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# Propagation of ultra-high-energy cosmic rays in the magnetized cosmic web

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A high concentration of ultra-high-energy cosmic ray (UHECR) events, called a hotspot, was reported by the Telescope Array (TA) experiment, but its origin still remains unsolved. One of the obstacles is that there is no astronomical object, which could be the source, toward its direction. In an effort to understand the origin of the TA hotspot, we suggested a model based on the magnetized cosmic web structure. The UHECRs were produced at sources in the Virgo cluster and confined by cluster magnetic fields for a while. Then, they preferentially escaped to and propagated along filaments. Eventually, some of them were scattered by filament magnetic fields, and come to us. To examine the model, we followed the propagation trajectories of UHE protons in a simulated universe with clusters, filaments, and voids, by employing a number of models for cosmic magnetic fields. We here present some of the first results, such as the fraction of the UHE protons confined within clusters during the GZK time and the fraction which escapes from clusters to filaments. We also discuss the feasibility of our model for the origin of the hotspot by examining the trajectories of UHE protons.

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## 1. Introduction

Since the existence of ultra-high-energy cosmic rays (UHECRs) was discovered, many observations have continued to increase event statistics in order to find out the nature and origin of UHECRs for more than 50 years. Owing to these great efforts, some of the main questions on UHECRs have been resolved. It is confirmed that UHECRs originate from extragalactic sources since they cannot be confined within the galactic plane by the galactic magnetic field (GMF) [1]. It has been observed, in addition, a nosedive of UHECR energy spectrum above threshold energy of around $5\times10^{19}$ eV, which is so-called Greisen-Zatsepin-Kuzmin (GZK) suppression [2, 3].

However, the origin of UHECRs has been unanswered yet. To find out the sources of UHECRs, there have been many correlation studies between the arrival direction distribution of UHECRs and the positions of astronomical source candidates, such as active galactic nuclei, radio galaxies, or starburst galaxies, but we have not yet reached conclusive results [4-11]. One of the main obstacles to narrow down the sources of UHECR is that they are charged particles; thus, their propagation trajectories from the sources could be deflected by magnetic fields in the universe. The magnetic fields are ubiquitous in astrophysical environments at various scales from stars to clusters of galaxies. Therefore, investigations on the propagation of UHECRs in the magnetized large-scale structure (LSS) of the universe would play an important role in the search for the astronomical sources of UHECRs.

From this point of view, it is necessary to investigate the origin of a high concentration of UHECR events, the so-called TA hotspot, reported by the Telescope Array (TA) experiment [12]. Since there is no prominent source candidate in the direction of the TA hotspot area, several astronomical objects which have large separation angles from the center of the hotspot, including M82, have been suggested as source candidates of the hotspot events [13]. However, it remains inconclusive because those models require assumptions about the strength of GMF or mass composition, which are not consistent with observational data. Specifically, if the primary particle of UHECRs would be light nuclei, which is estimated from TA experiment data analysis, a large angular distance between the position of M82 and the center of TA hotspot, ~26.5º, indicates a significant deflection during the propagation; the model requires stronger GMF than typically known strengths of GMF, a few $\mu$G. In short, no plausible point source candidates have been identified toward the TA hotspot, which may imply we need to pay attention not only to point sources but also to the galaxy structure in the local universe.

In the previous work [14], we focused on the local galaxy structure and the propagation of UHECRs in the magnetized LSS of the local universe. We reported the existence of filamentary structures of galaxies connected to the Virgo cluster and a statistically significant correlation of 5.6σ between the sky position of the filaments of galaxies and the arrival directions of the TA events. We suggested a model based on the magnetized cosmic web structure, which consists of galaxy clusters, galaxy filaments, and voids. The UHECRs were produced at sources in the Virgo cluster and confined by cluster magnetic fields for a while. Then, they preferentially escaped to and propagated along filaments. Eventually, some of them were scattered by filament magnetic fields, and come to us. Those UHECRs could be observed like an excess of events toward the area where no nearby prominent UHECR sources are, like the TA hotspot.

In this paper, we examine the model by investigating the propagation trajectories of ultra-high-energy (UHE) protons in a simulated universe. In Section 2, we describe our model for the formation of LSS and generation of magnetic fields, and the simulations of propagation of UHE protons will be given. The results of the simulation will be followed in Section 3. Finally, we conclude in Section 4.

