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On the correlation of short gamma-ray bursts and clusters of galaxies

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ABSTRACT

We cross-correlate gamma-ray bursts (GRBs) and X-ray selected clusters of galaxies at $z \leqslant 0.45$. We find a positive 2σ signal for the angular cross-correlation function $w_{\rm bc}(\theta)$ on scales $\theta \leqslant 3^\circ$ between short GRBs and clusters. Conversely, no correlation is found between clusters and the population of long GRBs. The comparison with the cluster autocorrelation function shows that short GRBs do not trace the cluster distribution, as not all short GRBs are found in clusters. A higher signal in $w_{\rm bc}(\theta)$ is found if we only consider the cluster population up to $z = 0.1$. By comparing the short-burst autocorrelation function with model predictions, we then constrain short bursts to mostly originate within ∼270 Mpc (i.e. $z \leqslant 0.06$). Our analysis also reveals that short GRBs are better correlated with 'normal' galaxies. The double compact-object merger model for short GRBs would associate them preferentially with early-type galaxies, but the present statistics do not allow us to exclude that at least a fraction of these events might also take place in late-type galaxies, in agreement with recent evidence.

Key words: methods: data analysis – gamma-rays: bursts.

1 INTRODUCTION

The population of gamma-ray bursts (GRB) presents a bimodal duration distribution (Kouveliotou et al. 1993): short GRBs (S-GRBs – lasting less than 2 s) and long GRB (L-GRBs – lasting more than 2 s). Further support for this bimodality comes from their different spectral properties, with S-GRBs being spectrally harder than longer events (Tavani 1998; Ghirlanda, Ghisellini & Celotti 2004).

One of the most accredited models associates S-GRBs with the coalescence and final merger of two compact objects in a binary system (Narayan, Paczynski & Piran 1992; Ruffert 1997). Binary systems evolve on different time-scales (Voss & Tauris 2003) and a testable consequence of this model is that S-GRBs should be found preferentially in evolved- (early-)type galaxies. Recently, *Swift* (Gehrels et al. 2004) and *Hete–II* (Lamb et al. 2004) detected for the first time the X-ray and optical afterglow emission of three S-GRBs, and in two cases a redshift was measured: GRB 050724 (Covino et al. 2005) was found to be associated with an elliptical galaxy at $z = 0.257$ (Berger et al. 2005) whereas GRB 050709 (Butler et al. 2005) was found to be associated with a blue dwarf galaxy at redshift $z = 0.16$ (Covino et al. 2005; Hjorth et al. 2005).

A third interesting case is represented by GRB 050509B (Hurkett et al. 2005): the afterglow, detected only in X-rays, was found to be spatially coincident with a giant elliptical galaxy at $z = 0.2248$ (Bloom et al. 2006) belonging to the cluster of galaxies ZwCl 1234.0+02916 at $z = 0.2214$ (Pedersen et al. 2005). Another S-GRB 050813 was found to be spatially coincident with a cluster at $z = 0.7$ (Gladders et al. 2005). Gal-Yam et al. (2005) recently reported a third significant positional coincidence of the S-GRB 790613 with the rich Abell cluster 1892 at $z = 0.09$. The possibility of a correlation of GRBs with clusters of galaxies has been debated in the past (Kolatt & Piran 1996; Struble & Rood 1997) by studying the direct and statistical association of BATSE bursts with optically selected Abell clusters, and opposing conclusions were reached (Hurley et al. 1999; Gorosabel & Castro-Tirado 1997). In these studies, however, the population of bursts was not separated into short and long events. Magliocchetti, Ghirlanda & Celotti (2003, hereafter MGC03) found evidence for anisotropy in the distribution of S-GRBs and suggested that they might originate in galaxies distributed up to $z \sim 0.5$. Tanvir et al. (2005) found that at least a fraction (between 5 and 25 per cent) of BATSE S-GRBs might be in the very local Universe (i.e. $z < 0.025$), preferentially in early-type galaxies. It has also been proposed that a fraction (e.g. Hurley et al. 2005) of S-GRBs might be the cosmological counterparts of the giant flares of soft gamma-ray repeaters (SGRs).

