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Search for cosmic strings using optical and radio astronomy methods

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1. Introduction

The last decade has seen an active search for cosmic strings by the methods of observational astronomy: both in optical and in radio surveys. The splash of this research is due, on the one hand, to significant progress in the area of investigations into the multidimensional structure of space-time and in the search for theories claiming to be the unified theory of all physical interactions. On the other hand, studies of the extragalactic object CSL-1 carried out by a joint Russian–Italian group made it possible for the first time to lay and develop the observational basis for the quest for cosmic strings by gravitational lensing techniques. Lastly, the rising accuracy of measuring the anisotropy of cosmic microwave background radiation (CMBR) [data of the processing of the seven-year-long observations in the WMAP (Wilkinson Microwave Anisotropy Probe) space mission, and data from the Planck space observatory] gives a good chance to find an unambiguous solution to the question of the existence of cosmic strings in a wide mass range.

According to modern observational data on the expansion of the Universe, obtained by studying supernovas, and to data on the anisotropy of CMBR, the Universe now resides at the stage of accelerated expansion, which is successfully explained by the existence of dark energy — a special form of a vacuum type energy [1]. However, the nature of dark energy has not been elucidated, which is a fundamental problem of modern cosmology and the key area of research at the interface between such disciplines as cosmology, astronomy, and elementary particle physics.

In the framework of this problem, of special interest is the investigation of dark energy of the early Universe, specifically, of possible soliton and soliton-like solutions. Stable one-dimensional structures — cosmic strings (CSs), which emerge in all the most realistic models of elementary particle physics — represent such a solution [2, 3]. Modern research in elementary particle physics gives ample evidence of the existence of new physics beyond the framework of the Standard Model. CSs emerge both in the models of Grand Unification and in superstring theory [4, 5]. Not only would the discovery of CSs permit revealing the nature and evolution laws of the dark energy of the early Universe, but it would also make it possible to study an energy scale unattainable with modern accelerators.

CSs, which were first predicted by T Kibble in 1976, were actively studied in subsequent papers by Ya Zeldovich and by A Vilenkin and E Shellard [3, 6–9]. The existence of CSs is not at variance with all the presently available cosmological observational data and, furthermore, is gaining support from the theory and receiving indirect confirmation from observations.

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2. Cosmic string in the Universe

2.1 Main definitions and properties

From the observational point of view, of greatest interest are topological CSs (solitons), since the mechanism of their formation (phase transitions of the vacuum) is rather simple and has been much studied experimentally in other areas of physics (transitions in ferromagnetics, the superconductivity phenomenon, etc.). Furthermore, this mechanism of string formation does not require special assumptions about dynamic processes in the Universe and is primarily based on the fact that the early Universe was higher in temperature than the contemporary one and cooled in its evolution.

The formation of topological defects with various dimensions is due to the fact that the vacuum manifold in the theory is structurally nontrivial: $\pi_N(M) \neq 0$. When space-time has a dimension $d+1$, it may contain topological defects with a dimension $d-N$: monopoles, strings, domain walls, as well as hybrid defects, for instance, 'necklaces' (monopoles and strings) and fleece (strings and walls). In the case of strings, one has $N=1$, and the nontriviality of the homotopy group $\pi_1(\mathrm{S}^1)$ signifies the existence of circumferences which cannot be contracted to a point by a continuous transformation.

The minimal string-containing model possesses a U(1)-gauge-invariant Lagrangian density [1]

$$L = D^\mu \phi^* D_\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \lambda \left(\phi^* \phi - \frac{T_c^2}{2} \right)^2 .$$

The ground state of this model is not gauge-invariant with respect to the U(1) group. The nonzero vacuum manifold is determined by the characteristic energy scale T_c. The potential reaches its minimum on a circumference:

$$\langle \phi \rangle = \frac{T_c}{\sqrt{2}} \exp\left[\mathrm{i}\alpha(x) \right] .$$

For $T \leqslant T_c$, the symmetry of the ground state is broken and in every causally coupled space-time domain the value of phase $\alpha(x)$ is fixed — the system changes to one of the energy preferred states in a random manner. Clearly, the phases in each of these domains do not correlate. Owing to the unambiguity of field ϕ, the phase variation along a closed path passing through different causally disconnected domains is expressed as $\Delta\alpha = 2\pi N$. When $N \neq 0$, a CS forms with a conserved topological charge N (N is the number of winds). The field ϕ, owing to its continuity, should assume a zero value inside of the phase variation path. Therefore, the new-phase domain encloses the old — 'relic' — phase domain. This mechanism of topological CS formation is termed the Kibble mechanism.

