Filaments of galaxies as a clue to the origin of ultrahigh-energy cosmic rays

Jihyun Kim¹, Dongsu Ryu¹*, Hyesung Kang², Suk Kim³, Soo-Chang Rey⁴

Ultrahigh-energy cosmic rays (UHECRs) are known to come from outside of our Galaxy, but their origin still remains unknown. The Telescope Array (TA) experiment recently identified a hotspot, that is, a high concentration of anisotropic arrival directions of UHECRs with energies above \(5.7 \times 10^{19} \text{ eV}\). We report here the presence of filaments of galaxies, connected to the Virgo Cluster, in the sky around the hotspot and a statistically significant correlation between hotspot events and the filaments. With 5-year TA data, the maximum significance of binomial statistics for the correlation is estimated to be 6.1σ at correlation angle 3.4°. The probability that the above significance appears by chance is \(2.0 \times 10^{-8}\). On the basis of this finding, we suggest a model for the origin of TA hotspot UHECRs; they are produced at sources in the Virgo Cluster, and escape to and propagate along filaments, before they are scattered toward us. This picture requires the filament magnetic fields of strength \(\gtrsim 20 \text{ nG}\), which need to be confirmed in future observations.

INTRODUCTION

Since their first discovery in the early 1960s, ultrahigh-energy cosmic rays (UHECRs) above the so-called Greisen-Zatsepin-Kuz’min (GZK) energy of \(E_{\text{GZK}} \approx 5 \times 10^{19} \text{ eV}\) (1, 2) have been observed for more than several decades (3, 4). However, their origin still remains unresolved. Super-GZK UHECRs are believed to originate from extragalactic objects, as they cannot be confined by the Galactic magnetic field and accelerated within the Galaxy. On the other hand, a substantial fraction of these cosmic rays should come from objects in the local universe within \(-100 \text{ Mpc}\), because the interaction with cosmic microwave background photons limits their propagation distance. One of the obstacles in study of super-GZK UHECRs has been the small number of observed events. To overcome this problem, international collaboration projects, such as the Pierre Auger Observatory and the Telescope Array (TA), which deployed large numbers of ground detectors along with fluorescence stations, were launched to collect UHECR data of high quantity and quality. These collaborations have investigated anisotropies in arrival directions of observed UHECR events as well as their correlations with nearby extragalactic objects to search for the sources (5–8).

The TA collaboration recently reported a high concentration of UHECR events in the sky, called a hotspot, centered at right ascension (RA) = 146.7° and declination (DEC) = 43.2°, from a study of anisotropic arrival directions of UHECRs above \(5.7 \times 10^{19} \text{ eV}\), using the scintillator surface detector (SD) data collected over a 5-year period (8). The Li-Ma statistical significance of the hotspot was reported to be 5.1σ, and the probability that the hotspot appears by chance was \(3.7 \times 10^{-9}\) (3.4σ). Despite the high statistical significance, however, astronomical objects that could be responsible for UHECRs have not been identified around the hotspot, leaving its nature mysterious.

In this report, we describe a new finding that there are filaments of galaxies connected to the Virgo Cluster around the hotspot; their locations in the sky are correlated to hotspot events with a high statistical significance. On the basis of this finding, we suggest a model for the origin of the hotspot.

RESULTS

Figure 1 shows the distribution of nearby galaxies within 50 Mpc, taken from the HyperLEDA database ([9]; see the Supplementary Materials for a short description of the database), along with the arrival directions of 72 TA events above \(5.7 \times 10^{19} \text{ eV}\), used in the hotspot study (8). The excess of the TA events within the circle of \(-20°\) radius around the hotspot center is evident, while there is no sign of an obvious excess of nearby galaxies. On the other hand, a deficit in events toward the large concentration of galaxies, the Virgo Cluster, is noticeable. It is the closest galaxy cluster in the direction of RA = 187.7° and DEC = 12.4° at the distance of about 16.5 Mpc and contains \(-1500\) galaxies (10, 11), including M87, one of the brightest radio sources in the sky (12). However, because of its position, which is about \(50°\) apart from the hotspot center, the Virgo Cluster has been excluded from consideration for the origin of the TA hotspot so far.

It has been shown that there is a structure made of galaxies, which are linked to the Virgo Cluster. For instance, a number of elongated structures, called clouds or spurs, were reported in an early study to reveal the Local Supercluster (13). More recently, using a dataset taken from HyperLEDA, which, in particular, includes a large number of low-luminosity, dwarf galaxies, seven filaments of galaxies and one sheet were either reaffirmed or newly identified around the Virgo Cluster. From a Hubble diagram analysis in the Virgo-centric reference frame, it was found that “six” filaments have galaxies infalling toward the Virgo Cluster, so they are dynamically connected to the cluster ([14]; see the Supplementary Materials for a further description of the filaments). Figure 2 shows the six filaments, labeled as F1 to F6. Among the six, “three” filaments, F1 to F3, are located within \(-20°\) from the hotspot center, and a number of the TA events are found to be aligned along them.

