THE ASTROPHYSICAL JOURNAL, 492:200–204, 1998 January 1

DEFLECTION OF ULTRA–HIGH-ENERGY COSMIC RAYS BY THE GALACTIC MAGNETIC FIELD: FROM THE SOURCES TO THE DETECTOR

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Received 1997 June 19; accepted 1997 August 12

ABSTRACT

We report the results of three-dimensional simulations of the trajectories of ultra–high-energy (UHE) protons and Fe nuclei (with energies $E = 4 \times 10^{19}$ and 2.5×10^{20} eV), propagating through the Galactic magnetic field (GMF) from the sources to the detector. A uniform distribution of antiparticles is back-tracked from the detector, at the Earth, to the halo of the Galaxy. We assume an axisymmetric, large-scale spiral magnetic field that permeates both the disk and the halo. A normal field component to the Galactic plane (B_z) is also included in part of the simulations.

We find that the presence of a large-scale GMF does not generally affect the arrival directions of the protons, although the inclusion of a B_z component may cause significant deflection of the lower energy protons ($E = 4 \times 10^{19}$ eV). Error boxes larger than or equal to $\sim 5°$ are most expected in this case.

On the other hand, in the case of heavy nuclei, the arrival direction of the particles is strongly dependent on the coordinates of the particle source. The deflection may be high enough ($>20°$) as to make any identification of the sources extremely difficult unless the real magnetic field configuration is determined accurately. Moreover, not every incoming particle direction is allowed between a given source and the detector. This generates sky patches that are virtually unobservable from the Earth. In the particular case of the UHE events of Yakutsk, Fly's Eye, and Akeno, they come from locations for which the deflection caused by the assumed magnetic field is not significant.

Subject headings: cosmic rays — Galaxy: halo — methods: numerical

1. INTRODUCTION

The detection of cosmic-ray events with energies above 100 EeV (1 EeV = 10^{18} eV) (Efimov et al. 1990; Bird et al. 1995; Hayashida et al. 1994b), beyond the Greisen-Zatsepin-Kuzmin cutoff energy (Greisen 1966; Zatsepin & Kuzmin 1966), has posed a challenge to the understanding of their origin and nature. Particles with energies above ~ 60 EeV will lose substantial amounts of energy through interactions with the 2.7 K cosmic microwave background radiation, so that their sources must be within few tens of megaparsecs (Protheroe & Johnson 1995; Sigl, Schramm, & Bhattacharjee 1994; Medina Tanco, de Gouveia Dal Pino, & Horvath 1997a).

An important clue to the origin of these events can be obtained from the correlation of their arrival direction with astrophysical sources. Based on events observed with the Haverah Park experiment (Watson 1994), Stanev et al. (1995) have suggested that the ultra–high-energy cosmic rays (UHECRs), observed in the northern hemisphere, show a statistical preference for arrival directions close to the supergalactic plane (SGP). On the other hand, a similar analysis, conducted with the events detected by the SUGAR experiment in the southern hemisphere (Kewley, Clay, & Dawson 1996) and the AGASA experiment in Japan, support a more uniform distribution throughout the sky, although some clustering is suggested by a few groups of events in the latter case (Hayashida et al. 1994b). Two major questions then arise about the UHECRs, regarding their propagation from the sources to the detector through the GMF: What is the angular correlation between the arrival directions of the particles and the parent sources after their passage through the GMF? How much are they deflected in a large-scale regular GMF?

Under the assumption that the UHECRs are mostly composed of protons, we have examined, in a previous work (Medina Tanco et al. 1997a), the nondiffusive propagation of UHECR through the stochastic intergalactic and an extended Galactic halo magnetic field, and found that the UHECRs, arriving in the Galaxy, seem to point to the sources more strongly than previously believed (within error circles of at most $\approx 8°$). In the present work, we address the propagation of the UHECRs in the regular large-scale GMF.

Stanev (1997) has recently performed a similar investigation by considering different GMF configurations. Searching for a possible correlation between sources in the supergalactic plane (SGP), he plotted the Volcano Ranch events above 2×10^{19} eV (Linsley 1963; Egorov 1963; Laurence, Reid, & Watson 1991; Yoshida et al. 1995), after correcting their positions for deflection in the GMF, and found that some groups of events seem to be closer to the SGP. On the other hand, for a vast region of the sky ($b > 0°$, $l < 130°$), he found that the corrected UHECR positions are farther away from the SGP.

