galactic cosmic rays and the turbulent heliospheric tail

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Midwest Magnetic Fields Workshop, Madison, WI
April 4\textsuperscript{th}, 2012
cosmic rays spectrum

- spectral structure & mass composition hold information on
  - **origin** of cosmic rays
  - **propagation** from sources to Earth
  - **anisotropy** in arrival distribution
    - energy dependence
    - angular scale
cosmic ray acceleration in supernova remnants

- diffusive shock acceleration in galactic SNR (Baade & Zwicky, 1934 & Fermi, 1949)

\[ n_{CR}(E) \approx \frac{E^{-\gamma} R_{SN}}{2\pi R_d^2} \cdot \frac{H}{D(E)} \]

density of cosmic rays

\[ D(E) \propto E^\delta \]
diffusion coefficient

\[ \phi_{CR} = \frac{c n_{CR}(E)}{4\pi} \]
cosmic ray flux

\[ \phi_{CR} \approx 2.4 \cdot \left( \frac{E_{SN}}{10^{51} \text{erg}} \right) \cdot \epsilon_{CR} \]
energy emitted by one SN

\[ \cdot \left( \frac{15 \text{kpc}}{R_d} \right)^2 \]
cosmic ray acceleration efficiency

\[ \cdot \left( \frac{R_{SN}}{30 \text{yr}} \right) \]
radius of galactic disk

\[ \cdot (\gamma - 2) \cdot 3^{-\delta} \]
rate of supernovae in the Galaxy

\[ \cdot (\frac{E}{1 \text{TeV}})^{-\gamma - \delta} [\text{TeV}^{-1} m^{-2} s^{-1} \text{sr}^{-1}] \]
propagation term

\[ X\text{-ray (Chandra)} \]

\[ \text{optical radio} \]

SN1006

W. Baade & F. Zwicky, Physical Review 46, 76, 1934

Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type of giant novae. As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that on the average one super-novae appears in every galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

- Our own galaxy in 1572
- Andromeda in 1885
- Messier 101 in 1907

These three systems are located within a sphere of radius

\[ 2 \times 10^5 \text{ light years} \]

We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

From the estimate of one super-novae per galaxy per thousand years it follows that 10^4 super-novae appear per year in the 10^5 nebulae which are contained in a sphere of 2 \times 10^5 light years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-novae will be essentially independent of time.

The lifetime of stars is supposed to be of the order of at least 10^9 years. A nebula contains about 10^5 stars. These estimates, combined with the frequency of occurrence of super-novae...
cosmic rays observations
all-particle spectrum

Pamela
Adriani et al. (2011)

He \approx E^{-2.48}
He (\times 0.1) \approx E^{-2.71}

\begin{align*}
p &\approx E^{-2.80} \\
p &\approx E^{-2.67} \\
He &\approx E^{-2.58} \\
p &\approx E^{-2.66}
\end{align*}

CREAM
Ahn et al. (2010)
cosmic rays observations
all-particle spectrum

Pamela
Adriani et al. (2011)

He (×0.1) \approx E^{-2.71}

p \approx E^{-2.67}

p \approx E^{-2.80}

He \approx E^{-2.48}

≈ E^{-3.0}

≈ E^{-3.1}

KASCADE-Grande
Artega-Velázquez et al. (2010)

Gaisser & Stanev
PDG

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cosmic rays observations
anisotropy

Nagashima et al. (1998)
Hall et al. (1999)

Tibet ASY
Amenomori et al. (2006)

Super Kamiokande
Guillian et al. (2007)

ARGO-YBJ
Zhang et al. (2009)

Milagro
Abdo et al. (2009)

IceCube
Abbasi et al. (2010)
cosmic rays observations
anisotropy

equatorial coordinates    relative intensity

Tibet-ASγ   5 TeV

IceCube-59   20 TeV

Amenomori et al. (2011)

Abbasi et al. (2012)
anisotropy vs. energy

- CR anisotropy changes phase ~100 TeV
- global amplitude is modulated

\[ \delta_{\text{fluctuations}} = \frac{3}{2^{3/2}} \frac{1}{\pi^{1/2}} \frac{D(E)}{Hc} \]

\[ D(E) \propto E^\delta \]
anisotropy vs. angular scale

- Large vs. small scale anisotropy
- Averaged modulation over a given angular range
- Low angular gradient
- High angular gradient
- Acceptance-corrected

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cosmic rays observations
anisotropy

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equatorial coordinates  statistical significance

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)

2 hr = 30°
360°
0°
4 hr = 60°

Milagro
Abdo et al. (2008)
1 TeV

IceCube
Abbasi et al. (2011)
20 TeV

significance [σ]
origin of small scale anisotropy?

