On the Maximum Energy of Accelerated Particles in Young SNRs

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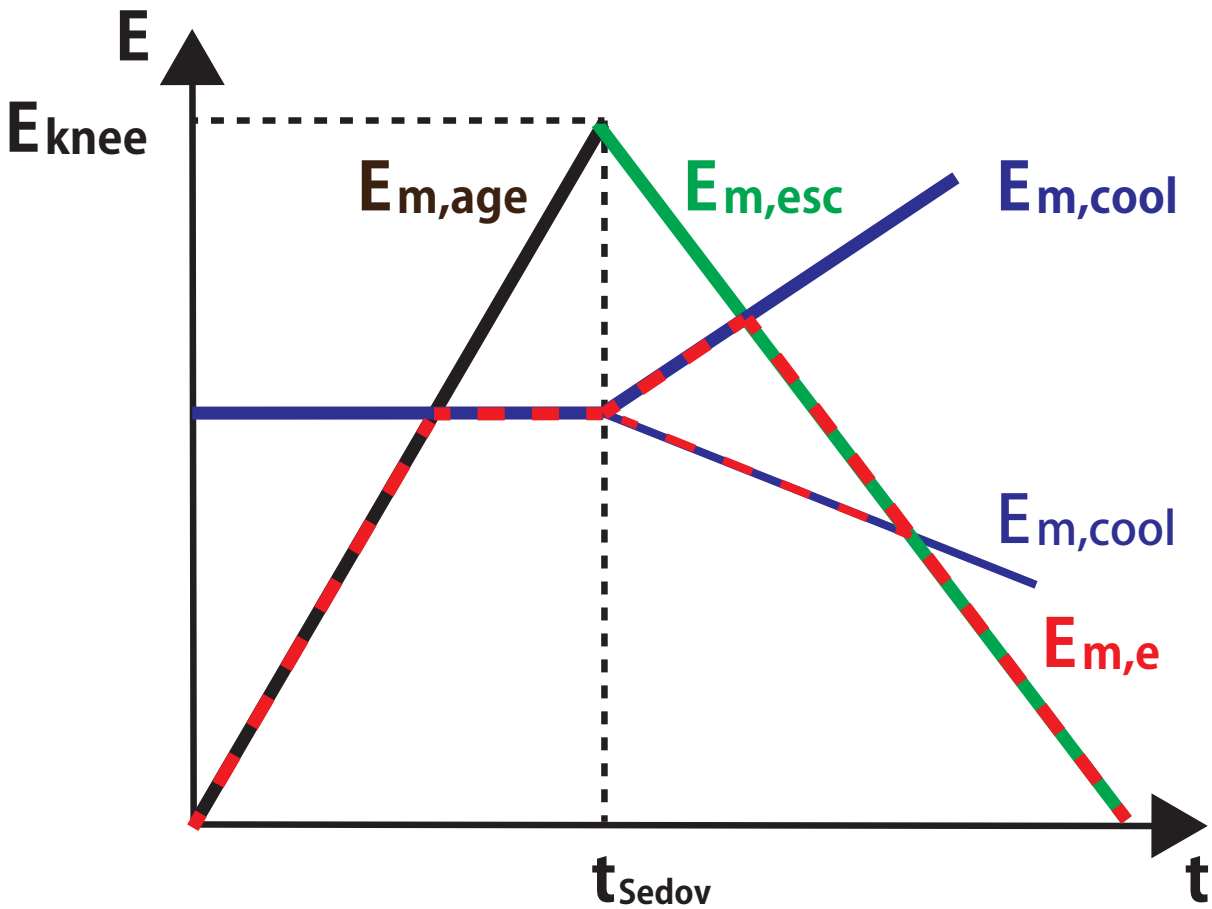
Previous Work in General



