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NEW EVIDENCE FOR THE COSMOLOGICAL ORIGIN OF GAMMA-RAY BURSTS

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ABSTRACT

We find that gamma-ray bursts (GRBs) at the 3B catalog are correlated (at 95% confidence level) with Abell clusters. This is the first known correlation of GRBs with any other astronomical population. It confirms the cosmological origin of GRBs. For a subsample of GRBs with accurate positions ($\delta < 2\overset{\circ}{.}3$), we compare the rich cluster autocorrelation and the cross-correlation of this subsample with the rich clusters. The amplitude ratio of the comparison suggests that $\sim$26% ± 15% of the members of this subsample are located within 600 h^{-1} Mpc ($z = 0.2$). For an $\Omega = 1$ cosmology with no source evolution, this result implies maximum redshift for the accurate position subsample of $z_{\max-a} = 0.36^{+0.27}_{-0.07}$, and $z_{\max} = 0.7^{+0.93}_{-0.07}$ for the entire GRBs population.

Subject headings: galaxies: clusters: general — galaxies: statistics — gamma rays: bursts — methods: statistical

1. INTRODUCTION

One of the major obstacles in Gamma-ray burst (GRB) research is the lack of any association of GRBs with any other astronomical population. The recent observations of the BATSE experiment on board the *Compton Gamma Ray Observatory* suggest that GRBs are cosmological (Meegan et al. 1992). The GRBs distribution appears to be isotropic, and there is a paucity of weak bursts. Both facts are naturally explained by a cosmological distribution. The observed peak flux distribution in the BATSE catalog agrees well with a theoretical cosmological peak flux distribution (Piran 1992; Mao & Paczyński 1992; Dermer 1992; Wickramasinghe et al. 1993; Cohen & Piran 1995). These facts can, however, be accommodated by some extended Galactic halo models, and there is an ongoing debate on the Galactic or extragalactic origin of GRBs (Paczyński 1995; Lamb 1995).

We have discovered a positive cross-correlation signal between GRB distribution in the 3B catalog and Abell clusters. This confirms our previous result that indicated the existence of such a correlation in the BATSE 2B catalog (Cohen, Kolatt, & Piran 1994). This correlation demonstrates the cosmological origin of GRBs. It also enables us to estimate directly the distance scale to GRBs. We did not find any significant autocorrelation of GRBs in the 3B catalog. Since GRBs are distributed over cosmological distances ($z \approx 1$), one should not expect a cross-correlation with galaxy catalogs that consist of relatively nearby objects. We checked this prediction by looking for cross-correlation with *IRAS* galaxies, as well as other optical galaxy catalogs (Uppsala General Catalog, ESO, and the Morphological Catalog of Galaxies). We did not find any cross-correlation signal with GRBs for any of these catalogs. Similarly, Hartmann, Briggs, & Mannheim (1996) did not find a correlation between GRBs and the supergalactic plane. However, the volume limited sample of Abell clusters (Abell 1958; Abell, Corwin, & Olwin 1989) extends to larger distances and may lead to a detectable cross-correlation.

