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AN OFF-AXIS MODEL OF GRB 031203

Enrico Ramirez-Ruiz,[1,2,3] Jonathan Granot,[1,4] Chryssa Kouveliotou,[1,5] S. E. Woosley,[1,6]
Sandy K. Patel,[1,7] and Paolo A. Mazzali[1,8]

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ABSTRACT

The low-luminosity radio emission of the unusually faint GRB 031203 has been argued to support the idea of a class of intrinsically subenergetic gamma-ray bursts (GRBs), currently comprising two members. While low-energy GRBs probably exist, we show that the collective prompt and multiwavelength observations of the afterglow of GRB 031203 do not necessarily require a subenergetic nature for that event. In fact, the data are more consistent with a typical, powerful GRB seen at an angle of about twice the opening angle of the central jet. The *intrinsic* peak energy E_p of GRB 031203 then becomes ~2 MeV, similar to that of many other GRBs.

Subject headings: gamma rays: bursts — hydrodynamics — ISM: jets and outflows — supernovae: general

Online material: color figures

1. INTRODUCTION

The first evidence that gamma-ray bursts (GRBs) might have a broad range of energies came with the discovery of GRB 980425, the first GRB also to be associated with a Type Ib/c supernova, SN 1998bw (Galama et al. 1998). While unremarkable in its timescale and spectrum, GRB 980425 had a total gamma-ray energy, assuming isotropic emission, of only $E_{\gamma,\,\mathrm{iso}} \sim 10^{48}$ ergs, some 4–6 orders of magnitude less than a typical GRB (Frail et al. 2001; Ghirlanda et al. 2004). Significant interest was aroused at the time by the possibility that such lower energy bursts might be more common than had been thought, but hard to detect given the current instrumental sensitivities. It took 5 more years before another event, GRB 031203, provided additional support for a faint population of GRBs. At a cosmological distance of $z = 0.1055$ (Prochaska et al. 2004), GRB 031203 was also atypical in its gamma-ray budget, with $E_{\gamma,\,\mathrm{iso}} \sim 10^{50}$ ergs (Sazonov et al. 2004). In fact, its gamma-ray power was intermediate between GRB 980425 and more typical bursts with (isotropic) energies of 10^{52}–10^{54} ergs (Frail et al. 2001; Ghirlanda et al. 2004). The burst profile was smooth and similar to GRB 980425, consisting of a single peak lasting about 20 s and a peak energy above 190 keV (Sazonov et al. 2004).

Soon afterward, an optical counterpart was identified and follow-up observations by several telescopes revealed a supernova, SN 2003lw, with a spectrum very similar to that of SN 1998bw (Malesani et al. 2004; Thomsen et al. 2004; Gal-Yam et al. 2004; Cobb et al. 2004). Subsequent X-ray observations of GRB 031203 with *XMM* and *Chandra* identified an X-ray source coincident with the optical transient. The decline rate and the isotropic luminosity of the X-ray afterglow also ranked the event as intermediate between GRB 980425 and classical GRBs (Kouveliotou et al. 2004). A very faint counterpart was also detected at centimeter wavelengths, where it displayed a peak luminosity more than 2 orders of magnitude fainter than typical radio afterglows (Frail et al. 2003), but again comparable to that of GRB 980425 (Kulkarni et al. 1998).

Given the many similarities with GRB 980425, it has been argued (Soderberg et al. 2004, hereafter S04; Sazonov et al. 2004) that the *only* explanation of the faint nature of both GRB 031203 and GRB 980425 is that they were intrinsically subenergetic, that is, that the energy ejected in relativistic matter at all angles was orders of magnitude less than in all other GRBs studied to date. Furthermore, it has been suggested that the afterglow data are only consistent with a nearly spherical explosion—that GRB 031203 was not a jetlike phenomenon (S04; Sazonov et al. 2004). We disagree with both conclusions and show here that the data from GRB 031203, especially the early X-ray afterglow light curve, do not require a subenergetic nature for this event and are in fact more consistent with a model in which GRB 031203 was a typical powerful *jetted* GRB viewed off-axis.[9]

