

ON THE KINETIC ENERGY AND RADIATIVE EFFICIENCY OF GAMMA-RAY BURSTS

NICOLE M. LLOYD-RONNING¹, BING ZHANG²

¹ Los Alamos National Lab., MS D436, Los Alamos NM, 87544; ronning@lanl.gov

²Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16803; bzhang@astro.psu.edu

Draft version April 12, 2019

ABSTRACT

Using measured X-ray luminosities to 17 Gamma-Ray Bursts (GRBs) during the afterglow phase and accounting for radiative losses, we calculate the kinetic energy of these bursts and investigate its relation to other GRB properties. We then use the observed radiated energy during the prompt phase to determine the radiative efficiency of these bursts, and explore how the efficiency relates to other GRB observables. We find that the kinetic energy in the afterglow phase is directly correlated with the radiated energy, total energy as well as possibly the jet opening angle and spectral peak energy. More importantly, we find the intriguing fact that the efficiency is correlated with the radiated energy, and mildly with the total energy, jet opening angle and spectral peak energy. XRF020903 also seems to follow the trends we find for our GRB sample. We discuss the implications of these results for the GRB radiation and jet models.

1. INTRODUCTION

In the past several years, there has been a significant increase in our understanding of the energetics of Gamma-Ray Bursts (GRBs). By measuring the fluence during the prompt phase (usually when most of the energy is emitted), and determining the burst redshift and degree to which the outflow is beamed from afterglow, one can make an estimate of the radiated energy of the burst. Frail et al. (2001) showed that in fact most GRBs with measured redshifts have radiated energies distributed very narrowly around the value 5×10^{50} erg. This conclusion is confirmed by Bloom, Frail & Kulkarni (2003) with a larger jet data sample. Understanding this energy output is of course crucial in helping constrain progenitor models. However, an often overlooked point in discussing GRB energetics is that the radiated energy is not necessarily the *total* energy of the burst. The radiated energy is some unknown fraction of the initial kinetic energy of the outflow - i.e. the kinetic energy is converted to radiation via some shock (or other) interaction(s) in the burst ejecta. It is this kinetic energy or, more precisely, the *efficiency* of converting kinetic energy to radiation that must be considered when discussing GRB energetics. This efficiency may help us better understand by what mechanism the kinetic energy becomes radiation. It may also play an important role in understanding so-called “X-ray Flashes” (XRFs; GRBs with lower spectral peak energy and flux) - i.e. XRFs may well be GRBs with much smaller emission efficiency. To assess the kinetic energy, the most adequate method is through broadband afterglow fits (e.g. Panaitescu & Kumar 2001), while another convenient method is to study the X-ray afterglow data alone (Freedman & Waxman 2001). Using both methods, it has been found that the kinetic energy - corrected for the degree of beaming of the outflow - is also narrowly distributed (Panaitescu & Kumar 2001; Piran et al. 2001, under the assumption that there is a correlation between X-ray luminosity and beaming corrections). The result (as well as the validity of the Piran assumption) is confirmed by Berger, Kulkarni & Frail (2003) with a larger

X-ray afterglow data sample. Although these works are the first to present calculations of burst kinetic energies, to our knowledge there are no detailed studies of correlations between kinetic energy or GRB efficiency with other burst properties.

With these points in mind, we derive the absolute values of GRB kinetic energy for a large data sample, and investigate the behavior of the kinetic energy and efficiency of GRBs, in relation to other burst properties (such as radiated energy, total energy, characteristic jet angle, and spectral peak energy). The paper is organized as follows: In §2, we describe how to compute the kinetic energy and efficiency of GRBs from the observed X-ray afterglow data. We also discuss the basic assumptions and caveats with our method. In §3, we present our results, including the correlation of kinetic energy and efficiency with other burst properties. Our main results shown that both kinetic energy and efficiency are correlated with radiated energy and to some extent, total energy. There are also suggestions of relations with the jet opening (or viewing) angle and the spectral peak energy, although additional data are needed to confirm this. In §4, we discuss the physical implications of these results, and in §5, present our summary and conclusions.

2. COMPUTING GRB EFFICIENCY

We define the GRB efficiency as

$$\zeta \equiv E_{\gamma}/(E_k + E_{\gamma}) \quad (1)$$

where E_{γ} is the radiated energy in the prompt phase and E_k is the burst kinetic energy remaining during the afterglow phase (see below). In what follows, all energies will refer to the isotropic equivalent energies. Since both energy components are corrected the same way when the beaming factor included, the GRB efficiency does not depend on the unknown beaming configuration, and is therefore jet model independent. The radiated energy is obtainable through direct measurement, and we take ours from Table 2 of Bloom, Frail and Kulkarni (2003). The kinetic energy can be readily calculated from the X-ray luminosity

during the afterglow phase, in the context of the standard afterglow model (Mészáros & Rees 1997; Sari, Piran & Narayan 1998). In this model, the specific flux at a particular frequency depends on, among other parameters, the total kinetic energy in the fireball. In particular, since at a late afterglow epoch the X-ray band is above the cooling frequency, the X-ray luminosity is only sensitively dependent on E_k and ϵ_e ¹ (the electron equipartition parameter), so that the X-ray luminosity at a certain afterglow epoch is a sensitive probe for E_k (Freedman & Waxman 2001).

