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What number of cosmic ray events do we need to measure source catalogue correlations?

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Recent analyses of cosmic ray arrival directions have resulted in evidence for a positive correlation with active galactic nuclei source positions that has weak significance against an isotropic source distribution. In this paper, we explore the sample size needed to measure a highly statistically significant correlation to a parent source catalogue. We compare several scenarios for the directional scattering of ultra-high energy cosmic rays given our current knowledge of the galactic and intergalactic magnetic fields. We find significant correlations are possible for a sample of >1000 cosmic ray protons.

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1. Introduction

The origin of ultra-high energy cosmic rays (UHECRs) is a long-standing unsolved problem, which has defied an observational solution in large part due to magnetic field scattering. As cosmic rays propagate from their sources, the galactic and intergalactic magnetic fields deflect their trajectories so that only the highest energy particles are rigid enough to point back to their sources. UHECRs also lose energy as they propagate through space due to interactions with photon backgrounds [1, 2], meaning that the sources of UHECRs observed with energies $\gtrsim 6 \times 10^{19}$ eV are expected to be $\lesssim$200 Mpc away. The intergalactic magnetic fields, although weak, interact with UHECRs over the whole course of their trajectory, which can result in large deflections. These combined effects mean that source directions can become isotropized resulting in weakly significant correlations with a parent source catalogue.

Recently, the Auger collaboration has been searching for correlation in the arrival directions of ultra-high energy cosmic rays with the active galactic nuclei (AGN) source distribution represented by the Veron-Cetty & Veron (VCV) catalogue [3, 4, 5]. They compare their catalogue correlation with the correlation due to an isotropic source distribution to estimate the statistical significance of their result. The test assumes three parameters: 1) the energy threshold, motivated by the expectation that above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1, 2] UHECRs are extra-galactic, 2) a correlation angle, motivated by the degree to which the galactic magnetic field may scatter events and result in significant source confusion, and 3) the maximum redshift of catalogue sources to consider in the correlation analysis, motivated by the expectation that UHECRs above the GZK cutoff are $\lesssim$200 Mpc away.

In their latest release [5] the correlation to VCV AGN provided only weak evidence of anisotropy along with weak clustering around Centaurus A. The HiRes and Telescope Array collaborations performed similar studies finding no evidence of deviation from isotropy [6, 7, 8].

Future UHECR detectors could provide the exposure needed to reveal anisotropy and clustering to source catalogues. Proposed space-based observatories such as the JEM-EUSO mission [9] and radio detection satellites [10, 11] offer the possibility of significantly extending the sample of UHECRs available for source correlation analysis.

This paper provides an estimate the UHECR sample size that could lead to a statistically significant source catalogue correlation with a full-sky survey of UHECRs above the the energy threshold, E_{th}, of 60 EeV. Given current limitations on knowledge of source composition as well as galactic and intergalactic magnetic fields, we provide estimates for various assumptions on these parameters.

2. Cosmic Ray Scattering due to Galactic and Intergalactic Magnetic Fields

Intergalactic magnetic fields: Current bounds in the strength of the intergalactic magnetic field constrain B_0 to a range $10^{-17} - 10^{-9}$ G. The upper bound $B_0 < 10^{-9}$ G is due to the impact of intergalactic magnetic fields on cosmological perturbations and CMB anisotropies using Planck data, see [13]. The lower bound $B_0 > 10^{-17}$ G is due to the non-observation of GeV γ-rays by the Fermi Large Area Telescope following from TeV γ-rays observed by HESS [14].

The intergalactic magnetic field coherence length λ_B is also poorly constrained over a large range. A theoretical argument of magneto-hydrodynamic turbulence decay results in a constraint that $\lambda_B > 0.1$ Mpc at $B_0 = 1$ nG and $\lambda_B > 10^{-6}$ Mpc at $B = 10^{-15}$ G. A detailed review of modern constraints of the IGMF parameters can be found in [15]. Motivated by the results of [16] we will assume $B_0 = 1$ nG and $\lambda_B > 0.1$ Mpc for our study.

