Galaxy Clusters Associated with Short GRBs. II. Predictions for the Rate of Short GRBs in Field and Cluster Early-Type Galaxies

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ABSTRACT

We determine the relative rates of short GRBs in cluster and field early-type galaxies as a function of the age probability distribution of their progenitors, $P(\tau) \propto \tau^n$. This analysis takes advantage of the difference in the growth of stellar mass in clusters and in the field, which arises from the combined effects of the galaxy stellar mass function, the early-type fraction, and the dependence of star formation history on mass and environment. This approach complements the use of the early- to late-type host galaxy ratio, with the added benefit that the star formation histories of early-type galaxies are simpler than those of late-type galaxies, and any systematic differences between progenitors in early- and late-type galaxies are removed. We find that the ratio varies from $R_{\text{cluster}}/R_{\text{field}} \sim 0.5$ for $n = -2$ to $\sim 3$ for $n = 2$. Current observations indicate a ratio of about 2, corresponding to $n \sim 0 - 1$. This is similar to the value inferred from the ratio of short GRBs in early- and late-type hosts, but it differs from the value of $n \approx -1$ for NS binaries in the Milky Way. We stress that this general approach can be easily modified with improved knowledge of the effects of environment and mass on the build-up of stellar mass, as well as the effect of globular clusters on the short GRB rate. It can also be used to assess the age distribution of Type Ia supernova progenitors.

Subject headings: gamma-rays:bursts — galaxies:clusters — galaxies:formation

1. Introduction

Gamma-ray bursts (GRBs) are divided into two broad classes of short/hard and long/soft bursts (Kouveliotou et al. 1993), which appear to have different progenitor populations. Observations of Type Ic supernovae in association with long GRBs provide a direct confirmation

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that they arise from the death of massive stars (Hjorth et al. 2003; Stanek et al. 2003). Short
GRBs, on the other hand, have long been suspected to arise from the merger of neutron star
and/or black hole binaries (NS-NS, NS-BH; e.g., Eichler et al. 1989; Narayan et al. 1992;
Rosswog & Ramirez-Ruiz 2002; Aloy et al. 2005). During the last year, follow-up observa-
tions of Swift and HETE-2 short GRBs have provided initial confirmation to this idea, based
in particular on the localization of some short GRBs to elliptical galaxies (Berger et al. 2005;
Gehrels et al. 2005; Bloom et al. 2006a), their lack of association with bright supernovae
(Fox et al. 2005; Hjorth et al. 2005; Soderberg et al. 2006), and their lower energy release
and wider beaming angles compared to long GRBs (Burrows et al. 2006; Soderberg et al.
2006).

Despite this observational progress we are still missing a clear understanding of the
progenitor population, due to the lack of direct observations (circumburst chemical abund-
dances, gravitational waves, or a sub-relativistic, radioactive component: Li & Paczyński
1998; Kulkarni 2005). Thus, statistical studies of the burst properties can be highly effec-
tive in understanding their progenitor population(s) (e.g., Gal-Yam et al. 2005; Nakar et al.
of short GRBs in early- and late-type galaxies as a constraint on the age distribution of
the progenitors. Their analysis combines the global star formation rate in each galaxy type
with a local galaxy stellar mass function, assuming the formation process of short GRB
progenitors does not depend on any other physical parameters. Since each galaxy type has
experienced a globally different star formation history, the ratio of bursts in each type is
predicted to vary as a function of the progenitor age distribution.

A complementary way to constrain the progenitor age distribution is to use the rates of
short GRBs in clusters and the field (Berger et al. 2006b; hereafter Paper I). This approach
takes advantage of the following differences between cluster and field environment. First, the
galaxy stellar mass function of clusters is more heavily dominated by massive galaxies than in
the field (Croton et al. 2003; Baldry et al. 2006). Since the star formation history is mainly
determined by galaxy mass, the overall growth of stellar mass is in turn affected by the large-
scale environment. Second, the fraction of early-type galaxies is larger in clusters than in
the field (Dressler 1980; Whitmore et al. 1993; Baldry et al. 2006). Finally, there appears to
be a systematic offset in the star formation histories of cluster and field early-type galaxies
of $\sim 1 - 3$ Gyr (e.g., Bernardi et al. 1998; Kuntschner et al. 2002; Thomas et al. 2005).
These effects lead to an overall difference in cluster and field star formation histories, which
combined with the progenitor age distribution, is expected to affect the relative fraction of
short GRBs in each environment.