In this work, we go further into this investigation by performing three-dimensional simulations of proton and Fe nucleus trajectories through the GMF and present full-sky maps (in Galactic coordinates) of their arrival direction distribution in both the detector (after deflection in the GMF) and outside the Galactic halo (before deflection in the GMF, where they point to the real source locations). Also, in order to make the visualization and data analysis easier, we have introduced a cube-based pixelization representation of the events in a similar way to that employed in the construction of the *COBE* maps (Chan & O'Neill 1976;

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Smoot et al. 1992; Tegmark 1996; see below). With this technique, the positions of the arrival directions of the Yakutsk, Fly's Eye, and Akeno UHECR events (Efimov et al. 1990; Bird et al. 1995; Hayashida et al. 1994a) are also plotted at the detector and outside the Galactic halo. As we will show below, the main advantage of this procedure is to allow a direct and transparent identification of the source for a given magnetic field configuration.

2. THE GMF MODEL

We assume an axisymmetric, spiral field without reversals, extending to Galactocentric distances of 20 kpc in all radial directions, and with an even (quadrupole type) parity in the perpendicular direction (z) to the Galactic plane. This configuration, called $ASS - S$, is described in detail by Stanev (1997) and is entirely consistent with the observations of Beck et al. (1996) and Kronberg (1994). The field is taken to be 6.4 μG at $r = 4$ kpc, and constant at this value in the central region of the Galaxy. The radial dependence is consistent with field strengths inferred from pulsar rotation measures. As in Stanev et al. (1995), we assume an exponentially decaying magnetic field with height from the Galactic plane. Two scale lengths are adopted, $z_0 = 1$ kpc for $z < 0.5$ kpc and $z_0 = 4$ kpc for $z > 0.5$ kpc. We have also performed some simulations of the UHECR trajectories, including the presence of a constant z-component in the GMF ($B_z = 0.3$ μG) pointing north in the northern Galactic hemisphere and to the opposite direction in the southern Galactic hemisphere. This component was superposed on the large-scale *ASS-S* spiral field. There is some observational support for this component that would be associated with the existence of a Galactic wind (e.g., Stanev 1997).

3. THE SIMULATIONS

We first assume that the UHECRs are mostly ionized hydrogen atoms (protons) of extragalactic origin (Hillas 1984; Rachen & Biermann 1993; Stanev et al. 1995; Medina Tanco et al. 1997a). In order to trace the particle trajectories through the GMF, we apply the *reversibility principle* (Stanev 1997; Flückiger et al. 1991; Bieber, Evenson, & Lin 1992) by backtracking antiprotons. An antiproton, injected in a certain direction at the Earth, will follow the same trajectory as a proton arriving at the same direction at the Earth. Assuming an isotropic distribution, we inject antiprotons at different Galactic longitude b and latitude l at the Earth, and follow their propagation through the GMF until they exit the Galactic halo. In this way, we can determine the particle direction outside the Galaxy before its direction can be altered by the GMF.

Let us start discussing the lower energies. Figure 1 depicts the results for protons of energy 4.0×10^{19} eV, propagating through the large-scale GMF, including the described B_z component. About 6×10^3 antiprotons (equivalent to the number of protons traveling in the opposite direction) were injected isotropically at the Earth. Their injection directions at the detector are represented by the points (or pixels) in the sky map of Figure 1*b*. Equivalently, these points map the arrival directions of the real protons *after* their passage through the GMF. The map is in Galactic coordinates. Figure 1*a* shows the orientation distribution of the same protons at their arrival in the Galaxy, before they are deflected in the GMF (or equivalently, the orientation of the antiprotons when they reach the Galaxy border *after* their passage through the GMF). Thus, if the intergalactic magnetic field is neglected, the protons in Figure 1*a* point to the true source locations. The UHECR pointing directions are coded in different shades of gray, according to their deflection angles as a result of their passage through the GMF. The uniform distribution of antiprotons in Figure 1*b* is mapped onto a nonuniform distribution in Figure 1*a*. Conversely, the nonuniform distribution of protons in Figure 1*a* is mapped onto a uniform distribution in Figure 1*b*. We find that there is a significant deflection of their trajectories, except for particles coming from very high latitudes. Error boxes larger than or equal to $\sim 5°$ are most expected at these energies. In fact, only $\sim 25\%$ of the particles present have deflection angles smaller than 5° in their trajectories through the GMF. When the constant B_z component is set to zero, we find that the deflection is drastically decreased (68% of the particles present deflections smaller than 5°, and 95%, smaller than 20°. Therefore, the presence or absence of the "wind" magnetic field component is very important to track the trajectories of the primaries inside the Galaxy.