Galactic magnetic fields: The galactic magnetic fields are classified in terms of the disk and halo contribution, each with their own parameters B_0, λ_B, and D. The disk and halo magnetic fields can have regular ($D \leq \lambda_B$) and turbulent ($D > \lambda_B$) components. The galactic disk's regular magnetic field effect on the scattering of UHECRs was studied by Stanev [17] with a magnetic field strength of $B_0 \sim 2\ \mu$G. The distance over which the UHECR is deflected is limited by the thickness of the disk and assumed to be $D \sim 2$ kpc. The turbulent component of the galactic disk's magnetic field is assumed to have a strength of $B_0 \sim 4\ \mu$G with a coherence length $\lambda_B \sim 50$ Mpc [18]. The magnetic field of the galactic halo is less well known. Studies conducted by Jansson et al. 2009, [19] estimate a regular magnetic field with strength $B_0 \sim 2\ \mu$G over a distance of $D \sim 8.7$ kpc. Other measurements [20] indicate the halo magnetic field strength may be significantly higher. No observational constraints on the turbulent component of the galactic halo magnetic field are known.

Scattering of UHECRs by Magnetic Fields: Several parameterizations of the magnetic field scattering of UHECRs exist in the literature [21, 22, 23]. In this work we adopt the results from Lee et al., 1995 [24], as presented in Neronov and Semikoz, 2009 [18], which provide a parameterization valid for energies $E > 10$ EeV, including the varying scales for the coherence length λ_B, magnetic field strength B_0, and charge number Z. This parameterization for the mean scattering angle of a UHECR due to interactions with a magnetic field is given by

$$\vartheta_{scat} = 2.6^\circ \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{D}{50\ \mathrm{Mpc}}\right) \left(\frac{B_0}{10^{-10}\ \mathrm{G}}\right) Z, \tag{2.1}$$

for a regular field and

$$\vartheta_{scat} = 0.23^\circ \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{D}{50\ \mathrm{Mpc}}\right)^{0.5} \left(\frac{B_0}{10^{-10}\ \mathrm{G}}\right) \left(\frac{\lambda_B}{1\ \mathrm{Mpc}}\right)^{0.5} Z \tag{2.2}$$

for a turbulent field.

UHECRs are scattered over a distance, D, which varies with magnetic field model. For intergalactic magnetic fields, D is the distance to the source, while for galactic magnetic fields, it is the bounding distance relevant to the different regions of the galaxy. Here we average over the structure in the galactic halo and disk. A more detailed treatment is described in [24]. The halo magnetic fields dominate the scattering while disk turbulent scattering tends to be a small effect. Iron nuclei are significantly deflected even for the galactic magnetic field disk turbulent contribution. For the IGMF, we set $B_0 = 1$ nG and provide results for three coherence length values $\lambda_B = 0.1$, 1, 10 Mpc according to the constraints provided by [15] and [16]. While the studies leading to the scattering models used here provide the average or root-mean-square scattering angles, they do not provide or discuss their statistical distribution. We assume that the scattering angles are Rayleigh distributed with mode σ_{scat}, which is related to the mean scattering angle via $\sigma_{scat} = \vartheta_{scat}\sqrt{2/\pi}$. The scattering from a source catalogue will be estimated by sampling this distribution.

3. Cosmic Ray Source Model and Propagation

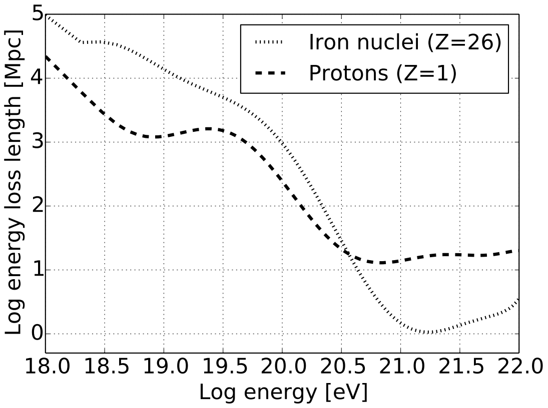


Figure 1: Energy loss length as function of cosmic ray energy. This plot has been implemented by considering [25] for protons ($Z = 1$) and [28] for iron nuclei ($Z = 26$).

