Radiation Mediated Shocks and SuperNova Shock Breakouts

Ranny Budnik

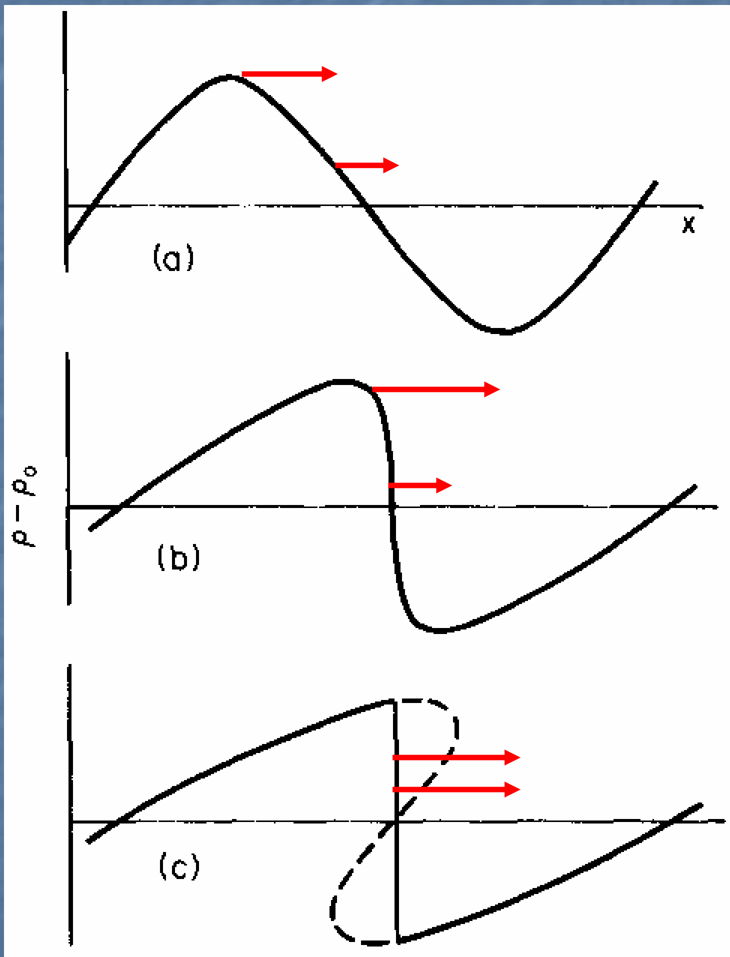
With

Boaz Katz, Amir Sagiv, Eli Waxman

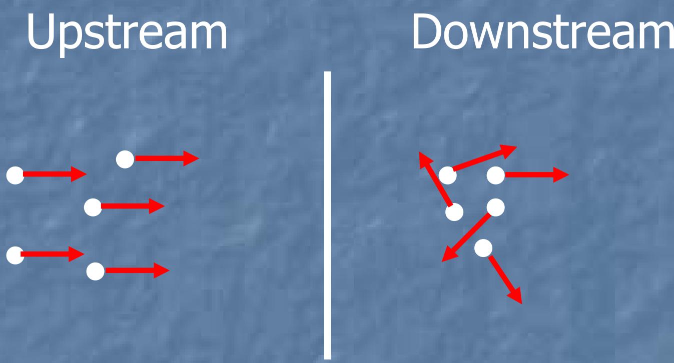
What is a shock?

- In a hydrodynamic flow, when solving the hydro equations (differential):
  - Everything changes smoothly
  - Entropy is conserved
- However, sometimes the equations don’t have a single valued solution!
  - A discontinuity appears, over which only conservation equations are solvable
  - This is a SHOCK.

