GALAXY CLUSTERS ASSOCIATED WITH SHORT GRBs. I.
THE FIELDS OF GRBs 050709, 050724, 050911, AND 051221a

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ABSTRACT

We present a search for galaxy clusters in the fields of three bona fide short gamma-ray bursts (050709, 050724, and 051221a) and the putative short-burst GRB 050911, using multislit optical spectroscopy. These observations are part of a long-term program to constrain the progenitor age distribution based on the fraction of short GRBs in galaxy clusters and early-type galaxies. We find no evidence for cluster associations at the redshifts of the first three bursts, but we confirm the presence of the cluster EDCC 493 within the error circle of GRB 050911 and determine its redshift, \( z = 0.1646 \), and velocity dispersion, \( \sigma \approx 660 \text{ km s}^{-1} \). In addition, our analysis of Swift XRT observations of this burst reveals diffuse X-ray emission coincident with the optical cluster position, with luminosity \( L_X \approx 4.9 \times 10^{42} \text{ ergs s}^{-1} \) and temperature \( kT \approx 0.9 \text{ keV} \). The inferred mass of the cluster is \( 2.5 \times 10^{13} M_\odot \), and the probability of chance coincidence is about 0.1\%–1\%, indicating an association with GRB 050911 at the 2.6–3.2 \( \sigma \) confidence level. A search for diffuse X-ray emission in coincidence with the 15 other short GRBs observed with XRT and Chandra reveals that, with the exception of the previously noted cluster ZwCl 1234.0+02916 likely associated with GRB 050509b, no additional associations are evident to a typical limit of \( 3 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \), or \( M \lesssim 5 \times 10^{13} M_\odot \), assuming a typical \( z = 0.3 \).

The estimated fraction of short GRBs hosted by galaxy clusters of about 5\%–20\% is in rough agreement with the fraction of stellar mass in clusters of \( \approx 10\%–20\% \).

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (EDCC 493) — gamma rays: bursts — X-rays: galaxies: clusters

Online material: color figures

1. INTRODUCTION

Several lines of evidence indicate that the progenitors of short-duration, hard-spectrum gamma-ray bursts (GRBs) are related to an old stellar population. These include the localization of GRB 050724 (Berger et al. 2005; Prochaska et al. 2006) and most likely GRB 050509b (Gehrels et al. 2005; Bloom et al. 2005) to bright elliptical galaxies, the lack of supernova emission in several low-redshift short GRBs (Hjorth et al. 2005a; Fox et al. 2005; Bloom et al. 2006; Soderberg et al. 2006), and the location of GRB 050709 outside of any star-forming region in its host galaxy (Fox et al. 2005). While this supports the popular notion that the progenitors are compact object binaries (DNS or NS-BH; e.g., Eichler et al. 1989; Narayan et al. 1992; Rosswog et al. 2003), the lack of direct observations (e.g., gravitational waves or a subrelativistic, radioactive active component: Li & Paczyński 1998; Kulkarni 2005) suggests that a more detailed understanding of the progenitor population has to rely on statistical studies.

In this vein, Nakar et al. (2006) and Guetta & Piran (2006) argue that the redshift and luminosity distributions of Swift and BATSE short GRBs are inconsistent with the nominal merger time distribution of DNS binaries in the Milky Way, \( P(\tau) \propto \tau^{-1} \) (Champion et al. 2004). They further conclude that the typical age of the progenitors is old, \( >4 \text{ Gyr} \) (Nakar et al. 2006). Similarly, Gal-Yam et al. (2005) and Zheng & Ramirez-Ruiz (2006) propose that the relative fractions of short GRBs in early- and late-type galaxies should constrain the progenitor lifetime distribution. This test derives from the fact that, on average, stars in early-type galaxies form earlier than in late-type galaxies. Finally, Hopman et al. (2006) investigate the redshift distribution of short GRBs in the context of dynamical formation (Grindlay et al. 2006) within globular clusters.