For the higher energy protons (with $E = 2.5 \times 10^{20}$ eV), we find a strong reduction in the deflection angles of the particle trajectories in both situations, that is, with or without the inclusion of the B_z component. In the first case, $\sim 79\%$ of the particles show deflections smaller than 2°, while in the second, more than 90% of the particles are deflected by less than 2°, so that the effect of the GMF on the highest energy particles is never important, as expected.

Dramatic changes do occur when heavy particles are considered. In this case, the UHECRs would come at most from an extended halo (see, e.g., Hillas 1984; Medina Tanco et al. 1997a). Applying the same scheme as in Figures 1*a* and 1*b*, we have calculated the mapping detector source for Fe nuclei at an energy 2.5×10^{20} eV for $B_z = 0$. Figure 2 shows the deflection angle distribution for the Fe nuclei. As in Figure 1, the UHECR directions are coded in different shades of gray, according to their deflection angles as a result of their passage through the GMF. Figure 2*a* depicts the Fe nuclei at the Galactic halo border, pointing to the source directions (before deflection), and Figure 2*b* depicts the particle arrival directions at the detector (after deflection). We find that the large-scale magnetic field component causes the arrival direction of the particles to be strongly dependent on the coordinates (l, b) of the particle source. Moreover, about 21% of the particles present deflection angles larger than 30° in their trajectories through the GMF, and this figure increases to 72% in the lower energy case (see Medina Tanco, de Gouveia Dal Pino, & Horvath 1997b for details). As a general feature, we see in some regions that the deflection may be high enough as to make any identification of the sources extremely difficult unless the true magnetic field configuration can be determined a priori. Only the events coming from the Galactic anticenter direction show deflections smaller than 10°, in the high-energy case, and this correlation is drastically reduced in the smaller energy case. In the particular case of the locations of the observed UHE events of Yakutsk, Fly's Eye, and Akeno (Efimov 1990; Bird et al. 1995; Hayashida et al. 1994a), the deflection is not very large if the primaries are assumed to be Fe nuclei (see the symbols in Figs. 2*a* and 2*b*).

Finally, we notice from the empty regions at high Galactic latitudes in Figure 2*a*, that some Galactic directions are

