



Resolving Gamma-Ray Burst 000301C with a Gravitational Microlens

Citation

Garnavich, Peter M., Abraham Loeb, and K. Z. Stanek. 2000. "Resolving Gamma-Ray Burst 000301C with a Gravitational Microlens." *The Astrophysical Journal* 544 (1): L11–15. <https://doi.org/10.1086/317297>

Published version

<https://doi.org/10.1086/317297>

Link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:41393270>

Terms of use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material (LAA), as set forth at

<https://harvardwiki.atlassian.net/wiki/external/NGY5NDE4ZjgzNTc5NDQzMGIzZWZhMGFIOWI2M2EwYTg>

Accessibility

<https://accessibility.huit.harvard.edu/digital-accessibility-policy>

Share Your Story

The Harvard community has made this article openly available.
Please share how this access benefits you. [Submit a story](#)

RESOLVING GAMMA-RAY BURST 000301C WITH A GRAVITATIONAL MICROLENS

PETER M. GARNAVICH

Department of Physics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556; pgarnavi@nd.edu

AND

ABRAHAM LOEB AND K. Z. STANEK¹

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; aloeb@cfa.harvard.edu, kstane@cfa.harvard.edu

Received 2000 August 4; accepted 2000 September 15; published 2000 November 3

ABSTRACT

The afterglow of the gamma-ray burst (GRB) 000301C exhibited achromatic, short-timescale variability that is difficult to reconcile with the standard relativistic shock model. We interpret the observed light curves as a microlensing event superposed on power-law flux decays typical of afterglows. In general, a relativistic GRB shock appears on the sky as a thin ring expanding at a superluminal speed. Initially the ring is small relative to its angular separation from the lens, and so its flux is magnified by a constant factor. As the ring grows and sweeps across the lens, its magnification reaches a maximum. Subsequently, the flux gradually recovers its unlensed value. This behavior involves only three free parameters in its simplest formulation and was predicted theoretically by A. Loeb & R. Perna. Fitting the available *R*-band photometric data of GRB 000301C to a simple model of the microlensing event and a broken power law for the afterglow, we find reasonable values for all the parameters and a reduced χ^2 /degrees of freedom parameter of 1.48 compared with 2.99 for the broken power-law fit alone. The peak magnification of ~ 2 occurred 3.8 days after the burst. The entire optical to IR data imply a width of the GRB ring of order 10% of its radius, similar to theoretical expectations. The angular resolution provided by microlensing is better than a microarcsecond. We infer a mass of approximately $0.5 M_{\odot}$ for a lens located halfway to the source at $z_s = 2.04$. A galaxy $2''$ from GRB 000301C might be the host of the stellar lens, but current data provides only an upper limit on its surface brightness at the GRB position.

Subject headings: gamma rays: bursts — gravitational lensing

1. INTRODUCTION

The rapid localization of gamma-ray bursts (GRBs) has brought a new dimension to GRB research by allowing many events to be followed up at longer wavelengths. Afterglows of bursts have been detected at X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997), and radio (Frail et al. 1997) wavelengths. Precise positions have allowed redshifts to be measured for a number of GRBs (Metzger et al. 1997), providing a definitive proof of their cosmological origin.

The afterglow of a GRB is thought to be synchrotron radiation from a relativistic shock driven into the circumburst environment (Mészáros & Rees 1993, 1997; Paczyński & Rhoads 1994; Katz 1994; Waxman 1997a). The light curves and spectral energy distributions are well fit by power laws, as expected from the shock model. There is recent evidence that at least some GRBs are not spherical explosions. A broadband break in the light-curve power-law index was predicted for shocks produced by collimated jets (Rhoads 1997), and such breaks have been seen in GRB 990510 (Stanek et al. 1999; Harrison et al. 1999), GRB 991216 (Halpern et al. 2000a), and GRB 000301C (Sagar et al. 2000; Masetti et al. 2000; Jensen et al. 2000; Berger et al. 2000). The ratio of the spectral index to the light-curve index also suggests nonspherical energy ejection for some events (e.g., GRB 991216: Garnavich et al. 2000b). In general, the synchrotron afterglow model has been very successful in matching most of the observations. However, it is heavily strained explaining the well-studied afterglow of GRB 000301C, which shows a peculiar achromatic fluctuation that deviates significantly from the broken power-law fit to the light curve (Sagar et al. 2000; Berger et al. 2000).