## 2. Simulations

### 2.1 Model universe simulation

To study the propagation and scattering of UHECRs in the magnetized cosmic web, we produce a model universe through numerical simulation for the LSS formation using a particle-mesh/Eulerian cosmological hydrodynamics code [15]. The ΛCDM cosmological model with the following parameters were assumed: baryon density of $\Omega_{BM}$ = 0.044, dark matter density of $\Omega_{DM}$ = 0.236, cosmological constant of $\Omega_{\Lambda}$ = 0.72, Hubble parameter of $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ = 0.7, RMS density fluctuation $\sigma_8$ = 0.82, and primordial spectral index n = 0.96.

A cubic box of the comoving size of 49 $h^{-1}$Mpc with periodic boundaries is generated using $1440^3$ uniform grid zone. Therefore, the resolution of the grid is 34.5 $h^{-1}$ kpc, which is smaller than the gyro-radius of UHE protons in most zones. There are two clusters with x-ray weighted temperature T $\gtrsim$ 2.5 keV in the simulation volume. We pick up one cluster sample with T = 2.8 keV as the source cluster of UHE protons because the other one is a merging cluster, which is not proper to mimic the Virgo cluster.

The generation of intergalactic magnetic fields (IGMF) is seeded by the Biermann battery mechanism at cosmological shocks, and their evolution and amplification were followed passively along with flow motions [16]. Alternatively, cosmological magnetohydrodynamic (MHD) simulations for the LSS formation can be used for UHECR propagation studies [17]; however, a currently available numerical resource cannot reproduce the full development of MHD turbulence. Therefore, we used the LSS formation simulation then included the IGMF passively. The overall magnetic field strength is rescaled to reproduce the observed strengths. The magnetic field strengths are rescaled on the basis of the magnetic field strengths of the sample cluster core within 1 $h^{-1}$Mpc from the x-ray center. In this work, we adopt three sets of model universes rescaled the core region to 1.5 $\mu$G, 2 $\mu$G, and 3 $\mu$G.

### 2.2 Particle trajectory simulation

In the model universe described above, we inject UHECRs and examine their propagation trajectories assuming their sources are in the core of the clusters. At random positions within the cluster core of 1 $h^{-1}$Mpc from the X-ray center position of the clusters, we launch $10^5$ protons having the energy of $6\times10^{19}$ eV toward random directions. Then, we trace their trajectories with the relativistic equation of motions for charged particles under magnetic fields given by

$$\frac{d\boldsymbol{r}}{dt} = v$$

$$\frac{d\boldsymbol{v}}{dt} = \frac{Ze}{mc}(v \times B).$$

## 3. Results

Figure 1 shows two-dimensional slices of the magnetic field strength in the model universe rescaled the core region to 1.5 $\mu$G. The sample cluster is located at the center of the box, and

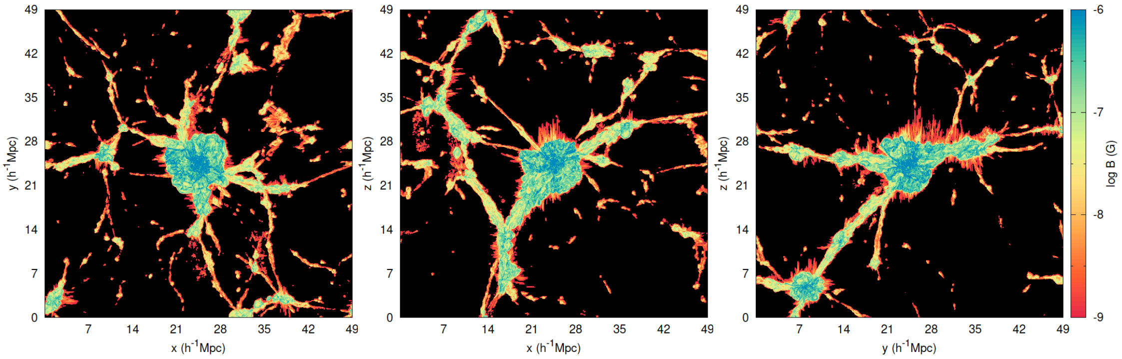


Figure 1. Two-dimensional slices of the magnetic field strength in the model universe, which is rescaled the core region to 1.5 $\mu$G.

filamentary structures are seen around the cluster. The color indicates the strength of magnetic fields.

We are interested in the propagation of UHECRs in the magnetized cosmic web to verify our model for explaining TA hotspot events—UHECRs produced at a source in the Virgo cluster could be confined by cluster magnetic fields for a while, then they preferentially escape to filaments and finally scatter to voids; therefore, we focus on the purpose. We analyze the fraction of the UHE protons which are confined within clusters during the GZK time of ~300 million years (Myr) and the fraction which escapes from clusters to filaments.

