Propagation of Supernova Blastwaves in the Circumstellar and Interstellar Medium

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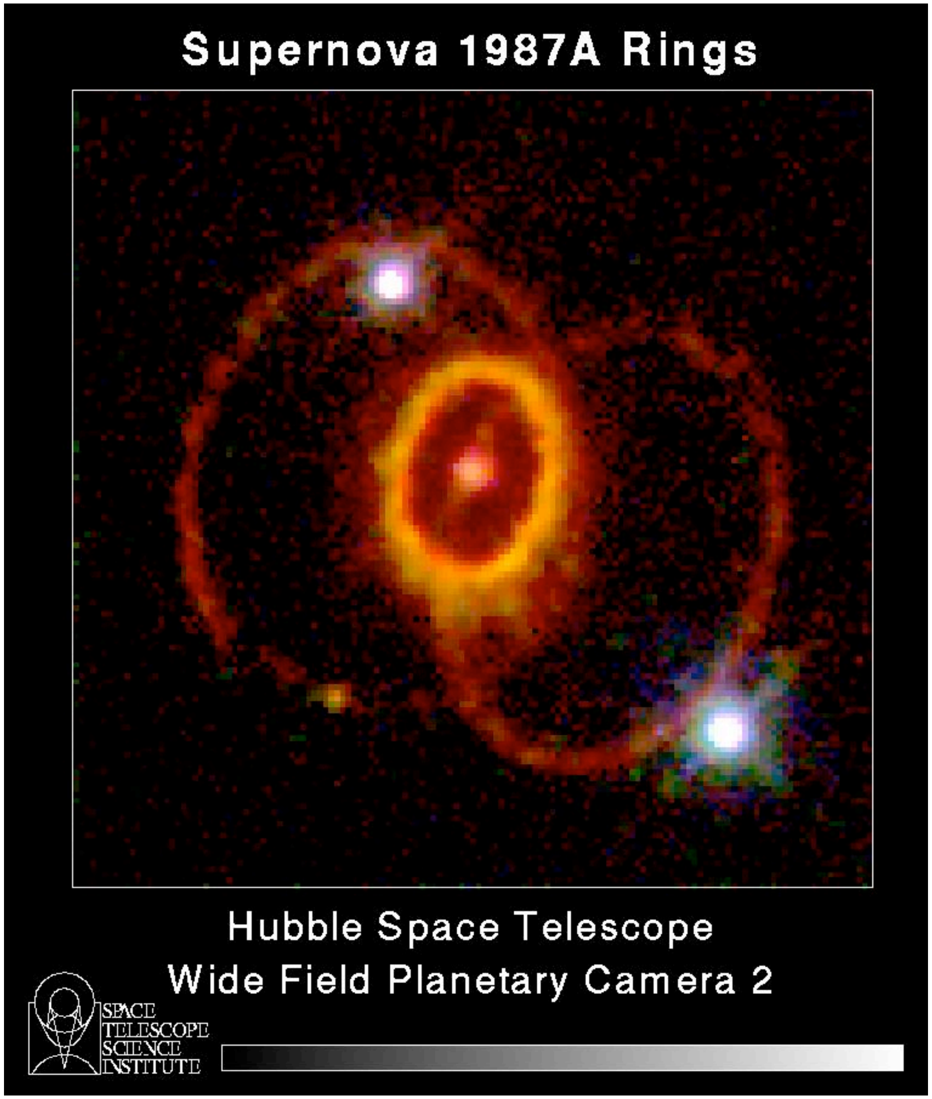
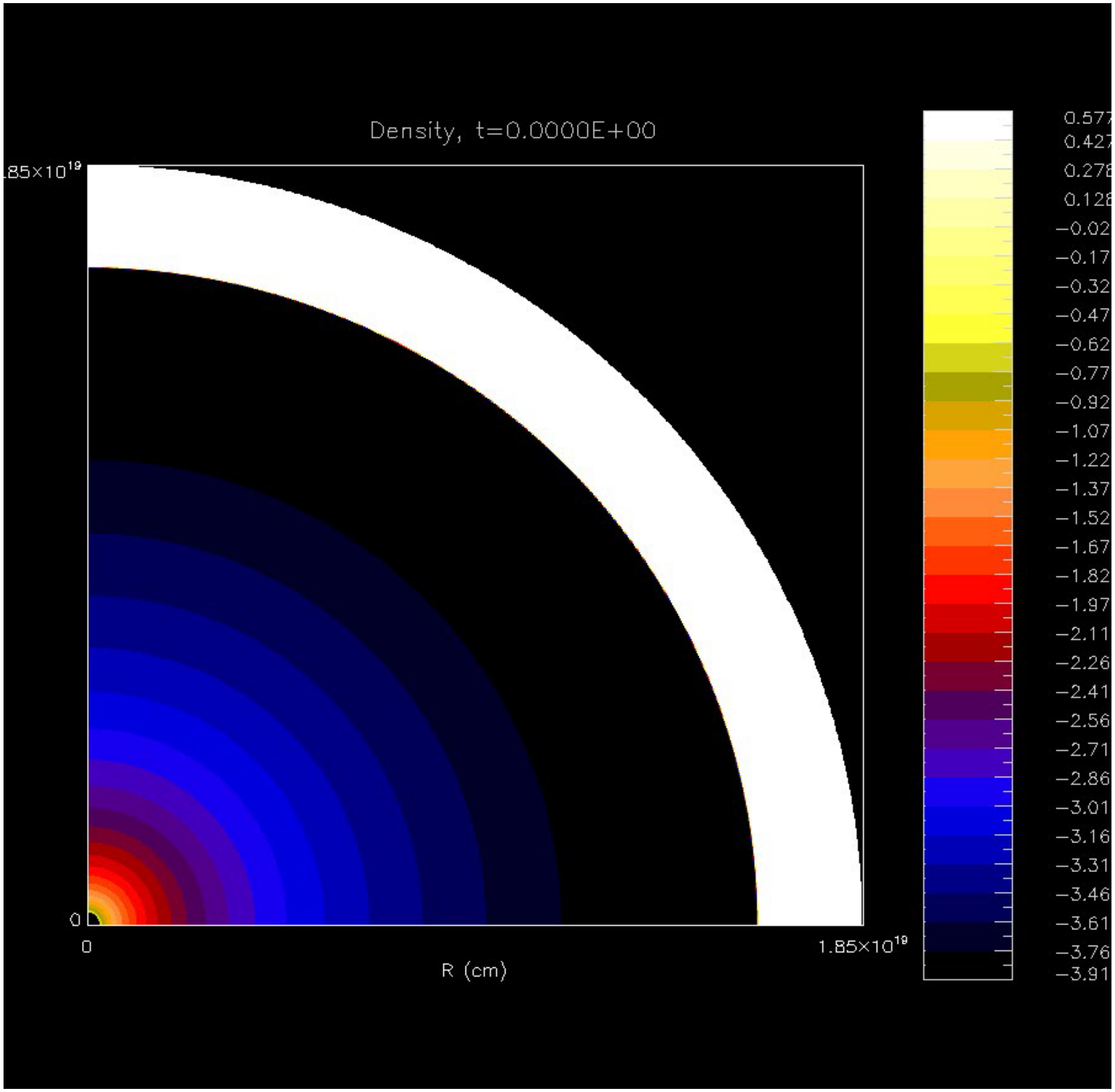
Core-Collapse SNe Evolve in the Winds of Progenitor Stars



Ionization-Gasdynamics Simulation of Wind-Blown Bubble from W-R Star

Simulation carried out using AVATAR code, including Ionization from the star

See Dwarkadas and Rosenberg (2011), AAS Poster. Paper in Progress.



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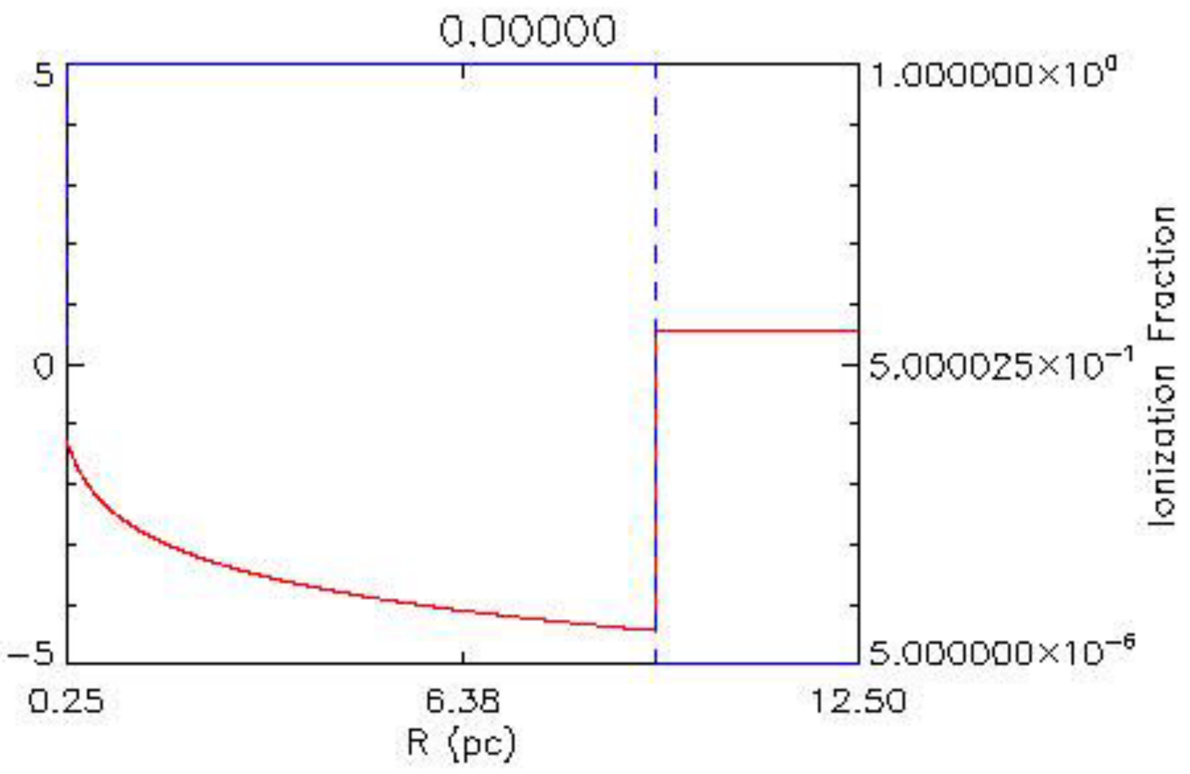
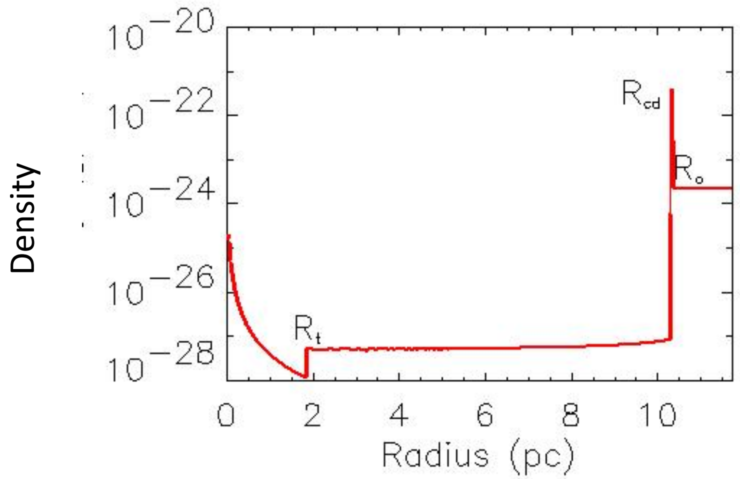
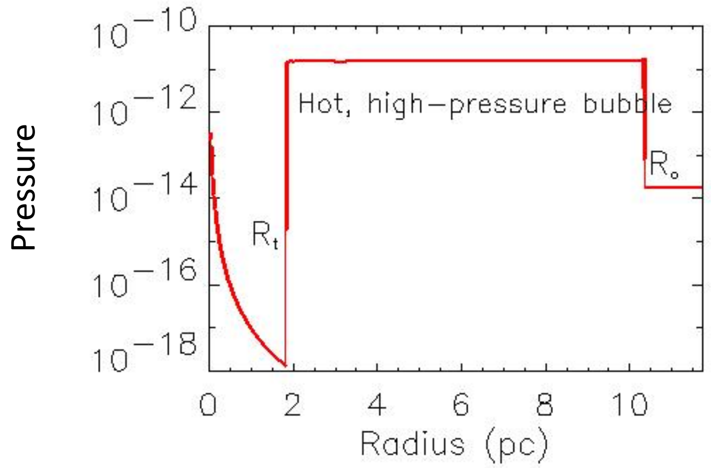


Structure of the Bubble

- Most of the volume is occupied by a high-pressure, low density, high-temperature region. Most of the mass is contained in cool, dense, thin shell.