Shock formation

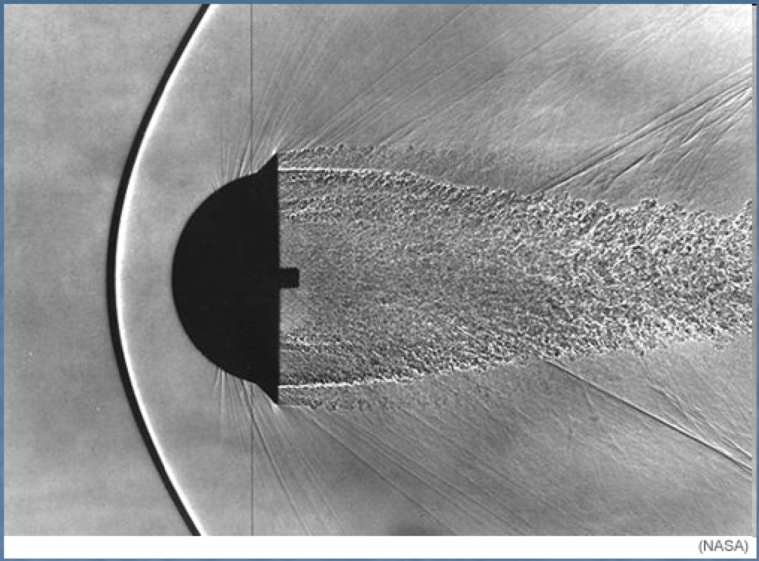


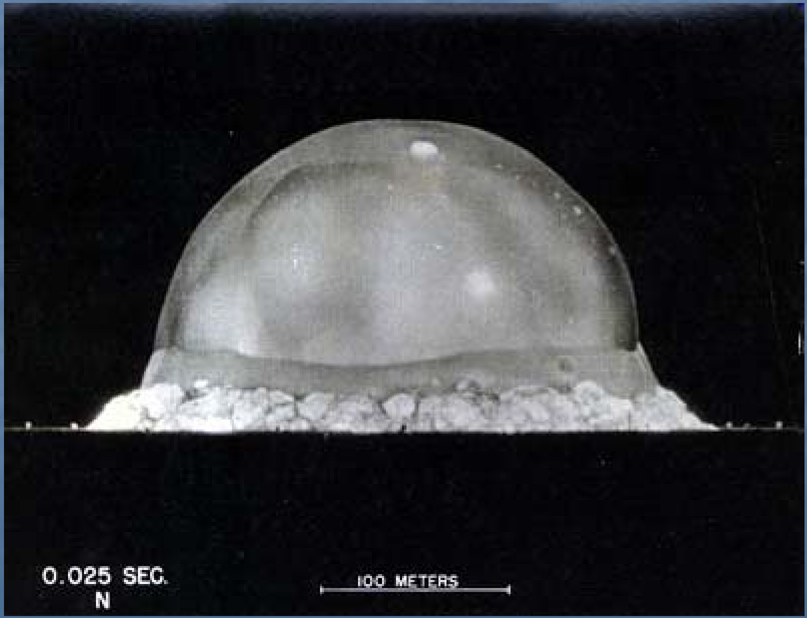
In the shock frame



Ordered kinetic energy -> Thermal energy

Lower density -> Higher density


(NASA)


0.025 SEC.
N
100 METERS

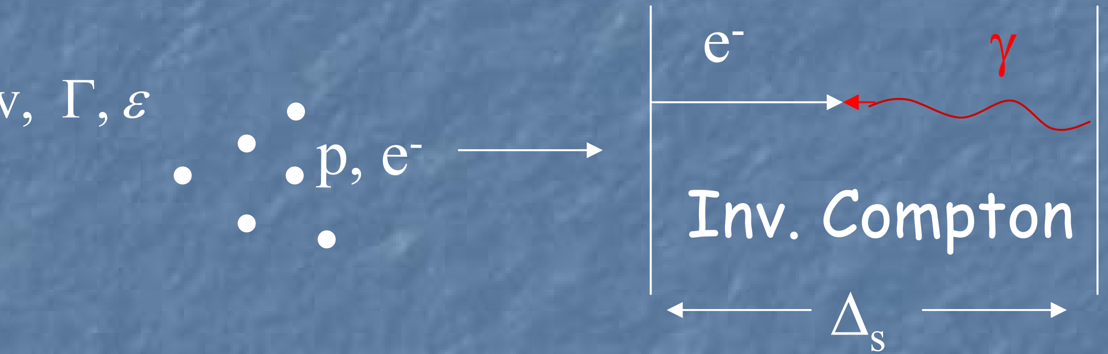
What “makes” the shock?