2. CALCULATION OF AFTERGLOW EMISSION

The afterglow light curves presented here are calculated using model 1 of Granot & Kumar (2003). The deceleration of the flow is calculated from the mass and energy conservation equations, and the energy per solid angle ϵ is taken to be independent of time. The local emissivity is calculated using the conventional assumptions of synchrotron emission from relativistic electrons that are accelerated behind the shock into a power-law distribution of energies, $N(\gamma_e) \propto \gamma_e^{-p}$ for $\gamma_e > \gamma_m$, where the electrons and the magnetic field hold fractions ϵ_e and ϵ_B, respectively, of the internal energy of the shocked fluid. The synchrotron spectrum is taken to be a piecewise power law (Sari et al. 1998). In § 3 we begin with a simple model in which we assume that the outflow is spherical. More realistic jet models are considered in § 4, where the Lorentz factor γ and ϵ are assumed, within the jet aperture, to be independent of the angle θ as measured from the jet axis. The lateral spreading of the jet is neglected. This approximation is consistent with results of numerical simulations (Granot et al. 2001) that show relatively little lateral expansion as long as the jet is relativistic. The light curves for observers located at different

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[1] Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550.

[2] Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540.

[3] Chandra Fellow.

[4] KIPAC, Stanford University, P.O. Box 20450, MS 29, Stanford, CA 94309.

[5] NASA Marshall Space Flight Center, NSSTC, XD-12, 320 Sparkman Drive, Huntsville, AL 35805.

[6] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064.

[7] USRA, NSSTC, SD-50, 320 Sparkman Drive, Huntsville, AL 35805.

[8] INAF Osservatorio Astronomico, Via Tiepolo 11, 34131 Trieste, Italy.

[9] The reader is referred to Granot et al. (2005) and references therein for a detailed analysis of the off-axis model in relation to X-ray flashes and X-ray–rich GRBs.

angles $\theta_{\rm obs}$ with respect to the jet axis are calculated by applying the appropriate relativistic transformation of the radiation field from the local rest frame of the emitting fluid to the observer frame and integrating over equal photon arrival time surfaces (Granot et al. 2002; Ramirez-Ruiz & Madau 2004).

3. THE IMPORTANCE OF THE X-RAY LIGHT CURVE

GRB 031203, or at least its gamma rays directed at us, was certainly very weak. A straightforward interpretation might be that the GRB was deficient in all its emissions in all directions (S04). This idea is compatible with the afterglow light curve at radio frequencies. However, when one combines the fact that a 20 s long GRB was observed, as well as an X-ray and infrared afterglow, the situation is more constrained.

The resulting light curves for a subenergetic spherical model are plotted against the data in Figure 1. The model parameters are chosen to coincide with those of S04: an energy of $E = 1.7 \times 10^{49}$ ergs, a uniform external medium of number density $n = 0.6$ cm^{-3}, $p = 2.6$, $\epsilon_e = 0.4$, and $\epsilon_B = 0.2$. Even though the model fits the radio and infrared light curves moderately well (given the sparse data for the latter), it is inconsistent with the slow decline of the X-ray light curve during the first 100 days. The following point should be emphasized here. The dynamical model used here is different from that used by S04. This explains why our fit to the radio data is slightly poorer in quality despite using similar model parameters. A similar goodness of fit to the radio light curve can be easily achieved by iterating over the physical parameters. Such an exercise, however, cannot at the same time provide an acceptable fit to the X-ray light curve. In fact, we find that most spherical models underpredict the late time X-ray flux by at least 2 orders of magnitude and cannot account for the slow initial decline rate seen in the X-ray afterglow, $F_\nu \propto t^{-\alpha}$, with $\alpha \approx 1/4$. This argues against a spherical explosion with low energy content.

It might be possible, for instance, that in addition to the quasi-spherical, relativistic component (relevant to the afterglow), there is also a subrelativistic outflow with lower γ (heavier loading of baryons) ejected by SN 2003lw in other directions. This slower matter could in principle produce a nearly flat X-ray light curve for the first few days, followed by a decay as the matter decelerated in the stellar wind (Waxman 2004; Granot & Ramirez-Ruiz 2004). This type of behavior bears some similarities to the X-ray light curve seen in GRB 980425 (Kouveliotou et al. 2004). This modified geometry, however, could not meet the constraints posed by the observations. This is because the corresponding (shock driven) radio emission produced by SN 2003lw would be ~30 times too high, thus rendering this type of model unacceptable.

