The impact of magnetic turbulence spectrum on particle acceleration in SNR IC443

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Particle acceleration in IC443
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Outline

> Particle acceleration
  - transport equation
  - diffusion coefficient and turbulence

> Magnetic turbulence spectrum
  - typical view
  - calculation
  - first results
  - approximation

> Model of supernova remnant IC443. First results.
  - (not so) known parameters
  - modeling
  - first results

> Preliminary conclusions
Particle acceleration: transport equation

> Assuming:

- CRs scatter elastically
- their distribution is isotropic ($v_{CR} >> v_{shock}$)

> CRs evolution can be described by **diffusion-advection** equation:

\[
\frac{\partial N}{\partial t} = \nabla \left( D \nabla N - \vec{u} N \right) - \frac{\partial}{\partial p} \left( N \dot{p} - \frac{\nabla \vec{u}}{3} N p \right) + Q
\]

- $N$ – energy differential number density of CRs
- $D$ – energy dependent diffusion coefficient
- $u$ – plasma flow velocity
- $p_t$ – energy losses
- $Q$ – source of thermal particles
Particle acceleration: diffusion coefficient and turbulence

> diffusion coefficient, \( D \), defines:

- injection of particles from thermal pool
- acceleration efficiency (small \( D \) \( \Rightarrow \) large CR’s residence time \( \Rightarrow \) high CR’s \( E_{\text{max}} \))
- number and spectral shape of escaping particles

> escaping particles

- produce magnetic turbulence that scatters next generation of injected particles
- re-fill Galactic CRs

> diffusion coefficient is related to magnetic turbulence

\[
D = \eta \frac{v_r g}{3}, \quad \eta = \frac{B_0^2}{\delta B^2} \quad \delta B^2 (k) = B_0^2 \frac{dW(k)}{dk} \quad k = B_0^2 \frac{dE_w(k)}{d \ln k} = B_0^2 E_w(k)
\]

\[
D = \frac{1}{E_w(k)} \frac{v_r g}{3}
\]

> assuming \( \eta = \text{const} \) same as \( E_w = \text{const} \) \( \Rightarrow \) strong (wrong) assumption
Magnetic turbulence spectrum: typical view

I. injection
II. cascading
III. damping
Magnetic turbulence spectrum: calculation

Magnetic turbulence spectrum is given by transport equation:

\[ \frac{\partial E_w}{\partial t} = k \frac{\partial}{\partial k} D_k \frac{\partial}{\partial k} \frac{E_w}{k} - \nabla (\vec{u} E_w) + (\Gamma_g - \Gamma_d) E_w \]

\[ D_k = k v_a \sqrt{\frac{E_w}{2U}} \]

\[ \Gamma_g = \frac{v_a q B_0}{3 k U} \frac{\partial N}{\partial x} \]

- \( E_w \) – differential (per \( \ln k \)) energy density of magnetic turbulence relative to background magnetic energy density \( U \)
- \( D_k \) – cascading coefficient (Schlickeiser 2002)
- \( u \) – plasma flow velocity
- \( v_a \) – Alfvén velocity
- \( \Gamma_g \) – resonant mode growth rate (Bell 1978)
- \( \Gamma_d \) – turbulence damping rate
- \( N \) – energy differential number density of CRs
Magnetic turbulence spectrum: first results
Magnetic turbulence spectrum: analytic approximation

![Graph showing the magnetic turbulence spectrum with logarithmic scales for both axes. The graph compares different time periods (10, 100, 1000, and 10000 years) and a Bohm reference. The y-axis represents \( \log E_w \) and the x-axis represents \( \log k \).]
IC443: multi-wavelength source, radio/optical

G. Castelletti et al. 2011
IC443: multi-wavelength source – x-rays

ROSAT (skyview)
IC443: multi-wavelength source – x-rays, HE $\gamma$-rays
IC443: multi-wavelength source – x-rays, HE, VHE $\gamma$-rays

ROSAT (skyview)

Fermi (skyview)

VERITAS (Acciari et al. 2009)
IC443: parameters

> type: mixed-morphology
  - radio shell, center-filled X-rays

> age (unclear): 3-30 kyr

> distance: 1.5 kpc

> size: 45' ➔ 20 pc
  - two hemispheres: $R_1 = 7.7$ pc, $R_2 = 12.1$ pc

> indications of interaction with dense material
  - $n = 10^{-10000}$ cm$^{-3}$

> radiative stage of evolution?
  - slow shocks
IC443: modeling HD and CRs

$t = 12500 \text{ yr}$

$E_{SN} = 1e51 \text{ ergs}$

$n_1 = 12 \text{ cm}^{-3} \Rightarrow R_1(t) = 7.7 \text{ pc}$

- $t_tr = 7780 \text{ yr}$, $V_{sh} = 0.5V_{sh}(t_tr) = 170 \text{ km/s}$

$n_2 = 1.9 \text{ cm}^{-3} \Rightarrow R_2(t) = 12.1 \text{ pc}$

$B_{0,1} = \sim2e-5 \text{ G}$

$B_{0,2} = \sim6e-6 \text{ G}$

$D$ is calculated from assumed (Kolmogorov) turbulence spectrum

$E_{CR} = 0.07 \ E_{SN}$
> Molecular cloud:
  - $d = \sim 19$ pc
  - size $\sim 4.5$ pc ($\sim 0.16^\circ$)
  - $M_{MC} \sim 1\times 10^4-10^5 \, M_{\odot}$

> $^{12}$CO image

> pion-decay
  - two SNR hemispheres
  - dense material illuminated by escaped CRs

Lee et al. 2012
IC443: first results – proton spectra
IC443: first results – radiation spectra
Preliminary conclusions

> Magnetic turbulence spectrum is not “white noise”

> When taken into account, it modifies CR spectrum
  - downstream of the shock
  - upstream, at the position of target material

> Thorough analysis of dense matter distribution and mass around IC443 is required

> Energy dependent morphology and more precise spectral measurements by VERITAS should help constrain model
  - do we see diffuse emission from denser hemisphere?
  - is power-law index of hot spot different from “CR sea”?