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Microlensing by cosmic strings

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ABSTRACT

We consider the signature and detectability of gravitational microlensing of distant quasars by cosmic strings. Because of the simple image configuration such events will have a characteristic lightcurve, in which a source would appear to brighten by exactly a factor of 2, before reverting to its original apparent brightness. We calculate the optical depth and event rate, and conclude that current predictions and limits on the total length of strings on the sky imply optical depths of $\lesssim 10^{-8}$ and event rates of fewer than one event per 10^9 sources per year. Disregarding those predictions but replacing them with limits on the density of cosmic strings from the cosmic microwave background fluctuation spectrum, leaves only a small region of parameter space (in which the sky contains about 3×10^5 strings with deficit angle of the order of 0.3 milli-seconds) for which a microlensing survey of exposure 10^7 source years, spanning a 20–40-year period, might reveal the presence of cosmic strings.

Key words: gravitational lensing – cosmology: miscellaneous.

1 INTRODUCTION

Cosmic strings are topological defects that arise during phase transitions in the early Universe, and are also predicted in some models of inflation (Kibble 1976; Vilenkin & Shellard 2000; Polchinski 2004). They are dynamical entities that move at close to the speed of light. During their evolution, strings can intersect each other (and themselves), which can lead to the formation of closed loops of strings that subsequently decay. A natural outcome of the evolution of a primordial network of strings in an expanding universe is therefore a few long, nearly straight strings that cross the horizon volume, accompanied by a population of decaying string loops.

The effect of cosmic strings on observational probes of the early Universe has most recently been described by Polchinski (2004). The most direct way of detecting cosmic strings in the sky is through their gravitational lensing effect: a string induces a deficit angle in space, which can lead to double images from sources projected behind a string. The lensing properties of strings were recently discussed by Mack, Wesley & King (2007) and Shlaer & Wyman (2005).

In this letter, we consider *microlensing by cosmic strings*. Microlensing (Liebes 1964; Refsdal 1964; Paczynski 1986) occurs when the source and lens move with respect to one another, leading to a time-variable image configuration and, consequently, a change in the total observed flux from the source. It provides a way to detect lensing even when the image splitting is too small to resolve with astronomical measurements. Microlensing has developed into a powerful probe of stellar populations, planetary companions to distant stars and dark haloes consisting of condensed objects (MACHOs). Particularly, since cosmological constraints have pushed the string tension down to levels where the deficit angle can be at most a few tens of milli-seconds (mas) (Wyman, Pogosian & Wasserman 2005; Fraisse 2007), microlensing might offer a feasible alternative route to detecting lensing from fast-moving strings. Thus, the question we address is: can microlensing by cosmic strings be observed and used as a way of measuring the string density?

This paper is organized as follows. In Section 2, we describe the image configuration produced by a cosmic string and the characteristic brightness variation expected from string microlensing. In Section 3, we calculate the expected optical depth, and specific event rate, for a typical cosmological string population microlensing distant quasars. Section 4 contains a short discussion of the results.

Recently, Chernoff & Tye (2007) analysed the expected microlensing event rates of stars due to cosmic string loops, and concluded that an intensive monitoring campaign would be a sensitive probe of an interesting range of string tension. Stellar sources offer the great advantage that they have a very compact angular extent, but the disadvantage is that the fluxes of individual stars can only be monitored to relatively small distances, limiting such searches to loops in the halo of the Galaxy, within a few tens of kpc from the sun. Unfortunately, a significant population of loops in the halo can only arise if the loops manage to lose most of their kinetic energy, and this process is not yet properly quantified.

