Distortion of UHECR spectra by regular magnetic fields

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Abstract

We propagate ultra high energy protons in the presence of large scale, extragalactic magnetic fields of regular structure and find that the observed proton energy spectrum depends strongly on the position of the observer in respect to both the source and the magnetic field configuration. Effects of the magnetic field exhibit themselves in many different ways.

1. Introduction

Structures of magnetic fields that are coherent over large scales can influence the arrival directions as well as the energy spectrum of ultra high energy cosmic rays (UHECR), see e.g.[1-6]. Here we study the effect of the possible existence of ordered extragalactic magnetic fields correlated with the matter density distribution assuming that the UHECR are protons. We consider an infinite Supergalactic plane (SGP) coinciding with the $y = 0$ plane in Cartesian coordinates as illustrated in Fig. 1. The magnetic field is in $+z$ direction. The non-random magnetic field strength is constant ($B_0 = 10$ nG) within 1.5 Mpc of the plane and decreases exponentially as $B \propto \exp -|y|/3\mathrm{Mpc})$. We also assume a random field component that is $B_0/2$ but never smaller than 1 nG. The random field os implemented as a turbulent magnetic field using a Kolmogorov distribution [7]. We concentrate on two simple source scenarios: a central source that emits UHECR isotropically in the $+z$ hemisphere and an external source that emits a plane wave of protons moving with $\hat{n}$ = (1,0,0). The two sources are shown in the lefthand panel of Fig. 1 labeled by a and b, respectively. The particles are emitted with energy above $10^{18.5}$ eV on a flat $\alpha = 2$ spectrum with an exponential cutoff at E_c = $10^{21.5}$ eV.

All particles are followed until they intersect a 20 or 40 Mpc "observer" sphere around the origin, where the central source is located. Particles propagating more than 1.3×10^9 years are abandoned. We account for the proton energy loss due to photoproduction, pair production and redshift. The propagation technique is described in detail in Ref. [7]. The Hubble constant in this calculation is $H_0 = 75$ km/s/Mpc.

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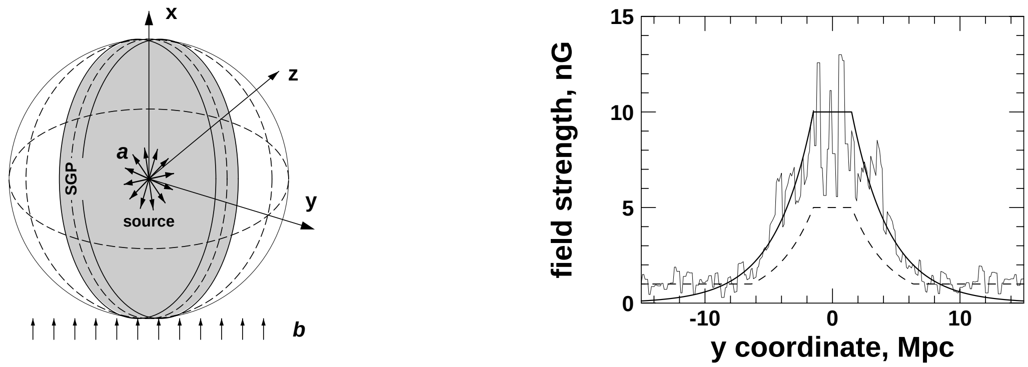

Fig. 1. Lefthand panel - geometry of the SGP and the *observer*'s sphere. The central source scenario is indicated as a and the external source scenario is indicated with b. Righthand panel - one of the realizations of $B_{\|}$ - the magnetic field component parallel to the SGP.

2. Central source

Fig. 2 shows the energy spectra of the protons emitted by the central source that leave the simulation through several 9 Mpc^2 patches on the surface of the sphere. Four of them are centered about one of the axes of the coordinate system: patch *front* is in positive z direction, *side* - in y direction and *top* - in x direction, and *back* is in $-z$ direction toward which no protons were injected. The other two patches are at positive z at angles of 45° in the appropriate planes.

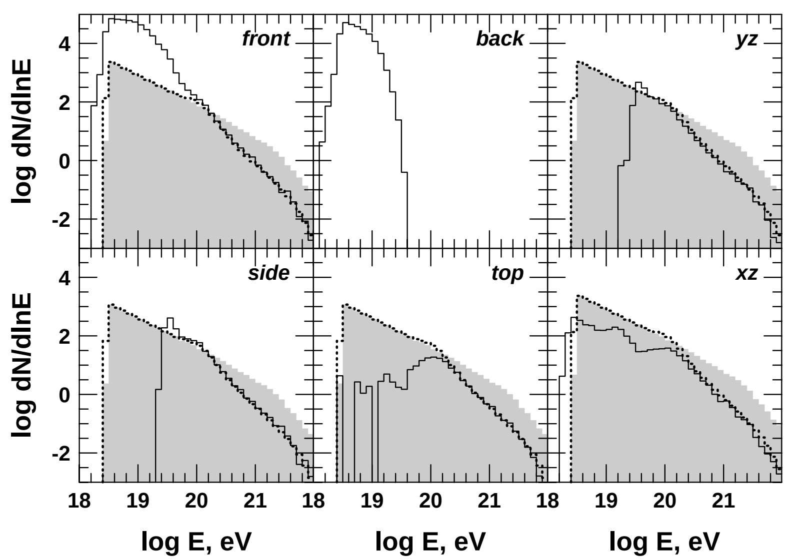

Fig. 2. Energy spectra of the particles leaving a 20 Mpc sphere around a central source in six patches described in the text. The shaded histogram shows the injection spectrum towards these patches. The dotted histogram shows spectra propagated over 20 Mpc without magnetic field.