The continuity of field ϕ also ensures the finiteness of string energy: the string is stable, having no ends in the causally coupled domain of space-time — it either 'pierces' through the horizon or forms loops. Long strings tend to straighten, and the loops tend to collapse. Simulations also show that 80% of the strings are long [10–12]. The below-proposed methods of searching for CSs are aimed at the search for straight segments of long individual strings.

The main parameter of a CS is its linear density $\mu = \mathrm{d}E/\mathrm{d}z = \pi T_c^2$. For convenience, one can introduce a dimensionless parameter $G\mu \propto (T_c/M_{\mathrm{Pl}})^2$. For most realistic CSs, those with energies of about $10^{15}-10^{16}$ GeV, the quantity $G\mu \propto 10^{-7}-10^{-6}$. Also, the linear density of the string is conveniently estimated using parameter $\mu_6 \approx 0.1-1$ [4] as $\mu = 1.35 \times 10^{21}\mu_6$ [kg m^{-1}] $= 2.09 \times 10^7 \mu_6 M_\odot$ [pc^{-1}].

2.2 Place of cosmic strings in modern physics

Recent investigations [4, 5, 13] have revealed tight theoretical interrelations between topological CSs and the fundamental superstring theory, which presently are the most promising candidates for the construction of matter and the unification of all types of physical interactions. This interrelation was made possible by the mechanisms of energy lowering for the strings of the fundamental theory.

The linear density of a string is proportional to the square of the temperature of the corresponding phase transition. For a CS, one has $G\mu \leqslant 10^{-6}$. For superstrings, $\mu \propto M_s^2$, and $G\mu = M_s^2/M_{\mathrm{Pl}}^2 \approx 1$. In models with extra noncompact dimensions, the superstring energy scale may be lowered: $M_s \ll M_{\mathrm{Pl}}$, which results in $G\mu \ll 1$. In models with a large fifth dimension (four-dimensional bran and bulk models), the superstring energy may also be lowered because a part of the string energy is transferred to the bulk.

Nontopological superstrings (so-called F- and D-strings) might have been formed in the early Universe. Observations of such objects could be the main way of studying fundamental superstrings. These objects are predicted by the newest models with extra noncompact dimensions (the process of bran–antibran annihilation) and by a broad class of inflation cosmological models. It has been established during the last several years that a vast family of CSs exists, which differ in properties, these properties being directly dependent on the geometry of the extra compactified dimensions of superstring theory.

As is well known, the key problem of modern multidimensional theories is that there is no way of giving preference of one theory to another — only observational facts, like the discovery of a CS, could sort out unrealistic theories and bring the modern physics of elementary particles to a radically new level. Furthermore, the discovery of CSs would yield information about the composition of the relic dark energy of the early Universe, which would allow making rapid strides towards understanding the reasons for the contemporary accelerated expansion of the Universe, which is governed by a yet unknown type of dark energy.

Among all possible types of topological defects, only CSs emerge in a natural way in the overwhelming majority of realistic models of the early Universe. CSs may exist in a broad mass range: from the energies of grand unified theories to those of electroweak theory.

2.3 Main properties of a cosmic string as an object of observations

The methods of searching for CSs rely on their special properties which are different from the properties of all known types of celestial objects. We shall indicate these properties by the simple model example of the Euclidean universe with a single string inserted in it [7, 14]. In the consideration of the real Friedmann–Robertson–Walker (FRW) cosmological model and of several strings, these properties will qualitatively persist. In a specially selected coordinate system [14], the metric of space-time with a string is conical. This metric coincides everywhere with the Minkowski metric

$$g_{\mu\nu} = \eta_{\mu\nu} = \mathrm{diag}\,(1, -1, -1, -1)$$

with the exception of one point — the vertex of the cone. For any circumference containing the vertex of the cone, the length-to-radius ratio equals $2\pi - \alpha$, where α, termed the deficit angle, is determined by the linear density of the string: $\alpha = 8\pi G\mu$. Everywhere, with the exception of the cone vertex, the space is Euclidean (Fig. 1).

