THE ASTROPHYSICAL JOURNAL, 512:L13–L16, 1999 February 10
© 1999. The American Astronomical Society. All rights reserved. Printed in U.S.A.

GRAVITATIONALLY LENSED GAMMA-RAY BURSTS AS PROBES OF DARK COMPACT OBJECTS

G. F. MARANI,[1,2] R. J. NEMIROFF,[3] J. P. NORRIS,[2] K. HURLEY,[4] AND J. T. BONNELL[2,5]

Received 1998 October 27; accepted 1998 December 11; published 1999 February 4

ABSTRACT

If dark matter in the form of compact objects comprises a large fraction of the mass of the universe, then gravitational lensing effects on gamma-ray bursts are expected. We utilize BATSE and *Ulysses* data to search for lenses of different mass ranges, which cause lensing in the milli, pico, and femto regimes. Null results are used to set weak limits on the cosmological abundance of compact objects in mass ranges from 10^{-16} to 10^{-9} $M_\odot$. A stronger limit is found for a much-discussed $\Omega = 0.15$ universe dominated by black holes of mass $\sim 10^{6.5}$ $M_\odot$, which is ruled out at the ~90% confidence level.

Subject headings: dark matter — gamma rays: bursts — gravitational lensing

1. INTRODUCTION

The possibility that a cosmological abundance of dark compact objects (COs) in the universe could be revealed by gravitational lensing of more distant sources was first suggested by Press & Gunn (1973). The detection of lensed images from any source provides an estimation of the fraction of the universe composed of COs and therefore the CO density. Nondetections offer a viable way to set constraints on the possible values of the CO mass $M_{\rm CO}$ and density $\Omega_{\rm CO}$. Depending on the angular separation of the lensed images, the gravitational lensing effect is classified into *milli-*, *micro-*, *pico-*, or *femtolensing*.

There is now overwhelming evidence that the majority of gamma-ray burst (GRB) sources lie at cosmological distances (Metzger et al. 1997; Kulkarni et al. 1998; Djorgovski et al. 1998). Their short duration and the transparency of the universe in gamma rays make GRBs ideal probes of dark matter in the form of COs over the mass range 10^{-16} to 10^{12} $M_\odot$. The probability of lensing a GRB depends on CO density (e.g., Nemiroff 1989; Mao 1993), but it is estimated to be less than 0.1% (Blaes & Webster 1992).

Multiple images of the same burst cannot be angularly resolved by present gamma-ray detectors, but they are easily temporally resolved (Paczyński 1987). Thus, rather than spatially identifying multiple images of lensed quasars, the lensed GRBs must be found by searching such events with identical temporal and spectral signatures. Marani et al. (1998) have compared the light curves of 1235 BATSE bursts, searching for gravitationally lensed GRBs caused by foreground galaxies, with negative results. The expected time delay between two detectable images can be written as (e.g., Krauss & Small 1991)

$$\Delta t = \frac{R_s(1+z_L)}{c}\left(\frac{f-1}{\sqrt{f}} - \ln f\right), \qquad (1)$$

where f is the brightness ratio of the two images also known as the dynamic range, z_L is the lens redshift, $R_s \sim 3$ km ($M_{\rm CO}/M_\odot$) is the Schwarzchild radius, and c is the speed of light. Mao (1993) found that for a point-mass lens, the median value of the time delay is $\Delta t \sim 50$ s $\times$ ($M_{\rm CO}/10^6$ $M_\odot$).

In this Letter, we present results of searches for different types of gravitational lensing of GRBs, looking for any indication of the presence of dark matter in the form of compact objects. In all of the cases, a monoluminous and nonevolving GRB source population is assumed. In § 2, we describe the lensing types, search algorithms performed using BATSE data (Meegan et al. 1996), and present results. We summarize and discuss these results in § 3.

2. SEARCHING FOR DARK COMPACT OBJECTS

2.1. *Millilensing*

In the case of millilensing, the COs have masses between 10^6 and 10^9 $M_\odot$. The time delay between the images may vary from a few seconds to $\sim 10^4$ s, and their average angular separation is $\sim 10^{-3}$ arcseconds. Note that $M_{\rm CO} = 10^{6.5}$ $M_\odot$ is the Jean mass at recombination in many early-universe scenarios and, consequently, a probable mass scale for dark matter. Gnedin & Ostriker (1992) proposed an open universe model with $\Omega_M = \Omega_{\rm CO} = 0.15$, filled with black holes of mass $\sim 10^{6.5}$ $M_\odot$, which would dominate the dark matter galactic halos.