In this letter we study the cross-correlation between S-GRBs detected by BATSE and X-ray selected clusters of galaxies covering the entire sky (±20° above and below the Galactic plane). We find that a positive correlation indeed exists between the two populations of objects on small angular scales. We investigate whether S-GRBs trace the cluster distribution and also test whether they preferentially correlate with early-type galaxies. In the following we assume a 'standard' cosmological model with $\Omega_M = 0.3$ and $\Omega_\Lambda = h = 0.7$.

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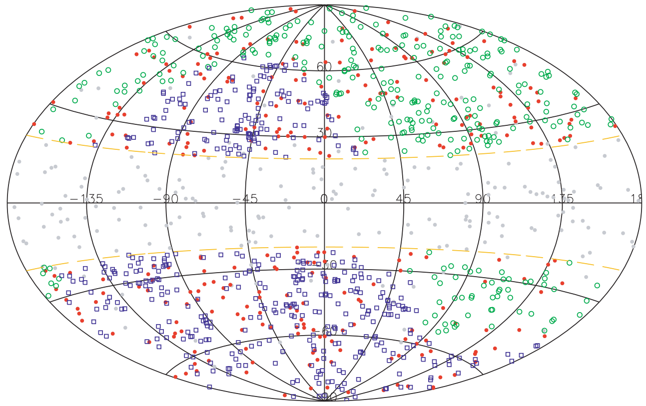

Figure 1. Sky distribution in Galactic coordinates of the sample of 497 BATSE short-GRBs (filled circles) and of 763 Clusters [449 REFLEX clusters (blue open circles) and 314 NORAS clusters (green open circles)]. The red filled circles represent the 283 short duration GRBs with position accuracy $<10°$ and $|b| > 20°$.

2 GRBS AND CLUSTERS SAMPLES

BATSE detected more than 2000 GRBs during its nine years of activity (Paciesas et al. 1999). From the online sample of BATSE–GRBs[1] we extracted 497 short events with duration $\leqslant 2$ s and 1540 L-GRBs with duration >2 s. In order to correlate the GRB sample with a sample of clusters of galaxies with as wide a sky coverage as possible, we considered the REFLEX (Böhringer et al. 2004) and the NORAS (Böhringer et al. 2000) surveys. The *ROSAT* ESO Flux Limited X-ray (REFLEX) galaxy cluster survey contains 449 clusters with a maximum redshift $z \sim 0.451$, and it is flux-limited to 3×10^{-12} erg cm^2 s^{-1} in the [0.1–2.4] keV band. It covers the Galactic latitudes $|b| \geqslant 20°$ and declination $\delta \leqslant 2.5°$ and it excludes $\sim$324 deg^2 of sky around the Large Magellanic Cloud and the Small Magellanic Cloud. The total area covered is 4.24 sr (i.e. $\sim$34 per cent of the entire sky) and the catalogue completeness is $\geqslant$90 per cent (Böhringer et al. 2004). The Northern *ROSAT* All-Sky galaxy survey (NORAS) contains 484 clusters (including the supplements to the original survey catalogue – Böhringer et al. 2000) with measured redshift up to $z \sim 0.459$. It covers the Galactic latitudes $|b| \geqslant 20°$ and declination $\delta \geqslant 0°$. We are aware that the NORAS sample is only 82 per cent complete with respect to the REFLEX survey and we tested our results for this difference (Section 3). In combining the two surveys, given the higher level of completeness of REFLEX, we cut NORAS at $\delta \geqslant 2.5°$, to avoid superpositions, and to the same flux limit of REFLEX. We end up with 314 (out of 484) NORAS clusters combined with the 449 REFLEX clusters (open green and blue circles in Fig. 1, respectively).

Since we do not have redshift measurements for the population of S-GRBs, we have to rely on projected quantities. Note that for the cross-correlation analysis we have considered only the 283 (out of 497) S-GRBs (red filled circles in Fig. 1) distributed at Galactic latitudes $|b| \geqslant 20°$ and with positional accuracy $\Delta < 10°$. The latter selection limits the large uncertainties associated with the position of BATSE bursts (see MGC03 and Section 3). The same selection, applied to the sample of 1540 long bursts, gives 973 events. In Fig. 1 we report the final samples of S-GRBs (filled circles) and the two samples of clusters (open symbols).