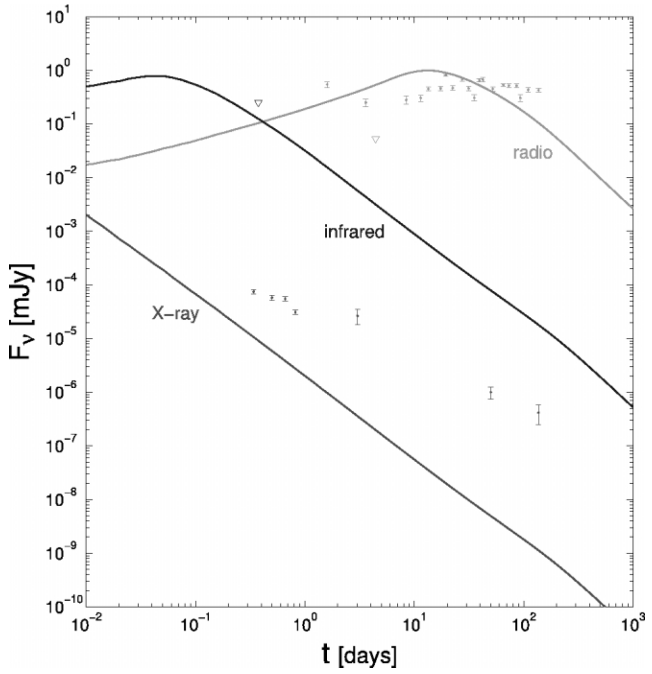

FIG. 1.—Afterglow emission from a spherical, subenergetic blast wave. A tentative fit to the radio (8.5 GHz; S04), infrared (*K* band; Malesani et al. 2004), and X-ray (0.3–10 keV; Watson et al. 2004b). The microphysical parameters and the properties of both the external medium and burst energetics are chosen to exactly match those derived by S04 for the emission of GRB 031203. The last X-ray point was obtained with 30 ks of *Chandra* Director's Discretionary Time. During that observation we detected a source with flux of $(4 \pm 3) \times 10^{-15}$ ergs cm^{-2} s^{-1}, assuming a power-law photon index of 1.7 and $N_{\rm H}$ consistent with the previous *Chandra* and *XMM* observations. [*See the electronic edition of the Journal for a color version of this figure.*]

4. AN OFF-AXIS MODEL

Given that most GRBs are collimated into narrow jets (Frail et al. 2001), their observed properties will inevitably vary depending on the angle $\theta_{\rm obs}$ from their symmetry axis at which they are viewed. If we assume a homogeneous sharp-edged jet, the burst seen by all observers located within the initial jet aperture, $\theta_{\rm obs} < \theta_0$, is practically the same, but beyond the edges of the jet the emission declines precipitously (Woods & Loeb 1999; Granot et al. 2002; Yamazaki et al. 2002). In the latter case, the observed prompt GRB emission and its early afterglow are very weak, owing to the relativistic beaming of photons away from the line of sight. Thus, an observer at $\theta_{\rm obs} > \theta_0$ sees a rising afterglow light curve at early times (as the Lorentz factor decreases with time) peaking when the jet Lorentz factor reaches $\sim 1/(\theta_{\rm obs} - \theta_0)$ and approaching that seen by an on-axis observer at later times. This is because the emission remains at a very low level until the Doppler cone of the beam intersects the observer's line of sight. This can be seen by comparing the $\theta_{\rm obs} = \theta_0$ and $\theta_{\rm obs} = 2\theta_0$ curves in Figure 2.

The off-axis jet interpretation of GRB 031203 requires the viewing angle to have been $\theta_{\rm obs} \sim 2\theta_0$ (Fig. 2). This interpretation assumes that our line of sight is a few degrees from a sharp-edged conical jet. A misaligned jet with a typical energy expanding into a stellar wind with properties similar to those of Wolf-Rayet stars is consistent with the observations, especially with the slow initial decline rates seen in both the X-ray (Watson et al. 2004a) and radio (S04) afterglows.[10] Interestingly, if the jet axis had been closer to the observer's direction ($\theta_{\rm obs} < 2\theta_0$), the brightness of its infrared afterglow would have prevented the detection of SN 2003lw (Malesani et al. 2004).

