Heliospheric Boundary and the TeV Cosmic Ray Anisotropy

Paolo Desiati\textsuperscript{1,2}, Alex Lazarian\textsuperscript{2}

1. Wisconsin IceCube Particle Astrophysics Center (WIPAC), University of Wisconsin, Madison, WI 53703
2. Department of Astronomy, University of Wisconsin, Madison, WI 53706
E-mail: desiati@wipac.wisc.edu

Abstract. Observations over the last few decades have shown that cosmic rays have a small non uniform distribution in arrival direction. Such anisotropy appears to have a roughly consistent topology between 10’s GeV and 100’s TeV, with a smooth energy dependency on phase and amplitude. However, above a few 100’s TeV a sudden change in the topology of the anisotropy is observed. The cosmic ray arrival directions are expected to depend on the distribution of their sources in the Milky Way, as well as on effects arising from propagation in the inhomogeneous and turbulent interstellar magnetic field. In particular, in the 1-10 TeV energy range, the gyroradius of cosmic ray particles, much smaller that the injection scale of interstellar magnetic field turbulence, is comparable to the size of the heliosphere. Resonant scattering processes of cosmic ray particles propagating through the heliosphere may be able to induce a redistribution of the small anisotropic component of their flux. In this paper we discuss on the processes that occurs to TeV cosmic rays in the heliosphere and on the possibility to probe the heliospheric magnetic fields on large scale by studying the arrival distribution of cosmic rays.

1. Introduction

In the last few decades a number of experiments have provided long term and high statistical significance evidence of a global anisotropy in the cosmic ray arrival distribution with a relative amplitude of order $10^{-4} - 10^{-3}$. Observations in the northern hemisphere were reported from energies of 10’s to several 100’s GeV with muon detectors [1, 2, 3], in the 1-10’s TeV energy range with various surface arrays and underground detectors [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14], up to 100’s TeV [15]. Recently, similar observations of a large angular scale anisotropy were reported in the southern hemisphere by the IceCube Observatory, in the energy range between 10 TeV and a few PeV [16, 17, 18]. These results show that the anisotropy matches the observations in the northern hemisphere in the 10 TeV energy scale (see top panel of figure 1), but that it changes topology at energy in excess of about 100 TeV, in a fashion that may be interpreted as a directional flip, confirming the observations by [15]. The amplitude of the high energy anisotropy, characterized by a wide deficit on a relatively uniform flux, increases with energy [18]. The transition between the two anisotropy regimes is preceded by a steady decrease of the amplitude with energy above 10 TeV, following an increase trend at lower energies (see [4] for instance). This might suggest that the 10 TeV energy scale is where the transition starts with the interference between the two different distributions disrupting the energy dependence.
of the anisotropy amplitude.

The global anisotropy cannot be described with a simple dipole, but as a superposition of spherical harmonic contributions, where statistically significant small angular scale features (i.e. less than $30^\circ$), with amplitude of order $10^{-5} - 10^{-4}$, are also observed [19, 14], in agreement with similar observations in the northern hemisphere [20, 21, 22, 13] (see the bottom panel of figure 1).

The origin of the observed anisotropy is not understood yet, however it is reasonable to assume that it is a combination of effects correlated to the distribution of the galactic sources of cosmic rays, of the geometry and turbulent properties of the galactic magnetic field and on propagation in this field. These are likely also the responsible of the complex shape of the energy spectrum [23]. Since we don’t know where the sources of cosmic rays are and we don’t know the details of the interstellar magnetic field, understanding the observations is not an easy task.

The large scale anisotropy can be qualitatively explained on the basis of diffusive propagation of cosmic rays in the Milky Way from stochastically distributed sources. Numerical studies show that it is possible to find a given realization of galactic source distribution that might explain the observed non monotonic energy dependence of the anisotropy amplitude, although for an ensemble of realizations the mean amplitude is overestimated compared to observations [24, 25, 26, 27, 28]. Even accounting for a more likely anisotropic diffusion, observations appear to be outliers compared to predictions [29, 30]. The fact that cosmic ray anisotropy is not a simple dipole but can be mostly explained with a superposition of a dipole and quadrupole term, seems to suggest that other transport processes might be important as well. For instance drift diffusion driven by a gradient of cosmic ray density in the local interstellar medium, producing a bi-directional anisotropy, was considered by [20, 31].