Cosmic ray energies are attenuated through particle interactions as they propagate through the Universe. Protons at the highest energies lose energy by producing pions through interactions with the CMB [1, 2]. The energy loss length for protons, shown here in Fig. 1, shows that UHECRs with energies above 4×10^{19}eV are likely to be substantially attenuated. We adopt the proton loss length calculations by [25], based on the analytical formulae from [26]. Heavy nuclei, such as iron, lose energy through pair production on the CMB and photo-disintegration through interactions with CMB and IR-UV background photons [27]. Photohadronic energy loss has been re-examined in recent years, as they are based on empirical measurements of the intergalactic background radiation and photonuclear interactions. We use [28] as our model for iron energy loss length, which is representative of the modern calculations [29, 30, 31].

As the cosmic ray propagates through space, it is subject to adiabatic losses due to the expansion of the Universe as well as losses due to interaction with background photons. The density and energy of background photons is also changing as the Universe expands. To account for these losses, we discretely propagate the cosmic ray energy from its source at redshift z to $z = 0$ in steps of Δz. Given the energy E_k at step k, the enegy E_{k+1} at step $k+1$ is given by

$$E_{k+1} = E_k \left(1 - \frac{\Delta z}{1+z_k} - \frac{\Delta z}{\lambda_\gamma(E_k)} \frac{cH_0^3}{H^2(z_k)}\right)$$

The second term in the right hand side is due to the adiabtic redshift losses while the third term is given by the interaction with background photons corrected for their evolution as the Universe expands. The energy-dependent cosmic ray attenuation length due to photon interactions is given by $\lambda_\gamma(E)$. The Hubble constant tuday is given by H_0 while the Hubble parameter at redshift z is given by $H(z)$.

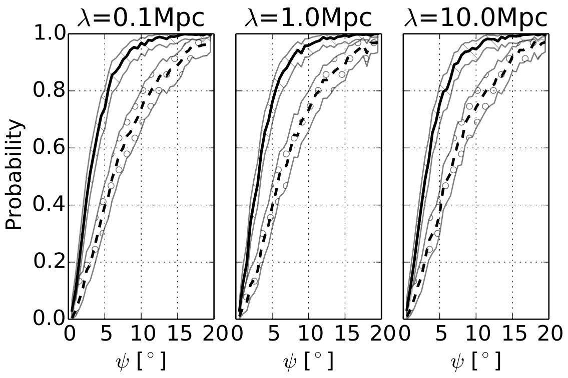
4. Correlation to the VCV source catalogue

The Veron-Cetty & Veron (VCV) catalogue 12th edition [33] is a compendium of known AGN, largely derived from the 2dF catalogue, and the Sloan Digital Sky Survey. While it is known to be a non-uniform survey, we use it here for direct comparisons with prior searches for correlations with AGN by Auger [3, 5], HiRes [6], and TA [7]. However, hereafter, we treat it as a mock catalogue of UHECR sources, by using it both as the source distribution and catalogue for correlation analysis.

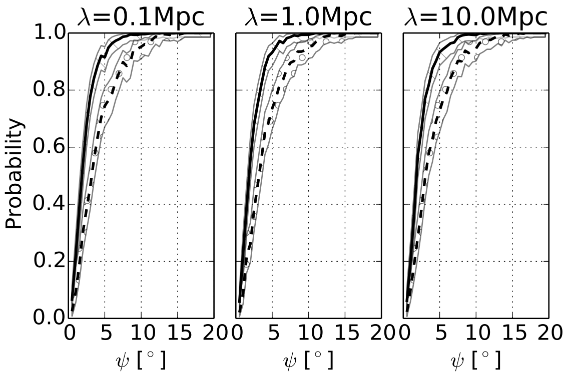
In this section, we describe the correlatetion of cosmic rays sampled from the VCV catalogue to VCV catalogue sources. The goal is to determine under which scenarios it is possible to discriminate between a catalogue correlation and an isotropic source distribution with $> 5\sigma$ confidence as a function of cosmic ray sample size.

The correlation analysis follows the procedure applied by the Auger collaboration [3, 5]. We compare the arrival direction of an event with the position the source in the source catalogue. An event correlates to the catalogue if the angular distance between the source and the arrival direction of the cosmic ray is within a correlation angle, ψ. We leave this as a free parameter, while the Auger collaboration [3, 5] fixed ψ at 3.1°. Given a sample of N cosmic ray events, k of which correlate to the catalogue, the probability of the data being correlated to the catalogue is given by that fraction $p_{data} = k/N$. We apply a cut on the distance of sources used for correlating against the event sample. We call this the correlation distance cutoff, which the Auger collaboration set at 75 Mpc.