The constraints imposed by the properties of the afterglow data thus favor the idea that GRB 031203 was a *typical* GRB jet seen at $\theta_{\rm obs} > \theta_0$. One question that naturally arises is whether the observed gamma-ray flux of GRB 031203 can be explained within the framework of this model. We consider below a geometry of a jet with sharp edges seen at $\theta_{\rm obs} > \theta_0$; in that case, the prompt emission comes from narrowly beamed material moving along the edge of the jet that is closest to our line of

[10] When comparing model predictions with radio observations one should expect an approximate rather than exact agreement, as large fluctuations seen in the centimeter-wave radio fluxes are likely due to interstellar scintillation when the early fireball is nearly a point source.

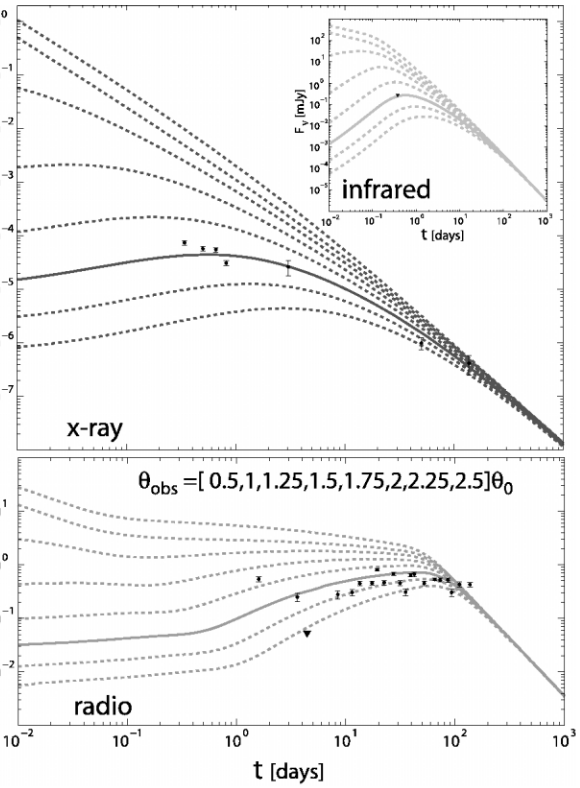

FIG. 2.—Afterglow emission from a sharp-edged uniform jet in GRB 031203. Light curves calculated for various viewing angles $\theta_{\rm obs}$ for a GRB with the standard parameters $E_{\rm jet} = 3 \times 10^{50}$ ergs, $p = 2.4$, $\epsilon_e = 0.15$, $\epsilon_B = 0.02$, $\theta_0 = 5°$, and $A_* = (\dot{M}/10^{-5}\ M_\odot\ {\rm yr}^{-1})(v_w/10^3\ {\rm km\ s}^{-1})^{-1} = 0.1$. The data for GRB 031203 can be reasonably fit by different sets of model parameters (i.e., the parameters cannot be uniquely determined by the data). For example, a sharp-edged jet with $\theta_0 = 3.^\circ5$ seen at $\theta_{\rm obs} \approx 2.25\theta_0$ also gives a reasonably good description of the observations provided that $\epsilon_e = 0.1$ and $\epsilon_B = 0.04$. [*See the electronic edition of the Journal for a color version of this figure.*]

sight. This is since the relativistic beaming of light away from our line of sight is smallest within this region when compared to other parts of the jet.

Because of the relativistic motion of jet ejecta, with Lorentz factor $\gamma \gtrsim 100$ during gamma-ray emission, the gamma rays are concentrated into a cone of opening angle comparable to the jet opening angle θ_0 (assuming $\theta_0 > 1/\gamma$). Thus, if the jet is viewed from a direction making an angle larger than θ_0 with the jet axis, the gamma-ray flux may be strongly suppressed. For an off-axis GRB jet with bulk Lorentz factor γ, $E_{\gamma,\rm iso} \propto [\gamma(\theta_{\rm obs} - \theta_0)]^{-6}$ (for $\theta_{\rm obs} - \theta_0 \gtrsim 1/\gamma$), while the typical peak photon energy in the cosmological frame scales as $E_p \propto [\gamma(\theta_{\rm obs} - \theta_0)]^{-2}$ (e.g., Granot et al. 2002). This also implies that when seen off-axis E_p will fall away from the Amati relation (Amati et al. 2002; Lloyd-Ronning & Ramirez-Ruiz 2002), $E_p \propto E^{1/2}_{\gamma,\rm iso}$, by a factor of $\gamma(\theta_{\rm obs} - \theta_0)$ (Fig. 3). The low $E_{\gamma,\rm iso}$ of GRB 031203 implies[11]

