Magnetic Reconnection as the Cause of Cosmic Ray Excess from the Heliospheric Tail

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Abstract: The observation of a broad excess of sub-TeV cosmic rays compatible with the direction of the heliospheric tail and the discovery of two significant localized excess regions of multi-TeV cosmic rays by the Milagro collaboration, also from the same region of the sky, have raised questions on their origin. In particular, the coincidence of the most significant localized region with the direction of the heliospheric tail and the small angular scale of the observed anisotropy ($\sim 10^\circ$) is suggestive a local origin and of a possible connection to the low energy broad excess. Cosmic ray acceleration from magnetic reconnection in the magnetotail is proposed as a possible source of the energetic particles.

Keywords: particle acceleration, cosmic rays, magnetic fields, magnetohydrodynamics (MHD)

1 Introduction

During the last decades, galactic cosmic rays have been observed to have a small but measurable energy dependent broad anisotropy in their arrival direction distribution, with a relative amplitude of order $10^{-4} - 10^{-3}$. This anisotropy was observed at energies of 10 to several hundreds GeV [1], and in the multi-TeV energy range in the northern hemisphere (Tibet ASγ array [2], Super-Kamiokande [3], Milagro [4] and ARGO-YBJ [5]). The first observation of cosmic ray anisotropy in the southern hemisphere in the 10 TeV range was also reported by IceCube [6].

The origin of cosmic rays anisotropy in arrival direction is still unknown. Even though an anisotropy of galactic cosmic rays might be caused by the discrete and stochastic nature of their sources [7, 8], the properties of cosmic ray propagation in the local interstellar medium likely have an important role as well [9, 10]. However, the combined study of the energy evolution of the anisotropy, its angular scale structure and time variabilities seem to suggest that the observation might likely be generated by a combination of effects, caused by phenomenologies at different distances scales from Earth. At the same time, some features observed at different energies and apparently uncorrelated, could also have the same origin.

In particular, the observation of sub-TeV cosmic rays anisotropy revealed the existence of two distinct features, with different energy dependence. One that persists up to TeV energies with increasing amplitude, and one that manifests itself as a broad excess in the direction of the heliospheric tail (of heliotail) that seems to disappear in the TeV energy range [1]. The heliotail is the region of the heliosphere downstream the interstellar wind delimited within the heliopause, i.e. the boundary that separates the solar wind and interstellar plasmas [11]. This broad excess was attributed to some unknown anisotropic process occurring in the heliotail, and thus it was called tail-in excess.

In addition, the discovery of localized excess regions (order of 10° in size) of multi-TeV cosmic rays in the northern hemisphere by Milagro [12], and also observed by Tibet ASγ [13] and ARGO-YBJ [14] has provided the first evidence of small angular scale features in cosmic ray arrival direction distribution. This discovery triggered an astrophysical interpretation based on the possibility that cosmic rays accelerated by the supernova that produced Geminga pulsar are focussed by an ad-hoc interstellar magnetic field structure [15, 16, 17]. Since the most significant of the excess regions coincides with the direction of the heliotail, and given its small angular scale, it is argued in this paper that its origin is likely related to a nearby phenomenology. In particular that the broad tail-in excess of sub-TeV cosmic rays and the localized excess of multi-TeV cosmic rays from the direction of the heliotail, have a common origin. Namely cosmic rays are accelerated in magnetic reconnection regions in between inverse magnetic field polarities induced by the 11-year solar cycle, and produce an excess with angular scale determined by the particle energy [18].

2 Astrophysical Interpretations

While no explanation has being attempted to explain the broad sub-TeV tail-in excess, a number of interpretations were provided to address the origin of the localized excess of multi-TeV cosmic rays.

