THE ASTROPHYSICAL JOURNAL, 316:L49–L54, 1987 May 15

GAMMA-RAY BURSTS FROM SUPERCONDUCTING COSMIC STRINGS AT LARGE REDSHIFTS

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Received 1987 January 2; accepted 1987 February 27

ABSTRACT

The universe is least opaque to gamma rays between 0.1 MeV and 100 MeV, and sources can be seen out to a redshift $z \approx 1000$. The only all-sky detectors that have been operating continuously for many years are sensitive to photons near 1 MeV. Spectacular and, in some cases, recurrent bursts from unidentified sources have been seen by these detectors. If the recurrence of gamma-ray bursters GB 790107 and GB 790324 is due to gravitational lensing, then the sources must be at cosmological distances.

Recent developments in the theory of superconducting cosmic strings suggest that their cusps may be possible sources of very intense and highly collimated bursts of energy. A cusp at a redshift $z \approx 1000$ may give rise to an intense burst of energy with a duration of a few seconds or less. The maximum amount of energy associated with such an event is limited to 10^7 ergs cm^{-2} by causality. If only one part in 10^{11} of this energy reaches Earth as 1 MeV gamma rays, then about 100 gamma-ray bursts should be detectable every year with the existing instruments. Furthermore, microlensing of this tight beam is quite likely to produce images with dissimilar spectral and time profiles. The number of events should vary with their observed energy (fluence) according to $N \approx S^{-1.7}$ for sources not affected by gamma-ray opacity, and more slowly for fainter, i.e., more distant and partially obscured, sources.

Subject headings: cosmology — gamma-rays: bursts

I. INTRODUCTION

The soft gamma-ray burst GB 790107 was discovered on 1979 January 7 and found to have more than 50 recurrent events over the next few years (Laros *et al.* 1986). Paczyński (1987) suggested that the recurrence might be due to gravitational microlensing by a cluster of massive objects such as a rich cluster of galaxies. GB 790324 is another burster whose recurrence may be due to gravitational lensing (Paczyński 1986). The lensing hypothesis requires that these bursters be at cosmological distances. Such distances are not ruled out by the observed spectra (Goodman 1986; Paczyński 1986), but a release of supernova-like energy in about 1 s is implied.

Arons and McCray (1969) have noted that: "the energy range $\varepsilon_0 > 1$ MeV offers the best chance of observing discrete sources at very large redshifts where, at our present state of understanding, anything is likely to happen." Their statement is just as true now as it was 18 years ago. The discovery of gamma-ray bursts was published in another issue of *The Astrophysical Journal (Letters)* (Klebesadel, Strong, and Olson 1973), and the possible implications of the work done by Arons and McCray has not been noticed. We recalculated the optical depth of the universe to X-rays and gamma rays of various energies, and our results are shown in Figure 1 and discussed in the next section. Indeed, with gamma rays, one can see back to a redshift as high as $z \approx 1000$.

Until recently no objects were believed to exist at such large redshifts. However, over the last few years, the possible existence of cosmic strings has become a matter of very intense study (cf. Vilenkin 1985 for a recent review). Cosmic strings can exist at any redshift. It has been suggested that these objects may have triggered the formation of galaxies and clusters of galaxies (Kibble 1980; Zel'dovich 1980; Vilenkin 1981). Much work has been done to explore this possibility (Turok 1986 and references therein). Recently, Ostriker, Thompson, and Witten (1986) have proposed that superconducting cosmic strings may also be responsible for the large-scale structure of the universe.

Cosmic strings are topological defects, trapped lines of false vacuum produced during a phase transition in the very early universe, soon after the Planck era. These strings can be extremely massive, with mass per unit length, μ, as large as 10^{22} g cm^{-1}. Witten (1985) has demonstrated that in some grand unified models, cosmic strings may be superconducting and may carry currents of up to $I \approx 10^{20}$ A; hence, magnetic fields as strong as $B \approx 10^{13}$ G may exist as far as 10 km from the string.