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2. THE DATA

The data consist of 3616 Abell clusters of richness class $R \geq 0$ (the richness class, R as defined by Abell 1958, IIh, is roughly proportional to the number of bright galaxies within the Abell radius, with $R \geq 0$ corresponding to more than 30 galaxies in this radius) and Galactic latitudes $|b| > 30°$. The cutoff is meant to reduce statistical noise emerging from low values of the cluster selection function $\phi_{\rm cl}$ (Scaramella et al. 1991). The clusters show a strong autocorrelation signal (Bahcall & Soneira 1983; Batuski et al. 1989; Peacock & West 1992), and their typical redshift values are $z \approx 0.15$–0.2. There are 549 GRBs in the 3B catalog with $|b| > 30°$. The GRB selection function, $\phi_{\rm GRB}$, is anisotropic because of different exposure durations in different directions. The longest exposure corresponds to $\phi_{\rm GRB} = 1$, and selection function values for shorter exposures are ascribed according to the exposure duration in units of the longest exposure. The GRB selection function has up to 20% variation across the sky. The position of the bursts is uncertain, with an angular error for the $j^{\rm th}$ burst given by $\delta_j = (\delta^2_{\rm sys} + \delta^2_{{\rm stat},j})^{1/2}$, where $\delta_{\rm sys} = 1\overset{\circ}{.}6$ is a systematic error and $\delta_{{\rm stat},j}$ is a statistical error that varies from one burst to another. The statistical error, $\delta_{{\rm stat},j}$, decreases with the burst strength. For a weak burst, $\delta_{{\rm stat},j}$ can be quite large (up to 20°), and it might be meaningless to include objects with such poorly known positions in our analysis. Hence, we have constructed an "accurate" subclass of the GRB sample—which contains 136 GRBs—with a good positional accuracy, namely for which the positional error δ_j satisfies: $\delta_j \leq \delta_{\max} \equiv \sqrt{2}\delta_{\rm sys}$. Clearly, because of the nature of this subclass, it contains stronger bursts on average.

3. CROSS-CORRELATION ESTIMATE

The cross-correlation of the Abell clusters and the anisotropic sky coverage of the BATSE data make it difficult to estimate the cross-correlation between these two data sets in the usual way. However, we like to start up with the conventional cross-correlation evaluation in order to obtain its model independent values. Let $N_{\rm GRB\text{-}cl}(\theta)$ be the number of GRB cluster pairs separated by an angle in the range $(\theta, \theta + \Delta\theta)$, where $\Delta\theta$ is the bin width. Then we generate a population of randomly distributed particles (Poisson distributed) that are subject to the cluster selection function, $\phi_{\rm cl}$. Similarly, we define $N_{\rm GRB\text{-}Po}(\theta)$ to be the number of pairs of GRB and those randomly distributed particles within the same angular range. Under these definitions, the angular cross-correlation function, $w(\theta)$, is given by

$$1 + w(\theta) = \frac{N_{\text{GRB-cl}}(\theta)}{N_{\text{GRB-Po}}(\theta)} \frac{n_{\text{Po}}}{n_{\text{cl}}}, \quad (1)$$

where n_{cl} and n_{Po} are the number densities of the clusters and the Poisson particles, respectively. In order to obtain a bias-free estimate of the correlation, we corrected for the GRB selection function by assigning a weight to each pair count inversely proportional to ϕ^{j}_{GRB}.

The main advantage of the cross-correlation assessment is that it allows us to reduce the noise level appreciably in comparison to the GRB autocorrelation. In the limit, where $n_{\text{Po}} \gg n_{\text{cl}}$, the Poisson error in $w(\theta)$ is $(\Delta w)_{\text{P}} = (1 + w)(N_{\text{GRB-cl}})^{-1/2}$ for each θ bin. The overall error in the correlation value is larger than the Poisson error because of the cluster autocorrelation, the possible GRB autocorrelation, and the assigned weights. Considering the cluster autocorrelation alone, we get a rough estimate for the error multiplicative factor (e.g., Olivier et al. 1990) by letting Σ be the cluster mean surface density and $w_{\text{cl-cl}}(\theta) \simeq A\theta^{-1}$. We then evaluate

$$u \simeq \Sigma \int d\phi \int_{\theta_{i-1}}^{\theta_i} w_{\text{cl-cl}}(\theta)\, d(\cos\theta), \quad (2)$$

to get $\Delta w \simeq (1 + u)^{1/2}(\Delta w)_{\text{P}}$. For θ expressed in degrees, $A \approx 0.7$ (cf. Batuski et al. 1989 for $R \geq 1$ and here $R \geq 0$) and a single 4° radius bin, we obtain $(1 + \text{u})^{1/2} \simeq 2.0$. Though this estimate is only approximate, it allows a model-free interpretation of our results later on.