As an extension of these ideas, the preponderance of short GRBs in galaxy clusters can also be used to constrain the age distribution and nature of the progenitor population. In the framework of \( \Lambda \)CDM cosmology, high-resolution numerical simulations suggest that the oldest stars reside in dense galaxy cluster environments, typically within \( \approx 150 \text{ kpc} \) of the cluster center (White & Springel 2000; De Lucia et al. 2006). This is supported by observations, which indicate that the difference in formation epochs for stars in cluster and field elliptical galaxies is \( \approx 1–3 \text{ Gyr} \) (e.g., Bernardi et al. 1998; Kuntschner et al. 2002; Thomas et al. 2005). Since \( M^* \) in clusters is larger than in the field (e.g., Baldry et al. 2006), this leads to an even more pronounced difference in star formation history than just the difference between early- and late-type galaxies discussed in Zheng & Ramirez-Ruiz (2006).

In addition, the early-type fraction in clusters, \( \approx 60\% \), is twice as high as in the field (Dressler 1980; Whitmore et al. 1993), suggesting that the fraction of short GRBs in clusters is intimately related to their rate in early-type galaxies. This is of particular importance in cases where the positional accuracy of the burst is not sufficient to associate it with a particular galaxy, but may be sufficient to associate it with a galaxy cluster. Finally, the specific frequency of globular clusters is at least a factor of a few higher in bright cluster ellipticals than in field galaxies (Harris 1991). Thus, the fraction of short bursts in galaxy clusters may shed light on whether globular clusters are an efficient site for the formation of short GRB progenitors, as proposed by Grindlay et al. (2006).

A complete search for clusters is also important from an observational point of view. These associations can be made at high significance based on the prompt \( \gamma \)-ray positions alone (typically, \( 2'–3' \)), whereas associations with individual galaxies require...
The X-ray luminosity is usually considered to be insensitive to the circum-
burst density,\(^4\) the latter approach may produce an observational bias in favor of gas-rich or disk galaxies.

To date, three associations of short GRBs with galaxy clusters have been claimed. GRB 050509b appears to reside in the cluster ZwCl 1234.0+02916 at \(z = 0.226\) (Pedersen et al. 2005; Bloom et al. 2006), GRB 050813 is apparently associated with a cluster at \(z \approx 1.8\) (Berger et al. 2006; M. D. Gladders et al. 2007, in preparation), and GRB 790613 may be associated with the cluster Abell 1892 at \(z \approx 0.09\) (Gal-Yam et al. 2005). The statistical significance of these associations is \(\sim 3 \sigma\).

Motivated by these considerations, we began the first systematic search for galaxy clusters hosting short GRBs, using multi-
slit optical spectroscopy and archival X-ray observations. This is part of a long-term program to constrain the age distribution of the progenitors using the properties of their large-scale environments. Here we present spectroscopy in the fields of GRBs 050709, 050724, 050911, and 051221a. We also reanalyze all of the available X-ray observations of short GRB fields to search for diffuse emission from hot intracluster gas associated with potential clusters. The layout of the paper is as follows. The optical observations are described in § 2.1, and the X-ray analysis in presented in § 2.2. In § 3 we summarize the results of our search, including a determination of the optical and X-ray properties of the cluster ECDC 493, which coincides with GRB 050911. We draw initial conclusions in § 4. Throughout the paper we use the standard ΛCDM cosmology with \(H_0 = 71\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.27\), and \(\Omega_{\Lambda} = 0.73\).

2. OBSERVATIONS

For a detailed discussion of the four bursts studied in this paper, we refer the reader to the following publications: GRB 050709: Fox et al. (2005), Hjorth et al. (2005b), and Villasenor et al. (2005); GRB 050724: Berger et al. (2005), Campana et al. (2006), and Barthelmy et al. (2005); GRB 050911: Page et al. (2006); GRB 051221a: Soderberg et al. (2006) and Burrows et al. (2006). We note that the classification of GRB 050911 is somewhat ambiguous. Formally, \(T_{90}\) for this burst is \(\sim 16\) s (Page et al. 2006), but the light curve is dominated by an initial pair of short pulses with a total duration of about 1.5 s, followed by a marginally softer component with a slow rise and decay. The latter component may be similar to the soft tails observed in GRBs 050709 (Villasenor et al. 2005) and 050724 (Barthelmy et al. 2005), and, moreover, would have been missed by BATSE (Page et al. 2006). In this framework, GRB 050911 would be classified as a short GRB. We note that if GRB 050911 is instead a long-duration burst, a cluster association is likely to be due to a chance coincidence, since long GRBs are associated with star-forming galaxies (e.g., Christensen et al. 2004) and to date none have been shown to be located in early-type galaxies or clusters.

