

## ARE ALL GAMMA-RAY BURSTS LIKE GRB 980425, GRB 030329, AND GRB 031203?

DAFNE GUETTA,<sup>1</sup> ROSALBA PERNA,<sup>2</sup> LUIGI STELLA,<sup>3</sup> AND MARIO VIETRI<sup>4</sup>

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### ABSTRACT

We study the probability that three GRBs (980425, 030329, 031203) are found within  $z = 0.17$ , given the luminosity functions consistent with the  $\log N$ – $\log S$  relationship for classical cosmological bursts (i.e., those observed by BATSE). We show that, in order for the probability of these three low- $z$  events to be nonnegligible (thus making it more likely that they belong to the same class of the classical cosmological bursts), the bursts' luminosity function must be a broken power law. By reasoning in analogy with beamed active galactic nuclei, we show that observations are consistent with the expectations if GRB 980425 and GRB 031203 are indeed normal bursts seen sideways. Within this model, no bright burst within  $z = 0.17$  should be observed by a *High Energy Transient Explorer*–like instrument within the next  $\sim 20$  yr.

*Subject heading:* gamma rays: bursts

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### 1. INTRODUCTION

After the discovery of the association of SN 2003dh with GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003), and of SN 1998bw with GRB 980425, it has been widely accepted that classical, cosmological GRBs arise from the simultaneous collapse of an SN to form a collapsar (Woosley 1994). Further evidence comes from the third nearby burst, GRB 031203, which also has been seen to be closely associated with a Type Ic SN (Tagliaferri et al. 2004; Malesani et al. 2004). This model appears plausible for all long GRBs, even the distant ones, in the light of the similarity between these two objects and GRB 011121/SN 2001ke (Bloom et al. 2002; Garnavich et al. 2003), an object located at  $z \approx 0.36$ . Still, the fact that only some bursts' afterglows display the rebumps now associated with the emergence of the optical contribution due to the underlying SN beckons the question of exactly which fraction of all GRBs (within the detectability range of SN rebumps, say,  $z \lesssim 1$ ) is in fact associated with simultaneous SNe. In order to tackle this problem, we study whether the detection of GRBs 980425, 030329, and 031203, the only ones unequivocally associated with a Type Ic SN of extreme properties within a very small distance ( $z = 0.17$ ) from us, is a statistical anomaly, for the luminosity functions (LFs) that are consistent with the GRB  $\log N$ – $\log S$  distribution.

### 2. PROBABILITIES OF DETECTING LOW- $z$ EVENTS

If the three low-redshift GRBs (980425, 030329, and 031203) are really typical of the global GRB population, then their discovery within the current time and sky coverage must be consistent with the local GRB explosion rate as deduced from the very large GRB samples made available by BATSE. A simple computation of the expected number of events within  $z = 0.17$  (the redshift of GRB 030329) shows that this is not the case. The volume out to  $z = 0.17$ , in an  $\Omega_\Lambda = 0.7$ ,  $\Omega = 1$  cosmology with  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , is  $V = 1.4 \text{ Gpc}^3$ . The association of a GRB with an SN requires an accurate position,

and thus only bursts revealed by the *BeppoSAX* Wide Field Cameras, or *High Energy Transient Explorer 2* (*HETE-2*) Wide Field X-Ray Monitor, can be used. Inclusion of *INTEGRAL* would only make matters slightly worse. These two X-ray telescopes monitor  $S_B = 0.123 \text{ sr}$  and  $S_H = 0.806 \text{ sr}$ , respectively (Band 2003). The total effective operation times for *BeppoSAX* and *HETE-2* are generously estimated as  $T_B = 4 \text{ yr}$  and  $T_H = 2 \text{ yr}$  (L. Piro 2004, private communication). If we call  $\dot{n}_0$  the observed local rate of GRBs, we find that the total expected number of GRBs located inside  $z = 0.17$  is

$$N = \dot{n}_0 V \frac{S_B T_B + S_H T_H}{4\pi} = 0.12 \frac{\dot{n}_0}{0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}}. \quad (1)$$

The probability of observing three bursts, assuming Poisson statistics, is then  $P_3 = 2.7 \times 10^{-4} [\dot{n}_0 / (0.5 \text{ Gpc}^{-3} \text{ yr}^{-1})]^3$ .

