

Will GRB 990123 perform an encore?

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ABSTRACT

The recent gamma-ray burst GRB 990123 has an absorption redshift $z_s = 1.60$, implying an apparent energy $E \geq 3 \times 10^{54}$ erg, and a peak luminosity $L_{\max} \geq 6 \times 10^{53}$ erg s⁻¹, assuming isotropic emission. This energy is 10 times larger than hitherto measured, and in excess of the rest mass of the Sun. Optical observations have revealed an associated galaxy displaced from the line of sight by ~ 0.6 arcsec. This raises the possibility that the burst is enhanced by gravitational lensing. We argue that existing observations probably only allow magnifications $\mu > 400$ if the galaxy is at $z_d = 1.60$ and the burst originates at much higher redshift. It should be possible to exclude this possibility by examining the burst time structure. Although we anticipate that multiple imaging can be excluded in GRB 990123, our analysis should be generally applicable.

Key words: gravitational lensing – gamma-rays: bursts.

1 INTRODUCTION

The majority of gamma-ray bursts appear to be located at cosmological distances. This raises the possibility that a small minority may be brightened anomalously through being multiply imaged by an intervening galaxy. This may lead to the detection of multiple bursts (e.g. Paczyński 1986), although the a priori probability of such an occurrence is not high (e.g. Blaes & Webster 1992). In the event of such a propitious alignment, we stand to learn much about the source and the deflector.

The recent burst GRB 990123 (Piro 1999) is the brightest yet detected by the *BeppoSAX* Wide Field Camera; given the lower limit to its distance set by the detection of absorption lines in the spectrum of the optical transient (OT) at $z_s = 1.60$ (Kelson et al. 1999), it is also the most luminous burst with a firm distance limit: adopting a world model with $h = 0.6$, $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$, the observed 20–700 keV X, γ -ray fluence of 3.5×10^{-4} erg cm⁻² translates into a minimum burst energy of $\sim 3 \times 10^{54} \mathcal{B}$ erg, where \mathcal{B} is the beaming fraction. This is 10 times larger than hitherto reported and, if the emission is isotropic and unmagnified, represents an energy in excess of the rest mass of a neutron star, comprehensively ruling out many theoretical models. In addition, the peak luminosity during the burst can be estimated as $6 \times 10^{53} \mathcal{B}$ erg s⁻¹, which is $2 \times 10^{-6} \mathcal{B} c^5/G$. The reported optical emission is much smaller, $\sim 1.5 \times 10^{51} \mathcal{B}$ erg, although still in excess of the energy associated with a conventional supernova.

Although initial reports of a foreground galaxy (Odewahn, Bloom & Kulkarni 1999) within 2 arcsec of the burst at a redshift $z \sim 0.29$ (Hjorth et al. 1999a) have been discounted (Yadigaoglu

et al. 1999; Hjorth et al. 1999b; Djorgovski et al. 1999a), the recent *Hubble Space Telescope* (*HST*) image (Bloom et al. 1999) reveals a fainter galaxy centred only ~ 0.6 arcsec from the burst afterglow. It is thus still important to explore the possibility that the burst has been magnified by lensing. In this note, we examine, in more detail, and in general, the possibility that lensing may be occurring and, if so, some of its ramifications.

2 MACROLENSING

The largest magnifications observed in known galaxy lenses are found in ‘quad’ geometries associated with elliptical mass perturbations, when the source is located close to a caustic surface and two images straddle the critical curve. In this case, the two bright bursts will be closely spaced in time and on the sky, and will be the second and third to arrive. In addition to the fainter and more widely separated events, labelled 1 and 4, there will also be a faint (or invisible) fifth image, located near the lens galaxy nucleus, which we shall ignore.

We make an elementary model of a nearly circular lens (cf., Blandford & Kovner 1988; Schneider, Ehlers & Falco 1992; Blandford & Hogg 1996). Let the scaled surface potential in the vicinity of the Einstein ring be written

$$\psi(r) = f(r) + g(r) \cos 2\phi, \quad (1)$$

where r is measured in units of the unperturbed Einstein ring radius θ_E , so that $f'(1) = 1$, and $g(r)$ is a perturbation which measures the ellipticity in the potential and its radial variation. As f and g depend quite heavily upon the dark matter halo, the ellipticity can only be guessed, although the position angle probably agrees with that of the luminous matter. (Observed lenses often require external shear to fit their image geometries.)