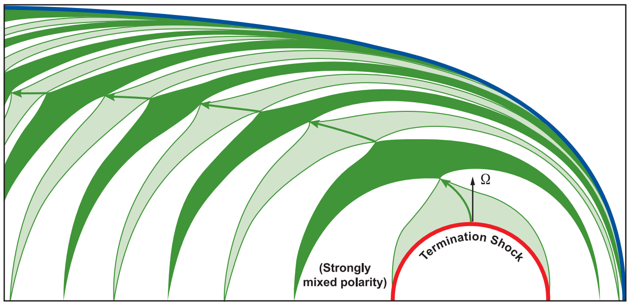

Figure 1: A meridional view of the boundary sectors of the heliospheric current sheet and how the opposite sectors get tighter closer to the heliopause and into the heliotail. The thickness of the outflow regions in the reconnection region depends on the level of turbulence. The length of the outflow regions L depends on the mean geometry of magnetic field and turbulence. Adapted from [19, 20].

Some proposed models rely on astrophysical origin. In [15, 16, 17] it is noted that the two observed localized excess regions surround the present day apparent location of Geminga pulsar. The supernova that gave birth to the pulsar exploded about 340,000 years ago, and the accelerated cosmic rays might have propagated along interstellar magnetic fields connecting the region of Geminga to Earth (see also [10]). Since nothing or very little is known of the local interstellar medium properties, cosmic ray diffusion is not sufficiently constraint to provide a coherent scenario that can explain the observations without considerable fine tuning.

The coincidence of the most significant localized excess observed by Milagro with the heliotail, supports the idea that the heliosphere could somehow have a role. The possibility that we are seeing the effects of neutron production in the gravitationally focussed tail of the interstellar material was considered in [16]. Cosmic rays propagating through the direction of the tail interact with matter and magnetic fields to produce neutrons and hence a localized excess of cosmic ray in that direction. But while the target size has about the right size compared to the decay length of multi-TeV neutrons ($\sim$ 0.1 pc), the increase of the gravitating matter density is too low to account for the observed excess.

It is possible to argue that the large angular scale anisotropy in cosmic rays arrival direction might be generated by a combination of astrophysical phenomena, such as the distribution of nearby recent supernova explosions [7], particularly in conjunction with the observed positron anomaly [8]. But also by propagation effects [9, 10] and the structure of the interstellar magnetic field. On the other hand it is hard to exclude local effects as possible explanation of the small angular scale anisotropies. It is hearby proposed that the excess of cosmic rays from the direction of the heliotail are connected to particle interaction and acceleration processes within the heliotail itself.

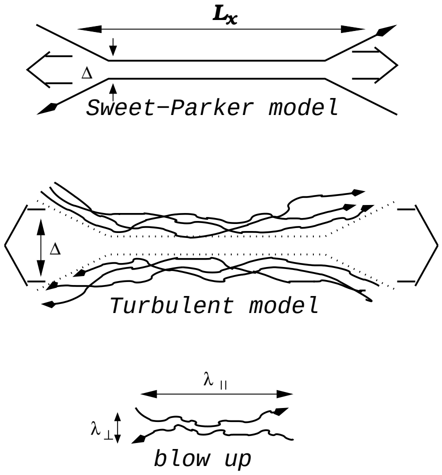

Figure 2: *Upper plot*: Sweet-Parker model of reconnection [26, 27]. The outflow is limited by a thin slot Δ, which depends on Ohmic diffusivity. The other scale is an astrophysical scale $L \gg \Delta$. *Middle plot*: Reconnection of weakly stochastic magnetic field according to Lazarian & Vishniac [28]. The outflow is limited by the diffusion of magnetic field lines, which depends on field stochasticity. *Lower plot*: An individual small scale reconnection region. The reconnection over small patches of magnetic field determines the local reconnection rate. The global reconnection rate is substantially larger as many independent patches come together. The bottleneck for the process is given by magnetic field wandering and it gets comparable to L as the turbulence injection velocity approaches the Alfvenic one. From [24].

3 Magnetic field structure at the heliotail

Fig. 1 represents the possible structure of the heliotail which arises from the solar magnetic field cycles [21]. Magnetic field regions of opposite polarities emerge as the result of 11 year solar dynamo cycle. As the magnetic field is carried away by solar wind, the reversed polarity regions are accumulated in the heliotail region. This is where reconnection is expected to occur.

The actual heliotail is subject to turbulence, which is not represented in the figure. Since the Alfven speed of the turbulence is smaller than the solar wind speed, magnetic reconnection does not change the overall magnetic field structure. Nevertheless, the effects of turbulence are very important from the point of view of magnetic reconnection and the particle acceleration that it entails.