In order to circumvent the difficulties in the cross-correlation evaluation, we have instead tested the null hypothesis, namely that the GRBs show no correlation with the rich clusters. We calculate $N_{\text{GRB-cl}}(\theta)$, the number of GRB cluster pairs whose separation is smaller than a given angle θ for $\theta = 1°–6°$. Then we create 500 random Poissonian realizations (artificial catalogs, ac) of particles with the same selection function and error distribution as the GRBs, and we calculate $N^{i}_{\text{ac-cl}}(\theta)$ for each realization i. Then we attempt to rule out the null hypothesis by considering the fraction of random artificial catalogs for which $N_{\text{GRB-cl}}(\theta) > N^{i}_{\text{ac-cl}}(\theta)$. This provides us with a direct estimate of the null hypothesis rejection level. Since we conduct a purely statistical experiment, we try to maximize the statistical significance by performing the same analysis for the full GRB sample ($|b| > 30°$) and for the "accurate" subclass. In each of the above cases, we have also carried out calculation for weighted correlation weighting each GRB cluster pair by the GRB error, δ_j^{-2}. Figure 1 shows the entire probability distribution for cross-correlation between artificial catalogs of the GRBs accurate weighted sample and the Abell clusters catalog. In only 5% of the 500 artificial catalogs was a correlation signal higher than the true correlation found. The results for the different subsamples and weighting schemes are summarized in Table 1 and plotted in Figure 2.

Checking for self-consistency within the table entries, we notice that for the last case ("accurate" subclass with statistical weighted cross-correlation), where we find the largest statistical significance, the maximum is obtained for 4° top hat on the sky. The same holds for the second case ("accurate" subclass with a regular correlation function) and for the third case (all bursts with weighted correlation function). These results reflect the combined effect of cross-correlation accompanied by systematic and random errors. Even if all GRBs reside in Abell clusters, we could not expect higher correlation at smaller angles because of the errors. The statistical significance increases when we use weighted correlation function (Table 1, col. [5] vs. col. [3]) and when we use the accurate subclass in place of the whole sample (col. [5] vs. col. [4] and col. [3] vs. col. [2]). Both trends are reassuring. We recall that the more accurate bursts are stronger on average; hence, they are nearer and therefore more correlated with the clusters.

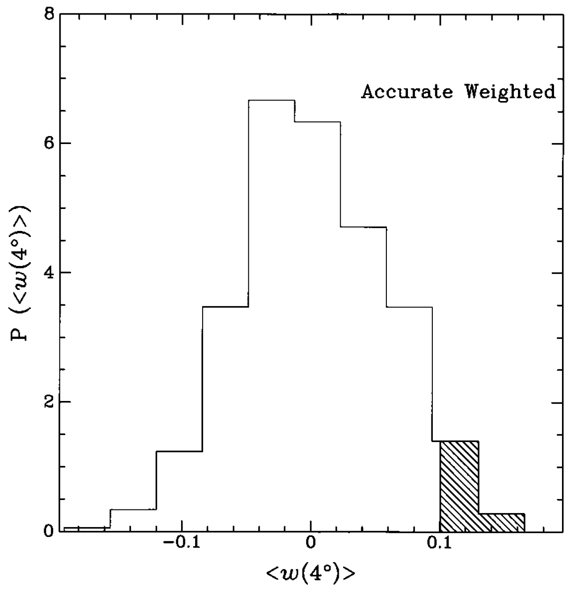

FIG. 1.—Probability distribution for random artificial GRB sample and Abell clusters cross-correlation. Only accurate GRBs weighted by their positional errors were used for the evaluation. Shaded area shows the 5% probability for a random GRB sample to produce higher cross-correlation signal than the true GRB sample signal.