2.1. Optical Spectroscopy

We selected targets for spectroscopy based on imaging observations from the Hubble Space Telescope (050709), the Magellan/Clay Low Dispersion Survey Spectrograph (050724), the Gemini Multi-Object Spectrograph (051221a), and the du Pont 100 inch (2.5 m) telescope at Las Campanas Observatory (050911). We used the program SExtractor (Bertin & Arnouts 1996) to estimate source magnitudes and to separate stars and galaxies (using a stellarity index of <0.5 for galaxies). From the spectroscopy, we find a star interloper fraction of 5% for GRB 050911, 12% for GRB 051221a, and zero for GRBs 050724 and 050709. The objects range in brightness from \(R = 17.9\) to 21.9 mag (050709; \(R_{host} \approx 21.2\) mag), \(I = 17.6\) to 21.1 mag (050724; \(r_{host} \approx 18.6\) mag), \(R = 15.3\) to 19.7 mag (050911), and \(r = 21\) to 22.5 mag (051221a; \(r_{host} \approx 22.0\) mag). The final source catalogs (not including stars) contain 33 objects (050709), 21 objects (050724), 79 objects (051221a), and 38 objects (051109).

All spectra were obtained with the Low Dispersion Survey Spectrograph (LDSS3) mounted on the Magellan/Clay 6.5 m telescope using a 300 line mm\(^{-1}\) grism, which provides a resolution of about 6 Å. For GRB 050724 we also used a volume-phase holographic grism, which provides a resolution of about 2 Å. The log of the observations is provided in Table 1. We reduced the data with the cosmos software package,\(^5\) using flat and HeNeAr arc exposures obtained following each mask exposure. The data were bias-subtracted, flat-fielded with a response-corrected flat, and sky-subtracted using a two-dimensional spline fit. The spectra were then extracted and combined following cosmic-ray rejection. Redshifts were determined manually using the IRAF task spec2d to measure the absorption and/or emission-line positions. We obtained redshifts for a total of 151 galaxies in the four GRB fields, or an overall success rate of 79%.

\(^4\) The X-ray luminosity is usually considered to be insensitive to the circum-
burst density (\(\nu\)), but this is only true when the X-ray band is located above the synchrotron cooling frequency, requiring a relatively high density (\(\nu \approx 10^{10} \text{ cm}^{-3}\)) to begin with. At lower densities, typical of the intracluster medium, the afterglow luminosity in all bands is expected to be low.

\(^5\) See http://shimura.ociw.edu:8200/Code/Groups/Cosmos.
TABLE 2  
X-RAY OBSERVATIONS OF SHORT GRB FIELDS