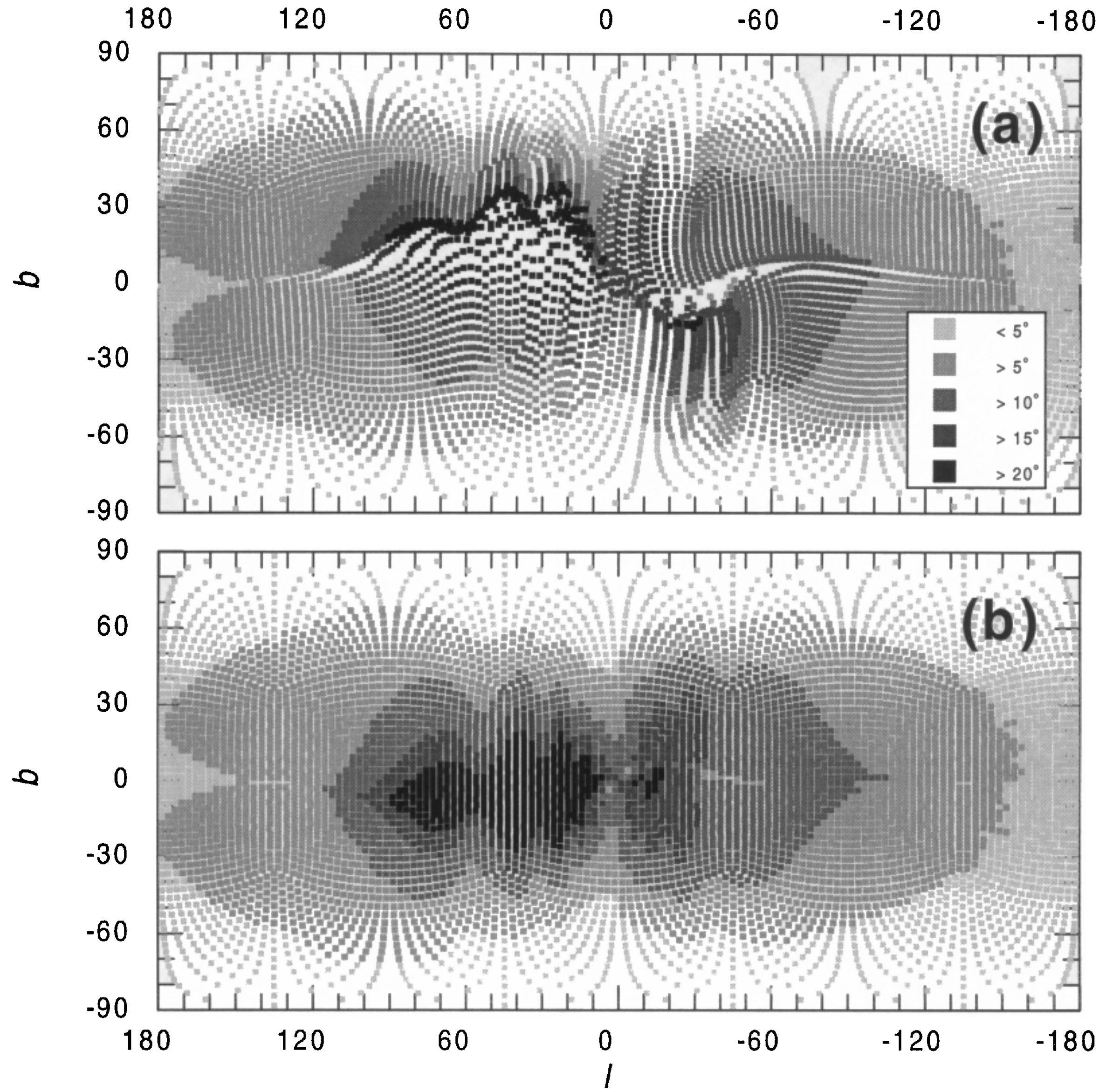

FIG. 1.—Arrival directions of protons of energy 4.0×10^{19} eV, distributed isotropically over 4π sr at the detector (panel *a*), are mapped onto the Galactic halo border (panel *b*), after their back propagation through the large-scale GMF; 6×10^3 antiprotons with momentum "$-p$" are injected isotropically at the Earth. Their positions at the detector are represented by the points in the sky map (panel *b*), in Galactic coordinates. These points also map the arrival directions of the real protons *after* their passage through the GMF. A constant B_z component has been included in this simulation. Panel *a* shows the pointing directions of the same protons at the Galactic halo border, before they are deflected in the GMF. Different shades of gray are used according to the deflection angles of the particles due to the GMF.

virtually unobservable at the Earth, so that not every incoming particle direction will be allowed between source and detector. The GMF acts as a kind of giant spectral analyzer, and the forbidden and allowed regions resemble the situation the dipolar magnetic field of the Earth creates on the low-energy cosmic rays.

4. DISCUSSION AND CONCLUSIONS

Although calculated for a particular magnetic field geometry, the results presented here indicate how significant the UHECR deflections can be in the large-scale ordered GMF, if heavy nuclei happen to be the primaries. As in Stanev's work (1997), we find that the magnitude of the deflections of the UHECRs in the GMF requires their arrival directions to be corrected before they are compared to astrophysical source locations. Moreover, we find that the arrival directions of the incoming particles are strongly dependent on the coordinates of the parent sources. For some directions of the sky, the deflection can be so high that a source identification becomes virtually impossible, unless the true GMF configuration can be accurately determined. This effect is larger for decreasing energy with the inclusion of a B_z component in the large-scale GMF. The importance of the presence of a B_z component cannot be overstated. Such a component is naturally expected if a Galactic wind exists. A thorough study of UHECR arrivals at different Galactic latitudes could shed some light on this issue. While B_z may be irrelevant for the (already large) deflections of Fe primaries, the low-energy protons are very sensitive to it and could be used as tools to study the B_z component.

We have found that for the magnetic field geometry assumed here, the observed UHE events of Fly's Eye,