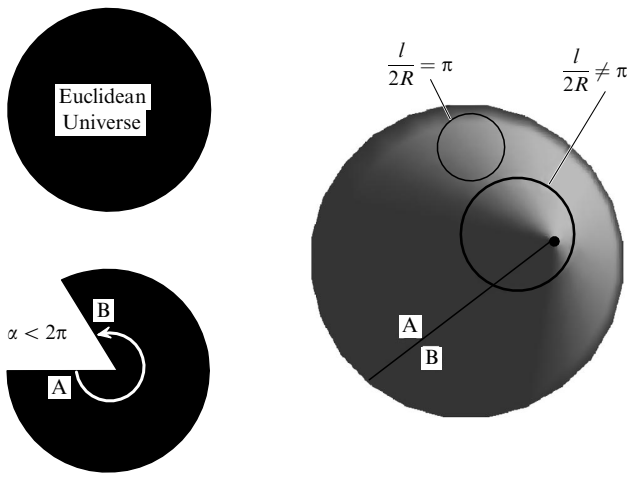

Figure 1. Illustration of the formation of a conical universe in the presence of a single cosmic string.

A straight CS does not possess a gravitational field. Nevertheless, the existence of a cut makes possible the formation of gravitationally lensed images of objects which are background relative to the string. Moving along straight lines, the light rays emanating from the background source nevertheless skirt the cone vertex to form images. The essential one-dimensionality of the CS dictates several special properties of such images. The string's one-dimensionality also manifests itself in a unique manner in the investigation of CMBR anisotropy which may be generated by a moving CS.

2.4 Current status of cosmic strings in observational cosmology

There are several methods for the observational search for CSs, which may be conventionally divided into three groups. The first method — finding strings by optical surveys — consists in the search for characteristic gravitational lensing events occurring in the lensing of background sources (primarily galaxies) by the strings. The second one involves investigations into the structure of CMBR anisotropy induced by strings, and the determination of the characteristic amplitudes of these structures. The third method implies the search for a large number of low-probability and model-dependent string manifestations, like the emission of gravitational waves by string loops, string–black hole interactions, decay of heavy particles emitted by strings, and the interactions between two or more strings. Only the first two methods are universal for all string types and will be the subject of our consideration.

The latest data on the anisotropy of CMBR rule out CSs as the source of primary density perturbations but do not forbid their existence. The previously employed statistical methods of analysis of CMBR anisotropy enable revealing strings which produce an anisotropy of no less than 100 μK [15]; no strings have been found by these methods. Selective searches (optical catalogs covering 1/6 of the celestial sphere) for gravitational lensing events for a string deficit angle of no less than 2″ have not met with success, either.

3. Effect of gravitational lensing by a cosmic string

3.1 Gravitational lensing of point and extended sources by a cosmic string

By analogy with how this is done in the modeling of classical gravitational lensing events, we define three parallel planes: the plane of a point source I $\{\xi, \eta\}$, the string–lens plane $\{x, y\}$, and the observer's plane. Let R_g be the distance between the observer's plane and the source plane, and R_s be the distance from the observer's plane to the lens plane. In each plane, the origin lies in the straight line passing through the observer perpendicular to all the three planes. When the source I is in the band $\delta\theta = \alpha(R_g - R_s)/R_g$, where $\alpha = 8\pi G\mu$, two images spaced at physical distances D_ψ and D_ϕ from the origin are formed in the string–lens plane (Fig. 2). The problem of the gravitational lensing of a point source involves finding these distances as functions of the position of source I in the $\{\xi, \eta\}$ plane, deficit angle α, and distances R_g and R_s between the planes [16].

The case of an extended source is investigatively similar [16]. The solution is sought for as the result of lensing of the set of point sources. The image exhibits clearly defined isophot cuts (Fig. 3).

Therefore, gravitational lensing by a CS is characterized by the presence of a chain of the image pairs of sources which are background relative to the string. The spacing between the images in each pair is determined by the string deficit angle. For instance, an angular distance of 2″ corresponds to a string energy on the order of 10^{16} GeV. Furthermore, when the background objects are optically resolved, the structure of the outer isophots of image brightness should exhibit characteristic cuts, which is due to the essential one-dimensionality of the string. To observe suchlike cuts requires, as a rule, high angular resolution, on the order of 0.1″.