The parameters tested in this study are source composition and the properties of the galactic and intergalactic magnetic fields. We look at the effects of galactic and intergalactic magnetic fields by testing the following scenarios: GMF halo and disk (regular+turbulent) components and IGMF, GMF disk (regular+turbulent) component and IGMF, only IGMF. In addition to testing the IGMF λ_B at 0.1, 1.0, and 10 Mpc for a magnetic field strength of B_0=1 nG in each case, we also compare source compositions comprising 100% protons and 100% iron nuclei.



(a) 75 Mpc correlation distance cutoff



(b) 200 Mpc correlation distance cutoff

Figure 2: Probability of correlation as function of correlation angle ψ for 1000-proton UHECRs, with 0.1, 1 and 10 Mpc IGMF coherence length, scattering in both the galactic halo and disk, and 1° angular resolution. (a) 75 Mpc correlation distance cutoff (b) 200 Mpc correlation distance cutoff. The dashed line is for isotropic events and the solid line is for catalogue sampled events. The shaded regions are 5σ confidence intervals.

The probability of correlation, p_{data}, as a function of correlation angle, ψ, for both the VCV catalogue and an isotropic source distribution are shown in Fig. 2. It is clear that an optimal value of ψ exists that statistically discriminates between source catalogue and isotropic source distribution correlations. In Fig. 2 we have plotted p_{data} vs. ψ assuming different values of the IGMF coherence length λ_B. We find that there is no significant effect on the optimal value of ψ that depends on λ_B. We have also plotted p_{data} vs. ψ for correlation distance cutoffs of 75 and 200 Mpc. In this case, a significant difference in the behavior is found, which favors a 75 Mpc correlation distance cutoff.

The impact of the choice of correlation distance cutoff on the optimal value of ψ is better represented in Fig. 3. Here we have subtracted the p_{data} for isotropic source distribution from p_{data} for the catalogue, including the 5σ uncertainty intervals. The optimal correlation angle is lower and more highly peaked for a correlation distance cutoff of 200 Mpc ($\psi = 2.0°$) than at 75 Mpc ($\psi = 4.0°$).

It is worth noting that a distance cutoff of 200 Mpc is a better match to the propagation distance at which UHECRs with E> 60EeV fall below this value in the estimates made as part of this study. It also includes 80% of the inverse-squared sampled sources from VCV catalogue, while only 50% are included with the 75 Mpc cutoff. In Table 1, we compare the statistical significance from isotropy for the two correlation distance cutoffs. The 75 Mpc correlation distance cutoff generally increases the significance of the correlation slightly.

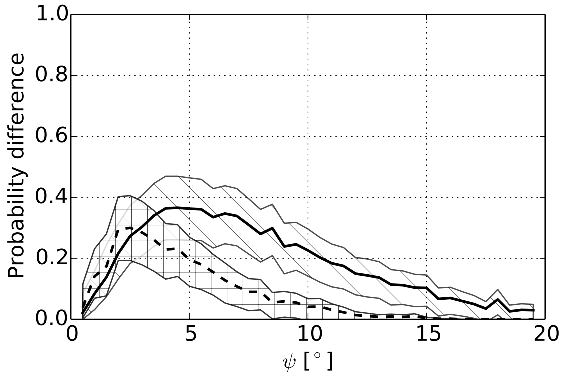


Figure 3: Probability difference between the 1 Mpc λ_B line and the assumed isotropic distribution from Figure 2. *Shaded region:* 75 Mpc correlation distance cutoff. *Squared region:* 200 Mpc correlation distance cutoff. These two regions are 5σ confidence intervals.

The confidence level intervals in Table 1 contain > 99.9% of the posterior probability for p_{data} given the measured values of k and N. The posterior probability distribution is $C_b(k,N)p_{data}^k(1-p_{data})^{N-k}$ corresponding to a binomial distribution, where $C_b(k,N)$ is the binomial coefficient. The confidence levels are computed assuming a 1° detector angular resolution.

