STANDARD GAMMA-RAY BURSTS, DIRTY FIREBALLS, AND THE EXCLUDED MIDDLE

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ABSTRACT

It is shown that the contribution of faint gamma-ray bursts (GRBs) to the total all-sky GRB energy flux is small. The all-sky flux of GRBs appears to be \(5.3 \times 10^{-3} \text{ erg cm}^{-2} \text{ yr}^{-1}\), with little additional component hidden within weak or otherwise undetectable GRBs. This significantly constrains physical models of GRBs and dirty fireballs, suggesting a rather sharp dichotomy between them should the latter exist.

Key words: gamma-ray burst: general

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1. INTRODUCTION

Gamma-ray bursts (GRBs) are understood to depend on baryon purity. With too much baryon contamination, their energy would end up in kinetic energy, and eventually afterglow. The rather stringent requirements for baryon purity needed for a successful GRB are consistent with the inference that there is only about 1 GRB per 10,000 supernovae, despite the known association between the two phenomena.

One might therefore ask whether there is a continuous spectrum of “semi-GRBs” that smoothly connects normal supernovae to bright GRBs. Dirty fireballs and X-ray flashes have been proposed as examples of this. As X-ray flashes are about as numerous as standard GRBs, but have much smaller values for \(V_{\text{max}}\), the maximum value within which they could have been observable at our location, their rate density is probably much higher, and one might ask whether the total luminosity input in such semi-GRBs could dominate the total. This is relevant to any question connected with GRB calorimetry and total luminosity density, e.g., the question of how much energy is available in GRBs to produce ultrarelativistic cosmic rays.

There is physical motivation for asking this question as well, as it constrains models of the central engine. If, for example, the baryon purity is a function of disk cooling, so that baryons from a hot atmosphere do not extend up to the slow-Alfvén critical point where they are injected into a magnetocentrifugal outflow (Levinson 2006), then one might suppose that, because this injection rate varies both with position on the disk and time, there are many GRBs in which the photons are cooled by adiabatic expansion before being released beyond the gamma ray photosphere. In fact, popular models of GRBs frequently invoke a saturation radius that is well within the photosphere, in which case the photons would cool adiabatically before escaping. If there is a continuous range of the extent of this adiabatic cooling, then one would expect a continuous range of GRB fluxes, and perhaps a sizable contribution to the total all-sky flux from very weak, very soft, or very prolonged (i.e., low luminosity) GRBs. Yet another parameter that seems quite variable in GRBs is the opening angle. The larger the opening angle, the dimmer the GRB appears. Very wide GRBs might thus escape detection, yet might dominate the total luminosity density of GRBs. Similarly, the peripheries of “structured jets” conceivably might contain most of the GRB energy, in which case different observers would see the peripheries as weak GRBs, but with a large rate per unit comoving volume, and the product of the rate density and apparent energy might conceivably be dominated by these weak GRBs.

In this paper, we examine to what extent weak, soft, wide angle, and/or high-redshift GRBs contribute to the present cosmic GRB radiation density. In contrast to previous works on this matter, which appear to be model dependent and give a large range of numbers, our approach is nearly model independent—we compute the total flux recorded by different GRB detectors, each with different ranges and sensitivities. We show that most of the GRB energy output comes in high-fluence GRBs in the spectral range 20–5000 keV, independent of detector and trigger sensitivity, and such bursts could be detected by most major detectors. Moreover, these bright bursts would typically overwrite data that were being transmitted from BATSE, should they have occurred during the time such data transmission was taking place (considered “dead time” except when overwritten; Paciesas et al. 1999), and would not have been overlooked by BATSE (see below).

We conclude from this that, in the context of total energetics, GRBs respect a law of excluded middle: there appears to be very little energy in “semi-GRBs,” compromised GRBs, ragged GRB peripheries, and the like. Theoretical models of GRBs should respect this principle of the excluded middle at a quantitative level. In other words, they should not predict that half or more of the total photon energy is sprayed or otherwise diluted in directions from which the burst would be perceived as a marginal, weak, or “semi-”GRB. While the detectability of any given weak GRB is a function of detector sensitivity, the measured all-sky flux in GRBs is nearly independent of detector.