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The time function is given by

$$t = r^2/2 - \psi - \mathbf{r} \cdot \boldsymbol{\beta}. \quad (2)$$

Images at \mathbf{r} have sources at $\boldsymbol{\beta}$ located as extrema of t . Hence

$$\boldsymbol{\beta} = [(1 - f')\delta - g' \cos 2\phi]\hat{\mathbf{r}} + 2g \sin 2\phi \hat{\boldsymbol{\phi}}, \quad (3)$$

where $\delta = r - 1$ and all derivatives are evaluated at $r = 1$. The Hessian matrix of t is given by

$$H = \begin{pmatrix} t_{,rr} & r^{-1}t_{,r\phi} - r^{-2}t_{,\phi} \\ r^{-1}t_{,r\phi} - r^{-2}t_{,\phi} & r^{-1}t_{,r} + r^{-2}t_{,\phi\phi} \end{pmatrix} \\ = \begin{pmatrix} 1 - f' & 2(g' - g) \sin 2\phi \\ 2(g' - g) \sin 2\phi & (1 - f')\delta + (4g - g') \cos 2\phi \end{pmatrix} \quad (4)$$

in polar coordinates (to lowest order), and the scalar magnification, μ , is the reciprocal of its determinant. Now, $\mu \rightarrow \infty$ when the image lies on the critical curve

$$\delta = \delta_c = \frac{(g' - 4g) \cos 2\phi}{1 - f'} \quad (5)$$

or, equivalently, when the source lies on the caustic

$$\boldsymbol{\beta} = \beta_c = 2g(-2 \cos 2\phi \hat{\mathbf{r}} + \sin 2\phi \hat{\boldsymbol{\phi}}) \\ = 4g(-\cos^3 \phi \hat{\mathbf{x}} + \sin^3 \phi \hat{\mathbf{y}}). \quad (6)$$

If we now displace the source perpendicular to the caustic, a pair of images will separate in opposite directions from the critical curve along a line with $\delta r = 2(g - g') \sin 2\phi \delta \phi / (1 - f')$, where $\delta \phi$ (assumed to be $\ll 1$) is the displacement of either image from the critical curve. Perturbing the Hessian, we find that

$$\mu_{2,3}^{-1} = |6(1 - f')g \sin 2\phi \delta \phi|, \quad (7)$$

for each of the neighbouring, bright images.

Expanding the time delay to third order, we find that the time delay between the two bright bursts is given by

$$t_3 - t_2 = 4g \sin 2\phi_2 \delta \phi^3 \\ = \frac{1}{54(1 - f')^3 g^2 \sin^2 2\phi_2 \mu_{2,3}^3} \quad (8)$$

to leading order. These expressions must be modified near a cusp when $|\sin \phi_2| < |\mu_{2,3}| \Delta t$. (Higher order catastrophes are possible, but less probable: e.g. Schneider et al. 1992.)

We can also locate the preceding (1) and following (4) bursts in the high-magnification, small-ellipticity limit at position angles

$$\sin \phi_1 = \left\{ \sin \phi_2 \left[\cos^2 \phi_2 - \left(1 - \frac{1}{4} \sin^2 2\phi_2 \right)^{1/2} \right] \right\}, \\ \sin \phi_4 = \left\{ \sin \phi_2 \left[\cos^2 \phi_2 + \left(1 - \frac{1}{4} \sin^2 2\phi_2 \right)^{1/2} \right] \right\}. \quad (9)$$

Measuring ϕ_2 from the minor axis, we find, without loss of generality, that when the merging pair is in the first quadrant, the preceding burst is in the second quadrant and the following burst is in the fourth quadrant. The corresponding delays are given by

$$t_2 - t_1 = \frac{[33 \cos 2\phi_2 + 2^{1/2}(7 + \cos 4\phi_2)^{3/2} - \cos 6\phi_2]g}{8}, \\ t_4 - t_2 = \frac{[-33 \cos 2\phi_2 + 2^{1/2}(7 + \cos 4\phi_2)^{3/2} + \cos 6\phi_2]g}{8}. \quad (10)$$

