Cosmic Strings Reborn?*

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Abstract

There are two main reasons for the recent renewal of interest in cosmic strings: Fundamental string-theory models suggest their existence; and there are at least two tentative observations of their possible effects. In this talk, I review their current status in the light of these two factors.

1 Introduction

Cosmic strings were very popular in the eighties, and much of the nineties [1, 2], because they seemed to offer a neat alternative to inflation as a means of generating the primordial density perturbations from which galaxies and clusters eventually grew [3, 4]. In particular, for GUT-scale strings, the predicted string tension was about right to explain their magnitude. But towards the millennium their popularity waned, swept away by the avalanche of data, especially the microwave background measurements from COBE, BOOMERanG, and, more recently, WMAP. This eventually showed beyond doubt that cosmic strings or other topological defects could not provide an adequate explanation for the bulk of the density perturbations [5, 6, 7]. There always remained the possibility that they might contribute at the level of a few per cent, but that hardly seemed a sufficiently exciting possibility to keep them alive. There were only 27 papers published on cosmic strings in 2001, compared to 67 in 1997.

But against the odds, there has been a remarkable revival of interest. The number of papers on cosmic strings has again begun to soar — 46 in 2003. There are two main reasons, one theoretical, one observational.

When I gave talks about cosmic strings twenty years ago, I always made a point of emphasizing that there was no connection whatever between these hypothetical macroscopic objects in the cosmos and the equally hypothetical microscopic fundamental strings of superstring theory. The characteristic energy scales were very different, the GUT scale or less for cosmic strings, something near the Planck scale for fundamental strings. But that is no longer true. The string scale may

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in fact be substantially less [8, 9, 10]. Moreover, string theory or M-theory predicts, even demands, the existence of macroscopic defects such as cosmic strings. Branes, which now play such a key role in string theory, are in essence defects of various dimensions (not necessarily topological). In particular, in the brane-world picture, colliding branes will in many cases generate cosmic strings [11, 12, 13, 14]. So the popularity of string theory spills over to cosmic strings. It is also worth noting that supersymmetric GUTs, which may often form a link between string theory and the standard model, seem to demand cosmic strings [15].

On the observational side, there has been no unambiguous detection of a cosmic string, but there have been tantalizing hints — observations whose most natural interpretation seems to be in terms of cosmic strings. There are at least two of these. Sazhin et al [16, 17] found a strange example, called CSL-1, of a gravitational lens which seems to involve two images of comparable magnitude of the same giant elliptical galaxy, and have subsequently found an unexpectedly large number of gravitational lens candidates in the vicinity. Schild et al [18] have found anomalous brightness fluctuations in a multiple-image lens system, Q0957+561A,B, which may be evidence for lensing by an oscillating loop of cosmic string.

Here, I want to review the physics of cosmic strings, and discuss their status in the light of these new developments.

2 Cosmic strings in the early universe

Let me begin by reviewing a few basic facts about cosmic strings in the early universe.

Cosmic strings are formed in many symmetry-breaking phase transitions. If the symmetry is broken from a group $G$ down to a subgroup $H$, the manifold of degenerate vacuum or ground states is $\mathcal{M} = G/H$, and the topology of this manifold determines the types of defect that can form [19]. In particular, strings can form if $\mathcal{M}$ is not simply connected, i.e., if its first homotopy group $\pi_1(\mathcal{M})$ is non-trivial.

There are many variants on the theme of cosmic strings – composite defects, embedded defects, semilocal strings, superconducting strings, and so on. I shall not have much to say about any of these, though no doubt others will.

From a cosmological point of view, most attention has been paid to GUT strings. In the standard model of particle physics, based on the symmetry group $G_{321} = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$, the energy dependence of the coupling strengths $g_3, g_2, g_1$ of the three interactions at laboratory energies suggests that all three may be united in a grand unified theory (GUT) at an energy scale of $10^{15}$ or $10^{16}$ GeV, at least provided we include supersymmetry. GUTs have been proposed based on simple groups $G$, such as SU(5) or SO(10), or on semisimple groups with extra discrete symmetries, like the left–right symmetric $G = \text{SU}(4) \times \text{SU}(4)$. In unified theories derived from string theory even larger groups appear.