The small scale anisotropy may be produced by the interactions of cosmic rays with isotropically turbulent interstellar magnetic field. Scattering processes with stochastic magnetic instabilities produce perturbations in the arrival direction distribution of an anisotropic distribution of cosmic ray particles within the scattering mean free path. Such perturbations may be observed as stochastic localized excess or deficit regions [32, 33], and the corresponding angular power spectrum can be analytically predicted from the Liouville Theorem [34]. The injection scale of interstellar turbulence is of order 10 pc within the galactic arms and 100 pc in the inter arm regions [35]. In the cascading processes down to smaller scales, the turbulent eddies become elongated along the magnetic field lines [36, 37]. This anisotropic turbulence makes scattering processes inefficient, and scattering mean free path can be larger than turbulence injection scale, so that particles basically stream along magnetic field lines with small cross fieldline transport [38, 39].

Besides the cascading interstellar magnetic field turbulence down to damping scale (typically of order 0.1 pc), there are other sources of magnetic perturbations on smaller scales. The closest to Earth is represented by the heliosphere, formed by the interaction between the solar wind and the interstellar flow, about 600 AU wide and extending several thousands astronomical units downstream the interstellar wind [40]. Globally, the heliosphere constitutes a perturbation in the 3 $\mu$G Local Interstellar Magnetic Field (LIMF) with injection scale comparable to $\sim$10 TeV proton gyroradius. It is therefore reasonable that the LIMF draping around the heliosphere might be a significant source of resonant scattering, capable of redistributing the arrival directions of TeV cosmic cosmic ray particles.

In this paper we briefly summarize the current understanding of the effects of the heliosphere on TeV cosmic rays and whether we can use the anisotropy observations as diagnostics on the heliospheric boundary with the local interstellar medium.
2. The Heliosphere

The solar system is located approximately 8 kpc from the galactic center and it is dragged by the global galactic rotation, similarly to the Local Interstellar Medium (LISM). However, the relative motion of the solar system with respect to the LISM is determined by the expansion of the Loop I superbubble from the Scorpion-Centaurus Association (at a distance of about 60 pc), which is near the apparent direction of the galactic center [41]. The solar system is currently located within an expanding shell of Loop I, which is breaking up in smaller cloudlets that share similar composition and velocities. And the LIMF appears to be almost parallel to the shell front and relatively coherent within a distance of 80-100 pc. One of these cloudlets, the so called Local Interstellar Cloud (LIC) is where the solar system is located, with a relative velocity to the LIC of approximately 23 km/sec [42]. The interaction between the supersonic outward solar wind and the incoming interstellar flow produces a comet shaped interface where the interplanetary and the interstellar magnetic fields rearrange. At a distance of about 80 AU from Earth the termination shock is formed where the solar wind becomes subsonic, but the separation between the heliospheric and the interstellar medium occurs at a distance of about 120 AU in the upstream direction, where the heliopause is located. From numerical simulations, the heliosphere is expected to be as wide as 600 AU and to form an elongated tail in the downstream direction, that can be long several 1000’s AU [40].

Since the LISM is a partially ionized medium, neutral particles can penetrate through the heliopause and have charge exchange with the highly ionized solar wind. Such processes create instabilities on the heliopause in the upstream direction, that propagate along the flanks and that can reach spatial scales of 10-100 AU [43]. Another source of instabilities on the heliopause is represented by the solar cycles, which affect the heliospheric magnetic field pressure, that regulates the distance of the heliopause from Earth [44]. The magnetic field polarity inversions due to solar cycles, produce unipolar regions of magnetic fields that, dragged by the solar wind, drift along the heliotail [40].

2.1. Heliospheric Influence on TeV Cosmic Rays

Globally, the heliosphere is a perturbation of the LIMF on a scale of about 600 AU. In addition, complex structures in the inner heliospheric magnetic field of about 100-200 AU and instabilities on the heliopause on scales of approximately 10-100 AU, have necessarily an effect on the charged particles that propagate through.

In [45] the scenario of TeV cosmic ray interaction with the heliosphere was first presented as a possible cause of the observed anisotropy. It is known that galactic cosmic rays below 100 GeV are strongly influenced by solar activity and by the geometry and small scale instabilities (sub-AU scale) of the interplanetary magnetic field within the termination shock. At TeV energies such small scale effects are subdominant because the gyroradius of a proton is larger than the termination shock size, in the inner heliospheric magnetic field. However TeV cosmic rays are in gyro-resonance with the large scale heliospheric magnetic field structure, with unipolar magnetic regions in the inner heliotail and with the instabilities on the boundary with the LISM, depending on the local pitch angle. Because of this, the heliosphere can actually have a significant impact on the distribution of TeV cosmic rays that cross the heliosphere.

