ULTRA–HIGH-ENERGY COSMIC-RAY SOURCES AND LARGE-SCALE MAGNETIC FIELDS

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Received 1997 April 21; accepted 1997 June 24

ABSTRACT

Protons of energies up to about 1020 eV can be subject to significant deflection and energy-dependent time delay in large-scale extragalactic or halo magnetic fields of strengths comparable to current upper limits. By performing three-dimensional Monte Carlo simulations of nucleon propagation, we show how observations of arrival direction and time distributions can be used to measure the structure and strength of large-scale magnetic fields and constrain the nature of the source of ultra–high-energy cosmic rays.

Subject headings: cosmic rays — magnetic fields

1. INTRODUCTION

If extragalactic magnetic fields (EGMFs) exist, then they are at a level below detectability with presently available techniques. Faraday rotation measures of distant powerful radio sources give upper limits to extragalactic fields of \( B_{\text{rms}} \lesssim 10^{-8} \text{ G Mpc}^{-1/2} \), where \( l \) denotes the reversal length of the field (see, e.g., Kronberg 1994). However, EGMFs below these current limits are of significant interest to cosmology, galaxy and star formation, and galactic dynamos (see, e.g., Kronberg 1994; Olinto 1997).

The propagation of ultra–high-energy cosmic-rays (UHECRs) is affected by the presence of EGMFs of strength \( 10^{-12} \text{ G} \lesssim B_{\text{rms}} \lesssim 10^{-8} \text{ G} \) and/or by Galactic halo fields \( 10^{-8} \text{ G} \lesssim B_{\text{H}} \lesssim 10^{-6} \text{ G} \). Protogalactic fields in the former range are actually expected if the Galactic magnetic field cannot be explained by a Galactic dynamo (Kulsrud & Anderson 1992). In this Letter, we study how EGMFs and the halo magnetic field, which we collectively name large-scale magnetic fields (LSMFs), affect UHECRs with energies \( E \approx 10 \text{ EeV} \) (\( \text{EeV} = 10^{18} \text{ eV} \)). We simulate the propagation of ultra–high-energy nucleons in the LSMF and the cosmic microwave background (CMB), and we show how the resulting angle-time-energy images of these UHECRs could be used, in turn, to probe LSMFs with strengths in the above range. Suitable UHECR statistics could be achieved with future experiments, such as the Japanese Telescope Array (Teshima et al. 1992), the High Resolution Fly’s Eye (Al-Seady et al. 1996), and the Pierre Auger Project (Cronin 1992), that have the potential to detect about 10–100 particles per source with \( E \approx 10^{19} \text{ eV} \), over an approximately 5 yr period. Although the origin and nature of UHECRs are not known, they are likely to be generated in extragalactic sources (e.g., Bird et al. 1995; Yoshida et al. 1995; Hayashida et al. 1996), such as powerful radio galaxies (e.g., Rachen & Biermann 1993), cosmological \( \gamma \)-ray bursts (Vietri 1995; Waxman 1995; Milgrom & Usoskin 1996), and/or topological defects (e.g., Bhattacharjee, Hill, & Schramm 1992; Sigl 1996). Our results can also be used to discriminate between models of the origin of UHECRs.

Previous studies of the effect of the LSMF on UHECRs have included a discussion of the energy-dependent deflection and time delay for extragalactic UHECRs (Cronin 1992; Waxman & Miralda-Escudé 1996; Medina Tanco, de Gouveia Dal Pino, & Horvath 1997). In addition, the effect of EGMFs on secondary \( \gamma \)-rays produced in the interaction of ultra–high-energy protons with CMB photons can also probe EGMFs below current upper limits: Plaga (1995) and Waxman & Coppi (1996) proposed to use the arrival time delay of secondary \( \gamma \)-rays in the TeV range to probe EGMFs of strength \( B_{\text{rms}} \lesssim 10^{-15} \text{ G} \), while Lee, Olinto, & Sigl (1995) showed how fields of strength \( B_{\text{rms}} \sim 10^{-6} \text{ G} \) affect the \( \gamma \)-ray spectrum around 10 EeV through electron synchrotron losses.