There are several proton-dominated scenarios which result in highly significant source catalogue correlations. Inclusion of galactic magnetic field scattering reduces the likelihood of a significant detection ($> 5\sigma$) the most. On the order of 1,000 events are required for scenarios with only protons and full scattering off the galactic halo and disk to discriminate between anisotropic and isotropic distribution of UHECRs at the 5σ level. There are no realistic scenarios wherein iron UHECRs result in significant correlations with the catalogue. Assuming that there is no scattering within the galaxy, small (0.1 Mpc) IGMF coherence lengths, a sample size of 1000 events, correlations at the 4 to 5σ level were found for the correlation distance cutoffs of 200 Mpc and 75 Mpc, respectively. Studies of the scattering off of the galactic magnetic field are relatively recent [18, 19], and we confirm their results that iron nuclei are likely to be isotropized by the galactic magnetic fields. We find that an improved detector resolution does not improve the chances of detecting a source catalogue correlation at greater than 5σ.The differences in correlation significance are consistent with statistical fluctuations at the 1-2σ level, when comparing results from a detector with 1° angular resolution and one with 3° angular resolution.

The effects of varying the coherence length is most pronounced in scenarios where we do not include galactic magnetic field scattering. Longer coherence lengths scatter both protons and iron more, making them more consistent with isotropy. Galactic magnetic field scattering diminishes this effect, such that the correlation significances vary by less than 1σ for all coherence lengths in cases where scattering in the galaxy was included.

Table 1: Statistical significance from isotropy, in units of σ for selected proton and iron scenarios, for energy index $\gamma = 2.7$. Last column contains the number of sigmas away from isotropic distribution for 100, 1000, 10000 proton UHECR events.

Z	IGMF λ_B[Mpc]	GMF	Dist.Cutoff [Mpc]	Resolution [°]	ψ_{max}[°]	N=10^2	N=10^3	N=10^4
1	0.1	Halo & Disk	75	1	4.5	1.3	4.9	15.8
1	0.1	Disk Only	75	1	5.5	1.6	5.4	17.3
1	0.1	None	75	1	2.5	4.3	16.0	50.8
1	1.0	Halo & Disk	75	1	6.0	1.4	5.3	18.1
1	1.0	Disk Only	75	1	6.0	0.9	5.5	18.6
1	1.0	None	75	1	3.0	2.9	13.0	44.8
1	1.0	Halo & Disk	200	1	3.5	0.8	4.0	13.7
1	1.0	Disk Only	200	1	3.0	1.3	3.9	12.6
1	1.0	None	200	1	2.5	2.9	11.2	38.2
1	10.0	Halo & Disk	75	1	6.0	1.8	4.7	16.6
1	10.0	Disk Only	75	1	4.0	1.4	4.3	14.0
1	10.0	None	75	1	4.0	2.1	8.6	27.4
1	0.1	Halo & Disk	75	1	0.5	0.5	1.3	3.0
1	0.1	Disk Only	75	1	1.0	1.0	2.0	5.2
1	0.1	None	75	1	5.0	4.0	15.6	63.6

5. Conclusions

The streamlined model presented here estimates the requirements for of an state-of-art experiment to detect significant correlations from a source catalogue. We analyzed the required event rate above an energy threshold of 60 EeV of a future UHECR all-sky instrument for identifying sources, assuming several realistic scenarios with differing cosmic ray composition and magnetic field models. Such a simple parametric simulation does not require large computing power, but is capable of characterizing the trends and challenges for source identification. For instance, we find that angular resolutions better than 3° do not improve the detectability of the source catalogue correlations. The peak correlation angle varies with magnetic field model, but was always $\geq 2°$. Assuming some scattering in the galaxy, the ψ resulting in maximum correlation indicates that a detector's minimum angular resolution need only be as good as $\sim 2°$, even in the case of longer λ_B. Scattering in the galactic disk isotropizes the cosmic ray distribution more than scattering outside of the galaxy, despite the relatively unconstrained intergalactic magnetic field coherence length. Longer coherence lengths of the IGMF scatter UHERCs even further, but that scattering does not dominate the results of the correlation analysis. Future experiments would benefit from an improved understanding of the magnetic fields within the galaxy. If cosmic rays are predominantly iron, a detection of greater than 10^4 events above 60 EeV would be required for source identification, and therefore, an exposure greater than 100 times the state of the art. However, if they are predominately proton, an experiment that detects 10^3 could expect a correlations with a source catalogue at $> 4\sigma$ even with the strongest deflection in the galactic halo and disk. A full sky survey of UHECRs should have an exposure greater than 10 times the current state-of-the-art and proposed instruments as well as an improved understanding of the composition of cosmic rays, which is consistent with [12].

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