| GRB  (1) |  z  (2) | Date (UT)  (3) | Telescope  (4) | Exposure Time (s)  (5) | N(H i) (10^20 cm⁻²)  (6) | Count Rate (s⁻¹)  (7) | \(F_X\) (10⁻¹⁴ ergs s⁻¹ cm⁻²)  (8) | \(L_X\) (10⁻¹² ergs s⁻¹)  (9) |
|----------|--------|----------------|---------------|------------------------|---------------------------|-----------------------|-------------------------------|-------------------|
| 050509b | 0.226  | 2005 May 9.17  | XRT           | 32080⁴  | 1.27  | 0.0092  | 37.6⁴  | 45.7⁴  |
| 050709  | 0.161  | 2005 Jul 11.55 | XRT           | 17316    | 0.006  | 0.0004  | <2.7  | <1.6  |
| 050724  | 0.257  | 2005 Jul 29.02 | XRT           | 24880    | 1.27  | 0.0054  | <3.8  | <2.3  |
| 050813  | 1.87   | 2005 Aug 13.28 | XRT           | 14210    | ...   | ...     | ...   | ...   |
| 051105a | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 051114  | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 051210  | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 051221a | 0.546  | 2006 Jan 2.09  | XRT           | 56663    | 0.008  | 0.0007  | <2.2  | <1.7  |
| 051227  | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 060121  | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 060313  | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 060502b | 0.287  | ...            | ...           | ...      | ...   | ...     | ...   | ...   |
| 060801  | 1.131  | 2006 Aug 2.04  | XRT           | 20942    | 0.008  | 0.0007  | <2.0  | <1.7  |
| 060801  | ...    | ...            | ...           | ...      | ...   | ...     | ...   | ...   |

Notes.—X-ray observations of short GRB fields obtained with Swift XRT and Chandra.

a Galactic neutral hydrogen column density from Dickey & Lockman (1990).

b Upper limits are calculated as 3σ of the number of counts in a 2′ radius aperture, corresponding to \(\sim 400-700 \text{ kpc at } z \sim 0.2-0.5\). For multiple observations, we provide the upper limit based on the combined data.

c Unabsorbed flux. Conversion from count rate to flux assumes a thermal bremsstrahlung model with \(kT = 1 \text{ keV}\) and the Galactic absorbing column densities given in col. (6).

* First 0.5 hr of data removed to eliminate the contribution from the afterglow.

This object is possibly a Galactic soft γ-ray repeater (Holland et al. 2005). No diffuse X-ray emission is evident in XMM-Newton observations of this field (de Luca et al. 2005).

References.—References for redshifts (in order): Bloom et al. (2006); Fox et al. (2005); Berger et al. (2005); Berger (2006); Soderberg et al. (2006); Bloom et al. (2007); and Cucchiara et al. (2006).

2.2. X-Ray Data

We retrieved from the High Energy Astrophysics Science Archive Research Center⁶ all publicly available observations of short GRBs taken with the Swift X-ray telescope (XRT) and the Chandra X-Ray Observatory. A summary of the observations and exposure times for the 16 available GRBs is given in Table 2.

We processed the XRT data with the xrtpipeline script packaged within the HEAsoft software, using the default grade selection and screening parameters. For the Chandra data we used the ev2f2 files provided by HEASARC. All event files were further filtered for the energy range 0.5–7 keV using xselect. We searched for diffuse emission at the positions of the short GRBs visually, using the CIAO routine csmooth to construct smoothed images.

3. RESULTS

We show the results of our spectroscopic observations overlaid on images of each of the four fields in Figures 1–4. The redshift distributions are presented in Figure 5. For GRB 050724 we do not find any galaxies in the 8′ diameter field, within \(\sim 9000 \text{ km s⁻¹}\) of the host redshift of \(z = 0.257\). A possible background galaxy group or cluster is located at \(z \approx 0.3\), but we do not detect any coincident X-ray emission with a limit of \(L_X \approx 8.3 \times 10^{42} \text{ ergs s⁻¹}\) (at \(z = 0.3\)). This indicates that this background structure is at most a poor cluster.

Similarly, of the 21 galaxies with spectroscopic redshifts in the \(2′ \times 2′\) field of GRB 050709, we find only two within 2000 km s⁻¹
of the burst redshift, \( z = 0.161 \). This is unlikely to constitute a significant structure, and in fact we place a limit of \( L_X \leq 1.6 \times 10^{42} \) ergs s\(^{-1}\) on diffuse X-ray emission associated with the burst environment.