Helder, Vink, Bykov et al 2012, arxiv

Maximum Energy of Accelerated Particles

$$t_{acc} \propto \frac{D}{v_{sh}^2}$$

D=Diffusion Coefficient (Lagage & Cesarsky)

$$D \propto \frac{E}{B}$$

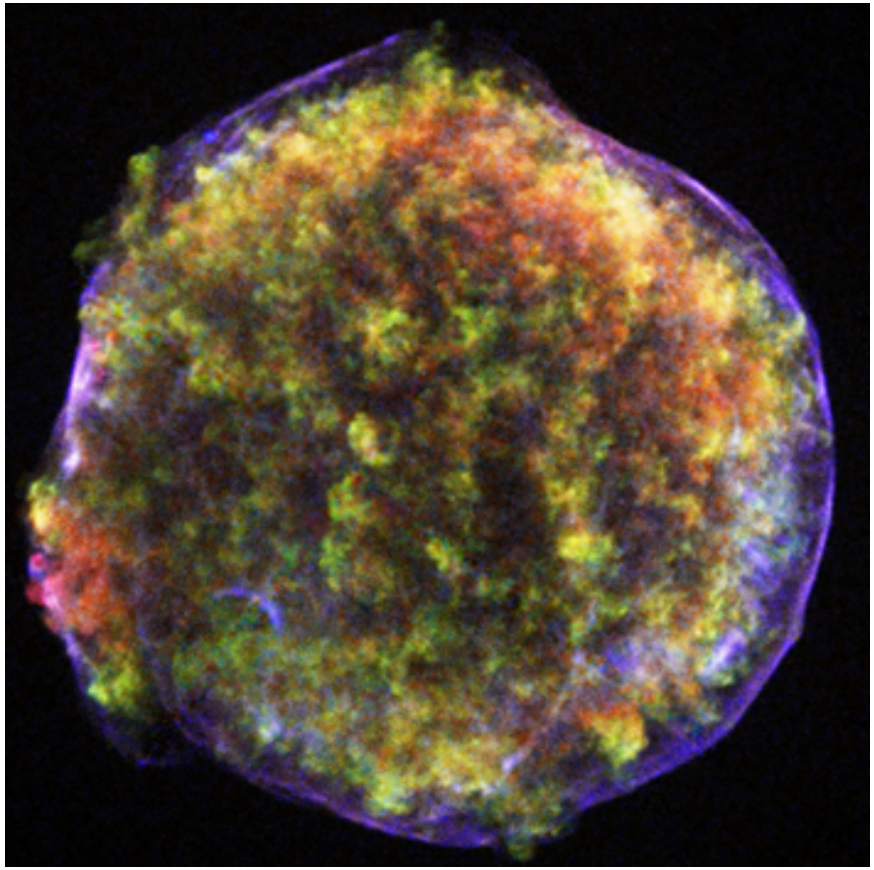
$$\Rightarrow t_{acc} \propto \frac{E}{Bv_{sh}^2}$$

$$Maximum \quad t_{acc} = t_{age}$$

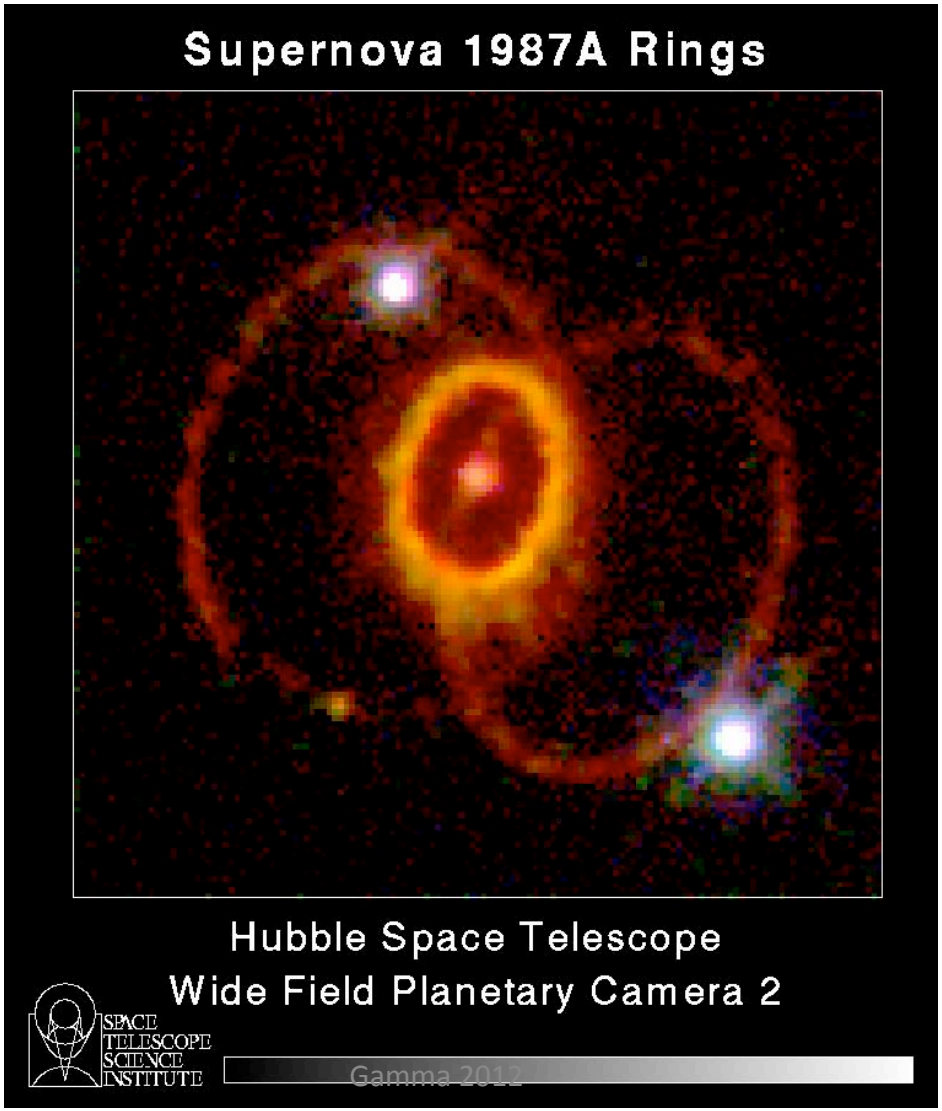
$$\Rightarrow E_{\max} \approx Bv_{sh}^2 t_{age} \approx BR\dot{R}$$