We find from the BATSE 4B catalog that the total all-sky flux in GRB photons \(F_\gamma\) is about \(5.3 \times 10^{-3} \text{ erg cm}^{-2} \text{ yr}^{-1}\). Specifically, we have summed the fluences of all the GRBs with reported fluences, divided by the number of years (5.3) and, assuming an effective field of view (FOV) of 2\(\pi\) sr, multiplied by 2 in order to obtain an average all-sky (4\(\pi\)) flux. This flux corresponds to a cosmic average energy input \(F_\gamma H/c = 1.24 \times 10^{33} \text{ erg Mpc}^{-3} \text{ yr}^{-1}\). The present-day, local input is about a factor of two lower due to the fact that the star formation rate, and hence the inferred long GRB rate, was considerably higher in the past (e.g., Eichler et al. 2010), i.e., enough to override the average redshift factor by a factor of two. These values include short bursts, and for long bursts would probably be lower by several percent or so.

Previously (Eichler et al. 2010), we summed the total fluence in Gamma-ray Burst Monitor (GBM) data from 2009 August...
to 2010 February, an 18 month interval, and found an average flux in long GRBs of $4 \times 10^{-3}$ erg cm$^{-2}$ yr$^{-1}$. The GBM catalog contains 212 long bursts over this period, or about 283 GRBs per year per 4$\pi$ sr.

The BATSE 4B catalog contains 1293 GRBs with fully reported fluences above 20 keV over 5.3 years. This corresponds to an all-sky rate of $\sim 450$–500 GRBs per year with measured fluences, about $10^2$ of which are short GRBs. This number is constant over subintervals of order 1 year to within $\sim 2\%$. In addition, there are about 70 per year that are interrupted by data gaps, so no measured fluence is available, and we may infer that a comparable number are not even triggered because they occur during the “dead time” when the satellite trigger is preoccupied with relaying data from the previous GRB, or in a region of high particle background flux. Finally, some GRBs may go unreported because the detector is not in its most sensitive trigger mode all of the time. In its most sensitive mode, BATSE is thought to trigger on about 333 GRBs per 2$\pi$ sr yr, or an all-sky flux of 606 per year (Paciesas et al. 1999). At least $\sim 150$ of these would be short GRBs, and we may infer that the number of long GRBs is $\sim 500$ per year. Band (2002) infers a somewhat lower all-sky rate (550 per year versus 666), which would imply less than 500 long GRBs per year. This suggests that a fraction $\eta$ between 18% and 34% of GRBs in the BATSE FOV went undetected because of dead-time effects or because the trigger threshold was not set at optimal levels. We suspect that $\eta$ is closer to 18% because at most 70/520 per 4$\pi$ sr yr of the triggered GRBs were interrupted by overwrites or data gaps. On the other hand, the average fluence per reported burst is likely to be stronger than for an interrupted or sub-trigger threshold burst, so, although this mistake is sometimes made, it would be incorrect to multiply the total number of inferred long GRBs by the average fluence in the proper subset of those with reported fluences, since the latter are brighter as a class than the former. Previous estimates in the literature for the GRB radiation luminosity density, which are often estimated by multiplying an inferred rate by an inferred average energy, are for this reason somewhat larger than what we estimate here, and we consider them to be overestimates. The problem is particularly severe given that the total fluence is dominated by bright bursts’ average fluence, $F \geq 10^{-5}$ erg cm$^{-2}$, whereas the total number of bursts is dominated by dimmer bursts, $F \leq 10^{-6}$ erg cm$^{-2}$.