The simulations of the magnetic fields in the heliotail are extremely challenging (see [22, 23]) and have not been done with the sufficient resolution and extent. While we believe that future research will provide details necessary for quantitative modeling, the schematic representation of the magnetotail structure depicted in Fig. 1 is true in terms of major features. In what follows, it will be used for describing the scenario for the origin of the cosmic ray excess that we advocate in this paper.

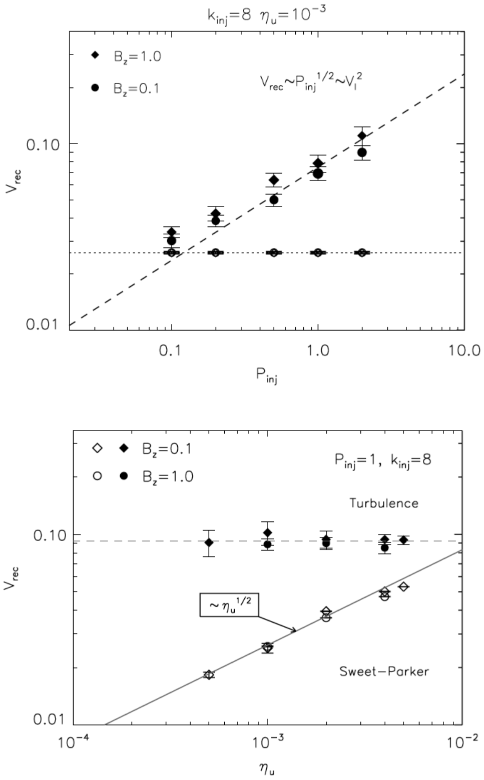

Figure 3: *Upper plot*: dependence of the reconnection speed V_{rec} on injection power P_{inj}. *Lower plot*: dependence of the reconnection speed V_{rec} on the uniform resistivity η_u. Open symbols are for Sweet-Parker reconnection scenario [26, 27], and filled symbols are for weakly stochastic reconnection scenario [28]. From [29].

4 Stochastic magnetic reconnection

Astrophysical plasmas are often highly ionized and magnetized [25], and they undergo dissipative processes, which convert electromagnetic energy into plasma energy. Due to these processes, plasma from regions of a given polarity becomes magnetically connected to the one of opposite polarity: this is when magnetic reconnection occurs. Turbulence that naturally permeates magnetized plasmas is important for the efficiency of magnetic reconnection and the corresponding particle acceleration processes. In the Sweet-Parker model of reconnection [26, 27] the outflow is limited within the transition zone Δ, which is determined by ohmic diffusivity (see top of Fig. 2). According to Lazarian & Vishniac model of reconnection of weakly stochastic magnetic field [28], on the other hand, the outflow is limited by the diffusion of magnetic field lines, which depends on turbulence only (see center of Fig. 2). The reconnection rate, as a consequence, is increased simply by the turbulent effect of many magnetic field lines, and its speed is close to the turbulent velocity of the medium.

Fig. 3 shows the dependence of reconnection rate on the turbulence injection power and on the plasma uniform resistivity, as obtained from numerical calculations [29].

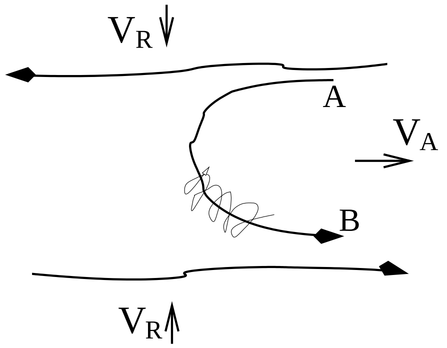

Figure 4: Cosmic rays spiral about a reconnected magnetic field line and bounce back at points A and B. The reconnected regions move towards each other with the reconnection velocity V_R. The advection of cosmic rays entrained on magnetic field lines happens at the outflow velocity, which is in most cases of the order of V_A. Bouncing at points A and B happens because either of streaming instability induced by energetic particles or magnetic turbulence in the reconnection region. In reality, the outflow region gets filled in by the oppositely moving tubes of reconnected flux which collide only to repeat on a smaller scale the pattern of the larger scale reconnection. Thus our cartoon also illustrates the particle acceleration taking place at smaller scales. From [30].