$t_2 - t_1$ ($t_4 - t_2$) varies between $8g$ (0) and 0 ($8g$) as ϕ increases from 0 to $\pi/2$. The associated magnifications are given by

$$\mu_1^{-1} = \frac{1}{4} [15 \cos 2\phi_2 + 2^{1/2}(5 - \cos 4\phi_2)(7 + \cos 4\phi_2)^{1/2} \\ + \cos 6\phi_2](1 - f')g, \\ \mu_4^{-1} = \frac{1}{4} [15 \cos 2\phi_2 - 2^{1/2}(5 - \cos 4\phi_2)(7 + \cos 4\phi_2)^{1/2} \\ + \cos 6\phi_2](1 - f')g. \quad (11)$$

Thus observation of either burst 2 or 3 allows one to specify completely the magnifications, time intervals and locations of the other three images. These expressions are only valid as long as $\delta \phi \ll 1$ and the magnification is large, specifically as long as $\mu \gg [6(1 - f')g]^{-1}$.

When the source is even farther from the caustic, it is possible to create four, similarly magnified bursts. These will be located at the solutions of the quartic

$$\beta_y \cos \phi - \beta_x \sin \phi = 4g \sin \phi \cos \phi. \quad (12)$$

In this case, it is necessary to observe two bursts optically in order to solve for the source location, $\boldsymbol{\beta}$. The associated magnifications are given by

$$\mu^{-1} = |(4g \cos 2\phi + \beta_x \cos \phi + \beta_y \sin \phi)(1 - f')| \quad (13)$$

and the arrival times (ignoring a constant) by

$$t = -g \cos 2\phi - \beta_x \cos \phi - \beta_y \sin \phi. \quad (14)$$

Note that if $\beta_x^{2/3} + \beta_y^{2/3} > (4g)^{2/3}$ then the source is located outside the caustic and only two bursts will be seen. Interestingly, if the source is located just outside the cusp, one of these bursts can be arbitrarily magnified and followed by a single, fainter burst. However, this is a relatively rare occurrence. Even less likely is a radial merger geometry, when two bright bursts, located much closer to the galaxy nucleus, will follow an isolated burst. Finally, if there is no multiple imaging, then the single burst will still be magnified by a factor that depends upon the detailed mass distribution closer to the nucleus. This factor is less than 2 for an isothermal sphere, as is typically assumed, and can only be large if the surface density is roughly constant at the observed image location.

To summarize, if we are able to locate a burst with respect to the deflector galaxy and can guess the ellipticity of the potential, then, on the hypothesis that the observed burst is the first of a merging pair (and the second overall), we have outlined a procedure for predicting the location, the magnification and the delay of the first, third and fourth bursts. Multiple bursts can still occur without strong magnification, but in this case we must observe another burst to make more predictions.

3 MICROLENSING AND MILLILENSING

If the lensing galaxy comprises mainly stars, then the optical depth in the vicinity of the critical curve is automatically $\Sigma/\Sigma_{\text{crit}} \sim 0.5$. This means that microlensing variations are unavoidable if the source is sufficiently small. As the characteristic time delays associated with individual stars are $< 100 \mu\text{s}$, the arrival times, locations and spectra of individual bursts should not be seriously affected. However, significant magnification fluctuations are possible as long as the source is smaller than $\sim 10^{16} \mu^{-1/2}$ cm, which can be true when the burst is less than a day old.

The mass distribution of the deflector galaxy is likely to have additional perturbations associated with arms, bars, etc., especially if it is a spiral; indeed, this is commonly observed in galaxy lenses

that do not obey magnification scalings close to catastrophes. This is known as millilensing. If the time delay between two neighbouring bursts is Δt , a perturbing mass as small as $\sim 10^5 (\Delta t/1 \text{ s}) M_\odot$, in the vicinity of the images, suffices to change the magnifications by $O(1)$.

4 APPLICATION TO GRB 990123

Assume first that the galaxy observed in the *HST* image is at $z = 0.29$. [Although spectra of the OT have not confirmed reported absorption lines at this redshift, the brightest galaxy in the vicinity does have $z = 0.28$ (Hjorth et al. 1999b), and so it is not excluded that the faint galaxy closest to the burst lies at this distance.] Adopting a magnitude of $V = 24.4$ and a mass-to-light ratio at the rest effective frequency of $\nu_0 = 7 \times 10^{14} \text{ Hz}$ ($\equiv B$), the luminosity is $\nu L_\nu(\nu_0) = 3 \times 10^8 L_\odot \sim 0.02 L^*$ ignoring the effects of reddening. The critical surface density is $\Sigma_{\text{crit}} = 0.45 \text{ g cm}^{-2}$ and the requisite mass-to-light ratio becomes $(M/L)_B = 200(\theta_E/0.6 \text{ arcsec})^2$, in solar units, for our world model, where we have assumed that all of the light is produced within the Einstein ring. This is far too large for a galaxy at this redshift to produce multiple images.