Cosmic strings oscillate at relativistic speeds. A looplike string with a length L oscillates with a period $P_{osc} = L/2c$. Every period, a generic nonconducting cosmic string will form two cusps, points on the string which momentarily reach luminal velocities (Turok 1984). For a superconducting cosmic string, true cusps most likely cannot form as they are probably truncated at some very large, but finite, Lorentz γ factor by electromagnetic back-reaction as well as by the inertia of the charge carriers along the string (Spergel, Piran, and

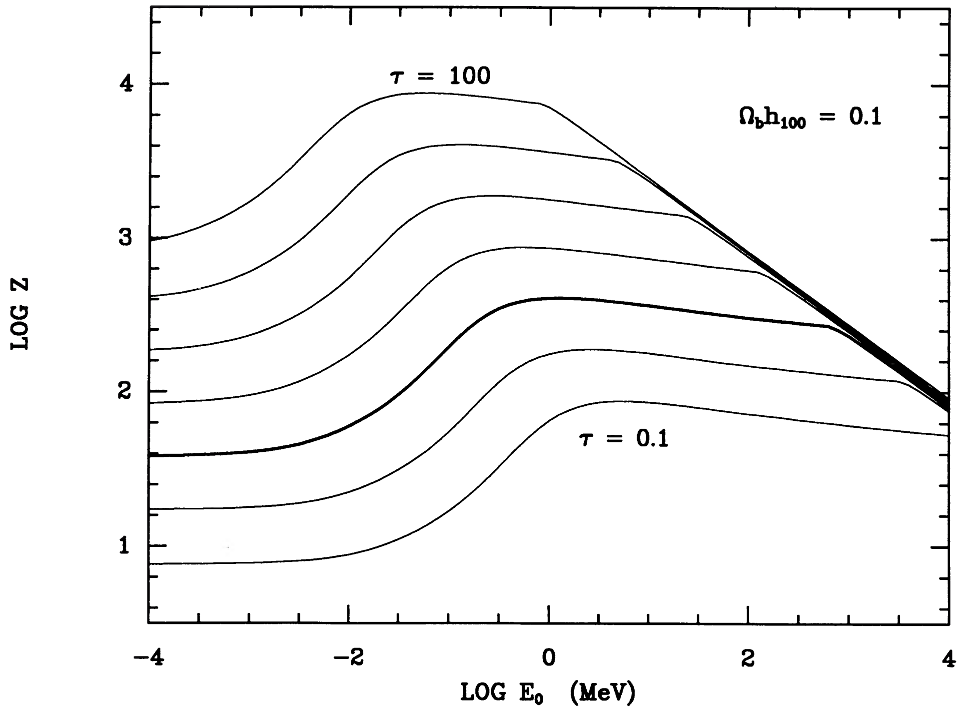

FIG. 1.—The lines of constant optical depth, from $\tau = 0.1$ to $\tau = 100$, are shown in the photon energy–redshift diagram for $\Omega = 1$. Thick line corresponds to $\tau = 1$ when $\Omega_b h_{100} = 0.1$, where Ω_b is the baryon mass density in the universe, and $h_{100} = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ is dimensionless Hubble constant. The optical depth is proportional to $\Omega_b h_{100}$. If we had $\Omega_b h_{100} = 0.01$, then the lines in this figure would cover the range from $\tau = 0.01$ to $\tau = 10$. Photon energies are expressed in MeV, as measured at Earth.

Goodman 1986; Vilenkin and Vachaspati 1986). Nonetheless, we shall, henceforth, use the term "cusp" to describe that small section of the oscillating string which attains the highest possible Lorentz γ factor.

In the cusp region, the string magnetosphere moves ultrarelativistically, giving rise to many spectacular phenomena even more complicated than those in the pulsar magnetospheres. We shall not attempt to discuss such complicated processes, but rather concentrate on the energies and time scales expected from cusp events. In particular, we shall explore the possibility that these events may be responsible for some of the observed gamma-ray bursts. The *AIP Conference Proceedings 141*, edited by E. P. Liang and V. Petrosian (1986), provides an excellent review of gamma-ray bursts.