While in the Sweet-Parker scenario, the reconnection rate depends on the resistivity of the plasma and it does not depend on the turbulence power, in the Lazarian & Vishniac scenario it shows no dependency on resistivity and it increases with injected power of the turbulence, as predicted in [28]. The fast nature of the weakly stochastic magnetic reconnection mechanism is a consequence of the turbulence in the plasma. Astrophysical plasmas are naturally turbulent and likely have low resistivity, and stochastic magnetic reconnection provides an efficient mechanism to transfer electromagnetic energy into plasma energy.

5 Acceleration in reconnection regions

While magnetic field regions of opposite polarities are compressed in the heliotail, the outflow volume is filled with the reconnected turbulent field lines moving closer to each other. Reconnection converts magnetic energy into kinetic energy of the outflow, and in the presence of cosmic ray particles, a portion of this energy can be utilized for their acceleration. As a particle bounces back and forth between converging magnetic lines it gains energy through first-order Fermi mechanism (see Fig. 4). If particle diffusion parallel to magnetic field lines is larger than perpendicular diffusion, this acceleration mechanism gains in efficiency.

As reconnection processes are ubiquitous in astrophysics, it is expected first-order Fermi acceleration mechanisms commonly occur in turbulent plasmas. Numerical 3D simulations of energetic particle transport in weakly stochastic reconnection regions provide results consistent with first-order fermi acceleration [29, 31]. In particular it is found that within contracting magnetic island or current sheets, particles mainly accelerate via first-order Fermi acceleration mechanism, while outside those regions drift acceleration occurs due to magnetic field gradients [32].

The energy spectrum, expected by accounting for acceleration and loss rate of energetic particles without taking into account the back-reaction of the accelerated particles on the flow, is similar to the one of diffuse galactic cosmic rays [33]

$$N(E)dE \sim E^{-\frac{5}{2}}dE, \qquad (1)$$

although preliminary studies of the effect of back-reaction showed that the energy spectrum can be harder [34]. This seems in agreement with the observation of harder than average cosmic ray spectrum within the localized excess region as reported by Milagro [12].

The highest energy that can be achieved by this acceleration mechanism can be estimated based on the requirement that accelerated particles must be within the the contracting magnetic loops

$$E_{max} \approx 20\,TeV\left(\frac{B}{1\mu B}\right)\left(\frac{L_{zone}}{134\,AU}\right), \qquad (2)$$

where B is the magnetic field in the heliotail and L_{max} is the size of the magnetized regions with a given polarity. Assuming the subsonic solar wind speed is lower than 100 km s^{-1} in the heliotail, the magnetic regions generated by the 11-yr solar cycle polarity change, are smaller than about 230 AU. This means, assuming a magnetic field of the order of 1 μG, that $E_{max} \approx 30$ TeV. In fact acceleration to energies much higher than about 10 TeV is rather unlikely with such a mechanism.

6 Conclusions

It is argued that the broad tail-in excess of sub-TeV cosmic rays and the highly significant localized excess region of multi-TeV cosmic rays are two manifestations of the same phenomenology. Namely it is proposed that cosmic rays propagating through the turbulent heliotail are accelerated via first-order Fermi acceleration mechanism via stochastic magnetic reconnection. In general 3D numerical simulation show that such an acceleration mechanism can be very efficient. Therefore a fraction of high energy cosmic rays could be accelerated up to about 10 TeV, depending on the particle injection energy. On the other hand the properties of magnetized plasma in the heliotail is not yet fully constraint, therefore details of cosmic ray propagation in this region are still uncertain. Sub-TeV cosmic rays may be accelerated over extended regions and may undergo scattering, thus producing a more diffuse arrival distribution. On the other hand multi-TeV cosmic rays undergo more efficient acceleration and their localized substructure in arrival direction are more related to the acceleration sites.

A similar process was proposed to explain the origin of anomalous cosmic rays as due to acceleration in stochastic reconnection region within the heliosheath, produced by magnetic polarity changes induced by the 27-day solar rotation [35, 36].

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