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A search for cosmic strings

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Abstract. A cosmic string is a topological defect thought to be made during a phase transition in the early universe. It is predicted by elementary particle theory and cosmology. It is also a good candidate for the origin of extremely high energy ($> 10^{20}$eV) cosmic rays (EHECRs). A search for cosmic strings was carried out using the Sloan Digital Sky Survey (SDSS) data, which is obtained using an optical telescope. Characteristic double images of galaxies are expected to be produced by cosmic strings due to gravity. However, we could not detect any signatures of global cosmic strings. An upper limit to the number of global cosmic strings within the GZK horizon (< 100 Mpc), N<1.1 with 95% confidence level, was derived.

1 Introduction

The Akeno Giant Air Shower Array (AGASA) has observed 8 events above 10^{20}eV up to the date of November 30, 1999 (Takeda et al., 1998), and the extension of the cosmic ray energy spectrum beyond the GZK cut-off has been established. Amongst many models of super-GZK particle origin, one of the most promising is the decay of cosmic strings. This model explains EHECRs as a secondary particle from cosmic string decay. In order to investigate this model, a search for cosmic strings was carried out using SDSS data. A cosmic string would make characteristic double images due to its gravity. These double images are made along a cosmic string with constant separation angles and identical images. This lensing effect is different from the normal gravitational one since that there is no amplification of light intensity. We have looked for cosmic strings by extracting the double images thought to be caused by them. The SDSS is a project to survey a vast region with an optical telescope. It covers a quarter of the whole sky. The data from this telescope is suitable for the search for cosmic strings, because a wide area of the sky is swept systematically and the sensitivity is great enough to measure galaxies down to magnitude 23. The analysis was carried out systematically with extensive Monte Carlo simulations. We could not find any signature of cosmic strings in the SDSS data. We turn obtained the upper bound for the number of global cosmic strings within the GZK horizon.

2 Extremely High Energy Cosmic Rays

AGASA shows a clear extension of the cosmic ray energy spectrum beyond the GZK cut-off energy. The GZK cut-off is expected to appear at 4×10^{19}eV in the cosmic-ray energy spectrum due to the resonant interaction with cosmic microwave background radiation (CMBR). In other words, it is expected that EHECRs above 10^{20}eV can't reach the Earth from beyond the GZK horizon of 100 Mpc distance. The origin of these EHECRs is still unknown.

There are two categories of models to explain the super-GZK particles: "bottom-up" processes and "top-down" processes.

In the first category, "bottom-up" models are based on acceleration in astronomical objects. There are two kinds of acceleration mechanism. Statistical acceleration called first/second order Fermi's accelerations and the unipolar induction mechanism. In these models the maximum acceleration energy is determined by the size of the acceleration region and the magnetic strength, as suggested by Hillas (1984). With this simple condition, the astronomical objects able to accelerate cosmic rays up to 10^{20}eV are limited. Promising sources are gamma ray bursts and active galactic nuclei.

In the second category, "top-down" models are basically a decay of heavy particles. Candidates are topological defects(such as monopoles and cosmic strings), super heavy relics in the halo etc. For example, in the case of a cosmic string, in the process of intersection and loop decay, or directly, extremely heavy gauge bosons are generated. These gauge bosons then decay into quarks and leptons. Through these processes, EHECRs are produced as secondary parti-

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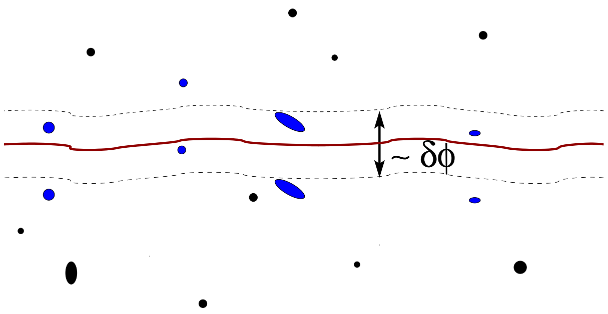

Fig. 1. Double images made by a cosmic string

cles. The main components of these particles are gamma rays and neutrinos.

The empirical fact that we can not find any astronomical sources in the arrival direction of EHECRs within 100Mpc, favors top down models.