Finally, we consider the event rate recorded by Swift. While the limited energy range of Swift makes it a bad instrument for measuring the total fluence, it is nearly an order of magnitude more sensitive than BATSE for merely detecting GRBs. It recorded $\sim 93.5$ GRBs per year over an FOV of 1.4 sr. This implies an all-sky event rate of 840 per year, which is 20%–50% more than the BATSE all-sky event rate. It may be assumed that the extra bursts are below the BATSE threshold and therefore are extremely weak. It may be inferred that an instrument with Swift trigger sensitivity and BATSE energy range would have recorded only a slightly higher flux than BATSE itself. It is also clear that the modest increase in the burst rate that results from the large increase in sensitivity indicates that the total burst rate converges at large sensitivity, unless there is a distinctly separate class of bursts at very low flux levels.

In Figure 1, we have plotted the cumulative four-channel fluence, $\sum NF_s(\geq F_s)$ (the fluence in channels 1–4, 20–1000 keV) for the 1293 GRBs in the BATSE 4B catalog that have a reported fluence, as a function of four-channel (i.e., total) fluence $F_s$. Here, the cumulative fluence is defined to be the sum of the fluences in all bursts brighter than $F_s$. We also plot the cumulative two-channel fluence (channels 1 and 2, 20–100 keV) for the BATSE 4B catalog as a function of the two-channel fluence. To assist the eye, we plot the cumulative fluence as $6.8 \sum NF_s(\geq 6.8 F_s)$ for the BATSE two-channel fluences, which expresses the simplifying assumption that the total fluence is 6.8 times the two-channel fluence $F_s$. The bolometric correction factor of 6.8 is motivated by the fact that it is the average ratio of $F_s/F_{4B}$ for the BATSE catalog. It can be seen that $6.8 F_s$ is nearly a proxy for $F_s$, except that the ratio $F_s/F_{4B}$ is somewhat higher than 6.8 for very bright bursts, which are probably seen head-on and therefore have harder than average spectra, and also higher for short bursts, which have very low fluences, and contribute significantly to the low-fluence population. (That the ratio $F_s/F_{4B}$ is lower in the range $10^{-6}$ to $10^{-5}$ erg cm$^{-2}$ s$^{-1}$ than at the extremes is consistent with the fact that moderate fluence bursts have softer spectra than the bright GRBs, as implied by the Amati relation.) Also plotted is the cumulative fluence versus fluence as recorded by Swift (15–150 keV) for 534 GRBs in the Swift catalog with (reported fluence) as of 2010 September 1 as a function the Swift-recorded fluence, $\sum NF_s(\geq F_s)$, with bolometric corrections of 3.15 and 1.8 (see the figure caption and below).

As Swift has a larger energy range than channels 1+2 of BATSE, it follows that the bolometric correction to Swift-measured fluences must be less than 6.8. As the average Swift-measured fluence was $\sim 3.15$ times less than the average BATSE four-channel fluence, and Swift sampled a fainter population on average, the bolometric correction should probably be less than 3.15. Finally, we may argue that because Swift detects an all-sky equivalent of 840 bursts per year and a total fluence of $1.82 \times 10^{-3}$ erg cm$^{-2}$ in 534 bursts, the implied all-sky flux is $[840/534] \times 1.82 \times 10^{-3} = 2.9 \times 10^{-2}$ erg cm$^{-2}$ yr$^{-1}$. Because Swift, with proper bolometric correction, should detect a higher flux than the less sensitive BATSE, it follows that Swift should detect an all-sky equivalent of at least $5.3 \times 10^{-3}$ erg cm$^{-2}$ yr$^{-1}$. So, the proper bolometric correction must be at least $5.3/2.9 = 1.8$. It is clear from Figure 1 that for any allowed choice of the Swift bolometric correction, the cumulative fluence plateaus at a fluence of $\sim 10^{-3}$ erg cm$^{-2}$, which is three orders of magnitude from the minimum. Note that choosing the lower limit for the bolometric correction would move the plateau to the right slightly, thus slightly shortening it, but it would also imply that the all-sky flux in Swift bursts is not significantly higher than in BATSE bursts, which is what the long plateau signifies.