The major uncertainty in the above equation concerns  $\dot{n}_0$ , which takes on different values depending on exactly which data property is fitted ( $V/V_{\text{max}}$ , or the  $\log N$ – $\log P$  relationship for BATSE data). For the local observed rate, Porciani & Madau (2001) consider three different star formation rates (SFRs) and correspondingly find three values for  $\dot{n}_0$ , between 0.11 and 0.17 bursts  $\text{Gpc}^{-3} \text{ yr}^{-1}$  (having converted their results to  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). Schmidt (2001) considers the same SFRs but fits different quantities, to obtain  $\dot{n}_0 = 0.48, 0.51, 0.72 \text{ Gpc}^{-3} \text{ yr}^{-1}$ . Perna et al. (2003) find  $\dot{n}_0 = 0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}$ , while Guetta et al. (2004) find  $\dot{n}_0 = 0.44 \text{ Gpc}^{-3} \text{ yr}^{-1}$ . In § 3, we repeat the analysis of Guetta et al. (2004) with a more updated sample, to obtain  $\dot{n}_0 = 1.1 \text{ Gpc}^{-3} \text{ yr}^{-1}$ . With this value, the probability of a triple event would be  $P_3 = 2.9 \times 10^{-3} [\dot{n}_0 / (1.1 \text{ Gpc}^{-3} \text{ yr}^{-1})]^3$ . The hypothesis that the three nearby bursts, 980425, 030329, and 031203, belong to the same group as the classical BATSE bursts, would thus be rejected with fairly high confidence.

However, this is not correct. The local rate discussed above has been derived by all authors under the hypothesis that classical bursts exceed by far the luminosity of GRB 980425 and they also exceed that of GRB 031203 (i.e., they considered a minimum luminosity for the LF  $L_b \gtrsim 5 \times 10^{49} \text{ ergs s}^{-1}$ , which from now on we assume to define the minimum luminosity for the classical population). Therefore, the derived probabilities are not self-consistent. A unified picture can only be obtained

<sup>1</sup> Hebrew University of Jerusalem; and Department of Condensed Matter, Weizmann Institute of Science, 76100 Rehovot, Israel.

<sup>2</sup> Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, Campus Box 391, Boulder, CO 80306-0391.

<sup>3</sup> INAF–Osservatorio Astronomico di Roma, Via Frascati 33, Monteporzio Catone, I-00040 Rome, Italy.

<sup>4</sup> Scuola Normale Superiore, Piazza dei Cavalieri, 7-56100 Pisa, Italy.