Nemiroff et al. (1993) searched the first 44 BATSE bursts for lensed images that came shortly after the main event by autocorrelating each burst, and no lens candidates were found. This null result was interpreted by using the detection volume formalism of Nemiroff (1989) and by modeling the brightness distribution to estimate GRB redshifts (Wickramasinghe et al. 1993). A standard (1, 0) universe composed to closure density with objects of mass $10^{6.5}$–$10^{8.1}$ $M_\odot$ was marginally ruled out (Nemiroff et al. 1993).

The data from Table I of Nemiroff et al. (1993) and their null results were used to set constraints on the CO mass and density for the Gnedin & Ostriker universe. Mao (1993) estimated that the lensing probability for this universe is ~5%. Following Nemiroff et al. (1993), for each burst we compute a detection volume between the observer and a burst at z_S, within which the lens with $M_{\rm CO}$ must fall to create a detectable image. Then, all 44 volumes are added and the expected number of detectable lenses in our sample is obtained. For a given ($\Omega_{\rm CO}$, $M_{\rm CO}$) pair, if the expected number is significantly greater than the null result obtained, we rule out such CO parameters. For a more detailed explanation of the method, see Nemiroff et al. (1993) and Marani (1998).

Figure 1 summarizes the results we obtain for the Gnedin

[1] Center for Earth Observing and Space Research, George Mason University, Fairfax, VA 22030; gmarani@science.gmu.edu.
[2] NASA/Goddard Space Flight Center, Greenbelt, MD 20771.
[3] Department of Physics, Michigan Technological University, Houghton, MI 49931.
[4] University of California at Berkeley, Space Sciences Laboratory, Berkeley, CA 94720-7450.
[5] Universities Space Research Association.

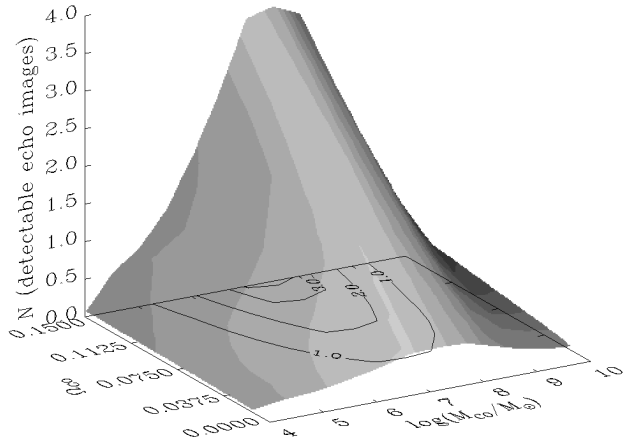


FIG. 1.—Expected number of detectable lensing images for the given (Ω_{CO}, M_{CO}) values in the (Ω_M, Ω_Λ) = (0.15, 0) universe proposed by Gnedin & Ostriker (1992). The first available 44 BATSE bursts are incorporated in this plot.

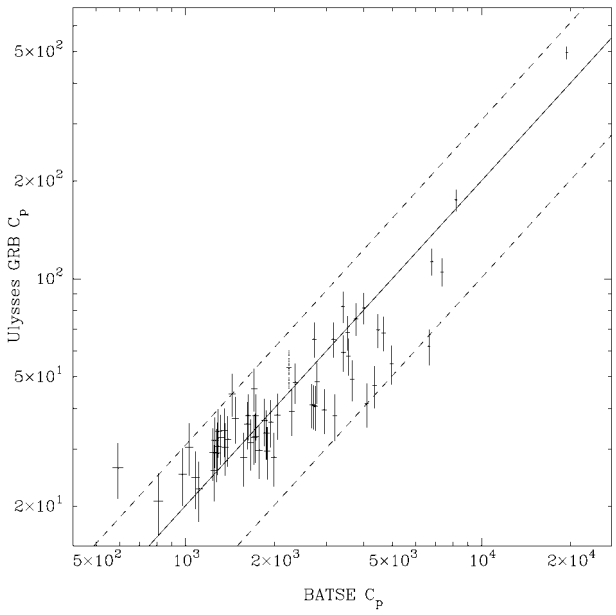


FIG. 2.—*Ulysses* GRB peak counts versus BATSE peak counts for 60 bursts that were triggered events in both detectors. The solid line represents the median value for the 64 ms peak count ratio, whereas the dashed lines enclose the 2 σ confidence level region centered in the median value.