In this paper we quantify these effects and show how the ratio of short GRBs in cluster
and field early-type galaxies can be used to understand the age distribution of the progenitors. This is part of our on-going systematic study of galaxy clusters hosting short GRBs, using multi-slit optical spectroscopy and X-ray observations (Paper I). We find that the current observations, albeit with a small number of events, favor \( P(\tau) \propto \tau^n \) with \( n \sim 0 - 1 \). Finally, we provide a comparison of the systematic effects in this approach and the approach of Zheng & Ramirez-Ruiz (2006).

2. The Rate of Short Bursts in Clusters and the Field

The approach used by Zheng & Ramirez-Ruiz (2006) can be generalized to formulate the short GRB rate per unit volume in cluster and field early-type galaxies at \( z \sim 0 \), using the star formation history function, SFH(\( \tau \)) instead of a star formation rate function:

\[
R_i = C \int_0^{t(z=\infty)} \text{SFH}_i(\tau) P(\tau) d\tau. \tag{1}
\]

Here \( \tau \) is both the look-back time and the time delay of a short GRB progenitor, and \( i \) designates a cluster or field environment. \( P(\tau) \) represents the time delay probability distribution of the progenitors with a normalization constant \( C \). In the context of NS-NS or NS-BH mergers we adopt the standard power-law form, \( P(\tau) \propto \tau^n \). We note that NS-NS binaries in the Milky Way appear to follow \( P(\tau) \propto \tau^{-1} \) (Champion et al. 2004). It is thus the convolution of \( P(\tau) \) with SFH(\( \tau \)) that determines the relative rate of short GRBs in cluster and field early-type galaxies.

Since the star formation history of early-type galaxies is determined by both the mass and environment of a galaxy, the total star formation history of each environment can be described in the following manner:

\[
\text{SFH}_i(\tau) = \int_{M_l}^{M_u} \phi_i(M) \text{SFH}_{gal,i}(\tau, M) dM, \tag{2}
\]

where \( \phi_i(M) \) is the galaxy number density function, \( \text{SFH}_{gal,i}(\tau, M) \) is the star formation history function of a single galaxy that has a stellar mass, \( M \), and \( M_u \) and \( M_l \) are the appropriate upper and lower mass integration limits (see \( \S \) 3).

From SDSS observations, it has been determined that the galaxy number density is well described by a double Schechter function (Baldry et al. 2006):

\[
\phi(M) dM = e^{-M/M^*} [\phi_1^*(M/M^*)^{\alpha_1} + \phi_2^*(M/M^*)^{\alpha_2}] \frac{dM}{M^*}, \tag{3}
\]
where the parameters \( \log M^*, \phi_1^*, \alpha_1, \phi_2^* \) and \( \alpha_2 \) for a cluster environment (\( \log \Sigma \sim 1.3 \)) are 11.06, 0.74, -1.09, 0.07, and -1.5, and for a field environment (\( \log \Sigma \sim -0.9 \)) they are 10.44, 2.7, -0.2, 0.8, and -1.5 (Baldry et al. 2006). Here, \( \Sigma \) is the projected density of neighboring galaxies, and the specific values are determined from a sample of \( \sim 1.5 \times 10^5 \) galaxies in the redshift range \( 0.01 - 0.085 \) in the SDSS Data Release Four (Baldry et al. 2006).

We are here only interested in the rates of short GRBs in early-type galaxies, whose star formation history is better understood than those of late-type galaxies, and in order to avoid any systematic differences between progenitors in late- and early-type host galaxies. We therefore need to modify \( \phi(M) \) by the fraction of early-type galaxies in each environment (Baldry et al. 2006):

\[
f_{r,i}(\Sigma, M) = 1 - \exp\{-[(\Sigma/b_1)^{b_2} + (M/b_3)^{b_4}]\},
\]

(4)

where the values of the parameters \( b_1, b_2, b_3, \) and \( b_4 \) are \( 10^{0.91} \) Mpc\(^{-2}\), 0.69, \( 10^{10.72} \) M\(_{\odot}\), and 0.59. Thus, \( \phi_i(M) = \phi(M)f_{r,i}(\Sigma, M) \). In a cluster environment, with a higher \( \Sigma \) and systematically larger masses, the early-type fraction is larger than in the field. A plot of \( f_r \phi(M) \) for cluster and field environments is shown in Figure 1a. Clearly, the most massive galaxies reside preferentially in clusters, while the bulk of the mass in galaxies with \( M \lesssim 10^{10.5} \) is in the field.