2. ANGLE-TIME-ENERGY IMAGES

Nucleons propagating in intergalactic space with energies \( \lesssim 10 \text{ EeV} \) are mainly subject to scattering on the LSMFs and pair production on the CMB (for protons), as well as photo-pion production on the CMB. Pair production dominates the energy loss below \( \approx 70 \text{ EeV} \), which we include as a continuous loss process (Chodorowski, Zdziarski, & Sikora 1992). Above \( \approx 70 \text{ EeV} \) photo-pion production dominates and gives rise to the Greisen-Zatsepin-Kuzmin cutoff (hereafter GZK cutoff; see Greisen 1966; Zatsepin & Kuzmin 1966). We model photo-pion production as a stochastic process in which the chance of interaction is drawn at random, as described in Lee (1996) and Sigl et al. (1997a). We model the EGMF as a Gaussian random field, with zero mean in Fourier space and a power spectrum of \( \langle B^2(k) \rangle \propto k^{\alpha} \) for \( k < 2 \pi/l_0 \), and \( \langle B^2(k) \rangle = 0 \) otherwise. Here, \( l_0 \) characterizes the cutoff scale of magnetic fluctuations; we choose \( l_0 = 1 \text{ Mpc} \) as a fiducial value for the EGMF. The power spectrum is normalized via \( B_{\text{rms}}^2 = V/(2\pi)^3 \int dk B^2(k) \). We leave the detailed description of our Monte Carlo code to Sigl, Lemoine, & Olinto (1997b).

A simpler version of the present study was carried out by Medina Tanco et al. (1997). These authors described the field as an assembly of randomly oriented bubbles of constant field, with diameter equal to the coherence length, and neglected the stochastic nature of pion production. Finally, they considered the limit \( D\theta_0 \gg l_0 \), where \( D \) denotes the distance to the source, and \( \theta_0 \) denotes the deflection angle at energy \( E \). In contrast, the limit \( D\theta_0 \approx l_0 \) is not only the most probable for \( E > 10^{19} \text{ eV} \), but it also is the most difficult to treat (see Sigl et al. 1997b). The importance of distinguishing the limits \( D\theta_0 \gg l_0 \) and \( D\theta_0 \ll l_0 \) was pointed out by Waxman & Miralda-Escudé (1996). In the latter limit, all nucleons emitted by the source and captured on the detector have essentially experienced the same magnetic structure along their paths; hence, the scatter around the mean of the correlations between the time delay \( \tau \), the deflection angle \( \theta \), and the energy \( E \), is of
order 1%. In the opposite limit, $D\theta_\parallel > l_\parallel$, the relative widths of these correlations are of order unity. Concerning the angular image, we note that for $D\theta_\parallel > l_\parallel$, one expects to see an image centered on the source, of angular width $\theta_\parallel$, whereas for $D\theta_\parallel \approx l_\parallel$, the source should be seen as one or several images, of negligible angular widths, displaced from the source by a systematic offset $\theta_\parallel$ (Lee et al. 1995). This offset depends inversely on the energy, so that if the source is seen at different energies, then the zero point of deflection, and hence $\theta_\parallel$, can be reconstructed.