Figure 1 shows the sky map of the relative intensity of the global cosmic ray anisotropy (on the top) and the sky map of statistical significance of the small scale anisotropy (on the bottom) obtained by filtering out all the cosmic ray count gradients compatible with a dipole and a quadrupole dependence. In both maps the observations from IceCube, at median particle energy of 20 TeV, are shown. In the northern hemisphere the figures show the results from Tibet-ASγ (with median energy of 5 TeV, on the top panel of the figure) and from Milagro (with median energy of about 1 TeV, on the bottom panel of the figure). The figures show a degree of matching compatibility between the different observations from the northern and
Figure 1. Top: map in equatorial coordinates constructed by combining relative intensity distributions of cosmic ray counts independently normalized within declination bands of order $1^\circ - 5^\circ$. The map shows the observation by Tibet AS\textgamma at about 5 TeV in the northern hemisphere [6] and by IceCube at a median energy of 20 TeV in the southern hemisphere [16]. Bottom: map in equatorial coordinates of the statistical significance of the observed cosmic ray counts. The map shows the observation by Milagro at about 1 TeV in the northern hemisphere (from [21]) and that by the IceCube Observatory at a median energy of 20 TeV in the southern hemisphere (from [19]). Also shown the equator “at infinity” (see text) in black continuous line, corresponding to the direction of LIMF inferred in [46, circular symbols], that in black dotted line from [47, square symbols], and that in black dashed line from [48, triangle symbols]. The star symbol indicates the downwind interstellar medium flow with coordinate (5 hr, $+17^\circ$). Color scale indicates relative excess (red) and deficit (blue) with respect to average intensity. From [45].

In the southern hemispheres, the differences possibly attributed to the different sensitivities of the cited experiments on the energy and, possibly, mass composition of the cosmic rays. Some visible features seem ordered by the LIMF (with three direction estimations represented with circle, square and triangle symbols in figure 1), in particular the fact that the magnetic equator “at infinity” (i.e. the plane perpendicular to the unperturbed LIMF and passing by Earth, and represented with black lines in figure 1) seems to be aligned with the boundary region between the excess and the deficit of the anisotropy. But there appears to be some ordering by the heliotail direction as well (almost coinciding with the downstream interstellar medium flow direction, represented with a white star in figure 1).

At 10 TeV, cosmic ray protons streaming along the LIMF have gyroradii comparable to the heliospheric size, thus making it possible for them to undergo resonant scattering. Therefore, 10 TeV represents a transition scale between the lower energies, where cosmic rays follows adiabatically the magnetic field lines, and the higher energies, where the heliospheric influence starts to become subdominant, making it possible for the interstellar-originated anisotropy to grow progressively visible. This is in general agreement with the energy dependence of the anisotropy amplitude that increases up to about 10 TeV and decreases above this energy [4]. Resonant scattering may be able to redistribute the $10^{-3}$ interstellar anisotropic component of the cosmic ray arrival distribution, depending on particle energy and pitch angle, and on the properties of heliospheric magnetic field inside the tail and on the heliopause. Backscattering on the magnetic instabilities at the boundary with the LISM (see figure 2 for a simple illustration) may have the effect to locally amplify particle density gradients which can be interpreted as localized features [45].

The localized excess region of cosmic rays observed in the direction of the heliotail, highly pronounced in the sub-TeV energy range [1], seems to be characterized by a harder than average energy spectrum up to about 10 TeV [21, 22]. If confirmed, such observations might indicate that
the small fraction ($10^{-4}$) of cosmic rays from this narrow angular region might be reaccelerated in magnetic reconnection processes occurring in between the unipolar magnetic domains generated by solar cycles [49, 50]. Such reacceleration processes would only involve a negligible fraction of the total turbulent energy transported by the solar wind across the heliotail.

In [51, 52] numerical calculations show that TeV cosmic ray arrival direction distribution, originally ordered by the LIMF, is perturbed so that they appear to be ordered by their entry into the heliosphere, assuming the direction of the interstellar medium flow velocity and of the LIMF as evaluated from the analysis of data by the Interstellar Boundary Explorer (IBEX). If a dipole anisotropy is assumed, either from the contribution of a nearby recent source of cosmic rays or simply from the convective gradient due to the relative motion with respect to the LISM, the deformation induced by the LIMF draping around the heliosphere was estimated and found to globally resemble the actual observations.

Another heliospheric scenario appeals to the possibility that electric fields arising from the motion of the heliospheric plasma might be able to produce the observed localized excess regions of TeV cosmic rays [53].

