Searching for a Long Cosmic String Through the Gravitational Lensing Effect

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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} 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 (30×30 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 gravitation lensing [6] and its detection can be an observational confirmation of the standard

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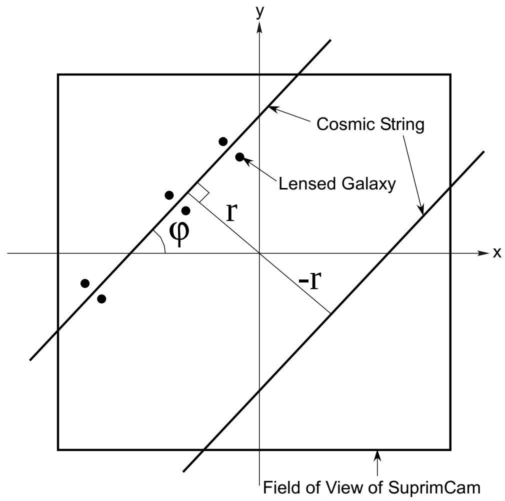

Fig. 1. Definition of string configuration parameters r and ϕ.

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 ϕ_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,ϕ) 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

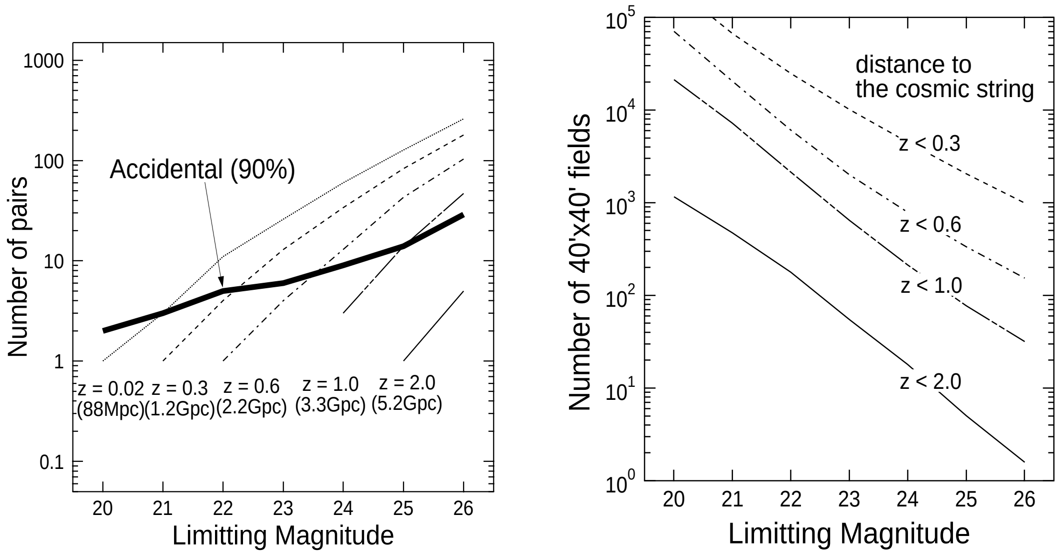

Fig. 2. Left panel shows the expected number of lensed images in a Suprime-Cam field of view as a function of limiting magnitude of the observation. The redshifts of the string are $z = 0.02$, 0.3, 0.6, 1.0 and 2.0 from left to right, respectively. The number of accidental alignment of pair galaxies 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.

numerical galaxy catalog developed by Nagashima and Yahagi to estimate the number of galaxy lensed by the string. In the left panel of Fig. 2., the numbers of observed pair galaxies for each limiting magnitude in R-band are shown for the cases that the string is at distances $z = 0.02$, 0.3, 0.6, 1.0 and 2.0. The numbers of accidental alignment of pair galaxies in 90% C.L. are also shown in the figure. From this figure, one can see that if a string is as close as $z = 0.02$ (~ 88 Mpc), observation with 21 limiting magnitude is enough to detect the cosmic string. If the string is as far as $z = 1.0$, we need to do an observation deeper than 25 magnitude. In the right panel of Fig. 2., the numbers of $40° \times 40°$ field necessary for detecting one string in average are shown for each limiting magnitude. For detecting one cosmic string which is at distance $z < 1.0$, we need 80 Suprime-Cam fields taken under the condition as deep as 25 limiting magnitude.

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

Filed	Size	available band and limiting magnitude
AGASA Field	1.8 deg^2	R<22.5
SDF	0.3 deg^2	B<26.8, V<26.6, R<26.7, $i' < 26.2, z' < 26.2$
SXDF	1.3 deg^2	B<27.4, R<27.3, $i' < 27.0, z' < 26.7$
2 deg^2 Field	2.2 deg^2	R<24.4, I<24.1

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	$Likelihood_{max}$	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 deg^2 Filed	3.322	10	4578	7.1%

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.

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 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.

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