II. OPTICAL DEPTH OF THE UNIVERSE

We assume an $\Omega = 1$ universe with a baryon mass density in diffuse matter Ω_b, helium abundance $Y = 0.25$, and the Hubble constant $h_{100} \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. We allow for the opacity due to Thomson and Compton scattering, as well as pair creation by gamma-rays interacting with protons and electrons. The optical depth to all these processes may be calculated as

$$\tau = 0.061 \Omega_b h_{100} \int_0^z (1+z)^{1/2} \frac{\sigma(z)}{\sigma_{\text{Th}}} dz, \qquad (1)$$

where $\sigma(z) = \sigma[E_0(1+z)]$ is the combined cross section for all processes, E_0 is the photon energy as seen by observer, and σ_{Th} is Thomson scattering cross section. The Compton contribution to σ was calculated according to a formula given by Rybicki and Lightman (1979, p. 197, eq. [7.5]), while the contribution due to pair creation on protons and electrons was adopted from Stepney and Guilbert (1983). Another important source of opacity, at very high energies, is pair creation by the gamma rays colliding with the microwave background photons. We calculated the associated cross section following Stecker (1971, p. 203, eq. [13-9]).

Figure 1 shows lines of constant optical depth for X-rays and gamma-rays with energies in the range $E_0 = 10^{-4}$ MeV to 10^4 MeV for $\Omega_b h_{100} = 0.1$. At small energies, the dominant opacity source is Thomson scattering and $\tau = 1$ is reached at a redshift $z \approx 40$. For $E_0 > 0.01$ MeV, the Klein-Nishina cross section falls off, and the universe becomes more transparent as $\tau = 1$ is reached at increasingly larger redshifts. Around $E_0 \approx 1$ MeV, the dominant loss mechanism for photons is pair creation on protons and electrons, maintaining $\tau = 1$ at $z \approx 400$. Finally, above $E_0 = 100$ MeV, the universe becomes opaque to gamma rays due to pair creation in photon-photon collisions. At these high energies, the optical depth $\tau_{\gamma\gamma} = 1$ occurs at the redshift $z_{\gamma\gamma} \approx 7.4 \times 10^3 (E_0/1 \text{ MeV})^{-0.484}$.

These results are almost exactly the same as those obtained by Arons and McCray (1969). Figure 1 shows the variation of optical depth with redshift. It is graphically clear that the opacity due to $\gamma + \gamma \rightarrow e^- + e^+$ sets in rather abruptly. The cross section for this process depends very weakly upon the uncertain cosmological parameters while the optical depth due to Compton scattering and pair creation on the protons and the electrons is directly proportional to the product $\Omega_b h_{100}$. If the value of this product differs from the one assumed, the lines corresponding to various values of optical depth in Figure 1 would need to be relabeled. For example, if $\Omega_b h_{100}$ was 0.01 rather than 0.1, then the optical depth $\tau = 1$ would be reached at a redshift as large as $z \approx 2000$ for gamma rays with $E_0 \approx 1$ MeV.

The best window to look deep into the universe at a large redshift is between 0.1 MeV and 100 MeV. It is very fortunate that the all-sky detectors exist for just this energy range. Perhaps it is not a coincidence that the most spectacular burstlike events were discovered near 1 MeV.

III. COSMOLOGICAL EVOLUTION OF COSMIC STRINGS

Vilenkin (1985) has reviewed the formation and evolution of cosmic strings. We shall summarize here only those results that are of interest to us. We are interested in cosmic string loops that are at a redshift of about $z \approx 1000$. These loops formed much earlier, at a redshift $z > z_{\rm eq} = 4.2 \times 10^4 h_{100}^2$, where $z_{\rm eq}$ corresponds to the redshift at which the radiation energy density in the universe equals the density in matter. The loops oscillate; they radiate their energy; they shrink. The number density of dying loops with a radius between R and $R + dR$ in the interval $0 < R < R_*$ (Brandenberger and Turok 1986) is

$$\frac{dn_l}{dR} = \frac{\nu (ct_{\rm eq})^{1/2}}{R_*^{5/2} (ct)^2}, \qquad (2)$$

where $\nu \approx 0.01$, $R_* = \beta G\mu/c^2 ct$, $\beta = 100$, $t = t_0(1+z)^{-3/2}$, $t_0 = H_0^{-1} = 3.1 \times 10^{17}\ h_{100}^{-1}$ s. In these formulae, t is age of the universe at a redshift z. We have departed from the common notation and will use β instead of γ in the definition of R_* in order to avoid confusion with the Lorentz factor. We have also neglected to count loops with $R > R_*$ as such loops are relatively rare and the total number of loops is dominated by the number of small loops.