$$\theta_0 = 3.^\circ8 \left(\frac{E_{\gamma,\rm iso}}{10^{50}\ {\rm ergs}}\right)^{-1/8} \left(\frac{E_{\rm jet}}{3 \times 10^{50}\ {\rm ergs}}\right)^{1/8} \left(\frac{\gamma\Upsilon}{50}\right)^{-3/4}, \qquad (1)$$

where $E_{\rm jet}$ is the kinetic energy of the jet and $\Upsilon = \theta_{\rm obs}/\theta_0 - 1$. The fiducial values in equation (1) were chosen to match those of GRB 031203, which were either observed ($E_{\gamma,\rm iso} \sim 10^{50}$ ergs) or inferred from the fit to its afterglow ($\theta_0 \sim 3°$–$5°$, $E_{\rm jet} \sim 3 \times 10^{50}$ ergs, $\Upsilon \approx 1$), and they imply $\gamma \sim 50$. Equation (1) gives

$$\gamma(\theta_{\rm obs} - \theta_0) = 3.3 \left(\frac{E_{\gamma,\rm iso}}{10^{50}\ {\rm ergs}}\right)^{-1/8} \left(\frac{E_{\rm jet}}{3 \times 10^{50}\ {\rm ergs}}\right)^{1/8} \left(\frac{\gamma\Upsilon}{50}\right)^{1/4}, \qquad (2)$$

which implies more typical values of $E_p \sim 2$ MeV (given the

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[11] This follows from the scaling $E_{\gamma,\rm iso} \propto [\gamma(\theta_{\rm obs} - \theta_0)]^{-6}$ for $\gamma(\theta_{\rm obs} - \theta_0) \gtrsim 1$, assuming that the energy radiated in the prompt emission, $E_\gamma \approx (\theta_0^2/2)E_{\gamma,\rm iso}(\theta_{\rm obs} < \theta_0)$, is comparable to $E_{\rm jet}$.