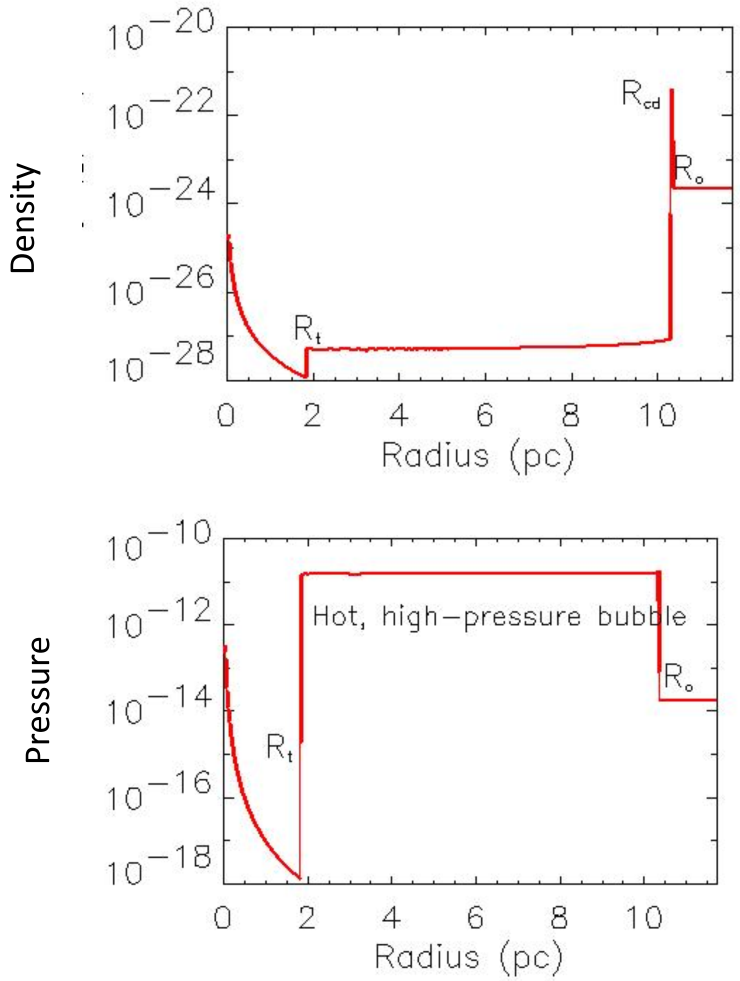
- This region is hot enough to radiate in X-rays, however the emission measure is quite low. Very few have actually been observed in X-rays.





Structure of the Bubble

- Note that initially the SN ejecta is interacting with a wind, followed by an almost constant density medium.
- If the wind is a steady wind (constant mass-loss rate and velocity) then its density will drop as r^{-2}.
- Therefore we need to study the SN shock propagation into at least: (1) a steady wind (2) a more or less constant density region (3) a dense shell.
- Depending on the scenario, the wind region may dominate, and the shell may be low mass or absent.



SN EJECTA

The expansion of SN ejecta into the surrounding medium gives rise to an outward moving forward shock, and a inner (reverse) shock that moves back into the ejecta in a Lagrangian sense, separated by a contact discontinuity.

Core-Collapse SN:

Ejecta Density: $\rho_{sn} \propto r^{-n}$

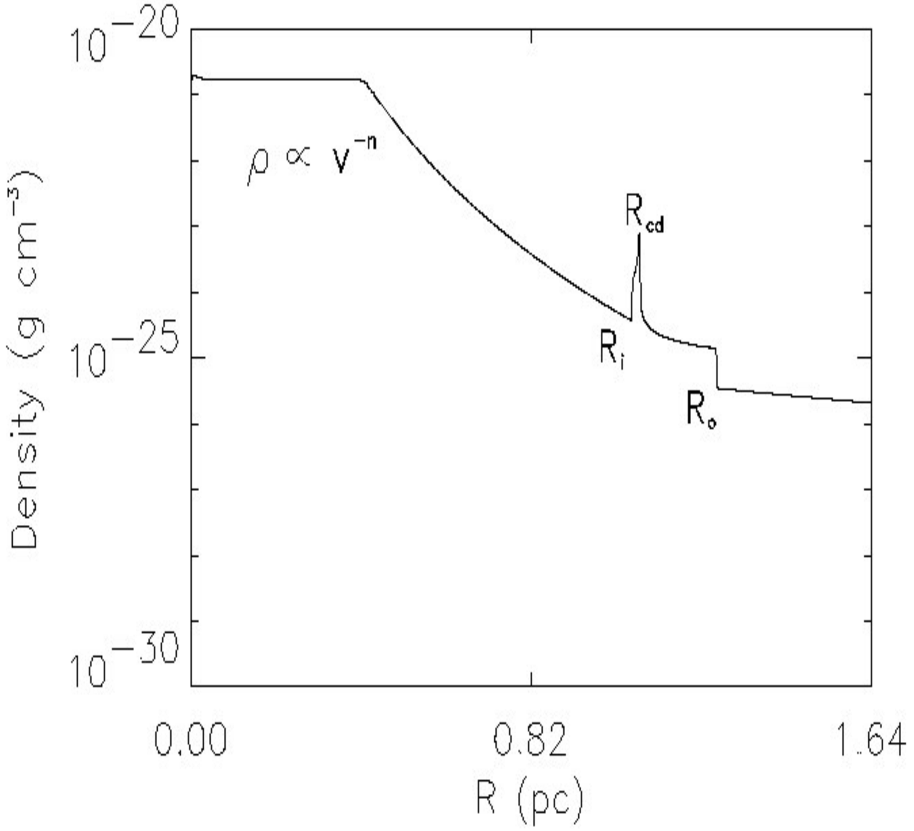
Density of ambient medium: $\rho_{am} \propto r^{-s}$

Then contact discontinuity evolves as:

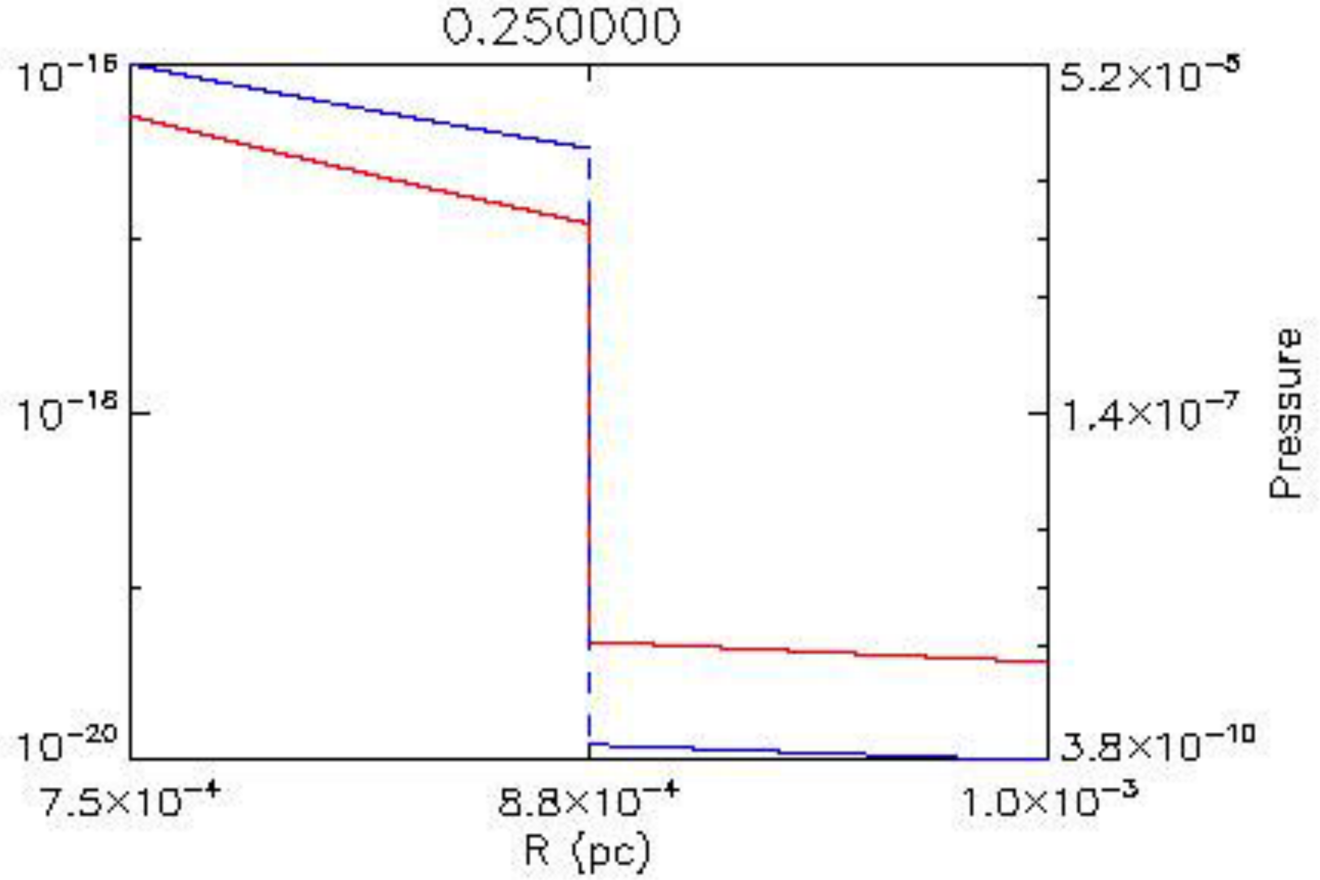
$$R_{CD} \propto t^{(n-3)/(n-s)}$$

Resulting evolution is self-similar.

N=9, s=2, R ~ $t^{0.86}$



Interaction of Power-Law ejecta with Power-Law CSM

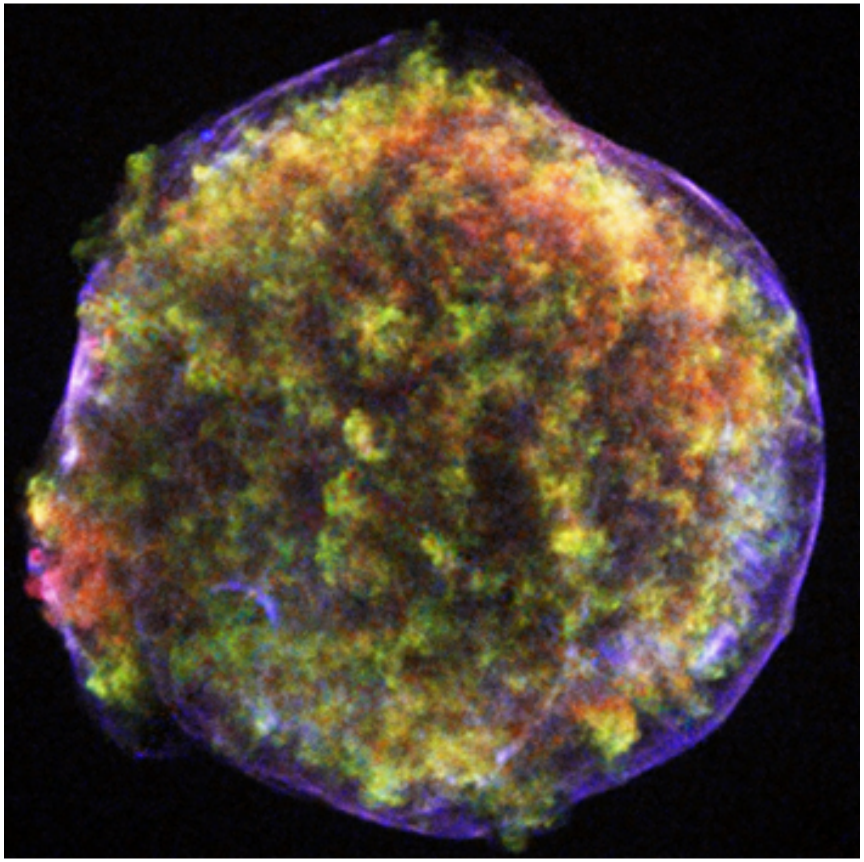


Important Points to Note

- For acceleration of particles, the important things to note are:
  - The density and density structure of the ambient medium, which depends on the progenitor star (RSG, WR, BSG, single or binary etc).
  - The velocity structure of the shocked interaction region, and the evolution of the velocity over time.
  - The mass and energy in the ejected material.
  - The amount of energy expended in accelerating particles. If more than about 10%, it will modify the shock structure. The low and high energy particles will see different shock jumps.