Here we propose an elegant solution to the GRB 000301C

problem: the GRB was microlensed. Previously, Loeb & Perna (1998) predicted that microlensing by a solar mass lens at a cosmological distance would produce a nearly achromatic fluctuation of similar amplitude and duration to that observed. In § 2 we describe the optical and near-IR observations available for our analysis. In § 3 we describe the simplest parameterization of a GRB microlensing event and discuss our technique in fitting the data. In § 4 we analyze the results and estimate the probability that a microlensing event can occur given the observational constraints. Finally, we summarize our conclusions in § 5.

2. THE BURST

GRB 000301C was detected by the *Rossi X-Ray Timing Explorer* All-Sky Monitor, *Ulysses*, and *NEAR* on 2000 March 1.41085 (UT) and localized to a region of about 50 arcmin² on the sky (Smith, Hurley, & Cline 2000). An optical transient was detected about 1.5 days after the burst (Fynbo et al. 2000), and its presence was confirmed in the near-IR (Stecklum et al. 2000) and at radio wavelengths (Bertoldi 2000). The initial optical decline was steep with a power-law index of $\alpha = 1.6 \pm 0.3$ (Halpern, Mirabal, & Lawrence 2000b), but by 3 days after the burst the decay rate slowed down (Garnavich et al. 2000a), a very unusual occurrence in an optical afterglow. This “standstill” did not last long, and 2 weeks after the burst the power-law index was $\alpha = 2.7$ (Veillet 2000b). Rhoads & Fruchter (2000) found that their near-IR data behaved differently than the optical, although the time sampling was more sparse in the IR.

Spectra of the afterglow show a strong Lyman cutoff in the UV (Smette et al. 2000), and absorption features of Ly α and metal lines were consistent with a large absorbing column at $z = 2.04$ (Jensen et al. 2000; Feng, Wang, & Wheeler 2000). This could be gas in the host or an intervening galaxy, but the

¹ Hubble Fellow.

lack of a Lyman break longward of 318 nm (Feng et al. 2000) places an upper limit on the redshift of the GRB of $z_s < 2.5$.

The most complete photometric compilation is by Sagar et al. (2000; shown in their Fig. 3) and is roughly described by two power laws with a break around 7 days after the burst. But there are clearly significant deviations from the broken power-law model, especially between 3 and 6 days after the burst. A similar break was seen in GRB 990510 (e.g., Stanek et al. 1999) and interpreted as the lateral spreading of the jet as its Lorentz factor dropped below the inverse of its opening angle. But GRB 000301C is unique in showing variability on the relatively short timescales of hours to a few days superposed on the more typical power-law trends. As noted by Berger et al. (2000) and Sagar et al. (2000), the rapid fluctuation is achromatic over a range of more than a factor of 5 in wavelength. Achromatic brightening of a source can be a sign of gravitational lensing, but the timescale for microlensing a point source at $z > 2$ is substantially longer than a few days as a result of the low velocities ($\sim 10^{-3}c$) of conventional sources and lenses. However, Loeb & Perna (1998) showed that the superluminal motion of a GRB source on the sky generically results in microlensing events with durations of hours to days.

For our analysis, we use the compilation of Sagar et al. (2000) with additional *UBVI* photometry (one point in each band) from Stanek et al. (2000). One *R*-band point has been removed because of its large deviation from other data taken near the same time. This leaves a total of 104 photometric data points in seven photometric bands, with the following distribution of points: $N(U, B, V, R, I, J, K) = (6, 18, 8, 46, 16, 3, 7)$.

3. ANALYSIS

3.1. Microlensing of a GRB

A spherical GRB fireball appears on the sky as a thin ring that exhibits superluminal expansion at a speed $\sim \gamma c$, where γ is the Lorentz factor of the GRB shock (Waxman 1997b). Figure 3 of Sagar et al. (2000) shows that the achromatic fluctuation in the light curve of GRB 000301C occurred well before the power-law break, and so we assume that during the microlensing event the jet still behaves as if it is part of a spherical fireball.

We use t to denote the observed time since the GRB trigger in units of days. There are two sets of parameters that will define the light curves. The first set describes the intrinsic GRB light decays: power-law slopes α_1 and α_2 , parameter β that describes the smoothness of the transition between them, and the transition time t_b . Each wavelength band also requires a parameter that sets the zero point of the power law.

