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Propagation of UHE protons through a magnetized large scale structure

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Abstract: The propagation of UHECRs is affected by the intergalactic magnetic fields that were produced during the course of the large scale structure formation of the universe. We adopt a novel model where the large scale extragalactic magnetic fields (EGMF) are estimated from local dynamic properties of the gas flows in hydrodynamic simulations of a concordance ΛCDM universe. With the model magnetic fields, we calculate the deflection angle, time delay and energy spectrum of protons with $E > 10^{19}$ eV that are injected at cosmological sources and then travel through the large scale structure of the universe, losing the energy due to interactions with the cosmic background radiation. Implications of this study on the origin of UHECRs are discussed.

Introduction

The enigma of ultrahigh energy cosmic rays (UHECRs) with energy $E \gtrsim$ 5 EeV (1 EeV = 10^{18} eV) has received considerable attention, both observationally and theoretically, over the past decades [1, 2]. Although the composition studies indicate that most of them are likely to be protons [3], the nature and origin of these CRs remain yet to be understood. At these high energies, UHECRs are not confined within the galactic magnetic plane and therefore their origin should be extragalactic. In particular, the isotropic distribution of arrival directions suggests that large number of UHECR sources might be distributed at sufficiently large distances [2, 4]. UHECRs from cosmological sources get significantly attenuated during their propagation due to interaction with the cosmic microwave background, resulting in the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff in the energy spectrum [5]. Interestingly, AGASA experiment failed to identify this cutoff [2], whereas HiRes recorded it [6]. Detection of super-GZK events with isotropic arrival directions is enigmatic, because powerful astronomical objects are very rare in the local universe. New results from Pierre Auger experiment reported in this conference may shed light on this puzzle.

Charged UHECRs are expected to be deflected by large scale extragalactic magnetic fields (EGMF), so their arrival directions can deviate from source directions and arrival time is delayed compared to the light travel time [7, 8]. At present, the main challenge is to estimate the EGMF, since observing it is still a difficult task. From this standpoint, we employ a novel model for the EGMF in which the strength of the intergalactic magnetic fields is estimated from local turbulence in a cosmological hydrodynamic simulation. The trajectories of UHE protons from active galactic nuclei (AGNs), propagating through the model EGMF, are calculated, including all relevant energy loss processes. We then study the angular deflection, time delay and energy spectrum of UHE protons that arrive in the regions similar to the Local Group.

Model

Extragalactic Magnetic Fields

Concordance ΛCDM cosmological simulations are carried out along with passively evolved magnetic fields in a cubic box of comoving size $100h^{-1}$ Mpc, using 512^3 grid zones with the following parameters: $\Omega_{BM} = 0.043$, $\Omega_{DM} = 0.227$, and

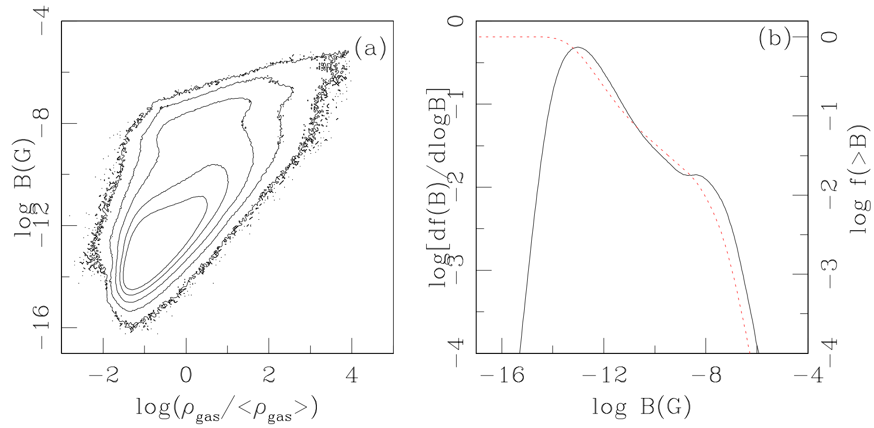

Figure 1: (a) Volume fraction in the gas density-EGMF strength plane with our model EGMF at $z = 0$. (b) Volume fraction, $df/d\log(B)$, (solid line) and its cumulative distribution, $f(> B)$, (dotted) as a function of EGMF strength.

$\Omega_\Lambda = 0.73$, $h \equiv H_0$/(100 km/s/Mpc) = 0.7, and $\sigma_8 = 0.8$. Six different initial realizations are used. Only the directional information of the passive fields is adopted. Assuming that the intergalactic magnetic fields result from turbulent motion of the intergalactic gas, the strength of the EGMF is computed directly by equating the magnetic energy to a suitable fraction of the turbulent energy of the intergalactic gas (see [9] for details).