[1] http://cossc.gsfc.nasa.gov/docs/cgro/batse/

3 GRB–CLUSTER CROSS-CORRELATIONS

The angular cross-correlation $w_{\rm bc}(\theta)$ represents the fractional increase, relative to a random distribution, of the probability per unit solid angle of finding objects separated by an angle θ. We computed $w_{\rm bc}(\theta)$ for the 283 S–GRB (B) and the 762 clusters (C) by counting the burst–cluster pairs (BC) at different angular separations θ. This is compared with the pairs found at the same angular scale θ between the burst sample and a random sample (BR) of $\sim 10^5$ objects distributed uniformly in the same sky portion covered by the clusters samples.

We use the Hamilton estimator for the angular cross-correlation function between S-GRBs and clusters (Hamilton 1993):

$$w_{\rm bc}(\theta) = \frac{N_{\rm BR}^2}{N_{\rm BC} N_{\rm RR}} \frac{\rm BC(\theta) RR(\theta)}{\rm BR^2(\theta)} - 1 \qquad (1)$$

where $N_{\rm BR}$ and $N_{\rm BC}$ represent the total number of pairs between the short burst sample and the random and cluster samples, respectively, and $N_{\rm RR}$ represents the number of pairs in the random sample. The errors on $w_{\rm bc}(\theta)$ were derived with the bootstrap method (see e.g. Ling, Frenk & Barrow 1986): a set of 100 bootstrap catalogues, each the same size as the data catalogue, were randomly extracted from the GRB catalogue. The cross–correlation (equation 1) was computed for each bootstrap catalogue and, for each θ, a set of normally distributed estimates of the correlation function were obtained. The variance around the mean represents the 1σ uncertainty on $w_{\rm bc}(\theta)$. In all our calculations we accounted for the BATSE sky exposure map (Chen & Hakkila 1998) and for the sky exposure of the REFLEX and NORAS samples, which are in fact quite uniform. As already shown in fig. 1 of MGC03, the typical positional error associated with short BATSE bursts is a few degrees, and the distribution of positional uncertainties of short bursts is nearly flat up to $\sim$5°, while that of L-GRBs peaks at 1–2°. The large uncertainty in the positions of S-GRBs might affect the correlation results. Following the same procedure adopted in MGC03, we tested how the cross-correlation signal changes by considering subsamples of S-GRBs with better positional determination (i.e. $\leqslant 5°$) and found results fully consistent with those presented in Fig. 2.

We find a positive 2σ correlation signal (Fig. 2 – red filled circles) on small angular scales (i.e. $\theta < 3°$) between S-GRBs and clusters, while no correlation is found between L-GRBs and clusters (star symbols in Fig. 2).

Given the incompleteness of the NORAS cluster sample (Section 2), we checked our results by computing the cross-correlation between S-GRBs and the REFLEX and NORAS samples separately. Although the signal has larger uncertainties due to the smaller number of objects in the individual samples, we still find a positive correlation signal on small angular scales, entirely compatible with the one obtained by considering the two samples together.

4 MODEL COMPARISON

To provide an insight into the findings of the previous Section, we have to compare our data with results available in the literature. We use the generalization of the Limber equation developed by Peebles (1974) and Lilje & Efstathiou (1988), which relates the angular two-point cross-correlation function $w_{{\rm c},i}(\theta)$ to the spatial one, $\xi_{{\rm c},i}(r)$:

$$w_{{\rm c},i}(\theta) = 2 \left[\frac{\int_0^\infty N_{\rm c}(x) \Phi_i(x) x^2 \, {\rm d}x \int_0^\infty \xi_{{\rm c},i}(r) \, {\rm d}u}{\int_0^\infty N_{\rm c}(x) \, {\rm d}x \int_0^\infty \Phi_i(x) x^2 \, {\rm d}x} \right], \qquad (2)$$

where x is the comoving coordinate, u and r are related by the expression (which only holds in the small angle approximation,