**astrophysics**

- CR from Geminga: ~90-200 pc, 340,000 yr ago
- magnetic connection & propagation in turbulent LIMF

**anisotropic MHD turbulence in the ISM**

- particles streaming along magnetic field lines over ~100 pc (from a source) interact with $O(1\text{pc})$ ISM turbulence
- pitch angle scattering peaked near the direction of LIMF

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Salvati & Sacco, arXiv:0802.2181
origin of small scale anisotropy? 
**effect of turbulence**

- diffusion regime breaks down **within mean free path**

- interaction with **turbulent** interstellar magnetic field

- assuming an underlying dipole anisotropy, fractional localized regions form the effect of magnetic field turbulence

- the residual maps provide an image of magnetic field turbulence < 10's pc

- cosmic ray energy spectra might also be affected by this propagation effects

Giacinti & Sigl, arXiv:1111.2536
diffusive propagation models ...

• ... assume uniform diffusion coefficient across the Galaxy

• ... do not account for energy-dependent interaction with ISM turbulence

• ... do not account for magnetic field geometry

• ... cannot explain non-dipolar anisotropy structures

• ... break down within mean free path
from the Galaxy to our local interstellar medium

Milky Way

< 30,000 pc >

Local Bubble

< 500 pc >

Local Interstellar Cloud

< 10-50 pc >

Heliosphere

< 0.001 - 0.05 pc >
the heliosphere and the LIMF

\[ R_g \sim \frac{10^{-3}}{Z} \left( \frac{E}{1 \text{TeV}} \right) \left( \frac{\mu G}{B} \right) \text{pc} \]

\[ V_{\text{interstellar flow}} \sim 26 \text{ km/s} \approx V_{\text{Alfén}} \]

**Pogorelov & Zank (2004)**

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the heliosphere magnetic structure

3D simulations of heliosphere
Opher et al., arXiv:1103.2236

3D simulation of heliosphere/heliotail

~0.1-1 AU  ~200 AU

~150 AU  ~1,000’s AU
the heliosphere turbulence

- the wake downstream the interstellar flow develops turbulence from plasma velocity difference across the heliopause (similar to Kelvin-Helmholtz instability)

- charge-exchange processes decelerate the solar wind near the heliopause, producing an effective drag force that pushes the higher ISM density into the heliosheath. This generates Rayleigh-Taylor instability oscillations with amplitude 10's AU over 100's years - Liewer et al. (1996).

- charge-exchange processes in plasma-neutral fluid model produces alternate growing and damping of Alfvénic, fast and slow turbulence modes, with amplitude 10-100 AU and slowly propagating downstream along the heliopause - Shaikh & Zank (2010).

- The 10-100 AU turbulent ripples propagate outward the ISM and are damped by ion-neutral collisions in mfp ~ 300 AU - Spangler et al. (2011).
scattering on heliospheric turbulence
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scattering on heliospheric turbulence

• cosmic rays > 100 TeV do not feel the influence of the heliosphere

• cosmic rays < 100 TeV are influenced by the heliosphere from the downstream region

• resonant scattering of 1-10 TeV cosmic rays with 100's AU turbulence ripples re-organizes the arrival direction distribution

• cosmic rays streaming along the LIMF experience the largest effect from the downstream region, and a minimal effect upstream

• perpendicular scattering is critical and determines the gradient region in cosmic ray arrival direction distribution

  ‣ evaluations and calculations to verify this scenario
scattering on heliospheric turbulence

LIMF direction compatible with
- Ca II absorption & H I lines, Frisch (1996)
- radio emission from inner heliosheath, Lallement et al. (2005), Opher et al. (2007)
- polarization measurements, Frisch (2010)
scattering on heliospheric turbulence

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spectral feature associated to anisotropy


Milagro & ARGO-YBJ

harder than average spectrum from region A

\[ \gamma < 2.7 \text{ at } 4.6 \sigma \text{ level} \]

\[ E_c = 3 - 25 \text{ TeV} \]

similar to hardening of “diffuse” cosmic rays by Pamela, CREAM, ATIC-2

\[ \frac{dN}{dE} \propto E^{\gamma} e^{-E/E_c} \]

harder spectrum in region A
origin of spectral hardening?

- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail

- turbulence makes reconnection fast and not affected by ohmic dissipation

- magnetic mirror @ single reconnection as site of acceleration (test particle)

Sweet (1959) Parker (1957)

The origin of spectral hardening?

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- Magnetic mirror @ single reconnection as site of acceleration (test particle).

\[ N(E)dE \sim E^{-5/2}dE \]

\[ E_{\text{max}} \approx 0.5 \left( \frac{B}{1 \mu G} \right) \left( \frac{L_{\text{zone}}}{100 \text{ AU}} \right) \text{TeV} \sim 0.5 - 6 \text{ TeV} \]
Conclusions

• < 100 TeV cosmic ray anisotropy generated by interaction with the very local interstellar medium

• scattering with turbulence inside and in the outer heliospheric boundary to play an important role to explain large scale and small scale TeV cosmic ray anisotropy

• might explain change of cosmic ray anisotropy between 20 TeV and 400 TeV

• spectral hardening observed by Milagro & ARGO-YBJ from the downstream direction from re-acceleration of a fraction of cosmic rays in stochastic magnetic reconnection within the heliotail

• similar hardening observed by Pamela and CREAM could be related to the heliotail, although astrophysical explanations @ source and from propagation are possible