Stochastic Acceleration by Turbulence in the Fermi Bubbles

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Fermi bubbles

- Fermi-LAT data
- gas-correlated emission
- Inverse Compton model
- some other stuff

- hard spectrum
- sharp edges
- no spectral variation

Hints

**Hα**


**X-rays**


**microwaves**

Ade et al., A&A 554 (2013) A139
Hard spectrum

hadronic model

😊 low energy hardening

😢 cutoff around few hundred GeV

leptonic model

😊 cutoff due to energy losses

😊 can also get hardening at low energies

😢 how to maintain TeV energies over Myrs?

⇒ in-situ acceleration

Sharp edges

Sharp edges

Edge $b, \ell = (17.4^\circ, 345.1^\circ)$
$\Delta \varphi = 2.4^\circ \pm 2.0^\circ$
$E = 10.0 - 500.0$ GeV
Sharp edges

No spectral variation

No spectral variation

Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118;
Narayanan & Slatyer, arXiv:1603.006582

Would naively expect variation
## Models

<table>
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<th>Details</th>
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<tr>
<td>Mertsch &amp; Sarkar, PRL <strong>107</strong> (2011) 091101</td>
<td>stochastic acceleration of e⁻; morphology</td>
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<tr>
<td>Yang et al., <strong>761</strong> (2012) 185 and MNRAS <strong>436</strong>, 2734 (2013)</td>
<td>jet; B-fields</td>
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<td>Fujita et al., ApJL <strong>775</strong> (2013)</td>
<td>scaled up supernova remnant</td>
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<td>Sarkar et al., MNRAS <strong>453</strong> (2015) 3827</td>
<td>starbust activity</td>
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<tr>
<td>Taylor &amp; Giacinti, arXiv:1607.08862</td>
<td>outflow</td>
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Morphology and spectrum

Homogeneous volume emissivity gives bump-like profile

thermal bubbles:
• What is the source of energy?
  • (M)HD simulations
  • Age, size & shape

non-thermal bubbles:
• What is accelerating CRs?
  • Kinetic simulations
    = solve transport equation
  • Morphology and spectrum in gamma-rays
Shock(s) and morphology

evidence for shock at bubble edges
(from ROSAT)

turbulence produced at shock and convected downstream

2nd order Fermi acceleration by large-scale, fast-mode turbulence

Mertsch & Sarkar, PRL 107 (2011) 091101
Shock(s) and morphology

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large-scale, fast-mode turbulence

Mertsch & Sarkar, PRL 107 (2011) 091101
A first model

Mertsch & Sarkar, PRL 107 (2011) 091101

- Bubbles filled with turbulence
- Acceleration by large-scale fast modes
- Inverse Compton scattering:
  \[ e^- + \gamma_{\text{soft}} \rightarrow \gamma + e^- \]
- Can use steady-state or time-dependent solutions

Stawarz & Petrosian (2008);
Mertsch, JCAP 12 (2011) 10
Open questions

- Steady-state
- Spatial transport
- Inhomogeneous radiation fields
Spatial transport

simplified transport equation:

\[
\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial p} \left( -\dot{p} \, \psi + p^2 D_{pp} \frac{\partial}{\partial p} \frac{\partial \psi}{\partial p} \right) - \frac{\psi}{\tau}
\]

full Fokker-Planck equation:

\[
\frac{\partial \psi}{\partial t} = \nabla \cdot \left( K \cdot \nabla \psi - \vec{V}_p \psi \right) + \frac{\partial}{\partial p} \left( \frac{p}{3} \left( \nabla \cdot \vec{V} \right) \psi \right) + \frac{\partial}{\partial p} \left( -\dot{p} \psi + p^2 D_{pp} \frac{\partial}{\partial p} \frac{\partial \psi}{\partial p} \right) - \frac{\psi}{\tau} + Q
\]

- **diffusion & advection**
- **discontinuous velocity \( \rightarrow \) shock acceleration**
Shock geometry

examples from (M)HD simulations of jets:

density of thermal gas

magnetic field


Coordinates

source

shock
Coordinates
Coordinates
Coordinates
Coordinates

toroidal coordinates

pseudo-radial

pseudo-polar $\parallel \vec{B}$
Score card

finite difference code:
- semi-implicit Crank-Nicolson scheme
- 3D: 1 momentum & 2 spatial variables
- cartesian, spherical or toroidal coordinates
- shock in (pseudo-)radial direction

radiation module:
- energy losses: ionisation, Coulomb, Bremsstrahlung, inverse Compton, synchrotron
- inverse Compton on CMB, IR & UV/opt.
  Porter & Strong, ICRC 2005
- synchrotron emission on B-field

other possible applications:
- solar flares/coronal mass ejection
- solar modulation of Galactic cosmic rays
- supernova remnants
- Galactic propagation of cosmic rays
advection:
• pseudo-radial

diffusion:
• isotropic everywhere
• anisotropic everywhere

stochastic acceleration:
• homogeneous
• homogeneous
• enhanced in shell

\[ D_{\perp} = D_{\parallel} \]

\[ D_{\perp} \neq D_{\parallel} \]
Setup 1: isotropic diffusion

electrons

gamma-rays
Setups

advection:
- pseudo-radial

diffusion:
- isotropic everywhere
- anisotropic everywhere

stochastic acceleration:
- homogeneous
- homogeneous
- pseudo-radial
- isotropic in shell
- anisotropic in halo and bubble
- enhanced in shell
Setup 2: *anisotropic diffusion*

Electrons

Gamma-rays
Setup 2: *anisotropic diffusion*

gamma-rays
Setups

**Advection:**
- pseudo-radial

**Diffusion:**
- isotropic everywhere

**Stochastic Acceleration:**
- homogeneous

- pseudo-radial

- anisotropic everywhere

- enhanced in shell
Setup 3: turbulent shell

electrons

gamma-rays
Setup 3: turbulent shell

gamma-rays
Setup 3: turbulent shell

microwaves
Summary

Mertsch & Sarkar, PRL 107 (2011) 091101

- Shock at bubble edge, e.g. from jets
- Large-scale, fast mode or small-scale Alfvénic turbulence
- Energy-dependent distribution such that profile is flat