Type Ia SNe

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



Core-Collapse SNe Evolve in the Winds of Progenitor Stars



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.

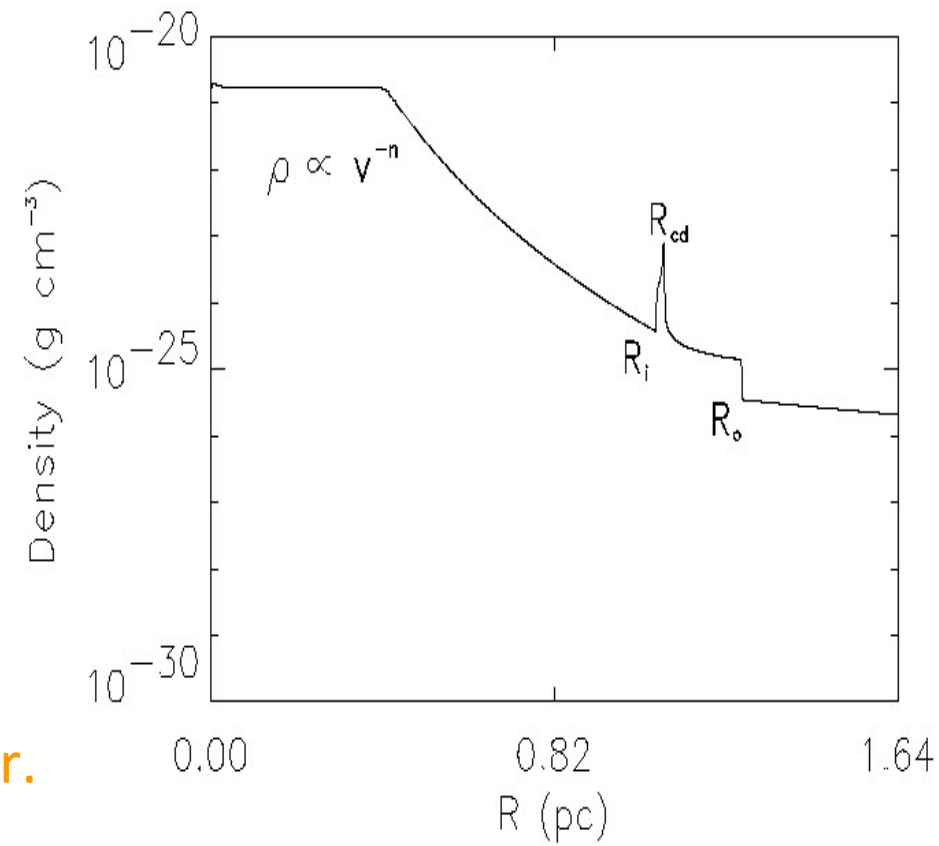
Core-Collapse SN:

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 - self-similar.

