Cosmic Ray Anisotropy and Magnetic Reconnection in the Heliospheric-Tail

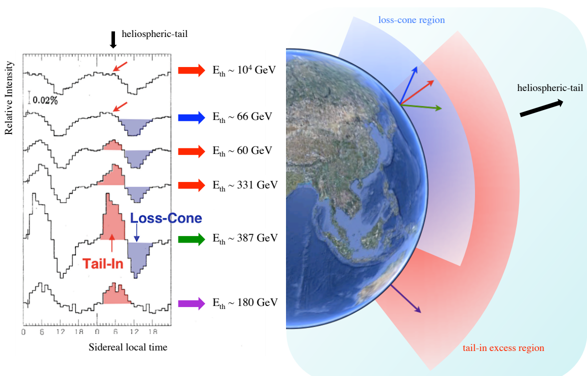
Paolo Desiati†, Alex Lazarian‡

Department of Physics†, Astronomy Department‡, University of Wisconsin, Madison, WI 53706

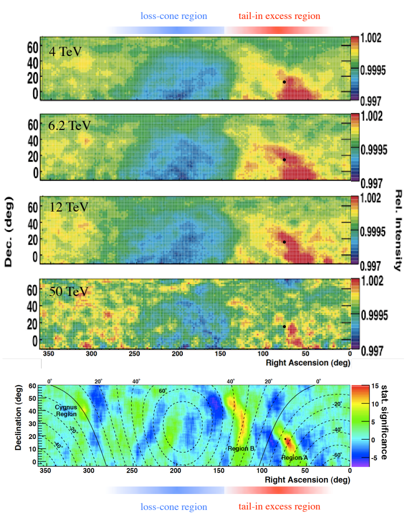
ABSTRACT: Cosmic ray detected on Earth have been observed to have an energy-dependent anisotropy in arrival direction of the order of $10^{-4} - 10^{-3}$. The origin of such anisotropy is not known but it is believed to provide a probe into the properties of the local interstellar magnetic field at distance scales proportional to the cosmic ray's gyro-radius. At sub-TeV energies (i.e. below 10^{12} eV), the cosmic proton's gyro-radius is of the order of the heliospheric size (~ 200 AU). In this energy range an excess of cosmic rays arrival direction is observed toward the direction of the heliospheric-tail (tail-in anisotropy), and it appears to be modulated in time, depending on the location of Earth relative to the heliosphere. This large scale excess seems to disappear at energies in excess of a few TeV, consistently with gyro-radius exceeding the heliospheric size. However a recent detection of a localized but significant excess of multi-TeV cosmic rays from the anti-galactic center by MILAGRO has triggered renewed attention. The coincidence of this excess with the direction of the heliospheric-tail and its limited angular size (~ 10°) might suggest this to be the high energy residual of the tail-in anisotropy observed at lower energy. We discuss the possibility that magnetic reconnection in the heliospheric-tail might be the origin of such an observation.

COSMIC RAY ANISOTROPY

The first comprehensive observation of a large angular scale anisotropy in the sub-TeV cosmic rays arrival direction was reported by Nagashima et al. [NFJ98].



The anisotropy features persist in the multi-TeV region, where small angular scale characteristics seem to overlap to the smooth broad modulation of the cosmic rays arrival direction distribution.

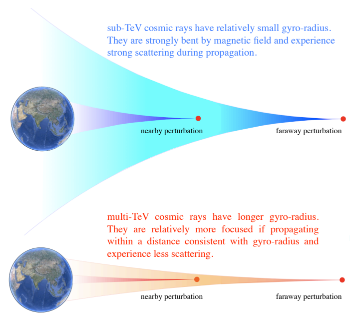


The Tibet ASγ array [A06] measured the cosmic rays arrival direction distribution at different median energies in the multi-TeV region. While the loss-cone deficit structure does not seem to change with energy, the tail-in excess seems to get thinner and to show smaller angular scale structures at higher energy.

The MILAGRO coll. [A08], with techniques used in γ ray detection, filtered out all anisotropy features wider than 30° and revealed two localized regions of multi-TeV (i.e. 1-10 TeV) cosmic rays.

The most significant region A (12 σ) coincides with the direction of the heliospheric-tail (the black dot in figure).