The significance of the association between filaments F1 to F3 and the TA events was examined with the following two statistics for correlation. One is the cumulative probability, \(P(\theta)\), of binomial statistics to observe excesses of events within the angular distance \(\theta\) from the spine of the closest filament. Figure 3 shows \(P(\theta)\); it has the minimum value, \(1.23 \times 10^{-7}\), at \(\theta = 3.4°\), within which \(n_{\text{obs}} = 18\) are observed tokens.

1Department of Physics, UNIST, Ulsan 44919, Korea. 2Department of Earth Sciences, Pusan National University, Busan 46241, Korea. 3Korea Astronomy and Space Science Institute, Daejeon 34055, Korea. 4Department of Astronomy and Space Science, Chungnam National University, Daejeon 34134, Korea.

*Corresponding author. Email: ryu@sirius.unist.ac.kr
among the total $N = 72$ events, while $n_{\text{exp}} = 3.12$ are expected. It is equivalent to a two-sided Gaussian significance of $6.1\sigma$. At the average distance of the filaments, $\sim 15$ $h^{-1}$ Mpc, the correlation angle, $\theta = 3.4^{\circ}$, corresponds to $\sim 1.3$ Mpc, which is about the radius of typical filaments. The other is the probability that this significance appears by chance. This post-trial probability, calculated using a Monte-Carlo simulation, is $2.0 \times 10^{-8}$, equivalent to a significance of $5.6\sigma$. For reference, the statistical significance of the correlation of the TA events with all the six filaments connected to the Virgo Cluster can also be inspected. The two statistics give $5.6\sigma$ and $5.1\sigma$, respectively. Lower significances agree with the visual impression that there are not many TA events around filaments F4 to F6.

The estimated significance for the correlation between filaments F1 to F3 and the TA events is rather high. This could be partially due to the small number of events. The TA events from 7-year SD data were shown in a figure (15); from the figure, it can be estimated that $n_{\text{obs}} = 21$ events among the total $N = 110$ events at $\theta = 3.4^{\circ}$, giving the binomial statistical significance of $5.7\sigma$. It is still sufficiently large, but a bit smaller than that from the 5-year data. Therefore, we point that the statistics quoted here needs to be further updated as more events accumulate.

DISCUSSION

The correlation between the TA hotspot events and filaments F1 to F3, if it is real, should provide us a clue for the origin of the UHECR events. The straightforward interpretation would be that UHECRs are produced at sources located in the filaments. However, by considering that the members of the filaments are mostly normal, not active, galaxies and many of them are dwarf galaxies (14), and also the total number of those galaxies is small, that would be a less likely scenario.

The correlation can also arise if UHECRs are produced inside the Virgo Cluster and escape preferentially to the filaments, before some of them are scattered toward us, as schematically shown in Fig. 4. Galaxy clusters host a number of potential accelerators of UHECRs, listed in the so-called Hillas diagram (3). As noted above, there is a powerful radio galaxy, M87, in the Virgo Cluster, and it has long been argued that radio galaxies could be the sources of UHECRs (16). A large number, $\sim 1500$, of cluster galaxies means that there is a good chance of previous episodes of transient objects like gamma-ray bursts, which have also been considered as possible sources (17). It was also suggested that cluster-scale shock waves could accelerate...
UHECRs (18). In addition, the Virgo Cluster is known to be young and dynamically active with substructures (10), suggesting a high possibility of energetic phenomena. However, the detailed processes of UHECR production need to be further investigated.

The medium between galaxies in clusters, the intracluster medium (ICM), is known to be magnetized at the level of the order of $\mu$G strength (19). In the Virgo Cluster, for instance, the Faraday rotation measure (RM) of a few hundreds of rad m$^{-2}$ was observed in the M87 jet (20). While most of the RM is likely to be associated with the sheath of the jet, it also implies the presence of ICM magnetic fields. In addition, constrained simulations, which were designed to reproduce the density and magnetic field distributions in the local universe, supported the magnetic fields of $\mu$G in the Virgo cluster (21). Such magnetic fields strongly influence the trajectory of UHECRs. The gyroradius of charged particles is given as

$$r_g \sim 50 \text{ kpc} \left( \frac{E}{Z} \right) \left( \frac{B}{1 \text{ $\mu$G}} \right)^{-1}$$

where $E$ and $Z$ are the particle’s energy and charge. Hence, UHECRs, if produced inside the Virgo Cluster, should be rather tightly confined by the cluster magnetic fields.