In the field of GRB 051221a, we find a nearly uniform redshift distribution between \( z \sim 0.1 \) and 1, with only two galaxies in the

\[
\begin{align*}
5' \times 5' \text{ field located within } 2000 \text{ km s}^{-1} \text{ of the burst redshift, } z = 0.5465. \text{ However, these galaxies, at } z = 0.550 \text{ and } 0.544, \text{ are situated about } 3.0' (1.2 \text{ Mpc}) \text{ and } 2.8' (1.1 \text{ Mpc}) \text{ away from the GRB host galaxy, respectively, suggesting that this is not likely to be a significantly overdense structure. The limit on diffuse }
\end{align*}
\]
We consider all galaxies within 3000 km s$^{-1}$ of GRB 050724, we do not find any galaxies within 9000 km s$^{-1}$ of the burst. In the case of GRB 050709, there are two galaxies in the field within 2000 km s$^{-1}$ of the burst redshift ($z = 0.161$), at $z = 0.154$ and 0.156. In the field of GRB 050724, we do not find any galaxies within 9000 km s$^{-1}$ of the burst redshift ($z = 0.257$). Two galaxies in the field of GRB 051221a are located within 2000 km s$^{-1}$ of the burst redshift ($z = 0.5465$), at $z = 0.550$ and 0.544. Finally, the cluster EDCC 493 at $z = 0.1646$ is clearly visible in the field of GRB 050911. The velocity dispersion of this cluster is 660 km s$^{-1}$ (inset).

X-ray emission coincident with the burst position is $L_X \approx 1.7 \times 10^{42}$ ergs s$^{-1}$, or about 50% fainter than the X-ray luminosity of the cluster associated with GRB 050509b (Pedersen et al. 2005; Bloom et al. 2006; Table 2).

### 3.1. The Galaxy Cluster EDCC 493 in the Error Circle of GRB 050911

The BAT error circle of GRB 050911, centered on α = 00$^h$54$^m$52.4$^s$, δ = −38$^\circ$51′42.8″ (J2000.0) with an uncertainty of 2.8′ radius (Page et al. 2006), intersects the galaxy cluster EDCC 493 (Berger 2005). This cluster has an Abell radius of about 9.5′ (Lumsden et al. 1992).

Our spectroscopic observations in this field quantify the properties of the cluster. We obtain redshifts for 14 cluster members, including the brightest elliptical galaxy. The properties of the cluster galaxies are summarized in Table 3. We estimate the cluster velocity dispersion using the ROSAT package (Beers et al. 1990). We consider all galaxies within 3000 km s$^{-1}$ of the mean cluster redshift and calculate the biweight estimators of the location (mean velocity) and scale (velocity dispersion). Objects with velocities greater than 3 times the velocity dispersion are removed from the sample, and a new location and scale are calculated iteratively until no more objects are clipped. In this particular system, no objects were clipped from the original list. We find σ = 660$^{+135}_{-95}$ km s$^{-1}$ and a redshift of $z = 0.1646$ (Fig. 5).

The early-type fraction in our sample of 14 cluster members is 80% ± 25%, at the high end of the distribution for groups/clusters with a similar velocity dispersion (Mulchaey et al. 2006). This suggests that GRB 050911 was most likely associated with an early-type galaxy. Another potential implication is that EDCC 493 is more evolved than a typical cluster of the same mass, perhaps a reflection of the old age of the GRB progenitor system. The determination of the early-type fraction for a larger sample of cluster members will show whether this effect is real.

We also detect diffuse X-ray emission in the XRT data coincident with the optical cluster position, at α = 00$^h$55$^m$01.39$^s$, δ = −38$^\circ$52′45.8″ (J2000.0), with an uncertainty of about 5″ in each coordinate (Fig. 6). This position is 8.5″ west and 15.7″ south of the optical position of the bright cluster elliptical.

To determine the source X-ray properties, we extract counts for each individual observation in an elliptical aperture with semi-major and semi-minor axes of 120″ and 80″, respectively, selected to match the scale at which the cluster diffuse emission matches the background level. We then bin the extracted counts in energy such that each bin contains at least 10 counts. Using a MEKAL model fit to the energy range 0.2–7 keV with an abundance fixed at Z/Fe = 0.3 (Mushotzky & Loewenstein 1997) and an absorbing column density of $N_H = 2.7 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990), we find $kT = 0.9^{+0.3}_{-0.2}$ keV and $L_X = 4.9^{+1.3}_{-1.2} \times 10^{42}$ ergs s$^{-1}$ ($\lambda X = 1.0$ for 19 degrees of freedom). The data and model fit are shown in Figure 7.