- Terrestrial shocks:
  - Ions collide and heat, then transfer the momentum to the electrons.
  - Cross section $\sim e^4/(mv^2)^2$
- Low densities, high energies:
  - “collisionless shocks”: no Coulomb collisions. Instead: plasma collective effects (e.g: SNR, Earth bow shock, interstellar shocks)

Radiation Mediated Shock: RMS

Cold Upstream ->

Radiation dominated Downstream



$$U_{\text{rad.}} >> U_{\text{part.}}$$

$$U_{\text{rad.}} \approx \Gamma^2 n m_p c^2$$

$$\text{or} \quad \frac{1}{2}\beta^2 n m_p c^2$$

$$t_\gamma \approx \frac{\Delta_s}{\lambda_\gamma}\frac{\Delta_s}{c} \approx t_e \approx \frac{\Delta_s}{\text{v}} \Rightarrow \boxed{\frac{\Delta_s}{\lambda_\gamma} \approx \frac{c}{\text{v}}}$$

$$T_d = \left(\frac{315}{4\pi^2}\varepsilon n_u \hbar^3 c^3\right)^{1/4} \approx 0.16\left(\frac{\varepsilon}{10\text{MeV}}\frac{n_u}{10^{15}}\right)^{1/4} \text{KeV}$$

Conditions for RMS

$$\beta >> \left(\frac{n}{a_{BB}}\right)^{1/6} \left(m_p c^2\right)^{-1/2} \approx 5\times 10^{-5}\left(\frac{n}{10^{15}}\right)^{1/6}$$

$$L > \Delta_s \approx \left(n\sigma_T \beta\right)^{-1}$$

$$E > 3\times 10^{39}\left(\frac{n}{10^{15}}\right)^{-2}\beta^{-1}\mathrm{erg} \qquad M > 6\times 10^{18}\left(\frac{n}{10^{15}}\right)^{-2}\beta^{-3}\mathrm{g}$$

Shocks running through CC SN are RMS.

$$E_{SN} \approx 10^{51}\ \mathrm{erg} \quad M_{SN} \approx 10^{33}\ \mathrm{g}$$

Physical assumptions

- Steady state shock
- P, e^+, e^- - one fluid (plasma)

$$\frac{t_{pl}}{t_{scat}} \approx 10^{-11} \frac{n_\gamma}{n_e} n_{e,15}^{1/2}$$

- Radiation mechanisms:
  - Compton scattering
  - Bremmstrahlung
  - Pair production and annihilation

Scaling relations: $\mathrm{Length:}\ d\tau \propto n_u dz$

$\mathrm{Intensity:}\ \tilde{I} \propto I / n_u$

Only free-free absorption does not scale with n_u !

Solving RMS profiles

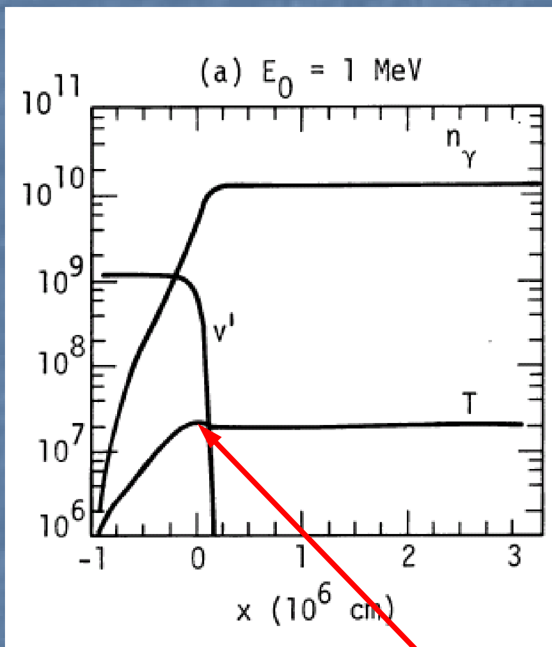
- Steady state, 1D, self consistent solutions of:
  - Radiation transport
  - Conservation of energy, momentum and particles.
- Numerical solutions, analytic estimates.
- NR:
  - Transport -> Diffusion
  - Wein equilibrium.