& Ostriker universe. The figure shows the number of images expected for the 44 GRBs and for different (Ω_{CO}, M_{CO}) parameters. The expected number of images for the Gnedin & Ostriker universe is ~2.5–3, in good agreement with Mao's (1993) estimations: 2.2 lenses from 44 bursts were expected. Since no images were found, the universe with

$$M_{CO} \sim 10^{6.5} M_\odot, \quad \Omega_M = \Omega_{CO} = 0.15 \tag{2}$$

can be excluded at a confidence level of ~90.0%.

2.2. *Picolensing*

Picolensing refers to a lensing mass range of $\sim 10^{-12}$ to 10^{-7} $M_\odot$. The expected angular separation is $\sim 10^{-12}$ arcseconds, and the average time delay is $\sim 10^{-18}$ s. The main lens candidates are primordial black holes, molecular clouds, and small planets. Currently, few arguments favor the hypothesis that extremely low mass objects compose a significant fraction of the dark matter. Nevertheless, if such objects were to exist, GRB lensing is an efficient method for their detection (Nemiroff & Gould 1995).

For these low-mass COs, the corresponding radius of the Einstein ring projected onto our solar system $\tilde{R}_E$ will be at most 1 AU: $\tilde{R}_E = [(2R_s D_{OL} D_{OS})/D_{LS}]^{1/2}$. Two spacecraft separated by 1 AU or more might see the same GRB event with very different amplification since, if the GRB were to lie within the $\tilde{R}_E$ of the lens for one spacecraft, it would lie outside $\tilde{R}_E$ for the other spacecraft. The ith spacecraft observes the GRB with total amplification $A_i = (\beta^2 + 2)/[\beta(\beta^2 + 4)^{1/2}]$, where $\beta = \beta/\beta_E$, with β the angular separation between source and lens, and β_E the angular radius of the Einstein ring. There are currently two GRB detectors on orbit separated by a distance of at least 1 AU: BATSE and *Ulysses* GRB (Hurley et al. 1992). If BATSE detects a strong burst while *Ulysses* determines it is a weak burst, the difference in the amplitude may be attributable to a gravitational lensing event due to masses in the range $\sim 10^{-12}$ to 10^{-7} $M_\odot$.

We have compared the peak counts of 60 bright bursts which were triggered events in BATSE and *Ulysses* data (Marani et al. 1998; Marani 1998). The energy range of the *Ulysses* GRB detector is ~20–150 keV. The *Ulysses* triggered data have temporal resolutions of 8 and 32 ms, but they were rebinned into 64 ms count bins. For BATSE data, we have used 64 ms concatenated ASCII data summed over energy channels 1 and 2, corresponding to the energy range ~20–100 keV.

Once the data were background-subtracted and rebinned, the peak counts and the BATSE-to-*Ulysses* amplitude ratios $dA = C_{p,\,\mathrm{BATSE}}/C_{p,\,Ulysses}$ were calculated. No evident discrepancy in the amplitude ratios has been found. Figure 2 shows BATSE peak counts versus *Ulysses* peak counts. The error bars are obtained assuming Poisson counts. The median value for the ratio, after normalization, is $dA = 1$, and the 2 σ upper and lower confidence levels are 2 and 0.68, respectively. A real difference in amplitude should be observable in all three timescales. We also compared peak counts for 256 and 1024 ms time resolutions, although no significant excess was found.