The measured velocity dispersion and X-ray luminosity are in good agreement with values measured for galaxy groups and poor clusters from the Röntgensatellit (ROSAT) Deep Cluster Survey (Mulchaey et al. 2006, but the temperature is somewhat lower than expected in comparison to the compilation of Horner et al. (1999), from which we estimate $kT > 2.5$ keV. Using the cluster mass-temperature relation (Arnaud et al. 2005), we estimate a mass of $M_{500} \approx 2.5 \times 10^{14} M_{\odot}$, or about a factor of 6 times lower than expected for a cluster of this mass.
than the cluster ZwCl 1234.0+02916 in the field of GRB 050509b (see § 3.2).

We next assess the probability that GRB 050911 is associated with EDCC 493. From the log $N$-log $S$ relation for X-ray clusters in the ROSAT Deep Cluster Survey, we find that for a flux of $F_X > 7.7 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ the surface density of sources is about 1.4 deg$^{-2}$ (Rosati et al. 1998). The probability of chance coincidence with the 2.8$''$ radius error circle is therefore $9.6 \times 10^{-3}$. Thus, we conclude that the association between GRB 050911 and EDCC 493 is significant at the 2.6$\sigma$ confidence level.

We note that taking into account the 13 additional searches (excluding GRB 050509b; see § 3.2), the probability of finding such a cluster in any of the BAT error circles is about 12% (or 1.6$\sigma$). Of course, of the other 14 short bursts, 11 have much more accurate positions from X-ray, optical, and/or radio afterglow observations.

If we consider the X-ray luminosity of the cluster, we find that the volume density of clusters with $L_X = 4.9 \times 10^{42}$ ergs s$^{-1}$ is $dN/dL_X \approx 3.3 \times 10^{-3}$ Mpc$^{-3}$ $(10^{44}$ ergs s$^{-1}$)$^{-1}$ (Rosati et al. 1998). Integrating the X-ray luminosity function with $\alpha = -1.83$ (Rosati et al. 1998), we find $N(L > L_X, EDCC) \approx 3.2 \times 10^{-6}$ Mpc$^{-3}$, or $2.7 \times 10^{-5}$ arcmin$^{-2}$ within the distance to EDCC 493. The probability of finding such a cluster within the error circle is therefore $7 \times 10^{-4}$, or a 3.4$\sigma$ significance level for an association with GRB 050911.

Turning to the brightest cluster galaxy (BCG), we find from the Two Micron All Sky Survey (2MASS) catalog that it has $K = 13.5 \pm 0.1$ mag in a 6.6$''$ aperture, or $I - K = 4.1 \pm 0.1$ mag compared to our $I$-band photometry. The surface density of sources with equal or greater brightness is about 18 deg$^{-2}$, or a probability of 0.12 of finding such an object within the error circle. The rest-frame $K$-band absolute magnitude of the BCG is $M_K \approx -25.4$ mag, or $L \approx 3L_\odot$ in comparison to the luminosity function from the Two Degree Field (2dF) Galaxy Redshift Survey and 2MASS (Cole et al. 2001). Integrating the $K$-band

![Fig. 7.—Spectrum of the diffuse X-ray emission from the cluster EDCC 493, located in the error circle of GRB 050911. We simultaneously fit the counts extracted from all four XRT observations of this field (Table 2). The data are binned with at least 10 counts per bin. We use a MEKAL model fit with an abundance fixed at 0.3 $Z_\odot$ and an absorbing column density of $N_H = 2.7 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). The best-fit parameters are $kT = 0.9^{+0.3}_{-0.2}$ keV and $L_X = 4.9^{+1.3}_{-1.2} \times 10^{42}$ ergs s$^{-1}$ ($\chi^2_r = 1.0$ for 19 degrees of freedom).](image)

