Transport of magnetic turbulence in supernova remnants

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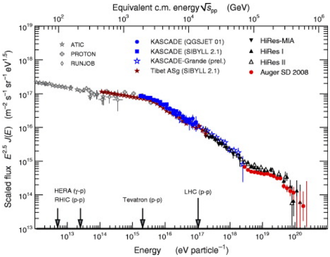
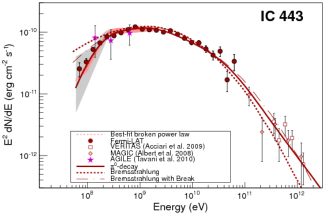
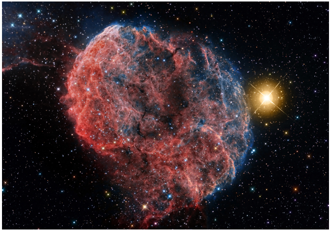
Outline

Introduction







top-left: Cosmic ray spectrum at earth

bottom-left: IC443 gamma-ray spectrum

right: IC443: multi-wavelength image

Cosmic ray acceleration

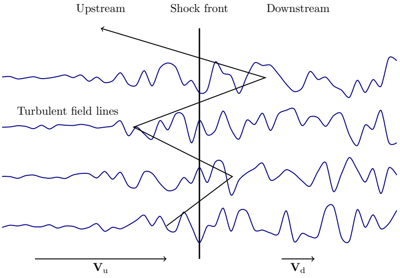


Figure: **First order Fermi acceleration** [Lee 2002]

There are three coupled sets of equations to solve:

- The MHD-equations for the SNR
- The cosmic ray transport equation
- The transport equation for the magnetic turbulence

Cosmic ray acceleration

Transport equation for cosmic rays:

$$\frac{\partial N}{\partial t} = \nabla(D_r \nabla N - \vec{v} N) - \frac{\partial}{\partial p}\left((N\dot{p}) - \frac{\nabla \vec{v}}{3} N p\right) + Q$$

Solving this equation:

- One-dimensional
- Spherically symmetric
- In a shock-centered coordinate system
- With a fine resolution near the shock and up to distance of several shock radii

Ansatz

Consider isotropic Alfvenic turbulence and account for

- Advection and compression
- Resonant amplification
- Damping due to cn-collisions and IC-damping
- Spectral energy transfer through cascading

Used Quantity: E_w is the energy density per unit logarithmic bandwidth.

The RMS-field associated with the Alfven-waves is given by:

$$\langle \delta b^2 \rangle = 4\pi \int \frac{E_w(k)}{k} dk$$

Transport equation

Transport equation:

$$\frac{\partial E_w}{\partial t} + \mathrm{u} \cdot (\nabla E_w) + C_w(\nabla \cdot \mathrm{u}) E_w + k \frac{\partial}{\partial k}\left(k^2 D_k \frac{\partial}{\partial k} \frac{E_w}{k^3}\right) = $$
$$= 2(\Gamma_g - \Gamma_d) E_w$$

Using Bells resonant growth-rate and Kolmogorov-cascading.
Initial diffusion coefficient:

$$E_w = \frac{4}{3\pi} \frac{v U_M}{k D_r}$$

$$D_{r,ism} = \left(10^{27} \frac{\mathrm{cm}^2}{\mathrm{s}}\right) \cdot \left(\frac{E}{10\ \mathrm{GeV}}\right)^{\frac{1}{3}} \left(\frac{B_0}{3\ \mu\mathrm{G}}\right)^{-\frac{1}{3}}$$

$\Longrightarrow$ Diffusion coefficient decreased by a factor of 100.

Properties

$\swarrow$ **Hydro Data** $\searrow$

$$\text{CRTE} \underset{\text{diffusion coefficient}}{\overset{\text{growth rate}}{\rightleftarrows}} \text{MTTE}$$

- **Time-dependend treatment of cosmic ray acceleration and turbulence transport**
- **Hydrodynamic data from separate calculations: Test particle approximation**
- **Simulations in 1-d and spherically symmetric**
- **Cooling for electrons through synchrotron radiation**
- **Frozen in magnetic field**
- **No free-escape-boundary**

