The metallicity properties of simulated long-GRB galaxy hosts and
the Fundamental Metallicity Relation

M.A. Campisi1, C. Tapparello2, R. Salvaterra1, F. Mannucci3, M. Colpi2

1 Dipartimento di Fisica e Matematica, Università dell’Insubria, via Valleggio 7, 22100 Como, Italy
2 Dipartimento di Fisica G. Occhialini, Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
3 INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Firenze, Italy

ABSTRACT

We study the implication of the collapsar model for Long Gamma-Ray Bursts (LGRBs) on the metallicity properties of the host galaxies, by combining high-resolution N-body simulations with semi-analytic models of galaxy formation. The cosmological model that we use reproduces the Fundamental Metallicity Relation recently discovered for the SDSS galaxies, whereby the metallicity decreases with increasing Star Formation Rate for galaxies of a given stellar mass. We select host galaxies housing pockets of gas-particles, young and with different thresholds in metallicities, that can be sites of LRGB events, according to the collapsar model. The simulated samples are compared with 18 observed LGRB hosts in the aim at discriminating whether the metallicity is a primary parameter. We find that a threshold in metallicity for the LGRB progenitors, within the model galaxies, is not necessary in order to reproduce the observed distribution of host metallicities. The low metallicities of observed LGRB hosts is a consequence of the high star formation environment. The star formation rate appears to be the primary parameter to generate a burst event. Finally, we show that only a few LGRBs are observed in massive, highly extincted galaxies, while these galaxies are expected to produce many such events. We identify these missing events with the fraction of dark LGRBs.

Key words: gamma-rays: bursts – host galaxies.

1 INTRODUCTION

The study of the host galaxies of Gamma-Ray Bursts (GRBs) is essential for understanding their nature. Current observations reveal that long-duration GRBs occur in star-forming galaxies, in contrast to short-duration GRBs that are found in both early- and late-type galaxies. The star formation rate (SFR) in the short GRB host galaxies is often lower than in the LGRB’s hosts (Berger et al. 2006, and references therein). The difference in the observed host properties for short and long GRBs supports the idea that short and long GRBs have different progenitors. Long-duration GRBs are believed to arise from the death of massive stars (collapsar model; Conselice et al. 2005; Fruchter et al. 2006; Tanvir & Levan 2007; Wainwright et al. 2007, and references therein), most likely Wolf-Rayet stars, while short-duration GRBs are likely produced by the coalescence of compact objects in binaries (Li & Paczyński 1998; O’Shaughnessy et al. 2008). The discovery of the connection between long GRBs and core-collapse Type Ibc supernovae (Galama et al. 1998; Li 2004; Woosley & Heger 2006, and references therein) supports the collapsar model of long-duration GRBs (MacFadyen & Woosley 1999; MacFadyen et al. 2001). So far no supernovae have been found to be associated with short-duration GRBs.

In current core-collapse models for long-duration GRBs (LGRBs hereafter), young stars with initial mass \( > 30 M_\odot \) should be able to create a black hole (BH) remnant. If the collapsing core has high angular momentum, the formation of the BH may be accompanied by a LRGB event (Woosley 1993; MacFadyen & Woosley 1999). The wind-driven mass loss in massive stars is a function of the metal content: high metallicity stars have strong stellar winds with main losses of both mass and angular momentum. Instead, when metallicities are low (0.1 – 0.3 Z_\odot; Woosley & Heger 2006), the specific angular momentum of the progenitor star allows for the loss of the hydrogen envelope while preserving the helium core that can still carry rotation (Woosley & Heger 2006; Fryer, Woosley & Hartmann 1999; Yoon, Langer & Norman 2006; Yoon, Langer, Cantiello, Woosley & Glatzmaier 2008). The loss of the hydrogen envelope reduces the material that the jet needs to cross in order to escape, while the helium core should be massive enough to collapse and power a LRGB. Vink & de Koter (2005) explored LGRB models with even lower metallicites (Z/Z_\odot \leq \)
tends to fall off the ples from the Sloan Digital Sky Survey (SDSS) representative of (Mannucci et al. 2009; Maiolino et al. 2008) with an evolution to-
compared the (Jabran Zahid et al. 2010; Erb et al. 2006) up to
been shown that similar relations hold also at higher redshifts
of the properties of nearby galaxies (Tremonti et al. 2004). It has
around this surface of about 0.05 dex; see Mannucci et al. 2010).
lar mass
metallicity range around $z < 1$
metallicity of the solar metallicity.
In particular an open question concerns the metallicity of the LGRB host galaxies: is the metallicity a discriminant for the formation of a LGRB? Do LGRBs form preferentially in metal poorer galaxies? The observational information gathered so far indicates that most LGRBs are found in faint, star forming galaxies dominated by young stellar populations with sub-solar gas-phase metallicities, although there are a few host galaxies with higher metal content (Prochaska et al. 2004; Wolf & Podsiaowski 2007; Fynbo et al. 2006; Price et al. 2005; Savaglio et al. 2003; Savaglio 2006; Stanek et al. 2006; Levesque et al. 2010, and references therein). We have to stress that low-metallicity progenitors do not necessarily imply low-metallicity host galaxies. Indeed, owing to the existence of metallicity gradients inside galaxies (Artale et al. 2011), LGRBs could form from low-metallicity progenitor stars collapsing on metal deficient clouds also in hosts with relatively high mean metallicities (Campisi et al. 2009).