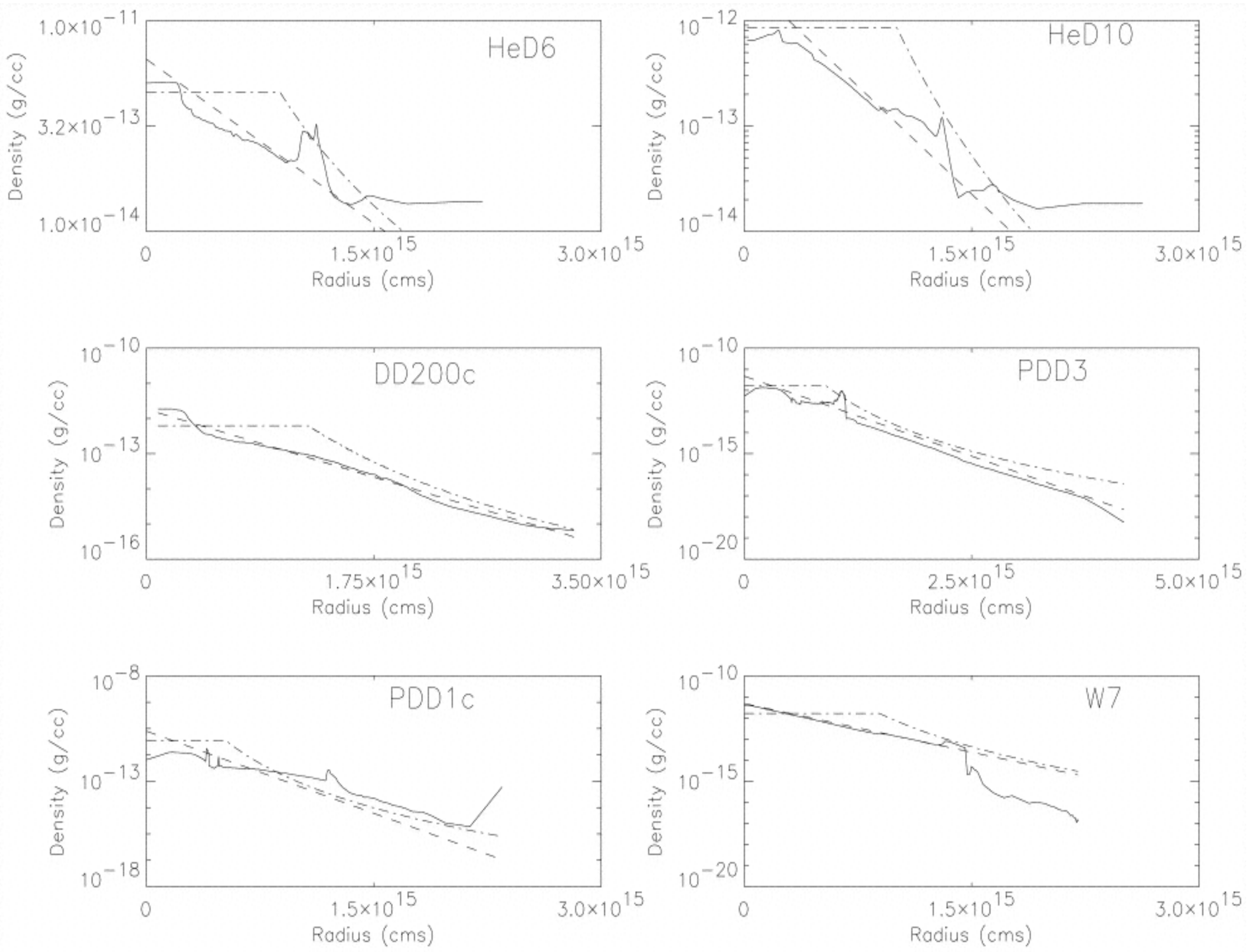
Type Ia SNe

- Arise from low mass progenitors (< 8 solar masses)
- Appear to be expanding into a mainly constant density medium (Badenes et al)

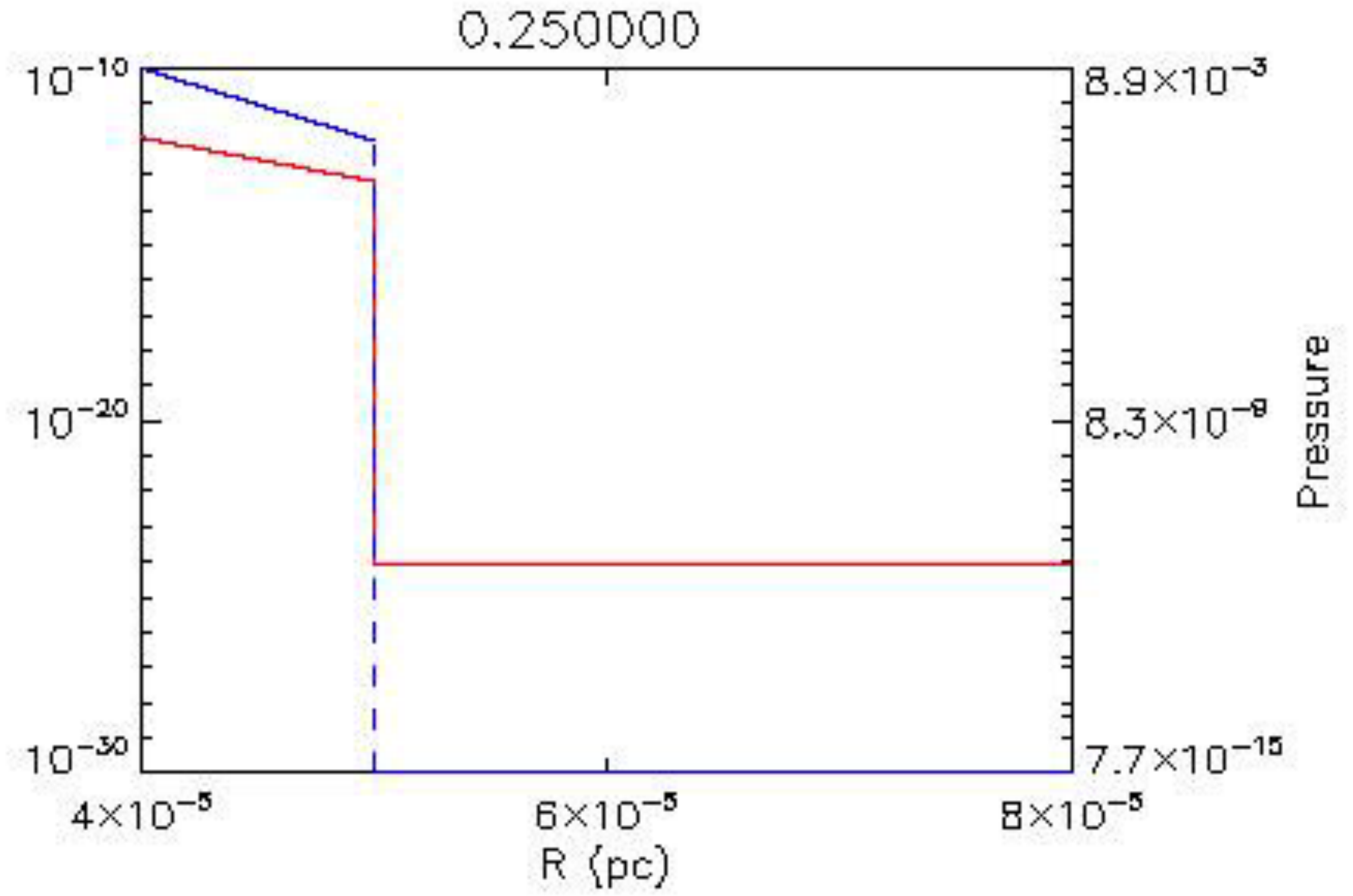


Type Ia SNe Ejecta Density Profile

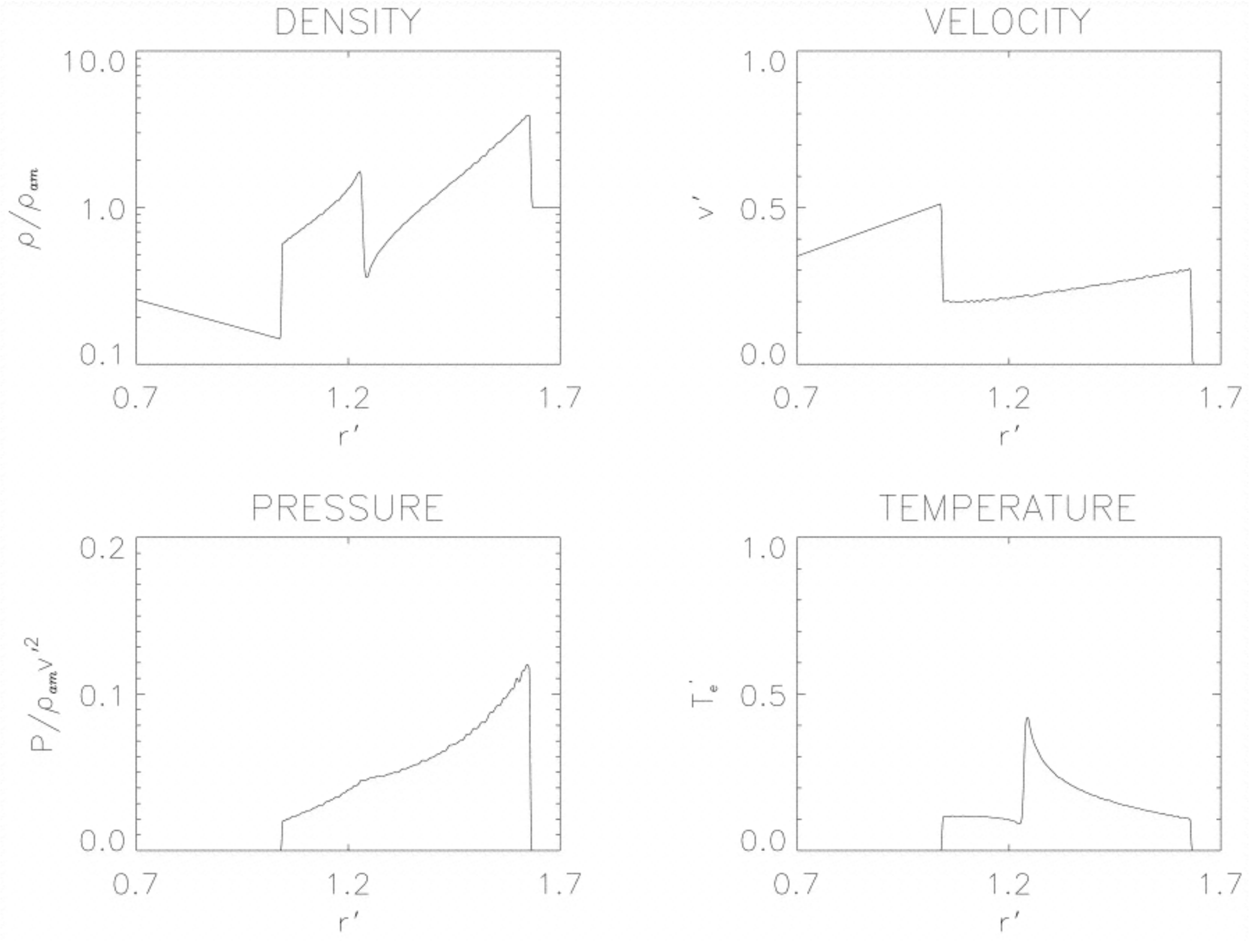
By comparison with Type Ia explosion models, the ejecta density in Type Ia's is best fit by an exponentially decreasing density profile (Dwarkadas & Chevalier 1998)



Interaction of Type Ia Ejecta with Constant-Density ISM



Interaction of Type Ia with Constant Density Ambient Medium



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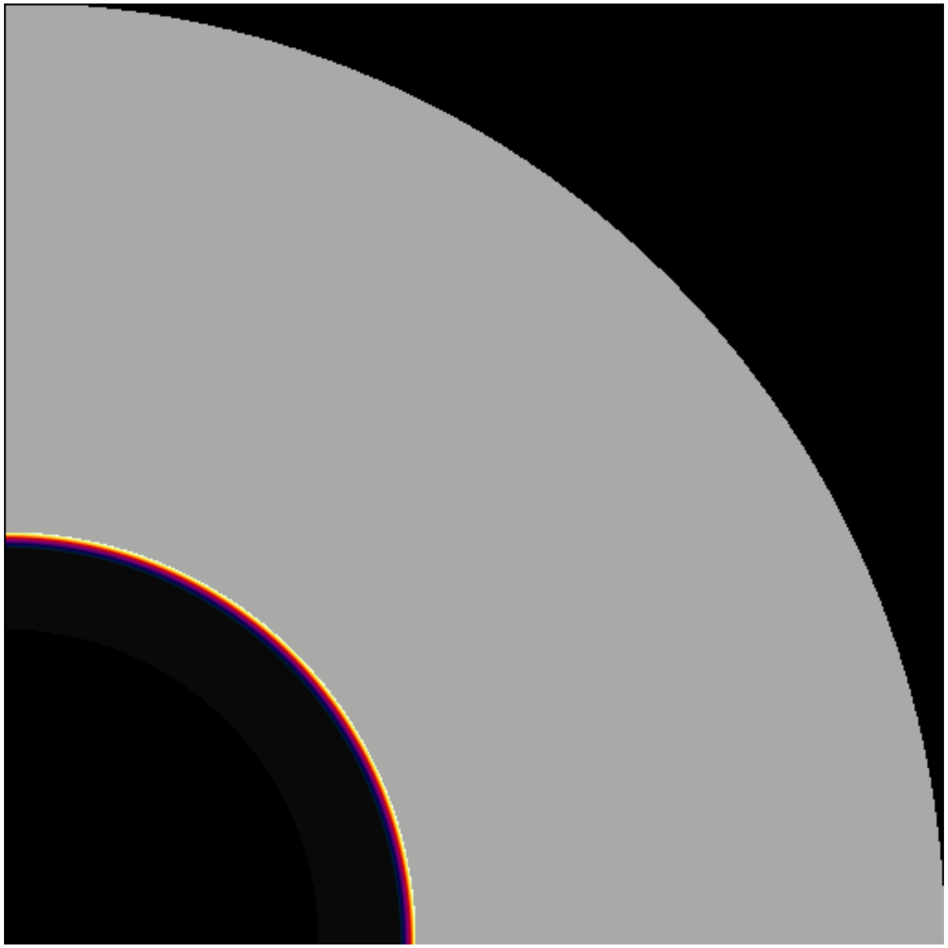
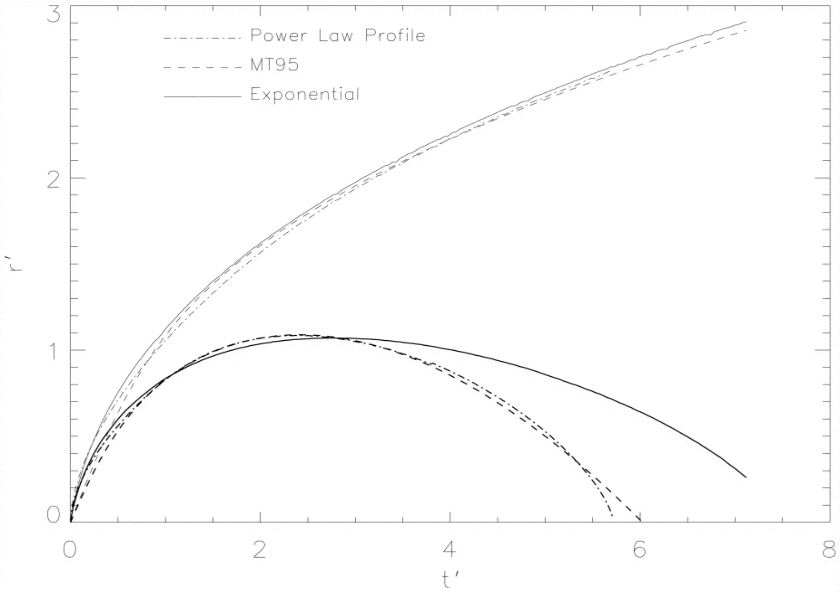
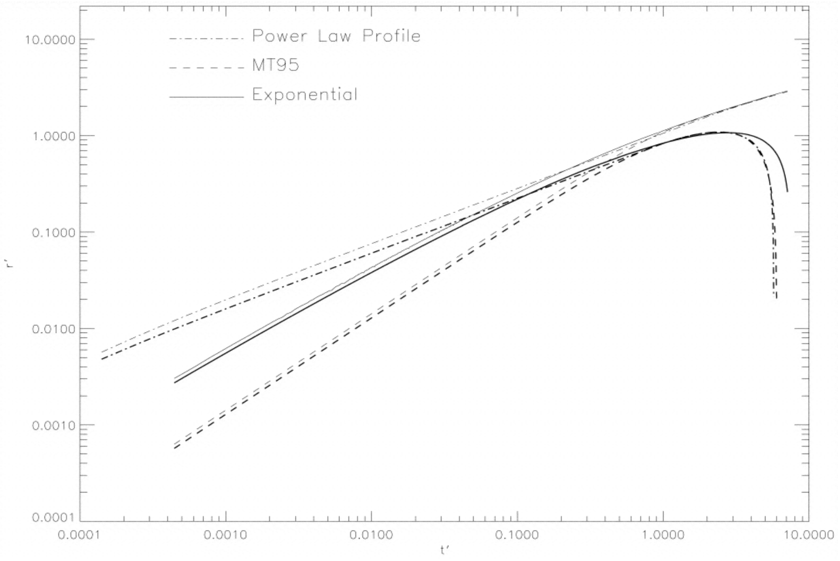
The Contact Discontinuity is Rayleigh-Taylor unstable