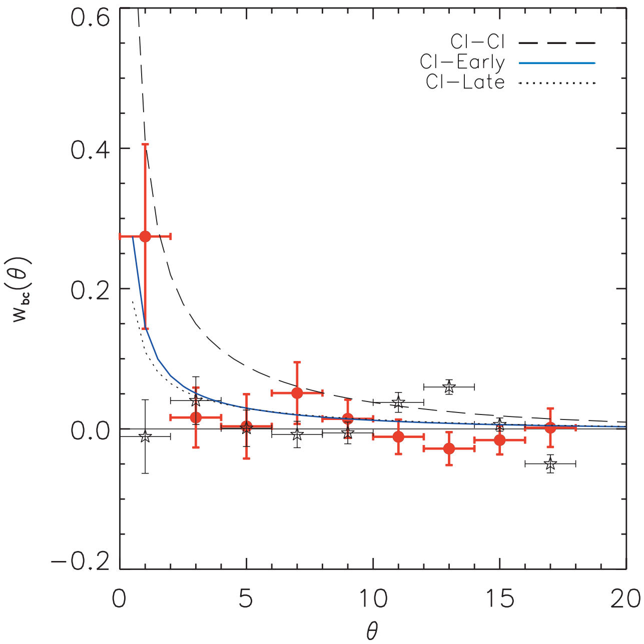

Figure 2. Angular cross-correlation (red filled circles) between S-GRBs and X-ray selected clusters of galaxies. Also shown is (open stars) the signal obtained with BATSE L-GRBs. The long-dashed line represents the auto-correlation function of clusters, while the solid and dotted lines represent the cross-correlation of clusters with early-type and late-type galaxies (see Section 3 for details).

$\theta \ll 1$ rad) $r^2 \simeq u^2 + \theta^2 x^2$, $N_c(x)$ is the number of clusters in the considered sample with distance between x and $x + dx$, and the selection function for a particular class of extragalactic sources $\Phi_i(x)$ is connected to their redshift distribution by

$$\int \Phi_i(x)x^2 dx = \frac{1}{\omega_s}\int N_i(z)dz, \quad (3)$$

where ω_s is the area covered by the survey. Note that the above equations have been obtained for a flat universe. For our analysis, we chose to consider three different cases for the spatial cross-correlation function: (i) $\xi_{c,i} \equiv \xi_{c,c}$ (i.e. cross-correlation function coinciding with the auto-correlation function of clusters); (ii) $\xi_{c,i} \equiv \xi_{c,e}$ (cross-correlation between clusters and early-type galaxies); (iii) $\xi_{c,i} \equiv \xi_{c,l}$ (cross-correlation between clusters and late-type galaxies).

As for the form of the cross-correlation function to be plugged into equation (2), in (i) we have used $\xi_{c,c}(r) = (r/r_0)^{-\gamma}$, with $r_0 = 18.8\,h^{-1}$ Mpc and $\gamma = 1.83$, as derived from the analysis of the clustering properties of REFLEX clusters (Collins 2000), while for the other two cases (ii, iii) we have written $\xi_{c,i}(r) = \xi_{c,c}\, b_c/b_i$, with b representing the bias factor. This latter expression can be easily derived as, theoretically, the cross-correlation function of two populations of extragalactic sources can be expressed as $\xi_{j,i} = b_j b_i \xi_{DM}$, with ξ_{DM} being the autocorrelation function of the underlying dark matter (see e.g. Mo, Peacock & Xia 1993). Under the assumption of scale independence, $b_i = \sigma_{8,i}/\sigma_8$, where σ_8 is the rms of matter fluctuations on a scale $8\,h^{-1}$ Mpc, and $\sigma_{8,i}$ can be obtained from measurements of the two-point autocorrelation function for a chosen class of sources as

$$\sigma_{8,i} = \left[c_{\gamma_i}\,(r_{0,i}/8)^{\gamma_i}\right]^{0.5},$$

with

$$c_{\gamma_i} = \frac{72}{(3-\gamma_i)(4-\gamma_i)(6-\gamma_i)\,2^{\gamma_i}}$$

(Peebles 1980). Values for the correlation length $r_{0,i}$ and the slope γ_i for the populations of early-type and late-type galaxies have been taken from studies of the clustering properties of 2dF galaxies (Madgwick et al. 2003), and for $\sigma_8 = 0.9$, as the latest results from CMB data seem to indicate (Spergel et al. 2003), we obtain $b_c = 4.05$, $b_e = 1.54$, $b_l = 0.97$ respectively for the bias factor of clusters, early-type and late-type galaxies.