Symmetry breaking can occur in one or more stages from $G$ down to $G_{321}$. In
many cases, this symmetry breaking is associated with topological defect formation. Almost always, monopoles are formed at one of the transitions, and must be eliminated in some way, for example by an intervening period of inflation. But more to the point for the present discussion, cosmic strings are often formed.

One of the things that initially made the idea of cosmic strings so exciting was an apparent coincidence of scales. They seemed to offer an explanation for the magnitude of the initial density perturbations from which galaxy and clusters eventually grew.

The symmetry-breaking scale $\eta$ determines the critical temperature $T_c$ for the transition. Also, those components of the gauge field that correspond to broken symmetries acquire masses $m_X$ of this order (multiplied by appropriate coupling constants). In these relativistic strings, because of Lorentz invariance under boosts along the direction of the string, the mass per unit length and the string tension are equal. This tension $\mu$ is of order

$$\mu \sim \eta^2 \sim m_X^2. \quad (1)$$

The most important observational consequences of cosmic strings (so long as they are non-superconducting) stem from their gravitational effects, whose strength is characterized by the dimensionless constant

$$G\mu \sim \frac{\eta^2}{m_{Pl}^2}, \quad (2)$$

where $G = 1/m_{Pl}^2$ is Newton’s constant. In particular, as I’ll discuss shortly, cosmic strings generate density perturbations in the universe with a typical amplitude $\delta \rho / \rho \sim G\mu$.

The key point is that for $\eta$ or $m_X$ of the order of the GUT scale, we have

$$G\mu_{\text{GUT}} \sim 10^{-6} \text{ to } 10^{-7}, \quad (3)$$

so the density perturbations predicted are at least in the right ballpark to provide a resolution of one of the long-standing puzzles of cosmology: where do the primordial density perturbations originate, from which galaxies and clusters eventually evolve?

Through the 80s and into the 90s, a huge amount of work was done to try to put flesh onto the bones on this appealing idea. A clear picture of cosmic string evolution gradually emerged, the result of both analytic studies and numerical simulations by several different groups. (For references, see [1, 2, 20].) We now think we have a pretty good idea of what will happen to a network of cosmic strings formed at an early phase transition, and how it might influence the cosmology — though it must be said there is still room for doubt about some of the details.

We start with a random tangle of strings, characterized by a length scale $\xi$, which may be defined as the length such that in a typical volume $\xi^3$ we expect to find a length $\xi$ of string. In other words, the strings contribute a mean density

$$\rho_{\text{str}} = \frac{\mu}{\xi^2}. \quad (4)$$
Equivalently, $\xi$ is roughly the typical distance between strings. The initial value of $\xi$ is determined by the interplay between microphysics and cosmic expansion. Typically we expect $\xi$ to be much smaller than the Hubble radius at the time.

The key to the subsequent evolution is the topological stability of the strings. They may stretch or shrink, but they cannot break, though when they meet they can exchange partners or intercommute. As the universe expands, the strings are stretched, and kinks are gradually straightened. But when the strings intercommute, new kinks are formed. If there were no other energy-loss mechanism, the strings would eventually come to dominate the energy density of the universe. But there is an energy-loss mechanism — the formation and decay of small loops. When a string intersects itself, it cuts off a closed loop. Once formed, a loop is doomed unless it happens to reconnect with a longer piece of string (which for small loops is improbable). The loop oscillates and gradually loses energy by gravitational radiation, until it disappears altogether. (A different view of the evolution is presented in another contribution to this meeting [21].)

In this process, the characteristic length scale $\xi$ of the network grows faster than the Hubble radius. It is believed to lead eventually to a scaling regime, in which $\xi$ grows proportionately to the Hubble radius $1/H$ or the age of the universe, $t$:

$$\xi \propto 1/H \sim t. \quad (5)$$

Consequently, in this regime the strings contribute a constant fraction of the critical density:

$$\Omega_{\text{str}} = \frac{8\pi G}{3H^2}\rho_{\text{str}} \sim G\mu. \quad (6)$$

However, the numerical coefficient here does change significantly when we pass from a radiation-dominated to a matter-dominated universe.