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

Max Energy in Constant Density Medium

$$R \propto t^m \qquad m = (n-3)/(n-s)$$

$$v_{sh} = t^{m-1}$$

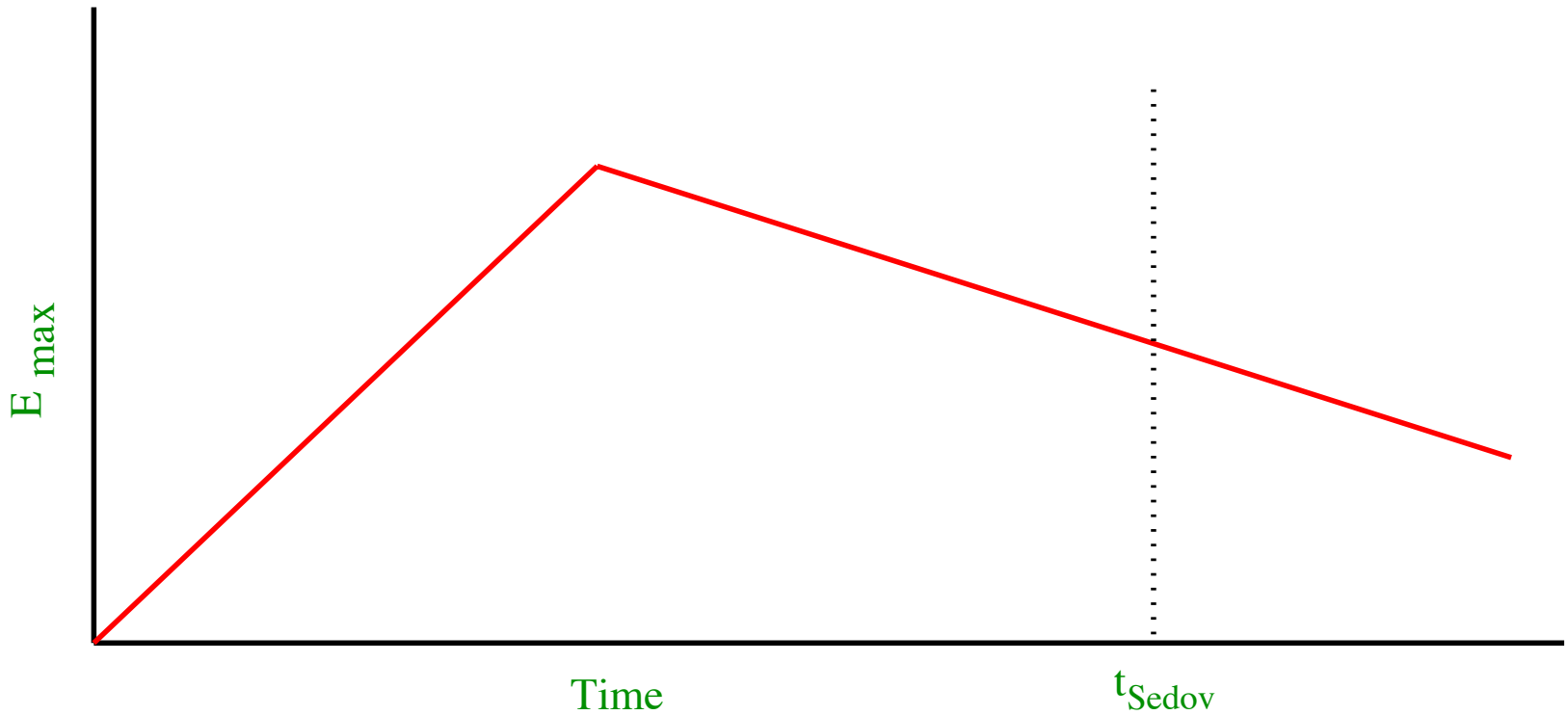
$$E_{\max} \approx Bt^{2m-2}\ t_{age} \approx Bt^{2m-1}$$

Note that expansion parameter 'm' essentially captures the entire evolution. In Chevalier model, it stays constant initially, then decreases. Sedov stage: m=0.4.
If *B* is constant:

$$E_{\max} \propto t^{2m-1}$$

As long as m > 0.5, which is always the case in the ejecta-dominated stage, energy will increase.
Eventually shock will slow down, m < 0.5, energy will decrease, still before it enters the Sedov phase (m=0.4).
Note that even though there is continuous deceleration, energy increases first, then decreases