![Fig. 8.—Smoothed Swift XRT and Chandra X-ray images of the fields of 15 short GRBs. The location of the burst is marked with a circle when only a BAT position is available, or an arrow if an afterglow has been detected. The diffuse X-ray emission from the cluster ZwCl 1234.0+02916 coincident with GRB 050509b (Pedersen et al. 2005; Bloom et al. 2006) is clearly visible in the XRT and Chandra images.](image)
luminosity function, we find that the number density of such galaxies is \( N(L > 3 L^* ) \approx 5.1 \times 10^{-5} \) Mpc\(^{-3} \), or \( 4.3 \times 10^{-4} \) arcmin\(^{-2} \) within the distance to EDCC 493. Thus, the probability of finding such a luminous galaxy within the BAT error circle of GRB 050911 is about 0.01 (2.6 \( \sigma \) confidence level).

We therefore conclude that the probability of chance association is only 0.1%–1%, and it is therefore likely that GRB 050911 occurred within the cluster. At the redshift of EDCC 493, the isotropic-equivalent \( \gamma \)-ray energy release of the burst was \( 1.9 \times 10^{49} \) ergs, similar to that of other short GRBs (Soderberg et al. 2006).

### 3.2. Diffuse X-Ray Emission

In Figure 8 we show smoothed XRT and Chandra X-ray images of the fields of the 15 short GRBs. With the exception of the previously detected diffuse X-ray emission from the cluster ZwCl 1234.0+02916 coincident with GRB 050509b (Pedersen et al. 2005; Bloom et al. 2006), we do not detect clear diffuse X-ray emission in coincidence with any of other short GRBs. We calculate upper limits on the X-ray flux using \( 3M_{\text{cts}}/t_{\text{exp}} \) within a 2' radius circle centered on each GRB position, where \( N_{\text{cts}} \) is the total number of counts within the circle in the 0.5–7 keV range (effectively the background level) and \( t_{\text{exp}} \) is the total exposure time. To convert from count rate to flux, we assume a thermal bremsstrahlung model with \( kT = 1 \) keV and an absorbing column given by the Dickey \& Lockman (1990) value for each burst. The typical upper limits are \( 3 \times 10^{-14} \) ergs s\(^{-1} \) cm\(^{-2} \), or a factor of 2 lower than for EDCC 493. Assuming a typical redshift, \( z \sim 0.3 \), the corresponding luminosity limit is \( \lesssim 7 \times 10^{42} \) ergs s\(^{-1} \), or roughly \( M_{500} \lesssim 5 \times 10^{13} \) \( M_\odot \).

For the cluster ZwCl 1234.0+02916 associated with GRB 050509b, we derive a temperature of \( kT = 3.0^{+0.5}_{-0.3} \) keV and an unabsorbed luminosity of \( L_X = 4.5^{+0.7}_{-0.3} \times 10^{43} \) ergs s\(^{-1} \) (\( \chi^2 = 0.64 \) for 12 degrees of freedom; Fig. 9). The absorbing column density is \( N_H = 1.1^{+0.6}_{-0.3} \times 10^{21} \) cm\(^{-2} \), about an order of magnitude larger than the Dickey \& Lockman (1990) value for the Galactic column. Here we used a MEKAL model with the abundance fixed to 0.3 Z_\odot. We note that our derived temperature is in good agreement with the value of about 3.65 keV found by Pedersen et al. (2005), but is lower than the value of 5.25 keV found by Bloom et al. (2006). Our derived luminosity is about 50% higher than that of Pedersen et al. (2005). The inferred cluster mass is \( M_{500} = 1.6^{+1.1}_{-0.6} \times 10^{14} \) \( M_\odot \).