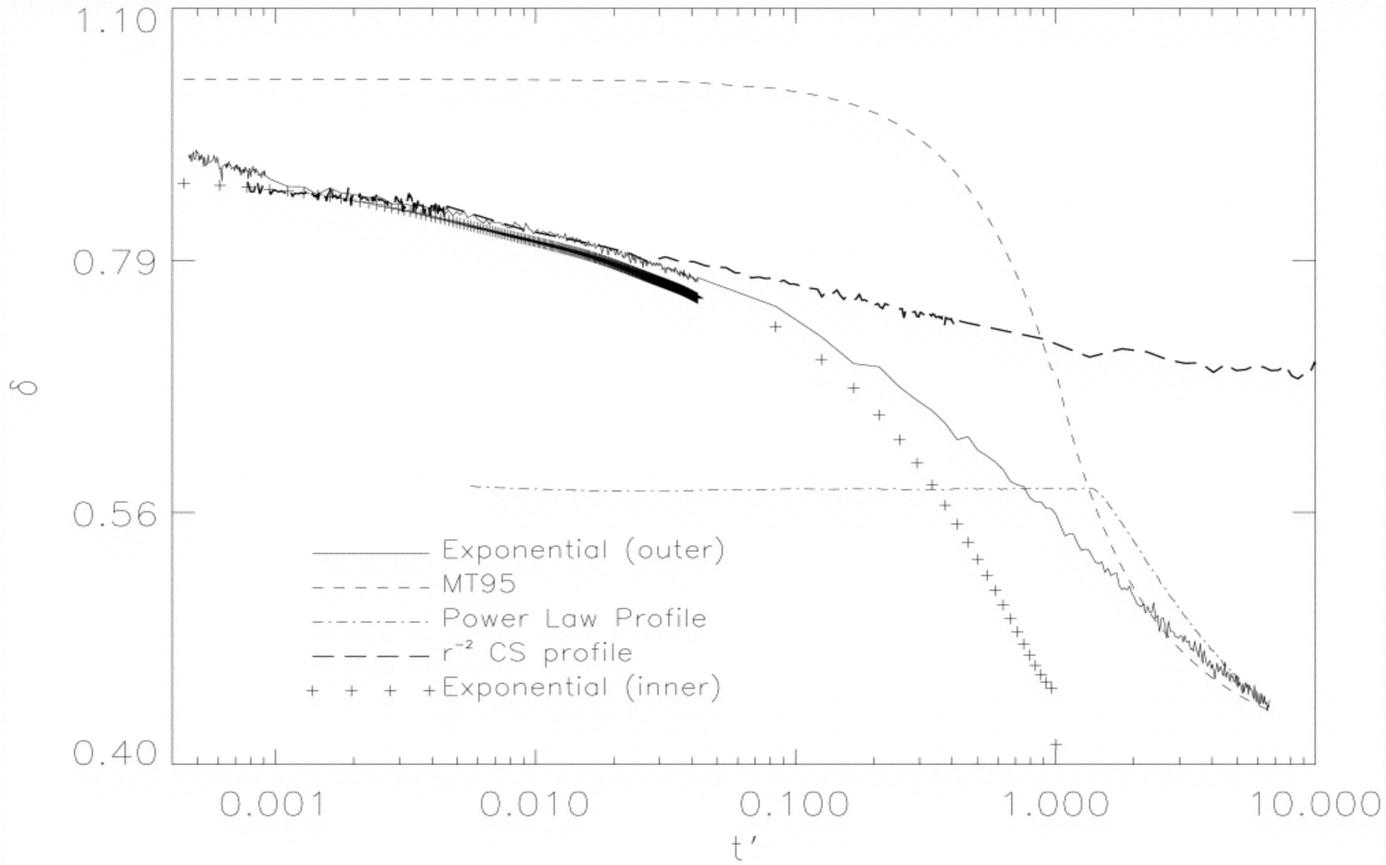
Evolution of SN Shocks in the Ambient Medium



Top: Forward (CSM) shock. Bottom: Reverse Shock. For 3 different ejecta models. Normalized radius and time. Note: Forward shock evolution is almost same in all cases. But reverse shock is different, depends on ejecta profile. (Dwarkadas & Chevalier 1998)



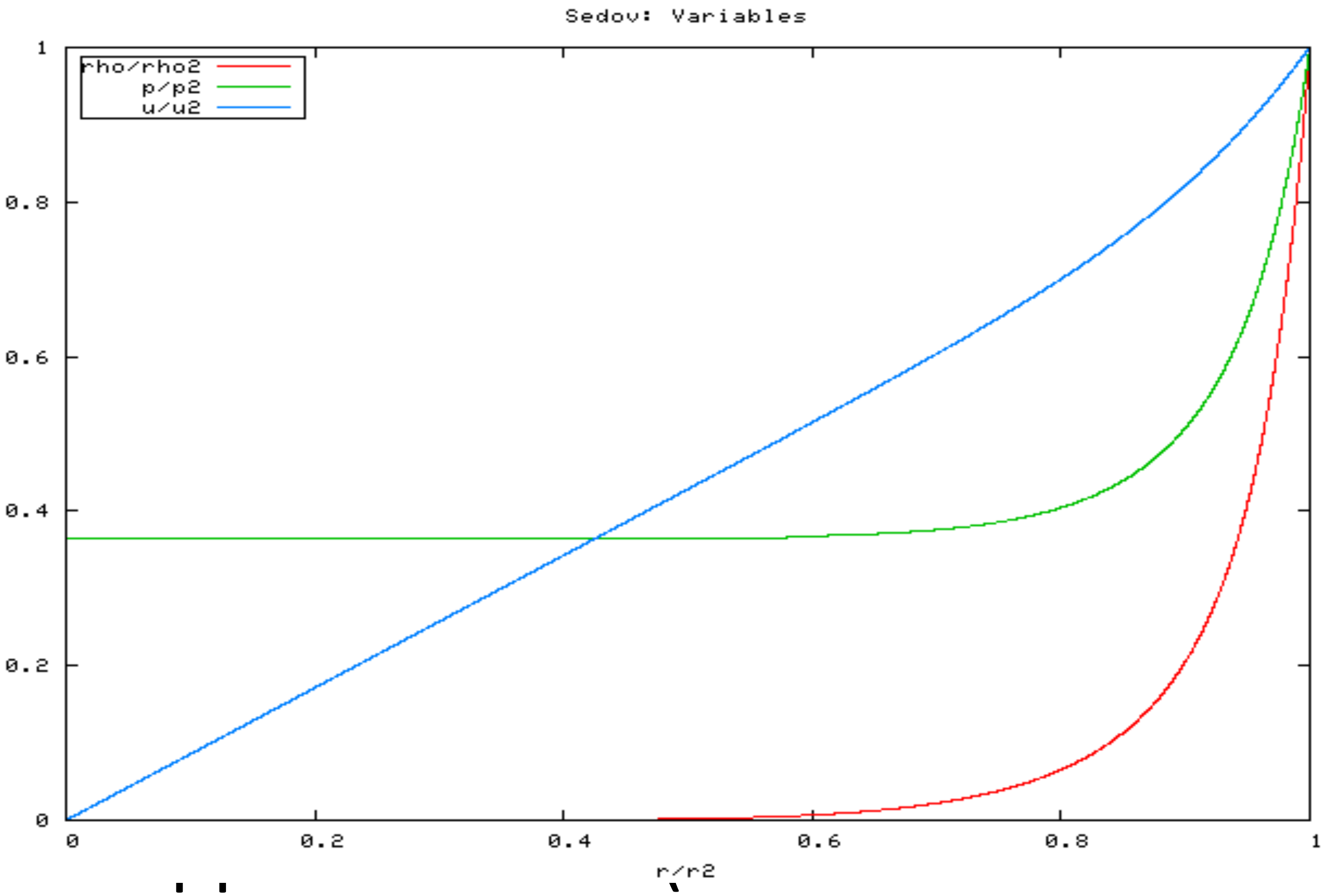
The same plot but in logarithmic co-ordinates. Note that initially, $R_f = 1.1 R_r$. Initially, both forward and reverse shocks are moving outwards, but then the reverse shock turns around and moves back towards the center. Note: Ratio of swept-up mass to ejecta mass in these units is R_f^3.



Evolution of the Expansion Parameter with Time – Approach to the Sedov Stage.

Expansion parameter δ, where R ~ t^{δ}. The plot shows how δ changes with time for different profiles.

Eventually the SN shock will sweep up enough material that it will enter the adiabatic or Sedov-Taylor stage. For a constant density medium, the shock in the Sedov stage goes as R ~ $t^{0.4}$. Note that it takes a very long time to reach the Sedov stage for some profiles.



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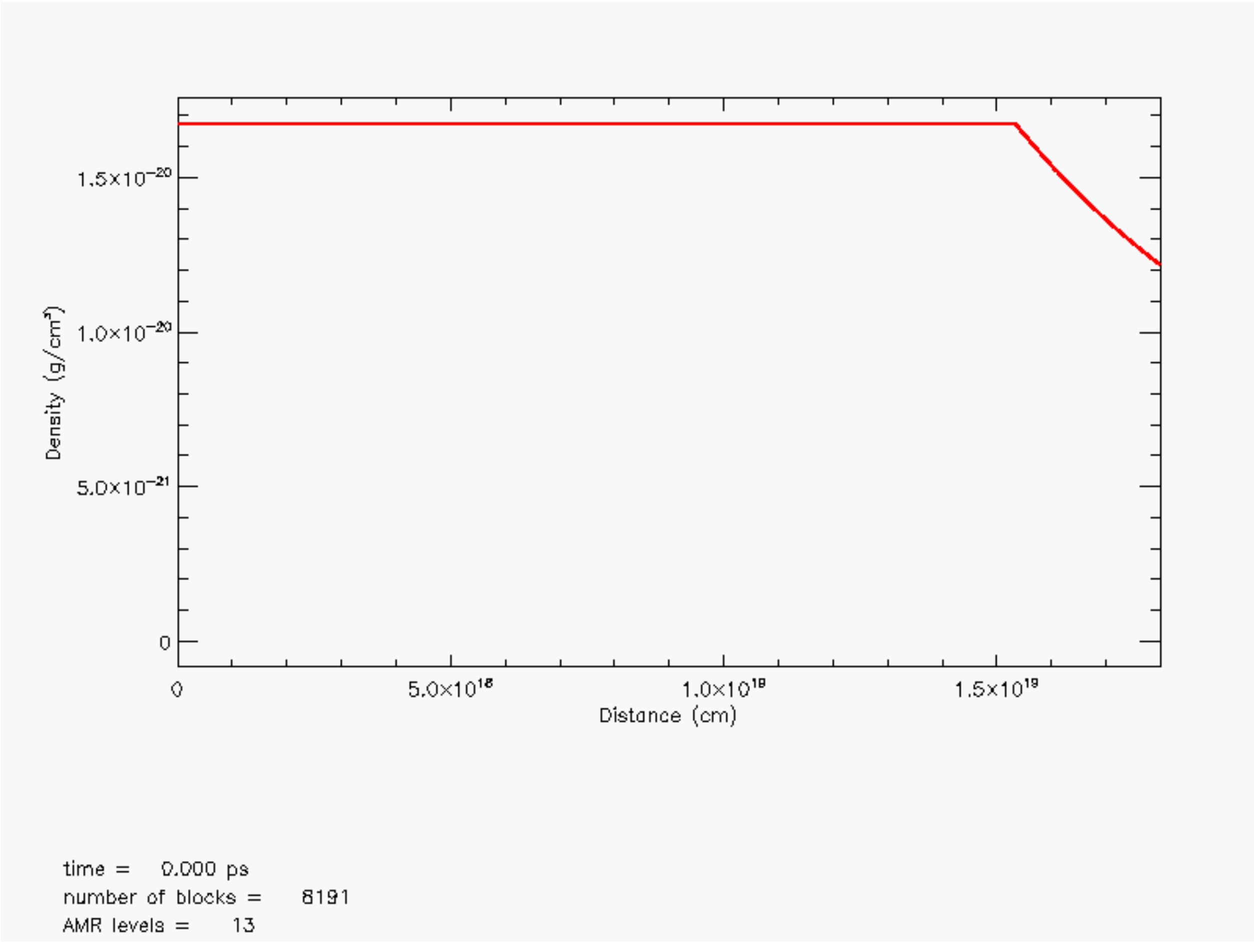
- The density, velocity and pressure profiles must change to the Sedov values.