Maximum energy in constant density medium



Maximum Energy in Constant Density Medium

From the Chevalier self-similar solution, for a medium with constant density B:

$$R_{SN} \propto \left(\frac{E^{(n-3)/2}}{M_{ej}^{(n-5)/2} B} \right)^{1/(n-s)} t^{(n-3)/(n-s)}$$

For a constant density, s=0. Then we get that:

$$R\dot{R} \propto \left(\frac{E^{(n-3)/2}}{M_{ej}^{(n-5)/2} B} \right)^{2/n} t^{(n-6)/n}$$

$$\propto \left(\frac{E^3}{M_{ej}^2 B} \right)^{2/9} t^{1/3} \qquad \propto \left(\frac{E^{2/3}}{M_{ej}^{4/9} B^{2/9}} \right) t^{1/3}$$

For n=9. Note that the density dependence is quite low, $B^{-0.22}$

Maximum Energy in Wind

The magnetic field in a rotating star takes the shape of an Archimedean spiral (Parker)
At large distances, the tangential component dominates, which goes inversely as the radius.

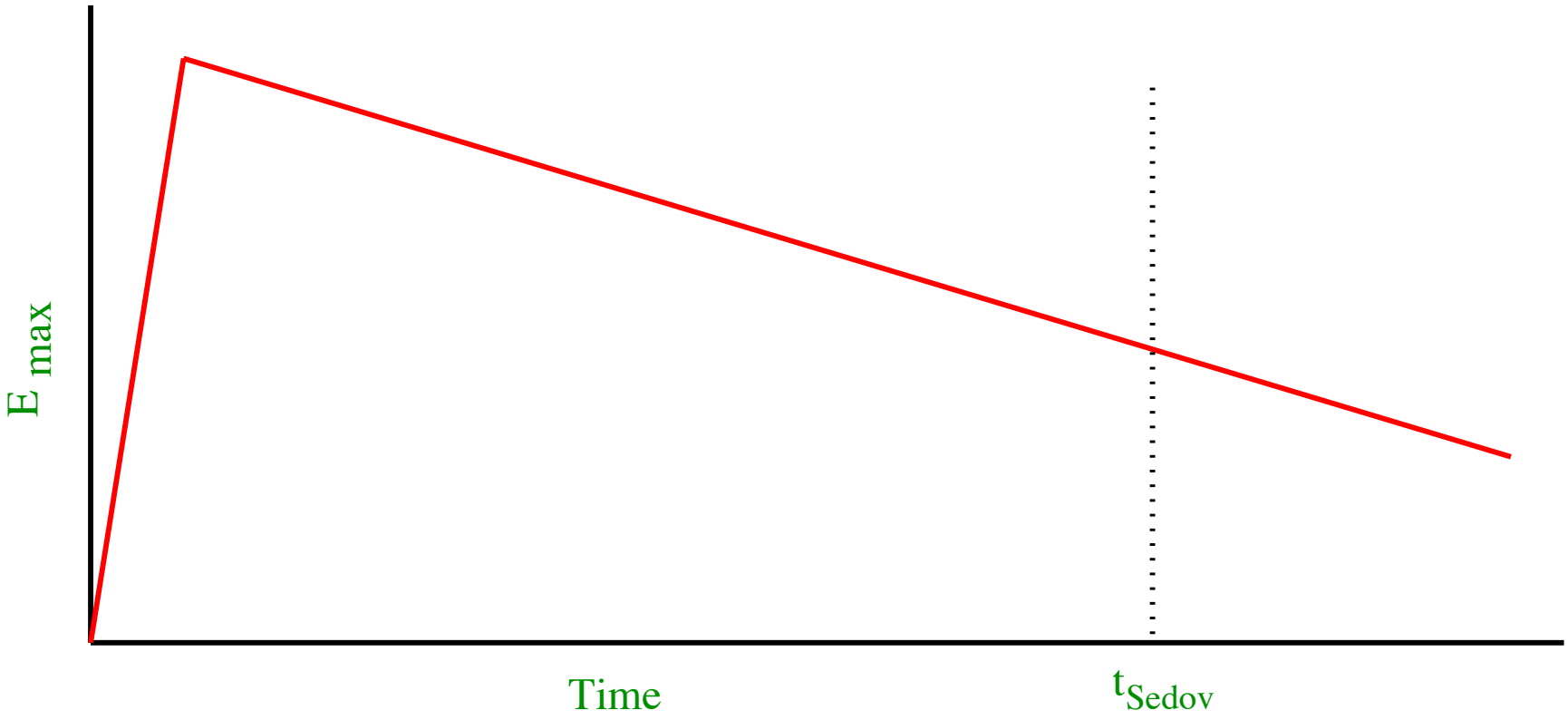
$$B \approx r^{-1}$$

$$E_{\max} \propto BRv_{sh} \propto v_{sh} \propto t^{m-1}$$

$$m < 1, \qquad m - 1 < 0$$

This can only happen after a certain radius, below which the energy will increase for a certain time.
Thus in a wind, the energy reaches a maximum quickly, and then continually decreases.

Maximum Energy in Wind



Maximum Energy in Wind

From the Chevalier self-similar solution:

$$R_{SN} \propto \left(\frac{E^{(n-3)/2}\, v_w}{M_{ej}^{(n-5)/2}\, \dot{M}} \right)^{1/(n-s)} t^{(n-3)/(n-s)}$$