Our simulations generate data consisting of the energy, arrival time, and angular direction for each UHECR emitted from the source. For general reference, we can estimate the rms deflection angle $\theta_\parallel$ and the average time delay $\tau_\parallel \approx D\theta_\parallel^2/4c$ induced on a proton of energy $E \approx 50$ EeV over a distance $D$ in the limit $D \gg l_\parallel$. Using Waxman & Miralda-Escudé (1996),

$$\tau_\parallel \approx 15.5 \left(\frac{3 + n_\parallel}{2 + n_\parallel}\right) \left(\frac{D}{10 \text{ Mpc}}\right)^2 \left(\frac{E}{10 \text{ EeV}}\right)^{-2} \times \left(\frac{B_{\text{rms}}}{10^{-11} \text{ G}}\right) \left(\frac{l_\parallel}{1 \text{ Mpc}}\right) \text{ yr},$$

and $\theta_\parallel \approx 0.052(D/10 \text{ Mpc})^{-1/2} (\tau_\parallel/1 \text{ yr})^{1/2}$. This estimate agrees with the empirical time delay derived from our simulations. The Faraday rotation bound $B_{\text{rms}}/c < 10^{-9} \text{ G Mpc}^{1/2}$ implies $\tau_\parallel \approx 2.3 \times 10^5(D/10 \text{ Mpc})(E/10 \text{ EeV})^{-2} \text{ yr}$, and $\theta_\parallel \approx 9/7(D/10 \text{ Mpc})^{1/2}(E/10 \text{ EeV})^{-1}$, assuming $n_\parallel \approx 0$. In what follows, we address the possible observables for different cases. In §§ 2.1 and 2.2, we discuss the case of an extragalactic bursting source. In § 2.3, we discuss the case of a continuously emitting source. In these sections, we consider the case in which the time delay induced by the EGMF dominates over that of the halo magnetic field of our Galaxy. In § 2.4, we discuss how the domination by a halo field would modify our conclusions. We use the notations $\tau_{\text{obs}} = \tau_{\parallel -100 \text{EeV}}$, $\theta_{\text{obs}} = \theta_{\parallel -100 \text{EeV}}$.

2.1. Observable Time Delays

When $\tau_{\text{obs}} \approx 1 \text{ yr}$, the time delay is comparable to the integration time of the experiment, $T_{\text{exp}}$. In this case, the limit $D\theta_\parallel < l_\parallel$ holds as the Faraday rotation bound is combined with $\tau_{\text{obs}} \approx 1 \text{ yr}$.

The distinction between a burst and a continuous source (emission timescale $T_{e} \gg 1 \text{ yr}$) becomes immediate: equation (1) implies a strong correlation between arrival time and energy for a burst, whereas arrival time and energy should be independent for a continuous source. In the case of a burst, the observation of the arrival time and energy of two events is sufficient to determine a zero point in time (time of emission), hence the value of $\tau_{\parallel}$ and, equivalently, $DB_{\text{rms}}/c$. The distance can be independently derived by fitting the energy spectrum above the GZK cutoff, provided there is enough statistics. Thus, one ends up with an estimate of the distance to the source, the nature of the source (e.g., burst vs. continuous emission), and the value of $B_{\text{rms}}/c$. Observations of several clusters of events would thus “map” the EGMF. Finally, one can show, from $\tau_{\text{obs}} \approx D\theta_\parallel^2/2 \approx 1 \text{ yr}$, that $\theta_\parallel$ could not be measured for a typical detector with resolution $\delta \theta \approx 0.5^\circ$. That typical time delays above tens of EeV may be of the order of a few years is suggested by a detailed likelihood analysis (Sigl et al. 1997b) of the three pairs of events that were recently reported by the AGASA experiment (see Hayashida 1996).