One important side effect of the breaking off of small loops is that the strings become quite kinky on small scales. Typically, the distance between kinks is much smaller than $\xi$. This also means there is substantial loss of energy by gravitational radiation from the long strings as well as the loops.

3 Cosmological effects

The next stage, once we had a fair idea of how strings evolve, was to estimate their likely cosmological effects. This inevitably involved a lot of numerical work, taking as input the results of simulations of the string evolution process, and using them to predict the large-scale density perturbations explored by galaxy distribution surveys, and the temperature inhomogeneities in the cosmic microwave background (CMB).

It gradually became apparent, however, that although the predictions were in the right ballpark, it was very difficult to get them to fit precisely, especially to fit both the large scale structure and the CMB simultaneously [5, 6, 7].

Meanwhile, the rival inflationary theory — the idea that the origin of the primordial density perturbations can be traced back to quantum fluctuations during
a very early period of inflation — was having much more success, in particular in fitting the peaks of the angular power spectrum, as measured by COBE and other instruments. These peaks can be traced back to the fact that all the Fourier modes of the density perturbation started out essentially in phase at the end of inflation. Their positions and heights are very characteristic of the inflationary scenario.

The coup de grâce was provided by WMAP in 2003, with the first measurements of the CMB polarization, and the temperature–polarization cross-correlation, which fitted the inflationary predictions excellently, and could not be well explained by cosmic strings or other defects [22, 23].

Of course, all this doesn’t prove there are no cosmic strings. It only proves that if they do exist they don’t contribute more than an insignificant proportion of the primordial density perturbation. The observations give an upper limit on the value of the parameter \( G\mu \). Pogosian et al [13] quote a limit

\[
G\mu \leq 1.3 \times 10^{-6} \sqrt{\frac{B\lambda}{0.1}},
\]

where \( \lambda \) is the probability of intercommuting when two strings meet (most often assumed to be 1), and \( B \) is the fraction of the CMB power spectrum attributable to cosmic strings, which certainly satisfies \( B < 0.1 \). On the other hand, a recent study by Jeong and Smoot [24], searching for evidence of a cosmic-string contribution in the WMAP data, has yielded the tighter bound

\[
G\mu \leq 3.3 \times 10^{-7}.
\]

If this is correct, as we shall see, it is at least marginally in conflict with the reported observational evidence for detection of cosmic strings; it is, however, somewhat dependent on assumptions about string evolution.

Another, possibly even stronger limit on \( G\mu \) can be obtained from limits on the gravitational radiation that would be emitted by cosmic strings. Observations of the regularity of pulsar timing put an upper limit on the fraction of the critical density in gravitational waves with periods of up to 10 years [25],

\[
G_{gw} \leq 4 \times 10^{-9}.
\]

An estimate of the gravitational radiation emitted by strings (see for example Ref. [2]) suggests that this implies a bound

\[
G\mu \lesssim 10^{-7}.
\]

If correct, this is in clear contradiction with the interpretation of observational evidence discussed later as due to cosmic strings. However, one should be cautious; the estimate is subject to considerable uncertainties. Because of the huge range of scales involved, one of the least certain aspects of cosmic-string dynamics is the long-term evolution of the small-scale structure on strings.
For obvious reasons, the discovery that cosmic strings could not provide an explanation for the primordial density inhomogeneities led to a widespread loss of interest in the whole idea. Why bother with something for which no real evidence exists, when a different theory provides a very satisfying and astonishingly accurate description of the data?

So why now the revival of interest?

4 Cosmic strings in string theory

As I said at the start, there are two main reasons. The first, and probably the most important, is that string theory cosmologists have discovered cosmic strings lurking everywhere in the undergrowth. These connections between fundamental strings and cosmic string will be discussed in this session by several other people, much better qualified to do so than myself. So I shall confine myself to a few remarks. (For a recent review, see Ref. [26].)

The big problem with string theory has been to connect its beautiful mathematical structure to any real measurements or observations. The chain of reasoning from fundamental string theory to phenomenology or cosmology is long, and it has proved hard to find definitive observational tests, or even to suggest where one might look. But it now appears that cosmic strings might actually provide the best observational window into fundamental string theory. There are several reasons for this.