4. THE INFERRED DISTANCES

Having found a cross-correlation signal and the optimal angle to look for it, we can estimate the fraction of GRBs that actually contribute to the signal, i.e., overlaps with the cluster sample volume. In a model where all GRBs reside in clusters, we compare the ratio between the detected cross-correlation and the two-dimensional top-hat average over the cluster autocorrelation. For a circle of radius θ_c, we get $\langle w_{\text{cl-cl}}(\theta_c)\rangle \simeq 2A\theta_c^{-1}$ and $\langle w_{\text{cl-cl}}(4°)\rangle \simeq 0.35$. The measured, minimally biased values for the cross-correlation at a 4° bin are 0.013 and 0.093 for all GRBs and for the "accurate" subsample, respectively.

TABLE 1

SIGNIFICANCE OF CROSS-CORRELATION COEFFICIENT

Radius Bin (deg)	All Regular[a] (%)	Accurate Regular[b] (%)	All Weighted (%)	Accurate Weighted (%)
1	36.6	80.4	55.0	78.0
2	73.4	90.4	90.4	81.4
3	70.0	89.0	87.2	91.0
4	63.6	93.4	91.0	95.0
5	80.8	94.2	93.2	94.2
6	65.0	86.8	87.2	88.6

[a] Number of all regular and weighted, 549.
[b] Number of accurate regular and weighted, 136.

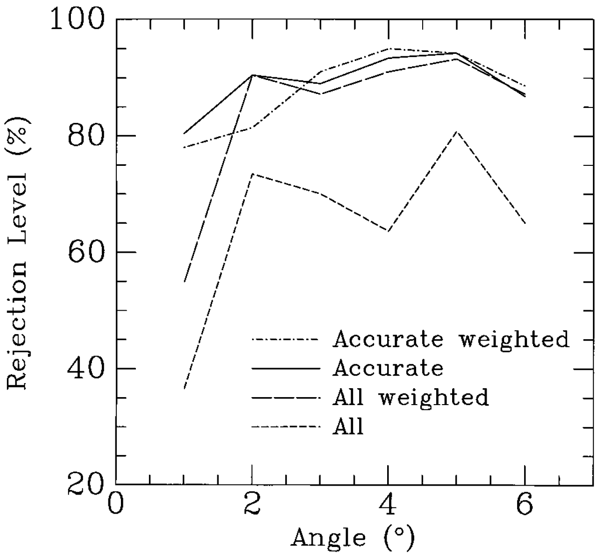

FIG. 2.—Rejection levels for the null hypothesis of no cross-correlation between GRBs and rich clusters. Different lines are for all GRBs and a subclass of accurate position GRBs, weighted or not, by their positional errors.

While the former is not much of a use due to a signal-to-noise ratio of $\sim$1, the error estimate for the latter is $\Delta w(4°) \simeq 0.053$. Notice that the statistical significance of the measurement has already been established, based on the null hypothesis rejection, and the current analysis is needed for the overlap estimate only. The overlapping fraction is therefore $\sim 0.093/0.35 = 0.26 \pm 0.15$. For the "accurate" subsample with 136 GRBs, we conclude that 35 ± 20 of them lie in a volume of a 600 h^{-1} Mpc sphere. Using the relative amplitudes and the expression for the expected angular cross-correlation (Lahav, Nemiroff, & Piran 1990, eq. [9]), one gets a characteristic depth for the GRBs "accurate" subsample of $R_{*,\,\mathrm{GRB}\text{-}a} = 940^{+300}_{-120}$ h^{-1} Mpc, i.e., $z_{\mathrm{GRB}\text{-}a} = 0.31^{+0.1}_{-0.04}$. In a different estimate, we calculate $n(z)$, the fraction of observed bursts up to a redshift z (e.g., Cohen & Piran 1995) in a given cosmological model. Given the fact there are 35 ± 20 GRBs within $z = 0.2$, we obtain for $\Omega = 1$ and no source evolution $z_{\mathrm{max}\text{-}a} = 0.36^{+0.27}_{-0.07}$ in which BATSE will detect 156 bursts. The equivalent estimate for all GRBs yields $\sim$4% overlap with the cluster sample, namely $\sim$22 GRBs within the same volume but with a large error. The much larger error can be interpreted as a steep buildup of the noise level because of nonoverlapping GRBs. For the whole sample, this implies a maximum detection redshift of $z_{\mathrm{max}} = 0.7^{+0.93}_{-0.07}$. The two estimates are consistent with each other and suggest that the main correlation contribution for the entire GRB sample essentially comes from the "accurate" subsample. An equivalent calculation, using the cluster-galaxy correlation function (Mo, Peacock, & Xia 1993; Lilje, & Efstathiou 1988), with approximately half the cluster autocorrelation function amplitude in the relevant range, and under the assumption that all GRBs reside in galaxies, leads to a larger overlapping fraction for the "accurate" subsample of $\sim$0.5 and to lower z values.