2.2. Large Time Delays

If $\tau_{\parallel} > T_{\text{obs}}$ and $\theta_{\text{obs}}$ is approximately a few years, then a given source will be seen only on a limited range in energy (Waxman & Miralda-Escudé 1996); indeed, protons with higher energy have already reached us in the past, while protons with lower energy have yet to reach us. These authors have derived the shape of the energy spectrum in the limit $D\theta_\parallel > l_\parallel$, for $E \approx 50 \text{ EeV}$, where the signal has significant scatter $\Delta E/E \sim 30\%$; in the opposite limit $D\theta_\parallel < l_\parallel$, $\Delta E/E \sim 1\%$. In principle, the measure of the width would tell us which limit applies and would give us some information about $B_{\text{rms}}$ and $l_\parallel$. However, this statement depends strongly on the distance, as $D\theta_\parallel/l_\parallel \propto D^{1/2}$. For sufficiently large time delays, the angular image of the source could be resolved for $E \approx 50 \text{ EeV}$, if $D\theta_\parallel > l_\parallel$, in which case the value of $B_{\text{rms}}/c$ becomes accessible. For $D\theta_\parallel < l_\parallel$, unless an optical counterpart can be identified, the offset $\theta_\parallel$ could not be measured, as the source is seen only in a limited range of energies (see also § 2). The argument developed by Waxman & Miralda-Escudé (1996) should tell us which limit applies.

For sources that are observed above the pion production threshold, the previous statements do not apply. However, in this limit, one can use a similar reasoning to obtain an estimate of the distance. At a fixed time, only a given range of energies is observed. Intuitively, the larger the distance, the more important the pion production, hence the broader the signal. This effect is illustrated in Figures 1 and 2. Figure 1 shows the image of the source in the time-energy plane for a source lying at $D = 60 \text{ Mpc}$. The correlation $\tau_{\parallel} \propto E^{-2}$ is shown as a dotted line. In this plane, the effect of pion production is mainly to downscatter from higher energies to lower energies, with a
trend toward increasing the time delay for a given energy at emission. Figure 2 shows the correlation between the width of the signal in energy, as actually seen by the detector, versus the mean energy of the signal. This signal is obtained as a slice in the $\tau_\gamma$-$E$ image, integrated between $t$ and $t + T_{\text{obs}}$, where $T_{\text{obs}} = 5$ yr in this case and $t$ is arbitrary; this slice is indicated in Figure 1 by the dashed lines. An example of the signal in energy so obtained is shown in Figure 3 (dashed line). The correlation shown in Figure 2 was obtained by measuring the width of the signal for different mean energies, corresponding to different choices of $t$, and adjusting a straight-line fit. The shaded areas denote the 1 $\sigma$ range of (numerical) uncertainty. These uncertainties actually provide a hint of the actual experimental uncertainties associated with such measurements, as the number of particles used in the Monte Carlo simulation fit (see Fig. 3). For sufficiently large time delays (see § 2.2), $\tau_\gamma$ should be measurable in either limit $D\theta_k \ll I$, or $D\theta_k \gg I$, as different energies are detected (see § 2). The actual magnitude of $\tau_\gamma$ can thus be derived, as $\tau_\gamma \propto D\theta_k^2$. Therefore, not only can the magnetic field strength $B_{\text{rms}}/I$ be determined, but the timescale of emission is also obtained as a by-product. If $T_s \sim T_{\text{obs}}$ then the deflection angle cannot be measured, but the time delay could be directly measured, as in § 2.1, and the above results still hold. In the intermediate case, 1 yr $\ll T_s \lesssim 10^3$ yr, one could only place an upper limit on the magnetic field strength, $B_{\text{rms}}/I \lesssim 10^{-25}$ G Mpc$^{-1/2}$ (see text). The dotted line shows how the spectrum would continue if $T_s \gg 10^4$ yr. The case of a bursting source corresponds to a slice of the image in the $\tau_\gamma$-$E$ plane, as indicated in Fig. 1 by dashed lines. For both spectra, $D = 30$ Mpc and $\gamma = 2$.