Volume of the universe between redshifts z and $z + dz$ is

$$\frac{dV}{dz} = 6\pi (ct_0)^3 (1+z)^{-5/2} \left[1 - (1+z)^{-3/2}\right]^2$$

$$\approx 6\pi (ct_0)^3 z^{-5/2}, \quad \text{for } z_{\rm eq} \gg z \gg 1. \qquad (3)$$

The number of loops out to a redshift z is

$$N_l(z) = \int_0^z \left(\int_0^{R_*} \frac{dn_l}{dR}\, dR \right) \frac{dV}{dz'}\, dz'$$

$$\approx 3 \times 10^{12} h_{100}^{-3/2} z_3^{15/4} \beta_2^{-3/2} \varepsilon_{-6}^{-3/2}, \qquad (4)$$

where $z_3 = z/10^3$, $\beta_2 = \beta/10^2$, $\varepsilon_{-6} = (G\mu/c^2)/10^{-6}$. There are so many cosmic string loops out to a redshift $z \approx 1000$ that we would expect to see some observable consequences of their existence.

A generic loop with length $L \approx 10\ R$ oscillates with a period $P_{\rm osc} = L/2c$ and forms two cusps every period. For an oscillating loop of superconducting cosmic string, the cusp points are of special interest as they are likely sites of very energetic events. The number of cusps that develop per unit redshift z, per unit loop radius, in a unit of observer's time is

$$\frac{dN_c}{dt_{\rm obs}\, dR\, dz} \approx \frac{2c}{L(1+z)} \frac{dn_l}{dR} \frac{dV}{dz}. \qquad (5)$$

IV. ENERGETIC EVENTS FROM COSMIC STRINGS

We have attempted to make some simple estimates of the energetics and time scales involved with the cusp phenomena. As noted earlier, for a superconducting cosmic string, true cusps, with the local string velocity reaching the speed of light, cannot form if all relevant physical processes are taken into account. Unfortunately, no solutions are available yet for the equations of motion of an oscillating loop with electric current. Therefore, we have analyzed the equations of motion that neglect the back-reactions and have extrapolated the results to the case of the truncated cusps expected for the superconducting strings. Figure 2 displays the cusp phenomena associated with a loop whose trajectory is described by one of Kibble and Turok's (1982) simple analytic solutions to the equations of motion of a loop with no back-reactions (cf. eq. [12.8] in Vilenkin's review article 1985).

For a superconducting cosmic string, we consider as cusps those sections of the loop which, for a short time, attain $\gamma > \gamma_{\rm max}$ where $\gamma_{\rm max}$ is some large characteristic Lorentz factor. The duration of such events, as measured in the inertial frame, is $\Delta t_{\rm inert} \approx P_{\rm osc} \gamma_{\rm max}^{-1}$. In this time interval, the maximum velocity of the string, attained somewhere along section under consideration, changes direction by $\gamma_{\rm max}^{-1}$ radians.

In the frame comoving with the ultrarelativistic section of a string, the truncated cusp lasts for $\Delta t_{\rm cusp} \approx \Delta t_{\rm inert} \gamma_{\rm max}^{-1} \approx Lc^{-1} \gamma_{\rm max}^{-2}$. Furthermore, in the comoving frame, the maximum possible energy discharged by a cusp, due to limitations imposed by causality, is $\Delta E_{\rm cusp} \approx \eta \mu c^2 \cdot c \Delta t_{\rm cusp} \approx \eta \mu c^2 L \gamma_{\rm max}^{-2}$, where $\eta < 1$ is an efficiency parameter. The form in which this energy may be discharged is a subject of many speculations (Hill, Schramm, and Walker 1986; Spergel, Piran, and Goodman 1986; Vilenkin and Vachaspati 1986).

In the inertial frame, this energy is boosted up by the Lorentz factor: $\Delta E_{\rm inert} \approx \Delta E_{\rm cusp} \gamma_{\rm max} \approx \eta \mu c^2 L \gamma_{\rm max}^{-1}$. All the power radiated from the cusp is beamed into a very small solid angle $\gamma_{\rm max}^{-2}$. Therefore, the power may be seen only by those observers who are in the beam. The beam sweeps an angle $\gamma_{\rm max}^{-1}$ in a time $\Delta t_{\rm obs} \approx \Delta t_{\rm cusp} \gamma_{\rm max}^{-1} \approx P_{\rm osc} \gamma_{\rm max}^{-3}$, and this is the time interval over which the observer sees the power radiated from the cusp. We have here a close analogy with the timing involved in the beamed synchrotron emission of an ultrarelativistic electron (cf. Rybicki and Lightman 1979, p. 171, eq. [6.10b]).