Loeb & Perna (1998) showed that the simplest microlensing model can be described by three parameters (which are all constants), namely, R_0 , b , and W . They are defined as follows:

1. The value of R_0 is the ring radius at $t = 1$ day in units of the Einstein radius of the lens. At other times the ring radius evolves as (Waxman 1997b)

$$R_s(t) = R_0 t^{5/8}. \quad (1)$$

Here $R_0 = \rho_0/r_E$ and

$$\rho_0 = 4 \times 10^{16} \left(\frac{E_{53}}{n_1} \right)^{1/8} (1 + z_s)^{-5/8} \text{ cm}, \quad (2)$$

where the factor involving the source redshift z_s is due to the cosmic time dilation, E_{53} is the “isotropic equivalent” of the energy release in units of 10^{53} ergs s^{-1} , and n_1 is the ambient gas density in units of 1 cm^{-3} . The actual energy release could, of course, be much smaller as a result of the small solid angle occupied by the jet, but this does not affect the source size until the break in the light curve. The Einstein radius of a lens of mass M_{lens} is

$$\begin{aligned} r_E &= \left(\frac{4GM_{\text{lens}}}{c^2} D \right)^{1/2} \\ &= 7.7 \times 10^{16} \left(\frac{M_{\text{lens}}}{1 M_\odot} \right)^{1/2} \left(\frac{D}{10^{28} \text{ cm}} \right)^{1/2} \text{ cm}, \end{aligned} \quad (3)$$

where $D \equiv (D_s D_l / D_o)$ is the ratio of the angular diameter distances between the observer and the source, the lens and the source, and the lens and the observer. The value of D depends on the lens and source redshifts and the cosmological parameters.

2. The value of b is the lens-source separation on the sky (or equivalently, the “impact parameter”) in units of the Einstein angle, $\theta_E \equiv r_E/D_s$. Since the apparent source radius is changing faster than the speed of light, all other nonrelativistic astrophysical motions are irrelevant. We may therefore consider the source center and lens positions as fixed on the sky. Initially, as long as $R_s \ll b$ the source is pointlike and is magnified by a time-independent factor. The maximum in the magnification curve is reached when $R_s \approx b$; the timing of this maximum can be used to fix the ratio R_0/b .

3. The value of W is the brightness-weighted width of the ring divided by its radius. The width determines the height and the duration of the magnification event. The larger the width is, the smaller the height is and the broader the duration is. This width was estimated theoretically to be $\sim 10\%$ in the optical to IR (see, e.g., Waxman 1997b; Sari 1998; Panaitescu & Mészáros 1998; Granot, Piran, & Sari 1999) but is still subject to uncertainties concerning the extent of the emission region behind the GRB shock front. Note that the assumption that the ring has sharp boundaries and that R_0 and W are the same for all wavelengths is an oversimplification (see ring profiles in Granot et al. 1999). Ring properties that vary significantly with wavelength would produce different light curves in the various observed bands (Wambsganss & Paczyński 1991). But, more parameters are required to fit a more elaborate model, and this is not justified by the quality of the available data on GRB 000301C. If W were close to unity, then the lensing signal would be very weak. Thus, GRB 000301C provides the first evidence that a GRB produces a ring on the sky. Previous data, such as the scintillations of GRB 970508, constrained the source size but not its shape (Waxman, Kulkarni, & Frail 1998). We calculate the magnification factor μ as a function of R_s , W , and b using equations (8) and (9) in Loeb & Perna (1998).

3.2. Fitting the Data

Using all the data for GRB 000301C (104 points), we performed χ^2 minimization fits using a broken power-law model (11 free parameters: four shape parameters plus seven photometric zero points), in the form described by Sagar et al. (2000), and using a broken power law plus microlensing model (14 free parameters: 11 parameters plus three microlensing parameters). We repeated the calculation using only the *R*-band data

(five and eight free parameters, respectively), since it had the most complete temporal coverage with the total of 46 points.

For the broken power-law model, the fits were clearly not good, with $\chi^2/\text{degrees of freedom (dof)} = 2.76$ for all seven bands and $\chi^2/\text{dof} = 2.99$ for the R -band data only, values similar to those found in the other papers describing GRB 000301C (e.g., Jensen et al. 2000). Adding the microlensing magnification has substantially improved the fits, with $\chi^2/\text{dof} = 1.77$ for all seven bands and $\chi^2/\text{dof} = 1.48$ for the R -band data only.