Firstly, there is the question of string scale. The string tension of fundamental strings is the square of the string energy scale, which always used to be identified with the Planck scale. Such heavy strings certainly do not exist in our universe today, and cannot have played any role in cosmological evolution except conceivably in the first few Planck times. But we now know of models with large compact dimensions, in which the string scale may be much lower, down to the GUT scale or even less [8, 9, 10]. So in principle fundamental strings of macroscopic length are not ruled out.

Secondly, string theory now provides a much richer family of defects [14, 27] — not only fundamental (F-) strings but also D-branes of all dimensions. These can include D-strings whose ends are tied to D-branes of higher dimension. And there may also be D-branes partly wrapped on the compact dimensions, which look like strings on a macroscopic scale [14, 28]. Some of the resulting cosmic strings have novel properties — for example, a probability less than unity of intercommuting when they meet [29, 30]. One can also have defects that are composites of F- and D-strings, which can form complex networks with vertices where three strings meet. Which of these possibilities is actually realized depends on the precise form of the dimensional reduction from 10 or 11 dimensions to 4. For that reason, if we could discover what kinds of macroscopic defects exist in our universe it would tell us a lot about the underlying fundamental theory.

Finally, it now appears that GUTs will almost inevitably lead to cosmic strings. In the long road from string theory or M-theory to the standard model, it is very
natural to go through an intermediate GUT stage. Successful grand unification
seems to demand supersymmetry — without it the running couplings of the three
fundamental interactions do not converge at a single energy. Since grand unifica-
tion does inevitably produce monopoles, it also demands an inflationary period to
eliminate them, and of course inflation is needed for other reasons too. In a very
interesting recent study, Jeannerot et al [15] looked exhaustively at all possible
simple GUT groups of rank \( \leq 8 \), and at all possible symmetry-breaking chains
down to the \( G_{321} \) of the standard model. Many of these can be ruled out because
their predictions are in conflict with observation, for example by predicting the
formation of monopoles or domain walls after inflation. The remarkable fact is
that, although many possibilities remain, every one of them predicts the forma-
tion of topological or embedded cosmic strings at the end of inflation. So it seems
that cosmic strings are almost unavoidable.

5 Gravitational effects of cosmic strings

Now let me turn to the other main reason for the renewed interest in cosmic
strings: the tantalizing hints that their effects may already have been detected.
All these possible observations of cosmic strings depend on their very distinctive
gravitational lensing effects.

The space-time around a straight cosmic string is very unusual. Because of
the equality between energy per unit length and string tension, nearby masses
experience no gravitational acceleration towards the string. The space is locally
flat, but globally curved. In fact, it is cone-shaped, with curvature confined to the
core of the cosmic string. For a string along the \( z \) axis in otherwise empty space, the
surrounding space-time metric is

\[
 ds^2 = dt^2 - dz^2 - d\rho^2 - (1 - 8G\mu)\rho^2 d\varphi^2, \tag{11}
\]

(assuming \( G\mu \ll 1 \)). Equivalently, the local flatness can be made explicit by
introducing a new angle coordinate \( \bar{\varphi} = (1 - 4G\mu)\varphi \), so that the metric becomes

\[
 ds^2 = dt^2 - dz^2 - d\rho^2 - \rho^2 d\bar{\varphi}^2. \tag{12}
\]

But here \( \bar{\varphi} \) runs not from 0 to \( 2\pi \) from 0 to \( (2\pi - \delta) \), where the defect angle \( \delta \) is

\[
 \delta = 8\pi G\mu \approx 5'' \left( \frac{G\mu}{10^{-6}} \right). \tag{13}
\]

For a GUT scale string, this angle is a few seconds of arc.

This means that a straight string acts like a cylindrical gravitational lens with
a very unusual and characteristic pattern of lensed images. In general, we should
see two images of a source behind the string, separated by an angle of order \( \delta \).
More precisely, the separation of the images is [31, 32]

\[
 \alpha = \frac{D_{ls}}{D_s} \delta \sin \theta, \tag{14}
\]
where $D_s$ is the angular diameter distance of the source from us, $D_{ls}$ is that of the source from the lens, and $\theta$ is the angle between the line of sight and the tangent to the string. In sharp contrast to the lensing pattern of ordinary gravitational lenses, the string induces no magnification or demagnification, and the two images are of equal magnitude (unless one of them is only a partial image).