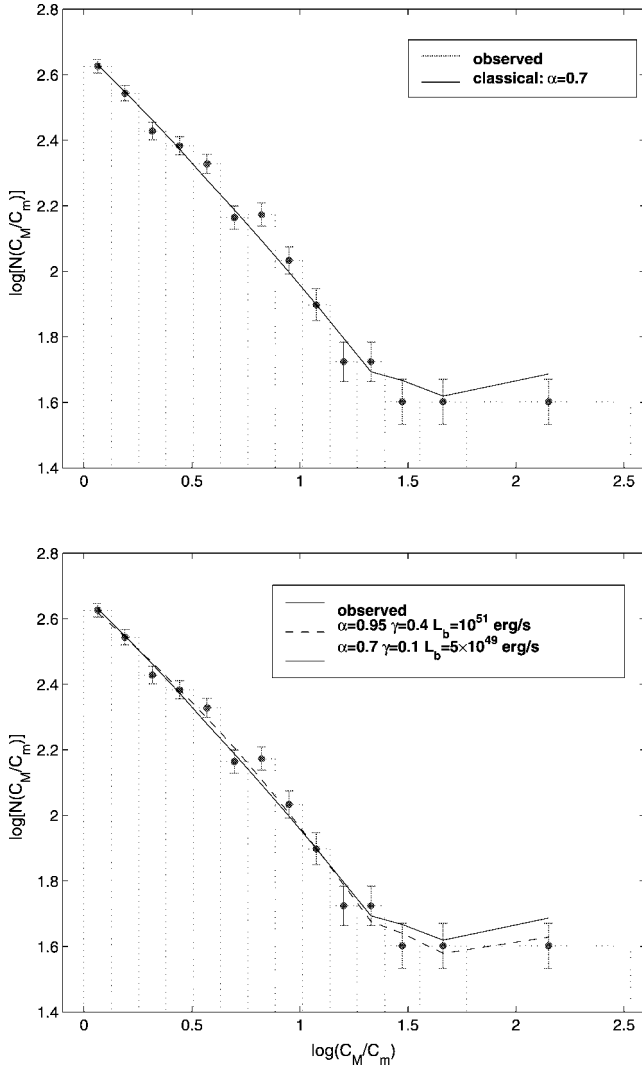


FIG. 1.—*Upper panel*: Best-fit differential distribution of the classical GRBs vs. the observed one taken from the GUSBAD catalog. *Lower panel*: Best-fit differential distribution of the GRBs in the case in which  $L_b$  marks the border between off-axis and on-axis GRBs (*solid line*) and in the case in which we leave  $L_b$  as a free parameter (*dashed line*) vs. the observed one taken from the GUSBAD catalog. For both panels, the  $\log(C_M/C_m)$  is divided into 14 bins, the first 11 of equal size and the remaining three with varying sizes chosen such that the number of bursts per bin in the observed sample is at least  $N_{\min} = 40$  (in order to have reasonable statistics, so that the Poisson error will not be too large), and  $N$  is the observed (*circles*) or theoretical (*lines*; only the values at the center of each bin count) number of bursts in each bin. The edges of the bins are also plotted. [See the electronic edition of the Journal for a color version of this figure.]

with an LF that includes all luminosities down to that of GRB 980425 and at the same time yields a high probability of observing the three low- $z$  events. This is what we achieve in § 4, after setting up the formalism and recomputing (for the more updated sample) the local rate for the classical population in § 3.

### 3. LUMINOSITY FUNCTION FOR CLASSICAL GRBS

We consider all 2204 GRBs of the GUSBAD catalog (see Schmidt 2004), which was derived from the continuous DISCLA data stream. We estimate  $C_{\max}/C_{\min}$  for each burst (where  $C_{\max}$  is the count rate in the second brightest illuminated detector and

$C_{\min}$  is the minimum detectable rate) and find  $\langle V/V_{\max} \rangle = 0.335 \pm 0.007$ .

The LF of the “classical” population of long-duration GRBs may be represented as a power law with lower and upper limits,  $L_b$  and  $L_2$ , respectively. The local LF of GRB peak luminosities  $L$ , defined as the comoving space density of GRBs in the interval from  $\log L$  to  $\log L + d \log L$  is

$$\Phi_0(L) = c_0 (L/L_b)^{-\alpha}, \quad L_b < L < L_2, \quad (2)$$

where  $c_0$  is a normalization constant. We stress that this LF is the “isotropic-equivalent” LF; it does not include the effects of beaming.

We assume that GRBs trace the star formation history and adopt the recent SFR derived by Rowan-Robinson (1999); this can be fitted with the expression  $R_{\text{GRB}}(z) = \dot{n}_0 \max(0.75, 0.75z)$ .

The modeling procedure involves the derivation of the peak flux  $P(L, z)$  of a GRB of peak luminosity  $L$  observed at redshift  $z$ :

$$P(L, z) = \frac{L}{4\pi D_L^2(z)} \frac{C[E_1(1+z), E_2(1+z)]}{C(E_1, E_2)}, \quad (3)$$

where  $D_L(z)$  is the bolometric luminosity distance and  $C(E_1, E_2)$  is the spectral energy distribution integrated between  $E_1 = 50$  keV and  $E_2 = 300$  keV. Schmidt (2001) finds that the median value of the spectral photon index in the 50–300 keV band for long-burst GRBs is  $-1.6$ . We use this value for our analysis to include the  $k$ -correction.

