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Feasibility of cosmic ray backtracking through future sparse local measurements of the galactic magnetic field

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Future optopolarimetric surveys of stars, including PASIPHAE and SOUTH POL, offer the potential for acquiring high-quality local measurements of the Galactic magnetic field (GMF) at interstellar cloud locations. However, the inherent sparsity of these measurements raises concerns regarding the feasibility of accurately backtracking Ultra High-Energy Cosmic Rays (UHECR) to their sources, a crucial aspect of charge-particle astronomy. In this study, we assess the achievable accuracy of UHECR backtracking using mock sparse local GMF data derived from the Jansson & Farrar 2012 (JF12) GMF model. By creating 1000 mock UHECR datasets that trace back within a 3° angular range from the galaxy M82, we investigate the impact of varying GMF measurement sparsity and rescaling of the GMF strength. Our findings demonstrate that an average GMF strength of $1\mu G$ yields satisfactory backtracking results even with sparse measurements, requiring an average GMF measurement spacing of approximately 1600 pc. However, when the average GMF strength is increased by a factor of 3 or 10, the accuracy of backtracking diminishes significantly, resulting in breakdowns at measurement spacings of 1600 pc and 400 pc, respectively. These findings emphasize the challenges associated with precise charge-particle astronomy using sparse local GMF measurements and underscore the importance of obtaining dense and high-quality GMF data through surveys like PASIPHAE and SOUTH POL to enable accurate backtracking of UHECR.

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1. Introduction

Cosmic rays (CRs) have been a subject of fascination for physicists since their discovery in 1912. These high-energy particles, primarily consisting of atomic nuclei, offer a unique opportunity to study the most energetic phenomena in the Universe.

At lower energies CRs have contributed significantly to our knowledge of particle physics. However, it is the ultra-high-energy cosmic rays (UHECRs) that pose a fascinating mystery. With energies exceeding 10^{18} eV and some reaching astonishing levels of 10^{20} eV, UHECRs challenge our understanding of particle acceleration and cosmic phenomena.

The study of UHECRs is inherently challenging due to their electric charge, which causes them to be deflected by both extragalactic and Galactic magnetic fields (EGMF and GMF). As these charged particles traverse the cosmos, their paths become distorted, making it difficult to precisely determine their sources. While neutral messengers, such as photons, can travel directly from their sources to us, UHECRs must navigate through magnetic fields, obscuring their origin information.

To overcome these challenges, researchers have focused on backtracking UHECRs to their source locations using models of the GMF and EGMF. By reconstructing the paths of UHECRs, scientists aim to identify their sources and gain insights into the acceleration mechanisms and propagation processes involved. However, accurately backtracking UHECRs requires a detailed understanding of the GMF and EGMF, which are complex and challenging to model.

In recent years, advancements in observational techniques have enabled high-quality local measurements of the GMF at the locations of interstellar clouds. Surveys such as PASIPHAE [2] and SOUTH POL employ optopolarimetry of stars to provide valuable data on the GMF. However, these measurements are inherently sparse, raising concerns about the accuracy of backtracking UHECRs and enabling charge-particle astronomy.

In this study, we aim to assess the accuracy of backtracking UHECRs using mock sparse local data from the Jansson & Farrar 2012 (JF12) [3] GMF model. By creating a set of 1000 mock UHECR events that backtrack within a 3° range of the starburst galaxy M82, we evaluate the feasibility of tracing these events back to their source. We investigate varying levels of sparsity in the GMF measurements and rescaling factors for the GMF strength to understand the limitations of backtracking accuracy.

2. Testing existing GMF models

When a relativistic particle with charge $q = Ze$ (where $Z \in \mathbb{Z}^*$ and e is the charge of an electron) moves through a constant magnetic field $\vec{B}$ and an electric field $\vec{E}$, its equation of motion is given by the Lorentz force. The equation of motion, accounting for the relativistic effects, is described as:

$$\frac{d}{dt}\left(m\gamma\vec{v}\right) = q\left(\vec{E} + \vec{v} \times \vec{B}\right), \tag{1}$$

where γ represents the Lorentz factor. Using this equation we can backtrack a charged particle in a Galactic magnetic field where there is practically no Electric field ($\vec{E} = 0$) and the speed of the particle is practically equal to the speed of light ($v = c$). Thus for the velocity of particle we get

$$\hat{v}_{\text{prev}} = \hat{v}_{\text{now}} - \frac{Zec^2}{E}\left(\hat{v} \times \vec{B}\right)\delta t. \tag{2}$$

By considering a small time interval δt and setting $\delta\vec{r} = \vec{r}_{\text{now}} - \vec{r}_{\text{prev}}$, where $\vec{r}$ represents the position, we find:

$$\vec{r}_{\text{prev}} = \vec{r}_{\text{now}} - \vec{v}\delta t = \vec{r}_{\text{now}} - \hat{v}c\delta t. \tag{3}$$

These equations, (2) and (3), are used in our code to numerically calculate the position and velocity of a UHECR during the depropagation process.