Using the standard afterglow model (e.g. Hurley, Sari & Djorgovski 2002), we can calculate ν_m , the characteristic frequency corresponding to the minimum electron energy, ν_c , the synchrotron “cooling” frequency, and $F_{\nu,m}$, the peak synchrotron flux, at 10 hr after the burst trigger.

$$\begin{aligned} \nu_m &= 1.15 \times 10^{15} \text{ Hz} \left(\frac{p-2}{p-1} \right)^2 \left(\frac{1+z}{2} \right)^{1/2} \\ &\times E_{52}^{1/2} \epsilon_{e,-1}^2 \epsilon_{B,-2}^{1/2} t_{10h}^{-3/2}, \end{aligned} \quad (2)$$

$$\begin{aligned} \nu_c &= 9.9 \times 10^{15} \text{ Hz} \left(\frac{1+z}{2} \right)^{-1/2} \\ &\times E_{52}^{-1/2} \epsilon_{B,-2}^{-3/2} n^{-1} t_{10h}^{-1/2}, \end{aligned} \quad (3)$$

$$\begin{aligned} F_{\nu,m} &= 4.0 \times 10^{-26} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \left(\frac{1+z}{2} \right) \\ &\times E_{52} \epsilon_{B,-2}^{1/2} n^{1/2} D_{L,28}^{-2}. \end{aligned} \quad (4)$$

where p is the electron particle spectrum index, z is the burst redshift, n is the ambient density assumed to be constant here, $E_{52} = E_k/10^{52}$ erg, $\epsilon_{e,-1} = \epsilon_e/0.1$ is the fraction of energy in the electrons, $\epsilon_{B,-2} = \epsilon_B/0.01$ is the fraction of energy in the magnetic field, $t_{10h} = t/10$ hr is the time of observation, and $D_{L,28} = D_L/10^{28}$ cm, where D_L is the luminosity distance.

We consider the X-ray band with typical frequency $\nu = 10^{18}$ Hz ν_{18} (which corresponds to ~ 5 keV, the mid-energy for the current X-ray detectors such Chandra or XMM-Newton). The specific flux at this frequency at 10 hours after the burst trigger is:

$$\begin{aligned} F_{\nu,x}(10\text{hr}) &= F_{\nu,m} \nu_m^{(p-1)/2} \nu_c^{1/2} \nu^{-p/2} \\ &= 8.0 \times 10^{-30} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \\ &\times \left(\frac{1+z}{2} \right)^{(p+2)/4} E_{52}^{(p+2)/4} \epsilon_{e,-1}^{p-1} \epsilon_{B,-2}^{(p-2)/4} \\ &\times t_{10h}^{(2-3p)/4} \nu_{18}^{-p/2} D_{L,28}^{-2}. \end{aligned} \quad (5)$$

To get the numerical value of the coefficient, $p = 2.2$ has been adopted. The power indices for various parameters are consistent with Freedman & Waxman (2001). The “isotropic” X-ray afterglow luminosity at 10 hour is then

$$\begin{aligned} L_x(10\text{hr}) &= 4\pi D_L^2 \nu F_{\nu,x}(10h) \\ &= 1.0 \times 10^{46} \text{ erg s}^{-1} \left(\frac{1+z}{2} \right)^{(p+2)/4} \\ &\times E_{52}^{(p+2)/4} \epsilon_{e,-1}^{p-1} \epsilon_{B,-2}^{(p-2)/4} t_{10h}^{(2-3p)/4} \nu_{18}^{(2-p)/2} \end{aligned} \quad (6)$$

¹When a radiative correction is taken into account it is no longer sensitive to ϵ_e ; see below for more discussion.

We finally get

$$\begin{aligned} E_k &= 10^{52} \text{ erg} \mathcal{R} \left(\frac{L_x(10\text{hr})}{10^{46} \text{ erg s}^{-1}} \right)^{4/(p+2)} \left(\frac{1+z}{2} \right)^{-1} \\ &\times \epsilon_{e,-1}^{4(1-p)/(2+p)} \epsilon_{B,-2}^{(2-p)/(2+p)} t_{10h}^{(3p-2)/(p+2)} \nu_{18}^{2(p-2)/(p+2)} \end{aligned} \quad (7)$$

where \mathcal{R} is a factor that accounts for radiative losses during the first 10 hours following the prompt phase (Sari 1997),

$$\mathcal{R} = \left[\frac{t(10h)}{t(\text{prompt})} \right]^{(17/16)\epsilon_e}. \quad (8)$$

Taking $t_{10h} = 1$ and $\nu_{18} = 1$, we can use the X-ray luminosity measurements at 10 hours from Berger, Kulkarni & Frail (2003; their Table 2) to calculate E_k at this time during the afterglow (without the \mathcal{R} correction). However, this kinetic energy is the amount left at 10 hours after the prompt phase. Including the correction factor \mathcal{R} for radiative losses during these initial 10 hours, we can estimate the value of the kinetic energy *at the end of the prompt phase* $\sim 50s$. A list of our energies and efficiencies is presented in Table 1. We note that our efficiencies are relatively high (between 0.4 and 1.0) which challenges the simplest internal shock model (Kumar 1999, Panaitescu, Spada, & Meszaros 1999), although it has been shown that such efficiencies are indeed achievable in an internal shock scenario (Beloborodov 2000, Kobayashi & Sari 2001).

Our error bars on E_γ are taken directly from measurement error listed in Table 2 of Bloom, Frail and Kulkarni (2003). For E_k , we compute the error bar from the measurement error of the X-ray luminosity listed in Table 2 of Berger, Kulkarni, and Frail (2003), and assume that all other parameters are known constants (indeed an important assumption as described in the next subsection). Finally, with both an error bar on E_γ and E_k we can compute the error bar on the efficiency ζ by the standard technique of error propagation (see, e.g. Bevington & Robinson, 2002).