NR RMS

- Numerical solution by Weaver (1976): diffusion approx.
- Shock structure:
  - Deceleration on a scale of $\beta^{-1}\lambda_T$
  - Production of downstream equilibrium radiation:
    - High density, low velocity: all in equilibrium
    - Low density, high velocity:
      - T increases inside the shock velocity transition
      - Slow thermalization follows until $T=T_d$

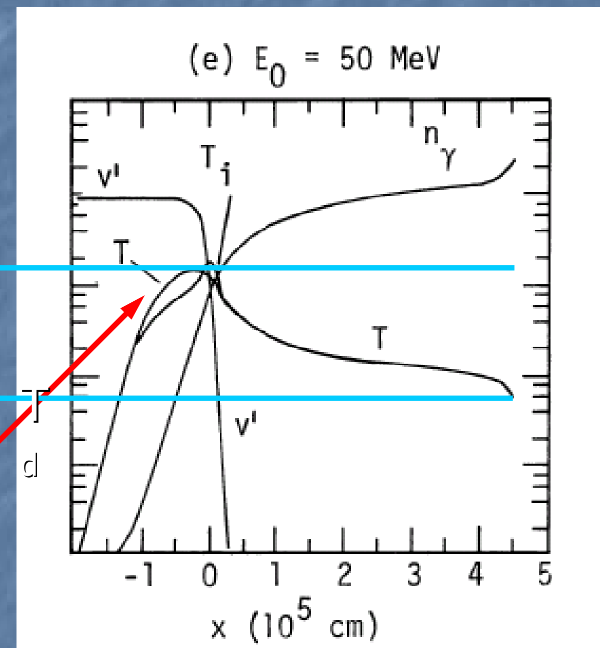
Low velocity: all in equilibrium

High velocity: $T_s >> T_d$



T_s

T_d



In and out of equilibrium

Weaver 1976

Analytic estimates

$n_{\gamma s}$: Production/Diffusion (Wein equilibrium):

Downstream Compton y parameter :

$$y \sim 4\left(L_T / \Delta_s\right)\frac{T}{100eV}\beta_{u,-1}^{-2}$$

Thermalization length :

$$L_T \sim \beta c \frac{n_{\gamma,\mathrm{eq}}}{\mathrm{Q}_{\gamma,\mathrm{eff}}\left(T_d\right)};\ \mathrm{Q}_{\gamma,\mathrm{eff}} \approx n^2 \alpha_e \sigma_T c \sqrt{\frac{m_e c^2}{T}} \Lambda_{eff} g_{eff}$$

High temperatures inside the shock transition :

$$\beta_s > 0.07 n_{15}^{1/30}\left(\Lambda_{eff} g_{eff}\right)^{4/15} \Rightarrow L_T > \Delta_s \ \Rightarrow\ T_s > T_d$$

$$\Lambda_{eff} \approx \log\left[\frac{T}{h\nu_a\left(@\, N_{\mathrm{coll.}} = m_e c^2 / 4T\right)}\right]$$