For a steady wind, s=2. Then we get that:

$$R\dot{R} \propto \left(\frac{E^{(n-3)/2}\, v_w}{M_{ej}^{(n-5)/2}\, \dot{M}} \right)^{2/(n-2)} t^{(n-4)/(n-2)}$$

$$\propto \left(\frac{E^{3}\, v_w}{M_{ej}^{2}\, \dot{M}} \right)^{2/7} t^{5/7} \qquad \propto \left(\frac{E^{6/7}\, v_w^{2/7}}{M_{ej}^{4/7}\, \dot{M}^{2/7}} \right) t^{5/7}$$

For n=9. Note that the dependence of 2/7 on wind mass-loss parameters is weaker than the dependence on SN ejecta mass M_{ej} and explosion energy E. However: wind parameters may be time variable

Amplified Magnetic Field

- According to Bell and Lucek (2000, 2001), the magnetic field may be amplified by resonant or non-resonant modes.
- We have worked out what happens in those cases (see arxiv paper by Dwarkadas, Telezhinsky, and Pohl).
- The exponents are different, but results similar:
  - In Constant density medium, the energy will increase upto a certain value of m, then begin to decrease
  - In wind medium, the energy will always be decreasing after the initial increase.

Scalings for Maximum Energy

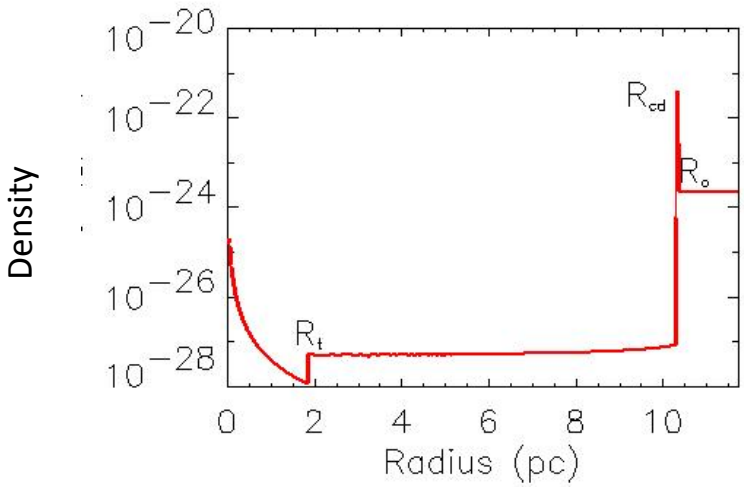
	Unamplified Magnetic Field	Amplified Field (Non-resonant Modes)	Amplified Field (Resonant Modes)
Constant Density Medium	t^{2m-1}	$t^{(7m-5)/2}$	$t^{(5m-3)/2}$
Wind Medium	t^{m-1}	$t^{5(m-1)/2}$	$t^{3(m-1)/2}$