Approach to the Sedov Stage

- Note that from the previous plots, the swept-up mass must be 20-30 times the ejecta mass before the reverse shock reaches the origin.
- In multi-dimensional simulations, the reverse shock will probably not remain spherical when it moves back towards the center.
- As shown before, the SNR takes a long time to reach the Sedov expansion parameter.
- Thus, in most cases, the idealized Sedov stage could take over 1000's of years, and in many cases it may never be realized.
- Note that the well-known galactic SNRs – Cas A, Tycho, Kepler, 1006 are far from the Sedov stage.

The Sedov Stage

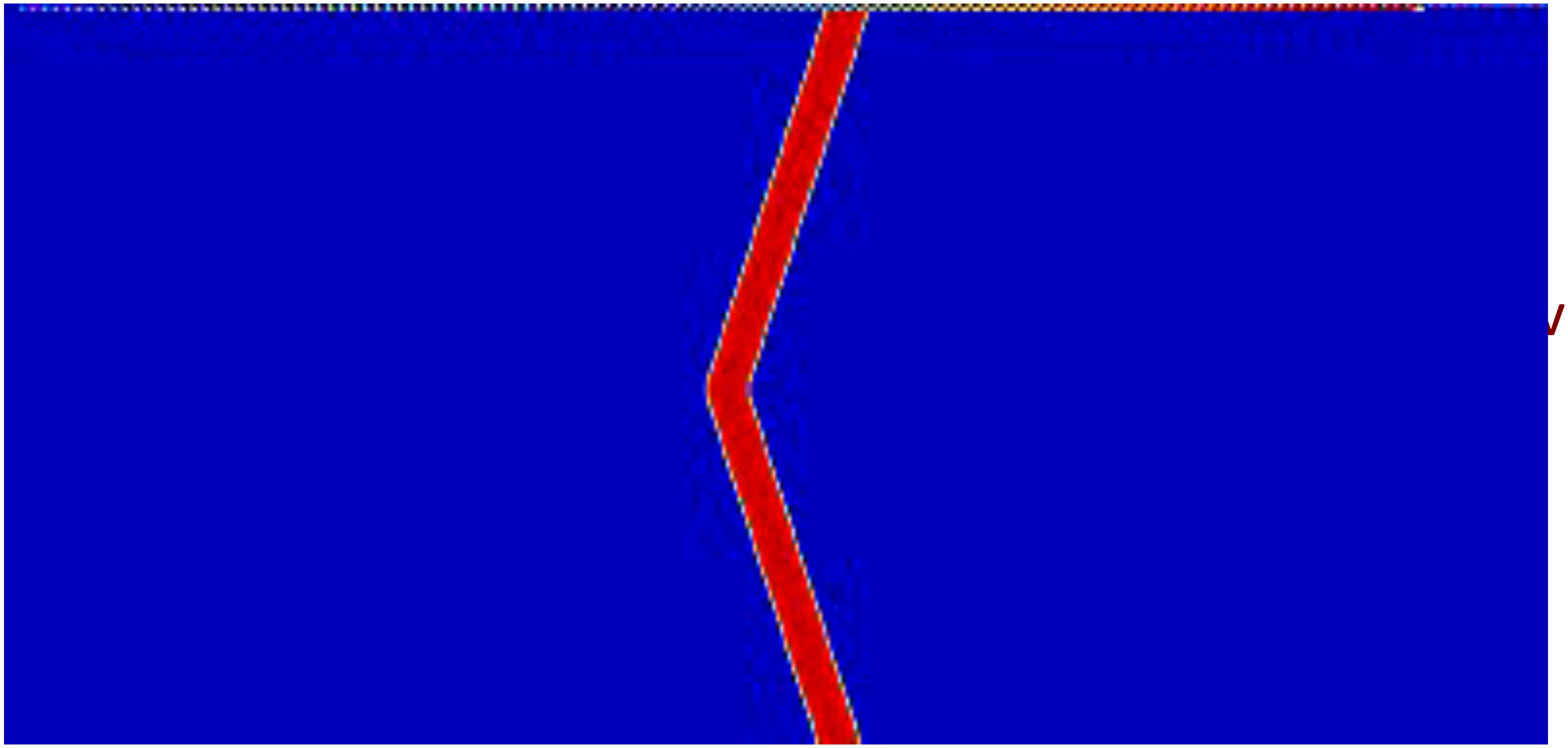


$R_s \sim t^{2/5}$
$V_s \sim t^{-3/5}$
$T_s \sim v_s^{2} \sim t^{-6/5}$

The Sedov-Taylor Stage

- Although most textbooks will tell you that the SNR lives in this stage for a long time, starting from when swept-up mass=ejecta mass, and till the shock becomes radiative, that is NOT correct.
- The transition into and out of the Sedov stage can take almost as much time as the Sedov stage.
- In some cases, such as SNRs in wind bubbles, this phase can be considerably shortened, or even completely avoided.

Approach to the Radiative Stage



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- The shock wave can become highly unstable during the transition from Sedov to radiative stage (Blondin & Marks)

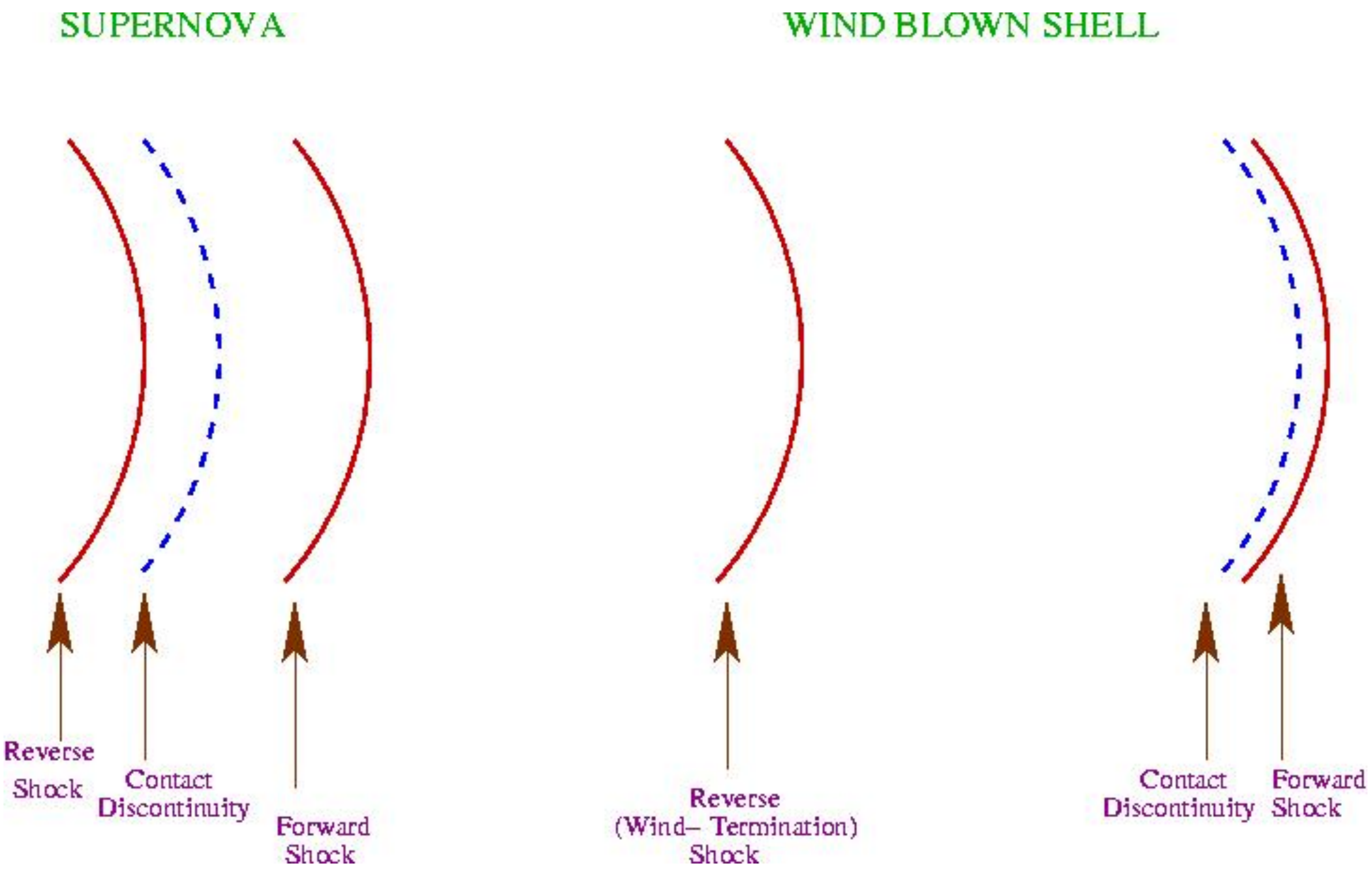
The Radiative Stage

- In the radiative stage, a simple self-similar solution can be obtained, $R \sim t^{1/4}$, for a momentum-driven flow.
- However, Ostriker & Mckee (1977) show that a better solution is $R \sim t^{2/7}$, appropriate for a pressure-driven snowplow model.
- And van Buren et al find that and offset solution of the form $R \sim t^{0.3}$ matches best the numerical simulations.
- No matter what the exact solution, one can see that by this time, the shock has slowed considerably from $R \sim t^{(n-3)/(n-s)}$
- Eventually, it will slow down enough to merge with the surrounding medium, IF it does not get stuck in a wind-blown shell and lose most of its energy that way.

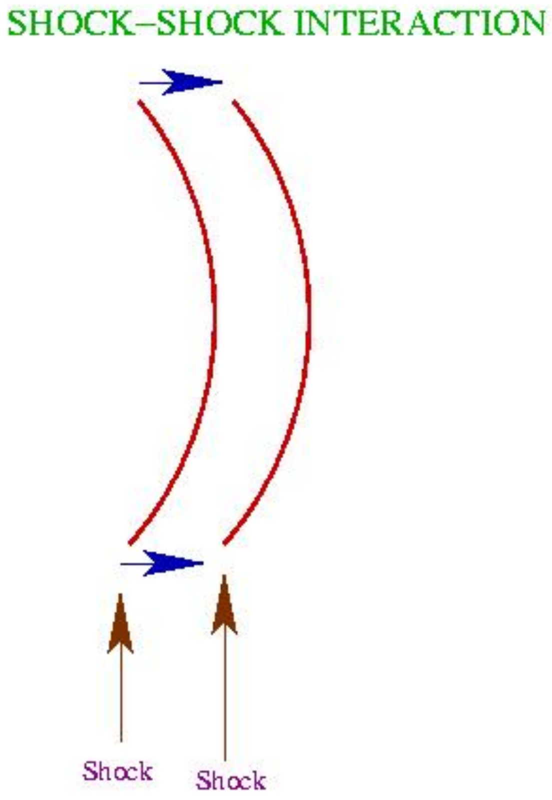
Realistic SNR evolution

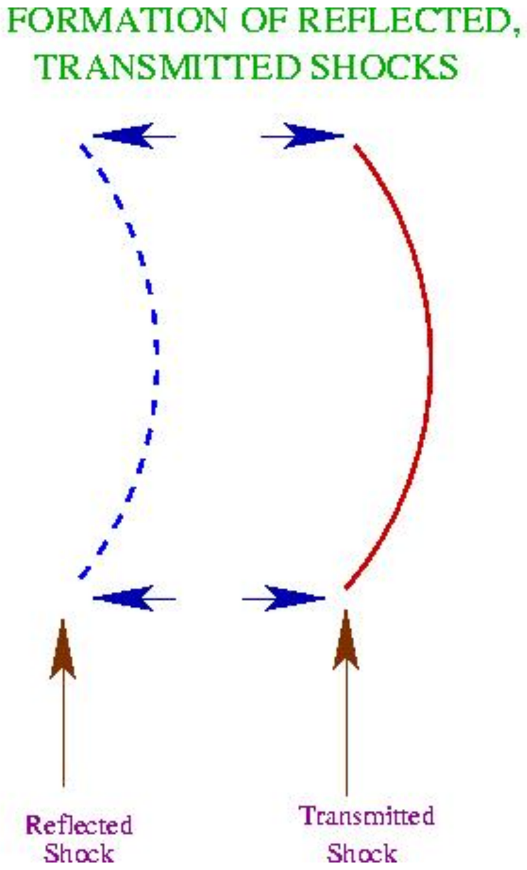
- We have studied how SN shocks will expand into different density circumstellar or interstellar medium.
- Lets take a look at the actual expansion in a few cases, for SNe and SNRs, and see what the hydrodynamic evolution actually looks like.
- We explore young SNe in a wind bubble (SN 1996cr and SN 1987A), SNR interacting with a cloud, and a SNR expanding in a large W-R bubble.