Only one XRF (XRF 020903) has been studied to infer E_k (Soderberg et al. 2004). In Table 1, we include this event although the error bars on the kinetic and radiated energies are not available. Because of only one data point, for all the correlations discussed below, this XRF event is excluded. The data point is however included in the figures when relevant.

2.1. Caveats

The absolute value of the kinetic energy of course plays a big role in the final conclusions we draw from our analysis. This expression depends on the parameters ϵ_e , ϵ_B , and p , but - as one can see from equation 7 above - appears to be most sensitive to ϵ_e . Without the radiative correction \mathcal{R} , the kinetic energy decreases (increases) as ϵ_e increases (decreases) as $E_k \propto \epsilon_e^{-1}$. Correcting for radiative losses, however, offsets this sensitivity to some degree since the exponent of the \mathcal{R} factor depends on ϵ_e . For the range of ϵ_e most commonly suggested by the data (see e.g., Panaitescu & Kumar 2001; Yost et al. 2003) the kinetic energy turns out to be fairly insensitive to ϵ_e . Meanwhile, increasing the exponent p causes the kinetic

energy to increase and hence the efficiency to decrease. The dependence on ϵ_B , as mentioned above is minimal. We also point out that strictly speaking the efficiency we define here (i.e. $\zeta = E_\gamma/(E_\gamma + E_k)$) is only an “apparent efficiency”. It is the real efficiency only when there is no additional kinetic energy injection in the afterglow phase (before 10 hour). This caveat has important implications for the discussions about the jet models in §4.

In what follows below, we present results for $\epsilon_e = 0.3$, $\epsilon_B = 0.01$ and $p = 2.2$. These are typical values obtained from multiwavelengths to the afterglow spectra (Panaitescu & Kumar 2001; Yost et al. 2003). For the often quoted “standard” value of $\epsilon_e = 0.1$, we get *quantitatively* the same results within the error bars. Our results are *qualitatively* the same for ϵ_e in the range of 0.01 – 0.3, p in the range 2.2 – 2.5 and ϵ_B in the range 0.001 – 0.1.

3. RESULTS

We have analyzed the relationship between E_k and E_γ , total energy E_{tot} , characteristic jet angle θ_j (as discussed below this is the jet opening angle in the uniform jet model and essentially the observer’s viewing angle with respect to the jet axis in the quasi-universal jet model), & spectral peak energy E_p , as well as ζ with these variables. In the text, we present all of our analysis, but only show the figures for the variables that exhibit either statistically significant correlations or have implications in interpreting the physics of the outflow. Note that we consider a correlation “statistically significant” if it is $\gtrsim 3\sigma$ according to a standard Kendall’s τ test (e.g., Press et al., 1994). We also point out two important relations which will play a role in the interpretation of our results below. These are the so-called “Frail” and “Amati” relations. The Frail relation (Frail et al., 2001) shows a distinct *negative* correlation between the isotropic radiated energy E_γ and the jet opening angle in a uniform jet model θ_j , such that $E_\gamma \propto \theta_j^{-2}$. The consequence of this is that the geometry corrected emitted energy turns out to be approximately constant (Frail et al., 2001, Bloom, Frail & Kulkarni, 2003). This can be interpreted in two ways. In the “uniform jet model” (Frail et al., 2001), this implies that the same energy is collimated into different opening angles θ_j varying from about 1 to 30 degrees. In the “quasi-universal jet model” (Rossi, Lazzati & Rees, 2002; Zhang & Meszaros 2002; Lloyd-Ronning, Dai & Zhang 2004; Zhang et al. 2004), all GRBs have approximately the same jet structure with an energy that varies (decreases) as a function of angle θ_j from the jet axis. We will return to these models for the GRB jet structure in the discussion. The Amati relation is a relation between the isotropic emitted energy and the spectral peak energy such that $E_\gamma \propto E_p^2$ (Lloyd, Petrosian & Mallozzi 2000; Amati et al., 2001; Lamb, Donaghy & Graziani 2004, Liang, Dai & Wu, 2004) This relation may be providing a key to the GRB emission mechanism (Lloyd, Petrosian & Mallozzi, 2000) and possibly the structure of the GRB jet.

3.1. $E_\gamma - E_k$

A Kendall’s τ test gives the correlation between the radiated energy E_γ and the kinetic energy E_k to be approximately 3σ with a functional form $E_\gamma \propto E_k^{1.0 \pm 0.4}$. These data are plotted in Figure 1. We can see that the XRF

data point, with a kinetic energy of 1.0×10^{50} erg and a radiated energy of 1.1×10^{49} erg qualitatively follows the similar dependence.

The tight correlation between the two components (except the two outliers) is expected. It has been found that both components are essentially constants when corrected by the geometric factor (Berger et al. 2003). This already hints that the two should be correlated. This validates the practice of using E_γ and E_k interchangeably as often done in the literature. We note that Berger et al. have also pointed that some outliers in their sample with apparently low kinetic energy also appear to have a low radiated energy, consistent with the trend we find here.