In practice, the situation will be more complicated, for at least two reasons. First, the strings are in general moving, often with quite large velocities. What is significant is the velocity component perpendicular to the line of sight. Suppose the string is moving with transverse velocity $v$, or equivalently, in the rest frame of the string, both observer and source are moving with velocity $-v$. Then the two images will have slightly different red-shifts: the image behind the string will be blue-shifted relative to that ahead of it, leaving a frequency difference $\delta \omega$ of order

$$\frac{\delta \omega}{\omega} \sim v \delta, \quad (15)$$

and the formula for the separation angle (14) is more complicated. This also applies to the CMB: a transversely moving string would induce a discontinuity in the temperature of the CMB [33], a unique signal of a cosmic string if it could be observed.

Secondly, as I explained earlier, the strings are not straight but kinky. This means that, viewed on a coarser scale, the effective energy per unit length $U$ and string tension $T$ are no longer equal [34]. For example, if the string is a zigzag of straight segments each making an angle $\psi$ with a median line, then

$$U = \mu \sec \psi, \quad T = \mu \cos \psi. \quad (16)$$

Note that

$$U > \mu > T, \quad \text{and} \quad UT = \mu^2. \quad (17)$$

These are in fact general results [35, 36].

Because of this, the ordinary gravitational attraction towards the string no longer vanishes; instead it is

$$g = \frac{2G(U - T)}{r}, \quad (18)$$

where $r$ is the distance from the string. Moreover, the defect angle is now

$$\delta = 4\pi G(U + T). \quad (19)$$

However, because of the gravitational attraction, the actual separation of the images is larger than this would suggest, namely

$$\alpha = \frac{D_{ls}}{D_s} 8\pi G U \sin \theta. \quad (20)$$
6 Possible observation of a cosmic string

Some years ago, possible observations of lensing by cosmic strings were reported [37, 38], but did not apparently stand up to further scrutiny. Recently, however, there have been two new observations that seem to suggest the presence of strings. I would like to devote the remaining part of this talk to an examination of these claims.

The first is the result of an Italian–Russian collaboration, in which Sazhin et al [16] report the observation of a lensing candidate named CSL-1 (Capodimonte-Sternberg Lens Candidate no. 1). There are three other candidates, named CSL-2 to CSL-4, that have not yet been fully analyzed. This candidate consists of a pair of galaxy images found in the OACDF survey (Osservatorio Astronomico di Capodimonte — Deep Field). The two images, separated by 2′′, or approximately 20 kpc, look nearly identical, both have a red-shift of $z = 0.46 \pm 0.008$, and their magnitudes in three different frequency bands are equal within errors:

|       | B       | V       | R       |
|-------|---------|---------|---------|
| $m_A$ | $22.73 \pm 0.15$ | $20.95 \pm 0.13$ | $19.67 \pm 0.20$ |
| $m_B$ | $22.57 \pm 0.15$ | $21.05 \pm 0.13$ | $19.66 \pm 0.20$ |

One hypothetical explanation might be that this is an image of a single large galaxy, with the central part of the image obscured by a dust lane. It would of course be a remarkable coincidence for this to leave two equal images, and in any case the authors rule out this possibility by examining the spectral profile.

Another possibility which cannot be ruled out is that what we see are two almost identical galaxies that just happen to be one nearly behind the other and quite close together in red-shift space. However, this would require a remarkable coincidence.

If the images are indeed of the same galaxy, it is theoretically possible that this is due to some more conventional lensing object, but in that case two identical images would be extremely unlikely. Moreover, the authors show that it would have to be a giant galaxy, which should be readily visible, and no such object is seen. So they conclude that the most likely explanation is lensing by a cosmic string. If so, we should expect

$$G\mu \geq 4 \times 10^{-7},$$

which appears at least marginally in conflict with the limit set by Jeong and Smoot [24], and even more so with the limit (10) derived from gravitational radiation. Moreover, $G\mu$ would have to be larger than this if either of the other factors in (20), $D_{ls}/D_l$ or $\cos \theta$, is substantially less than unity. On the other hand, it should also be noted that it is really a limit on $GU$; if the strings are kinky, $G\mu$ could be less.