Consider a cusp at a noncosmological distance d away from the observer who is swept by the beam of energy. As the solid angle of the beam is $\gamma_{\rm max}^{-2}$, the maximum energy flux reaching the observer is

$$F_{\rm obs} \approx \frac{\Delta E_{\rm inert}}{\Delta t_{\rm obs}} \frac{\gamma_{\rm max}^2}{4\pi d^2} \approx \frac{\eta \mu c^3 \gamma_{\rm max}^4}{4\pi d^2}\ (\text{ergs cm}^{-2}\ \text{s}^{-1}). \qquad (6)$$

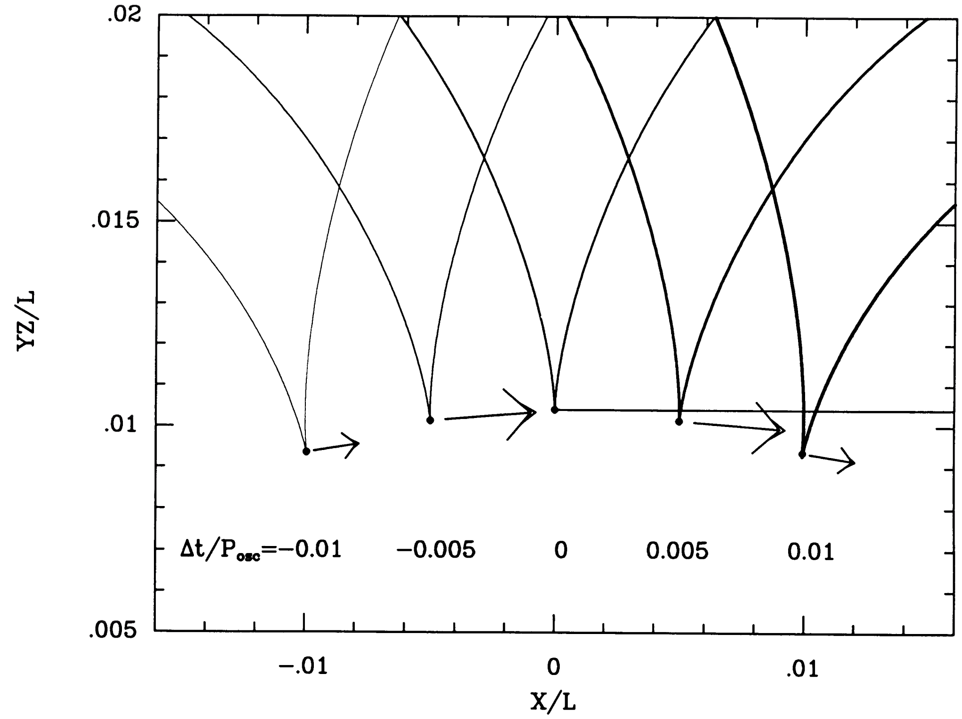

FIG. 2.—Snapshots of the cusp region, in the plane X vs. YZ, where $YZ \equiv Y + 5Z$, taken at time intervals $\Delta t = P_{osc}/200$ about the cusp event. The cosmic string's trajectory is one of Kibble and Turok's (1982) simple analytic solutions to the equations of motion of a loop with no back-reactions (cf. Vilenkin's review article, 1985, eq. [12.8], with $\alpha = 0.5$). The snapshots of the region prior to the cusp event are depicted as light images, while the snapshots of the loop after the cusp event are drawn with thick lines. The vectors associated with each diagram show the instantaneous direction of motion of the cusp region and the associated magnitude of the maximum Lorentz factor. The beam sweeping effect is clearly visible.