SN Circumstellar Interaction

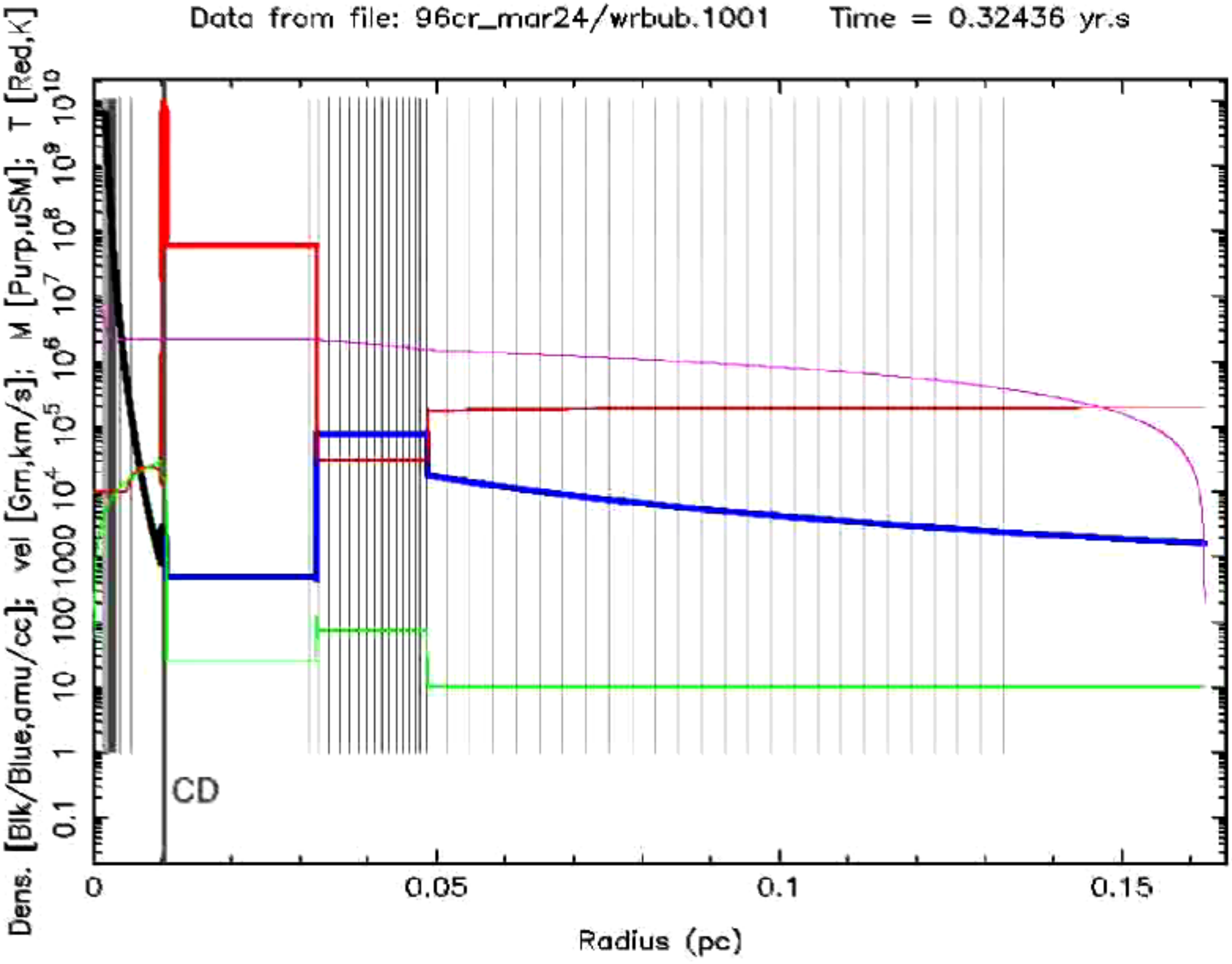


SHOCK-SHOCK INTERACTION

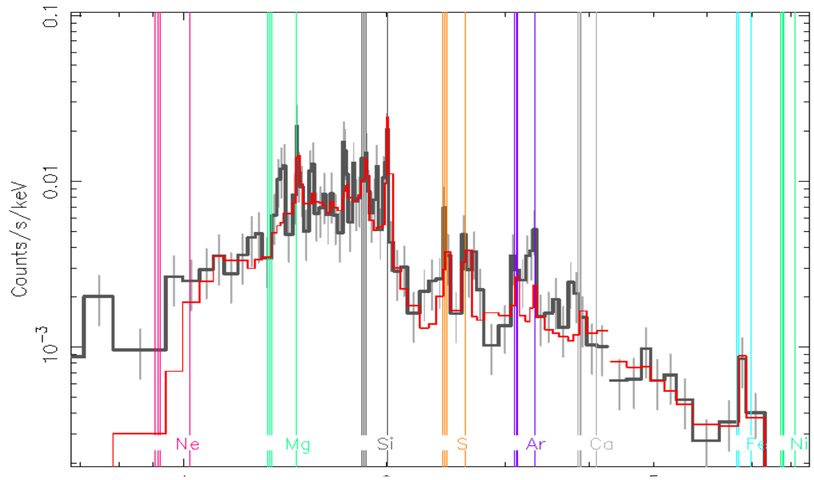




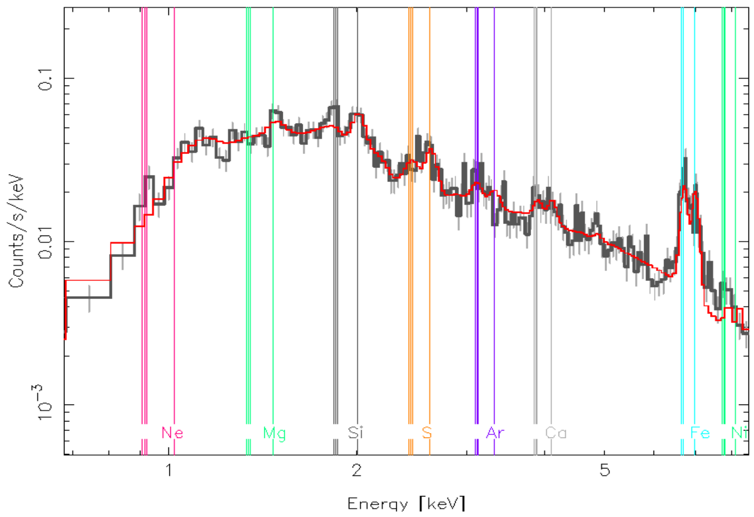
SN 1996cr Hydro Model



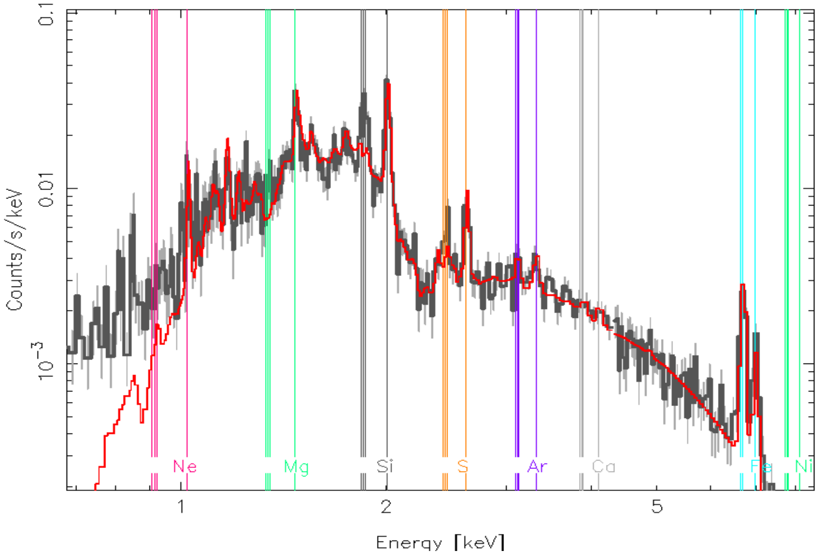
SN 1996cr (Comparison between Observed and Simulated Spectra)



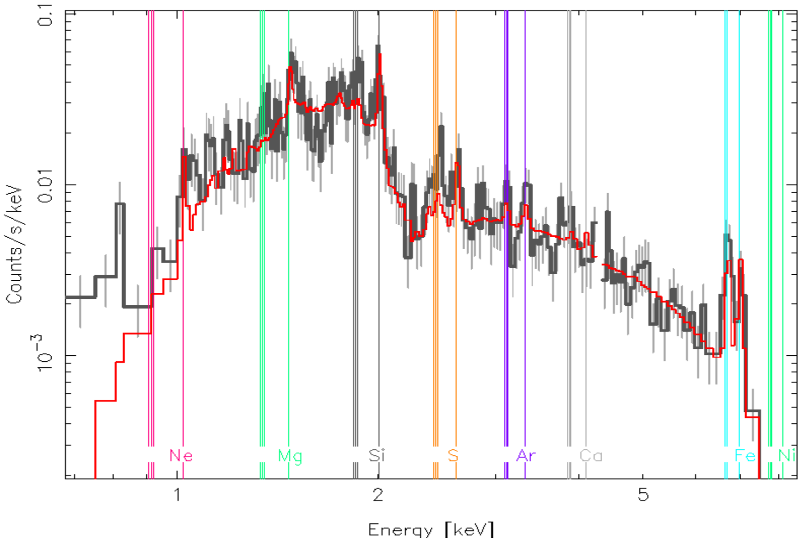
HETG−00 Data (Black) with Mar24−i34−Hydro Model (x1.36, Red)



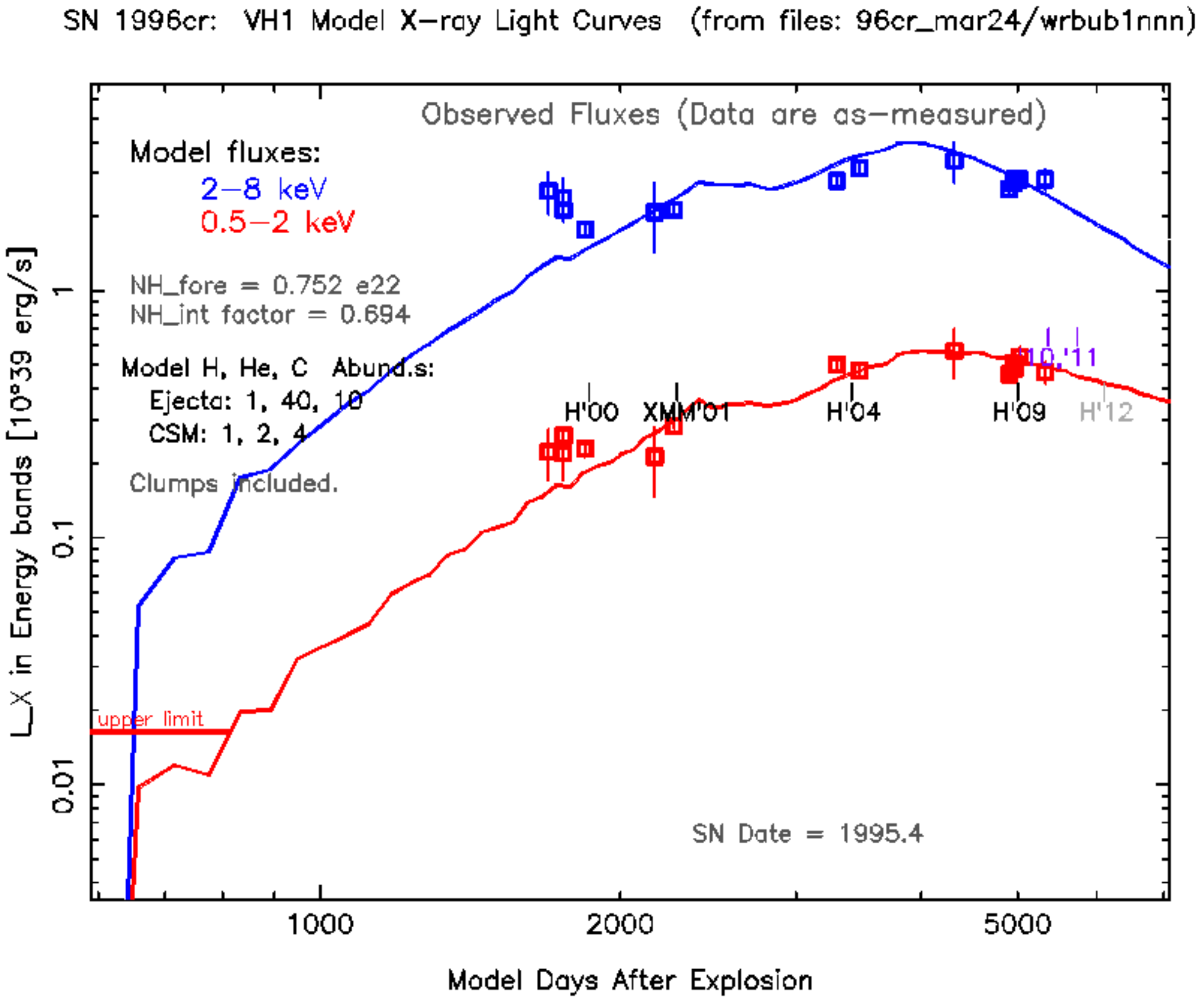
XMM−01nb Data (Black) with Mar24−i42−Hydro Model (x0.79, Red)



