Deriving the Jet Opening Angle of GRBs from the Prompt Gamma-Ray Emission

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Background

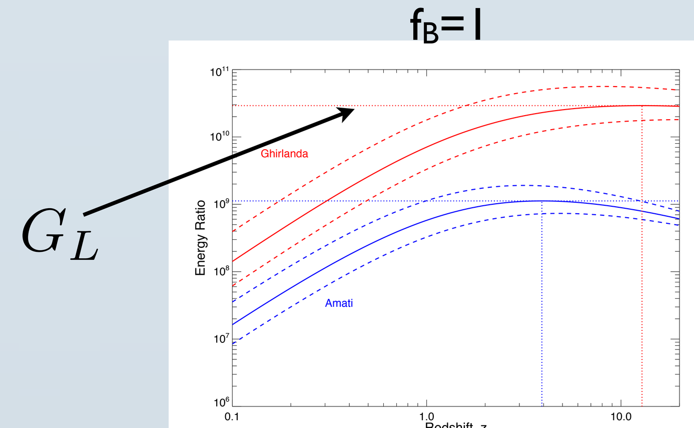
The jet opening angle is an important parameter for determining the characteristics of the progenitor, and the information contained in the opening angle gives insight into the relativistic outflow and the total energy that is contained in the burst. Unfortunately, a confident inference of the jet opening angle usually requires broadband measurement of the afterglow of the GRB, from the X-ray band down to the radio and from minutes to days after the prompt gamma-ray emission, which may be difficult to obtain. For this reason, very few of all detected GRBs have constrained jet angles. We present an alternative approach to derive jet opening angles from the prompt emission of the GRB, given only that the GRB has a measurable and constrained E_{peak} and Fluence. We present the distribution of derived jet opening angles for bursts from the first two-years of the Fermi/GBM as well as from the entire mission of BATSE, and we compare a number of our derived opening angles to the reported opening angles using the traditional afterglow method. We derive the collimation-corrected gamma-ray energy E_γ, for GRBs with redshift and find that some of the GRBs in our sample are inconsistent with a proto-magnetar progenitor. Finally, we show that the use of the derived jet opening angle results in a tighter correlation between the rest-frame E_{peak} and E_γ than has previously been presented, which places long GRBs and short GRBs onto one empirical power law.

The derivation of jet opening angles from prompt emission was realized when studying the E_{peak}-Fluence distributions of BATSE GRBs and the indication that a combination of E_{peak} and Fluence produce a distinction between long and short GRBs (Goldstein et al. 2010). Nakar & Piran (2005) and Band & Preece (2005) devised a method using the observed E_{peak} and Fluence to test the E_{peak}-Energy relations, namely the Amati (Amati et al. 2002) and Ghirlanda (Ghirlanda et al. 2004) relations, with GRBs that have no known redshift. They rearranged the power law relations between E_{peak} and E_{iso} into equations with a ratio of physical observables on one side and a function of redshift on the other:

$$\frac{(E_{peak}^{obs})^{1/\eta_i}}{S_\gamma} \propto F(z)$$

where S_γ is the "bolometric" Fluence and η_i is the best fit power law index for the respective relations. They showed that this ratio was degenerate as a function of redshift, and therefore had a maximum value as shown below. Note that the beaming factor for the Ghirlanda relation is unity for this plot, indicating no collimation.

