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AN OFF-AXIS MODEL FOR GRB 031203

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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 sub-energetic 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 sub-energetic 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 (redshift corrected) peak energy, $E_{\rm p}$, of GRB 031203 then becomes ~ 2 MeV, similar to many other GRBs.

Subject headings: stars: supernovae – gamma-rays: bursts – hydrodynamics – ISM: jets and outflows

1. INTRODUCTION

The first evidence that gamma-ray bursts 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 time scale and spectrum, GRB 980425 had a total gamma-ray energy, assuming isotropic emission, of only $E_{\gamma,\rm iso} \sim 10^{48}$ ergs, some 4-6 orders of magnitude less than a typical GRB (Frail et al. 2001). 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 five 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 $E_{\gamma,\rm iso} \sim 10^{50}$ ergs (Sazonov et al. 2004). In fact its gamma-ray power was intermediate between GRB 980425 and more typical bursts with (isotropic) energies in excess of 10^{53} ergs (Frail et al. 2001). 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 afterwards, 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). 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 two 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) that the *only* explanation of the faint nature of both GRB 031203 and GRB 980425 is that they were intrinsically sub-energetic, that is the energy ejected in relativistic matter at all angles was orders of magnitude less than in all other GRBs studied to date. Further it has been suggested that the afterglow data are only consistent with a nearly spherical explosion - that GRB 031203 was not a jet-like phenomenon (S04). We disagree with both conclusions and show here that the data of GRB 031203, especially the early X-ray afterglow light curve, do not require a sub-energetic 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.

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. The synchrotron spectrum is taken to be a piecewise power law (Sari, Piran & Narayan 1998). In §3 we begin with a simple model where 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) which show relatively little lateral expansion as long as the jet is relativistic. The light curves for observers located at different 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.

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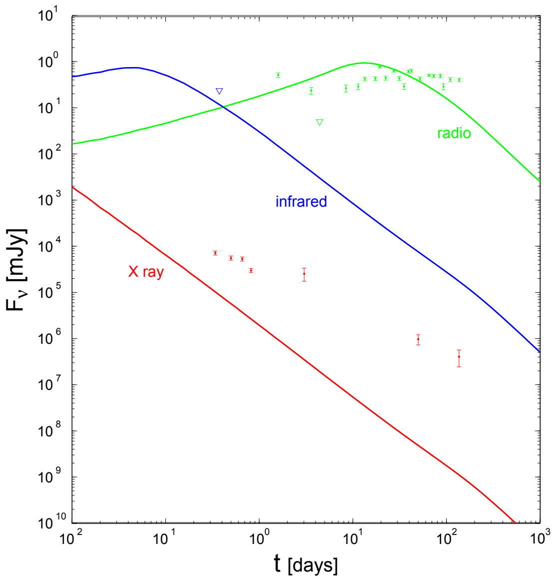

FIG. 1.— Afterglow emission from a spherical, sub-energetic blastwave. The micro-physical parameters and the properties of both the external medium and burst energetics are chosen to exactly match those derived by S04 for the emission of GRB 031203. The last X-ray point was obtained with 30 ks of Director's Discretionary Time of Chandra. During that observation we detected a source with flux of $4\pm3\times10^{-15}$ erg cm^{-2} s^{-1}, assuing a power law photon index of 1.7 (consistent with the extrapolation of the previous two observations; see also Watson et al. 2004b).