5. CONCLUSIONS AND DISCUSSION

We have found a cross-correlation of GRBs with Abell clusters. The large rich cluster sample helps to overcome the statistical noise that prevents us from finding any GRB autocorrelation. The correlation we found is believed to be a true spatial correlation. However, weak lensing magnification bias could also contribute to the observed effect. The predicted magnification correlation averaged on a θ_c radius window is given by (e.g., Bartelmann 1995),

$$\langle w(\theta_c)\rangle = 2\theta_c^{-2}(-a-1)b\int_0^{\theta_c} w_{\mu\delta}(\theta)\,d(\cos\theta)\,, \qquad (3)$$

where $w_{\mu\delta}$ is the matter-magnification correlation, b is the considered lenses biasing factor, and a is the power-law index for the intrinsic GRB source counts as a function of their flux. For the most favorable case for magnification, we assume all GRBs are at $z = 1.5$, consider $z < 0.2$ clusters along the line of sight, with a biasing factor $b = 5$, and use the standard CDM model function for these parameters (Bartelmann 1995) of $w_{\mu\delta} \simeq 7 \times 10^{-4}\ \theta^{-0.6}$. The obtained value is then $\langle w(4°)\rangle \leq (-a-1)0.014$, which is one sixth of the detected signal for the accurate sample, and comparable to the (uncertain) signal for all GRBs (for reasonable values of a).

If real spatial correlation is responsible for the detected signal, we know that Abell clusters extend up to $z \approx 0.15$–0.2, and, therefore, the relative amplitudes of the cluster autocorrelation and the GRBs cluster cross-correlation provides an estimate for the GRBs redshift distribution. For a subsample of accurately measured GRBs, we found that $z_{\mathrm{max}\text{-}a}$ of this population is $0.36^{+0.27}_{-0.07}$ if all accurate GRBs are in clusters and $z_{\mathrm{max}\text{-}a} \simeq 0.27^{+0.12}_{-0.05}$ if they are all in galaxies. For the whole GRB sample, this implies $z_{\mathrm{max}} = 0.7^{+0.93}_{-0.07}$ if GRBs originate in clusters and $0.5^{+0.3}_{-0.15}$ if they are all in galaxies. The upper limits of these values are within the range of z_{max} estimates, as obtained from fitting the peak-flux distribution to a cosmological distribution. Cohen & Piran (1995) find $z_{\mathrm{max}} = 2.1^{+1.0}_{-0.7}$ for the long bursts and $z_{\mathrm{max}} \leq 0.5$ for the short bursts, while Fenimore et al. (1993) find $z_{\mathrm{max}} \approx 0.9$ for the combined population. However, in a more recent analysis, Fenimore & Bloom (1995) find that if GRB time dilation is entirely attributed to cosmological redshift stretching, then $z_{\mathrm{max}} > 6$. Here we have a combined population of long and short bursts. The average values are on the low side, and this may indicate that lensing magnification and not just spatial correlation contributes to the observed signal. More data is needed to decrease the error estimates and to determine which of the two possibilities is the dominant contribution.

The cross-correlation is the first association of GRBs with any other population of astronomical objects. It demonstrates, of course, the cosmological origin of the bursts. It does not mean, however, that the GRBs originate necessarily in clusters, as it is consistent with the picture in which the bursts originate in galaxies or galaxy halos that, in turn, are strongly correlated with Abell clusters.

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