3 Cosmic Strings

A cosmic string is a kind of topological defect which could be created during the cooling down process of the hot big bang universe. It is predicted by elementary particle theory and cosmology. Cosmic strings can be made born through a spontaneous symmetry breaking, called a Higgs mechanism, and through the effect of canceling phase gaps, called a Kibble mechanism (Kibble, 1976). They evolve in the expanding universe, intersecting each other and generating loops. The number of global cosmic strings is scaled to the evolution of the universe, and they can exist up to now, therefore they can be a candidate for the origin of EHECRs. In the radiation era, the number of global cosmic strings was estimated to be about 4 (Bennett and Bouchet, 1989; Allen and Shellard, 1993).

A cosmic string is very heavy because it retains the previous condition after the phase transition. Bennett et al.(1992) derived the linear mass density of cosmic strings from observations by COBE of fluctuations in the CMBR, assuming cosmic strings are responsible for all of the observed fluctuations.

$$G\mu = (1.5 \pm 0.5) \times 10^{-6} \tag{1}$$

Here G is the gravitational constant and μ is a linear mass density of a cosmic string in natural units. Since cosmic strings have a string shape, as its name suggests, it produces characteristic double images along its length (Fig.(1)). These images are identical and have constant separation angles. The light intensities of the two corresponding lensed images are identical because of the flat metric around the cosmic string. The separation angle between pair images corresponds to a deficit angle. However, in realistic situations, it can vary slightly, because it is dependent on the angle θ between the string and the line of sight. It also depends on the ratio of the distance d between the observer and the string to the distance l between the string and the lensed object. The separation angle becomes smaller as shown below:

$$\begin{aligned} \delta\phi &= 8\pi G\mu \, l(d+l)^{-1} \sin\theta & (2) \\ &= 5.2'' \left(\frac{G\mu}{1.5\times10^{-6}}\right) l(d+l)^{-1} \sin\theta & (3) \end{aligned}$$

Sinθ represents a mass projection effect and $l(d+l)^{-1}$ represents an effect of light geometry.

4 The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (SDSS) is a project which aims to observe a quarter of the whole sky. A main purpose of this project is to make a 3D map of the universe. The SDSS telescope is installed at Apache Point Observatory (APO) on Sacramento Peak in New Mexico, USA. Its geographical coordinates are $105°49'W$, $32°47'N$ and its altitude is about 2800m. The optical system is a modified Ritchey-Chrtien comprising a 2.5m main mirror and 1.1m sub mirror. The telescope has 30 photometric CCDs (2048×2048 pixel) for observations and 22 astrometric CCDs (2048×400 pixel) for calibration. Each CCD is covered with a filter constituted of 5 colors; u', g', r', i', z'. SDSS has adopted a Time-Delay and Integrate (TDI) mode, which is a way of making the speed of CCD reading coincide with the speed of diurnal motion. This mode provides continuously long observational regions with a $2.5°$ width. In SDSS terminology an observation is called a “run”. The data taken at during the run is called a “strip” because there are gaps between CCDs. The same sky is then observed with a small angular offset in order to fill these gaps. The combined data with two compensating strips is called a “stripe”. The image resolution is about $1.5''$ which is governed by sky condition. Observed data is processed by computers and various parameters, such as the positions, brightnesses, shapes of objects, are extracted automatically.

5 Data Analysis

5.1 A search for cosmic strings

We analyzed SDSS data to search for cosmic strings. Analyzed stripes are shown in Fig.(2) with red region. The circles designate the arrival directions of EHE events and cluster events observed by AGASA.

Firstly we extracted pair images thought to be lensed by cosmic strings. We used the following criteria to select pair images.

1. $2.0'' <$ a separation angle $< 6.0''$
2. Coincidence of brightnesses in each color band (99% Confidence Level)
3. Coincidence of shapes in each color band (99% C. L.)
4. Only objects with magnitude of r’ band < 22.5

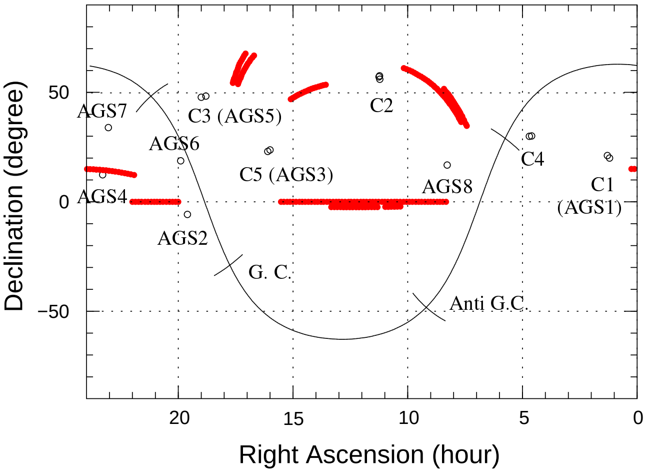

Fig. 2. Regions searched for cosmic strings (red region) and extremely high energy events and cluster events observed by AGASA