In this paper, we assume that cosmic rays consist solely of protons ($Z = 1$). The starting position for the backtracking of all cosmic rays is set to $\vec{r} = (-8.5, 0, 0)$ kpc in a Cartesian system centered on the Galactic center, as the depropagation process begins from Earth. The velocity unit vector (i.e., the direction of velocity) is determined from the Galactic coordinates (l, b) as follows:

$$\begin{aligned} v_z &= \sin b,\ \ v_x = \cos b \cos l, \\ v_y &= \cos b \sin l \end{aligned} \tag{4}$$

and the Galactic coordinates are determined from the velocities as follows:

$$\begin{aligned} b &= \arcsin v_z, \\ l &= sign v_y \arccos \frac{v_x}{\cos b}, \end{aligned} \tag{5}$$

If $l < 0$, we increase it by 2π to avoid negative angles. Additionally, we neglect the intergalactic magnetic field and assume that cosmic rays propagate as free particles until they enter the Galaxy.

Next we perform backtracking by calculating the angular position θ of 74 real cosmic rays based on their Galactic coordinates with respect to the M82 galaxy. The angular position is given by:

$$\theta = \arccos\left[\sin b_{cr} \sin b_{M82} + \cos b_{cr} \cos b_{M82} \cos\left(l_{cr} - l_{M82}\right)\right], \tag{6}$$

where l represents the longitude and b represents the latitude in gGlactic coordinates. We compare the angular distances before and after backtracking as a function of E^{-1} to assess the accuracy of the backtracking process.

3. Creation of fake events

We will create a set of 1000 mock CRs events that originate within an angular distance of 3° from M82. In order to get the same energies distribution, we plotted in a histogram the energies of real CR events [4] and fitted upon that a shifted exponential Probability Distribution Function (PDF) of the form

$$f(x;\lambda) = \lambda e^{-\lambda(x-k)}, \tag{7}$$

where λ is the parameter of the distribution and k the shift in the position of the distribution. In Fig. 1 we can see that the exponential fit is a quite good approximation for the energies distribution.

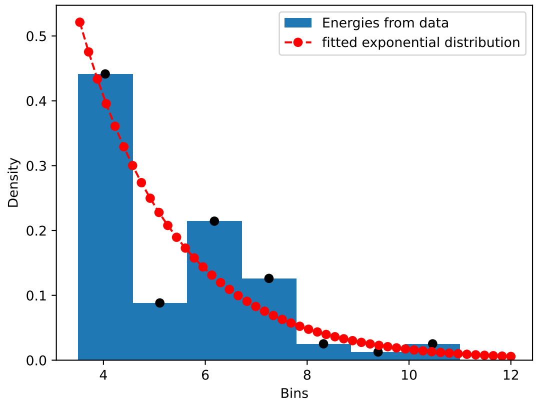

Figure 1: Histogram of energies of the CRs from the data. On the horizontal axis are the values of the energy and on the vertical axis is the number of CRs with that energy range over total number of CRs.

To create these fake CRs we need three quantities: (a) their energy E, which is defined as an exponential random variable with a PDF that of the fit made to the real data and described in Eq. (7); (b) Their longitude l, which is defined as a uniform random variable in the range $[0, 2\pi]$; and (c) their latitude b whose cosine is defined as a uniform random variable in the range $[-1, 1]$ and then found by taking the arccos of the previous value. The other parameters for our cosmic rays are either fixed, i.e. their starting position in the Galaxy being that of the Earth's or their charge which is $Z = 1$, or can be derived from these 3 quantities, that is their velocity direction can be found using the latitude and longitude from eqs. (4). In order to remove the bias for high energies in the process of whether a fake cosmic ray is suitable for our set or not, that is determining if it originates within an angular distance of 3° from M82, since higher energy particles are deflected less than lower ones, we added an extra step in our code that if the particle didn't fit the criteria we kept the same energy and then we generated a different set of l and b up until it passed the aforementioned test.

In [1] it is hinted that the magnetic field of our Galaxy may be stronger that the models predict, so in order to account for that possibility we multiplied the non-random part of the model with a strength amplification factor f that we set to 1, 3 or 10. So for each of these values we created a separate set of fake events.