3. Conclusion
The possibility that the heliosphere may actually shape the high energy cosmic rays arrival distribution is reasonable based on purely dimensional arguments. State of the art numerical simulations of the heliosphere, that include dynamical processes such as charge exchange between neutral and ionized components of the medium, solar cycles and plasma instabilities are starting to provide a clearer idea of the properties of the heliosphere at large distances from Earth and, at the same time, reproduce observations by spacecrafts [40, 44]. The study of how such properties may influence TeV cosmic ray arrival direction distribution will provide the basis of exploring the boundary region between the heliosphere and the LISM with cosmic rays, and it will open the doors to the understanding of our local interstellar medium, as well. Numerical studies
currently under development will be reported in a future publication.

References

[1] Nagashima et al. 1998 J. of Geophys. Res. 1031 17429.
[2] Hall, D. L. et al. 1999 J. of Geophys. Res. 104 6737.
[3] Munakata, K. et al. 2010 Astrophys. J. 712 1100.
[4] Amenomori, M., et al. 2005 Astrophys. J. Lett. 626 L29.
[5] Amenomori, M., et al. 2006 Science 314 439.
[6] Amenomori, M., et al. 2011 Proc. 32nd ICRC Beijing China.
[7] Guillain, G., et al. 2007 Phys. Rev. D 75 062003.
[8] Abdo, A. A., et al. 2009 Astrophys. J. 698 2121.
[9] Zhang, J. L. 2009 Proc. 31st ICRC Lodz, Poland.
[10] Shuwang, C.: 2011 Proc. 32nd ICRC Beijing China.
[11] Di Sciascio, G. 2013 EPJ Web Conf. 52 04 004.
[12] de Jong, J. 2011 Proc. 32nd ICRC Beijing, China.
[13] BenZvi, S. Y. et al. 2013 Proc. 33rd ICRC Rio de Janeiro, Brazil.
[14] Santander, M. et al. 2013 Proc. 33rd ICRC Rio de Janeiro, Brazil.
[15] Aglietta, M., et al. 2009 Astrophys. J. Lett. 692 L130.
[16] Abbasi, R., et al. 2010 Astrophys. J. Lett. 718 L194.
[17] Abbasi, R., et al. 2012 Astrophys. J. 746 33.
[18] Aartsen, M. et al. 2013 Astrophys. J. 765 55.
[19] Abbasi, R., et al. 2011 Astrophys. J. 740 16.
[20] Amenomori, M., et al. 2007 Proc. 30th ICRC Merida, Mexico.
[21] Abdo, A. A., et al. 2008 Phys. Rev. Lett. 101 221 101.
[22] Bartoli, B., et al. 2013 Phys. Rev. D 88-8 082001.
[23] Giacinti G. & Sigl G. 2012 Phys. Rev. Lett. 109 071101.
[24] Biermann P. L. et al. 2013 Astrophys. J. 768 124.
[25] Ahlers M. 2014 Phys. Rev. Lett. 112 021101.
[26] Pohl M. & Eichler, D. 2013 Astrophys. J. 766 9.
[27] Svidzinsky, L. G. et al. 2013 Astropart. Phys. 50 33.
[28] Effenberger, F. et al. 2012 A&A 547 A120.
[29] Kumar R. & Eichler D. 2014 Astrophys. J. 785 129.
[30] Mizoguchi Y. et al. 2009 Proc. 31st ICRC Lodz, Poland.
[31] Giacinti G. & Sigl G. 2012 Phys. Rev. Lett. 109 071101.
[32] Blasi, P., & Amato, E.: 2012 JCAP 1 11.
[33] Ahlers M. 2014 Proc. 33rd ICRC Rio de Janeiro, Brazil.
[34] Borovikov S. N. et al. 2008 Astrophys. J. 682 1404.
[35] Frisch P. C. et al. 2011 Annu. Rev. Astron. Astrophys. 49 237.
[36] Schwadron N. A., et al. 2009 Science 326 966.
[37] Schwadron N. A., et al. 2009 Science 326 966.
[38] Lazarian A. & Yan H. 2008 Astrophys. J. 673 942.
[39] Lazarian A. & Yan H. 2014 Astrophys. J. 784 38.
[40] Pogorelov N. V. et al. 2009 Astrophys. J. 696 1478.
[41] Schwadron N. A., et al. 2009 Science 326 966.
[42] Lazarian A. & Desiati P. 2010 Astrophys. J. 722 188.
[43] Desiati P. & Lazarian A. 2012 NPG 19 351.
[44] Schwadron N. et al. 2014 Science 343 988.
[45] Schwadron N. et al. 2012, in these proceedings.
[46] Drury L. O’C. 2013 Proc. 33rd ICRC Rio de Janeiro, Brazil.