Fig. 1 shows the volume fraction in the ρ_{gas} - B plane in our model. The EGMF are correlated with the large scale structure: the strongest around clusters of galaxies and the weakest in voids. In the regions of galaxy clusters with $\rho_{gas}/\langle\rho_{gas}\rangle \gtrsim 10^3$, $\langle B\rangle \sim 10^{-6}$G. For typical filamentary regions with $\rho_{gas}/\langle\rho_{gas}\rangle \sim 30$, $\langle B\rangle \sim 10^{-8}$G, while in void region, $\langle B\rangle \sim 10^{-12}$G.

CR Sources and Observers

Assuming that UHECRs originate from AGNs, we identify galaxy clusters with $kT > 1.0$ keV in the cosmological simulation as sources, since AGNs are likely to form in high density environment. There are 20-30 such clusters in the simulated volume, corresponding to the source density of $n_s = 2 - 3 \times 10^{-5} h^3 \mathrm{Mpc}^{-3}$ and the mean separation of $l_s \sim 40 h^{-1}\mathrm{Mpc}$. The field strength in source locations ranges $0.1 < B_s(\mu\mathrm{G}) < 10$ with $\langle B_s\rangle \sim 1\mu$G. UHE protons with a power-law energy spectrum of $E^{-\gamma}$ for 10 EeV $\leq E \leq 10^3$EeV are distributed among the sources and then launched in random directions. We follow the trajectory of individual protons by numerically integrating the equation of motion in the model EGMF, considering continuous energy loss due to photo-pair and photo-pion production [5].

An observer is placed at each 10^3 groups of galaxies with $0.05\mathrm{keV} < kT < 0.5\mathrm{keV}$ in order to select locations similar to the Local Group. These groups are not distributed uniformly, but located mostly along filaments, following the matter distribution of the large scale structure. Around observer locations, $10^{-4} < B_{obs}(\mu\mathrm{G}) < 0.1$ with $\langle B_{obs}\rangle \sim 10$nG. Once a particle visits an observer within a sphere of $R_{obs} = 0.5h^{-1}$ Mpc, the arrival direction, time delay and energy of the particle are registered as an ‘observed’ event. We let the particle continue its journey, visiting several groups during its full flight, until its energy is reduced to 10 EeV. With 10^4 protons injected at sources, about 10^5 events are recorded.

Results

Deflection Angle and Time Delay

Note that the gyroradius of proton is $r_g = 10\mathrm{kpc}\ (E/10^{19}\mathrm{eV})(B/\mu\mathrm{G})^{-1}$. With our model EGMF, the trajectories of ∼10 EeV protons could be severely deflected when they leave the source regions with $\langle B_s\rangle \sim 1\mu$G and when they fly by the cluster/group regions with $B \gtrsim 10^{-8}$G, since clus-

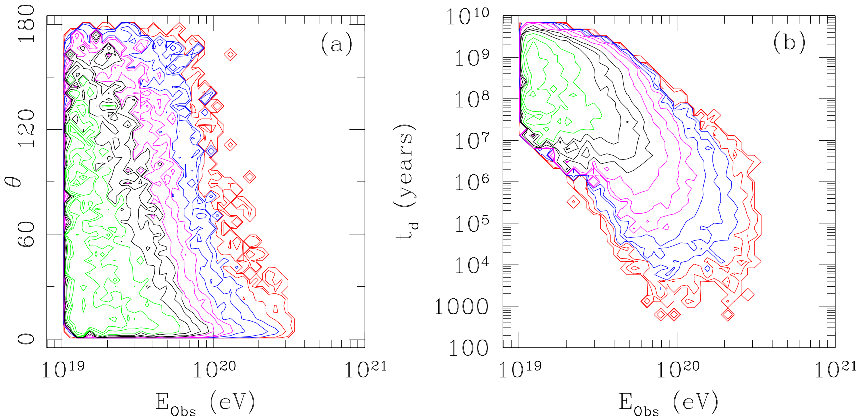

Figure 2: (a) Distribution of events in the plane of observed particle energy and deflection angle. (b) Distribution of events in the plane of observed particle energy and time delay. Protons are injected with a power-law spectrum of $\gamma = 2.7$ at sources.

ters/groups have a typical radius of $\langle R \rangle \sim 1\text{Mpc}$. According to Fig. 1 the volume filling factor with $B > 10^{-8}$G is $f(> 10^{-8}\text{G}) \approx 0.02$.

