Stochastic acceleration and magnetic damping in Tycho's SNR

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Tycho's supernova remnant

Young historical type Ia SNR

NRAO/VLA Archive Survey

O.Krause et.al.

VERITAS Collaboration Acciari et al.

Soft radio spectrum $\sim 0.65$ (Kothes et al. 2006)

Inconsistent with the standard prediction of Diffusive Shock Acceleration
Possible explanation: Alfvénic drift

Shock restframe

For radio data compression factor $r=3.5$ is required!

$$r = \frac{v'_u}{v'_d} = \frac{v_u - v_{A,u}}{v_d + h \cdot v_{A,d}}$$

For Tycho: $M_A = 10$ with $h=0$

Morlino & Caprioli 2012; Slane et. al 2014

Contradictions:

Alfvén wave transmission: helicity $h$ negative!

$r > 4 \implies$ harder spectrum!

Vanio and Schlickeiser 1999

Growth of Bell’s instability to debatable

Niemiec et al. 2008

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Alternative approach

Magnetic turbulence in the post-shock region
Additional mechanism to Diffusive Shock Acceleration:

**Stochastic Acceleration**

Fast-mode waves are efficient

Acceleration time: \( \tau_{acc} \sim \) of few years

Damping mechanism: particle acceleration

Thickness of the turbulent region is small

More details: Pohl et. al. 2015
Momentum diffusion coefficient

Calculated at lower energies:

\[ \tau_{acc} = const := \tau \quad \text{for} \quad p \leq p_0 \sim 1 \text{ GeV} \]

Parametrization at higher energies:

\[ \tau_{acc} = \tau \left( \frac{p}{p_0} \right)^m \]

\[ D_p = \frac{p^2}{\tau} \quad \text{for} \quad p \leq p_0 \]

\[ D_p = \frac{p^2}{\tau} \left( \frac{p}{p_0} \right)^{-m} \quad \text{for} \quad p > p_0 \]
Modeling SNR

Particle acceleration via \textbf{kinetic approach}:

\[
\frac{\partial N}{\partial t} = \nabla \left( D_s \nabla N - \mathbf{v} N \right) - \frac{\partial}{\partial p} \left( N \dot{p} - \nabla \frac{\mathbf{v}}{3} N p \right) + \frac{\partial}{\partial p} \left( p^2 D_p \frac{\partial}{\partial p} \frac{N}{p^2} \right) + Q
\]

\text{Diffusion} \quad \text{Advection} \quad \text{Losses} \quad \text{DSA} \quad \text{SA} \quad \text{Injection}

\begin{itemize}
  \item Plasma velocity profiles \( \mathbf{v} \) from hydrodynamical simulations
  \item Computation of advected magnetic field (alternative: analytical profiles)
  \item Solving Transport equation for particle number density \( N \) (electrons & protons)
  \item Synchrotron emission from electrons in magnetic field \( \mathbf{B} \)
  \item \( \gamma \)-rays from protons via neutral pion decay
  \item \( \gamma \)-rays from electrons via inverse Compton scattering
\end{itemize}

\text{Emission spectrum}
Results

Electron-to-proton ratio:

$$K_{e/p} := \frac{N_e}{N_p} \approx \frac{1}{100}$$

Minimum magnetic field:

$$B_d \sim 80 \, \mu \text{G}$$

Reacceleration region:

$$\sim 10^{-3} \, R_{sh}$$
Filaments

How can we explain the narrow rim structure in x-ray and radio?

Tran et al. 2015

Blue: X-ray
Red: Radio

B_d ~ 80 μG fails to produce filaments
Two scenarios

**Synchrotron losses limited case**

- Lack of electrons!
- \( B_d = 330 \, \mu G \) required (Molino & Caprioli 2012)
- Strong energy-dependence \( \rightarrow \) radio filaments unexplained

**Magnetically limited case**

- Lack of magnetic field!
  
  \[
  B(r) = (B_d - B_0) \exp\left(\frac{-(r - R_{sh})}{l_d}\right)
  \]

  where \( l_d \) is the damping length

- Energy-dependence at the cut-off
- \( B_d = 173 \, \mu G \quad B_0 = 20 \, \mu G \quad l_d = 0.015 \, R_{sh} \)
Summary

- Stochastic acceleration can explain soft radio spectrum
- No Alfvénic drift needed
- Soft hadronic γ-spectrum in GeV band
- Filaments:
  - X-ray filaments require 330 µG in loss-limited case
  - 173 µG needed in damping scenario
  - Radio profiles prefer magnetic field damping

Thank you for your attention!
Backup slides: Filament width

![Graph](image)

**Graph 1:**
- X-axis: \( r/R_{sh} \)
- Y-axis: \( F/F_{max} \)

- Curves for 0.2 keV, 1 keV, 5 keV, and 10 keV.

**Graph 2:**
- Y-axis: \( x_{1/2} \)
- X-axis: \( E_{sy} [\text{keV}] \)

- Curves for Model B_{low}, Model B, and Model C.
Results: Impact from Stochastic acceleration

Particle number density $N$

- Deviates from DSA prediction: $N \sim p^{-2}$
- SA peak determined by $m$, $p_0$ and $\tau$
- To stay in agreement with radio data:
  
  $m \in [0.15, 0.25] \quad \tau \in [2.4, 3.0]$
Results: three different cases

**Model A:**
Transported MF
$B_d = 83 \, \mu G$
$K_{e/p} = 1/100$

**Model B:**
Damped MF
$B_d = 173 \, \mu G$
$I_d = 0.015 \cdot R_{sh}$
$K_{e/p} = 1/100$

**Model C:**
Damped MF
$B_d = 330 \, \mu G$
$I_d = 0.02 \cdot R_{sh}$
$K_{e/p} = 1/600$