Investigation of the Displacement Angle of the Highest Energy Cosmic Rays Caused by the Galactic Magnetic Field

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Abstract. **Ultra-high energy cosmic rays (UHECR) are deflected by magnetic fields during their propagation. Different theoretical parameterizations of the Galactic magnetic field are examined using a numerical tool which simulates their propagation through models of these fields. We constrain the possible parameter space of the models by comparing data on UHECR obtained with the Pierre Auger Observatory with the results of the simulations.**

Keywords**: Auger, magnetic field, constraints**

I. Introduction

Current knowledge on the strength and shape of the Galactic magnetic field is limited [1], [2], [3], [4], [5], [6], [7]. While there are hints [3], [4], [5], [6], [7] at the form and magnitude of the regular component of the Galactic magnetic field there is currently no consensus on its general form or magnitude. Presented here is a method for determining regions of magnetic field model parameter space which are compatible with a given set of assumptions. Combining this method with complementary methods [8] employing multi-wavelength observations will improve the global delimiting power. This method is applied to determine regions of parameter space for two Galactic magnetic field models and under two dramatically different sets of assumptions: 1) the Pierre Auger Observatory [9] (Auger) anisotropy result with a pure proton composition and 2) Centaurus A as a dominant source with a pure iron composition.

II. Data Set

This analysis uses data recorded by the southern site of the Auger Observatory between 1 January 2004 and 31 March 2009 with energies greater than 55 EeV and zenith angles smaller than 60°.

III. Galactic Magnetic Field Models

Logarithmic symmetric spiral field models [1], [10] are used to model the large scale regular Galactic magnetic field in this work. Axisymmetric [Bi-symmetric] (denoted herein as ASS_* [BSS_*]) fields exhibit [anti-]symmetry under rotations of π around the Galactic pole. Fields [anti-]symmetric under reflection across the Galactic plane are denoted with *SS_S [*SS_A]. A precise description of the models used, including the nominal parameter values, is given by Harari et al. [1].

These models are likely not a complete description of the Galactic magnetic field [2], [3], [5], [7], [11]. There is evidence of turbulent and halo fields in the Galaxy [2], [3], [4], [7], [6], [12] and others [13], [14], [11]. Furthermore, extra-galactic magnetic fields [15], [16], [17] will also have an effect on the results of this work. However, logarithmic symmetric spirals represent a priori reasonable models for the functional form of the regular component of the Galactic magnetic field [4], [14][1]. Here we present results using two logarithmic symmetric spiral models: BSS_S and ASS_A.

IV. Method

Regions of compatible parameter space are determined by testing the Auger Observatory data under a set of assumptions. The general method presented here requires a hypothesis which defines the following: 1) A charge for each observed event, 2) a catalog which traces the true source distribution and parameters for correlation (Ψ_{max}), 3) a model for the magnetic field. A region of interest in parameter space is then gridded and all events are backtracked through the model at each grid point. The region around the direction of the exiting velocity vector for each event is then searched for the nearest catalog object. Finally, the number of events (N_{corr}) correlating ($\Psi \leq \Psi_{max}$) with the hypothesized source catalog are interpreted relative to the number of correlations determined without backtracking through the magnetic field model.

The statistical significance of N_{corr} is determined by assuming that the number of correlations with the non-backtracked arrival directions (N^0_{corr}) is an estimate of the true number of correlations for the parameters given. We take the number of correlations with the non-backtracked arrival directions as an estimate of the mean of a Poisson distribution. We expect this to be a conservative estimator of the true probability mass function[2]. A region of compatibility is defined as lying centered on the mean and containing 68% of random N_{corr} values sampled from this distribution. Scan points with N_{corr} values lying outside this region are considered incompatible with the full set of assumptions (field, source, and composition). Figure 1 shows two Poisson distributions with shaded regions found using the above method.

[1]The results presented herein may depend on the specifics of turbulent, halo, or extra-galactic magnetic fields which are poorly constrained, as such the effects of such fields have been ignored in favor of presenting a clear description of the method used.

[2]We have verified this by smearing the data with a 2D gaussian and examining simple Monte Carlo realizations.

TABLE I: Example Assumptions

	VCV	CenA
Composition	Pure proton	Pure iron
Source Distribution	VCV Catalog	Centaurus A
Correlation Scale (Ψ_{max})	3.1°	15°
Minimum Energy (E_{max})	55 EeV	55 EeV
Poisson Mean (N^0_{corr})	27	9

V. Examples

Here we present two examples for clarity. Each example explicitly assumes a composition, a source distribution, and angular correlation window which can be found in Table I.

