Supergalactic Structure of Multiplets with the Telescope Array Surface Detector

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Abstract. Evidence of supergalactic structure of multiplets has been found for ultra-high energy cosmic rays (UHECR) with energies above $10^{19}$ eV using 7 years of data from the Telescope Array (TA) surface detector. The tested hypothesis is that UHECR sources, and intervening magnetic fields, may be correlated with the supergalactic plane, as it is a fit to the average matter density within the GZK horizon. This structure is measured by the average behavior of the strength of intermediate-scale correlations between event energy and position (multiplets). These multiplets are measured in wedge-like shapes on the spherical surface of the field-of-view to account for uniform and random magnetic fields. The evident structure found is consistent with toy-model simulations of a supergalactic magnetic sheet and the previously published Hot/Coldspot results of TA. The post-trial probability of this feature appearing by chance, on an isotropic sky, is found by Monte Carlo simulation to be $\sim 4.5\sigma$.

1 Introduction

The supergalactic plane (SGP) is the average matter distribution of the local universe up to a distance of $\sim 200$ Mpc (a large percentage is within the GZK cutoff of 100 Mpc) [1]. Large scale magnetic fields are known to exist between some clusters of galaxies which make up the supergalactic plane such as the Coma Cluster [2]. And it has been shown that $\sim 90\%$ of the baryonic mass of the universe is between galaxies of which $\sim 40\%$ is warm-hot protons outside gas clouds [3]. This may allow the formation of intra-galactic large scale magnetic fields ([4],[5]).

The presence of large scale magnetic fields suggest that energy dependent deflection of ultra-high energy cosmic rays (UHECR) should appear correlated with the SGP. Previous energy-position correlation studies have not had significant results ([6],[7],[8]). These multiplet searches for significant small scale magnetic deflection patterns included scanned parameters chosen by assumed magnetic field models and compositions. This analysis uses intermediate-scale energy-position correlations to look for significant large scale magnetic structure and minimal assumptions are made regarding particular magnetic field models or composition.

2 Energy-Position Correlations

It is assumed that UHECR travel through uniform fields, approximated by Equation 1a, and random fields where the root mean square deflection is approximated by Equation 1b ($Z$ is mass number, $S$ angular distance, $B$ field strength, $E$ energy, and $L_c$ is mean magnetic field coherence length).

\[ \delta \approx 0.5^\circ Z \frac{S}{\text{kpc}} \frac{B}{\text{EeV}} \times 10^{20} \frac{\text{eV}}{E} \]  

(1a)

\[ \delta_{\text{rms}} \approx 0.1^\circ Z \frac{B_{\text{rms}}}{\text{EeV}} \times 10^{20} \frac{\text{eV}}{E} \sqrt{\frac{S}{\text{kpc}}} \sqrt{\frac{L_c}{100\text{pc}}} \]  

(1b)

2.1 Correlation

The angular distance between two points on a sphere is the great circle distance (Equation 2 for normal vectors). Correlations between energy and angular distance are found using Kendall’s $\tau_b$ ranked correlation that measures monotonic dependence [10]. Ranked correlation removes magnetic model and composition assumptions and also detector exposure effects on the correlation strength.

\[ \delta_{ij} = \arctan \frac{|\hat{\mathbf{h}}_i \times \hat{\mathbf{h}}_j|}{\hat{\mathbf{h}}_i \cdot \hat{\mathbf{h}}_j} \]  

(2)

The simplified $\tau_{ab}$, not taking into account duplicate values, is shown in Equation 3 for brevity. The difference between $\tau_a$ and $\tau_b$ in this analysis is small. Ranks are the ordering of a sorted variable (1st, 2nd, etc.). A pair of observed ranks $(x_i, y_i)$ and $(x_j, y_j)$ are concordant if $x_i > x_j$ and $y_i > y_j$ (or the converse). They are discordant if $x_i > x_j$ and $y_i < y_j$ (or the converse).

\[ \tau_a = \frac{(\# \text{ concordant pairs}) - (\# \text{ discordant pairs})}{n(n-1)/2} \]  