The best-fit microlensing models are shown in Figure 1 for all seven bands. Also shown, in an insert, is the best-fit model for the R -band data only. The best fit to all data provides an impact parameter $b = 1.04 \pm 0.02$ and a fractional ring width of $W = 0.16 \pm 0.02$. The best fit to the R -band data only yields an impact parameter $b = 1.09 \pm 0.02$ and a substantially smaller width of the ring, $W = 0.07 \pm 0.02$. In both cases $R_0 = 0.49 \pm 0.02$, and microlensing provides an angular resolution better than a microarcsecond in probing the GRB fireball. The values for the broken power-law parameters obtained by us are very similar to those obtained by Sagar et al. (2000): $\alpha_1 = 1.1$, $\alpha_2 = 2.9$, and $t_b = 7.6$ days, regardless if all the data or R -band only were fitted. The value of β is not well constrained, but it is always large, $\beta > 5$, indicating a sharp break.

The errors in the microlensing parameter estimations are based on conditional probability distributions, obtained by fixing the rest of the parameters at their most probable values, and should be treated only as rough estimates. It is clear from Figure 1 that the actual errors of the photometry are not Gaussian but are dominated by systematic errors, probably resulting from different reduction procedures applied to the various data. Given the special nature of GRB 000301C, it would be well worth the effort for one of the groups, possibly one that obtained much of the photometric data for this afterglow, to reduce the CCD data obtained by the other groups in order to ensure a uniform reduction procedure. Such uniform reduction would allow for better statistical testing of the GRB 000301C microlensing hypothesis.

4. DISCUSSION

The global fit to the data matches the light curves of the individual bands well. The fit to the R band alone is also of high quality and gives similar values for the microlensing parameters. The main difference between the global and R band is in the sharpness of the microlensing peak, which is narrower and therefore favors smaller values of W in the R band.

We can estimate the mass of the lens from our measurement of the ring radius parameter R_0 . The lens mass can be written as

$$M_{\text{lens}} = 0.13 M_{\odot} \left(\frac{E_{53}}{n_1} \right)^{1/4} \frac{D_l}{D_{ls}} R_0^{-2}, \quad (4)$$

assuming a source redshift of $z_s = 2.04$ and a flat universe with $h = 0.7$ and $\Omega_m = 0.3$. Hence, for $R_0 = 0.5$, the lens mass is of order $\sim 0.5 M_{\odot}$, i.e., stellar size, for a wide range of reasonable GRB energies and circumburst densities. This is reassuring for the microlensing interpretation since it does not rely on some peculiar and rare object to do the lensing. In a case analogous to GRB sources, Koopmans et al. (2000) have recently interpreted variability of the macrolensed superluminal radio source B1600+434 as being a result of microlensing.