### 4. DISCUSSION

We present the first systematic search for galaxy clusters hosting short GRBs using multislit optical spectroscopy in the fields of GRBs 050709, 050724, 050911, and 051221a and a reanalysis of all publicly available X-ray observations. Future papers in this series will present optical spectroscopy of additional short GRB fields and a detailed analysis of the galaxy cluster statistics. No apparent clusters were found in the fields of GRBs 050709, 050724, and 051221a from optical and X-ray observations. In the error circle of the putative short-burst GRB 050911, we show that the cluster EDCC 493 has mean redshift \( z = 0.1646 \), velocity dispersion \( \sigma = 660 \) km s\(^{-1} \), \( \gamma \)-ray temperature \( kT = 0.9 \) keV, and luminosity \( L_X = 4.9 \times 10^{42} \) ergs s\(^{-1} \). These values are typical for poor clusters, and the inferred mass is about \( 2.5 \times 10^{13} \) \( M_\odot \).

This result highlights the ability to associate short GRBs with galaxy clusters based on \( \gamma \)-ray positions alone, thus removing a potential bias in favor of associations with gas-rich galaxies when relying on afterglow positions.

It has been suggested that the relative fraction of early- and late-type host galaxies of short GRBs can be used to constrain the age distribution of the progenitor population (Zheng \& Ramirez-Ruiz 2006). Making the association between GRB 050911 and EDCC 493 and using all of the available observations to date, we find that of the Swift short GRBs, as many as five may be associated with early-type galaxies (050509b, 050724, 050813, 050911, and 060502b) and two are associated with late-type galaxies (050709 and 051221a). Taken at face value, this would argue for an age distribution \( P(r) \propto r^n \) with \( n \sim 2 \) (Zheng \& Ramirez-Ruiz 2006). Naturally, in making a more accurate derivation of this value, one has to take into account the respective probability of association for each burst. In fact, if we consider only secure associations, the relative numbers are \( 1:2 \), instead of \( 5:2 \), leading to \( n \sim -1 \). This highlights the need for additional observations and methods to constrain the value of \( n \).

Independent of associations with individual galaxies, the fraction of short GRBs in clusters is also of interest in assessing the age distribution. Of the 16 available bursts, three have claimed cluster associations (050509b, 050813, and 050911) with a significance of about 3–4 \( \sigma \). Within the inherent uncertainty, the fraction of short GRBs in clusters is therefore \( \sim 5\%–20\% \), in rough agreement with the value of \( \sim 10\% \) for the overall fraction of stellar mass in galaxy clusters (Fukugita et al. 1998), or about \( 20\% \) in clusters equal to or more massive than EDCC 493 (Eke et al. 2005). Of course, not all stars are capable of producing short GRBs, but assuming that the initial mass function and binary fractions are independent of galaxy properties, the total stellar mass provides a good proxy for the mass in short GRB progenitors. Thus, at present there is reasonable agreement between the fraction of short GRBs and the baseline fraction of stellar mass in galaxy clusters.

Finally, we note that the frequency of short GRBs in galaxy clusters may reflect a potential association with globular clusters.

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7 For example, the probability of association for GRB 050509b is estimated at 3–4 \( \sigma \) (Gehrels et al. 2005; Pedersen et al. 2005; Bloom et al. 2006), while that for GRB 060502b is only 2 \( \sigma \) (Bloom et al. 2007).

8 This fraction does not change if we include the claimed cluster association for GRB 790613 out of four IPN short-burst error boxes searched by Gal-Yam et al. (2005).
(Grindlay et al. 2006; Hopman et al. 2006). The latter are thought to provide an efficient environment for the production of DNS binaries and may account for a substantial fraction of all short GRB progenitors (Grindlay et al. 2006). In particular, the specific frequency of globular clusters increases significantly from a value of $\sim 1$ for S+Ir galaxies to $\sim 4$ for E+SO galaxies and $\sim 12$ for cD galaxies (Harris 1991). Given that massive elliptical galaxies are overrepresented in galaxy clusters compared to the field, we expect that an association with globular clusters will increase the fraction of galaxy cluster associations compared to the baseline level of $\sim 10\%$–$20\%$ indicated above (see also Hopman et al. 2006). Thus, continued searches for galaxy clusters hosting short GRBs and more detailed predictions for the expected fraction as a function of cluster mass and redshift may hold the key to a clearer understanding of the progenitor population.

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