$N_c(x)$ in equation (2) has been derived from the redshift distribution of REFLEX clusters. Note that in this case we have also made the choice $N_c(z) \equiv N_i(z)$, i.e. we have assumed that galaxies of both types follow the redshift distribution of REFLEX clusters. This choice was forced by the lack of a statistically significant spectroscopic sample of different types of galaxies which probes their redshift evolution from the local universe up to $z \simeq 0.45$, the maximum redshift of the clusters analysed in this work.

5 RESULTS

Direct comparison with the data shows that the distribution of S-GRBs (red filled circles in Fig. 2) does not trace that of clusters (long dashed line in Fig. 2), i.e. there is not a strong correspondence between clusters and S-GRBs, as not all S-GRBs are found to reside in clusters. If one instead compares the results with the cluster–galaxies cross-correlation function (solid and dotted lines in Fig. 2 respectively for early-type and late-type galaxies), a much better agreement is obtained.

This implies that S-GRBs exhibit clustering properties similar to those of 'normal' galaxies, i.e. that they are present in these classes of sources. Unfortunately, the size of the error-bars does not allow us to discriminate between early-type and late-type galaxies, preventing us from associating S-GRBs with a particular class of galaxies.

The local population of short bursts might be 'contaminated' by a more distant (i.e. $z > 0.5$) and isotropic population of objects which reduces the correlation signal with clusters at $z < 0.5$. Under this hypothesis we should expect the cross-correlation signal to decrease when selecting sub-samples of clusters at lower redshifts.

We tested for this possibility by cutting the REFLEX+NORAS cluster sample at different redshifts. At variance with what we might have expected, we found (Fig. 3) a *stronger* correlation signal between S-GRBs and the 420 clusters with $z \leqslant 0.1$ than was found with the 693 clusters distributed out to $z = 0.2$ or out to $z \sim 0.4$. We also tested for any dependence of the cross-correlation signal on the cluster luminosity. In order to do this, we have divided the REFLEX and NORAS cluster samples in two sub-samples by considering the median values of their X-ray luminosity distribution: $L_X \sim 1.94 \times 10^{44}$ erg s^{-1} and $L_X \sim 1.37 \times 10^{44}$ erg s^{-1} for the NORAS and REFLEX surveys, respectively. This selection corresponds to having a roughly equal number of clusters ($\sim$424) in the two luminosity samples. As shown in Fig. 4, we find a higher signal from the sub-luminous clusters than from the more luminous clusters.[2]

[2] Given the higher signal found with clusters at $z \leqslant 0.1$, we also tried to apply both the luminosity and redshift cuts. With these combined cuts, our results are strongly affected by the paucity of clusters in the more luminous bin (e.g. only 78 with $L > L_*$ and $z < 0.1$), which does not allow us to draw any conclusions.

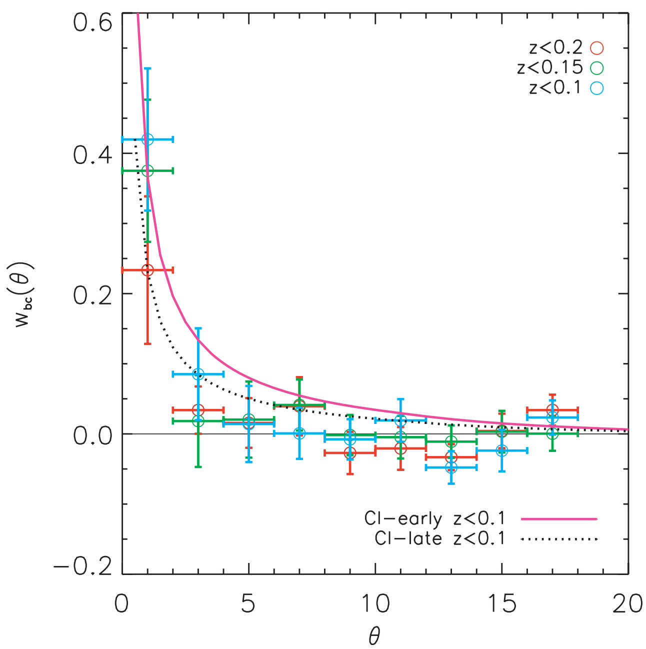

Figure 3. Cross-correlation between S-GRBs and redshift-limited samples of clusters of galaxies ($z < 0.1, 0.15, 0.2$). The solid (dotted) line represents the cross-correlation between clusters and early-type (late-type) galaxies at redshifts $z \leqslant 0.1$.