ANGULAR SCALE OF COSMIC RAY ANISOTROPY



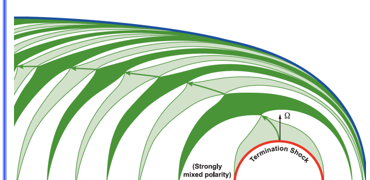
A localized excess of multi-TeV cosmic rays is more likely produced by a perturbation in their directional propagation that occur nearby, with respect to their gyro-radius.

Sub-TeV cosmic rays hardly have small angular scale structures even if nearby effects are responsible of their origin. Scattering in magnetic field is more significant at low energy.

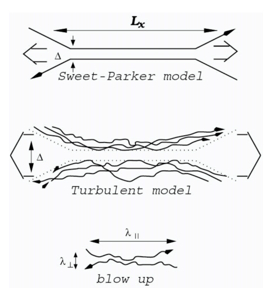
It is likely that the broad sub-TeV tail-in excess and the multi-TeV localized region are manifestations of the same local phenomenology at different energies.

We propose that the broad sub-TeV tail-in excess and the localized multi-TeV excess are caused by acceleration from magnetic reconnection in the heliospheric-tail.

MAGNETIC RECONNECTION IN THE HELIOSPHERIC-TAIL



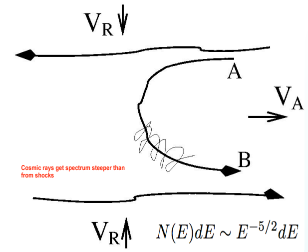
The 11-year solar dynamo cycle generates magnetic field of opposite polarities. As the magnetic field is carried away by the ~ 450 km/sec solar wind, the reversed field regions are accumulated in the magneto-tail region. This is where reconnection is expected to occur. Turbulence is also expected to exist, which affects reconnection speed, i.e. the speed at which in-flowing magnetic field is annihilated by ohmic dissipation.



In the Sweet-Parker model of reconnection [S58, P57], the outflow is limited within the width of transition zone Δ, which is determined by ohmic diffusivity.

In the Lazarian-Vishniac [LV99] model of reconnection of weakly stochastic magnetic field, the outflow is limited by the diffusion of magnetic field lines, which depends on turbulence.

Reconnection rate is consequently increased by the turbulence effect of many magnetic field lines. In particular reconnection speed is close to the turbulent velocity in the fluid.



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

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

The magnetic reconnection region is a site of cosmic ray acceleration.

As a particle bounces back and forth between converging magnetic field lines, it gains energy through first order Fermi acceleration mechanism [GL03].

The energy spectrum resulted from acceleration is steeper than the one from shocks, but similar to that of diffuse cosmic rays.

The maximum energy of protons that can be accelerated through this process depends on the magnetic field and the size of the region $L_{zone} \approx$ 670 AU between the 11-year solar cycle magnetic field polarity reversals in the heliospheric-tail [LD10].

This provides $E_{max} \approx$ 50 TeV.

More detailed calculations should provide a more accurate estimation of the magnetic field intensity and size scale. In fact, we can predict that, unless some process of field amplification occurs in the turbulent heliospheric-tail, the acceleration of the cosmic rays of energies much larger than 10 TeV is unlikely possible with magnetic reconnection. This is about the energy where the MILAGRO collaboration observes an apparent cut-off the the cosmic rays from the localized regions [A08].

DISCUSSION AND SUMMARY

We attempt to explain the cosmic ray excess in the range from 50 GeV to 1-10 TeV as arising from magnetic reconnection in the heliospheric-tail. The direction of the multi-TeV localized excess of cosmic rays seems correlated to the sites of acceleration via reconnection. The lower energy particles, on the other hand, can be accelerated over extended regions of the heliospheric-tail and they are also expected to experience more scattering prior to reaching the observer at the Earth. This would give rise to a broad excess of cosmic rays toward the heliospheric-tail [LD10].

The high energy cutoff observed corresponds roughly to what is expected from the reconnection-driven acceleration. It is virtually impossible to explain the acceleration of higher energy particles with this mechanism, unless appealing to some hypothetical magnetic field acceleration processes.

This study has still exploratory character, as the quantitative description of mechanisms of cosmic ray acceleration in the reconnection regions are still at its infancy. Even though the models of acceleration in the reconnection regions require more study, we think that the proposed scenario has more realistic grounds than the astrophysical interpretations (see e.g. [SS08] and [DA08]).

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