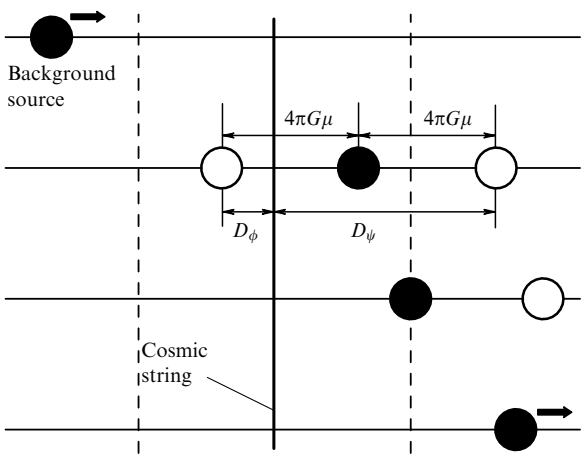

Figure 2. Simulation of the gravitational lensing of a moving point source by a cosmic string viewed in the plane of the string. The string is parallel to the plane of the drawing.

Figure 3. Simulation of the gravitational lensing of an extended source (a galaxy) by a cosmic string viewed in the plane of the string. The string is parallel to the plane of the drawing. One can see the cuts of outer isophots of the source. Angular resolution is 0.1″.

3.2 Investigation of object CSL-1

In 2003, a deep survey by the INAF's Astronomical Observatory of Capodimonte (Naples, Italy) resulted in the discovery of a pair of objects, which was termed CSL-1 and had supposedly gravitational lensing origin [17, 18]. This conclusion was drawn on the basis of spectroscopic and photometric analysis of this pair of objects: both components possessed a zero difference of radial velocities and the same brightness profiles, being resolved in this case. The spectra of both components are identical to an accuracy exceeding 99%. No tidal distortions were observed, either. The absolute stellar magnitude of both components (with filter R) is −22.3. The components of the pair are spaced at 1.9″, and the red shift is 0.46. The distance to the observer is about 1.9 Gpc.

Being supposedly a gravitationally lensed object, CSL-1 showed no characteristic arc-like distortions of the outer isophots. The phenomenon of gravitational lensing of galaxies by other objects (galaxies, groups of galaxies, etc.) is not infrequent in our Universe. However, the uniqueness of the CSL-1 double object consists in the fact that the only type of a gravitational lens which can produce observable morphologically identical undistorted images is a CS. For a classical gravitational lensing of a background galaxy by known cosmic objects, owing to the nonuniformity of gravitational fields of the latters, the images of the background galaxy are significantly distorted. The gravitational potential of a straight CS is equal to zero, and so the resulting images are undistorted. Acting as a gravitational lens, a CS forms a conical space wherein the light rays from the background galaxy pass relatively along opposite sides of the cone vertex to form two images.

Therefore, the lens forming this pair of images must have a one-dimensional structure, which is evidence of a CS. Simulations demonstrated that lensing by the CS corresponds to the real data acquired by the ground-based

telescopes TNG (Telescopio Nationale Galileo), NTT (New Technology Telescope), and VLT (Very Large Telescope) at a 2σ confidence level. Specifically, the processing of images showed that the spectra of objects in the pair are highly correlated (for a thousand points the correlation coefficient reached 0.85, and in this case it was *a priori* assumed that both components are elliptical galaxies and possess equal spectrum slopes; this dependence did not enter into the correlation coefficient). The difference between the spectra of the two components represented random noise with an autocorrelation function close to unity.

This spectral identity suggested that there was a dust bar passing along the middle of one strongly prolate elliptical galaxy. Furthermore, in order for two circular sources to be formed eventually, the bar had to possess the strongly pronounced shape of an hourglass. This exotic hypothesis, which nevertheless had the right to exist, was refuted by observations with an infrared filter on the 3.5-meter Galileo National Telescope in 2003. The point is that dust should be transparent in the infrared range for a conventional dust absorption law. Moreover, the absorption coefficient is wavelength-dependent for any dust absorption law, and therefore the dust bar should be different in appearance with different filters, which was not observed for the CSL-1 object. The 2005 observations with the VLT telescope system of the European Southern Observatory (ESO) located on the Paranal Plateau in Chile confirmed the identity of the spectra of both components of the pair with an even higher accuracy (99.9%).