Objects with luminosity  $L$  observed by BATSE with a flux limit  $P_{\text{lim}}$  are detectable to a maximum redshift  $z_{\max}(L, P_{\text{lim}})$  that can be derived from equation (3). We consider an average limiting flux  $P_{\text{lim}} = 0.25$  photons  $\text{cm}^{-2} \text{s}^{-1}$  taken from the BATSE catalog.

The number of bursts with a peak flux greater than  $P$  is given by

$$N(>P) = \int \Phi_0(L) d \log L \int_0^{z_{\max}(L, P)} \frac{R_{\text{GRB}}(z)}{1+z} \frac{dV(z)}{dz} dz, \quad (4)$$

where the factor  $(1+z)^{-1}$  accounts for cosmological time dilation and  $dV(z)/dz$  is the comoving volume element.

To be consistent with previous calculations, we take the low-luminosity cutoff  $L_b \sim 5 \times 10^{49}$  ergs  $\text{s}^{-1}$ , while the high luminosity,  $L_2 \sim 5 \times 10^{52}$  ergs  $\text{s}^{-1}$ , is taken on the order of the maximum luminosity detected until the time of writing (Bloom et al. 2003). The slope  $\alpha$  of the LF is constrained by fitting the model with the observed peak flux distribution with a non-linear Levenberg-Marquart minimum  $\chi^2$  method. To avoid problems with error correlation in a cumulative distribution like  $N(>P)$  propagate in an unknown way, we use the differential distributions  $n(P) \equiv dN/dP$  for this analysis. We find that the best fit is given for  $\alpha \sim 0.72$ ; the  $p$ -value of the fit is  $\sim 0.70$  (see Fig. 1, *upper panel*). Both  $\alpha$  and the normalization value are somewhat insensitive to the choice of  $L_b$  below a value  $\sim 10^{50}$  ergs  $\text{s}^{-1}$ . This is mainly because GRBs with very low luminosity appear above the sensitivity limit of  $\sim 0.25$  photons  $\text{cm}^{-2} \text{s}^{-1}$  in a very small volume around the observer.

To obtain the observed local rate of GRBs per unit volume,  $\dot{n}_0$ , we need to estimate the effective full-sky coverage of our GRB sample. The GUSBAD catalog represents 3.185 yr of

BATSE full-sky coverage, implying a rate of 692 GRBs per year. Using our LF, we find  $\dot{n}_0 \sim 1.1 \text{ Gpc}^{-3} \text{ yr}^{-1}$ .<sup>5</sup>

#### 4. LUMINOSITY FUNCTION FOR BURSTS SEEN FROM ANY DIRECTION AND REVISED PROBABILITIES

We are thus left with the question of how to include GRB 980425 and GRB 031203 within our analysis. It is quite possible that these bursts belong to a different, local population of bursts, as occasionally claimed by some authors for GRB 980425 (Bloom et al. 1998). Still, there are at least two arguments suggesting that 980425 is just a normal burst seen sideways (Nakamura 1998; Eichler & Levinson 1999; Woosley et al. 1999). One is the exceptional similarity of the two underlying SNe in 980425 and 030329, within a class (that of extreme Type Ic SNe) known instead for its lack of common patterns. The other is that GRB 021211 (Della Valle et al. 2003), and all bursts with the so-called optical rebumps, are likely associated also to SNe.

For this reason, we consider an LF model that includes GRBs seen sideways. We follow the analogy with beamed active galactic nuclei (AGNs), according to which (Urry & Shafer 1984) the total LF is simply a broken power law, agreeing, at the bright end, with the LF of the objects seen face-on. We thus take

$$\Phi_0(L) = c_0 \begin{cases} (L/L_b)^{-\gamma}, & L_1 < L < L_b, \\ (L/L_b)^{-\alpha}, & L_b < L < L_2. \end{cases} \quad (5)$$