If the string loop with the cusp is at a cosmological distance from the observer, at a redshift z in the $\Omega = 1$ universe, the observed flux depends on the "luminosity distance" d_L:

$$d_L = 2cH_0^{-1}\left[(1+z)^{1/2} - 1\right](1+z)^{1/2}$$
$$= 1.85 \times 10^{28} h_{100}^{-1}\left[(1+z)^{1/2} - 1\right](1+z)^{1/2}\ (\mathrm{cm}). \tag{7}$$

Therefore, for cusps at large redshifts ($z \gg 1$), the energy flux reaching the observer is

$$F_{obs} \approx \frac{\Delta E_{inert}}{\Delta t_{obs}} \frac{\gamma_{max}^2}{4\pi d_L^2} \approx \eta\mu c^3 \gamma_{max}^4 \frac{H_0^2}{16\pi c^2 z^2}$$
$$\approx 10^6 h_{100}^2 z_3^{-2} \eta \gamma_4^4 \varepsilon_{-6}\ (\mathrm{ergs\ cm^{-2}\ s^{-1}}), \tag{8}$$

where $z_3 = z/10^3$ and $\gamma_4 = \gamma_{max}/10^4$.

The duration of the event is just the time interval over which the observer is in the beam. Allowing for the redshift of the cusp, the duration is

$$\Delta t_{obs} \approx \frac{L}{c} \frac{1+z}{\gamma_{max}^3} \approx 10 h_{100}^{-1} z_3^{-1/2} \beta_2 \varepsilon_{-6} \gamma_4^{-3} \frac{R}{R_*}\ (\mathrm{s}). \tag{9}$$

The maximum energy that could possibly reach an observer swept by the beam from a single cusp is

$$\Delta E_{obs} \approx F_{obs}\, \Delta t_{obs} \approx 10^7 h_{100} z_3^{-5/2} \eta \beta_2 \varepsilon_{-6}^2 \gamma_4 \frac{R}{R_*}\ (\mathrm{ergs\ cm^{-2}}). \tag{10}$$

According to equation (5), the number of cusps is the same for every logarithmic interval of loop sizes. Therefore, very small loops with $R \ll R_*$ produce the largest number of events; however, according to equation (9), the duration of these events is very short; furthermore, the above equation reveals that the energy generated by very small loops is less than that discharged by cusp events associated with larger loops.

We are interested in events which deposit, at the observer, energy greater than some minimum energy, E. According to equation (10), a cusp generating $\Delta E_{obs} > E$ has a redshift $z_3 < z_{3,\,max}$, where

$$z_{3,\,max} \approx h_{100}^{2/5} \beta_2^{2/5} \varepsilon_{-6}^{4/5} \gamma_4^{2/5} (R/R_*)^{2/5} \left(\frac{\eta 10^7\ \mathrm{ergs\ cm^{-2}}}{E} \right)^{2/5}. \tag{11}$$

Combining equations (2), (3), (5), and (11), we obtain the rate at which cusps with $\Delta E_{\rm obs} > E$ are formed:

$$\frac{dN_c}{dt_{\rm obs}\, d(R/R_*)} \approx h_{100}^{1.2}\beta_2^{-0.8}\varepsilon_{-6}^{0.9}\gamma_4^{1.7}(R/R_*)^{0.7} \times \left(\frac{\eta 10^7\ {\rm ergs\ cm^{-2}}}{E}\right)^{1.7} ({\rm s}^{-1}). \quad (12)$$

The above equation may be integrated over all loop sizes, from $R/R_* = 0$ to $R/R_* = 1$ to obtain

$$\frac{dN_c}{dt_{\rm obs}} \approx 0.6 h_{100}^{1.2}\beta_2^{-0.8}\varepsilon_{-6}^{0.9}\gamma_4^{1.7}\left(\frac{\eta 10^7\ {\rm ergs\ cm^{-2}}}{E}\right)^{1.7} ({\rm s}^{-1}). \quad (13)$$

As the radiation from the cusps is emitted in a very tight beam, only cusps whose beam sweeps past the observer are seen and, therefore a very small fraction of all cusps $\pi\gamma_{\rm max}^{-2}/4\pi = 2.5 \times 10^{-9}\gamma_4^{-2}$, gives rise to an observable event. Combining this with equation (13) we estimate the frequency of bursts of energy reaching Earth as

$$N_b \approx 10^2 h_{100}^{1.2}\beta_2^{-0.8}\varepsilon_{-6}^{0.9}\gamma_4^{-0.3}\left(\frac{\eta 10^5\ {\rm ergs\ cm^{-2}}}{E}\right)^{1.7} ({\rm yr}^{-1}). \quad (14)$$

It is interesting that the slope of the apparent luminosity function is -1.7, so close to -1.5, the slope expected if the sources are uniformly distributed in flat space. Note that equation (14) was derived assuming that universe is transparent to the beam.