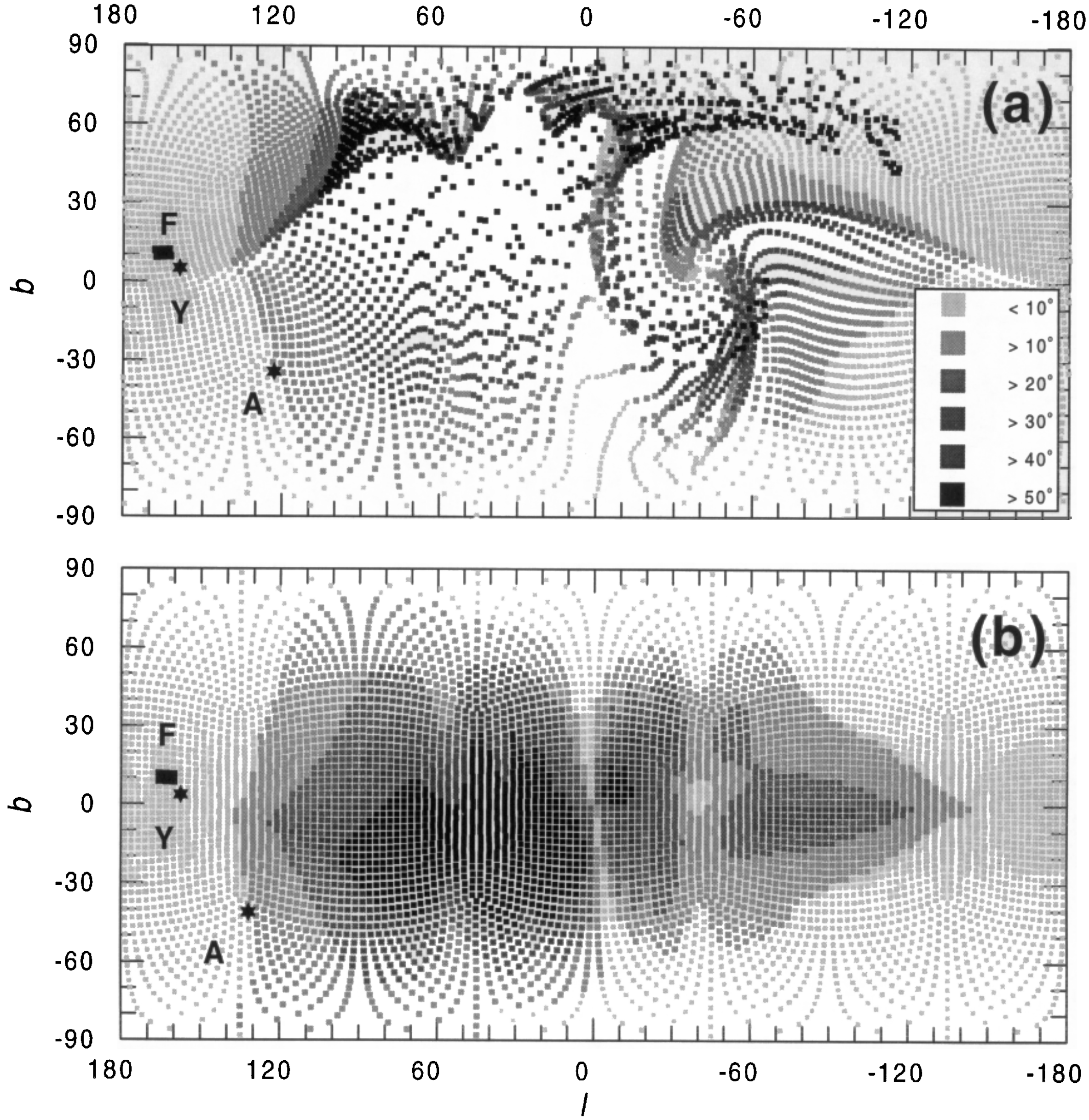

FIG. 2.—Deflection angle distribution for Fe nuclei of energy 2.5×10^{20} eV propagating through the large-scale GMF (without including a B_z component). As in Fig. 1, the UHECR positions are distributed in different shades of gray according to their deflection angles as a result of their passage through the GMF. Panel *a* depicts the arrival directions of Fe nuclei at the Galactic halo border (before deflection by the GMF), and panel *b* depicts the particle arrival directions at the detector (after deflection by the GMF). Note that the observed UHE events of Akeno, Fly's Eye, and Yakutsk (marked with symbols) do not reveal strong deflections from their original positions.

Akeno, and Yakutsk come from a region of the sky where the deflections in the particle trajectories are not very significant in all cases.

An interesting consequence of the above results (which was also pointed out by Stanev et al. 1995) regards the strong dependence of the magnitude of a UHECR deflection on the viewing area of a given experiment. This dependence could lead to shifts in the arrival directions of incoming events detected by different experiments in different viewing areas.

The current number of UHECR events so far detected is not large enough to delineate definite conclusions on their origin or arrival directions. Nonetheless, the Pierre Auger Observatory project (1995), which proposes the construction of two air shower arrays in the Northern and Southern hemispheres, in order to provide an all-sky coverage of the events, will contribute to improving the statistics of the events as well as, most importantly, probing for valuable information on the large-scale structure of the GMF, thus making it possible to trace the particle trajectories and source directions. (URL addresses for the Auger Project may be obtained from the authors.)

Finally, we should note that the possible existence of large-scale regular extragalactic magnetic field components (e.g., Arp 1988) could provoke further nonnegligible UHECR deflections in the megaparsec scales that would, of course, increase the complexity of the picture presented here.

This work has been partially supported by the Brazilian Agencies FAPESP and CNPq. We are thankful to the referee for his relevant remarks.

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