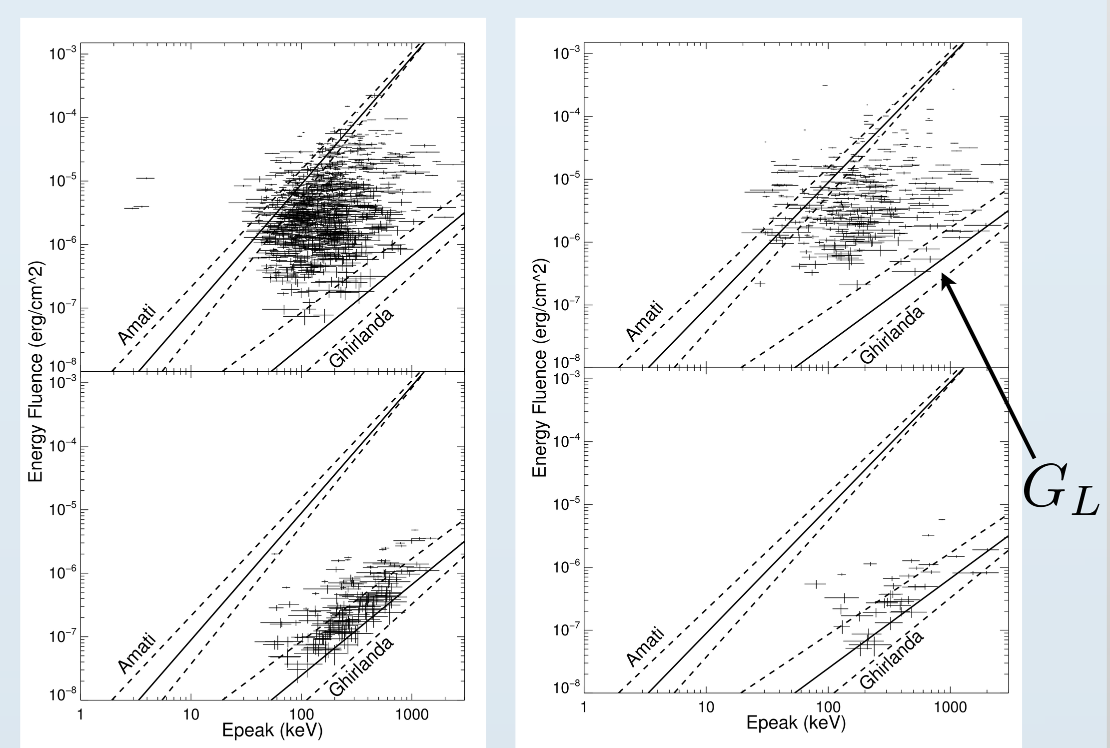
$f_B = 1$



The maximum enforces a physical upper limit in this plot, whereby a particular combination of E_{peak} and Fluence is not physically allowable above the upper limit for the relation to be valid. If a burst does fall above this limit, it cannot conform to the proposed relation, even if the redshift is not known.

Derivation

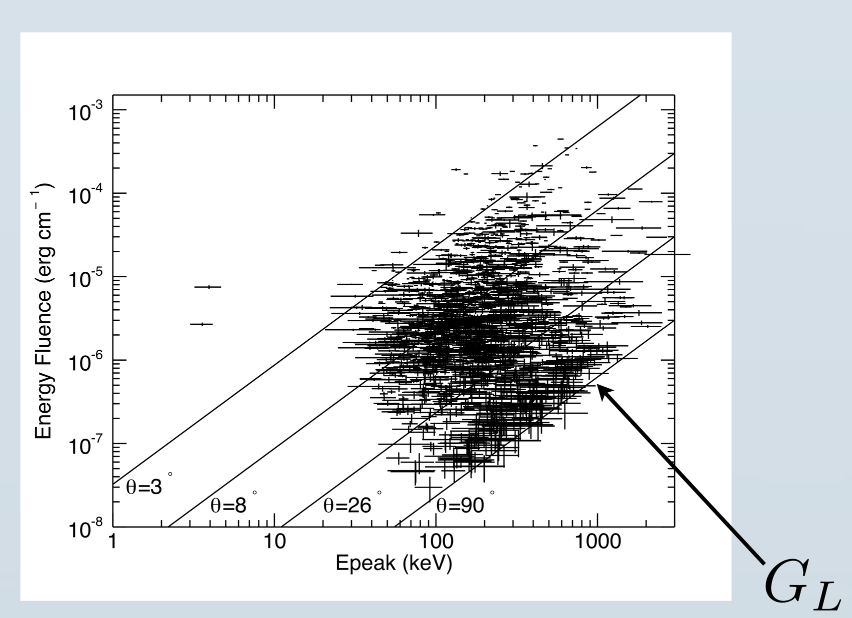
The upper limit can then be translated into a lower limit in the observed E_{peak}-Fluence plane and constrained burst values can be over-plotted to determine if the relations were violated by a large number of bursts. Below, we show the plot of BATSE GRBs (left) and GBM GRBs (right) separated by burst classification. Although a large percentage of the GRBs violate the Amati lower limit, even accounting for dispersion, not a single GRB in our sample of over 1500 violate the Ghirlanda limit. In fact, it is worth noting that a cutoff is apparent near the Ghirlanda limit and tracks a power law.