Apart from gravitational lensing interpretation, there persisted, as before, a nonzero probability that CSL-1 comprises two different galaxies spaced at a projection distance of less than 10 kpc. Clearly, the physical distance between them should be longer; otherwise, it would have been possible to observe tidal effects for the 10% photometric accuracy involved. On the other hand, the distance should not be too long; otherwise, the galaxy more distant from the observer would be lensed by the closer one, which was not observed, either. In view of the zero difference between radial velocities, the length of admissible physical distance between the galaxies lowered to only 15 Mpc. On raising the photometric observational accuracy to 0.1%, the interval of intergalactic distances is further lowered almost threefold, to 123 kpc – 5 Mpc, which is hardly probable in view of the same morphology of the two resolved components of the pair and the identity of their spectra. Therefore, the hypothesis of the gravitational lensing origin of CSL-1 prevailed.

Our group also obtained additional arguments in favor of the CS-based explanation of the CSL-1 phenomenon. They consist in the discovery of candidates for gravitational lensing events in the vicinity of CSL-1, as predicted by the theory. Using comprehensive photometric data gathered with different color filters, it was possible to discover 11 such candidates, whose gravitational lensing nature had to be verified with the ESO VLT telescope in future projects. Also submitted were applications for observations with the newest VLT Survey Telescope (VST) — a general survey telescope for the ESO VLT, a project of the Astronomical Observatory of Capodimonte. The VST telescope enables collecting a huge amount of photometric data, including those from very weak sources (up to the 25th stellar magnitude with the R filter). This would allow validly using this instrument for investigating the CSL-1 object and the candidates for gravitational lensing events, most of which are weak sources (from the 19th to 24th stellar magnitude).

Observations with the NASA's Hubble Space Telescope performed on 11 January 2006 helped to finally solve the question about the nature of this mysterious binary object. Six satellite orbits were allocated to our project, and observations were carried out with a resolution of 0.05″ for about 14,000 s. To interpret the observational data, numerical simulations were made of the gravitational lensing of a background object by a CS, and analytical equations were derived for a gravitational lens.

According to theoretical calculations, if lensing by a CS occurs, there must be no isophot distortions for an extended background source (which emerge in its lensing by an extended object), the spectra of the objects in the pair should be identical, and the radial velocity difference should be equal to zero. All these requirements were met for the CSL-1 object. In the case of lensing by a CS and the high angular resolution attainable with the HST, characteristic cuts of outer isophots should be observable in the background source images. Furthermore, structure doubling should be observable: for instance, when some morphological features are present in one image and its vicinity with a size smaller than or equal to the linear dimension of the string deficit angle, they are bound to be present in the second image as well.

Yet another indication of string existence is a chain of object pairs which also possess the characteristic cuts of outer isophots. The separation of the objects in each pair must not exceed the linear dimension of string deficit angle. The gravitational lensing effect begins to show up as soon as the background source comes into the vicinity-belt of action of the string, whose width is determined by the string deficit angle; while in the case of a two-galaxy projection effect there are bound to be observable tidal distortions for the HST resolution. The HST observations showed that there is a weak tidal interaction between the two elliptic galaxies which were unobservable for ground-based telescopes.

Therefore, the question about the nature of the CSL-1 double object was finally elucidated: it is an extremely rarely occurring gravitationally coupled system of two galaxies (Fig. 4).

Despite the fact that the hypothesis of a CS was not confirmed, the investigation carried out made it possible to

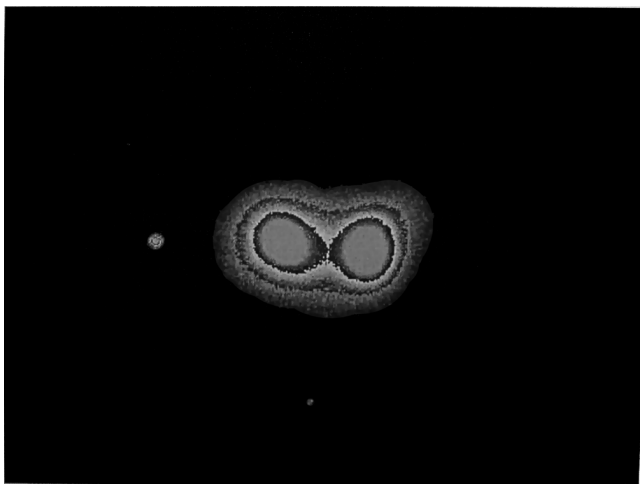

Figure 4. CSL-1 object. Image from the Hubble Space telescope. One can see tidal distortions of outer isophots.

develop for the first time the complete theory of the gravitational lensing of extragalactic objects by a solitary straight CS, to reveal all possible observational manifestations of the CS, and to calculate the required characteristics and resources of the ground-based and space instruments needed for conducting these investigations. The results obtained are actively being used by the world scientific community (see Refs [19, 20] and references cited therein).