To summarize, the cumulative fluence plateaus near its maximum value at a fluence that is about a factor of $10^3$ higher than the minimum for both BATSE and Swift, suggesting that there is not a significant amount of flux in weak GRBs, at most of order 15% or so. A significant part of this can be attributed to short GRBs. While it might have otherwise been argued that there remains a reservoir of not-yet-detected dim, long GRBs, we would expect, if that were the case, that Swift would have detected at least part of that reservoir, and shown more of a rise in cumulative fluence in the range of low-fluence bursts. We conclude that long GRBs and their total luminosity have been fairly sampled by existing instruments, and that what we see is what we get.

Similar remarks can be made for GRBs at high redshift. Swift would have been better suited, because of its high sensitivity and lower energy range, to see GRBs at high redshift $z$. While the average redshift of GRBs in the Swift catalog is certainly higher than that of the BATSE catalog, there is no evidence that the population of high-$z$ GRBs makes any significant contribution to
the cumulative fluence. In any case, whatever the contribution of GRBs that, because of high redshift, are presently undetectable, this contribution would not greatly affect the estimate of the present-day, local estimates, which are usually figured by assuming that the GRB redshift distribution follows that of star formation. This is independent of whether high-redshift activity is more conspicuous, relative to low-redshift activity, in young stars or in GRBs. Uncertainties in the GRB event rate at high $z$ therefore do not affect the estimate of the local ($z \sim 0$) GRB luminosity density.

We note that this result is consistent with the Amati relation, which finds that the isotropic equivalent luminosity $E_{\text{iso}}$ goes as the square of the spectral peak energy $E_{\text{peak}}$, i.e., that the total photon number decreases in proportion to the spectral peak. If the number of GRBs per logarithmic interval in $E_{\text{peak}}$ is roughly constant, then the number of photons contributed by X-ray flashes is much less than by the harder GRBs.\(^1\) The Amati relation is thus consistent with spectral softening due entirely to off-axis viewing (Eichler & Levinson 2004), which reduces the photon flux as well as the photon energy. It is not consistent with the hypothesis that X-ray flashes are the same as GRBs except for more adiabatic cooling of the photons, because such adiabatic cooling would leave the total number of photons unchanged.

We conclude that most of the energy flux, burst rate, and probably even the photon flux have all been measured to good accuracy, and that the hidden contribution from weak GRBs is small. We find that the net all-sky energy flux in GRB (electromagnetic) radiation is $\sim 5.3 \times 10^{-3}$ erg cm$^{-2}$ yr$^{-1}$, which is consistent with M. Schmidt (2002, private communication with V. Berezinsky) who estimated a net GRB photon luminosity density of $6 \times 10^{52}$ erg Mpc$^{-3}$ yr$^{-1}$. It is, however, a factor of several below some estimates that are based on nominal average GRB energy as deduced from a selected subsample from known redshifts. This may be attributable to the fact that GRBs with known redshifts have higher fluxes on average than those of undetermined redshifts and that using the former as a representative of the latter leads to an overestimate.

We emphasize that the measured flux applies only to photons. No limit on kinetic energy is placed by such considerations. Thus, if GRBs, including those beamed away from us, occur at a rate of $100$ Gpc$^{-3}$ yr$^{-1}$ and each GRB has $10^{53}$ erg in kinetic energy, then an energy input rate of $10^{46}$ erg Mpc$^{-3}$ yr$^{-1}$ is possible; it would simply mean that the kinetic energy input rate exceeds that of photons by three orders of magnitude. One might expect some of this kinetic energy to escape as orphan afterglow radiation, however, in some other part of the spectrum, or, if this outflow contains particle-accelerating internal shocks (Levinson & Eichler 1993), even ultra-high energy neutrinos (Eichler 1994).

