Searching for a Long Cosmic String Through the Gravitational Lensing Effect.

Yuji SHIRASAKI,1 Ei-ichi MATSUZAKI,2 Yoshihiko MIZUMOTO,1 Fumio KAKIMOTO,2 Syoichi OGIO,2 Naoki YASUDA,3 Masahiro TANAKA,1 Hideki YAHAGI,1 Masahiro NAGASHIMA,1 and George KOSUGI3
(1) National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588, Japan
(2) Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo, Japan
(3) Subaru Telescope, NAOJ, Hilo, HI 96720, USA

Abstract

It has been suggested that cosmic strings produced at a phase transition in the early universe can be the origin of the extremely high energy cosmic rays (EHCR) observed by AGASA above $10^{20}$ eV. Superheavy cosmic strings with linear mass density of $10^{22} \text{g/cm}$ can be indirectly observed through the gravitational lensing effect the distant galaxies. The lensing effect by a long straight object can be characterized by a line of double galaxies or quasars with angular separation of about 5 arcsec. We have searched for aligned double objects from the archived data taken by the Subaru Prime Focus Camera (Suprime-Cam). The Suprime-Cam has a great advantage in observing the wide field of view ($30 \times 30$ arcmin$^2$) with high sensitivity ($R<26$ 400s exposure), so it is suitable for this research. In this paper, we describe the result of simulation study for developing the method of searching the objects lensed by cosmic strings, and present the observational result obtained by this method.

1. Introduction

The cosmic ray with energies higher than $10^{19}$ eV is believed to be originated out of our galaxy, since no concentration is observed toward the galactic plane [5]. In addition to this, the cosmic rays which exceed the GZK cut off are observed by AGASA experiment [4], which suggests that the source is at distance closer than 100 Mpc. No prominent active sources, however, are found toward the direction where the extremely high energy cosmic (EHCR) rays are detected, so the decay of heavy relics from early universe, such as a cosmic string, has been considered as one of the candidates of origin of the EHCR [1]. The standard theory of particle physics predicts a symmetry breaking in the early universe and, as a result, the production of topological defects [7]. If the defects were generated at the GUT energy, the cosmic string can be observed as the origin of gravitational lensing [6] and its detection can be an observational confirmation of the standard
theory. The recent observations of cosmic microwave background radiation rule out pure topological defects model as the origin of large scale structure of the universe [3], however, they still do not rule out the existence of the defects. So it is of great importance to constrain the existence experimentally.

In this paper, we propose a method to search for gravitational lensing by a cosmic string, especially by a long straight string. The method is applied to the actual data and the results are presented.

2. Method

Our strategy presented here is dedicated to searching for a straight string. In this case, double images lensed by the string are aligned along it, so the strategy is simply to find such aligned objects which have a pair of similar brightness, color, and morphology separated to the same direction within 5 arcseconds. The procedure to find the aligned pair objects is: (1) Make an object catalog for each Suprime-Cam image. (2) Select objects which have a pair of similar brightness and color within 5 arcseconds. (3) Calculate the string configuration parameter $r_i$ and $\phi_i$ for each $i$-th pair. These parameters are defined in Fig. 1. (4) Calculate error density function $P_i(r, \phi)$. (5) Likelihood for a set of parameters $(r, \phi)$ is obtained by taking a sum of $P_i(r, \phi)$. (6) Estimate chance probability for the likelihood to be greater than the maximum of $P_i(r, \phi)$. If the chance probability is smaller than 1%, it indicates the existence of a straight string.

3. Simulation Study

We have estimated probability to detect double images lensed by a string under the assumption that the total length of the string is 31 in horizon units [2] and it is straight at least in the field of view of the Suprime-Cam. We used
Fig. 2. Left panel shows the expected number of lensed images in a Suprime-Cam field of view as a function of limiting magnitude of the observation. The redshifts of the string are \( z = 0.02, 0.3, 0.6, 1.0 \) and 2.0 from left to right, respectively. The number of accidental alignment of pair galaxies is represented by a heavy line. Right panel shows the numbers of \( 40' \times 40' \) fields to be observed for detecting one string for each string redshift.

4. Application to observation data

We have applied the string search procedure described above to the archived Suprime-Cam data. The data used for this analysis are summarized in Table 1. In constructing a list of pair objects, the following conditions are applied to make a pair: the difference of the magnitudes in R band is less than 1.0 mag and the color difference is less than 0.05 for \( V-R, \ i'-R \) and \( z'-R \), and 0.15 for \( B-R \) if the data of each band is available. The result is shown in Table 2. The chance probability is calculated by Monte Carlo simulation, that is, (1) rearrange the
Table 1. Summary of the data used for this analysis. The AGASA field is one of the directions where the EHCR cosmic rays are observed by AGASA experiment.

| Field       | Size     | available band and limiting magnitude |
|-------------|----------|---------------------------------------|
| AGASA Field | 1.8 deg² | R < 22.5, B < 26.8, V < 26.7, i' < 26.2, z' < 26.2 |
| SDF         | 0.3 deg² | B < 26.8, V < 26.7, R < 26.7, i' < 26.2 |
| SXDF        | 1.3 deg² | B < 27.4, R < 27.3, i' < 27.0, z' < 26.7 |
| 2 deg² Field| 2.2 deg² | R < 24.4, I < 24.1 |

Table 2. The result of the straight string search. The column of 'total pairs' represents the number of pair galaxies which has similar brightness and/or color with 6 arcsec separation. The column of 'aligned pairs' represents the number of the pairs separated to the same direction and aligned in a straight line.

| Field       | Likelihood<sub>max</sub> | aligned pairs | total pairs | chance probability |
|-------------|--------------------------|---------------|-------------|--------------------|
| AGASA Field | 1.947                    | 7             | 3383        | 3.3%               |
| SDF         | 0.827                    | 3             | 99          | 49.0%              |
| SXDS        | 1.642                    | 5             | 1214        | 21.2%              |
| 2 deg² Field| 3.322                    | 10            | 4578        | 7.1%               |

observed pairs at a random position in the observed field in a random direction, (2) calculate the maximum likelihood, (3) repeat this 1000 times, and then obtain the distribution of maximum likelihood. The distribution obtained by the simulation can be regarded as that for a null-string condition. We could not find any significant evidence of existence of a long straight cosmic string in the four fields in 99%C.L.

References

1. P. Bhattacharjee, astro-ph/980329, reference therein.
2. A. A. de Laix, Phys.Rev. D56 (1997) 6193
3. L. Pogosian and T. Vachaspati, Phys.Rev. D60 (1999) 083504
4. M. Takeda et al., Phys. Rev. Letters 81 (1998) 1163-1166
5. Y. Uchihori et al., Astropart. Phys. 13 (2000) 151-160
6. A. Vilenkin, ApJ 282 (1984) L51
7. A. Vilenkin and E.P.S. Shellard (2000) Cosmic Strings and Other Topological Defects, Cambridge University Press