4. Relic radiation anisotropy induced by a cosmic string

The last three years have observed investigations of CMBR anisotropy generated by a CS (see Refs [14, 21] and references therein).

According to the findings of our research, a moving straight CS should generate characteristically shaped structures with enhanced and reduced brightness. The anisotropy structure comprises a sequence of regions with lower and higher temperatures: specifically, a cold spot ahead of the CS motion front, then a pronounced temperature step and a hot spot, which is replaced with a cold spot again (Fig. 5).

To be certain about the discovery of a string with the employment of this technique, independent observations of the same region in the sky should be carried out in another frequency region. The quest for gravitational lensing effects would be the best observation of this kind. It is significant that the characteristic CS length should be great, no less than 100°, if the CS is to be simultaneously observable in the optical range and in the radio frequency band. This magnitude stems from the fact that only relatively close objects with a red shift $z \leqslant 7$ are accessible to optical observations, while for CMBR one has $z \approx 1000$. Hence, it follows, in particular, that the number of cosmic strings which may be discovered by purely optical methods of observation amounts to only 20% of the total number of strings in the Universe. This fact provides for the first time an explanation for the failure to discover a CS by exploring gravitational lensing effects.

The following simple model was considered in Ref. [14]. An observer is located at the center of the sphere $\{O, \xi, \eta, \zeta\}$. The sphere radius is the distance to the surface of the last scattering. The sphere may be assumed to be nonexpanding to a sufficient accuracy. A straight string is moving with velocity v at an angle ψ perpendicular to the plane $\{O, \xi, \eta\}$, piercing the sphere at points A and B. The CMBR anisotropy produced by the string is caused by the Doppler effect. The temperature fluctuation takes on the form

$$\delta T = 27\,\frac{\alpha}{2''}\,\frac{\beta}{0.9}\,F(\psi, \phi, \theta)\ [\mu\mathrm{K}]\,.$$

The contribution of the string velocity to the Doppler effect is made only by the quantity β — the projection of the string velocity (in units of the speed of light) onto the axis perpendicular to the line of sight. The function of spherical angles reduces to $F(\psi, \phi, \theta) \approx 1$.

The anisotropy structure is independent of the magnitudes of model parameters. For a relativistic $(v/c \approx 1)$ CS possessing an deficit angle of about $1-2''$, the amplitude of the generated anisotropy is of order (15–30) μK.

If a CS is to be searchable both by optical gravitational lensing techniques and by the analysis of CMBR anisotropy, the deficit angle should range from several tenths of an arc second $(\delta T/T \approx 1.5)$ to $5-6''(\delta T/T \approx 100)$. The lower bound is defined by the highest resolution attainable in the optical region (by HST) in the quest for string-induced galactic gravitational lensing events. The upper bound gives a magnitude of string anisotropy comparable to the standard anisotropy caused by adiabatic density perturbations.

The signal delay effect [22], which is caused by the string extent, should also be taken into account: when an infinitely long straight string is moving some distance away from the observer, they see different parts of the string at different instants of time.

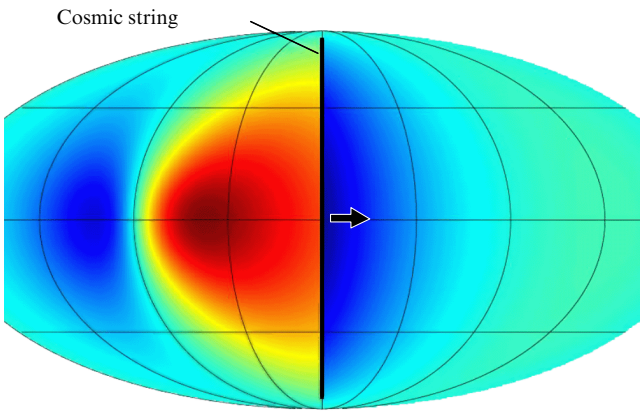

Figure 5. Simulation of CMBR anisotropy generated by a moving straight cosmic string. Mollweide projection of celestial sphere. The string is parallel to the plane of the drawing, coincides with the axis connecting the poles, and moves from left to right. Characteristic structure of the anisotropy: a cold spot ahead of the front, a delta-like temperature step, a hot spot behind the front, and a cold trailing spot.