(3)
Drift-diSGB has a $-\delta \cos \tau$ relationship. The parameters $^2_\phi * - B \tau = Z_j D$ and shown in Figure 2(a). With 29 events $\sin \tau (5a)$, $\cos W$ corr $S$ $\tau \cos (\phi - B \leq \Delta B - \Delta)$ is the maximum angular distance. The supergalactic latitude (SGB) has an azimuth, $\phi_j$, which is given by Equation 5b. The azimuths go clockwise. The pre-trial significance of a correlation (probability $^2_\tau = 0$ with infinite samples) is a function of correlation strength and sample size. This is found by permutations of the sample or the large sample limit of Equation 4 (again for $^2_\tau$) that follows the standard normal distribution.

$$z = \frac{\tau_a 3n(n-1)/2}{\sqrt{n(n-1)(2n + 5)/2}} \quad (4)$$

### 2.2 Correlation Filter

With the drift-diSGB picture of Figure 1 in mind, possible UHECR deflections from a source are found by calculating energy-position correlations inside spherical cap sections, or “wedges,” on a grid of points with an equal spacing of 2° within the field of view (FOV) [11].

These wedge bins are defined by a maximum radius $\delta_i$ from the grid point, $i$, (Equation 2) and the boundaries of two azimuths (Equation 5a). The azimuths go clockwise and a wedge pointed towards 90° supergalactic latitude (SGB) has an azimuth, $\phi_j$, of zero and one pointed towards -90° SGB has a $\phi$ of 180°. The angular distance between the wedge pointing direction, $\phi_i$, and an events azimuth is given by Equation 5b.

$$\phi_{ij} = \text{atan} \left( \frac{\cos B_i \sin (L_i - L_j)}{\cos B_j \sin B_i - \sin B_j \cos B_i \cos (L_i - L_j)} \right) \quad (5a)$$

$$\Delta \phi_{ij} = \text{mod}(|\phi_{ij} - \phi_i| + 180, 360) - 180 \quad (5b)$$

With this correlation filter shape four parameters must be scanned at every grid point to maximize the pre-trial significance. Though negative correlations are physically expected from magnetic deflections; the sign of the correlation, and its strength, are not scanned for nor restricted. The limits on these parameters are large to account for conceivable deflection scenarios and are the following:

1. Energy Threshold, $E_i$: 10 to 100 EeV, 5 EeV steps.
2. Wedge Angular Distance, $D_i=\max(\delta_i)$: 15° to 90°, 5° steps.
3. Wedge Direction, $\phi_j$: 0° to 355°, 5° steps.
4. Wedge Width, $W_i = 2 \times \max(|\Delta \phi_{ij}|)$: 10° to 90°, 10° steps (5° on each side of $\phi_i$).

Events are in the wedge if $E_i \geq E_i & \delta_i \leq D_i & -W_i/2 \leq \Delta \phi_{ij} \leq W_i/2$ (i is the grid point index). The parameters $(E_i, D_i, \phi_i, \text{ and } W_i)$ are chosen for the minimum energy-position correlation, corr$(\delta_i, E_i)$, p-value (Equation 4).

The most significant correlation is at 18.3° SGB, -12.9° SGL and shown in Figure 2(a). With 29 events $(E_{\geq 30 \text{ EeV}})$ $\tau_a=-0.675$ has pre-trial significance of 5.5σ. Figure 2(b) shows a scatter plot of energy versus angular distance and a linear fit (Equation 1a with $Z=1$) results in an estimate of $S*B = 49.24 \text{ kpc*} \mu G$. If the source is assumed to be at the distance to M82 (3.7 Mpc) the uniform magnetic field required to cause this deflection would be $B=13 \text{ nG}$.