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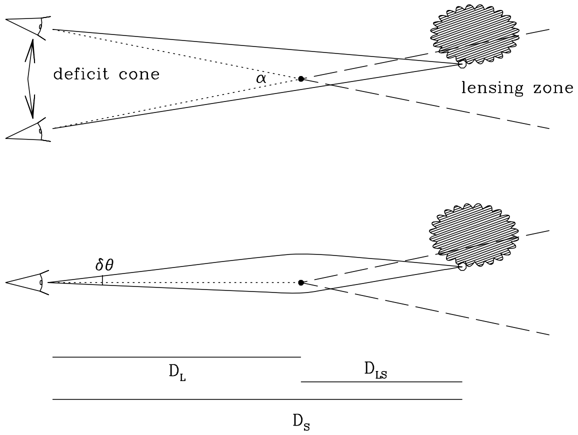

Figure 1. Lensing by a cosmic string that passes in front of an extended source. In the top diagram, we have placed the deficit cone induced by the string along the observer-string line, so the dotted lines are to be identified. Light rays reaching the observer's eye are straight lines in this diagram. In the bottom diagram, the same configuration is shown, but now the deficit cone has been closed by stretching the azimuthal coordinate centred on the string. The lensing effect of the string is evident: rays passing either side of the string get deflected by an angle $\alpha/2$ towards it. The space between the dashed lines is the lensing zone. The observer sees two images of any point in this region, separated by an angle $\delta\theta$. On the sky, two copies of the lensing zone are visible, separated by the cosmic string.

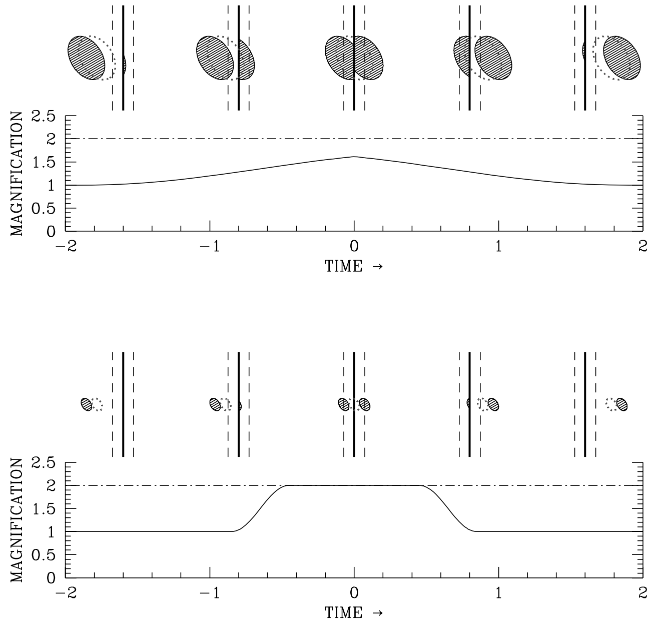

Figure 2. Image configuration and lightcurve for a source larger than the lensing angle $\delta\theta$ (top panel) and smaller than $\delta\theta$ (bottom panel). The dotted outlines show the unshifted locations of the object in our picture of the conical space shown in Fig. 1. The extra images fall between the dashed lines, $\delta\theta/2$ from the string (heavy line). Only for the small source will the observed flux reach a plateau of the factor of 2 magnification. The large source is never doubly imaged all at once.

2 IMAGING BY COSMIC STRINGS

The effect of a straight cosmic string is to induce a 'deficit angle' α in space, which has the effect of turning parallel rays that pass on either side of a string into a converging beam. Effectively light rays passing the string are bent towards the string by an angle $\alpha/2$. As a result, background sources that project sufficiently close to a cosmic string are doubly imaged (see Fig. 1).

Because gravitational lensing preserves surface brightness, and because straight strings do not distort the images they produce, a doubly imaged source will be exactly twice as bright as the unlensed source. If a cosmic string were to pass in front of a source therefore, then the lightcurve would show a sharp step up by a factor of 2, followed some time later by a decrease in brightness back to the original level. The sharpness of the step is determined by the angular size of the source: for a point source, the step is instantaneous, but the second image of an extended source will only gradually be built up (down) as the string tracks across the sky, smoothing the increase (decline) in brightness.