These null results are used to impose limits on the density and mass of COs, again using the detection volume formalism (Nemiroff 1989). In the case of two observers, where a positive detection requires an amplitude difference between them, the volume within which a pointlike lens must fall to create a discernible magnification is much more complicated than in the millilensing case, and no analytical expression is available. To find the expected number of lenses, we implemented a Monte Carlo simulation (Marani 1998): For each burst in the sample, we randomly draw several lens positions on the lens plane, fixed at z_L. We then compute the amplifications each observer would see if the lens is located in that particular position, take the ratio of those amplifications, and check if that ratio is above or below the 2 σ confidence level. Finally, we place the lens plane at another z_L and recompute the steps described above. When the lens plane reaches the source plane at z_S, we obtain the detection volume V_{det} and the expected number of detectable lenses for that particular burst, given by $N_{det} = n_{CO} V_{det}$. Here, $n_{CO} = 3H_0^2(1 + z_L)^3 \Omega_{CO}/(4\pi R_s c^2)$ is the CO comoving number density. We then add all volumes of all bursts and repeat the calculations for different CO masses and densities.

Figure 3 shows the results that we obtained with this sim-

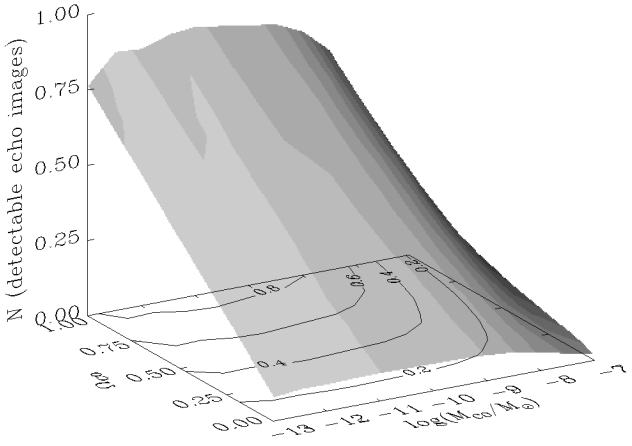


FIG. 3.—Expected number of detectable picolensing images for the given (Ω_{CO}, M_{CO}) values, incorporating 60 bursts that simultaneously triggered *Ulysses* GRB and BATSE.

ulation, assuming an Einstein–de Sitter universe. Less than ~0.9 detectable images are expected in our sample. Thus, the mass and density ranges of

$$M_{CO} \sim 10^{-12.5} \text{ to } 10^{-9.0}\ M_\odot, \quad \Omega_{CO} \geq 0.9 \tag{3}$$

may be ruled out only at ~1 σ statistical significance.

2.3. *Femtolensing*

The femtolensing mass range is $M_{CO} \sim 10^{-16}$ to $10^{-13}\ M_\odot$. The expected image separation is $\sim 10^{-15}$ arcseconds, and the average time delay between the images is $\sim 10^{-24}$ s. Snowballs, primordial black holes, and comets are some examples of these COs.

These extremely low-mass lenses would produce interference fringes in the GRB energy spectrum. These features are evenly separated in energy space and might be confused with cyclotron absorption lines (Gould 1992). Spectral lines between 10 and 100 keV were seen in missions like *Konus* (Mazets et al. 1982), *HEAO 1* (Hueter 1987), and *Ginga* (Fenimore et al. 1988; Murakami et al. 1988) and indeed have been attributed to cyclotron lines due to magnetic fields $B \sim 10^{12}$ G. However, these interpretations are still controversial. Briggs et al. (1996) pointed out that many spectral line analyses performed in these GRB data sets used simplistic continuum models and incomplete statistical techniques.

Several authors have analyzed BATSE spectra for spectral line features like the absorption lines detected by *Ginga* at ~20 and ~40 keV (see, for example, Band et al. 1996, 1997; Briggs et al. 1996). Briggs et al. (1998) have recently performed a computerized search of 118 bright BATSE bursts. They have found only four candidates with one possible absorption line, but none of them with evenly spaced, multiple lines. Note that Stanek et al. (1993) and Ulmer & Goodman (1995) have argued that the detectability of the femtolensing signature depends on the source size. The more extended the source, the less pronounced the spectral lines. Lines at higher energies are progressively weaker for finite angular extent, since the source appears larger at higher energies. However, the short duration of GRBs (the vast majority lasting from milliseconds to a few tens of seconds) and their cosmological distances suggest that GRBs can be considered compact sources.