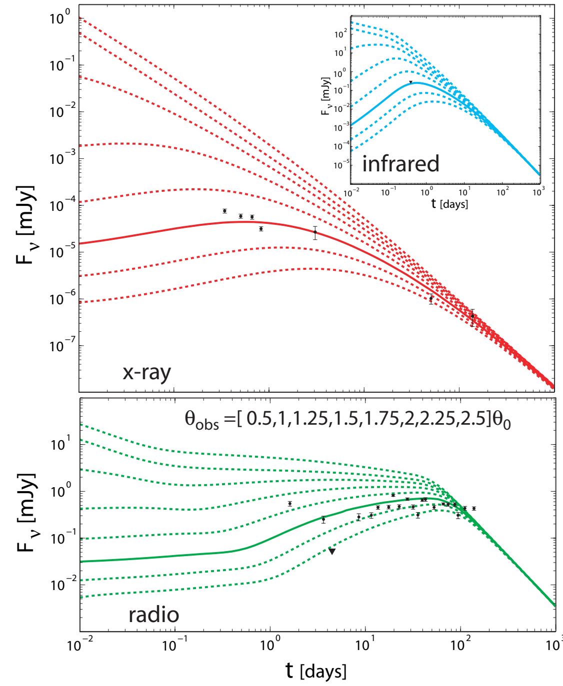

FIG. 2.— Afterglow emission from a sharp edged uniform jet in GRB 031203. Light curves calculated for various viewing angles $\theta_{\rm obs}$ for a GRB with the standard parameters $E_{\rm jet}=3\times10^{50}$ erg, $p=2.4$, $\epsilon_e=0.15$, $\epsilon_B=0.02$, $\theta_0=5^\circ$, and $A_*=(\dot{M}/10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1})(v_w/10^3\,{\rm km\,s}^{-1})^{-1}$=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 $\theta_0=3.5^\circ$ seen at $\theta_{\rm obs}\approx2.25\theta_0$ gives also a reasonably good description of the observations provided that $\epsilon_e=0.1$ and $\epsilon_B=0.04$.

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) and this idea is not incompatible 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 infra-red afterglow, the situation is more constrained.

The resulting lightcurves for a sub-energetic spherical model are plotted against the data in Fig. 1. The model parameters are chosen to coincide with those of S04: an energy of $E=1.7\times10^{49}$ 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 moderately well the radio and infrared light curves (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 lightcurve 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 two orders of magnitude and cannot account for the slow initial decline rate seen in the X-ray afterglow, $F_\nu\propto t^{-\alpha}$, with $\alpha\approx1/4$. 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.

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 upon 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 prompt GRB emission and its early afterglow are very weak, owing to the relativistic beaming of photons away from our 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 $\sim1/(\theta_{\rm obs}-\theta_0)$, 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

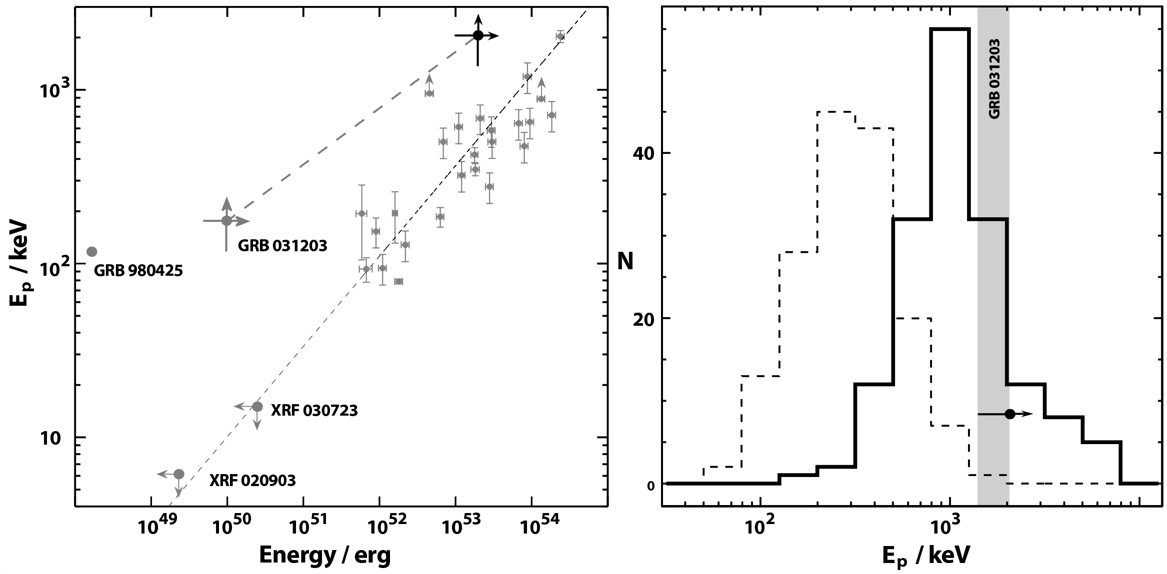

FIG. 3.— Constraints on the possible existence of a misaligned, sharp-edged jet in GRB 031203. *Left Panel:* The location of GRB 031203 in the $E_p - E_{\gamma,\rm iso}$ plane. The compilation of observed E_p and $E_{\gamma,\rm iso}$ in the source frame derived by Ghirlanda, Ghisellini & Lazzati (2004) are also illustrated. If GRB 031203 was 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 Panel:* 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.

$\theta_{\rm obs} = 2\theta_0$ curves in Fig. 2.