The key point of microlensing is that this lightcurve can be measured even without resolving the double images: provided the lightcurve is sufficiently different from other, astrophysical, variability these events can be found and studied from large monitoring campaigns of many objects.

The microlensing described above will only be seen if all of the source is doubly imaged at once, which means that the source must be smaller in angular extent than the lensing angle $\delta\theta$. The most compact sources that can be seen to cosmological distances are quasars, whose nuclear regions are $\lesssim$1 pc in radius, corresponding to an angular diameter of 0.08 mas [1] at redshift 1. If $\delta\theta \simeq \alpha/2$ is smaller, not all of the source can be doubly imaged simultaneously, and therefore we will not see the full factor of 2 brightening. Such lightcurves would not show the characteristic step in brightness either, but a single bump whose shape and peak amplification is determined by the core structure and size. We therefore impose the requirement that the flat top of the light curve lasts at least as long as the rise time (angular diameter of the source less than $\delta\theta/2$), which implies that we are sensitive to cosmic strings with deficit angles with

$$\alpha >\sim 0.3 \text{ mas}.$$

Image configurations and lightcurves for different source sizes are shown in Fig. 2.

As long as the cosmic string is straight on scales comparable to the source size (and smaller), then the above still holds. Otherwise bends in the string will spoil the exact factor of 2 magnification, and may also lead to complex brightness fluctuations as the string tracks across the source. Such complex lightcurves will be difficult to recognize as anything other than intrinsic source variability, and so will not be considered further here.

3 OPTICAL DEPTH AND EVENT RATE

3.1 Event duration

A string with deficit angle α (Fig. 1) that lenses a point source will produce two images that are separated by an angle

$$\delta\theta = \alpha(D_{\rm LS}/D_{\rm S}),$$

where $D_{\rm LS}$ is the angular diameter distance from source to string and $D_{\rm S}$ is distance to the source. Such image splitting takes place if the source lies within a projected angle $\delta\theta/2$ of the string, so if the string moves in front of the source, at transverse speed V, the

[1] 1 mas is about 5×10^{-9} radian.

duration T of the double-image phase is given by

$$T = \delta\theta D_L/V = \frac{\alpha D_L D_{LS}}{V D_S}.$$

Typically (for all reasonable cosmological models including the current standard model of a flat Universe with $\Omega_\Lambda \simeq 0.7$), D_{LS}/D_S will be about 0.5 (for a string at redshift $\sim$1 and a source at redshift $\gtrsim 2$), so that the image splitting is about half of the deficit angle. The distance D_L to a string at redshift 1 is about c/H_0 where $H_0 \simeq (14 \times 10^9\,\mathrm{yr})^{-1}$ is the Hubble constant. A typical value for V is around 0.3 times the speed of light (Vilenkin & Shellard 2000). Thus, the duration T of a microlensing event, from beginning of ingress to the beginning of egress, is of the order of

$$T \sim \frac{\alpha}{0.6 H_0} \simeq 120 \left(\frac{\alpha}{1\,\mathrm{mas}}\right)\,\mathrm{yr}.$$

A similar calculation shows that the time over which the source brightness doubles (or halves again) is about 20 yr, for a 0.08 mas source size.

Very similar lensing behaviour would result from dense gas filaments in the intergalactic medium, provided their angular width on the sky is thinner than the source size and than their own deficit angle of $8\pi G\lambda/c^2$, for linear mass density λ (Bozza & Mancini 2005). Indeed, the same applied to filaments of dark matter. However, because such filaments would move a factor of 100–1000 times more slowly than cosmic strings, the microlensing time-scales involved would be 100–1000 times longer.

3.2 Optical depth

The *optical depth* τ for lensing is the probability that a given source is doubly imaged at any given time, and is therefore equal to the fraction of sky that is covered by strips of angular width $\delta\theta$ along all visible strings.