In Fig. 2(a) we present the distribution of the deflection angle between the arrival direction of UHE protons and the source direction, θ, as a function of the observed energy. This distribution depends rather sensitively on the power-law index of the injection spectrum, γ, and the minimim distance between sources and observers, D. Here, the results of the case with $\gamma = 2.7$ and $D = 20$Mpc are presented. On average the deflection angle decreases with the energy, showing a transition from diffuse transport regime to rectilinear propagation region at $E \sim 100$ EeV. For $E \geq 40$ EeV 30 % of 'observed' events arrive with $\theta \leq 5°$ from source directions, while 60 % with $\theta \leq 5°$ for $E \geq 100$ EeV. Some super-GZK protons can avoid flying through strong field regions around clusters and do not get significantly deflected by weak fields in filamentary structures.

Since the deflected path length is longer than the rectilinear distance, the particle travel time is delayed compared to the light travel time. In Fig. 2(b), we show the distribution of t_d, the delay of the particle travel time compared to the light travel time, as a function of the observed energy. The rectilinear travel time for the mean separation of sources, $t_{rec} \equiv l_s/c \approx 10^{8.25}$ years. On average the time delays are longer for lower energy particles, with $\langle t_d \rangle \sim 10^9\text{yrs} \sim 6t_{rec}$ around 10 EeV and $\langle t_d \rangle \sim 10^5\text{yrs} \sim 10^{-3}t_{rec}$ above 100 EeV.

Energy Spectrum

Fig. 3 shows the predicted energy spectra of UHE proton events for the injection spectrum of $N_{inj}(E) \propto E^{-\gamma}$ with $\gamma = 2.0$, 2.4 and 2.7 and $D = 5$, 10, and 20 Mpc. We note that $J(E)E^3$ in the plot is given in an arbitrary units, since the amplitude of the injected spectrum at sources is arbitrary. In all the cases the presence of GZK supression above 50 EeV is obvious, so the AGASA data cannot be consistent with our results. In case of $D = 5$ Mpc, there is a significant number of particles above 100 EeV that come mainly from nearby sources. Below 50 EeV, the spectrum gets flatter due to the pileup of the particles that had higher initial energies but have lost their energy via photo-pion production. The injection spectrum with $\gamma = 2.7$ seems to produce the best fit for the HiRes-2 data, although the case with $\gamma = 2.4$ can be considered as being consistent with the HiRes observations.

Conclusion

We study the propagation of UHE protons that originate from cosmological sources located at galaxy clusters, travel through the EGMF correlated with the large scale structure of the universe, and arrive in the regions similar to the Local Group. A novel model for the EGMF based on turbulence dynamo is adopted. Since the volume filling factor, $f(> 10^{-7}\text{G})$ is less than 5×10^{-3}, about

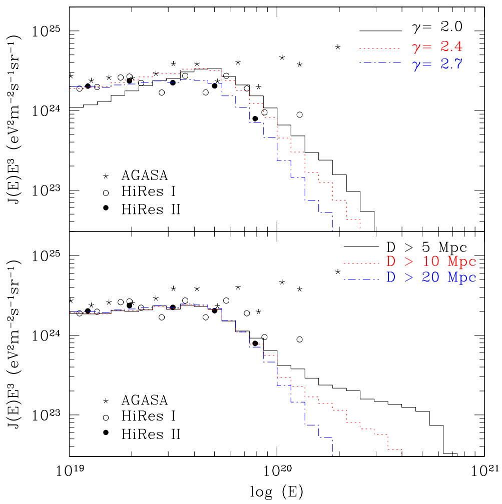

Figure 3: Predicted energy spectra of UHE protons that are injected with a power-law spectrum of $N_{inj}(E) \propto E^{-\gamma}$ at sources and propagated through a universe with the adopted model EGMF. *Top panel:* the case with the minimum source-observer distance $D = 20$Mpc is shown for $\gamma = 2.0$ (solid line), 2.4 (dotted) and 2.7 (dot-dashed). *Bottom panel:* the case with $\gamma = 2.7$ is shown for $D = 5$ Mpc (solid line), 10 Mpc (dotted) and 20 Mpc (dot-dashed). Filled circles are the observational data from HiRes-2 [6]. and open circles are from HiRes-1, while stars are from AGASA [2].

60 % of UHE protons above 100 EeV could avoid visiting strong field regions and arrive at Earth within $5°$ of their sources, although the deflection angle is overall distributed over a wide range. Below the GZK energy, the propagation is in the diffusion limit and both the deflection angle and time delay are substantial. This indicates that in the present scenario, UHE proton astronomy may be possible only for $E > 100$ EeV. The predicted energy spectrum of UHE protons exhibits the GZK supression, and fits the HiRes observations, if the injection spectrum has $\gamma = 2.4 - 2.7$.

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