We impose here  $L_1 = L_{980425}$ ,  $L_2 = 5 \times 10^{52} \text{ ergs s}^{-1}$ , and  $L_b$  to be the border value between GRBs seen sideways (weak bursts) and the ones seen face-on (classical bursts). We choose somewhat arbitrarily  $L_b \sim 5 \times 10^{49} \text{ ergs s}^{-1}$  and fit the same data as in § 3 with  $\alpha$  and  $\gamma$  as free parameters. Note that it has been proposed that X-ray flashes (XRFs) are simply GRBs viewed off-axis. If this interpretation is correct, then XRFs could be included in our analysis in the lower part of the LF broken power law (recalling that XRFs are generally underluminous compared to GRBs). The best fit ( $\alpha = 0.7$ ,  $\gamma = 0.1$ , and  $p$ -value  $\sim 0.76$ ) is shown in Figure 1 (*lower panel*).<sup>6</sup> With this LF, the total local rate of events, down to the lowest luminosity (that of 980425), is now much higher,  $\dot{n}_0 = 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$ , while the rate for  $L > L_b$  remains unaffected. Using equation (1), we find that the expected number of events within  $z = 0.17$ , and luminosity even as low as GRB 980425, is  $N_l = 2.4$ , which is clearly highly compatible with the current observation of three events.

A strong radio emission is expected from bursts seen sideways at  $\sim 1 \text{ yr}$  delay (Waxman 2004a, 2004b and references therein; Livio & Waxman 2000) as the jet decelerates to sub-relativistic speed and its emission approaches isotropy. However, no late-time rebrightening was detected for either GRB 980425 or GRB 031203 (Soderberg et al. 2003, 2004a, 2004b). These results suggest that neither GRB 980425 nor GRB 031203 were off-axis events and instead were intrinsically sub-

energetic GRBs. Therefore, we also consider the possibility that both GRB 980425 and GRB 031203 might have intrinsically low luminosity and all GRBs are seen on axis. The LF can still have an *intrinsic* break for some (unknown) reason, and therefore it can still be represented by equation (5) (as in Schmidt 2001). In this case, we can leave  $L_b$  as a free parameter in our fit and look for the best-fit parameters  $\alpha$ ,  $\gamma$ ,  $L_b$ . The results ( $\alpha = 0.95$ ,  $\gamma = 0.4$ ,  $L_b = 10^{51} \text{ ergs s}^{-1}$ , and  $p$ -value  $\sim 0.64$ ) are shown in Figure 1 (*lower panel*). With this LF, the total local rate of events is  $\dot{n}_0 = 20 \text{ Gpc}^{-3} \text{ yr}^{-1}$ . However, if all GRBs are seen on-axis, then there is no natural explanation for the break in the LF. Indeed, a single-power-law LF with  $L_1 = L_{980425}$ ,  $L_2 = 5 \times 10^{52} \text{ ergs s}^{-1}$  could be representative of these bursts. However, in this case we get a very high local rate,  $\dot{n}_0 \sim 100 \text{ Gpc}^{-3} \text{ yr}^{-1}$ , which would predict about 24 events within the  $z = 0.17$  volume (again using eq. [1]). The probability of having only three occurrences is  $\sim 10^{-7}$ , which makes this scenario very unlikely. Therefore, we conclude that a broken power law for the LF is highly preferred to a single power law, if the three low- $z$  events do belong to the same class as the classical ones. Also note that the rate for the single power law would yield about 400 galactic events per million years, implying an implausibly large number of GRB remnants (Loeb & Perna 1998; Efremov et al. 1998) at any given time.

Our model also allows us to compute the probability of finding one object (GRB 980425) as close as  $z = 0.008$ , which would be of course prohibitively small if we were to apply to this burst the statistics for classical GRBs discussed in § 3. For our best-fit power-law model, we find that the probability of bursts as luminous as GRB 980425 within the volume accessible to *BeppoSAX* and *HETE-2* is  $\approx 10^{-3}$ , small but still not completely ruled out. For the detection threshold of *Swift* (Gehrels et al. 2004), this rate would be 0.05, while that of all bursts with  $L < L_b$  is  $\sim 2$  for a 2 yr observation period.

#### 5. CONCLUSIONS

We have shown in this Letter that the presence of three nearby GRBs does not pose a problem for the current view (according to which both distant and nearby bursts belong to the same class), if we modify the LF to include an extension to luminosities as low as that of GRB 980425. We did this by means of a *minimum impact* extension, i.e., by assuming, in complete analogy with beamed AGNs, that the LF of the bursts is a broken power law, with the bright-end distribution equal to what we derived when we neglected the presence of faint, sideways bursts. In addition, we showed that this yields a non-negligible probability for the detection of a GRB 980425-like event, which is also a new result.