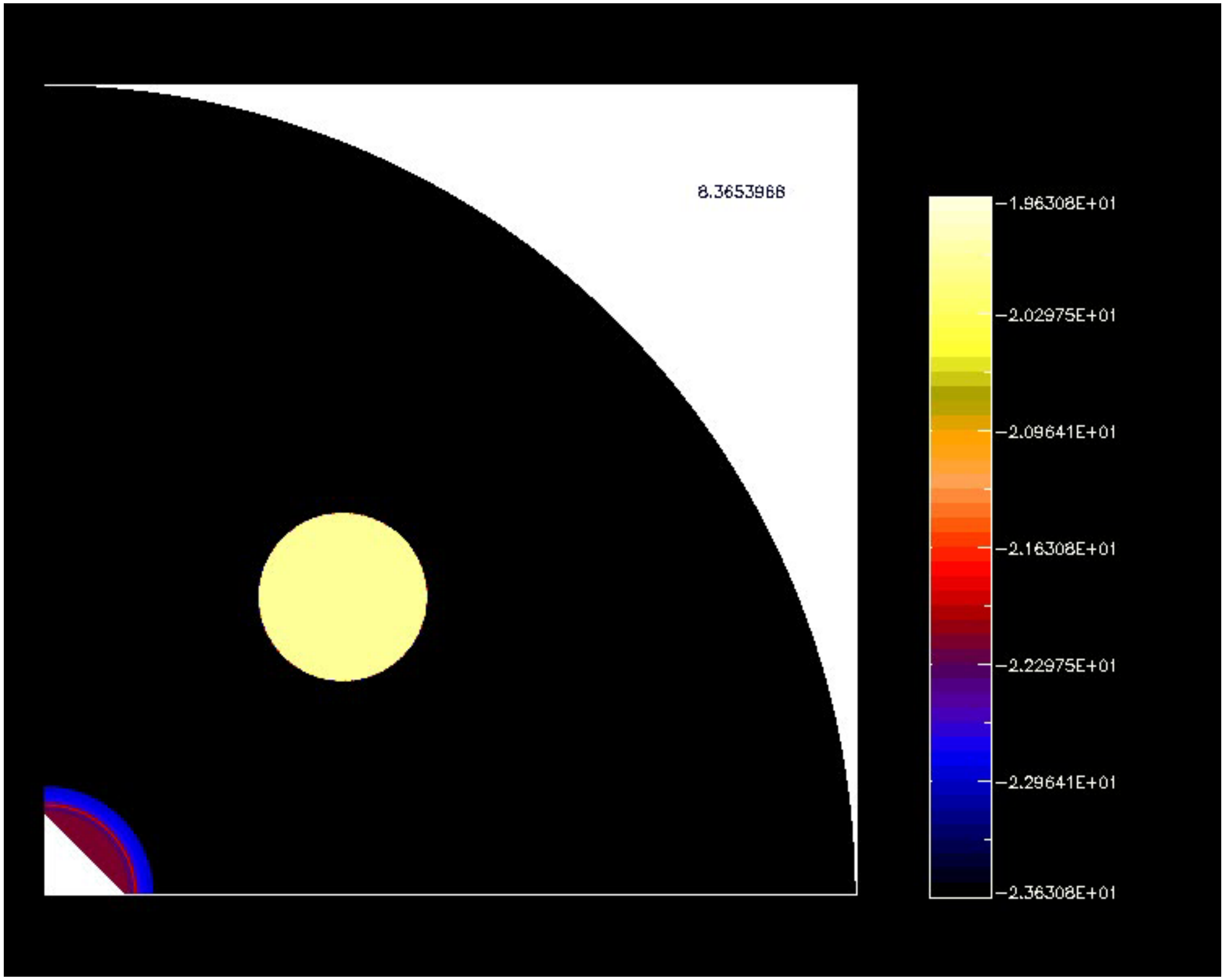
HETG−09 Data (Black) with Mar24−i79−Hydro Model (x1.13, Red)



1996cr - Comparison with X-Ray data

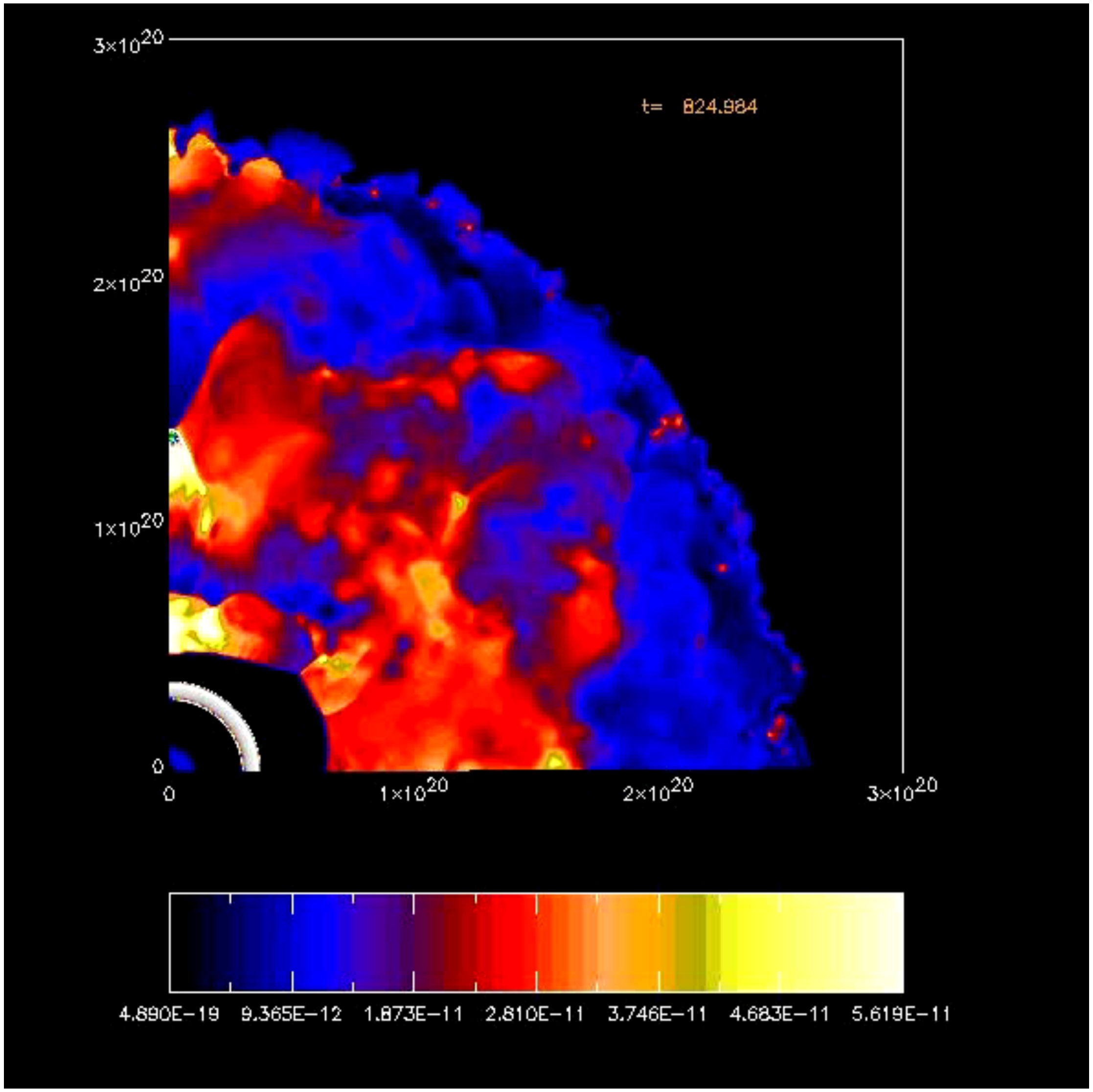


SNR interacting with a cloud



Simulation carried out with the VH-1 code, including radiative cooling.

SNR expanding in a Clumpy, Turbulent Wind Bubble



Summary

- SNR propagation in the ambient medium depends on the structure of the ambient medium, the structure of the material ejected in the SN explosion, and the energy and mass of the ejected material.
- Although SNR evolution is traditionally classified as going through various phases, a SNR could spend most of its time in transition between these phases, and thus may not be adequately described by the self-similar solutions.

Summary (Contd)

- The Sedov stage is NOT reached when the swept-up mass equals the ejecta mass, it generally takes a lot longer than that. In some cases it could be truncated or totally bypassed.
- SN shocks can become radiative depending on their velocity and the ambient density. This can happen at any time, not necessarily in the radiative stage.

Summary (Contd)

- In order to understand the acceleration of particles to relativistic energies and the production of cosmic rays in SNRs, it is important to understand the velocity structure of the shocked region.
- This requires doing detailed calculations or high-resolution hydrodynamic modelling.
- For younger remnants, like the Galactic remnants, both forward and reverse shocks can accelerate particles and must be considered.