### 3 Simulations

Two Monte Carlo (MC) simulated event sets are used in this analysis. This first is an isotropic simulation assuming no specific sources or correlation with the supergalactic (or galactic) plane. The analysis is applied to isotropic simulations for the significance calculation of any anisotropy found as described further in Section 4. The second is a simple simulation of a supergalactic magnetic sheet resulting in an energy dependent diffusion of events away from the supergalactic plane. This is used to motivate the statistic that tests the hypothesis of supergalactic sources and magnetic fields; this test statistic is described in Section 4 and is searched for in the isotropic MC. These simulations can also be used as an estimate of the average uniform field strength between us and supergalactic sources.

#### 3.1 Isotropic Simulation

Events are defined by energy, zenith angle, azimuthal angle, and trigger time. Latitude and longitude are the center of Telescope Array (39.3° Long., 112.9° Lat.). These horizontal coordinates are used to calculate the supergalactic longitude (SGL) and latitude (SGB) coordinates. Actual data coordinates are used for the isotropic simulations.
3.2 Supergalactic Magnetic Sheet Simulation

A simple toy-model simulation of an intervening supergalactic magnetic sheet is made by embedding event deflections in supergalactic latitude (SGB), proportional to $1/\text{energy}$, for a fraction of events in isotropic simulations. The approximate apparent deflection from the source of a charged particle in a uniform magnetic field is shown in Equation 1a [9]. A supergalactic sheet simulation, with an $F = 65.7\%$ isotropic fraction (1988 out of 3027 events) is simulated by sampling the trigger times of 264,499 data events with $E > 10^{17.7}$ eV. The azimuthal angle distribution is uniform from 0° to 360° and the zenith angle distribution is $g(\theta) = \sin(\theta)\cos(\theta)$ due to the flat SD array.

The deflections $\delta_j$ are calculated for each MC event, $j$, assuming proton ($Z=1$) and an $S*B$; events with initial positive $SGB$ have a positive deflection and a negative $SGB$ have a negative deflection. Then the event positions, $SGB_j$, and energies, $E_i$, are decoupled into separate sets. The energies, $E_i$, and their deflection from $SGB = 0$ ($\delta_i$) are assigned to the closest $SGB_j$ value ($\min|\delta_i - SGB_j|$ in random order.

For any $S*B$ there will be a number of event positions that must be assigned isotropic energies due to the minimum deflection and the FOV. After the assignment of an $SGB_j$ the energies, $E_i$, with a position-deflection error of $|SGB_j - \delta_i| > 10^\circ$ are put into the isotropic proportion. This allows some random noise in the simulation.

Event positions of $SGB_j < \min(\delta_i)$ (the center of Figure 3), or $SGB_j > \max(\delta_i)$ (the edges of Figure 3), are also part of the isotropic proportion. For larger isotropic total fractions, $F$, a random selection of energies and positions are taken from the anisotropic portion and randomized.

4 Supergalactic Structure

No single correlation tests the hypothesis that sources and magnetic fields are correlated with local large scale structure. And no single correlation can be significant when taking into account the >100,000 scan parameter combinations at all 6553 grid points. To test for supergalactic structure of multiplets the mean $\tau_b$ inside equal solid angle bins of angular distance ($SGB_b$) from the supergalactic plane are used. The pre-trial significance of the correlations are not used as they were scanned for. The correlation strength, $\tau_b$, is used because it is not explicitly scanned for and contains more information by its sign ($\pm$).

The expectation is that negative correlations will be closer to the supergalactic plane. Furthermore, since negative correlations viewed from the opposite direction appear as a positive correlations ($(x_j, y_j) \rightarrow (x_j, -y_j)$), positive correlations are expected at large angular distances from the supergalactic plane. This is shown by a projection of the $\tau_b$ for the magnetic sheet simulation in Figure 4(a) and its averages $\tau_b$ in Figure 4(b).
Figure 4. Supergalactic magnetic sheet simulation. (a) Projection of the correlation strength $\tau_b$ for all grid points. Solid curves indicate the galactic plane (GP) in blue and supergalactic plane (SGP) in red. (b) Mean $\tau_b$ inside equal solid angle bins for the supergalactic magnetic sheet simulation. The parabola shows the curvature parameter, $a$, chosen as the test statistic. $a = 2.5 \times 10^{-4}$.