Assuming that GRB sources subtend sufficiently small angular sizes to produce multiple, detectable lines in the spectra, the nondetections of spectral lines in 118 BATSE bursts by Briggs et al. (1998) can be used to impose lower limits on the mass and density of COs. Nemiroff (1989) estimated that the probability of lensing is $\sim\Omega_{CO}/8$ if the average distance to the GRBs is $z_{GRB} \sim 1$, or $\sim\Omega_{CO}/3$ if $z_{GRB} \sim 2$. Therefore, we can rule out, at 95% confidence levels, universes composed of COs with $M_{CO} \sim 10^{-16}$ to $10^{-13}\ M_\odot$ and

$$\Omega_{CO} \geq 0.2, \text{ if } z_{GRB} \sim 1; \text{ or } \Omega_{CO} \geq 0.1, \text{ if } z_{GRB} \sim 2. \tag{4}$$

The above estimations assume an Einstein–de Sitter cosmology and point-mass lenses.

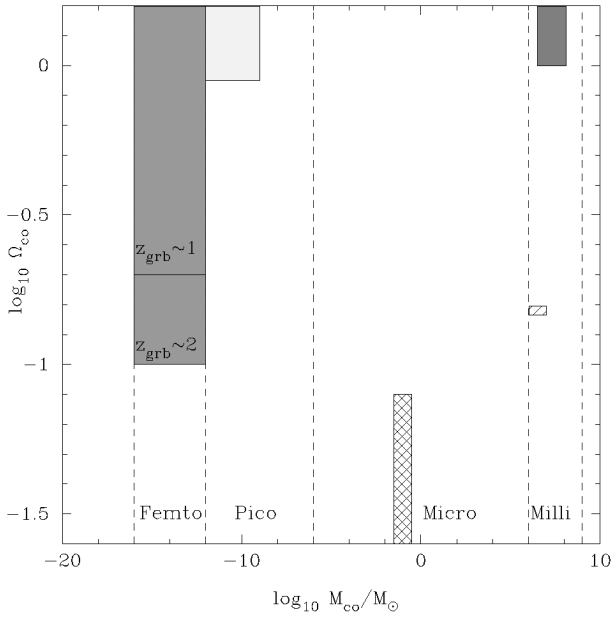


FIG. 4.—Constraints on the density and mass of individual compact objects, derived from the null results of gravitational lensing searches in BATSE data.

3. SUMMARY AND DISCUSSION

The nondetections of lensing images in the current GRB data have been used, for the first time, to set conservative limits on the composition of dark compact objects with masses between 10^{-16} and $10^{-7}\ M_\odot$. Different searches in radio, optical, and gamma-ray data have been conducted in the past to search for gravitationally lens-induced images caused by masses between 10^{-6} and $10^{12}\ M_\odot$ (Carr 1994), but no search previous to the present one was carried out for the pico- and femtolensing cases. The derived constraints on the density and mass parameters in different mass ranges are shown in Figure 4. The shaded areas show the excluded values of Ω_{CO} and M_{CO}. Light gray shadings represent very weak limits, whereas dark gray shadings are the imposed limits at ~2 σ confidence level. Three additional regions are shown in Figure 4. The crosshatched area corresponds roughly to the range of values required to explain the MACHO and EROS microlensing results (Carr 1994). In the millilensing region, a universe proposed by Carr & Rees (1984) with $(\Omega_M, \Omega_\Lambda) = (1, 0)$ and $\Omega_{CO} \sim 0.15$, $M_{CO} \sim 10^6\ M_\odot$ is shown as a hatched, very small area. The constraints previously found by Nemiroff et al. (1993) are also illustrated. Using gravitational lensing data from the millilensing search done by these authors and the detection volume formalism (Nemiroff 1989), we were able to reject a popular

universe proposed by Gnedin & Ostriker (1992) with $M_{CO} \sim 10^{6.5}\ M_{\odot}$ and $\Omega_M = \Omega_{CO} = 0.15$, at a confidence level of ~90%.

No search for microlensing events ($\Delta t \sim 5$–10 ms) in BATSE archival data was conducted in the present work. However, Nemiroff et al. (1998) have argued that such short events might not be detected by BATSE due to its threshold setting for 64 ms timescale.