Sazhin et al [16] pointed out that the hypothesis that this is an example of lensing by a cosmic string should in principle be easy to test by doing more precise photometric studies. They also point out that if there is a string between us and
the source galaxy it should be lensing the CMB, producing a line of discontinuity, so high-resolution radio-frequency measurements would also be useful.

Meanwhile, they have produced additional evidence of different kind [17]. If this is a genuine case of lensing by a cosmic string, there should be other lensed pairs in the vicinity [39]. So they looked at images of galaxies in a $4000 \times 4000$-pixel section of the field ($16' \times 16'$) centred on CSL-1 to see how many possible examples they could find.

They estimate, based on other surveys, that in this region there should be approximately 2200 galaxies within the magnitude range 20 to 24 (in the R band). This is indeed roughly what they do see. They then ask how many of these should be lensed by a cosmic string across the field. Roughly speaking, all galaxies within a strip of width $2 \delta$ centred on the string should produce double images. How long the strip is depends of course on how straight the string is on the relevant scale, but the extreme limits are a straight string and a random walk [39]. So they estimate that the number of lensed pairs of galaxies should lie between 9 (for a straight string) and around 200 (for a random walk). By contrast, in the same area they expect no more than two lensed pairs due to conventional lensing objects such as galaxies.

They then looked at pairs of objects with angular separations between $1''$ and $4''5$, and used a statistical test due to Schneider et al [40], based on matching colours, to decide whether these pairs were in fact images of the same object. They found 11 classified as very likely candidates, several times what would be expected from conventional lenses. This provides added weight to the hypothesis that a cosmic string has been seen. The authors emphasize, however, that to confirm that these really are lensed pairs, spectroscopic analysis will be required.

Another important piece of information concerns the distribution of the possible image pairs across the $16' \times 16'$ section of the field. Given that the number is not much larger than would be expected for a straight string, we might expect that they are concentrated on a roughly linear strip. That does not seem to be the case [41, 42], but equally they do not appear to be scattered randomly. They could perhaps match a string with a couple of kinks, zigzagging across the field. Another useful test would be to look for similar image pairs in a quite different region of the field where there is no lensing candidate.

To be fair, we should also note that there have been other similar searches for lensed pairs that have not yielded positive results, for example that of Shirasaki et al [43]. But of course, that was in four randomly chosen patches of the sky, not one already including a cosmic-string candidate.

7 Possible observation of a loop

The other intriguing piece of evidence comes from an analysis by Schild et al [18] of brightness fluctuations in a very well known gravitational lens system, Q0957+561, that has been studied intensively for 25 years. It consists of two quasar images separated by approximately 6''. They are known to be images of
the same quasar not only because of the spectroscopic match, but also because the images fluctuate in brightness, and the time delay between fluctuations is always the same; a brightening of \( A \) is matched by a brightening of \( B \) 417.1 days later. This pair is famous because the time delay has been used to provide a measure of the Hubble constant, independent of the distance ladder based on Cepheid variables. The reason for the lensing is well known — it is a foreground galaxy readily visible between the two images, about 1" from \( B \).

The brightness curves do not of course match precisely; the images also fluctuate independently, principally due to microlensing by individual stars in the lensing galaxy. However, what Schild and colleagues have found is evidence of another component in the fluctuation, in which the images fluctuate synchronously, with no time delay. A plot of the simultaneous magnitude fluctuations for the period between September 1994 and July 1995 seems to show a short-lived, quasi-periodic, synchronous fluctuation, with an amplitude of about 0.2 magnitudes and a period that appears from the figure to be about 80 days (though the authors quote 100 days), lasting for three or four periods.

For comparison, they show the data for \( A \) for the same period compared with those for \( B \) 417 days later, and also the data for \( B \) matched against those for \( A \) 417 days earlier. Neither of these plots shows the degree of correlation found in the first figure, although, as might be expected, both do (at least to me) seem to show some correlation. It is difficult to judge by visual comparison how strong the evidence for synchronous, quasi-periodic oscillations really is. Certainly it is not as yet conclusive. As the authors point out, we lack a proper statistical test for the hypothesis.