3.2. $\zeta - E_\gamma$

A Kendall’s τ test gives the correlation between the efficiency ζ and the radiated energy E_γ to be approximately 3σ with a functional form $\zeta \propto E_\gamma^{15 \pm 0.05}$. These data are plotted in Figure 2. Notice that XRF 020903 also falls onto the same correlation. This result is very intriguing. Although for a single burst one expects a higher radiated energy for a higher value of efficiency, there is no a priori reason to expect such a correlation to hold among bursts without introducing any specific GRB models. In fact, if E_γ and E_k is linearly correlated, one should expect ζ to be essentially a constant. Our result is consistent with this expectation to first order, since the correlation index (0.15) is very shallow. Yet, a positive correlation is revealed, which hints that there is a high-order non-linear dependence between E_γ and E_k . Also such a positive correlation potentially carries more information about GRB radiation physics, and may hold the key to differentiate among GRB models. We discuss this further in §4.

3.3. $\zeta - E_k$

The Kendall’s τ test indicates that there is no correlation between the efficiency ζ and the kinetic energy E_k .

3.4. $E_k - E_{tot}$

A Kendall’s τ test gives the correlation between the kinetic energy E_k and the total energy E_{tot} to be approximately 3.6σ with a functional form $E_k \propto E_{tot}^{0.8 \pm 0.2}$. These data are plotted in Figure 3. XRF 020903 also fits the trend we find in the GRB sample, as seen in Figure 3. Such a correlation is not surprising given the correlation between E_k and E_γ and the definition of $E_{tot} = E_k + E_\gamma$.

3.5. $\zeta - E_{tot}$

The Kendall’s τ test indicates that there is no statistically significant correlation between the efficiency ζ and the total energy E_{tot} . However, although the formal significance of the correlation is only $\sim 2\sigma$, the data plotted in Figure 4 suggest that a trend of increasing ζ for increasing E_{tot} . XRF020903 appears to also follow this relationship, as evident in Figure 4.

3.6. $E_k - \theta_j$

A Kendall’s τ test indicates a very mild negative correlation between the kinetic energy E_{kin} and the jet characteristic angle θ_j at the 2.6σ level, with a functional form $E_k \propto \theta_j^{-1.7 \pm 0.4}$. These data are plotted in Figure 5. This

correlation can be understood as a result of the correlation between kinetic energy and radiated energy as well as the Frail relation which shows that radiated energy is inversely proportional to the jet opening angle θ_j . There was no break in the afterglow lightcurve observed for XRF 020903. This could indicate that the characteristic jet angle is very large (which would imply a late or non-existent break in the afterglow light curve), which fits qualitatively with the trend of decreasing kinetic energy for increasing jet angle, as we see here.

3.7. $E_k - E_p$

A Kendall's τ test indicates a 2.2σ (i.e. no significant) correlation between the kinetic energy E_k and spectral peak energy E_p although the eye suggests otherwise; assuming such a correlation the best fit functional form is $E_k \propto E_p^{1.5 \pm 0.5}$. If this correlation is in fact present it can be understood as a consequence of the $E_k - E_\gamma$ correlation and the Amati relation which shows that E_γ is correlated with E_p . This implies that the kinetic energy should be correlated with E_p . Taken at face value, the power-law index of the correlation is also consistent with the Amati relation. XRF 020903, with an $E_p \approx 5$ keV, seems to follow this trend.

3.8. $\zeta - \theta_j$

The Kendall's τ test indicates that there is no statistically significant correlation between the efficiency ζ and the jet opening angle θ_j , although by eye this trend (decreasing efficiency for increasing jet angle) seems apparent, and could be explained as a consequence of the $\zeta - E_\gamma$ correlation and the Frail relation. These data are plotted in Figure 6.

3.9. $\zeta - E_p$

A Kendall's τ test gives the correlation between the efficiency ζ and the spectral peak energy E_p to be approximately 2.5σ . These data are plotted in Figure 7. One can see a clear outlier at high efficiency and $E_p \approx 350$ keV. Eliminating this outlier, the correlation has a significance of 3σ with a functional form $\zeta \propto E_p^{0.45 \pm 0.1}$. Such a relation could be explained by the $\zeta - E_\gamma$ correlation and the Amati relation. Again, XRF 020903 seems to follow this trend with its low efficiency ($\zeta = 0.1$) and $E_p = 5$ keV.

Although fits to afterglow spectra do give surprisingly similar values for ϵ_e , ϵ_B , and p among different bursts, we of course do not expect that all bursts have exactly the same values for these parameters (although simulations of particle acceleration in shocks do find consistently an electron index with a universal value of 2.2). As mentioned in §2, it turns out that the kinetic energy is fairly insensitive to the values of ϵ_B and ϵ_e when the radiative correction is taken into account. We can, however, further explore the sensitivity of our results to the value of the electron index p , by using the measured X-ray afterglow spectral index (i.e. column 5 of Table 1 of Berger, Kulkarni & Frail 2003) to estimate the value of p for each burst. For example, at the time of the afterglow this index is measured, we are in an adiabatic, slow-cooling fireball scenario (see, e.g. Sari, Piran, & Narayan, 1998). In this case we expect that the X-ray spectral index $\alpha_X = 3p/4 - 1/2$. We

can use this equation to solve for p for each burst, and use this p in our computation of the kinetic energy for the GRB. It is important to point out that there is large uncertainty in value of α_X and in fact most of the data from Berger, Kulkarni & Frail are consistent with an electron index $p = 2.2$. Nonetheless, we perform this exercise as an additional check on the robustness of our results. We find that when using individual values of p computed from the X-ray afterglow spectral index, all of the correlations remain with the same functional form as reported above, although the significance is slightly reduced in the case of the $\zeta - E_\gamma$ correlation (from 3σ to 2.5σ . In the case of the $E_k - E_{tot}$ correlation, the significance *increases* from 3.6σ to 4σ .