The millilensing and picolensing limits are strong functions of the GRB redshift distribution, which is derived by modeling the observed brightness distribution. This model assumes no rate density evolution, standard candle, and a simple power-law spectrum, $dN/dE \propto E^{-1}$. Several authors have recently suggested that the GRB rate density is proportional to the star formation rate in the universe (Totani 1997; Wijers et al. 1998) and that the intrinsic peak luminosities are described by a power-law distribution (Kommers et al. 1999; Krumholz, Thorsett, & Harrison 1998; Mao & Mo 1999). In both cases, larger redshifts are expected. Therefore, the probability of lensing by COs would increase and the limits imposed on Ω_{CO} and M_{CO} would be stronger.

This research was supported by grants from NASA. *Ulysses* data reduction is supported by JPL contract 958056 and by NASA grant NAG5-1560. G. F. M. acknowledges support from a National Research Council Research Associateship while at NASA GSFC. R. J. N. acknowledges additional support from the NSF.

REFERENCES

Band, D. L., et al. 1996, ApJ, 458, 746
———. 1997, ApJ, 485, 747
Blaes, O. M., & Webster, R. L. 1992, ApJ, 391, L63
Briggs, M. S., et al. 1996, in AIP Conf. Proc. 384, Gamma-Ray Bursts, 3rd Huntsville Symposium, ed. C. Kouveliotou, M. F. Briggs, & G. J. Fishman (New York: AIP), 153
———. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts, 4th Huntsville Symposium, ed. C. Meegan, R. Preece, & M. Koshut (New York: AIP), 299
Carr, B. J. 1994, ARA&A, 32, 531
Carr, B. J., & Rees, M. J. 1984, MNRAS, 206, 315
Djorgovski, S. G., et al. 1998, GCN Circ. 139 (http://gcn.gsfc.nasa.gov/gcn/gcn3/139.gcn3)
Fenimore, E. E., et al. 1988, ApJ, 335, 71
Gnedin, N. Y., & Ostriker, J. P. 1992, ApJ, 400, 1
Gould, A. 1992, ApJ, 386, L5
Hueter, G. J. 1987, Ph.D. thesis, Univ. California, San Diego
Hurley, K., et al. 1992, A&AS, 92, 401
Kommers, J., et al. 1999, ApJ, submitted
Krauss, L. M., & Small, T. A. 1991, ApJ, 378, 22
Krumholz, M., Thorsett, S. E., & Harrison, F. A. 1998, ApJ, 506, 81
Kulkarni, S. R. et al. 1998, GCN Circ. 027 (http://gcn.gsfc.nasa.gov/gcn/gcn3/027.gcn3)
Mao, S. 1993, ApJ, 402, 382
Mao, S., & Mo, H. J. 1999, A&A, submitted
Marani, G. F. 1998, Ph.D. thesis, George Mason Univ.
Marani, G. F., et al. 1998, in AIP Conf. Proc. 428, Gamma-Ray Bursts, 4th Huntsville Symposium, ed. C. Meegan, R. Preece, & M. Koshut (New York: AIP), 166
Mazets, E. P., et al. 1982, Ap&SS, 84, 173
Meegan, C. A., et al. 1996, ApJS, 106, 65
Metzger, M. R., et al. 1997, Nature, 387, 879
Murakami, T., et al. 1988, Nature, 335, 234
Nemiroff, J. P., et al. 1998, ApJ, 494, 173
Nemiroff, R. J. 1989, ApJ, 341, 579
Nemiroff, R. J., & Gould, A. P. 1995, ApJ, 452, 111
Nemiroff, R. J., et al. 1993, ApJ, 414, 36
Paczyński, B. 1987, ApJ, 317, L51
Press, W. H., & Gunn, J. E. 1973, ApJ, 185, 397
Stanek, K. Z., et al. 1993, ApJ, 413, 7
Totani, T. 1997, ApJ, 486, 71
Ulmer, A., & Goodman, J. 1995, ApJ, 442, 67
Wickramasinghe, W. A. D. T., et al. 1993, ApJ, 411, 55
Wijers, R. A. M. J., et al. 1998, MNRAS, 294, L13