It is believed that magnetic fields also exist in the medium of galaxy filaments, although their nature is less well known than that of ICM fields. In a dataset of NVSS (the NRAO VLA Sky Survey) RMs of extragalactic radio sources, the contribution due to the magnetic fields in the cosmic web was estimated to be $\sigma_{\text{RM}} \sim 6$ rad m$^{-2}$ (22). It was shown that the dispersion of RM can be reproduced, if filaments are magnetized at the level of ~10 nG (23). More recently, a search for the synchrotron emission from the cosmic web set an upper limit of ~30 nG in filaments (24, 25). Such fields were also predicted in theories and simulations; for instance, the fields could develop through turbulence dynamo during the formation of the large-scale structure (LSS) of the universe (26). In addition, in the hierarchical formation of the LSS, matter falls to clusters along filaments, dragging filament magnetic fields into clusters. Therefore, field lines are expected to be connected to those of clusters. If such a picture is applied to the Virgo Cluster and the neighboring filaments, then UHECRs, which were produced and have roamed around for a while in the cluster, would preferentially escape to the filaments through connected field lines.

Along filaments, whose radius is of the order of Mpc, UHECRs can be confined and guided by the magnetic fields of strength $\gtrsim 20$ nG, if they are protons. In addition to the regular component, the filament magnetic fields should have the random (or turbulent) component, which can scatter UHECRs. The average scattering angle depends on the characteristics of turbulent fields as

$$\delta \sim f \frac{\pi}{2} \left( \frac{5 \times 10^{19} \text{ eV}}{E/Z} \right) \left( \frac{L}{25 \text{ Mpc}} \right)^{1/2} \left( \frac{l_c}{1 \text{ Mpc}} \right)^{1/2} \left( \frac{B_{\text{random}}}{20 \text{ nG}} \right)$$

where $L$ is the propagation distance and $l_c$ is the coherence length of random magnetic fields, $B_{\text{random}}$. Here, $f$ is a reduction factor of the order of unity (27). Therefore, UHECRs, again if they are protons, could be scattered out of filaments, after they propagate a few tens of Mpc. These estimates are consistent with the picture presented in Fig. 4, provided that the filament magnetic fields have the strength of $\gtrsim 20$ nG and $l_c$ of a sizable fraction of the filament radius.

The propagation and scattering of UHECRs in the cosmic web were previously studied through numerical simulations (28, 29); it was shown that the arrival direction of super-GZK protons could be substantially deflected. To further examine the plausibility of the picture in Fig. 4, we followed and inspected the trajectories of UHE protons in the intergalactic space of a simulated model universe (see Materials and Methods). Figure 5 shows two of them with $6 \times 10^{19}$ eV around a cluster of $T = 3.5$ keV; here, the magnetic field strength is
1.5 μG in the cluster core, ~0.1 μG in the cluster outskirts, and a few tens of nG in filaments. Figure 6 shows their displacement from the launching positions, color-coded with the local magnetic field strength, as a function of time. The two UHE protons roam around the cluster core for ~40 million years (Ma) (case 1) and ~100 Ma (case 2) and move to the outskirts; they escape through filaments, propagate ~10 $h^{-1}$ Mpc (case 1) and ~35 $h^{-1}$ Mpc (case 2), and lastly scatter to voids. However, we should note that the specific trajectory depends sensitively on the exact configuration of magnetic fields. Therefore, the relevant statistics such as the fraction of the UHE protons confined within the cluster during the GZK time (~300 Ma), the fraction of the UHE protons escaping to filaments, and the propagation distance along filaments rely on accurate modeling of magnetic fields.

For the true test of the picture, hence, we need to know the magnetic field distribution in the regions of the Virgo Cluster and the hot-spot, especially the field line topology from the cluster to filaments F1 to F3. As pointed above, however, the magnetic fields in the cosmic web including those in filaments F1 to F3 are not yet well known. However, upcoming large-scale astronomical projects, such as the Square Kilometre Array, list the exploration of intergalactic magnetic
fields as one of the key sciences (30). Therefore, the magnetic fields in the cosmic web may be better constrained in the near future.

The lack of an obvious excess of TA events near filaments F4 to F6 is still unexplained. One possibility could be the following: If cluster magnetic field lines are preferentially connected to those of filaments F1 to F3, then UHECRs could escape mostly toward F1 to F3, just as fast solar wind particles flow out through open magnetic field lines associated with coronal holes of the Sun (31). We also mention two interesting observations; first, the brightest elliptical galaxies are oriented toward the tips of F1 to F3, hinting that the galaxies might form a structure connected to the filaments, and second, the jet of M87 also expands in that direction [see the Supplementary Materials for a further description of these observations and (32–34)]. In addition, we indicate a geometrical factor that should contribute to the bias; the region containing the upper filaments, F1 to F4, is subject to a larger TA exposure than that of the lower filaments, F5 and F6. Although an event has been observed within $\theta = 3.4^\circ$, there is no TA event around F5 and F6.