The first example is inspired by the Auger Observatory anisotropy result [9] and will be referred to as the VCV example throughout. By correlating the arrival directions of UHECR with Active Galactic Nuclei (AGN) from the Veron Catalog of Quasars & AGN, 12th Edition [18] (VCV catalog) and comparing the results with what one would expect from a truly isotropic source distribution, the Auger Observatory found that their observations were consistent with a sampling of a distribution similar to the VCV catalog. The Auger Observatory scanned over three parameters: maximum redshift (z_{max}), maximum angular correlation scale (Ψ_{max}), and minimum energy (E_{min}) finding the strongest correlation signal for $z_{max} = 0.018$, $\Psi_{max} = 3.1°$ and $E_{max} = 55$ EeV (equivalent to 57 EeV as reported in [9] due to a small change in our energy calibration). This analysis uses VCV catalog objects with a redshift ≤ 0.018.

The second example assumes that Centaurus A (Cen A) is the dominant source in a region centered around it. This example is referred to as the Cen A example throughout. We have arbitrarily chosen $\Psi_{max} = 15°$.

Both examples use the minimum energy ($E > 55$ EeV) found in the Auger Observatory anisotropy result [19], [20]. Compatible regions for both BSS_S and ASS_A Galactic magnetic field models are presented. Neither the overall strength nor the scale height of the Galactic magnetic field is well constrained [1], [2], [4], [10]. Thus for each of the two models two parameters are varied: the strength of the field in the solar vicinity ($B_\odot$) and the dominant scale height (z_1). $B_\odot$ is varied from -2.5 μG to 2.5 μG in steps of 0.01 μG and from 0.05 kpc to 3.05 kpc in z_1 in steps of 0.1 kpc.

VI. Results

A. VCV

Figures 2a and 2b show the regions of $B_\odot$- z_1 parameter space compatible with the Auger Observatory anisotropy result. The regions of compatibility are defined using the method described in Sec. IV above. This example uses a $N^0_{corr} = 27$ to define the mean of the Poisson distribution from which we determine our compatibility regions. The shaded regions correspond to the similarly shaded regions in Fig. 1a. There are some general features to both field models which should be noted. First, z_1 is not well constrained as both models have regions compatible with the Auger Observatory anisotropy result extending across all reasonable scale lengths. Second, that connected statistically compatible regions lie within the range over which $B_\odot$ is varied.

There is marked difference in the compatible parameter space between ASS_A (Fig.2a,) and BSS_S (Fig.2b) models. ASS_A has large connected compatible regions only for a small range in $B_\odot$ centered around zero. Furthermore, no regions appear to improve the number of correlations, thus it is likely that the compatible regions are simply where the correlation with the arrival directions have yet to be destroyed. ASS_A is compatible only with $|N_\odot| < 1$ μG which is lower than the expected value [1], [3], [4], [5]. Overall, the ASS_A model is incompatible with the VCV correlation hypothesis in the regions deemed acceptable due to other constraints.

The connected compatible (gray and dark gray) region for BSS_S model is much larger and extends over a significant range in $B_\odot$. Furthermore, extended regions exist where N_{corr} is above 27, the nominal value, indicating candidate models where the correlations are preserved and new correlations are made.

B. Cen A

Figures 3a and 3b show the regions of $B_\odot$- z_1 parameter space compatible with the Cen A hypothesis. This example uses a $N^0_{corr} = 9$ to define the mean of the Poisson distribution from which we determine our compatibility regions. The shaded regions correspond to the similarly shaded regions in Fig. 1b.

This parameter space shares features with the previous example, mainly that z_1 is not well constrained and compatible regions of parameter space tend to prefer positive field strengths. The most striking feature of this parameter space is the very limited range in field strength compatible with the underlying hypothesis; both models require a field strength in the solar vicinity of less than 0.24 μG.

VII. Conclusion

Presented is a method which can be used to determine compatible regions of parameter space for magnetic field models using UHECRs. Regions of parameter space are shown for two common Galactic magnetic field models compatible with either the Auger Observatory anisotropy results and a pure proton composition or with Cen A as a dominant source on a $15°$ scale with a pure iron composition. These regions are determined through a statistical comparison between the results of correlations between Auger Observatory data and either the VCV catalog or Cen A and similar correlations between particles backtracked through BSS_S and ASS_A Galactic magnetic field models.

By assuming a pure proton composition and VCV catalog correlation parameters, it is found that the ASS_A model has a smaller compatible parameter space while

BSS_S model is largely compatible with the Auger Observatory anisotropy result. The BSS_S model appears to improve the correlation with VCV catalog objects for a wide range of parameters. While the limited number of events available for this analysis limits our ability to make concrete predictions, there are hints that regions of parameter space for BSS_S model in particular should be examined for consistency with other measurements. When Cen A is assumed to be a dominant pure iron source, the compatible regions of parameter space for both BSS_S and ASS_A Galactic magnetic field models are much smaller than expected from other measurements. Both examples do not constrain the scale height of the models.