V. DISCUSSION

According to equation (14), we should see about 100 bursts of energy per year with $\Delta E_{\rm obs} > \eta 10^5$ ergs cm^{-2} if the string parameters are $\varepsilon_{-6} = 1$, and $\gamma_4 = 1$, i.e., $\varepsilon = G\mu/c^2 = 10^{-6}$ and the maximum Lorentz factor $\gamma_{\rm max} = 10^4$. Of course many other combinations of parameters could give the same answer. Unfortunately, the grand unified theories which predict the existence of cosmic strings do not provide bounds on the value of ε but rather predict that strings might exist for a wide range of values for ε. Furthermore, at this time, maximum value of the Lorentz factor attainable by a truncated cusp of a superconducting string is not known. Without stronger constraints on the "free" parameters, we cannot predict the expected frequency of bursts, but we note that on the basis of this analysis, an interesting frequency of burst events may be obtained using parameters not very different from those fashionably used for other purposes (cf. Ostriker, Thompson, and Witten 1986 and references therein; Vilenkin and Field 1986).

The efficiency of energy released from a cusp is one of the many unknown parameters in equation (14). However, we have attempted to estimate its order of magnitude. The time-averaged rate of emission if gravitational radiation has been estimated as $\dot{E}_{\rm grav} \approx 100\ G\mu^2 c = \eta_{\rm grav}\mu c^3$ (cf. Vilenkin 1985, eq. [14.8]). Hence, $\eta_{\rm grav} = 100\ G\mu/c^2 = 10^{-4}\varepsilon_{-6}$. The energy radiation rate from the cusps is known to be much larger than the average. Of course, bursts of gravitational radiation are not easy to observe. Estimates by Ostriker, Thompson, and Witten (1986), by Vilenkin and Vachaspati (1986), and by Spergel, Piran, and Goodman (1986) suggest that the cusps associated with current-bearing cosmic strings will radiate electromagnetic energy with an efficiency much higher than that for emission of gravitational radiation. Since precise calculations are not available, we take the conservative approach and restrict the total efficiency of energy released at the cusp in all forms to be $10^{-4} < \eta < 1$.

In order to estimate the efficiency for energy discharged as gamma rays, we consider $S = (\eta_\gamma/\eta)\,\Delta E_{\rm obs}$, where the fluence of gamma ray bursts, S, is the time-integrated flux of energy in gamma rays as measured by a detector, and (η_γ/η) is the fraction of total discharged energy that is emitted as gamma rays. Present gamma-ray instruments have a detection limit of approximately $S_{\rm min} \approx 10^{-6}$ ergs cm^{-2}. Therefore, only bursts with $\Delta E_{\rm obs} > \eta_\gamma^{-1}\eta 10^{-6}$ ergs cm^{-2} would be observed as gamma ray bursts. Assuming that the string has the usual parameters, we require, according to equation (14), $\Delta E_{\rm obs} > E \approx \eta 10^5$ ergs cm^{-2} to obtain about 100 gamma-ray bursts per year, an interesting frequency. Comparing this condition with the one for detection, we find that the efficiency factor for radiation emitted as gamma rays need only be $\eta_\gamma \approx 10^{-11}$.

Since these sources are at large redshifts, they are likely to be gravitationally lensed. Microlensing due to a cluster of massive objects can produce numerous recurrent images (Paczyński 1987). Whenever the bending angle due to lensing is comparable to the width of the beam from the source, the spectra and the time profiles of the bursts may vary from image to image. Since the beam from the cusps is very tight, the above situation is quite probable, and therefore we expect recurrent but dissimilar burst images.

Aside from the gamma-ray bursts, the energy discharged from the cusps is likely to be in a variety of forms. Hill, Schramm, and Walker (1986) have explored the possibility of emission of high energy neutrinos and neutrons from the cosmic strings. We expect that discharges of such particles from the cusp region will also be confined to a narrow beam. Such a beam, upon reaching Earth's atmosphere, may give rise to high-energy cosmic-ray secondary events, coincident with the gamma-ray flashes. As detectors of cosmic-ray showers are also omnidirectional, it would perhaps be useful to review the archival cosmic-ray records in order to search for correlations with observed gamma-ray bursts.