4.1 Significance Test

The single parameter necessary to test the supergalactic structure of multiplets hypothesis is the curvature parameter, “$a$”, of a parabolic fit ($ax^2 + bx + c$) to the mean $\tau_b$ in the supergalactic latitude bins shown in Figure 4(b). Due to the boundaries of $|\tau_b| \leq 1$ and $|SGB| < 90^\circ$, greater correlation curvature, $a$, corresponds to a minimum closer to the supergalactic plane as shown in Figure 5. It also means that the minimum negative correlation, and maximum positive correlation, averages are larger in magnitude.

$\chi^2/df < 10$.

The additional cuts on pointing direction error and boundary distance improve the agreement between the distribution of zenith angles compared to the geometrical zenith angle exposure $g(\theta) = \sin(\theta)\cos(\theta)$. The azimuthal angle distribution is in very good agreement with the theoretical flat distribution. The energy spectrum is also in good agreement with the published spectrum ([14],[16]).

The energy resolution and zenith angle resolution of events in the data set range from $\sim 10$ to $15\%$ and $\sim 1.0^\circ$ to $1.5^\circ$ respectively, depending on core distance from the array boundary and improve with increasing energy. These resolutions are sufficient to search for UHECR energy anisotropies.

6 Results

The resulting data energy-position correlations are shown in Figure 6(a). Individual correlations with the highest pretrial significance are negative which means that there is a trend for the angular distance to increase with decreasing energy. This is the expectation for a grid point that happens to be near a UHECR source of magnetically scattered events. It can be seen that the negative $\tau_b$ correlations appear well correlated with the supergalactic plane.

Figure 6(b) shows the mean $\tau_b$ correlation of the data inside equal solid angle bins parallel to the supergalactic plane. The parabola curvature test statistic is $a = 2.4 \times 10^{-4}$ and the minimum is at $-1.1$ SGB. It can be seen that the data correlations have a very similar form to that of the supergalactic magnetic sheet simulation, shown in Figure 4(b), that has a slightly higher $a = 2.5 \times 10^{-4}$ at $-1.7$ SGB.
the Gaussian fit from $a=2.4 \times 10^{-4}$ to $a=\infty$ gives a significance of 4.6$\sigma$. Therefore, the resulting significance of a supergalactic structure of multiplets is about 4.5$\sigma$.

6.2 Scan Parameter Distributions

Clues about UHECR sources, and intervening fields, may be found from the maximum significance wedge scan parameters of the apparent magnetic deflection multiplets. Due to the significance maximization there is a bias towards larger statistics so the data is compared to isotropic MC by taking the ratio of the parameter PDFs (Data/MC). PDF ratio plots for the wedge angular distance and energy threshold parameters are shown in Figure 8.

These ratios are for negative correlations at positions $-40^\circ < SGB_i < 40^\circ$ and have a linear fit to $1/E$ versus angular distance with $R^2>0$. An $R^2=0$ is a better fit than a horizontal line and the $\delta\propto E$ model explains some of the variance. For data there are 2045 correlations used and greater than $3.99 \times 10^8$ for MC.

The data distributions of wedge angular distance, $D$, and width, $W$, do not show significant deviations from isotropy. The distribution of wedge pointing directions, Figure 8(a), indicates supergalactic structure with three deviations correlated with the supergalactic plane (SGP). Two peaks are approximately perpendicular to the SGP and one is parallel. This suggests diffusion of low energy events away from the supergalactic plane similar to the supergalactic magnetic sheet simulation. Three deviations of the energy threshold parameter are 35 EeV, 45 EeV, and 60 EeV. The last may correspond to the 57 EeV threshold of the TA hotspot analysis [15].

There are two MC sets with a larger curvature than data which gives a significance of $4.3\pm0.2\sigma$. The area under

Figure 6. Data result. (a) Projection of the correlation strength $\tau_b$ for all grid points. Negative correlations expected for magnetic deflections are apparent around the supergalactic plane. Solid curves indicate the galactic plane (GP) in blue and supergalactic plane (SGP) in red. White and grey hexagrams indicate the Galactic center (GC) and anti-galactic center (Anti-GC) respectively. (b) Mean $\tau_b$ inside equal solid angle bins. The correlation curvature for the data is $a=2.4 \times 10^{-4}$.