That the GRB population has a reasonably sharp edge in the context of cumulative fluence does not rule out the possibility that most GRBs, as counted by external observers, are dirty fireballs, and/or that the dirty fireball component of a GRB has a much larger solid angle than the radiative core of the fireball. However, it constrains the dirty fireballs to be extremely dirty—qualitatively different from the radiative core rather than there being a continuous transition between the two. In fact, we have argued in a previous paper (Mandal & Eichler 2010) that the thermal component of GRB 060218 is a dirty fireball, as it is the only known exception to the Amati relation that lies to its bright, soft side (the lower right as the Amati relation is usually plotted). The non-thermal component of this GRB does in fact respect the Amati relation (Campana et al. 2006; Amati et al. 2007), as it has comparable or only slightly more isotropic equivalent energy ($\sim 4.5 \times 10^{49}$ erg) than the thermal component ($\sim 3 \times 10^{49}$ erg) while having a higher spectral peak ($\sim 4.9$ keV as opposed to $\sim 0.486$ keV, the Wein peak at a temperature of 0.17 keV).\(^2\) It has also been noted (e.g., Guetta & Eichler 2010)\(^3\) that the event rate density of GRB 060218 type events is more than

\(^1\) In fact, the Amati relation is actually an inequality (Nakar & Piran 2005) in that there are GRBs with $E_{\text{iso}}$ less—but none with $E_{\text{iso}}$ much greater—than the value given by the Amati relation, and the number of photons may for many bursts decrease even more rapidly with peak energy.

\(^2\) From Figure 2 of Campana et al. (2006), the $0.3–10$ keV luminosity is $\sim 7.6 \times 10^{49}$ erg s$^{-1}$ and the thermal component is $\sim 3.1 \times 10^{49}$ erg s$^{-1}$. The authors state a luminosity of $\sim 6.2 \times 10^{49}$ erg s$^{-1}$ above 1 keV.

\(^3\) In Guetta & Eichler (2010) there is a typo as the sky coverage of Swift is not 0.17 sr but rather 0.17.
two orders of magnitude higher than that of standard GRBs. However, the thermal component of GRB 060218 has a spectral peak that is more than three orders of magnitude below that of the brightest GRB and is at least three orders of magnitude dimmer, in terms of $E_{\text{iso}}$, than the brightest GRB. There do not seem to be any GRBs on a line connecting GRB 060218 with the brightest GRB lying in between the two extremes—which would correspond to less dirty fireballs—despite the fact that such GRBs would, if they existed, have a much higher $V_{\text{max}}$ than that of GRB 060218, and that they would be brighter than GRBs of comparable spectral peak that do respect the Amati relation (of which there are many). This would, under the assumption that the thermal component of GRB 060218 is a dirty fireball, support the picture that dirty fireballs are extremely dirty and that there is no known class of objects that parametrically connects dirty fireballs to standard GRBs. Figure 2 shows that the thermal component of GRB 060218 is the only burst or flash to lie to the lower right of the line depicting the Amati relation. It connects to the bright GRB in the upper right along a line of constant photon density, which would correspond to adiabatic cooling of a typical GRB photon output by an excessive amount of baryonic contamination that traps the photons in the expanding flow, but there are no known GRBs in between the bright GRB and GRB 060218 on this line.

What are we to make of this sharp dichotomy between standard GRBs and dirty fireballs? One obvious interpretation is that long GRBs are collimated by their host stars and have sharp edges. Apparently, very little of their energy escapes into a peripheral spray that would be observed as weak GRBs. It would be interesting to do a similar analysis on short GRBs to see if a similar effect obtains, given that short GRBs do not emerge from giant envelopes because their host stars do not possess them. Such an analysis seems only marginally possible at present, because short GRBs are of much lower fluence and rarer than long GRBs, but it should eventually be feasible.

If dirty fireballs (be they material from the inner accretion disk of the GRB’s central engine or entrained envelope material) ensheathe the radiative cores of GRB fireballs, then it appears that they do not parametrically connect smoothly to the radiative core. They may, rather, connect smoothly to the supernova ejecta. This would be consistent with the picture that standard GRB fireballs are very uncontaminated by baryons because they emerge along field lines that connect to an accretion disk. The “either/or” nature of the event horizon then creates a large parametric gap, nearly a discontinuity, between the baryon content of the radiative core and the dirty fireball.

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