Assuming the cutoff is true and not an artifact of detector sensitivity or selection effects, the relation between the E_{peak}, fluence, and lower limit can be formed. Utilizing the definition of the Ghirlanda relation, we can show that the limit contains information about the opening angle, and we can rearrange the definition to derive the opening angle for every single burst from the following equation:

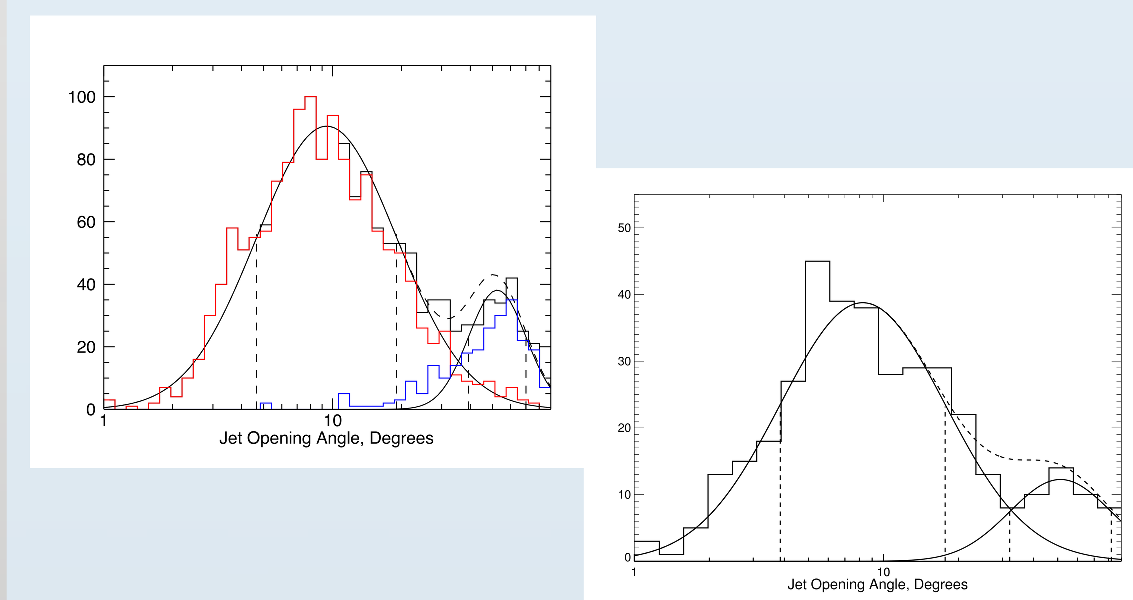
$$\theta = \cos^{-1}\left(1 - \frac{E_{peak}^{1/\eta}}{S_\gamma\ G_L}\right)$$

The effect of changing the beaming factor (opening angle) effectively causes the line to shift along the fluence axis such that any burst that falls on the line is described by that particular opening angle. Effectively, this produces contours of constant opening angle as shown below.



Jet Opening Angles

It is worth noting that although the Ghirlanda limit is remarkably similar to the cutoff in the E_{peak}-Fluence plane, any number of functions could be devised to peak and roll-over at the same upper limit. Therefore, it is the combination of parameters describing the upper limit that is important rather than the particular best fit parameters for the Ghirlanda relation. The additional constraint that we impose is that the limit is representable of an opening angle, which is the main reason why we draw a parallel to the Ghirlanda relation; it shows a relationship between E_{peak}, Fluence, and opening angle. We exploit this relationship and show the derived opening angles below for BATSE GRBs (left) and GBM GRBs (right).



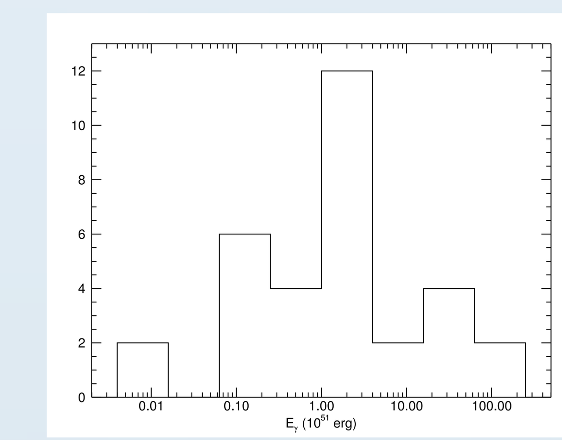
The over-plotted red histogram in the BATSE distribution indicates the opening angles for traditionally long GRBS (> 2s) and the blue distribution shows the opening angles for short GRBs. This suggests that on the average long GRBs are much more collimated than short GRBs. The distributions agree with current theory on GRB jet formation and geometry (Livio & Waxman 1999; Panaitescu & Kumar 2002, Nakar 2007). In the table below we show the reported jet opening angles for GBM bursts and compare them to our derived jet opening angles in degrees. A number of the derived angles in the table have large errors which are not necessarily representative of the error in the distributions, due to the fact that some of the bursts in the table have spectra which are not well constrained, and so the error propagates from the poor spectral fits. Roughly half of the angles in the distributions have a relative error better than 10%. The table shows that so far we have agreement within errors of the reported angled from the afterglow method, although this sample is relatively small, and we obviously require a larger sample to make a more confident statement.

