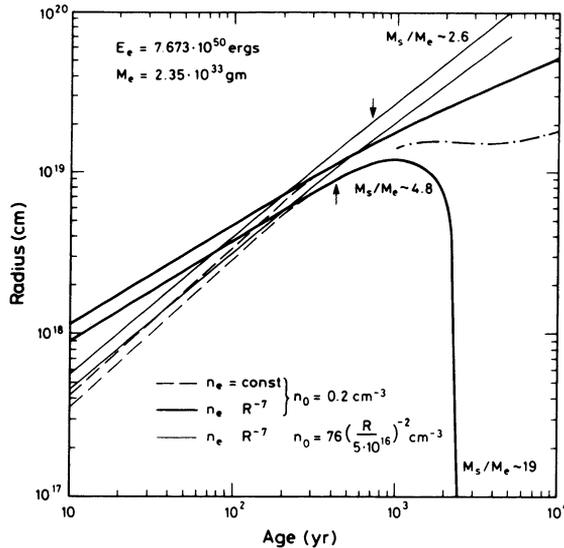
Fig. 1. Evolution of the inner and outer shocks from a low mass super-
nova of ejecta mass and energy M_e, E_e, into a surrounding medium of
density n_0 which is either constant or representative of a wind. The
solid curves are for an initial density distribution of ejecta, $n_e \propto R^{-7}$
over 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 ~ 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 ~ 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
~ 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 $M_\odot$, 5.3×10^{51}
ergs supernova into a wind of mass-loss rate 5×10^{-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.
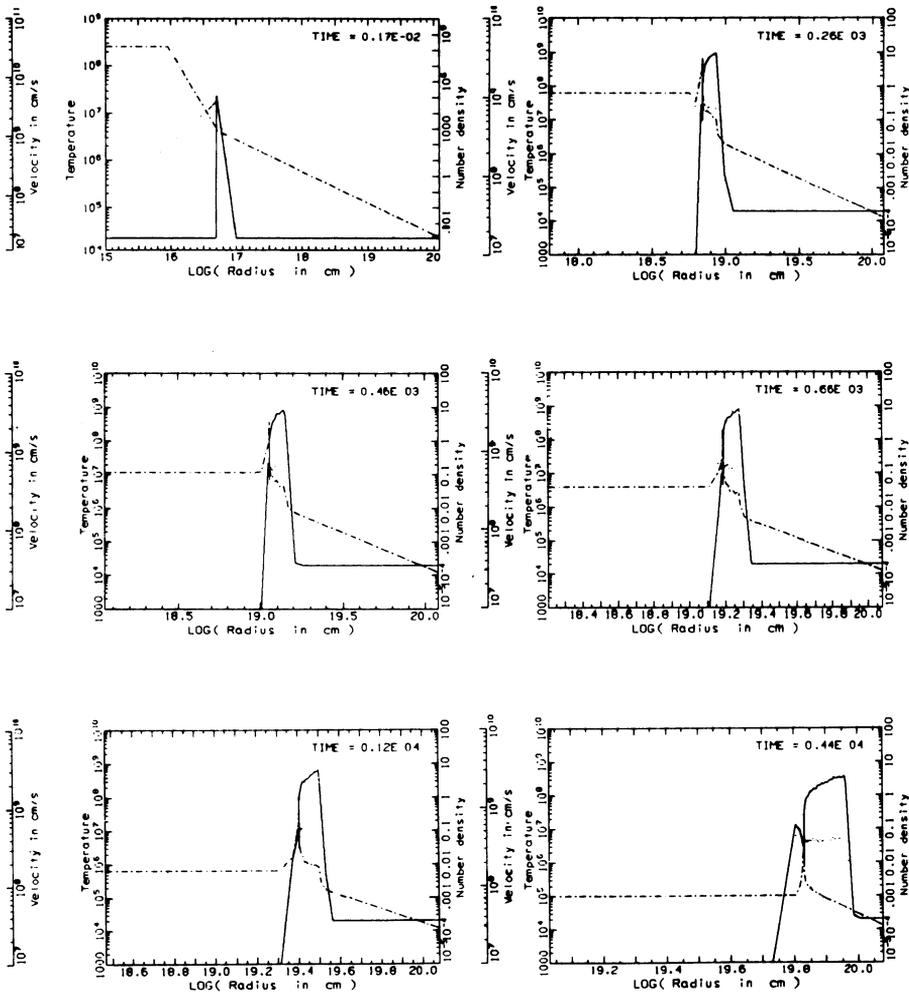

Fig. 2. Velocity (dots), density (chain) and temperature (solid) evolution of the model shown as a fine solid line in fig. 1. The time is given in yr.
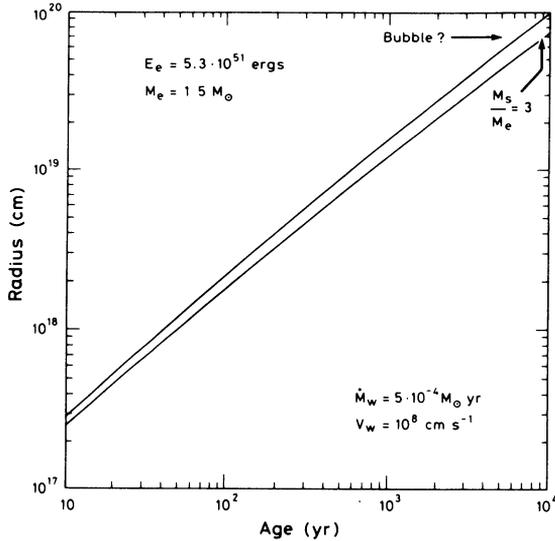
Fig. 3. Evolution of a 15 $M_\odot$, 5.3 x 10^{51} erg supernova in a stellar
wind. About 45 $M_\odot$ have been swept up in $\sim 10^4$ yr. A possible size of
bubble blown by such a wind is indicated

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 ($\Delta R/R \gg 0.1$) 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 estab-
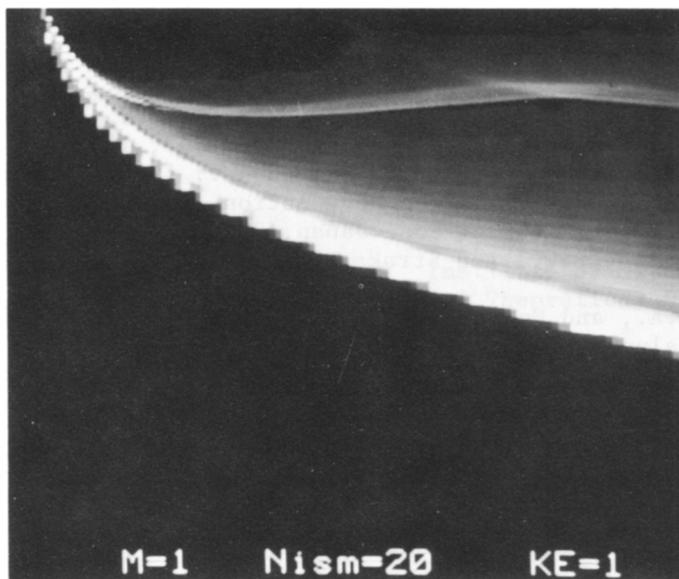lished when the centre has been reached by the reverse shock ($M_s/M_e > 19$).

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

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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.