4. DISCUSSION

We have investigated some correlations between the GRB kinetic energy or efficiency and other observables such as radiated energy, spectral peak energy, characteristic jet angle, etc. Although some of these correlations are expected from the Frail and Amati correlations, we do discover some new correlations, which give us a further glimpse into the physics of GRBs. In particular the correlation between efficiency ζ and radiated energy E_γ has the potential of differentiating between different models for the GRB prompt phase (note that this correlation was also indirectly suggested in Lamb, Donaghy & Graziani, 2003). For example, this relation is consistent with the internal shock model. This is because E_γ has been found to be correlated to the burst variability parameter (a measure of the ‘‘spikiness’’ of the prompt phase lightcurve, Fenimore & Ramirez-Ruiz 2000; Reichart et al. 2001). In the internal shock model of Kobayashi & Sari (2001), the shells separate after each collision and then collide again with other shells. Even with the same Lorentz factor contrast, more shells lead to more collisions and therefore both a higher efficiency and variability. If this hypothesis is true, we should see higher efficiency for bursts with higher variability. Unfortunately, there are currently not enough data to explore a ζ -variability relation. This may be tested with future missions such as Swift or GLAST. Similarly, future more data are needed to verify whether there is a significant $\zeta - E_{tot}$ correlation.

The $\zeta - E_\gamma$ correlation also plays an important role in interpreting the other correlations found in §3 above, when combined with previously determined relations ($E_\gamma \propto \theta_j^{-2}$ and $E_\gamma \propto E_p^2$). For example, the relationship between ζ and E_p is a consequence of the $\zeta - E_\gamma$ correlation and the Amati relation $E_\gamma \propto E_p^2$.

At least for the GRB sample (excluding the XRF data point), we have verified that using E_k and E_γ interchangeably, as done previously in the studies of both the quasi-universal structured jets (Zhang et al. 2004) and the uniform jets (Lamb et al. 2004), is approximately valid. However, the discovered positive $\zeta - E_\gamma$ correlation has profound implications for both jet models. This correlation indicates that interchanging E_k and E_γ is no longer a good approximation in XRFs (this point has previously been made by Soderberg et al. (2003) for XRF020903). In fact, E_k of XRF 020903 is one order of magnitude larger than E_γ . This fact is particularly fatal for the suggestion that GRBs have a very narrow jet (Lamb et al. 2004) within

the uniform jet model. In that model, it is required that GRBs and XRFs all have a same total energy. Since XRFs have a very small total prompt emission energy, a narrow beam for GRBs is inferred (Lamb et al 2004). However, our finding indicates that the total energy of XRFs is actually much larger (if the efficiency is the real one). Keeping a constant energy, the typical GRB beaming angle should be much larger than 1 degree. So even using the arguments presented in Lamb et al. (2004), the GRB beams are not narrow.

Alternatively, as we have recently promoted (Zhang et al. 2004), GRBs and XRFs may be unified within a framework of a quasi-universal Gaussian-type jet model. In this model, we have also used E_k and E_γ interchangeably for XRFs. However, the E_k in this model likely changes with time. Since the jet is structured with more energy concentrated around the jet axis, there is a pole-to-equator energy flow during the interaction of the jet with the ambient medium (Kumar & Granot 2003; Zhang et al. 2004). So in this model, the kinetic energy measured at 10 hour after the burst could be much larger than the initial value, especially when the line of sight is far away from the jet axis (as is required to account for XRFs). Since our current measured efficiency ζ is derived by extrapolating the inferred kinetic energy measured at 10 hour back to the end of the prompt emission without invoking any energy injection, the $\zeta - E_\gamma$ correlation could be simply an ‘‘apparent’’ correlation due to the pole-to-equator energy flow.

Of course, it could be the case that the $\zeta - E_\gamma$ correlation is intrinsic. In this picture, XRFs are simply inefficient GRBs, but they no longer necessarily share a ‘‘standard’’ total energy, and there is no unified picture to incorporate both types of events.

These relations and their physical implications can be further explored with the Swift satellite, set to launch in September, 2004. For example, if we can get a uniform sample of X-ray luminosities at an early epoch (e.g. 1000 seconds or 1 hour) as well as at later times (say 10 hours), we may be able to test whether there is additional injection of kinetic energy during the afterglow phase. Swift may also allow the ζ -variability relation to be explored in detail, and eventually unveils the origin of the $\zeta - E_\gamma$ correlation.

5. SUMMARY AND CONCLUSIONS

We have computed the kinetic energy and radiative efficiency of a sample of 17 GRBs and 1 XRF, accounting for radiative losses during the initial afterglow phase. We have found that both of these GRB properties are related to a number of other GRB observables such as radiated energy, total energy, jet characteristic angle, and spectral peak energy. We have shown that kinetic energy is directly proportional to the radiated energy of the burst, as well as the total energy and spectral peak energy. The kinetic energy also decreases with increasing jet characteristic (opening or viewing) angle. More importantly, we have also found that the efficiency is correlated with the radiated energy of the burst, which appears to be consistent with an internal shock picture for the GRB prompt phase. The efficiency also appears to increase with increasing total energy and spectral peak energy, and decreases with increasing jet angle. XRF 020903 (the only XRF for which we are able to compute the kinetic energy and efficiency) seems to follow all of the trends we find for the 17 GRBs.