Finally, we turn to the star formation history function, \( \text{SFH}_{\text{gal}}(\tau, M) \). Early-type galaxies in different environments show different star formation histories for a given galaxy mass (Kuntschner et al. 2002; Thomas et al. 2005; De Lucia et al. 2006; Schawinski et al. 2006). Moreover, the star formation history is also determined by the galaxy mass. Following Thomas et al. (2005), we use a Gaussian form for the star formation history:

\[
\text{SFH}_{\text{gal}}(\tau, M) = \frac{M}{\sqrt{2\pi \Delta t}} \exp\left[-\frac{(\tau - t_{\text{peak}})^2}{2(\Delta t)^2}\right],
\]

(5)

where the peak of the star formation history function, \( t_{\text{peak}} \), is determined by both the mass of a galaxy and its environment (Equations 2 and 3 of Thomas et al. 2005), and \( \Delta t \) is determined by the mass of a galaxy. Here, we assume that the low-density environment of Thomas et al. (2005) corresponds to the field, while clusters correspond to the high-density environment \( ^1 \). The overall trend is that less massive galaxies form their stars later (i.e., smaller \( t_{\text{peak}} \)) and over a wider timescale (i.e., larger \( \Delta t \)). In addition, \( t_{\text{peak}} \) in clusters is systematically larger than in the field. These effects are shown in Figure 1b, where we plot the star formation histories of galaxies with \( 10^8, 10^9, 10^{10}, \) and \( 10^{11} \) M\(_{\odot}\) in both environments.

\(^1\)Following Thomas et al. (2005) we adopt the following cosmological parameters: \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\).
The final ingredient is the overall normalization of Equation 3. In its current form this equation was normalized to a total mass of $10^{10} \, M_\odot$ for each environment by Baldry et al. (2006). Since we are interested in the overall rate per unit volume, we therefore need to know what fraction of the stellar mass is in clusters versus the field at $z \sim 0$. From the study of Baldry et al. (2006), as well as Fukugita et al. (1998) and Eke et al. (2005), it appears that about 20% of the total stellar mass is included in cluster environments\(^2\), which we adopt here.

3. Constraints on the Age Distribution of Short GRB Progenitors

To illustrate the combined effect of the trends discussed in the previous section we begin by making the simplified assumption that there is a single typical galaxy mass, $M_{\text{typ}}$, for each environment. This typical mass in turn determines the typical star formation history of each environment. In this scenario, Equation 2 can be simplified as:

$$\text{SFH}_i(\tau) = \phi_i(M_{\text{typ}}) \times \text{SFH}_{\text{gal},i}(\tau, M_{\text{typ}}),$$

while $M_{\text{typ}}$ is determined by (Baldry et al. 2006):

$$\log (M_{\text{typ}}) = 10.73 + 0.15 \log \Sigma.$$ \hspace{1cm} (7)

Therefore, $M_{\text{typ}} \approx 10^{10.6} \, M_\odot$ and $\sim 10^{10.9} \, M_\odot$ for field and cluster environments, respectively.

We are now in a position to use Equations 1, 3, 4, 5, and 6 to predict the relative rate of short GRBs in cluster and field early-type galaxies. The result as a function of the power law index $n$ is shown in Figure 2. We note that the absolute scale in this plot is irrelevant since we did not integrate over the full mass function, but it provides insight into the overall trend. Namely, as $n$ increases, i.e., as the distribution is more heavily weighted to older progenitors, the fraction of short GRBs in clusters increases. This can be understood as the combined effect of a systematically earlier star formation episode and a higher typical mass in clusters.