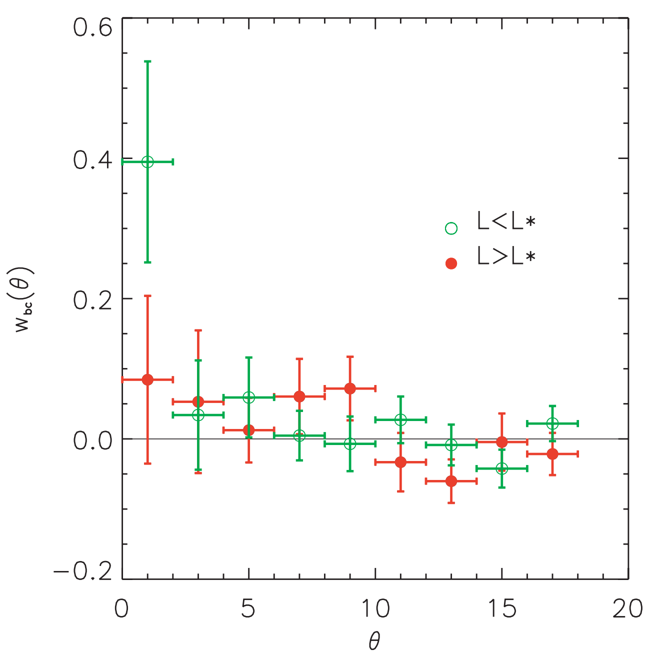

Figure 4. Cross-correlation function of the sample of S-GRBs and the 'clusters of galaxies' sample separated into two luminosity sub-samples of roughly equal total numbers of objects. The open symbols represent the galaxy clusters with X-ray luminosity $< 1.4 \times 10^{44}$ erg s^{-1} ($< 1.9 \times 10^{44}$ erg s^{-1}) for the REFLEX (NORAS) sample.

Since the cluster surveys considered in our work are both flux-limited, it appears that, in general, more luminous sources will be more local than sub-luminous ones. What the data then shows is that S-GRBs might preferentially inhabit low-redshift ($z \lesssim 0.1$) systems. In fact, this evidence is further strengthened by the comparison of

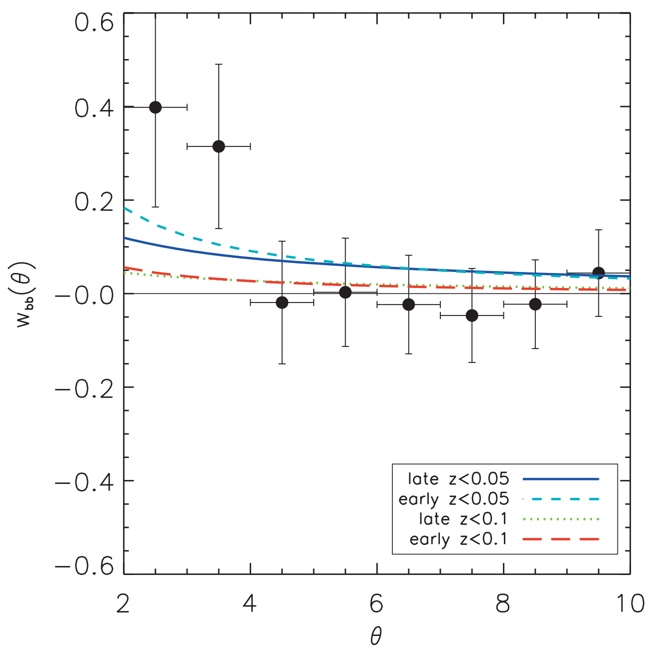

Figure 5. Two-point angular auto-correlation function for the short GRB sample with positional error $\Delta < 10°$. The lines represent different autocorrelation functions for early- and late- type galaxies with limiting redshift of 0.1 and 0.05.

our results with the angular cross-correlation function of clusters and galaxies, obtained as in equation (2) by applying a redshift cut $z_{\rm max} = 0.1$. One can see (Fig. 3) that there is a very good match between data and 'models'. Note that in this case the redshift distribution adopted for early-type and late-type galaxies has been taken in a self-consistent way from the 2dF Galaxy Redshift Survey (Madgwick et al. 2002), complete at least up to $z \simeq 0.15$.