Results I: Sedov Phase

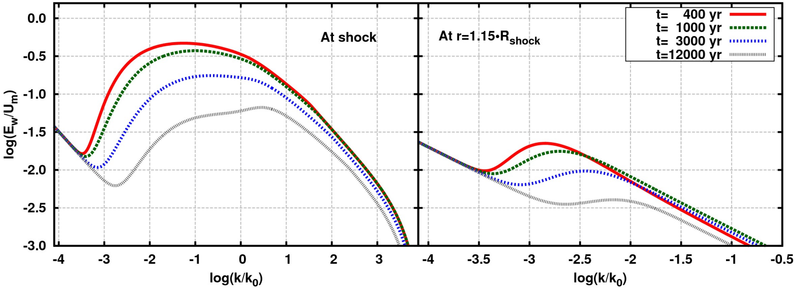


Figure: **Turbulence spectra**

Results I: Sedov Phase

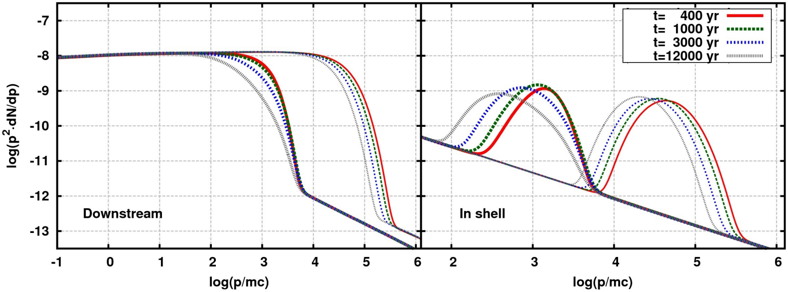


Figure: **Cosmic ray spectra**

Results II: Free expansion Phase

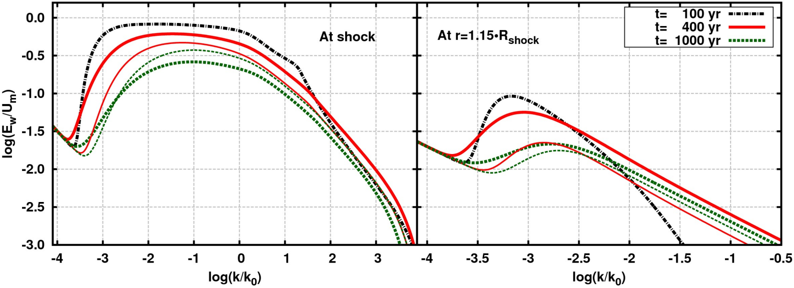


Figure: **Turbulence spectra**

Results II: Free expansion Phase

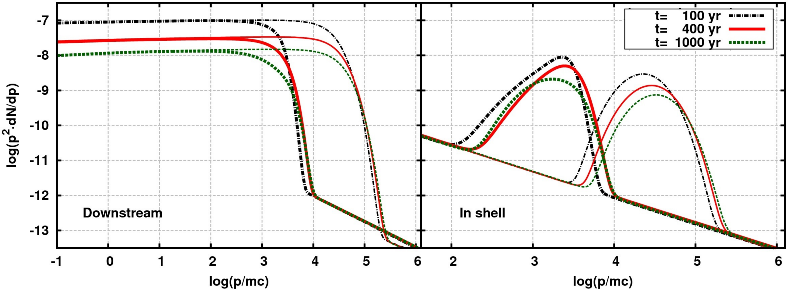


Figure: **Cosmic ray spectra**

Conclusion

- Diffusion coefficient not uniformly Bohm-like
- Even for older SNR: No steady-state reached
- Softer CR-spectra for old remnants due to cosmic-ray escape
- Decrease in maximum cosmic-ray energy faster than predicted in steady-state models

See also: arXiv:1606.04477

Thank You for your attention!

Sources

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Cosmic-Ray Streaming from Supernova Remnants and Gamma-Ray Emission from nearby Molecular

Used growth rate [Bell 1978] and cascading coefficient [Schlickeiser 2002]:

$$D_k = k v_a \sqrt{\frac{E_w}{2 U_M}}$$

$$\Gamma_{cr} = \frac{v_a q B_0}{3 k U_M} \frac{\partial N}{\partial x}$$

Numerical stability

High Resolution near shock constrains time steps.
Compromise between numerical stability and physical situation needed.

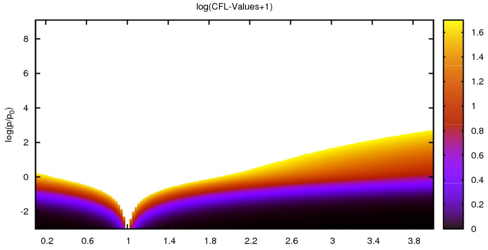

Figure: stability criteria

Numerical stability

Compromise: Decreased diffusion-coefficient and accordingly decreased time-steps.

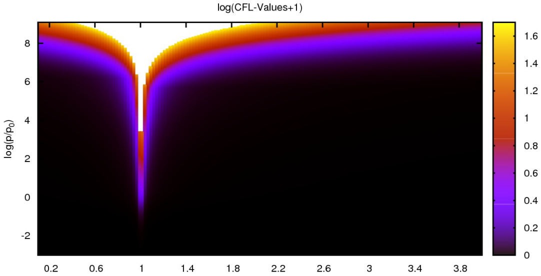

Figure: stability criteria