QUESTIONS & DISCUSSION

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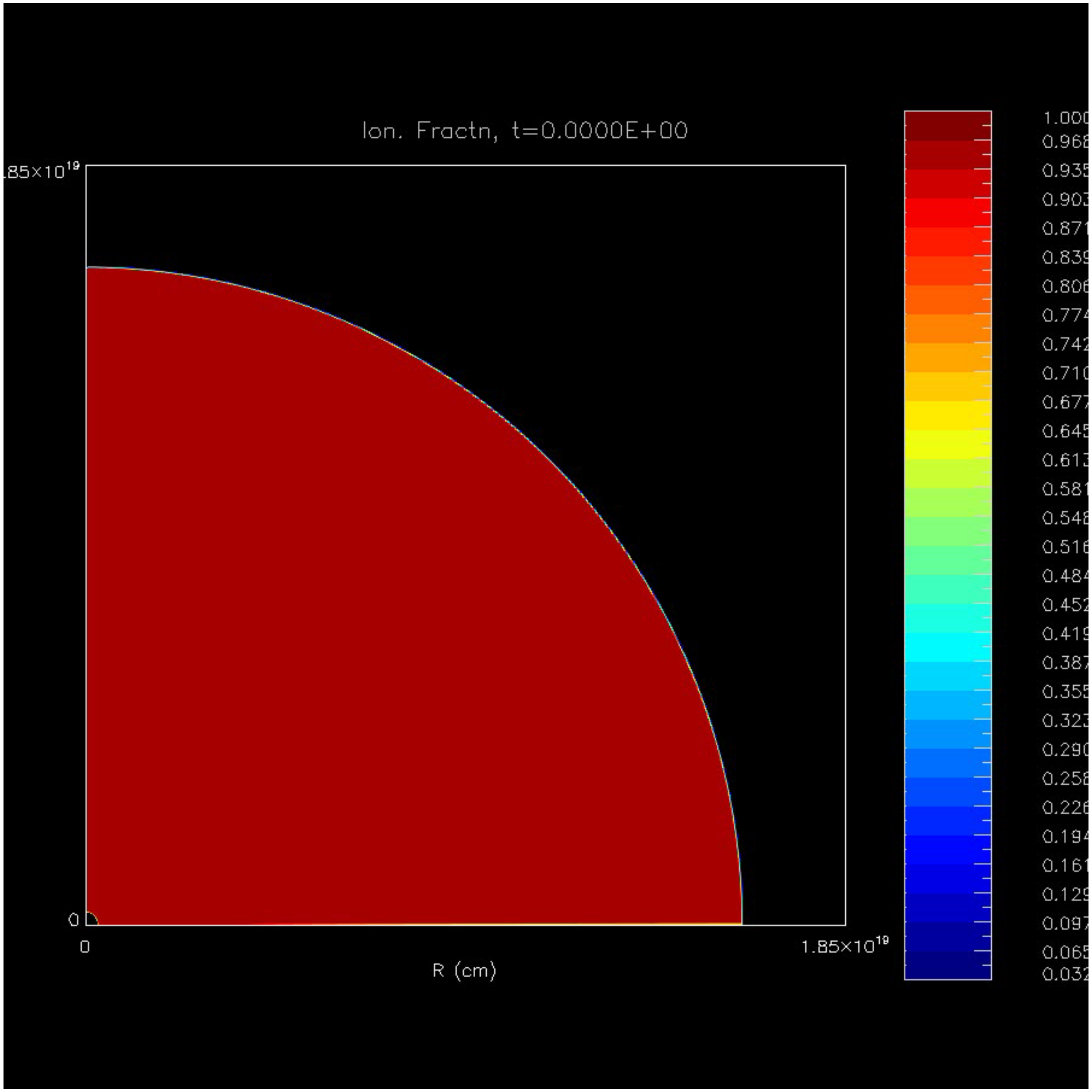
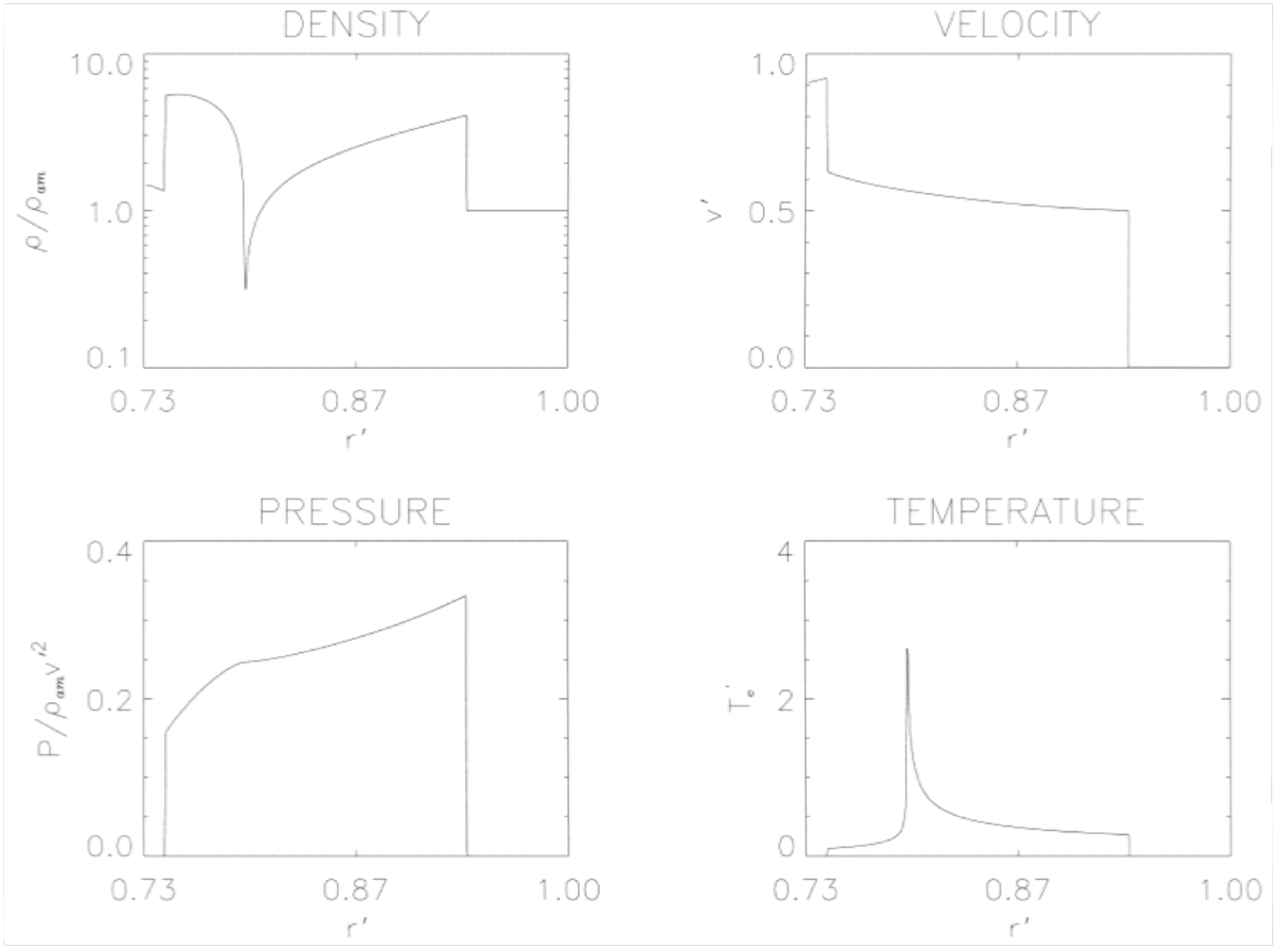
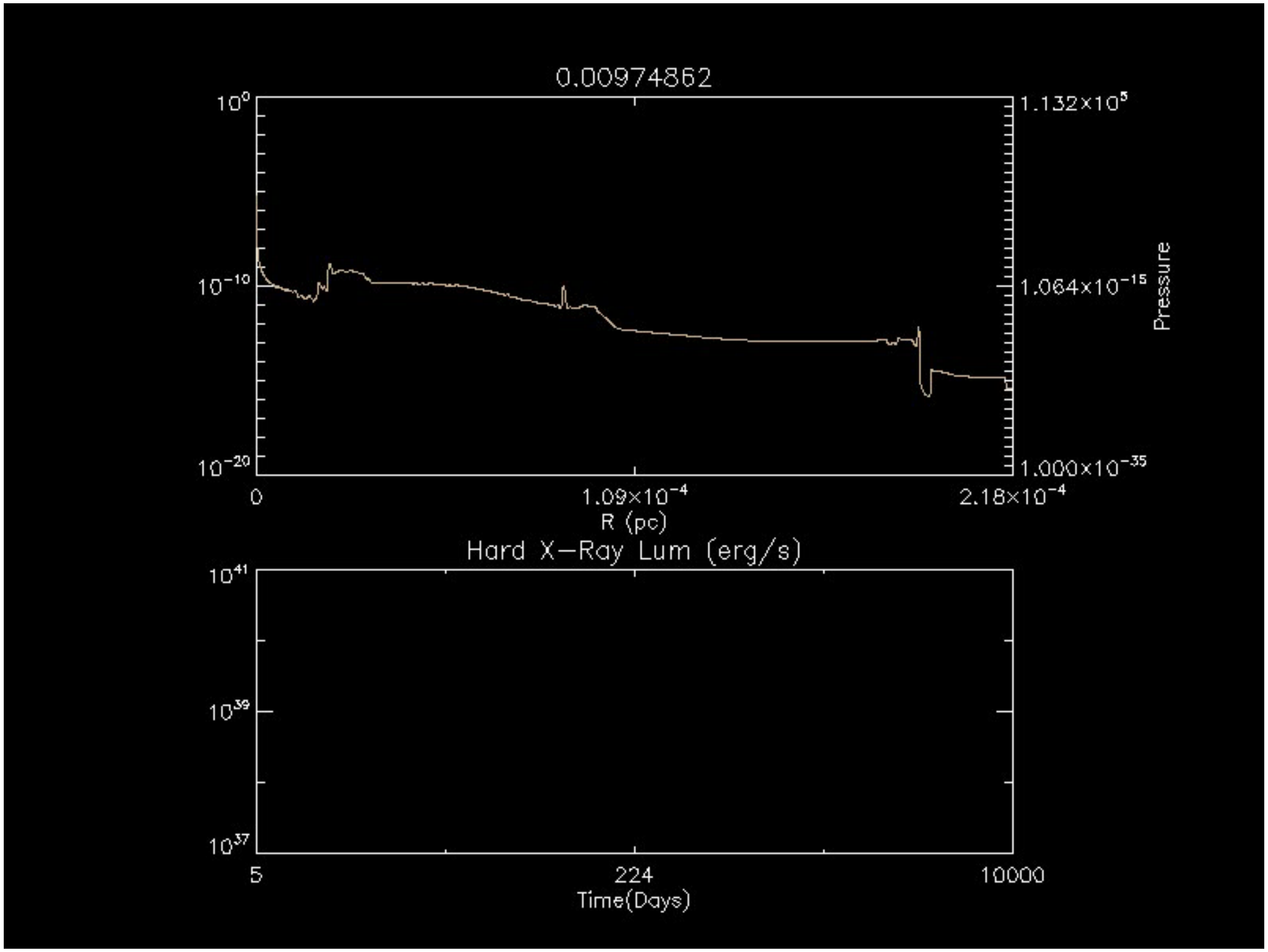


Interaction of Power-Law Ejecta with Constant Density Medium

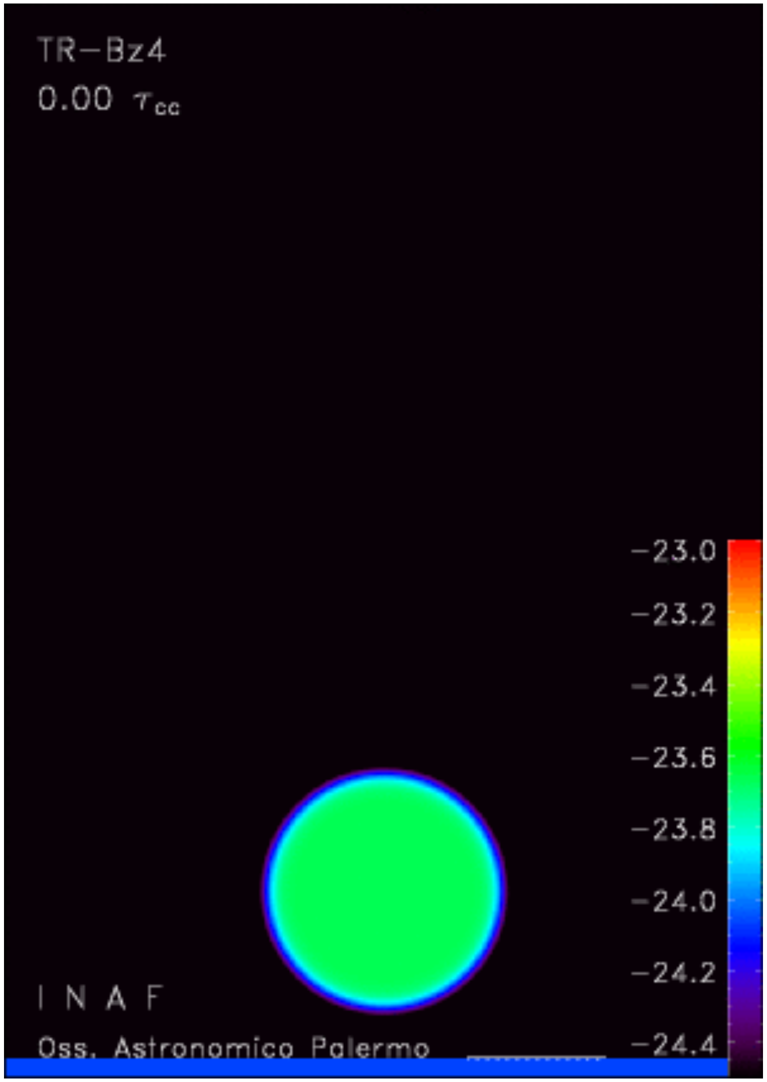


SN 1993J – Used to compute radio and X-ray Light curves



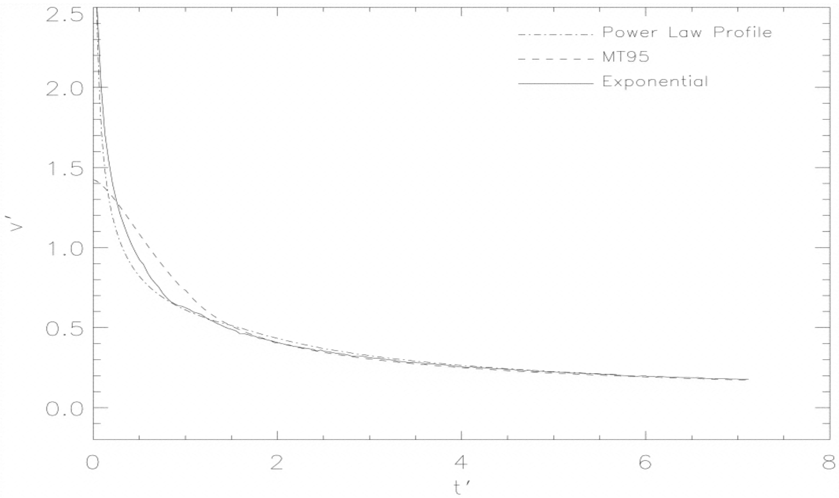
Ejecta profile used – 4H47 model from suzuki and Nomoto (1995). Wind – varies as r$^{-1.5}$, then r$^{-2.1}$, and then r$^{-2.6}$ An expanding grid is used, and the hard X-ray lightcurve is calculated.

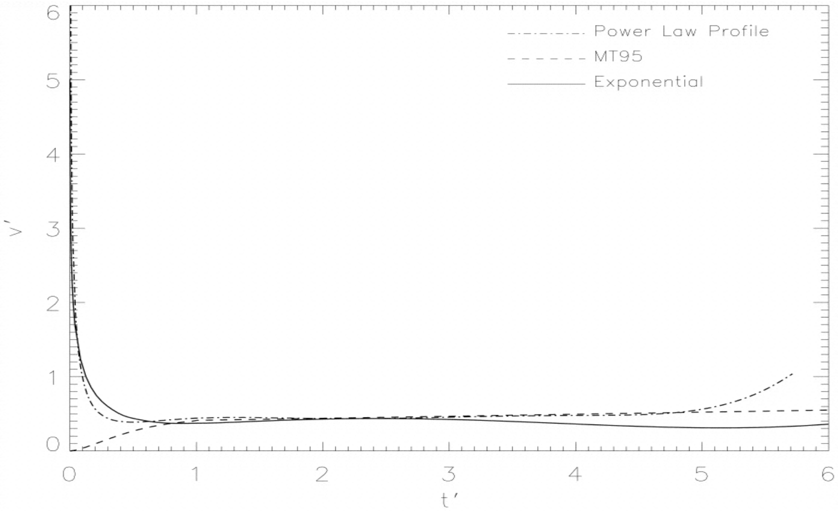
SNR interacting with a cloud – 3D



SNR shocks interacting with molecular clouds in the presence of a magnetic field. Simulation carried out with the FLASH code. From Orlando et al 2008, ApJ, 678, 274

Evolution of SN Shocks in the Ambient Medium





Forward Shock velocity with time in different models. The velocity decreases with time as expected, although the decrease is different for different ejecta profiles.

Reverse shock velocity with time for different ejecta profiles. Note that at late times the velocity is almost constant