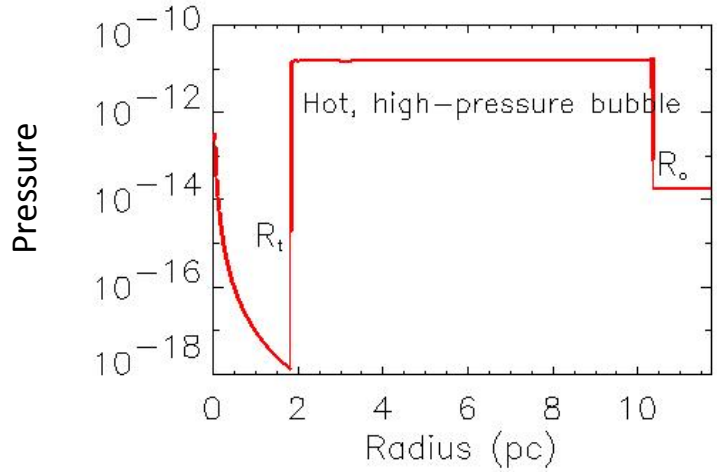
Wind Bubbles

- So what happens in more complicated but more familiar environments, such as wind bubbles or superbubbles?
- Remember, in a wind bubble
  - First, wind medium
  - Wind termination shock
  - Constant density (almost)
  - Contact discontinuity, etc.

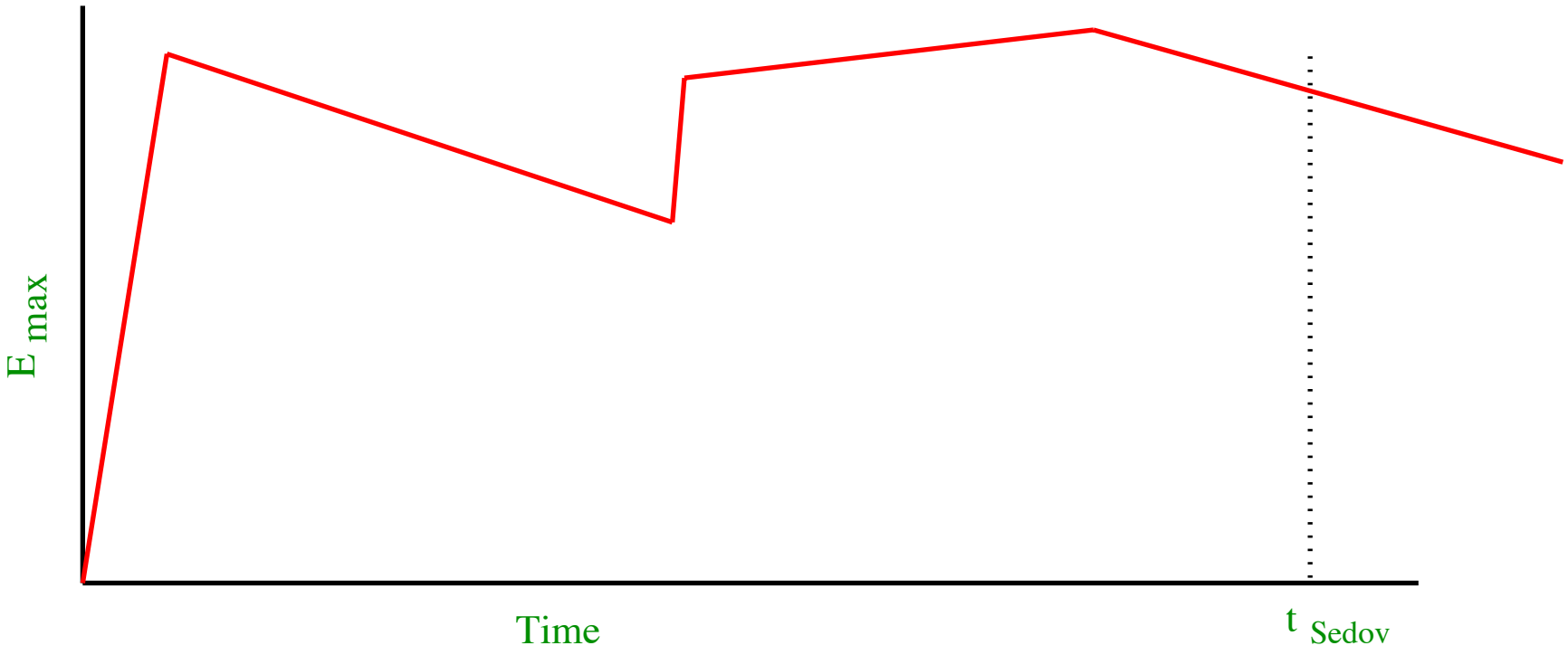
Structure of the Bubble

- 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.
- If the wind is a steady wind (constant mass-loss rate and velocity) then its density will drop as r^{-2}.