5. Stars were excluded

We have assumed a cosmic string mass density as suggested by Bennett et al.(1992). In this case the separation angle becomes about $5''$. Therefore we put constraints for a separation angle's upper bound at a slightly larger value. The telescope image resolution is about $\sim 1.5''$, but it changes slightly as seeing becomes worse. We therefore adopted $2.0''$ as the lower bound. We have also chosen brighter objects (magnitude < 22.5) than the limiting magnitude 23. Stars in our galaxy were excluded because an astronomical object must be located behind a cosmic string and cosmic strings are expected to be outside our galaxy.

Next we tested the geometry of pair images, geometrical alignment and their direction alignment in a certain region. We used a rectangular region of 1° long and $6'$ width, because we expect pair images would be made along a cosmic string and perpendicular bisectors would be aligned. The number of pair images in the rectangular region, whose perpendicular bisectors are aligned with long axis within $\pm 15^\circ$, were counted. In order to evaluate the chance probability, this number was compared with the expected number assuming a binomial distribution. This test was carried out by rotating the rectangle box in increments of 5° in each sky position. The most significant value is defined as the chance probability at each point. The same procedure was done on a $1.5'$ grid, then finally a continuous chance probability map was obtained. For example, the chance probability map for stripe 10 (make up of run 752 and run 756) is shown in Fig.(3). The chance probability in each grid is represented with a logarithmic scale. In order to check whether or not these values are significant, we compared them with simulation results. Figure (4) shows a result of simulations where there was no string. The Simulation data set was generated from observational data by rotating the directions of perpendicular bisectors of pair images at random. In Fig.(5), an string is embedded artificially assuming the linear mass density derived by Bennett et al.(1992). The sensitivity of our analysis for cosmic strings is well illustrated.

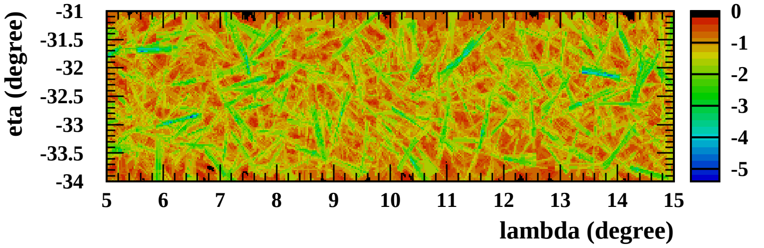

Fig. 3. A continuous chance probability map obtained from data of run 752 and run 756. The value is represented with a logarithmic scale.

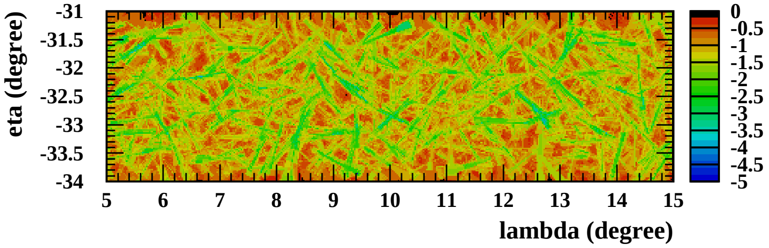

Fig. 4. A continuous chance probability map simulated without cosmic strings

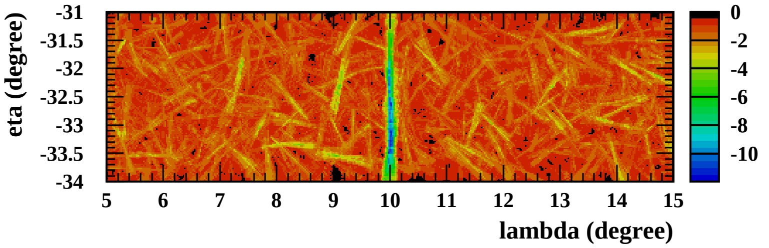

Fig. 5. A continuous chance probability map with artificial cosmic string

The same procedure have been done for several linear mass densities smaller than the original one suggested by Bennett et al.(1992). Figure (6) shows the cumulative number of positions in the sky as a function of chance probabilities. The distribution of observed data agrees well with the simulated data set with no cosmic string. Other runs were also analyzed with the same procedure. However, we could not find any sky region giving a significant chance probability. Therefore we conclude that no cosmic string was found.