Finally, we note that usually there are three objections to the hypothesis that gamma-ray bursters are at cosmological distances: No object can release enough energy in short enough time interval, pair formation at the source would cut off the spectra above the pair formation threshold, and Ruderman (1975) limit cannot be satisfied. We have shown in this *Letter* that it is quite possible for cusps on superconducting cosmic strings to release more than sufficient amount of energy even at a redshift of $z \approx 1000$. Goodman (1986) and Paczyński (1986) have shown that hard spectra can be obtained without any difficulty if there is high enough energy density at the source. Ruderman limit follows from the condition that the speed of propagation of a disturbance in the source cannot be faster than the speed of light. However, this condition is strictly applicable only to thermal sources as it assumes that we may use the spectral temperature to infer source's surface brightness. The known radio pulsars violate this limit by many orders of magnitude because their emission is due to coherent processes. There is no particular reason to believe that gamma-ray bursters ought be thermal. Furthermore, if gamma-ray bursts are events related to the cusps of oscillating loops of cosmic strings, then the observed variation in the intensity may be due to the sweeping of the beam, and under such conditions the Ruderman limit may be violated even by a thermal source.

It is our pleasure to acknowledge many stimulating discussions with J. Goodman, J. P. Ostriker, T. Piran, C. Thompson, E. Witten, and A. Zdziarski. We also acknowledge the anonymous referee for comments which led us to clarify certain sections of this letter. B. P. is supported by NSF grant AST85-19552 and by NASA grant NAGW-765. A. B. is supported by a NSERC postgraduate scholarship and D. N. S. is supported by NSF grant PHY82-17352.

REFERENCES

Arons, J., and McCray, R. 1969, *Ap. J. (Letters)*, **158**, L91.
Brandenberger, R. H., and Turok, N. 1986, *Phys. Rev.*, **D33**, 2182.
Goodman, J. 1986, *Ap. J. (Letters)*, **308**, L47.
Hill, C. T. Schramm, D. N., and Walker, T. P. 1986, preprint.
Kibble, T. W. B. 1980, *Phys. Rep.*, **67**, 183.
Kibble, T. W. B., and Turok, N. 1982, *Phys. Letters*, **116B**, 141.
Klebesadel, R. W., Strong, I. B., and Olson, R. A. 1973, *Ap. J. (Letters)*, **182**, L85.
Laros, J. G., *et al.* 1986, *Nature*, **322**, 152.
Liang, E. P., and Petrosian, V., eds. 1986, *Gamma-Ray Bursts, AIP Conference Proceedings 141* (New York: AIP).
Ostriker, J. P., Thompson, C., and Witten, E. 1986, *Phys. Letters*, **180**, 231.
Paczyński, B. 1986, *Ap. J. (Letters)*, **308**, L43.
———. 1987, *Ap. J. (Letters)*, submitted.
Ruderman, M. 1975, *Ann. NY Acad. Sci.*, **262**, 164.
Rybicki, G. B., and Lightman, A. P. 1979, *Radiative Processes in Astrophysics* (New York: Wiley).
Spergel, D. N., Piran, T., and Goodman, J. 1986, preprint.
Stecker, F. W. 1971, *Cosmic Gamma Rays* (Washington: NASA, Scientific and Technical Information Office).
Stepney, S., and Guilbert, P. W. 1983, *M.N.R.A.S.*, **204**, 1269.
Turok, N. 1984, *Nucl. Phys.*, **B242**, 520.
———. 1986, in *Nearly Normal Galaxies: From Planck Time to the Present*, Santa Cruz Workshop, ed. S. Faber, in press.
Vilenkin, A. 1981, *Phys. Rev. Letters*, **46**, 1169.
———. 1985, *Phys. Rept.*, **121**, 263.
Vilenkin, A., and Field, G. 1986, preprint.
Vilenkin, A., and Vachaspati, T. 1986, preprint.
Witten, E. 1985, *Nucl. Phys.*, **B249**, 557.
Zel'dovich, Y. B. 1980, *M.N.R.A.S.*, **192**, 663.

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