The energy spectrum above $E_b$ can be used to estimate the distance $D$, for a given injection spectrum, via a pion production fit (see Fig. 3). For sufficiently large time delays (see § 2.2), $\theta_k$ should be measurable in either limit $D\theta_k \ll I$, or $D\theta_k \gg I$, as different energies are detected (see § 2). The actual magnitude of $\tau_\gamma$ can thus be derived, as $\tau_\gamma \propto D\theta_k^2$. Therefore, not only can the magnetic field strength $B_{\text{rms}}/I$ be determined, but the timescale of emission is also obtained as a by-product. If $T_s \sim T_{\text{obs}}$ then the deflection angle cannot be measured, but the time delay could be directly measured, as in § 2.1, and the above results still hold. In the intermediate case, 1 yr $\ll T_s \lesssim 10^3$ yr, one could only place an upper limit on the magnetic field strength, $B_{\text{rms}}/I \lesssim 10^{-25}$ G Mpc$^{-1/2}$ (see text). The dotted line shows how the spectrum would continue if $T_s \gg 10^4$ yr. The case of a bursting source corresponds to a slice of the image in the $\tau_\gamma$-$E$ plane, as indicated in Fig. 1 by dashed lines. For both spectra, $D = 30$ Mpc and $\gamma = 2$.

2.3. Continuously Emitting Sources

The case of a continuous source, emitting on a timescale $T_s$, is obtained by folding, on the time axis, the angle-time-energy image of a corresponding bursting source, with a top hat of width $T_s$. In principle, for a given magnetic field configuration, there will be an energy $E_b$, such that $T_s = \tau_\gamma$. For $E \gg E_b$, no correlation is expected between arrival times and energies, as the arrival time distribution is dominated by the uniform top hat in this limit. In contrast, for $E \ll E_b$ the source behaves just like a burst with respect to the observations; since, in general, $T_s \gg T_{\text{obs}}$ (for radio galaxy hot spots, for instance), one also has $\tau_\gamma \gg T_{\text{obs}}$. Thus, this situation would be analogous to that discussed in § 2.2, i.e., the energy spectrum should show a cutoff around about $E_b$, as the UHECRs with $E \ll E_b$ have not yet reached us, even if they were among the first emitted. The transition between these two regimes is only observable if $10$ EeV $\lesssim E_b \lesssim 50$ EeV, where the lower bound ensures that the deflection angle is less than a few degrees, so that observed events can be associated with a common source. The simulation of a possible case is shown in Figure 3, where the energy spectrum, as seen by the detector, is plotted for a total of 50 detected particles.

The energy spectrum above $E_b$ can be used to estimate the distance $D$, for a given injection spectrum, via a pion production fit (see Fig. 3). For sufficiently large time delays (see § 2.2), $\theta_k$ should be measurable in either limit $D\theta_k \ll I$, or $D\theta_k \gg I$, as different energies are detected (see § 2). The actual magnitude of $\tau_\gamma$ can thus be derived, as $\tau_\gamma \propto D\theta_k^2$. Therefore, not only can the magnetic field strength $B_{\text{rms}}/I$ be determined, but the timescale of emission is also obtained as a by-product. If $T_s \sim T_{\text{obs}}$ then the deflection angle cannot be measured, but the time delay could be directly measured, as in § 2.1, and the above results still hold. In the intermediate case, 1 yr $\ll T_s \lesssim 10^3$ yr, one could only place an upper limit on the magnetic field strength, $B_{\text{rms}}/I \lesssim 10^{-25}$ G Mpc$^{-1/2}$ (see text). The dotted line shows how the spectrum would continue if $T_s \gg 10^4$ yr. The case of a bursting source corresponds to a slice of the image in the $\tau_\gamma$-$E$ plane, as indicated in Fig. 1 by dashed lines. For both spectra, $D = 30$ Mpc and $\gamma = 2$.

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timescales and time delays. In case no low-energy cutoff is seen down to \(10 \text{ EeV}\), but the deflection angle can be measured, the above estimates of \(T_s\) turn into lower limits. The opposite limit is given if \(T_s \ll \tau_D\) for all \(E\) up to the value at which the experiment runs out of statistics. In this case the source behaves like a bursting source, and the discussion in § 2.2 applies.