The off-axis jet interpretation 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) afterglow[9]. 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 ux 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 which is closest to our line of sight (Granot et al. 2002). 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 ux 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 $E_p \propto [\gamma(\theta_{\rm obs} - \theta_0)]^{-2}$. 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), $E_p \propto E_{\gamma,\rm iso}^{1/2}$, by a factor of $(\theta_{\rm obs} - \theta_0)\gamma$ (Fig. 3). The low $E_{\gamma,\rm iso}$ of GRB 031203 implies

$$\theta_0 = 3.8^\circ \left(\frac{E_{\gamma,\rm iso}}{10^{50}\,\rm erg}\right)^{-1/8} \left(\frac{E_{\rm jet}}{3\times10^{50}\,\rm erg}\right)^{1/8} \left[\frac{\gamma(\Upsilon-1)}{50}\right]^{-3/4}, \tag{1}$$

where $E_{\rm jet}$ kinetic energy of the relativistic jet, and $\Upsilon = \theta_{\rm obs}/\theta_0$. This gives

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

The observed low $E_{\gamma,\rm iso}$ of 031203 combined with the constraints from its afterglow observations give $3E_{\gamma,\rm iso}/E_{\rm jet} \sim 1$. This implies more typical values of $E_p \sim 2$ MeV (given the observed value $E_p \sim 190$ keV) and $E_{\gamma,\rm iso} \sim 10^{53}$ ergs when observed on-axis (Fig. 3). These results are applicable in the present context provided only that one further condition is satis ed, namely, that the (on axis) jetted out ow 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. 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 factor

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

that extend to large θ. Such a picture of the jet was suggested by Woosley, Eastman & Schmidt (1999) and is consistent with the relativistic studies of the collapsar model by Ramirez-Ruiz, Celotti & Rees (2002) and Zhang, Woosley & Heger (2004). GRB 031203 would then be produced by the the interaction of relativistic material moving in our direction with the circumstellar medium – the wind of the pre-explosive star. Unfortunately it is dif cult, 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. 1992), 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 “sub-energetic” 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 upon 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 two times the opening angle of the central jet. Early and detailed X-ray observations of GRB afterglows would provide more stringent constraints on the jet geometry and energetics.

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REFERENCES

Amati, L. et al. 2002, A&A, 390, 81
Galama, T. J. et al. 1998, Nature, 395, 670
Frail, D. A. et al. 2001, ApJ, 562, L55
Frail, D. A., Kulkarni, S. R., Berger, E. & Wieringa, M. H. 2003, AJ, 125, 2299
Ghirlanda, G., Ghisellini, G., & Lazzati, D. 2004, ApJ in press, astro-ph/0405602
Granot, J, Miller, M., Piran, T., Suen, W. M., & Hughes, P. A. 2001, in Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 312
Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. 2002, ApJ, 570, L61
Granot, J., & Kumar, P. 2003, ApJ, 591, 1086
Granot, J., & Ramirez-Ruiz, E. 2004, ApJ, 609, L9
Horack, J. M. et al. 1992, ApJ, 426, L5
Kouveliotou, C. et al. 2004, ApJ, 608, 872
Kulkarni et al. 1998, Nature, 395, 663
Lithwick, Y., Sari, R. 2001, ApJ, 555, 540
Lloyd-Ronning, N., & Ramirez-Ruiz, E. 2002, ApJ, 576, 101
Malesani, J. et al. 2004, ApJ, 609, L5
Prochaska, J. X. et al. 2004, ApJ, 611, 200
Ramirez-Ruiz, E., Celotti, A., & Rees, M. J. 2002, MNRAS, 337, 1349
Ramirez-Ruiz, E., Lloyd-Ronning, N. M. 2002, New Astron., 7, 197
Ramirez-Ruiz, E., & Madau, E. 2004, ApJ, 608, L89
Sazonov, S. Y., Lutovinov, A. A. & Sunyaev, R. A., 2004, Nature, 430, 646
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Soderberg, A. M. et al. 2004, Nature, 430, 648
Thomsen, B. et al. 2004, A&A, 419, L21
Watson, D. et al. 2004a, ApJ, 605, L101
Watson, D. et al. 2004b, A&A, 425, L33
Waxman, E. 2004, ApJ, 605, L97
Woods, E., & Loeb, A. 1999, ApJ, 523, 187
Woosley, S., Eastman, R., & Schmidt, B. 1999, ApJ, 516, 788
Yamazaki, R., Ioka, K, & Nakamura, T. 2002, ApJ, 571, L31
Zhang, W., Woosley, S. E., & Heger, A. 2004, ApJ, 608, 365