However, it is also possible that the galaxy is at the absorption redshift $z_d = 1.6$ (Hjorth et al. 1999a; Djorgovski et al. 1999b) while the burst occurred at a larger redshift. In this case, the K -band magnitude $K = 21.6$ (Bloom et al. 1999) can be used to interpolate a rest B luminosity $(\nu L_\nu)_B \sim 1.5 \times 10^{10} L_\odot \sim 0.8 L^*$. The galaxy is quite blue, suggesting that the reddening is not very large. For illustration, let us suppose that $z_s = 3$ (our results are not very sensitive to this choice). The critical density is $\Sigma_{\text{crit}} = 0.45 \text{ g cm}^{-2}$ and the required mass-to-light ratio has a value $(M/L)_B \sim 20$ in solar units if $\theta_E \sim 0.6 \text{ arcsec}$ (6 kpc), which, although large, cannot be ruled out. The observed galaxy has an axial ratio of ~ 4 . However, the total mass distribution is likely to be more circular. We adopt, for illustration, $f(r) = r$, $g(r) = 0.1r$, consistent with a density axial ratio of ~ 2 , and we measure $\phi = 65^\circ$ for the observed burst. (This excludes a single, magnified, cusp image.)

If we suppose that the observed burst was a merging double, then the first and fourth bursts are located at $\phi_1 = 138^\circ$ and $\phi_4 = 273^\circ$. (More detailed lens models do not change our qualitative conclusions, and only affect them significantly, quantitatively, through the scaling with g .) We can use the unit of time delay, which is 188 d, to compute the intervals:

$$\begin{aligned} t_2 - t_1 &= 8(g/0.1)d, \\ t_3 - t_2 &= 50 \left(\frac{\mu_{2,3}}{100} \right)^{-3} (g/0.1)^{-2} s, \\ t_4 - t_3 &= 110(g/0.1)d. \end{aligned} \quad (15)$$

Given the potentially short time interval $t_3 - t_2$ for cases of large magnification, it is necessary to ask if the multiple bursts might have occurred within the 100-s duration of the burst itself. cursory examination of the BATSE light curve at 0.5-s resolution indeed reveals two distinct peaks separated by $\sim 12 \text{ s}$; the obvious ~ 25 per cent difference in peak flux could conceivably be produced by differential milli- or microlensing along the two paths. However, examination of the spectra of the two peaks shows that the second is distinctly softer: taking 8-s intervals (approximately the FWHM) centred on each peak yields count ratios of 1.07, 1.09, 1.11, 1.41 and 1.82 in the 20–50, 50–100, 100–300, 200–1600 and 600–11 000 keV bands respectively, where the first three data points are derived from BATSE (Kippen et al. 1999) and the last two from COMPTEL (Connors & Kippen 1999). In addition, the distinct

peak 76 s after the BATSE trigger has no counterpart with the same separation as the earlier pair of peaks; the closest local maximum is over 19 s away. Finally, the overall spectral evolution of the burst is from hard to soft as is typical for BATSE bursts (e.g. Preece et al. 1998). We conclude that the 100 s long burst profile does not conceal a temporally resolved double burst at ~ 1 -s resolution.

The lower limit on this interval can be extended to several tens of minutes, depending on the location of the observing satellites with respect to the Earth and the South Atlantic Anomaly (SAA) at the time of the burst. *SAX*, for example, saw no burst within a factor of 40 in intensity in the Wide Field Camera from this location for the 1450 s preceding the burst (following the emergence of the satellite from the SAA); after the burst, only 170 s elapsed before the Earth occulted the burst position (*SAX* Team, private communication). In BATSE, the burst was observed 64° above the horizon, implying that the source remained visible for at least ~ 15 min after the trigger; thus $\pm 900 \text{ s}$ is a conservative lower limit for the interval between two resolved bursts. [Also relevant are the data from *Ulysses* which saw no burst consistent with the location of GRB 990123 for a period of at least 3 d before and after the event (K. Hurley, private communication), although coverage was only about 80 per cent complete and we cannot entirely exclude a second burst.]