5. Conclusions

The following investigations have made significant contributions to the progress of observational methods in the quest for CSs.

The binary extragalactic CSL-1 source was discovered and explored. Observations from the HST in 2006 were able to refute the CS hypothesis by showing that a projection effect occurs for two galaxies with similar morphologies and spectra, which possessed close peculiar velocities. Nevertheless, the meticulous theoretical and observational work carried out enabled for the first time constructing a rather complete model of the gravitational lensing of background objects by a CS as applied to real observations, especially those reliant on instruments with a high angular resolution.

A study was made of the Q0957+561A, B quasar. Anomalous brightness fluctuations were discovered in the gravitational lensing system; one of the possible reasons for their occurrence is the gravitational lensing effect by a cosmic CS.

New evidence for the presence of a CS was found in the WMAP satellite data on the anisotropy of CMBR generated by a uniformly moving straight CS. The number of strings which can be found by optical methods amounts to 20% of their total number, i.e., the quest for them in the optical range should be necessarily complemented with analysis of the radio maps of CMBR anisotropy. For strings with an deficit angle of $1''-2''$, the generated anisotropy amplitude ranges 15–30 μK [for strings with the most realistic energies ($10^{15}-10^{16}$ GeV) and the corresponding densities ($G\mu \propto 10^{-7}-10^{-6}$)]. If a string is to be detected

by two independent methods (optical and radio methods), the CS deficit angle should lie in the range between 0.1″ and 5–6″. When a CS is detectable by optical methods, the characteristic 'spot' size on the anisotropy map should be no less than 100°.

The fields of the HST (4.5 square degrees in all) were studied in the search for gravitationally lensed pairs formed by straight long CSs. Four candidates for CS-induced gravitational lenses were discovered; however, the accuracy accessible to researchers is not high enough to unambiguously elucidate the nature of these candidates.

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Search for exoplanets using gravitational microlensing

A F Zakharov

1. Gravitational lensing: introduction

There are different regimes of gravitational lensing depending on the mass of the gravitational lens. Assuming that both the lens and the source are located at cosmological distances, different regimes correspond to different angular distances between images. The case of a stellar-mass gravitational lens is referred to as gravitational microlensing. The angular distance between images in this case is proportional to the square root of the lens mass, so the lensing of a planet with a mass a few times smaller than Earth's ($10^{-6} M_\odot$, where $M_\odot$ is the solar mass) is called nanolensing.

Thus, searches for sufficiently light exoplanets using gravitational lensing can be dubbed gravitational nanolensing. Different methods of searches for exoplanets are known, including the Doppler shift of spectral lines, transits, and pulsar timing. In this paper, we show that gravitational microlensing is one of the most promising methods of searching for Earth-like exoplanets (with masses of order $M_\oplus$) located at distances of several astronomical units (AU) from a star, and there is hope that exoplanets with a solid surface temperature in the range 1–100 °C (i.e., with the temperature of liquid water) can be discovered.

A detailed discussion of gravitational lensing can be found in monograph [1] (see also review [2]). Nevertheless, we shall remind the reader of the basic facts and report on new results in this field.

Gravitational lensing is based on the gravitational light bending effect. It can be visualized as if a gravitating body attracts photons. Gravitational light bending was first discussed by Sir Isaac Newton [3]. Such a bending appears to be the natural conclusion from the corpuscular theory of light advocated by Newton. A derivation of the light deflection angle in Newtonian gravity was first published by the German astronomer Johann Georg von Soldner [4].

In General Relativity (GR), the light deflection angle in the gravitational field was obtained by Albert Einstein [8]:

$$\Theta = \frac{4GM}{c^2 p}\,, \tag{1}$$

where M is the mass of the gravitating body, p is the impact parameter, c is the speed of light in vacuum, and G is the Newtonian constant of gravitation. If $M = M_\odot$ and $p = R_\odot$ (where $R_\odot$ is the solar radius), the respective light deflection angle is 1.75″. In 1919, this prediction was confirmed by

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