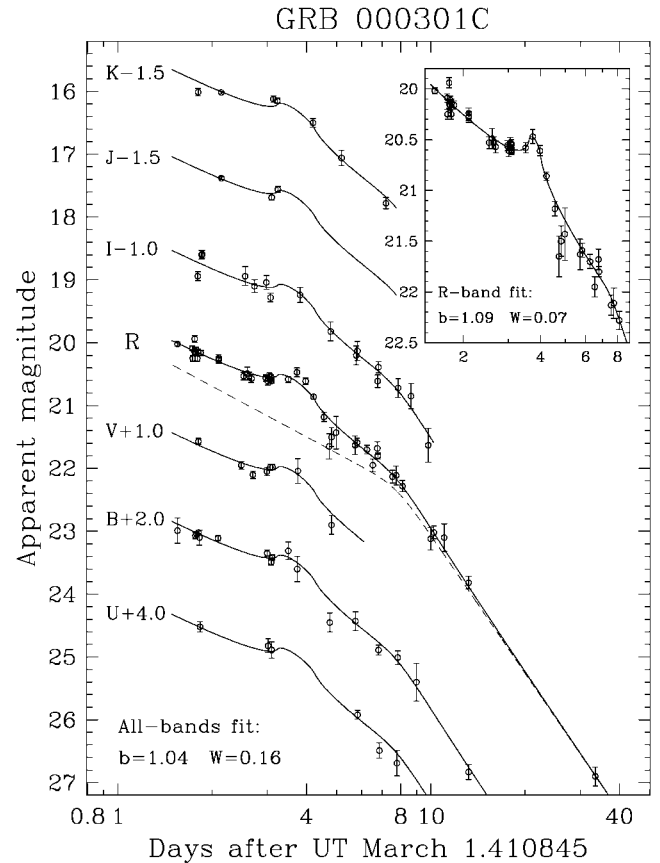


FIG. 1.— $UBVRIJK$ light curves of GRB 000301C from the Sagar et al. (2000) compilation plus data from Stanek et al. (2000). The solid line is the best-fit broken power law plus microlensing model obtained using all the data. The dashed line shows the expected GRB light curve if it had not been lensed. The insert shows the best-fit model using the R -band points only.

4.1. Probability for Microlensing

Deep *Hubble Space Telescope* (*HST*) imaging of the GRB and field were obtained by Fruchter, Metzger, & Petro (2000), but no host or intervening galaxy was detected to a limit of 28.5 mag. A galaxy with $R = 24.3 \pm 0.3$ mag (Veillet 2000a) is $2''$ from the position of the GRB. Our analysis of the deep Space Telescope Imaging Spectrograph exposures obtained on 2000 April 19 suggests that the surface brightness profile along the major axis of the galaxy is best fit by an exponential with a scale length of $0''.22$. This implies that the light is from a rather compact disk. The redshift of this nearby galaxy is unknown. The galaxy is not detectable out to the position of the GRB, and extrapolation of the surface brightness profile implies a very low surface brightness of less than $10^{-23} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ arcsec}^{-2}$ at an effective wavelength of 585 nm. Of course, a dark halo may extend well beyond the visible disk. From the background variations in the *HST* images, we place a limit on the surface brightness at the GRB of more than 28.5 mag arcsec $^{-2}$ in approximately the V band.

What is the probability for microlensing by a solar mass star at a cosmological distance? This probability can be written as $P_{\text{ml}} = \Sigma_*/\Sigma_{\text{crit}}$, where Σ_* is the surface mass density of stars in an intervening galaxy close to the line of sight and $\Sigma_{\text{crit}} = (c^2/4\pi G)(D_s/D_l D_{ls})b^{-2}$. If the mass-to-light ratio of these stars is M/L , then their apparent surface brightness is $\mu_{\text{SB}} = (M/L)^{-1} [\Sigma_*/4\pi(1+z_l)^4]$. Hence, the expected surface brightness of stars around the location of the afterglow is given

by

$$\mu_{\text{SB}} = \frac{c^2}{16\pi^2 G b^2} \left(\frac{M}{L}\right)^{-1} \frac{D_s}{D_l D_{\text{ls}}} \frac{P_{\text{ml}}}{(1+z_l)^4}. \quad (5)$$

The simple point-lens model is adequate for $P_{\text{ml}} \ll 1$, so that the caustics induced by the external shear occupy a region much smaller than r_E (Chang & Refsdal 1984). For $P_{\text{ml}} \sim 0.1$, $z_s = 2$, $b = 1$, $M/L = 5$ in solar units, and a flat universe with $h = 0.7$ and $\Omega_m = 0.3$, we find $\mu_{\text{SB}} \approx 29$ mag arcsec $^{-2}$ in the V band for a lens galaxy at $1 \lesssim z_l \lesssim 1.7$, assuming a K -correction of ~ 4 V magnitudes as required for an elliptical galaxy in this redshift interval (see Fig. 10 of Fukugita, Shimasaku, & Ichikawa 1995). This value of μ_{SB} is below the inferred upper limit on the surface brightness from the *HST* image. Coincidentally, it is comparable to the $R^{1/4}$ -law extrapolation of the surface brightness of the nearby galaxy, but well above the exponential extrapolation. The above constraint is much weaker if the lensing star belongs to a halo population of compact objects (MACHOs) that have a high M/L . The microlensing probability would inevitably be large if the H I column density, $\sim 10^{21}$ cm $^{-2}$, detected at $z = 2$ (Jensen et al. 2000; Smette et al. 2000), is due to the galactic host of the lens (Perna & Loeb 1997); however, the observed damped Ly α absorber is more likely to be the host galaxy of the GRB.