GRB	Reported Angle(s)	Derived Angle	Reference
080810	> 4[b]	13.8 +/- 6.4	Page et al. 2009
080916C	> 6.1[a]	5.2 +/- 1.6	Greiner et al. 2009
081008	> 2.1[a]	6.4 +/- 4.0	Yuan 2010
090323	< 2.1[a], 2.6[b] (+0.6/-0.1)	4.3 +/- 1.3	McBreen et al. 2010, Cenko et al. 2010
90328	< 5.5[a], 5.2[b] (+1.4/-0.7)	6.6 +/- 11.9	McBreen et al. 2010, Cenko et al. 2010
090423	> 12[a]	11.0 +/- 7.0	Chandra et al. 2010
090902B	> 6.4[a], 3.4[a] (+0.4/-0.3)	4.1 +/- 0.6	McBreen et al. 2010, Cenko et al. 2010
090926A	> 9.9[a], 7.0[b] (+3.0/-1.0)	7.6 +/- 2.6	Rau et al. 2010, Cenko et al. 2010

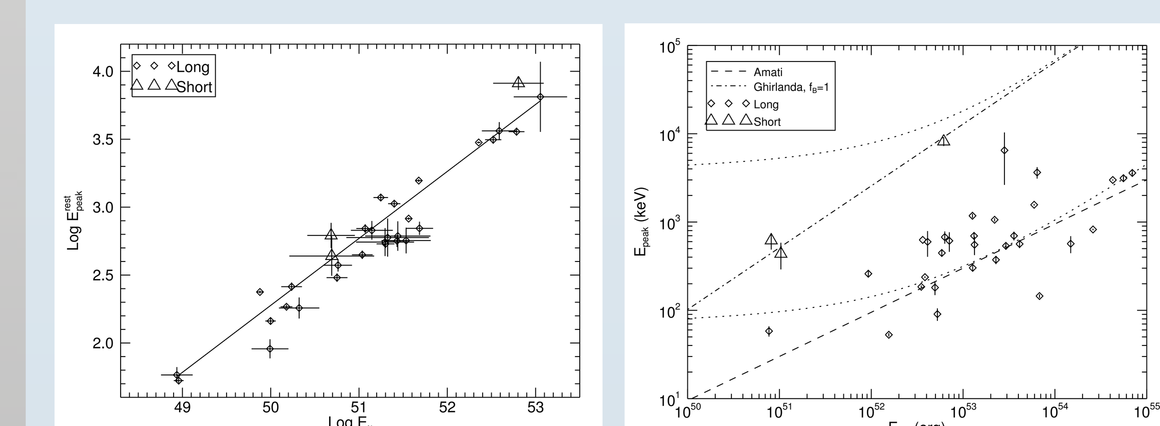
[a]ISM [b]Wind medium

Results

Using the jet opening angle and the redshift, we can calculate the collimation-corrected energy, E_γ. We present the distribution of E_γ for 32 GBM GRBs that have an observed redshift. The distribution peaks at about 10^{51} erg, similar to the distribution found by Frail et al. (2001), but the distribution is much broader. This may be due to the fact that our sample size is 3 times larger than the sample used in Frail et al. (2001). It should be noted that 6 GRBs (5 long, 1 short) have an E_γ > few x 10^{52} erg, which implies that some potential progenitor models, such as proto-magnetars cannot be used to describe these bursts.



In addition, we show the rest-frame E_{peak}-E_γ correlation (left). For the first time, we show long and short GRBs follow the same power law relation with very little scatter. For comparison we show the same data over-plotted on the Amati and Ghirlanda (no collimation) relations (right). Note the reason that short GRBs do not follow the Amati relation is that they appear to be much less collimated.



$$E_{peak}^{rest} = (589 \pm 18\ \mathrm{keV})\left(\frac{\mathrm{E}_\gamma}{10^{51}\ \mathrm{erg}}\right)^{0.49 \pm 0.01}$$

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