The relation between kinetic energy and radiated energy, efficiency and radiated energy, combined with the previously known Frail and Amati relations can explain the additional correlations we find in our sample. The results are compatible with the quasi-universal model, although a large data sample for the GRB kinetic energy derived at an earlier epoch (attainable from the Swift observatory) is essential to fully test this hypothesis. The results also strongly disfavor a ‘‘narrow beam’’ interpretation of GRBs.

The relationship between efficiency and other GRB parameters is an important one in elucidating GRB physics - we can further explore these and other relations (such as efficiency and variability) and potentially distinguish between various GRB radiation and jet models with the launch of the Swift satellite in September, 2004.

We thank the anonymous referee for useful comments and suggestions. B.Z. acknowledges NASA LTSA program for support.

REFERENCES

- Amati, L., et al. 2002, *A&A*, 390, 81
 Beloborodov, A.M. 2000, *ApJ*, 539, L25
 Berger, E., Kulkarni, S.R., Frail, D.A. 2003, *ApJ*, 590, 379
 Bevington, P.R. & Robinson, K.D., ‘‘Data Reduction and Error Analysis for the Physical Sciences’’, 2002, McGraw-Hill
 Bloom, J.S., Frail, D.A., Kulkarni, S.R., 2003, *ApJ*, 594, 674
 Fenimore, E. & Ramirez-Ruiz, E. 2000, *astro-ph/0004176*
 Frail, D.A., et al 2001, *ApJ*, 562, 55
 Freedman, D.L. & Waxman, E. 2001, *ApJ*, 547, 922
 Hurley, K., Sari, R., Djorgovski, S.G. 2002, *astro-ph 0211620*
 Kobayashi, S. & Sari, R. 2001, *ApJ*, 551, 934
 Kumar, P. 1999, *ApJ*, 532, L113
 Kumar, P. & Granot, J. 2003, *ApJ*, 591, 1075
 Lamb, D.Q., Donaghy, T. Q., & Graziani, C. 2004, *ApJ*, submitted (*astro-ph/0312634*)
 Liang, E.W., Dai, Z.G., Wu, X.F. 2004, *ApJL* in press, *astro-ph 0403397*
 Lloyd, N.M., Petrosian, V., Malozzi, R.S., 2000, *ApJ*, 534, 227
 Lloyd-Ronning, N.M., Dai, X. & Zhang, B. 2004, *ApJ*, 601, 371
 Mészáros, P. & Rees, M. J. 1997, 476, 232
 Panaitescu, A., Spada, M. & Meszaros, P. 1999, *ApJ*, 522, L105
 Panaitescu, A. & Kumar, P. 2001, *ApJ*, 560, L49
 Piran, T., Kumar, P., Panaitescu, A. & Piro, L. 2001, *ApJ*, 560, L167
 Press, W.H., et al., ‘‘Numerical Recipes’’, 1994, Cambridge University Press
 Reichart, D. et al. 2001, *ApJ*, 552, 57
 Rossi, E., Lazzati, D., Rees, M.J. 2002, *MNRAS*, 332, 945
 Sari, R. 1997, *ApJ*, 489, L37
 Sari, R., Piran, T. & Narayan, R. 1998, *ApJ*, 497, L17
 Soderberg, A. et al. 2004, *ApJ* in press, *astro-ph 0311050*
 Yost, S., Harrison, F. A., Sari, R. & Frail, D. A. 2003, *ApJ*, 597, 459
 Zhang, B., Dai, X., Lloyd-Ronning, N. & Mészáros, P. 2004, *ApJ*, 601, L119
 Zhang, B. & Mészáros, P. 2002, *ApJ*, 571, 876

TABLE 1

GRB	$E_\gamma/10^{52}\text{erg}$	$E_k/10^{52}\text{erg}$	ζ
970228	1.42 ± 0.25	1.90 ± 0.21	0.43 ± 0.05
970508	0.55 ± 0.06	0.99 ± 0.14	0.36 ± 0.04
970828	21.98 ± 2.40	4.06 ± 0.75	0.84 ± 0.03
971214	21.05 ± 2.58	8.48 ± 0.97	0.71 ± 0.03
980613	0.54 ± 0.10	1.22 ± 0.38	0.30 ± 0.08
980703	6.01 ± 0.66	2.41 ± 0.63	0.71 ± 0.06
990123	143.79 ± 17.78	20.28 ± 1.85	0.88 ± 0.02
990510	17.63 ± 2.00	13.16 ± 1.12	0.57 ± 0.03
990705	25.60 ± 2.03	0.34 ± 0.12	0.99 ± 0.00
991216	53.54 ± 5.94	36.64 ± 1.79	0.59 ± 0.03
000210	16.93 ± 1.41	0.50 ± 0.12	0.97 ± 0.01
000926	27.97 ± 9.90	9.97 ± 3.75	0.74 ± 0.10
010222	85.78 ± 2.17	22.79 ± 2.48	0.79 ± 0.02
011211	6.72 ± 0.86	1.32 ± 0.22	0.84 ± 0.03
020405	7.20 ± 0.92	4.60 ± 1.29	0.61 ± 0.07
020813	77.50 ± 31.06	22.16 ± 3.15	0.78 ± 0.07
021004	5.56 ± 0.72	8.35 ± 1.45	0.40 ± 0.05
XRF020903	.0011	.01	0.10

NOTE.—The columns are (left to right): (1) GRB name, (2) radiated energy (3) kinetic energy (4) efficiency.