If, as we argue, $1 \text{ s} \leq t_3 - t_2 \leq 900 \text{ s}$ is excluded, then so are magnifications $40 \leq \mu_{2,3} \leq 400$. Furthermore, we can use limits on additional point sources in the *HST* image within 2 arcsec of the afterglow to place constraints on lensed images. If $\mu_{2,3} < 40$, then using $\mu_1 = 4$ (from equation 11) we find that burst 1 would have had a fluence $> 3 \times 10^{-5} \text{ erg cm}^{-2}$ on or around January 15. It is unlikely, although not completely excluded, that this failed to trigger any detector. However, the afterglow associated with burst 1 would have been brighter than $V \sim 28.8$ at the time of the *HST* image, even allowing for its additional fading with time. We have performed two-dimensional Gaussian fits (including sloping, planar baselines) to all local maxima within 2 arcsec of the OT in the *HST* image. The only feature consistent with the point spread function (derived from a similar fit to the OT as $\text{FWHM} = 3.2 \pm 0.1 \text{ pixel}$) is the faint object located 1.4 arcsec north of the OT. This $\sim 4\sigma$ excess has a magnitude of approximately $V \sim 28.4$ [scaled to the value of $V = 25.2$ for the OT reported by Bloom et al. (1999)]. We take this as an upper limit to the magnitude of the first afterglow. We can therefore almost exclude $\mu_{2,3} \leq 40$.

The remaining parameter space is described by $t_{2,3} \leq 1 \text{ s}$ and $\mu_{2,3} \geq 400$. In this case, the first afterglow will be undetectable. However, the finite size of the source becomes a factor at these high magnifications. For a source angular size $B(t)$, the magnification is limited to

$$\mu_{2,3}(t) < [6g \sin 2\phi B(t)/\theta_E]^{-1/2} \sim 400(B/8 \mu\text{as})^{-1/2}. \quad (16)$$

This limit should not affect the burst itself, although it will eventually influence the afterglow. Unfortunately, our lack of understanding of the ambient environment and the nature of the explosion precludes a confident expression for $B(t)$. However, a naive estimate for a spherical, relativistic blastwave with $E \sim 10^{52} \text{ erg}$ and $n \sim 1 \text{ cm}^{-3}$ (e.g. Blandford & McKee 1977) gives $B \sim 2(t/1 \text{ d})^{5/8} \mu\text{as}$. This limits the magnification to $\mu_{2,3} \leq 600(t/17 \text{ d})^{-0.3}$. After this inequality is violated, the afterglow emission will decline correspondingly more steeply with time. In fact, just such an increase in the rate of decline has been reported at $t = 11 \text{ d}$ (Yadigaroglu & Halpern 1999). We therefore cannot confidently exclude lensing with $\mu_{2,3} \sim 400$ at this stage. However, if it were possible to examine the subsecond time variations in the

BATSE light curve of GRB 980123 and thereby limit $t_3 - t_2$ to ≈ 10 ms, then $\mu_{2,3}$ would have to exceed ≈ 1000 , and all multiple imaging by a $z_d = 1.6$ deflector would effectively be ruled out.

In summary, three arguments (the high mass-to-light ratio of the galaxy, and the implausibility of missing the first burst and of failing to detect its afterglow) can already be marshalled against the lensing hypothesis. Three additional steps might effectively eliminate it – searching for double structure on subsecond time-scales in the BATSE data, setting a better limit on the presence of additional afterglow images at the predicted locations, and obtaining a reliable photometric or spectroscopic redshift for the galaxy. Contrariwise, if it turns out that the burst was highly magnified by lensing, then the burst energy would be reduced to $\sim 9 \times 10^{51} B(2\mu_{2,3}/1000)^{-1}$ erg.

5 CONCLUSION

GRB 990123 serves as a reminder that multiple imaging of a gamma-ray burst is to be expected eventually in a large enough sample, and the analysis of Section 2 should be generally applicable. While we cannot completely rule out the possibility that it has been multiply imaged and strongly magnified, it should be possible to do so soon. In this case, if we have not observed (or do not observe) an echo of GRB 990123, then the magnification is limited to $\mu \sim 2$, except under quite contrived models, leaving GRB 990123 as the most intrinsically luminous (per sterad) cosmic event yet observed in its entirety.

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