A quantitative determination of the relative rates requires a full integration of Equation 2. The results of this integration are shown in Figure 3. Overall, the dependence of the ratio of short GRBs in clusters and the field on $n$ is similar to the one found in the simple

\(^2\)This corresponds to the assumption that cluster environments can be described by $\log \Sigma \gtrsim 0.5$; see Appendix A of Baldry et al. (2006) for details.
case. However, the integration over the full mass function of each environment brings out additional trends. For a low mass cutoff smaller than $10^{10} \, M_\odot$, there is sharp downturn in the ratio for $n \lesssim -1$. This can be understood from the plots of $\text{SFH}_{\text{gal}}(\tau) \times P(\tau)$ shown in Figures 1c and 1d. In particular, for $n = -2$ the short GRB rate in the field is larger than in clusters since the field has a higher abundance of low mass ($\lesssim 10^{10} \, M_\odot$) early-type galaxies (Figure 1a), which have young or intermediate stellar populations. For such low values of $n$ the ratio is sensitive primarily to recent star formation. We note that the same effect is seen in the analysis of Zheng & Ramirez-Ruiz (2006) for the ratio of early- to late-type hosts.

In this context ($n \lesssim -1$) the lower mass cutoff in Equation 2 plays an important role. In Figure 3 we show the effect of setting $M_l = 10^8$, $10^9$, and $10^{10} \, M_\odot$. As noted above, for $M_l = 10^{10} \, M_\odot$ we do not see an obvious downturn because galaxies above this limit do not exhibit any obvious recent star formation activity. For the lower values of $M_l$, we find that the largest downturn is for $M_l = 10^9 \, M_\odot$. The reason for this is evident in Figure 1a, which shows that the largest difference between the field and cluster mass functions is at $M \gtrsim 10^9 \, M_\odot$. At lower masses the mass functions converge, leading to a ratio that is $\sim 1$.

For $n \gtrsim -1$, on the other hand, the rate is dominated by the oldest, and hence most massive galaxies (Figure 1d). In this case the ratio does not depend on $M_l$, and the predominance of massive galaxies in clusters, along with the systematically earlier star formation episodes, results in an increased fraction of short GRBs in clusters for larger $n$. In fact, for $n = 2$, we find that there are three times as many short GRBs in cluster early-type galaxies as there are in field early-type galaxies.

4. Discussion

We now turn to a comparison of our model with observation of short GRBs. To date two short bursts have been localized to clusters at $z \sim 0.2$: GRB 050509b (Gehrels et al. 2005; Bloom et al. 2006a) and GRB 050911 (Paper1). We note that in the latter case the large error circle prevents an association with a specific cluster galaxy, but the large early-type fraction of 80% (Berger et al. 2006b) suggests that the burst was likely hosted by an early-type galaxy. On the other hand, only one short GRB has been localized to a field early-type galaxy, GRB 050724 (Berger et al. 2005). We do not consider GRB 050813, which was hosted by a cluster at a much higher redshift ($z \sim 1.8$; Berger 2006a), and GRB 060502b, which may be hosted by an early-type galaxy (Bloom et al. 2006b), but whose large-scale
environment has not been fully explored yet. Thus, the current ratio of short GRBs in cluster versus field early-type galaxies is about 2 : 1, with a large uncertainty due to the small number of events. From Figure 3, we find that this ratio corresponds to $n \sim 0 - 1$. This value is lower than $n \gtrsim 3/2$ claimed by Zheng & Ramirez-Ruiz (2006), but is in rough agreement with $-1 \lesssim n \lesssim 0$ found by Berger et al. (2006c) based on their revised redshift distribution with $1/4 - 2/3$ of all short GRBs at $z \gtrsim 1$.

Clearly, in both methods of estimating the age of short GRB progenitors the uncertainty in the inferred value of $n$ is currently dominated by the small number of bursts with a known redshift, host galaxy, and large-scale environment type. Since this uncertainty will eventually diminish with a larger sample of events, it is interesting to consider systematic uncertainties in both theoretical approaches. Our analysis suffers from the somewhat poor definition of cluster and field environments. We have used an overall cluster mass fraction of 20%, as indicated by several researchers, but this number may range from 10 to 30%. Second, we have used the simplified bimodal star formation history model of Thomas et al. (2005), but these authors do not use the same quantitative definition of galaxy environment that was used for the mass functions by Baldry et al. (2006). Since we have used representative mass functions, and then scaled the results by the overall mass fraction in clusters and the field, this effect should not be significant. Third, the uncertainty in the definition of field galaxy environment leads to an overall uncertainty of about 20% in our calculated ratio. Finally, since for $n \lesssim -1$ the ratio depends on $M_l$, it is essential to understand the appropriate low mass limit for early-type galaxies. With the current inferred value of $n \sim 0 - 1$, however, this may not be a relevant issue for short GRBs.