5.2 A derivation of an upper limit to the number of global cosmic strings within the GZK horizon

As we described above we could not find any signature of cosmic strings. Therefore we derived an upper limit to the number of global cosmic strings within the GZK horizon using a simulation. The procedure is detailed below.

We assumed a sphere corresponding to the universe with diameter $d_H \sim 8$Gpc from the age $t_0 = (12.9 \pm 2.9) \times 10^9$

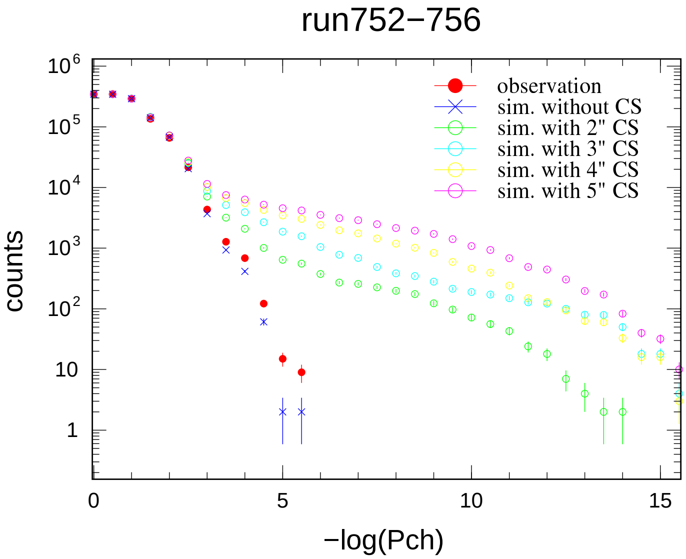

Fig. 6. A cumulative distribution of chance probabilities

year derived by Carretta et al.(Carretta et al., 2000). Theoretically, a cosmic string walks randomly with a step size of a third of the universe horizon scale(Bennett and Bouchet, 1990). Strings with linear mass density of 1.5×10^{-6}, derived by Bennett et al.(1992), were made to enter into the universe, walking randomly with the same step size. Strings of whole length greater than d_H were regarded as a global cosmic string. The lensing effect from a cosmic string depends on the geometrical relationship of the string and the lensed object and an angle between the string and the line of sight. In this analysis, we have used galaxies brighter than magnitude 22.5. The magnitude 22.5 can be translated to $z \sim 0.51$, using the database of red shift in Glazebrook's thesis(Glazebrook et al., 1995). This value of red shift corresponds to about 1720Mpc with $H_0 = 68{\pm}6$ km/s/Mpc(Mould et al., 1999). For simplicity, we have assumed all of the objects are located at a distance of 1720Mpc. With these assumptions, we can calculate the separation angle of pair images from the cosmic string position and its direction using the Eq.(3). As you can see in Fig.(6), our analysis with SDSS data is sensitive to the cosmic strings producing the separation angle greater than $2.0''$. When a cosmic string entered into an analyzed region, we checked whether or not the string is observable from the separation angle obtained by Eq.(3). If it turned out to be observable, we stopped making strings enter the simulation and counted up the number of cosmic strings entering the GZK horizon ($<$ 100Mpc from the earth). The same procedure was carried out 10^5 times. In this way, we could obtain a distribution of the number of strings that can enter within 100Mpc when a string would not be observable. From this distribution we obtained an upper limit to the number of global cosmic strings within the GZK horizon ($<$ 100 Mpc); N<1.1 with 95% confidence level.

6 Conclusion

A systematic search for cosmic strings was carried out using SDSS data, but we could not find any characteristic signature. We derived an upper limit to the number of global cosmic strings with GUT scale mass within the GZK horizon: $N < 1.1(95\%$ C. L.). This value is not so strong, when we consider the number of cosmic strings in the universe is about 4 (Bennett and Bouchet, 1989; Allen and Shellard, 1993), however, this is the first systematic experimental search for cosmic strings. This experimental result strongly constrains the cosmic string decay model for EHECRs. Our result is also consistent with recent results obtained by BOOMERANG and MAXIMA. They observed fluctuations of CMBR and found Doppler peaks fitted well with the expectation from a Cold Dark Matter model(Jaffe et al., 2000). CMBR results may require that the linear mass density of a cosmic string is much smaller than 1.5×10^{-6}.

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