Further evidence on the proximity of S-GRBs can be obtained by comparing the projected auto-correlation function for this class of sources, as obtained by MGC03, with the autocorrelation function of both late-type and early-type galaxies evaluated in a fashion similar to equation (2) up to some maximum redshift $z_{\rm max}$. This is carried out in Fig. 5, where the dotted (long dashed) line represents the autocorrelation function of late (early) type galaxies at $z \leqslant 0.1$. The solid (dashed) line is instead that for $z \leqslant 0.05$. This comparison with the data also seems to hint that short GRBs are more local than $z \leqslant 0.1$, possibly being distributed only up to redshifts $z = 0.05$. Again we note that, with the available data, it is not possible to discern whether S-GRBs are mainly hosted in early-type or late-type galaxies. Better data (probably samples of a size about 3–5 times the one considered in this work) are needed in order to draw more firm conclusions.

At face value, these results point to S-GRBs being local and preferentially associated with less dense environments (i.e., by extrapolation, normal galaxies) rather than with those identified by the clusters themselves. This last conclusion is reached as less-X-ray-luminous clusters are generally associated with less-massive systems (see e.g. Borgani et al. 2002).

A consequence of these results is that, given the average fluence (integrated $>$25 keV) of 4.3×10^{-7} erg cm^{-2} s^{-1} of our sample of S-GRBs, we estimate a typical isotropic equivalent energy of $\sim 2.4 \times 10^{48}$ erg, by assuming $z = 0.05$. Another consequence of having S-GRBs at lower redshift than previously thought is the increase of

S-GRB rate as recently pointed out by Guetta & Piran (2005), Nakar et al. (2006) and Gal-Yam et al. (2005).

6 CONCLUSIONS

By cross-correlating BATSE bursts and REFLEX + NORAS X-ray-selected samples of clusters (distributed out to $z \simeq 0.45$), we find that short-duration ($T_{90} < 2$ s) GRBs are correlated with clusters, while we do not find any correlation with the population of L-GRBs. By comparing the S-GRBs–cluster correlation signal with the cluster–cluster autocorrelation signal, we can exclude the idea that short bursts trace the cluster distribution. Instead, through the comparison with the cluster–galaxy correlation functions, we conclude that S-GRBs are associated with 'normal' galaxies.

We explored the hypothesis that S-GRBs are local events. In fact, we find a higher cross-correlation signal with low-redshift clusters (i.e. up to $z \leqslant 0.06$) or with sub-luminous clusters. What further supports our conclusion is (i) the similarity of the short GRBs–clusters and local galaxies–clusters cross-correlations, and (ii) the S-GRBs auto-correlation, which is similar to the auto-correlation function of local ($z \leqslant 0.1$) galaxies.

The present statistics do not allow us to exclusively associate S-GRBs with early-type galaxies as expected if they are produced – in the double compact merger scenario – by an old stellar population.

These results represent a challenge, because on the one hand they seem to contradict the (still very few) redshift measurements of S-GRBs which place them at $z = 0.16$ (GRB 050709 – Covino et al. 2005; Hjorth et al. 2005) and $z = 0.25$ (GRB 050724 – Berger et al. 2005), and on the other hand they predict a typical energy of $\sim 10^{48}$ erg for S-GRBs. The apparently different (lower) redshift of BATSE short bursts (as found with our analysis, but see also Tanvir et al. 2005) with respect to the few *Swift*-measured redshifts might be due to one, or to a combination, of several effects: (i) an unknown bias of *Swift* to detect systematically larger redshifts (as also shown for the population of L-GRBs) with respect to BATSE; (ii) a possible contamination of the BATSE short burst population by extragalactic SGR (as suggested by Hurley et al. 2005), although direct positional searches (Nakar et al. 2005) and spectral analysis (Lazzati, Ghirlanda & Ghisellini 2005) hardly support this scenario; (iii) a complex luminosity function (e.g. Guetta & Piran 2005).

For these reasons, the redshift distribution of short bursts still represents an open issue which needs more direct redshift determinations, as well as a better understanding of the possible selection effects.

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