However, let us assume that the oscillation is real. It would of course be very difficult to explain on the basis of microlensing, because it would require an accidental coincidence of timing for at least three successive pairs of microlensing events. So what is the alternative? The authors suggest that the effect may be due to lensing by an oscillating loop of cosmic string between us and the lensing system.

To get some estimate of the effect, Schild et al rely on earlier work of De Laix and Vachaspati [44]. They look at a particularly simple model, a loop comprising a rotating double line, rotating in the plane normal to the line of sight about its mid-point. The position of the loop is given by

\[
\begin{align*}
x &= R \cos \frac{t}{R} \sin \sigma, \\
y &= R \sin \frac{t}{R} \sin \sigma,
\end{align*}
\]

where the parameter \( \sigma \) runs from 0 to 2\( \pi \). Obviously, the oscillation period (half the rotation period) is \( \pi R \). If this is to match the observed period of the brightness fluctuations, 100 days, one finds

\[ R \approx 0.02 \text{ pc} \approx 4400 \text{ au}. \]  

To have smooth quasi-periodic oscillations, \( R \) should be subtend an angle \( \theta_R \) substantially smaller than the angle between the images (otherwise there would
be sharp spikes or discontinuities in the record), so this suggests $\theta_R \sim 1.5''$, whence the distance of the string from us is

$$D_{\text{loop}} \sim 3 \text{ kpc}. \quad (24)$$

This is remarkably close; if there is a loop this near us, well inside our galaxy, either the density of loops is much higher than generally expected, or we have been very fortunate!

The fact that we saw only a few oscillations suggests that the loop is moving across our field of view, possibly with a velocity $v$ of order $0.7c$.

The expected size of the magnitude fluctuation for this simple case is

$$\Delta m \approx \frac{384\pi^2 (G\mu)^2 \theta_R^4}{\theta_I^6}, \quad (25)$$

where $\theta_I$ is the angular impact distance of the line of sight relative to the centre of the loop. The authors suggest that $\theta_I$ should be about half the distance between the images, say $\theta_I \approx 3''$. This allows an estimate $G\mu \approx 3 \times 10^{-8}$. However, the very strong dependence of $(25)$ on the poorly known parameters $\theta_R$ and $\theta_I$ means that this can only be a very rough estimate. The authors say that a more accurate calculation based on simulations leads to $G\mu \approx 6 \times 10^{-7}$, but there must still be a large error on this figure.

There is at first sight a possible alternative to the hypothesis of lensing by an oscillating loop, namely lensing by a double star. However to get the required period and amplitude, the stars would have to be at least $1.2 \text{ pc}$ from us, with an orbital radius of $\sim 1.8 \text{ au}$. That would mean masses of order $78 M_\odot$. It is inconceivable that such a large pair of stars could have escaped detection. So if the synchronous magnitude fluctuations are real, a cosmic string loop very near us may be the least implausible explanation.

## 8 Conclusions

Modern string theory certainly encourages the belief that cosmic strings should make an appearance in the early universe, even if they are not the primary source of initial density perturbations. There is very good reason for continuing to search for them.

As to whether they have already been found, the jury is still out. Speaking personally, it seems to me that a reasonably strong case has been made for the hypothesis that the lensing candidate CSL-1 is an example of lensing by an intervening string, though serious questions remain to be answered. In any case, more detailed studies of the other possible lensed pairs in the vicinity should put the question beyond doubt. So far as the synchronous oscillations observed in the lensed quasar pair are concerned, the explanation in terms of a very nearby oscillating loop seems to require rather a lot of special circumstances. The real question is: are these apparent synchronous oscillations a real effect, or the result of chance fluctuations? We certainly need a good statistical test.
Whether these pieces of evidence stand up or not, the search for cosmic strings will certainly continue for some time to come. If it turns out that these observations are not due to cosmic strings, and if the upper limit on $G\mu$ drops significantly below $10^{-7}$, then direct detection via gravitational lensing is unlikely to be feasible. In that case, the most likely way of verifying their existence would be via the gravitational radiation they emit; they should be detectable by LIGO or LISA [26]. But more theoretical work is needed to tie down the predictions.

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