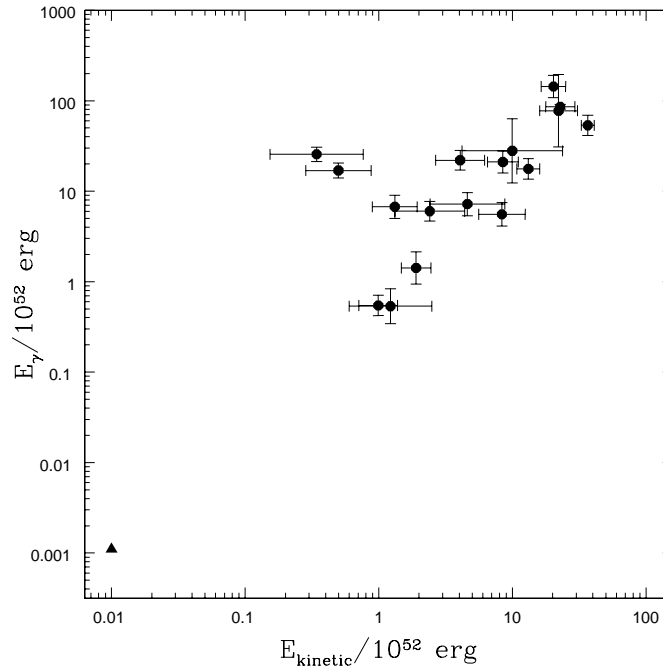


Fig. 1.— Radiated energy vs. kinetic energy for our sample of 17 GRBs. The triangular point in the lower right corner is XRF020903.

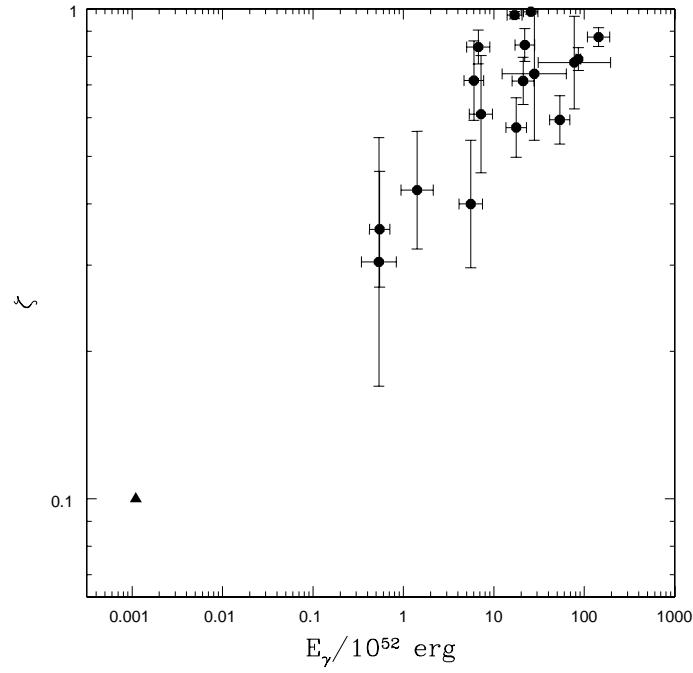


Fig. 2.— Efficiency ζ vs. radiated energy E_γ . The triangular point in the lower right corner is XRF020903.

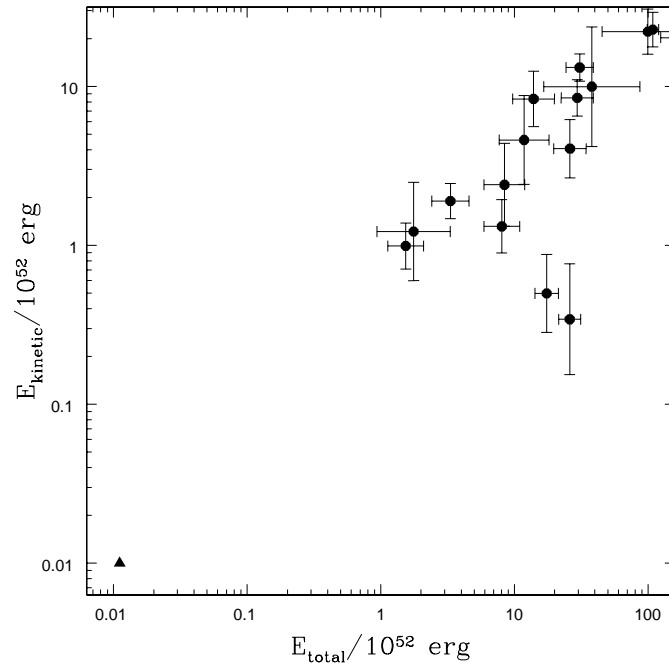


Fig. 3.— Kinetic energy vs total energy. The triangular point in the lower right corner is XRF020903.