We need to comment on the implication of the Galactic magnetic field. Outside the Galactic disc, it has the strength of $\sim$μG and the coherence scale of $\sim$kpc (35). The magnetic field can deflect the trajectory of UHE protons above $5.7 \times 10^{19}$ eV by a few degrees (36). The deflection should be much larger if they are heavier nuclei. Hence, the correlation presented in this paper, if real, should indicate that UHECRs are mostly protons.

In this paper, we have focused mainly on the origin of the TA events around the hotspot. However, there are super-GZK UHECRs observed in other parts of the sky, which were likely produced at sources outside of the Virgo Cluster. Considering that most of them should still come from nearby sources within the GZK horizon as mentioned above, understanding the cosmic web structure, including the distribution of galaxy filaments, in the local universe would be essential to the exploration of the origin of UHECRs. As for the identification of the filaments connected to the Virgo Cluster, however, the task can be completed only when very deep spectroscopic data of low-luminosity, dwarf galaxies are available, so it should be left as a future work.

MATERIALS AND METHODS
The binomial statistics presented above was calculated as follows. Let $n_{\text{obs}}$ be the number of events observed within the angular distance $\theta$ from the spine of the closest filament, and $n_{\text{exp}}$ be the number expected from the isotropic distribution after the geometrical exposure of the TA experiment, $g(\psi) = \sin \psi \cos \psi$ ($\psi$ is the zenith angle), is taken into account. Then, the cumulative probability to observe $n_{\text{obs}}$ or more events within $\theta$ is calculated as

$$P(\theta) = \sum_{x=n_{\text{obs}}}^{N} \binom{N}{x} p^x (1-p)^{N-x}$$

where $N$ is the total number of events and $p = n_{\text{exp}}/N$. It shows the minimum value, $1.23 \times 10^{-3}$, at $\theta = 3.4^\circ$, as mentioned above.

The probability that the above significance appears by chance was estimated as follows. Through a Monte-Carlo simulation, $10^8$ datasets were generated; each contains 72 events within the TA field of view, which were drawn randomly after the exposure factor, $g(\psi)$, was taken into account. The cumulative binomial probability as a function of $\theta$ was calculated for each dataset, and the cases with the minimum probability smaller than $1.23 \times 10^{-9}$ were counted. This yields the post-trial probability of $2.0 \times 10^{-8}$.

The model universe, where the trajectories of UHE protons were followed, was generated through a numerical simulation for the LSS formation using a particle-mesh/Eulerian cosmological hydrodynamics code (37). Assuming a ΛCDM cosmological model, the following parameters were used: baryon density $\Omega_{\text{b}0} = 0.044$, dark matter density $\Omega_{\text{DM}0} = 0.236$, cosmological constant $\Omega_{\Lambda} = 0.72$, Hubble parameter $h = H_0/(100$ km s$^{-1}$ Mpc$^{-1}) = 0.7$, rms density fluctuation $\sigma_8 = 0.82$, and primordial spectral index $n = 0.96$. A cubic box of comoving size of $57^4$ Mpc with periodic boundaries, divided into $1650^3$ uniform grid zones, was used; the grid resolution is 34.5 h$^{-1}$ kpc, which is smaller than the gyroradius of UHE protons in most zones. Three clusters with x-ray weighted temperature $T \gtrsim 3$ keV formed within the simulation volume, and a cluster with $T = 3.5$ keV was selected as the source cluster of UHE protons (see Fig. 5).

Assuming that the intergalactic magnetic fields were seeded by the Biermann battery mechanism, their evolution and amplification were followed (38). However, with the numerical resolution used, the cluster magnetic fields are not amplified to the level of observed strengths (39). Therefore, the magnetic field strength in the core (within $1 h^{-1}$ Mpc from the x-ray center) of the source cluster was rescaled to $\sim 1$ μG; then, it became $\sim 0.1$ μG in the cluster outskirts, and a few tens of nG in filaments, as mentioned above. At random positions within the cluster core, UHECRs with $6 \times 10^{19}$ eV were injected toward random directions, and their trajectories were followed with the relativistic equation of motions for charged particles under magnetic field.

SUPPLEMENTARY MATERIALS
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/1/eaau8227/DC1

Supplementary Materials
Fig. S1. Leo Minor filament, or F3, in the three-dimensional Supergalactic coordinates.
Fig. S2. Six filaments dynamically connected to the Virgo Cluster and their names.
Fig. S3. Blow-up of a sky region including the Virgo Cluster and filaments F1 to F3.
Data File S1. Sky positions of galaxies for six filaments connected the Virgo Cluster.

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