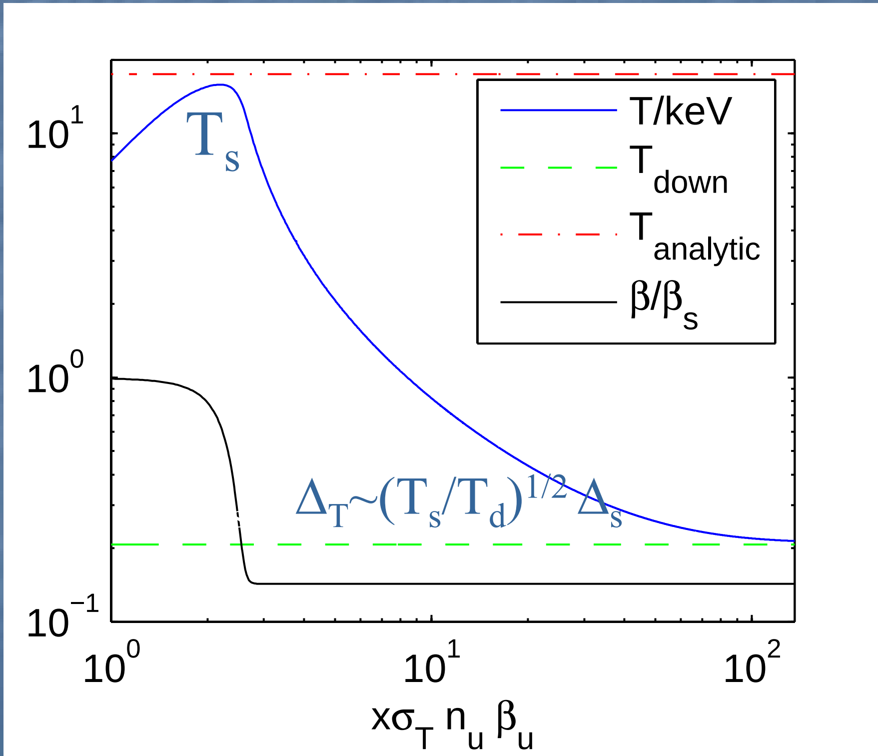
Analytic estimates and solutions

$$n_{\gamma,s} \approx Q_{\gamma,eff}(T_s, n_d)\frac{1}{3n_d\sigma_T\beta_d^2 c} \quad \text{(Diffusion)}$$

$$n_{\gamma,s}T_s = \frac{12}{7}\varepsilon n_u \quad \text{(Momentum cons.)}$$

Velocity - Temperature relation :

$$\beta_s \approx 0.2\left(\frac{\Lambda_{eff}}{10}\frac{g_{eff}}{2}\right)^{1/4}\left(\frac{T_s}{10\mathrm{KeV}}\right)^{1/8}$$



$v_s/c=0.25$, $n_u=10^{15}/cm^3$

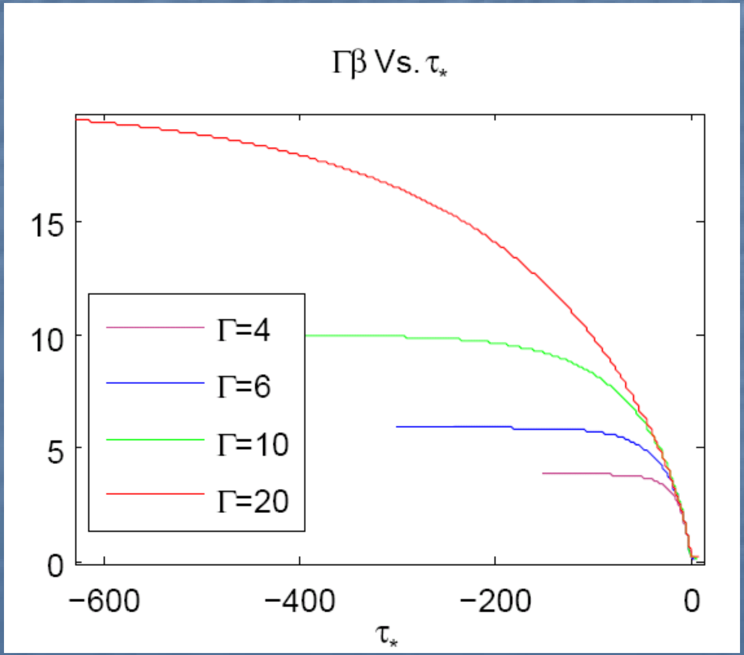
Astro-ph 0902.4708

Relativistic RMS

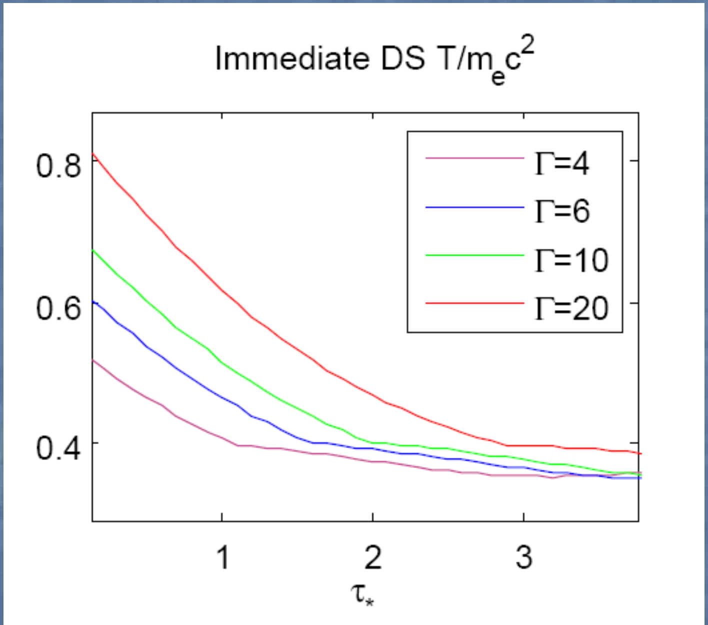
- We obtained a self consistent solution for the shock profile up to Γ=20:

$$\Gamma\beta(\tau)$$

$$\frac{T}{m_e c^2}(\tau)$$

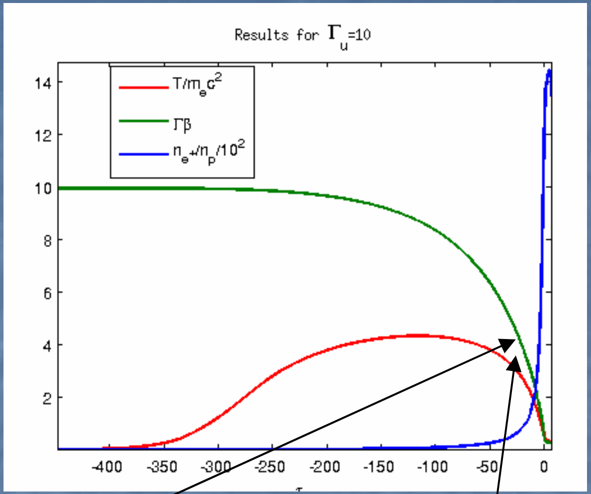


Velocity transition

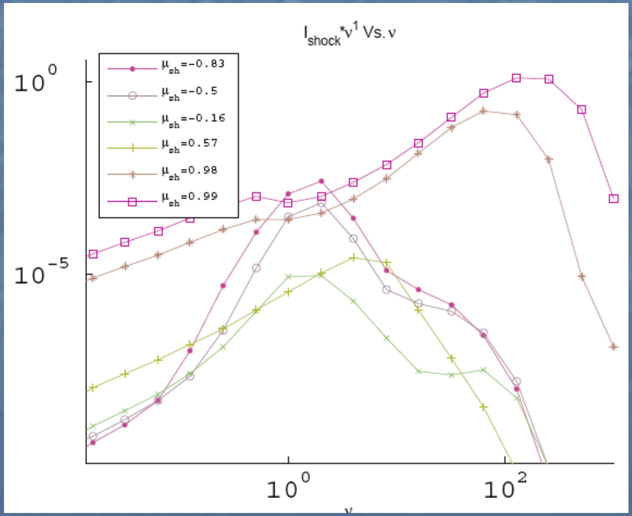


Immediate DS temp.

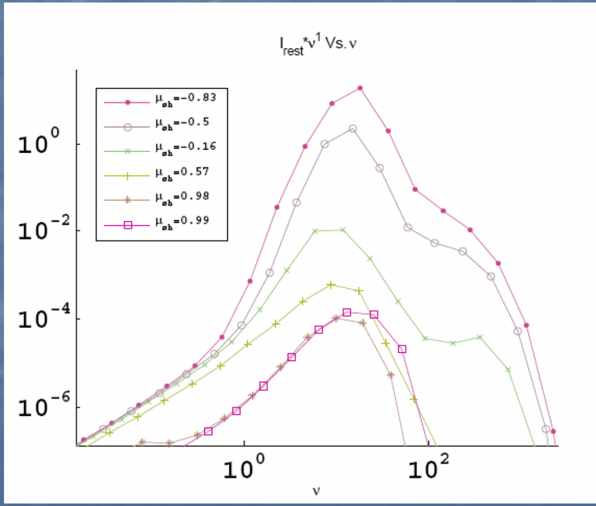
Γ=10 profiles and spectra



Shock profile



Spec. inside the transition: shock frame



Spec. inside the transition: rest frame

Understanding of immediate DS in relativistic RMS

Highly relativistic limit $\beta_d \rightarrow 1/3$:

Wein + pair eq. (at $T<\sim m_e c^2$):

$$\frac{n_{\gamma,s}}{n_{\pm,s}} \approx \frac{m_e c^2}{2T}$$

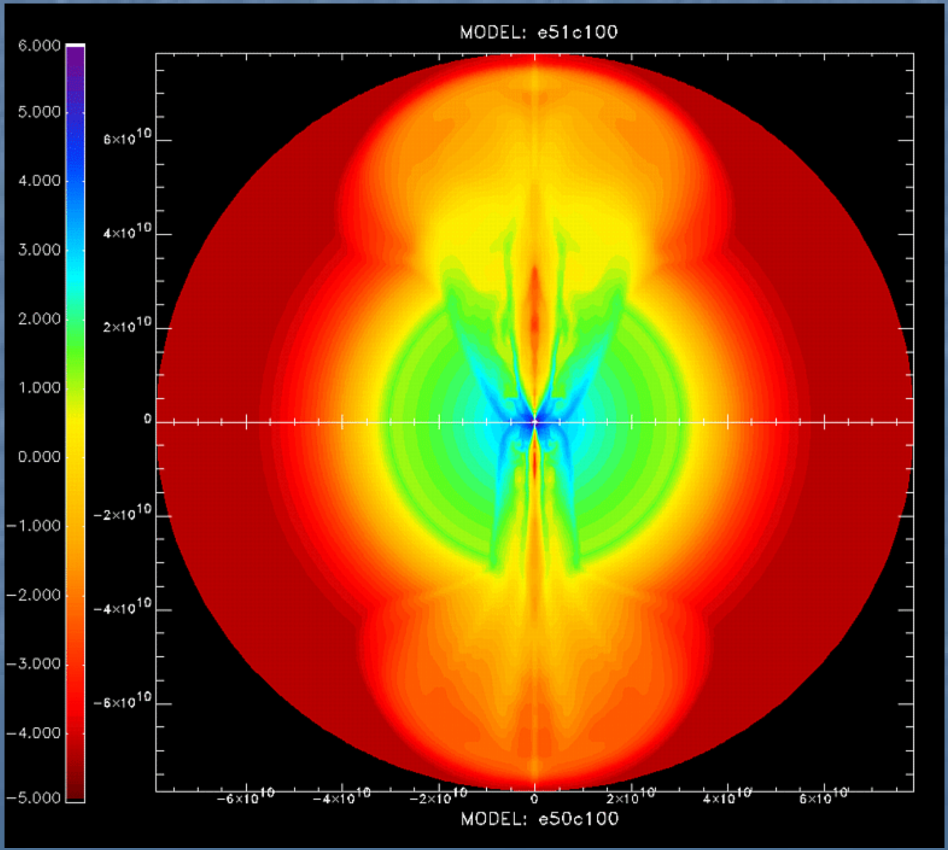
production/diffusion:

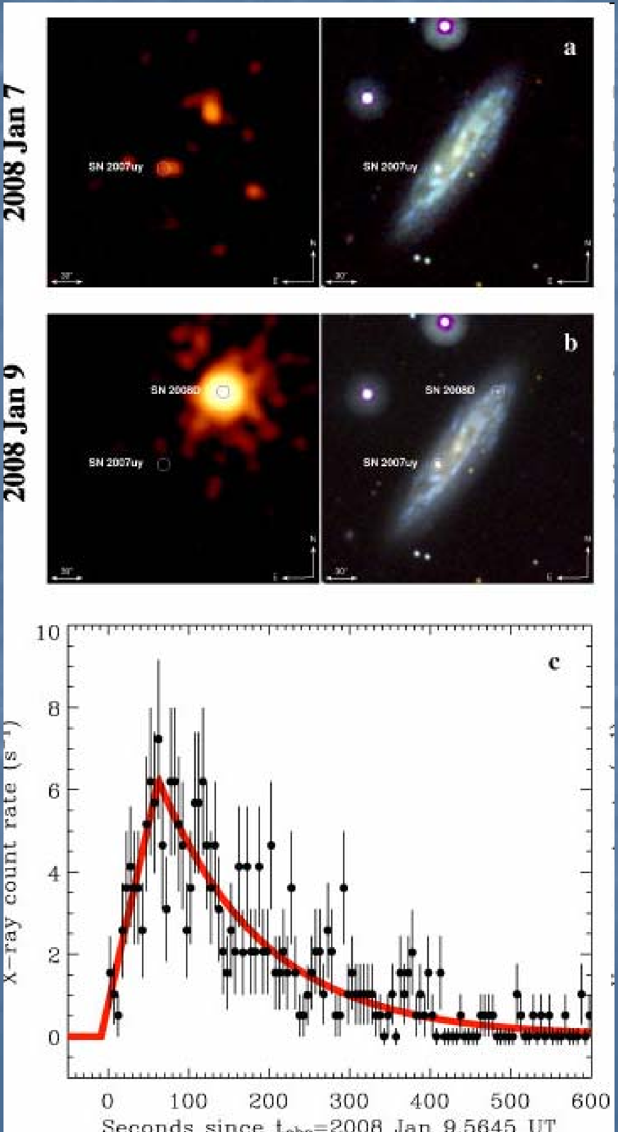
$$\frac{n_{\gamma,s}}{n_{\pm,s}} \approx 2.5\left(\frac{\Lambda}{15}\right)^2\left(\frac{\beta_d}{1/3}\right)^{-2}$$