Based on the examination of the shape of the sample cluster considering the distribution of magnetic fields, its radius is defined as $R_{cluster} \sim 3.5\ h^{-1}$Mpc. It is found that about 3% of injected UHE protons are confined within $R_{cluster}$ during the GZK time of ~300 Myr. The fraction which escapes from clusters to filaments and that which directly escapes from clusters to voids are similar. Displacement from the center of the cluster for two UHE protons as a function of time is shown in Figure 2. The color bar shows the magnetic field strength that the particles experience at the position. The left panel is a representative example of particles directly escape from the cluster to voids. This UHE proton roams around the cluster for ~30 Myr, then directly escape to voids where the strength of the magnetic field is weaker than $10^{-9}$ G. By contrast, the right panel represents a particle escapes from the cluster via the filament. After wandering inside the cluster for more than ~50 Myr, this UHE proton propagates along the magnetic field line to the filament where the strength of the magnetic field is weaker than that of the cluster. It propagates around 10 $h^{-1}$Mpc along the filament and finally scatters to voids.

It is possible to classify the particles into two groups according to where they escape to, like the above; however, the specific trajectories of UHE protons are very sensitive to the configuration of magnetic fields. Even if some particles enter into the same filament, their trajectories and the last scattering points by the turbulent magnetic fields in the filament vary widely.

## 4. Conclusion

This model can explain another characteristic distribution of TA UHECR data in the one frame. If we take a look at the distribution of TA events, we can see a deficit of events toward the Virgo cluster, which is the closest (~16 Mpc) and contains ~1500 galaxies, such as lots of active galactic nuclei and radio galaxies. Under the simple assumption that a UHECR flux is inversely

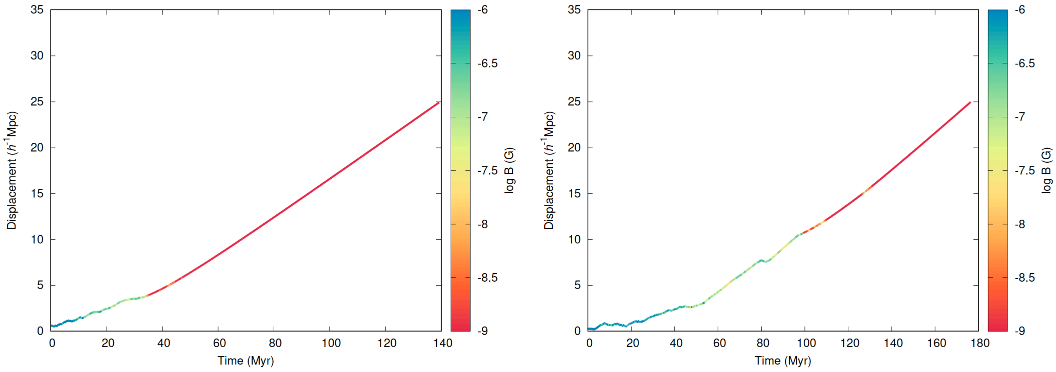


Figure 2. Displacement from the center of the cluster for two UHE protons. The left panel is the case of a particle directly escape from the cluster to voids, and the right panel is that of a particle escape from the cluster to the filament, then scatter to voids.

proportional to the square of the distance from sources, the expected distribution of UHECRs is concentrated in the direction of the Virgo cluster, which disagrees with the observed distribution of UHECRs. The discrepancy makes the previous correlation studies with astronomical objects, such as active galactic nuclei, failed to confirm the close correlation of UHECRs [6, 7]. If the magnetic field line of the Virgo cluster is mostly closed in the direction to us so that UHECRs preferentially escape through the filaments of galaxies, the small number of observed events toward the cluster would be expected in the same context of the excess of events toward the filaments.

The results of this study confirm that a UHE proton produced from a source in a cluster of galaxies can escape to filaments of galaxies connected to the cluster and propagate along the filaments. Since the propagation trajectories of particles in the magnetized cosmic web depend on the specific configuration of magnetic fields, the information on the magnetic field distribution in the regions of the Virgo Cluster and the hotspot is required for realistic tests to reproduce the TA hotspot. Future astronomical projects for exploration of intergalactic magnetic fields will make it possible for us to impose essential constraints on the magnetic fields in the cosmic web.

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