4. Implementation and Results

The magnetic field can be measured locally in interstellar clouds within the Galaxy, but these clouds are not close to one another. The distance between clouds varies. To simulate this reality of sparse measurements, as a zeroth order of approximation, we divided the Galaxy into cubes of side length L and inside each cube we assumed a constant magnetic field value and direction that was found by calculating these quantities at the center of each cube. In this way we can control the sampling of the magnetic field values (the number of cubes), by changing the value of L. Using this new "measurement" of the GMF we backtracked the previously created sets of CRs, using the appropriate factor f for each set, for various values of L and after the process of depropagation we calculated the mean angular distance from M82 $\overline{\theta}$ from the sample mean equation

$$\overline{\theta} = \frac{1}{N}\sum_{n=1}^{N}\theta_n, \tag{8}$$

where N is the total number of CRs, thus $N = 1000$, and θ_n is the angular distance from M82 of the n-th CR. Another quantity we calculated in order to quantify the effectiveness of the backtracking process is the sample variance for the angular distance σ_θ, which was calculated from the sample deviation formula

$$\sigma_\theta = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(\theta_n - \overline{\theta})^2}. \tag{9}$$

After evaluating these two quantities for every value of f and L, we plotted $\overline{\theta}$ and σ_θ as a function of L. In Fig. 2 we can see the mean angular position of our fake events after the depropagation, in the corresponding field strength for each case, as a function of the slice length of the cubic grid.

To simulate the more realisting situation of measuring local magnetic fields with a significant observational uncertainty, we sampled the new value of the magnetic field strength value through a Gaussian distribution with mean that of the strength given by the model and a standard deviation of 0.25 or 0.5 times that value. In Fig. 3 we can see the standard deviation of the angular distance of our fake events after the backtracking. We can see that for both the $f = 1$ and $f = 3$ cases we get reasonably accurate results for all cube length sizes we consider, whereas for the more extreme case, $f = 10$ the results are much poorer due to the loss of resolution.

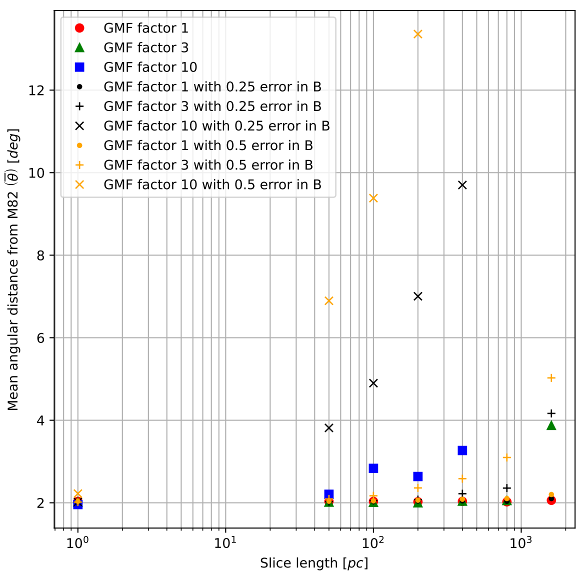

Figure 2: Mean angular position of our fake events after the depropagation as a function of the slice length of the cubic grid.

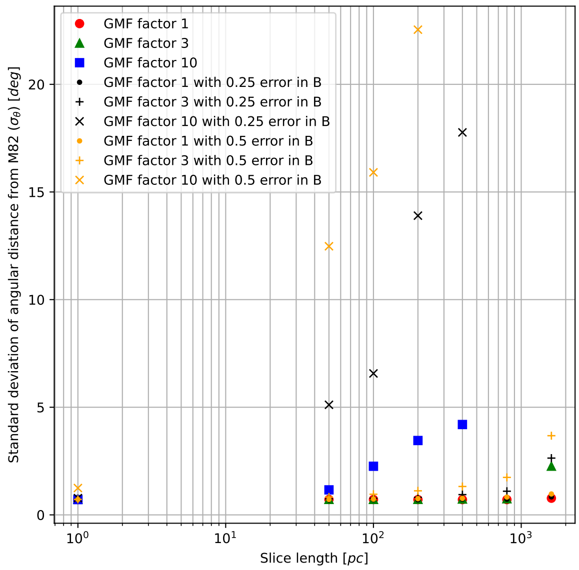

Figure 3: Standard deviation of the angular position of our fake events after the depropagation as a function of the slice length of the cubic grid.

5. Conclusion and Discussion

The analysis of the backtracking process reveals that, when considering an average GMF strength of 1 μG, even with sparse measurements that have an average spacing of 1600, pc, satisfactory results can be achieved in tracing the trajectories of UHECRs back to their potential source, M82. This suggests that, under these conditions, the GMF exerts a relatively small effect on the deflection of UHECRs, allowing for accurate backtracking over considerable distances.

However, the study also demonstrates that as the GMF strength increases, the accuracy of backtracking deteriorates, particularly when the measurement spacing become larger. This observation highlights the need for precise measurements of the GMF in order to gain a better understanding of the sources of these energetic particles.

The finding that sparse measurements with larger spacings can still provide reliable backtracking results in the presence of a moderate GMF strength suggests that, in cases where dense measurements are not available or feasible, it may still be possible to infer the likely source regions of UHECRs using a limited number of measurements taken at larger intervals as long as these measurements are accurate enough.

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