The particles leaving the 20 Mpc sphere through the *front* patch show an enhancement by almost two orders of magnitude at energy below $10^{19.5}$ eV. The source of the enhancement is the proton diffusion along the field lines, as demonstrated in the spectrum of the *back* patch, towards which no protons were injected. Only back scattered low energy protons reach this patch.

There is a deficit of low energy particles in all other patches. To reach those patches the protons have to propagate across magnetic field lines and only the highest energy protons can do that. The *side* and *yz* patches are underpopulated below $10^{19.5}$ eV because of deflection in the magnetic fields. The deflection in the *top* and *xz* is even stronger, but proton propagation in these directions is assisted by drifts.

To study the dependence of these effects on the radius of the *observer* sphere we enclosed the 20 Mpc one in a 40 Mpc concentric sphere. The effects were qualitatively similar. In addition the 20 Mpc *observers* within the SGP observe a strong flux of back-scattered 10^{19} eV protons similarly to the *back* patch in Fig. 2.

3. External source

The patches defined for a central source were not suitable for studies of a plane wave external UHECR proton flux and we define 6 different patches, all centered in the $z = 0$ plane and azimuth angles $\phi = 0(\hat{x})$, 45, 135, $180(-\hat{x})$, 225, and 315 degrees. The energy spectra

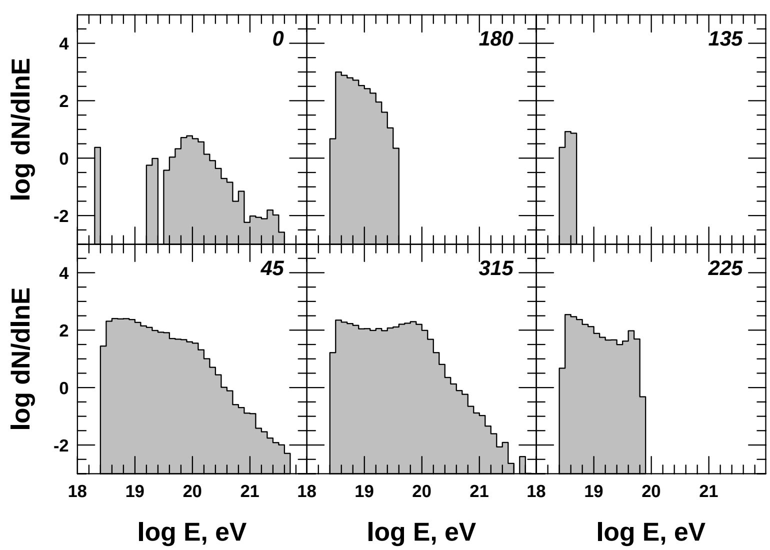

Fig. 3. Energy spectra of the particles leaving a 20 Mpc sphere in different locations around the *z=0* plane after injection as a plane wave in *+x* direction on the negative *x* hemisphere. The patches are marked with the values of the ϕ angle on which they are centered.

of the protons leaving the 20 Mpc sphere through these patches are shown in Fig. 3. The spectrum in the $\phi = 0$ patch consists only of UHE protons that manage to penetrate all the way through the SGP. Patch 180 accepts only lower energy particles that exit mostly after traveling half a gyro-orbit in the field. Patch 135 - (-20/$\sqrt{2}$, 20/$\sqrt{2}$) accepts no particles at all, while the opposite patch 315 has an excess of 10^{20} eV particles, that are swept out of the SGP. Patch 225 - (-20/$\sqrt{2}$-20/$\sqrt{2}$) accepts mainly low energy particles which drift back and the opposite patch 45 has a spectrum similar to the injected one, since both high and low energy particles that drift are accepted.

4. Conclusions

We have intentionally dealt with single sources in a simple geometry to be able to understand the proton propagation in the presence of non-random magnetic fields. These fields affect strongly not only the directions of the protons reaching the observer, but also change their energy spectrum. A separate set of spectral changes is related to the time delay of particles emitted in bursts.

We show that in both the case of an internal or an external source observers located at different positions on the 20 Mpc sphere would observe spectra that have no similarity with each other or with the injection spectrum. At energies below $10^{19.5}$ eV the differences can reach 3-4 orders of magnitude.

It is thus very dangerous to attempt estimates of the luminosity of the UHECR sources from observational data in the energy range of 10^{19} eV.

Only above 10^{20} eV UHECR follow the injection spectrum after accounting for the energy loss due to propagation. It is thus a task left for future giant air shower detectors, such as the Pierre Auger Observatory [8], EUSO and OWL [9] to study the location and luminosity of these sources.

Once the proper statistics of such events is collected, the data can be used for estimates of magnetic fields structure of the cosmologically nearby Universe.

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5. References

1. M. Lemoine et al., Ap. J., **486**, L115 (1997)
2. G.A. Medina Tanco, Ap. J., **505**, L79 (1998)
3. G. Sigl, M. Lemoine & P.L. Biermann, Astropart. Phys., **10**, 141 (1999)
4. Y. Ide et al., Publ. Astr. Soc. Japan, **53**, 1153 (2001)
5. P.L. Biermann et al., Nucl. Phys. B (Proc. Suppl.), **87**, 417 (2000)
6. T. Stanev, D. Seckel & R. Engel, astro-ph/0108338
7. T. Stanev et al., Phys. Rev. D**62**: 093005 (2000)
8. J. Blümer et al., Pierre Auger Collaboration, J. Phys. G, **29**, 867 (2003)
9. The status of the proposals is available at *http//www.ifcai.pa.cnr.it* and *http//owl.gsfc.nasa.gov*