4.2. Alternative Interpretations

Fluctuations in the light curve may result from shell collisions within the fireball (Dai & Lu 2000), but such collisions would reenergize the fireball and change its spectrum by increasing the peak frequency of its emission. There is no evidence for a *chromatic* change of this type during the event (Berger et al. 2000). The activity of the central engine of the GRB has to be fine-tuned in an ad hoc manner so as to produce a collision only after ~ 4 days when the Lorentz factor of the expanding shell ($\gamma \sim 5$) already declined by more than an order of magnitude relative to its initial value.

Berger et al. (2000) suggested an alternative interpretation of the *achromatic* fluctuation in terms of an inhomogeneity of the ambient density into which the fireball is propagating, n . Naively, one may argue that the flux from a fireball propagating into a uniform ambient medium scales is proportional to $n^{1/2}$ at all wavelengths, and so a brightening of the flux by a factor of 1.7 may be achieved if the fireball encounters a clump of gas that is a factor of ~ 3 denser than the mean. The required clump location ($\sim 5 \times 10^{17}$ cm), transverse size ($\geq 10^{17}$ cm), depth ($\leq 5 \times 10^{17}$ cm), and overdensity (~ 3), can all be chosen ad hoc so as to fit the data. However, the standard model for the fireball dynamics and emission implies that the flux at a particular observed time is emitted with different weights on a particular spatial region for frequencies above and below the peak spectral frequency (see eqs. [15] and [16] in Wang & Loeb 1999). This results in two effects: (1) the ring is narrower and has a higher contrast (center-to-limb variation in brightness) at higher frequencies (see Figs. 11 and 12 in Granot et al.

1999), and (2) the limb of the ring is influenced by the clump region at a later observed time than its center because of the geometric time delay. Since the peak frequency is ~ 300 GHz at ~ 4 days (Berger et al. 2000; Sagar et al. 2000), the fluctuation is therefore expected to brighten to a maximum earlier in the radio than in the optical and IR. The chromaticity should be even more pronounced below the synchrotron self-absorption frequency (Berger et al. 2000), as this frequency depends on n . Although it may not be possible to rule out the above chromatic behavior with the sparse radio data for GRB 000301C, achromaticity does not trivially follow from this model at wavelengths ranging all the way from the optical to the radio.

The ring parameters W and R_0 , which define the microlensing light curves, should also depend on wavelength (Panaitescu & Mészáros 1998; Granot et al. 1999) but in a generic predictable way. Hence, with better analysis of the existing data for GRB 000301C or with detailed monitoring of future GRBs, it should be possible to test it against the above interpretations.

5. CONCLUSIONS

We successfully model the light curve of GRB 000301C as a standard broken power law plus a gravitational microlensing event. We find the lens mass required for the event is $\sim 0.5 M_{\odot}$, thus requiring only a normal star to explain the lensing. No galaxy or diffuse light from the stellar population is detected along the line of sight, but reasonable lensing probability is expected even for surface brightness below the deep *HST* images we analyzed. Ground-based images with a large telescope may detect the lensing population.

New GRB satellites such as *HETE-2* and *Swift* will provide many opportunities to study GRB afterglows. This is the first of what will be a number of microlensed GRBs, and we show that analysis of high-quality data covering a large wavelength range can be a useful tool for probing the physical structure of GRB afterglows with submicroarcsecond resolution. Our estimate of W confirms the prediction that afterglow shocks appear as thin rings on the sky (Waxman 1997b; Sari 1998; Panaitescu & Mészáros 1998; Granot et al. 1999). Better broadband data could check for variation with wavelength of the ring width and radius, and polarimetric observations could confirm the predictions of the polarization variations made by Loeb & Perna (1998). Future observations could also constrain the properties of the dark matter by taking a census of the number and masses of microlenses.

We thank Bohdan Paczyński and Eli Waxman for useful comments on the manuscript and Dave Bennet for helpful discussions. Support for K. Z. S. was provided by NASA through Hubble Fellowship grant HF-01124.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. This work was supported in part by NSF grant AST 99-00877, the Israel-US BSF, and NASA grant NAG5-7039 for A. L. Support for P. M. G. was provided by NASA LTSA grant NAG5-9364.