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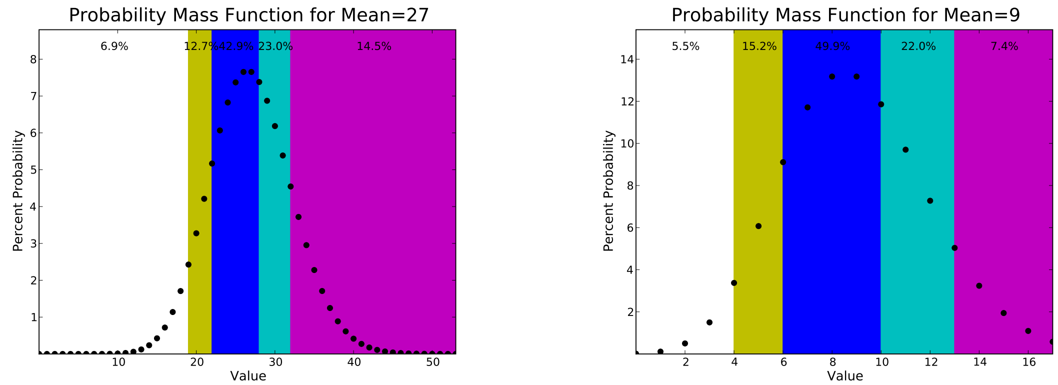
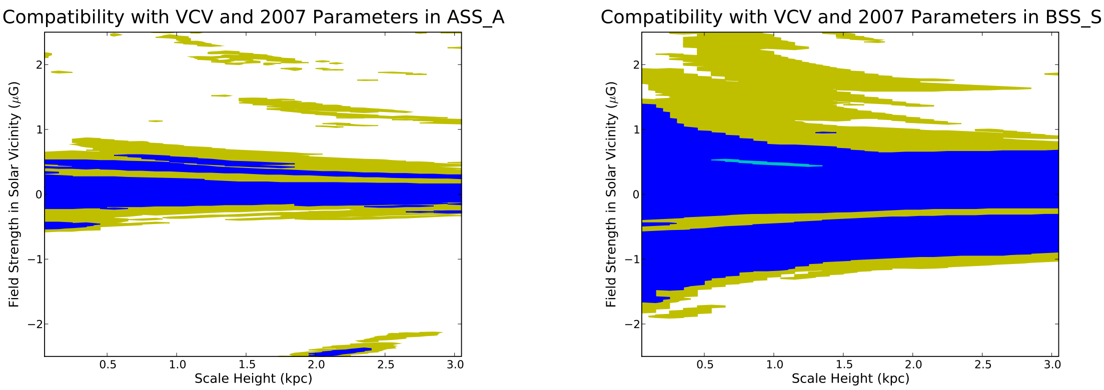


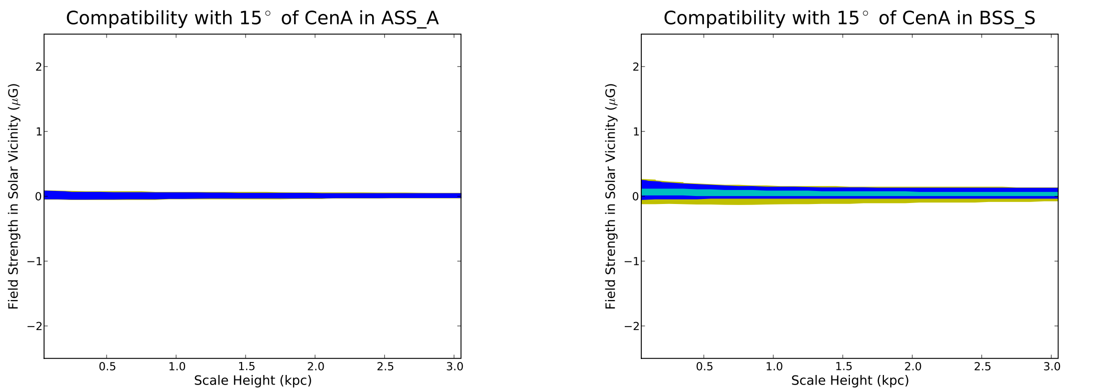
(a) Poisson distribution corresponding to the VCV example. (b) Poisson distribution corresponding to the CenA example.

Fig. 1: Circles represent the percent probability of obtaining each value. Regions shaded to indicate the portion of probability space occupied by corresponding regions in Figs. 2 and 3



(a) ASS_A Galactic magnetic field model. (b) BSS_S Galactic magnetic field model.

Fig. 2: Regions shaded in: white has [0-19), light gray has [19,22), gray has [22,28), and dark gray has [28,32) correlations. The ASS_A model reaches a maximum of 28 correlations while the BSS_S model has a maximum of 29.



(a) ASS_A Galactic magnetic field model. (b) BSS_S Galactic magnetic field model.

Fig. 3: Regions shaded in: white has [0-4), light gray has [4,6), gray has [6,10), and dark gray has [10,13) correlations. The ASS_A model reaches a maximum of 10 correlations while the BSS_S model has a maximum of 13.