Similarly, the analysis of the short GRB rate in early- and late-type galaxies performed by Zheng & Ramirez-Ruiz (2006) also suffers from systematic effects. First, the ratio is affected by the uncertain star formation history at high redshift when early-type galaxies formed most of their stars. Second, their estimation of star formation rate does not consider environmental effects that appear to be important in current observations from SDSS and 2dF, and which we have accounted for here. Finally, as noted by Zheng & Ramirez-Ruiz (2006), it is possible that late-type galaxies have an altogether different age distribution of short GRB progenitors than early-type galaxies. This problem is overcome by our method since it considers only early-type host galaxies. We note that if both derivations are in fact correct, then the estimated values of $n$ can be used to assess any systematic differences of short GRB progenitors in early- and late-type galaxies, as suspected to exist for type Ia.

\footnote{The limit on the X-ray luminosity at the redshift of the putative host galaxy, $L_X \lesssim 6 \times 10^{42}$ erg s$^{-1}$, is lower by a factor of eight than that of the cluster hosting GRB 050509b, but it is somewhat higher than that of the cluster hosting GRB 050911 (Paper I).}
Future applications of our approach will include the effect of globular clusters, which are thought to provide an efficient environment for the production of NS-NS binaries, and may account for a substantial fraction of all short GRB progenitors (Grindlay et al. 2006; Hopman et al. 2006). We expect that since the specific frequency of globular clusters increases significantly with galaxy mass (Harris 1991), an association with globular clusters will increase the fraction of short GRBs in galaxy clusters compared to the trend shown in Figure 3. Similarly, our approach can be extended to higher redshift to investigate the evolution in the fraction of short GRBs in clusters. We expect that the lack of strong evolution in the last several Gyr likely makes our analysis applicable out to \( z \sim 1 \). However, if some short GRBs are in fact associated with clusters at \( z \sim 2 \), this presents an opportunity to assess any systematic changes in the value of \( n \) with redshift.

We end with the following conclusion. If our current estimate of \( n \gtrsim 0 \) continues to be supported by future observations, then this implies that the majority of short GRBs in early-type galaxies will occur in clusters. This therefore suggests that short GRBs can provide an efficient tool for finding forming galaxy clusters at high redshift, as already appears to be the case for GRB 050813 (Berger 2006a). Continued near-IR imaging and optical spectroscopic observations of short GRB fields may therefore provide an efficient method for finding the highest redshift clusters.

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Fig. 1.— A summary of the model ingredients that determine the relative rate of short GRBs in cluster and field early-type galaxies. Panel (a) shows the mass function in each environment (solid line: cluster; dashed line: field), including the different early-type fractions (Equation 4), and an overall cluster mass fraction of 20% ($\mathcal{F}$). Panel (b) shows the star formation history as a function of environment and galaxy mass (red: $10^{11} \, M_\odot$; purple: $10^{10} \, M_\odot$; green: $10^9 \, M_\odot$; blue: $10^8 \, M_\odot$). Bottom panels show the product of the star formation history with the short GRB progenitor age distribution function for a power law index $n = -2$ (c), and $n = 2$ (d). Clearly, a distribution weighted to short merger timescales heavily favors lower mass host galaxies (and hence the field), while a distribution weighted to long merger timescales favors massive host galaxies (and hence clusters).
Fig. 2.— Ratio of the short GRB rate in cluster and field early-type galaxies as a function of the age distribution power law index, $n$, assuming that each environment is described by a typical galaxy mass (§3). The scale on the ordinate is arbitrary since we do not consider the full mass function, but the overall trend is representative. Since the typical galaxy mass is higher in clusters than in the field, the typical star formation epoch is earlier in clusters. We therefore expect more short GRBs in cluster early-type galaxies when $n$ is high.
Fig. 3.— Ratio of the short GRB rate in cluster and field early-type galaxies as a function of the age distribution power law index, $n$, considering the full mass function in each environment. Different colors represent the effect of different mass integration limits: $10^8 < M < 10^{12} \, M_{\odot}$ (black), $10^9 < M < 10^{12} \, M_{\odot}$ (blue), and $10^{10} < M < 10^{12} \, M_{\odot}$ (red). The current observed ratio, based on only three events, is about 2, suggesting that $n \sim 0 - 1$. 