REFERENCES

- Berger, E., et al. 2000, preprint (astro-ph/0005465)
 Bertoldi, F. 2000, GCN Circ. 580 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/580.gcn3>)
 Chang, K., & Refsdal, S. 1984, A&A, 132, 168
 Costa, E., et al. 1997, Nature, 387, 783
 Dai, Z. G., & Lu, T. 2000, preprint (astro-ph/0005417)
 Feng, M., Wang, L., & Wheeler, J. C. 2000, GCN Circ. 607 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/607.gcn3>)
 Frail, D. A., Kulkarni, S. R., Nicastro, L., Feroci, M., & Taylor, G. B. 1997, Nature, 389, 261
 Fruchter, A., Metzger, M., & Petro, L. 2000, GCN Circ. 701 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/701.gcn3>)
 Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
 Fynbo, J. P. U., Jensen, B. L., Hjorth, J., Pedersen, H., & Gorosabel, J. 2000, GCN Circ. 570 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/570.gcn3>)

- Garnavich, P. M., Barmby, P., Jha, S., & Stanek, K. Z. 2000a, GCN Circ. 581 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/581.gcn3>)
- Garnavich, P. M., Jha, S., Pahre, M. A., Stanek, K. Z., Kirshner, R. P., Garcia, M. R., Szentgyorgyi, M. H., & Tonry, J. L. 2000b, ApJ, in press (astro-ph/0003429)
- Granot, J., Piran, T., & Sari, R. 1999, ApJ, 513, 679
- Halpern, J. P., et al. 2000a, ApJ, in press (astro-ph/0006206)
- Halpern, J. P., Mirabal, N., & Lawrence, S. 2000b, GCN Circ. 578 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/578.gcn3>)
- Harrison, F. A., et al. 1999, ApJ, 523, L121
- Jensen, B. L., et al. 2000, A&A, submitted (astro-ph/0005609)
- Katz, J. I. 1994, ApJ, 422, 248
- Koopmans, L. V. E., de Bruyn, A. G., Wambsganss, J., & Fassnacht, C. D. 2000, in *Micro lensing 2000: A New Era of Micro lensing Astrophysics*, ed. J. W. Menzies & P. D. Sackett (San Francisco: ASP), in press (astro-ph/0004285)
- Loeb, A., & Perna, R. 1998, ApJ, 495, 597
- Masetti, N., et al. 2000, A&A, 359, L23
- Mészáros, P., & Rees, M. J. 1993, ApJ, 405, 278
- . 1997, ApJ, 476, 232
- Metzger, M. R., et al. 1997, Nature, 387, 879
- Paczynski, B., & Rhoads, J. E. 1993, ApJ, 418, L5
- Panaiteanu, A., & Mészáros, P. 1998, ApJ, 493, L31
- Perna, R., & Loeb, A. 1997, ApJ, 489, 489
- Rhoads, J. E. 1997, ApJ, 487, L1
- Rhoads, J. E., & Fruchter, A. S. 2000, ApJ, in press (astro-ph/0004057)
- Sagar, R., et al. 2000, Bull. Astron. Soc. India, in press (astro-ph/0004223)
- Sari, R. 1998, ApJ, 494, L49
- Smette, A., et al. 2000, ApJ, submitted (astro-ph/0007202)
- Smith, D. A., Hurley, K., & Cline, T. 2000, GCN Circ. 568 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/568.gcn3>)
- Stanek, K. Z., Garnavich, P. M., Barmby, P., & Jha, S. 2000, GCN Circ. 766 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/766.gcn3>)
- Stanek, K. Z., Garnavich, P. M., Kaluzny, J., Pych, W., & Thompson, I. 1999, ApJ, 522, L39
- Stecklum, B., et al. 2000, GCN Circ. 572 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/572.gcn3>)
- Wambsganss, J., & Paczyński, B. 1991, AJ, 102, 864
- Wang, X., & Loeb, A. 2000, ApJ, 535, 788
- Waxman, E. 1997a, ApJ, 489, L33
- . 1997b, ApJ, 491, L19
- Waxman, E., Kulkarni, S. R., & Frail, D. A. 1998, ApJ, 497, 288
- van Paradijs, J., et al. 1997, Nature, 386, 686
- Veillet, C. 2000a, GCN Circ. 598 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/598.gcn3>)
- . 2000b, GCN Circ. 623 (<http://gcn.gsfc.nasa.gov/gcn/gcn3/623.gcn3>)