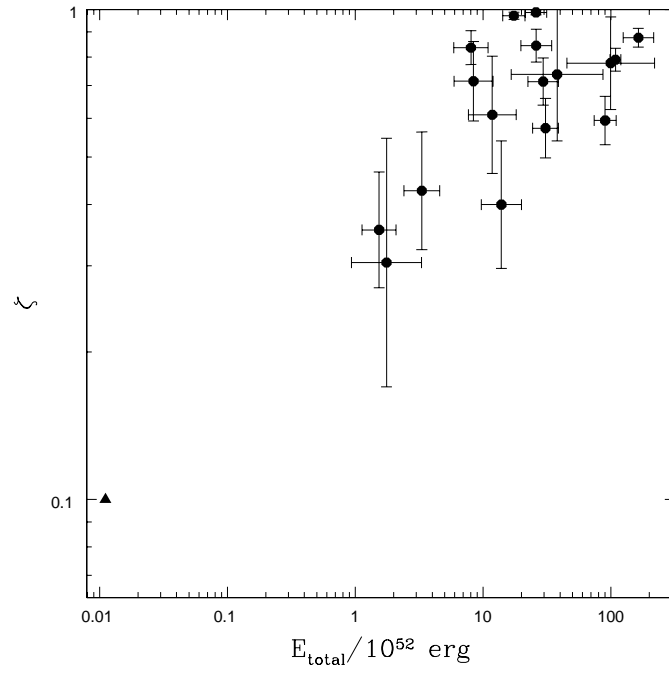


Fig. 4.— Efficiency ζ vs. total energy E_{tot} . The triangular point in the lower right corner is XRF020903.

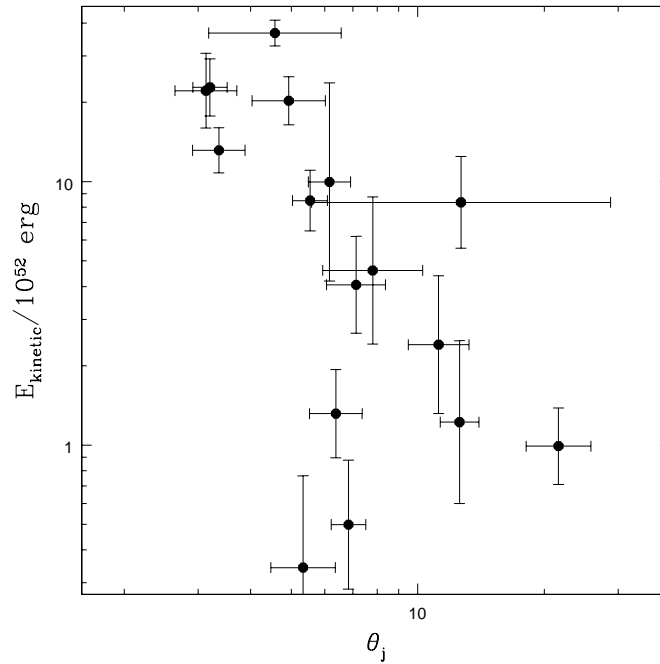


Fig. 5.— Kinetic energy vs jet opening angle.

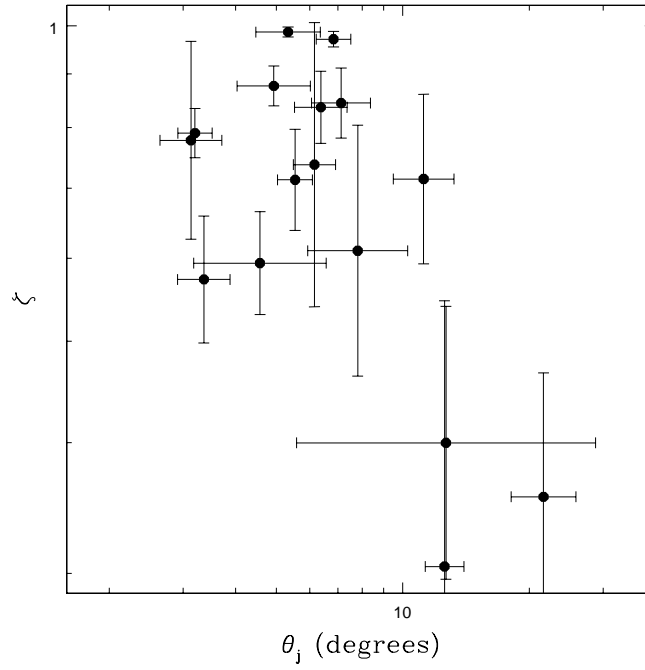


Fig. 6.— Efficiency ζ vs. jet opening angle θ_j .

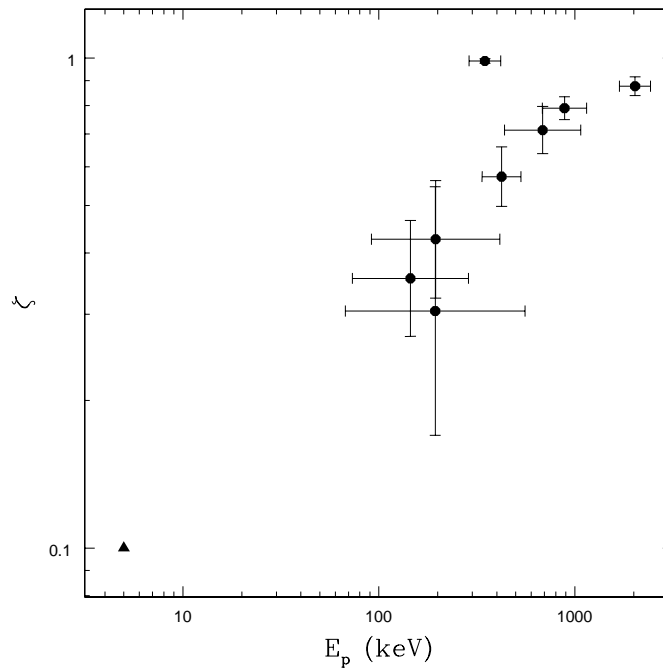


Fig. 7.— Efficiency ζ vs. spectral peak energy E_p . The triangular point in the lower right corner is XRF020903.