→ T_s<200keV

Assumptions of pair-radiation equilibrium in agreement with numerical results.

Supernova shock breakout





SN Breakout X-rays: a simple model

- Envelope density $\rho \sim \delta^n$, $\delta = (1 - r/R)$
  (n=3, 3/2 for radiative (BSG, WR), convective (RSG))

[Colgate 74; Falk 78; Klein & Chevalier 78]

- Shock velocity (interpolating ST-Sakurai)

[Matzner & McKee 99]

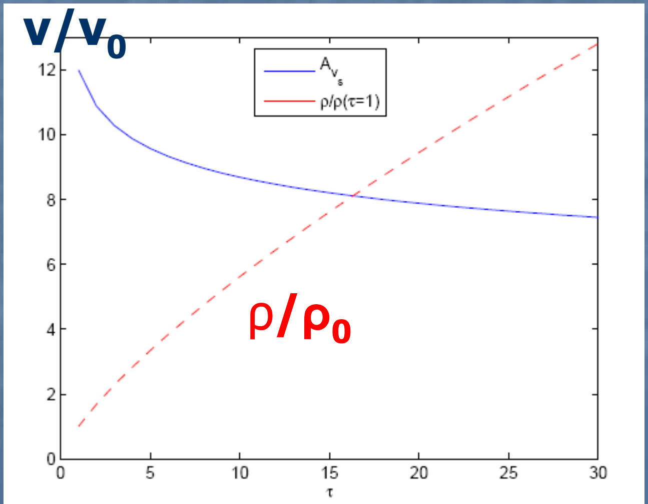
$$v_s \approx 0.8 \left(\frac{E}{M} \right)^{1/2} \delta^{-0.2n}.$$

- Post-shock thermal energy

$$U_{rad} = (18/7) \rho v_s^2$$

$$10 \left(\frac{E_{51}}{M_{Sol}} \right)^{1/2} \approx 0.24c \quad \Rightarrow T_s > 10\,\mathrm{KeV}$$

BSG, $M = M_\odot$, $R = 10^{12}$ cm



Optical depth

Breakout X-rays: a simple model

Velocity amplification factor for n = 3 (BSG):

$$\frac{v_s}{v_{ej}} \approx 11\left(\frac{M}{M_{Sol}}\right)^{0.14}\left(\frac{\kappa}{\kappa_T}\right)^{0.14}\left(\frac{R}{10^{12}\,cm}\right)^{-0.28}\left(\frac{\tau}{3}\right)^{-0.14}$$

Velocity amplification factor for n = 3/2 (RSG):

$$\frac{v_s}{v_{ej}} \approx 4\left(\frac{M}{M_{Sol}}\right)^{0.11}\left(\frac{\kappa}{\kappa_T}\right)^{0.11}\left(\frac{R}{10^{13}\,cm}\right)^{-0.23}\left(\frac{\tau}{3}\right)^{-0.11}$$

[Matzner & McKee 99]

Energy emitted in the x - ray outburst:

$$E \approx 4\times10^{46}\,\beta_s^2\left(\frac{R}{10^{12}\,cm}\right)^{2}\left(\frac{\kappa}{\kappa_T}\right)^{-1}\left(\frac{\tau}{3}\right)\text{erg}$$

Summary

- We obtained numerical solutions for relativistic and NR RMS.
- We found simple analytic expressions for the temperatures and structure of these shocks.
- High velocities $\beta>0.2$ => 200 KeV> T>10 KeV
  - Has important consequence for x-ray breakout interpretation and detection, e.g. 2008d, 2006aj.

Simple diffusion Vs. Weaver