particle acceleration in reconnection regions
the case of cosmic ray excess from the heliotail

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cosmic rays

- CR below the knee ($\sim 3 \times 10^{15}$ eV) believed to be galactic

- CR below $\sim 10^{18}$ eV believed to be predominantly galactic (transition to extra-galactic @ $\sim 10^{18}-10^{19}$ eV)

- galactic CR believed to be accelerated in expanding shock waves initiated by supernova explosions

- anisotropy in arrival direction expected from discrete sources distribution & propagation
low energy cosmic ray anisotropy in arrival direction


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medium / small scale anisotropy

- global amplitude of large scale anisotropy increases with energy up to ~ 1-10 TeV and decreases above it

- origin of anisotropy is unknown

- large scale anisotropy shows smaller angular features, some of which highly significant

- small angular features might reveal properties of the boundary region between solar wind and interstellar wind

- isolate small scale features

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[Image of energy levels: 0.7 TeV, 1.5 TeV, 3.9 TeV, 4 TeV, 6.2 TeV, 12 TeV, 50 TeV]
medium / small scale anisotropy


Milagro

$2.2 \cdot 10^{11}$ events
median CR energy $\sim 1 \text{ TeV} = 10^{12} \text{ eV}$
average angular resolution $< 1^\circ$

2hr time window
10° smoothing

- filter all angular features $> 30^\circ$
- technique used in gamma ray searches
medium / small scale anisotropy

Milagro

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\[ \frac{dN}{dE} \propto E^\gamma e^{-\frac{E}{E_c}} \]
origin of small scale anisotropy: astrophysics?

- localized excess of cosmic rays from nearby (~150 pc ~ $3 \times 10^7$ AU) recent (~ 350 kyr) supernova that gave birth to Geminga Pulsar

- fine tuning of propagation through interstellar medium

- incidentally requires magnetic connection to the faraway source

- small scale features likely from local processes

origin of “tail-in anisotropy”

- broad tail-in excess of **sub-TeV** cosmic rays attributed to heliotail
- localized excess of **multi-TeV** cosmic rays from the direction of the heliotail
- medium/small scale modulation to be connected to **nearby** perturbations
- first-order Fermi acceleration in magnetic reconnection regions in the heliotail


magnetic reconnection @ heliotail

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

“more realistic” numerical simulation of the turbulent heliosphere and heliotail
magnetic reconnection @ heliotail

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

- ubiquitous turbulence makes reconnection fast and not affected by ohmic dissipation

Sweet, IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics, 123, 1959.
Parker, J. Geophys. Rev., 62, 509, 1957


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stochastic magnetic reconnection

- verification of Lazarian & Vishniac 1999 with numerical calculations
- reconnection speed does not depend on resistivity
- reconnection speed increases with turbulence injection power
- reconnection speed $\sim$ local turbulent velocity
acceleration in reconnection regions

- first order Fermi acceleration from volume-filling magnetic reconnection

- magnetic mirror @ reconnection as site of acceleration

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

- magnetic tubes contraction leads to increase of particle energy as long as they are within the contracting magnetic loop

\[ E_{\text{max}} \approx 10^{13} \text{ eV} \cdot \left( \frac{B}{1 \mu G} \right) \cdot \left( \frac{L_{\text{zone}}}{134 \text{ AU}} \right) \]

application to pulsars, microquasars, solar flares acceleration

de Gouveia Dal Pino & Lazarian, 2000, 2003, 2005
Lazarian, 2005
acceleration in weakly stochastic reconnection regions

- test particle verification of Lazarian & Vishniac 1999 with numerical calculations

- magnetic energy transferred into energy of contracting loops

- fast reconnection induces efficient acceleration of cosmic rays

- complexity of acceleration: contracting loops & current sheets; 1st order Fermi & drift acceleration

more studies: Kowal et al., arXiv:1103.2984
acceleration in reconnection regions

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

- harder spectrum if **back reaction** of accelerated particle

\[ E_{\text{max}} \approx 10^{13} \text{ eV} \cdot \left( \frac{B}{1 \, \mu G} \right) \cdot \left( \frac{L_{\text{zone}}}{134 \, AU} \right) \]

- solar wind \( \approx 100 \text{ km/sec} \)

- \( E_{\text{max}}(1 \, \mu G) \approx 20 \text{ TeV} \)

\[ \implies \text{unlikely to expect energies} \geq 10 \text{ TeV} \]
application on anomalous cosmic rays

- magnetic field reversals from Sun’s rotation compress at the heliopause

- reconnection and acceleration induced in the heliosheath closer to the heliopause

- Voyager did not observe ACR passed the termination shock

- other models available as well

conclusions

• broad tail-in excess of sub-TeV cosmic rays and localized excess of multi-TeV cosmic rays from the direction of the heliotail could have a common origin

• 1\textsuperscript{st} order Fermi acceleration in magnetic reconnection regions in the heliotail

• HE cosmic rays excess related to reconnection site - LE cosmic rays smeared by scattering

• no need to tune interstellar medium properties

› on-going numerical calculations to verify whether magnetic reconnection regions in the heliotail may be site of efficient acceleration

› acceleration mechanisms in stochastic reconnection regions might explain the puzzling localized excess region of multi-TeV cosmic rays
back up slides
sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail

solar magnetic field reversal should affect galactic anisotropy

origin of excess is “heliospheric”
anisotropy vs energy: probing different causes

Amenomori et al., astro-ph/0505114

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