Figure 7. The distribution of the correlation curvature parameter $a$ chosen as the supergalactic structure of multiplets test statistic for 200,000 isotropic MC sets. The purple bars are the MC PDF. The red line is a Gaussian distribution fit to the MC distribution. The data curvature is $a=2.4 \times 10^{-4}$ shown as a blue vertical line.

Figure 8. PDF ratio plot of scanned parameters. (a) Wedge pointing direction parameter, $\phi$. Blue lines are perpendicular to the SGP and red lines are parallel. (b) Energy threshold, $E$. The three largest deviations are at 35 EeV, 45 EeV, and 60 EeV.
7Summary

Intermediate-scale energy-position correlations inside spherical cap sections are shown to be correlated with the supergalactic plane. This structure has a $\sim 4.5 \sigma$ significance using 7 years of Telescope Array SD data. This is possible evidence of large scale magnetic diffusion of ultra-high energy cosmic rays from their sources correlated with the local large scale structure. Confirmation of this result may be done once sufficient data is collected by the Telescope Array expansion to TAx4 [17].

References

[1] G. de Vaucouleurs, Astrophys. J. 202, 610 (1975)
[2] A. Bonafede, L. Feretti, M. Murgia, F. Govoni, G. Giovannini, D. Dallacasa, K. Dolag, G.B. Taylor, Astron. Astrophys. 513, A30 (2010), 1002.0594
[3] F. Nicastro, J. Kaastra, Y. Krongold, S. Borgani, E. Branchini, R. Cen, M. Dadina, C.W. Danforth, M. Elvis, F. Fiore et al., Nature 558, 406 (2018)
[4] P.L. Biermann, H. Kang, D. Ryu, p. 9 p (1997), astro-ph/9709250
[5] D. Ryu, H. Kang, P.L. Biermann, Astron. Astrophys. 335, 19 (1998), astro-ph/9803275
[6] Pierre Auger Collaboration, P. Abreu, M. Aglietta, E.J. Ahn, I.F.M. Albuquerque, D. Allard, I. Allekotte, J. Allen, P. Allison, J. Alvarez Castillo et al., Astropart. Phys. 35, 354 (2012), 1111.2472
[7] A. Aab, P. Abreu, M. Aglietta, E.J. Ahn, I.A. Samarai, I.F.M. Albuquerque, I. Allekotte, J. Allen, P. Allison, A. Almela et al., EPJ C 75, 269 (2015), 1410.0515
[8] H.P. Bretz, Ph.D. thesis, Rheinisch-Westphalian Technical University of Aachen (2011)
[9] P.G. Tinyakov, I.I. Tkachev, Astropart. Phys. 24, 32 (2005), astro-ph/0411669
[10] M.G. Kendall, Biometrika 33, 239 (1945)
[11] N.A. Teanby, Computers and Geosciences 32, 1442 (2006)
[12] R.U. Abbasi et al. (HiRes), Phys. Rev. Lett. 100, 101101 (2008), astro-ph/0703099
[13] D. Ivanov, Ph.D. thesis, Rutgers, the State University of New Jersey (2012), http://telescopearray.com/images/papers/theses/thesis_ivanov_rev2016.pdf
[14] T. Abu-Zayyad et al. (Telescope Array), Astrophys. J. 768, L1 (2013), 1205.5067
[15] R.U. Abbasi et al. (Telescope Array), Astrophys. J. 790, L21 (2014), 1404.5890
[16] R.U. Abbasi et al., Astropart. Phys. 68, 27 (2015), 1410.3151
[17] H. Sagawa, The Plan of the Telescope Array Experiment for the Next Five Years, in Proceedings, 33nd ICRC (ICRC2013): Rio de Janeiro, Brazil, July 2-9 (2013), p. 0121, http://www.cbpf.br/~icrc2013/papers/icrc2013-0121.pdf