A typical long string crossing our horizon volume will have a projected length on the sky of $\sim \pi$ radians. If there are N such cosmic string in the sky then the area of sky that is multiply imaged is about $\delta\theta \times \pi N$ radians, which represents a fraction of $N\delta\theta/4$ of the sky. Hence,

$$\tau = \frac{N\alpha D_{LS}}{4 D_S} \simeq 6 \times 10^{-10} N \left(\frac{\alpha}{1\,\mathrm{mas}}\right),$$

where the estimate is based on the same assumptions as in Section 3.1.

This tiny probability means that a huge number of background sources, sufficiently compact (angular size $\ll \delta\theta$) to be lensed significantly, would have to be observed in order to have a reasonable chance of detecting one lensed source.

3.3 Event rate

The *event rate* Γ at which a given source will enter the microlensing regime is given by the lensing probability divided by the typical duration:

$$\Gamma = \tau/T = \frac{NV}{4D_L} \simeq \frac{N}{4}\frac{V}{c} H_0 \simeq 5 \times 10^{-12} N\,\mathrm{yr}^{-1}.$$

Note that the lensing rate is independent of the deficit angle α: it is purely determined by the rate at which cosmic strings sweep regions of sky, which is a function only of their angular diameter distance, transverse velocity and total length. As the transverse velocity is of the order of the speed of light, the angular motions on the sky for strings at cosmological distances are of the order of the Hubble constant.

4 DISCUSSION

The calculation above shows that the event rate to be expected from a network of straight cosmic strings is tiny: a typical source at high redshift will be microlensed by a cosmic string of the order of N times per Hubble time, where N is the number of long strings that exist in our horizon volume. Predictions derived from simulations of the simplest variety of strings (Hindmarsh & Kibble 1995; Vilenkin & Shellard 2000) put N at 10–100, leading to a very low event rate indeed: 10^9– 10^{10} sources would have to be monitored for a year in order to see a few events.

Furthermore, the duration of the events is of the order of 40 yr, even for the lightest strings (those with deficit angles $\sim$0.3 mas) that are heavy enough to microlens parsec-sized (pc-sized) cores of distant quasars, so it would require a very sustained campaign to observe a full lightcurve. Typical values of the rise (or decay) time are 20 yr. Only if a suitable background population of bright, numerous, compact (subpc) sources at redshifts above $\sim$2 can be identified can strings with smaller deficit angles, with correspondingly shorter lensing time-scale, be probed. The time-scale would also be shortened if there were a population of cosmic strings at low redshift.

There are suggestions that networks of cosmic superstrings – which have the same lensing properties as ‘ordinary’ cosmic strings – evolve differently because they are less likely, perhaps by as much as a factor of 1000, to intercommute when they cross (see Tye 2006, and references therein). This may lead to an enhancement by up to a factor of 1000 in the length of string on the sky, i.e. N. Even with this boost the event rate remains small, at one event per several million sources per year at best. It remains to be seen whether future radio surveys will contain a sufficiently large number of compact sources that can be monitored for microlensing events.

Thus far, we have concentrated on long-lived, horizon-crossing strings, but it is also possible that the length of string in loops is much larger than that in long strings. Loops with radii much larger than $\delta\theta$ lens distant sources in the same way as straight strings. Whether there is a substantial loop population or not depends on details of cosmic string network evolution that have yet to be resolved. Currently, there are two possibilities. The first is that loop sizes are determined by gravitational back reaction. If that is the case then loops are short-lived and the length of string in loops is at all times comparable to the length in long strings (Vilenkin & Shellard 2000).