How could this picture change? Some authors have insisted that it is not possible to throw GRB 980425 in the same cage as classical GRBs, because of its unique properties in the radio band. Within our model, the local rate of nearby bright bursts ( $L \geq 5 \times 10^{49} \text{ ergs s}^{-1}$ ) observable by *HETE-2* within  $z = 0.17$  is  $\dot{n}_0 V S_H / 4\pi = 0.057 \text{ yr}^{-1}$ . This implies that we ought to observe the next such event  $\sim 20 \text{ yr}$  from now. Should we see one significantly earlier than that, then the argument suggesting a similarity between the distant, classical bursts and the nearby ones would have to be reassessed.

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<sup>5</sup> Note that for a different SFR like, for example, model SF2 of Porciani & Madau (2001), we still find a good fit and a local rate smaller by a factor of  $\sim 2$ . We find a similar result also for the LF studied in § 4.

<sup>6</sup> Note that the curve is almost identical to the one corresponding to the best-fit LF obtained for the classical bursts shown in the upper panel. This is because to add a low-luminosity ( $L < 5 \times 10^{49} \text{ ergs s}^{-1}$ ) tail to the LF does not affect the log  $N$ -log  $S$  distribution (low-luminosity GRBs appear above the BATSE sensitivity limit in a reduced volume as explained in § 4).

## REFERENCES

- Band, L. 2003, *ApJ*, 588, 945  
Bloom, J. S., Frail, D. A., & Kulkarni, S. R. 2003, *ApJ*, 594, 674  
Bloom, J. S., Kulkarni, S. R., Harrison, F., Prince, T., Phinney, E. S., & Frail, D. A. 1998, *ApJ*, 506, L105  
Bloom, J. S., et al. 2002, *ApJ*, 572, L45  
Della Valle, M., et al. 2003, *A&A*, 406, L33  
Efremov, Y. N., Elmegreen, B. G., & Hodge, P. W. 1998, *ApJ*, 501, L163  
Eichler, D., & Levinson, A. 1999, *ApJ*, 521, L117  
Garnavich, P. M., et al. 2003, *ApJ*, 582, 924  
Gehrels, G., et al. 2004, *ApJ*, 611, 1005  
Guetta, D., Piran, T., & Waxman, E. 2004, *ApJ*, in press (astro-ph/0311488)  
Hjorth, J., et al. 2003, *Nature*, 423, 847  
Livio, M., & Waxman, E. 2000, *ApJ*, 538, 187  
Loeb, A., & Perna, R. 1998, *ApJ*, 503, L35  
Malesani, D., et al. 2004, *ApJ*, 609, L5  
Nakamura, T. 1998, *Prog. Theor. Phys.*, 100, 921  
Perna, R., Sari, R., & Frail, D. 2003, *ApJ*, 594, 379  
Porciani, C., & Madau, P. 2001, *ApJ*, 548, 522  
Rowan-Robinson, M. 1999, *Ap&SS*, 266, 291  
Schmidt, M. 2001, *ApJ*, 552, 36  
———. 2004, *ApJ*, in press (astro-ph/0406519)  
Soderberg, A. M., Frail, D. A., & Wieringa, M. H. 2004a, *ApJ*, 607, L13  
Soderberg, A. M., et al. 2003, *GCN Circ.* 2483, <http://gcn.gsfc.nasa.gov/gcn/gcn3/2483.gcn3>  
———. 2004b, *Nature*, 430, 648  
Stanek, K. Z., et al. 2003, *ApJ*, 591, L17  
Tagliaferri, G., et al. 2004, *IAU Circ.* 8308  
Urry, C. M., & Shafer, R. A. 1984, *ApJ*, 280, 569  
Waxman, E. 2004a, *ApJ*, 602, 886  
———. 2004b, *ApJ*, 605, L97  
Woosley, S. E. 1994, *BAAS*, 26, 1413  
Woosley, S. E., Eastman, R., & Schmidt, B. P. 1999, *ApJ*, 516, 788