2.4. Magnetized Galactic Halo

In principle, the results of §§ 2.1, 2.2, and 2.3, should be considered as constraints on both the EGMF and the halo magnetic field, in the sense that \(\theta_E^d \simeq \theta_M^d + \theta_g\), where \(\theta_E^d\) and \(\theta_g\) denote the deflections induced by the EGMF and by the halo field, respectively. The halo field has a significant effect if its strength is in the range \(10^{-3} \leq B_H \leq 10^{-2} \text{ G}\) and its scale height is \(\simeq 1 \text{ kpc}\). Present observational constraints are not conclusive (see, e.g., Beck et al. 1996; Kronberg 1994); some authors argue for significant halo fields with large scale heights, while others argue for smaller scale heights, \(\leq 1 \text{ kpc}\). Therefore, one cannot a priori rule out the possibility that the deflection and time delays are dominated by the influence of the halo magnetic field, even if the nucleons originate from an extragalactic source. If the effects of EGMFs are weak, the results of §§ 2.1, 2.2, and 2.3 can be applied to the halo magnetic field by substituting the scale height of the magnetic halo for the distance to the source. The only exception is that, for a bursting source, a strong correlation between arrival time and energy is expected even above the GZK cutoff irrespective of its distance. This is due to the absence of pion production during propagation through the halo when most of the time delay and deflection is accumulated. As well, in case the energy spectrum above the GZK cutoff could be observed, for instance, for a continuous source, as in § 2.3, or a burst with a small time delay, then the absence of pion production would constitute a signature of the proximity of this source.

3. CONCLUSIONS

We have shown that an EGMF of strength \(10^{-12} \text{ G} \leq B_{\text{rms}} \leq 10^{-9} \text{ G}\) and/or a Galactic halo magnetic field of strength \(10^{-6} \leq B_H \leq 10^{-4} \text{ G}\) leave distinct signatures in the angle-time-energy space. The absence of a lower cutoff implies \(TS\) comparable to the typical time delay \(\tau_D\) at the cutoff energy. Information on the actual magnitude of \(T_s\) is contained in the high end of the observed spectrum and in the arrival directions. The absence of a lower cutoff implies \(T_s > \tau_{\text{HEE}}\). In the limit of large time delays, deflection angles of events around \(10 \text{ EeV}\) should be measurable, and the value of \(B_{\text{rms}} \sqrt{\langle DI \rangle}\) could be derived therefrom. If both the typical time delay and \(T_s\) are smaller than the integration time, then the whole spectrum above \(10 \text{ EeV}\) would be “scanned through.” In this case, both \(D\) and \(B_{\text{rms}} \sqrt{\langle DI \rangle}\) could be determined. A more quantitative implementation of the effects discussed here should involve a likelihood approach. We have performed such an analysis for the three UHECR pairs recently suggested by AGASA (Hayashida et al. 1996). Although present data are much too sparse to draw any quantitative conclusions, we observed some potentially interesting tendencies (Sigl et al. 1997b). One of the pairs, for instance, turns out to be inconsistent with a burst, and comparatively small time delays of the order of a few years may be favored.

Strictly speaking, the analysis in the present Letter applies to models that predict UHECRs to be nucleons in the relevant energy range. Topological defect models predict a domination of \(\gamma\)-rays above \(\approx 50 \text{ EeV}\) (e.g., Sigl et al. 1997a). However, because of its electronic content, the deflection and delay of an electromagnetic cascade roughly correspond to those of a nucleon of the same energy, modified by the relative lifetime of the pairs, for instance, turns out to be inconsistent with a burst, and comparatively small time delays of the order of a few years may be favored.

We acknowledge P. Biermann, J. Cronin, and A. Dubey for useful discussions. We thank the Max-Planck-Institut für Physik, München, Germany and the Institut d’Astrophysique de Paris, France for providing CPU time. We thank the Aspen Center for Physics for hospitality and support. G. S. acknowledges financial support by the Deutsche Forschungs Gemeinschaft under grant SFB 375 and by the Max-Planck-Institut für Physik. This work was supported, in part, by the DoE, NSF, and NASA at the University of Chicago.

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