The second possibility, suggested by recent numerical simulations, is that loop sizes are determined by the large-scale dynamics of the network (Martins & Shellard 2006; Vanchurin, Olum & Vilenkin 2006; Ringeval, Sakellariadou & Bouchet 2007). In this case, loops may be long-lived, slowly shrinking in length L by emission of gravitational radiation at a rate $\mathrm{d}L/\mathrm{d}t \sim -\alpha c$ (Vilenkin & Shellard 2000). Assuming that the largest loops to form have sizes $\sim$10 per cent of the horizon size ct_f (Vanchurin et al. 2006), for a formation time t_f they will survive to the present time t_0 provided $\alpha \lesssim 0.1\, t_\mathrm{f}/t_0$. Thus, because the loop density in the radiation era is much larger than in the matter era, large numbers of string loops with $\alpha \lesssim 10^{-7}$ formed around or before the end of the radiation era could still exist. It turns out they do not enhance the microlensing rate significantly: using the loop length distribution from equation (70) in Siemens et al. (2006), we find that the total length in loops scales as $\alpha^{-1/2}$, and even in the most favourable case of $\alpha \sim 10^{-9}$ it only reaches the equivalent of $N \simeq 50$.

Perhaps these predictions for N will turn out to be unduly pessimistic, so let us assume that somehow a very large length of cosmic string has managed to survive to redshift $\sim$1. Our calculations of the

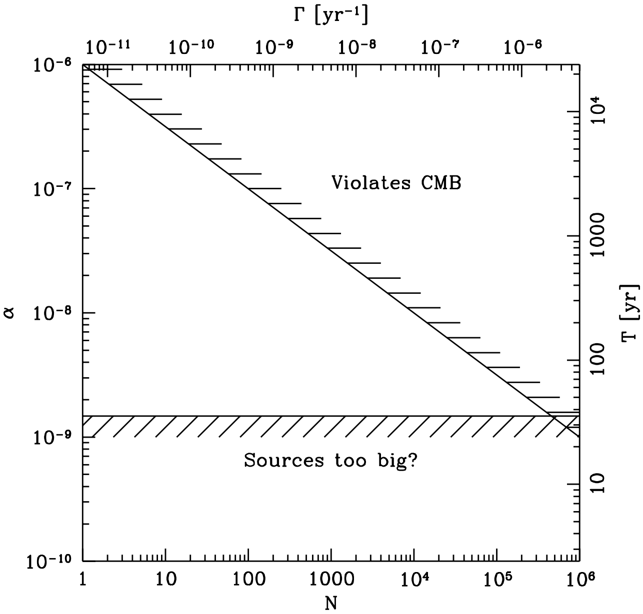

Figure 3. Available parameter space (deficit angle α in radians, versus string length *N*) for microlensing surveys. The top axis gives the event rate expected, the right-hand axis the event duration. For parameters above the diagonal line, the strings would generate fluctuations in the cosmic background radiation inconsistent with observations. Below the horizontal line sources as small as 1 pc in radius (angular diamater 0.08 mas at redshift 1) would be too large in angular extent to be completely lensed. For details see the text.

event rate have shown that in this case a cosmic string microlensing survey of several million sources might find some events. But in this case, we run into another observational limit: the strong constraint that arises from the spectrum of fluctuations in the cosmic microwave background (CMB). As shown by Wyman et al. (2005), the density fluctuations arising from strings (δ_s) must be less than $\sim$10 per cent of the primordial adiabatic density fluctuations $\delta_a \sim 10^{-5}$. The density fluctuations due to strings are characterized by rms fluctuations in the number of strings. Therefore, as the total energy density per horizon-crossing string is $\sim \alpha$ times the critical density, $\delta_s \sim \sqrt{N}\alpha < 0.1 \times 10^{-5}$. As discussed above, for sources of physical radius 1 pc a Hubble distance away, $\alpha \gtrsim 1.5 \times 10^{-9}$ is required for the characteristic microlensing lightcurve to be produced. So, the maximum possible number of strings is $N_{\max} \sim 3 \times 10^5$ and the maximum observable event rate is $\Gamma_{\max} \sim 1.5 \times 10^{-6}\,\mathrm{yr}^{-1}$. Even in this most favourable case, millions of sources would need to be monitored to observe a few events per year.

These limits, which are independent of the cosmic string formation scenario, are plotted in Fig. 3. We conclude that the prospects for detecting cosmic strings through simple microlensing of quasars are bleak!

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