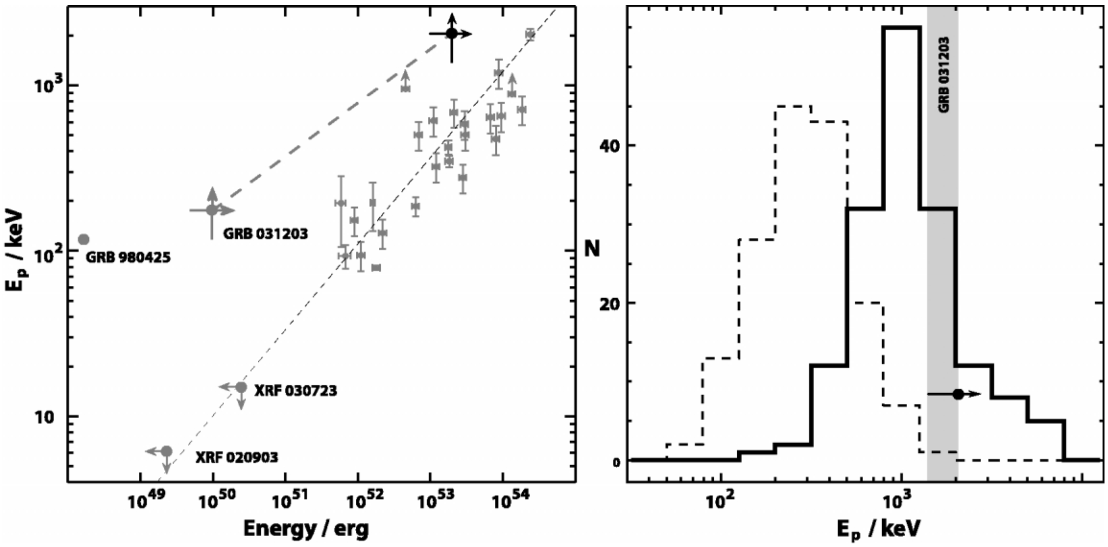

FIG. 3.—Constraints on the possible existence of a misaligned, sharp-edged jet in GRB 031203. *Left*: Location of GRB 031203 in the E_p-$E_{\gamma,\rm iso}$ plane. The compilation of observed E_p and $E_{\gamma,\rm iso}$ in the source frame derived by Ghirlanda et al. (2004) are also illustrated. If GRB 031203 were viewed on-axis (at $\theta_{\rm obs} < \theta_0$), the peak of the spectrum and the isotropic equivalent energy would be ∼2 MeV and $\sim 10^{53}$ ergs, respectively (*black symbol*). *Right*: Histogram of burst peak energies in their cosmological rest frame for BATSE events (Lloyd-Ronning & Ramirez-Ruiz 2002). Superposed on the plot (*dotted line*) is the histogram of the observed peak energy.

observed value $E_p \sim 190$ keV) and $E_{\gamma,\,\mathrm{iso}} \sim 10^{53}$ ergs when observed on-axis (Fig. 3). These values fall somewhat above the Amati relation, but this is not alarming given that a reasonable fraction of BATSE bursts are also not consistent with this empirical law[12] (e.g., Nakar & Piran 2004).

These results are applicable in the present context provided only that one further condition is satisfied, namely, that the (on-axis) jetted outflow be optically thin to high-energy photons (e.g., Lithwick & Sari 2001). For a burst with $E_p \sim 2$ MeV, γ must exceed ∼50.

We consider the required value of $\gamma \sim 50$ and an inferred core value of $E_p \sim 2$ MeV to be reasonable for a jet viewed outside of the core. Close to the rotation axis, γ may be high, while near its edge there will likely be an increasing degree of entrainment with a corresponding decrease in γ (Zhang et al. 2004). Moreover, in the internal shock model, $E_p \propto \gamma^{-2}$ (e.g., Ramirez-Ruiz & Lloyd-Ronning 2002), so that for most lines of sight within the jet aperture, where γ is slightly higher than in the edges, an observer would naturally detect bursts with lower values of E_p. Off-axis observers, on the other hand, see mainly the edge of the jet where γ is lower than in the axis and would thus tend to infer higher (on-axis) values of E_p.

Another possibility is that the jet does not have sharp edges but wings of lower energy and Lorentz factors that extend to large θ. Such a picture of the jet was suggested by Woosley et al. (1999) and is consistent with the relativistic studies of the collapsar model by Ramirez-Ruiz et al. (2002) and Zhang et al. (2004). GRB 031203 would then be produced by the interaction of relativistic material moving in our direction with the circumstellar medium—the wind of the preexplosive star. Unfortunately, it is difficult, in the simplest version of this model, to account for the prompt emission in GRB 031203. If one is restricted to producing the burst by an external shock interaction using a geometrically thin blast wave, the observed duration and hardness are incompatible. Details of this model and attempts to extend it will be discussed elsewhere.

5. CONCLUSION

The characteristic energy scale for common GRBs has been debated for a long time, in particular, the question of whether all GRBs are, in some sense, a standard explosion with a nearly constant energy. The GRB community has vacillated between initial claims that the GRB intrinsic luminosity distribution was very narrow (Horack et al. 1994), to discounting all standard candle claims, to accepting a standard total GRB energy of $\sim 10^{51}$ ergs (Frail et al. 2001), to diversifying GRBs into “normal” and “subenergetic” classes (S04).

The recent discovery of the faint GRB 031203 has been argued to support the existence of at least two classes of GRB/SN Ib/c events based on different amounts of energy released during the initial explosion. In this Letter, we have examined two possible interpretations of the observations of GRB 031203 based on the premise that it was either an *ordinary* GRB observed off-axis or an intrinsically weak, nearly isotropic explosion. We conclude that the observations, especially the slow initial decline rates seen in the X-ray afterglow, are more consistent with an off-axis model in which GRB 031203 was a much more powerful GRB seen at an angle of about 2 times the opening angle of the central jet.[13] Early and detailed X-ray observations of GRB afterglows would provide more stringent constraints on the jet geometry and energetics.

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[12] Although this conclusion is debated (see, e.g., Bosnjak et al. 2005).

[13] This conclusion is also supported by a statistical argument for the number of observed low-redshift GRBs (Guetta et al. 2004).

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