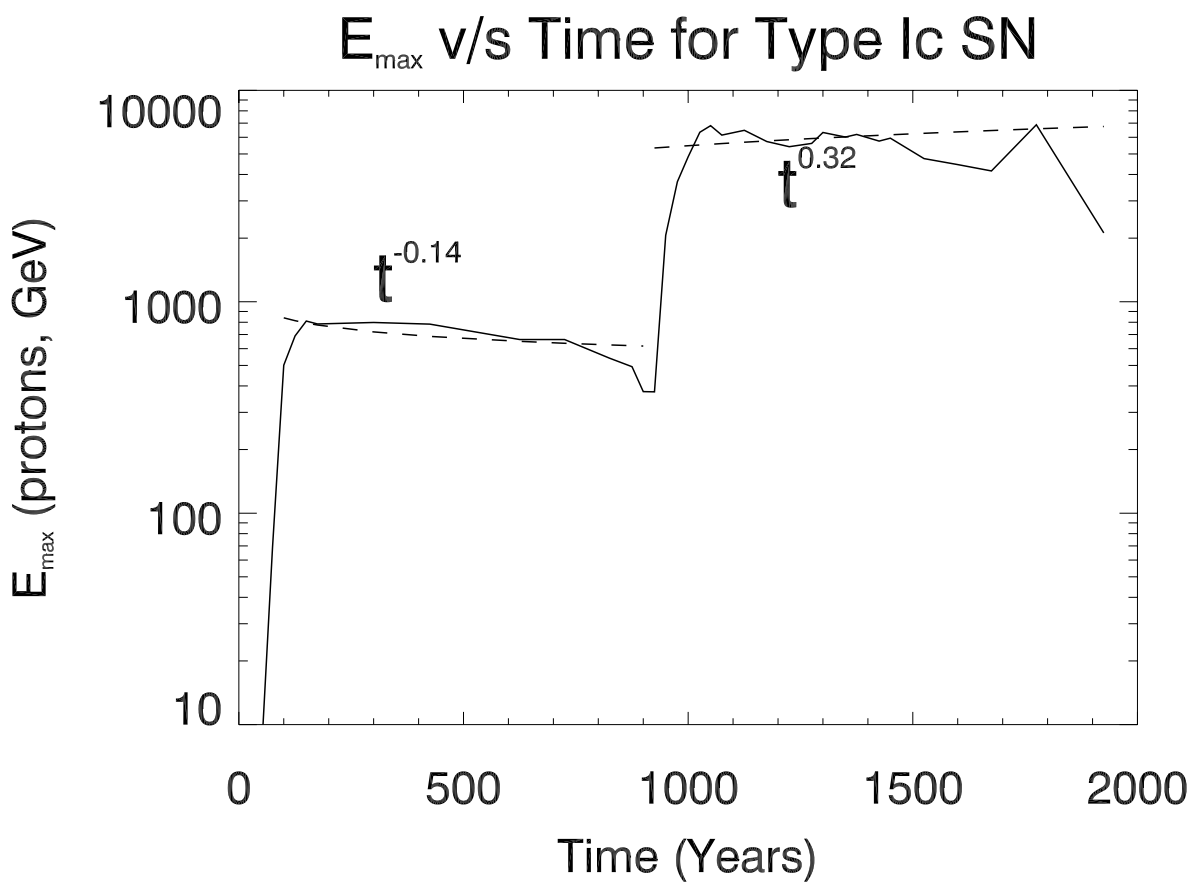




Max Energy in Wind Bubbles



Comparison to Numerical Simulations



For details of numerical simulations, see Telezhinsky et al. poster

Conclusions

- Most previous analyses have postulated that the maximum energy increases with time until the Sedov stage, then begins to decrease.
- Our calculations show otherwise – in a wind, the maximum energy is reached very quickly (tens to hundreds of years) and then continually decreases.
- In a constant density medium, the maximum energy increases for a while, but begins to decrease before the start of the Sedov phase.
- Our numerical calculations agree with this.

Questions and Discussions