The existence of a possible metallicity discriminant in the GRB selected galaxies with respect to the overall field galaxy population can be tested comparing observed phenomenological relations in the two samples. In particular, the relation between stellar mass $M_\ast$ and metallicity $Z$ provides a good description of the properties of nearby galaxies (Tremonti et al. 2004). It has been shown that similar relations hold also at higher redshifts (Jabran Zahid et al. 2010; Erb et al. 2006) up to $z \sim 3 - 4$ (Mannucci et al. 2009; Maiolino et al. 2008) with an evolution towards lower metallicities with increasing redshift.

Recently, Han et al. (2010) and Levesque et al. (2010) have compared the $M_\ast - Z$ relation for LRGB host galaxies with samples from the Sloan Digital Sky Survey (SDSS) representative of the general star-forming galaxy population (Tremonti et al. 2004). They find that the metallicity content of low redshift LRGB hosts tends to fall off the $M_\ast - Z$ relation, and suggest that LGRBs do occur preferentially in lower metallicity galaxies. In order to further explore the origin of this offset, Mannucci et al. (2011) compared the observed properties of LRGB host galaxies, defined in the context of the collapsar model, and suitably selected within the simulated cosmic volume. In Section 4, we explore the loci in the SSFR – $Z$ and $M_\ast - Z$ planes where we have the higher probability to host a LRGB. Finally, in Section 5 we present our conclusions.

2 THE FMR OF SIMULATED GALAXY CATALOGUES

In this Section we test whether the simulated galaxies reproduce the FMR. Readers interested to the galaxy’s catalogues are referred to Wang et al. (2008), Croton et al. (2006), De Lucia & Blaizot (2007) and references therein for details on the physical processes explicitly modelled. Here, we give a short description of the catalogue, focusing on the treatment of metal enrichment.

The galaxy catalogue used was constructed by Wang et al. (2008) with cosmological parameters consistent with the third-year WMAP results (Spergel et al. 2007). The simulation corresponds to a box of $125 h^{-1}$ Mpc comoving length and a particle mass $7.78 \times 10^8 M_\odot$. Simulation data were stored in 64 outputs and analysed with the post-processing software originally developed for the Millennium Simulation (Springel et al. 2005). Merging history trees for self-bound structures extracted from the simulations were used as input for the Munich semi-analytic model of galaxy formation described in De Lucia & Blaizot (2007). In particular, in the simulated galaxies the metals are produced primarily in the supernovae and are deposited directly in the cold gas present in the disc of the galaxy (instantaneous recycling approximation; Croton et al. 2006; De Lucia et al. 2004).

We limit our analysis to galaxies with stellar mass larger than $8 \times 10^8 M_\odot$, which is above the resolution limit of the N-body simulations used. In order to be consistent with the observed local sample of SDSS galaxies, we select, in our simulated cosmological volume, galaxies with redshift $0.07 < z < 0.3$ as in Mannucci et al. (2010), for which the SFR, stellar mass and mean metallicity are known. The resulting sample includes 1075878 galaxies.

---

3 The interpretation of the FMR in the context of the simulated catalogues is beyond the goal of present work.
The FMR of LGRBs hosts

Figure 1. Simulated galaxies in the local Universe \((0.07 < z \leq 0.3)\) (lines) and galaxies of the SDSS (points in panels a, b, c); lines/points refer to the median values. Panel (a) shows the metallicity \(Z\) versus stellar mass \(M_*\) (in units of \(M_\odot\)); colored lines/points show the \(M_* - Z\) relation, in three selected SFR bins. Solid line is the observed relation (eq. 1 of the footnote). Panel (b) shows the metallicity versus SFR (in units of \(M_\odot\ yr^{-1}\)), for galaxies in three different \(M_*\) bins; Panel (c) shows the Fundamental Metallicity Relation, i.e. metallicity \(Z\) versus \(\mu_{0.32}\). Dark-solid line refers to the FMR relation from Mannucci et al. (2011; eq. 2 of the footnote).

The analytical expression of the FMR for local galaxies is

\[
12 + \log(O/H) = 8.90 + 0.37m - 0.14s - 0.19m^2 + 0.12m^2s - 0.054s^2 \quad \text{for } \mu_{0.32} \geq 9.5 \\
= 8.93 + 0.51(\mu_{0.32} - 10) \quad \text{for } \mu_{0.32} < 9.5
\]

where \(m = [\log(M_*/M_\odot) - 10]\), and \(s = \log(\text{SFR})\) with SFR expressed in units of \(M_\odot\ yr^{-1}\).
trend is clearer in panel (b) where the SFR – Z relation is plotted in three different M*, bins. This finding is in agreement with the behavior of the observed SDSS galaxies in the same redshift range (depicted as points). As shown in panel (c), once the dependency on the SFR and M* is included into the parameter μ0,32, the medians, in each SFR bin, collapse into a single, well defined line consistent with the observed FMR shown as dark-solid line.

In conclusion our tests have shown that the simulated galaxy population provides a good description of the observed properties of local SDSS field galaxies.

3 SIMULATED LGRB HOST GALAXIES

In this Section, we use the simulated galaxy sample to select possible LGRB hosts in the light of the collapsar scenario.

Following Woosley & Heger (2006), LGRBs occur more favorably in stellar environments with metallicities lower than 0.1–0.3 Z⊙. Accordingly, we extracted from the simulated catalogue the galaxies which contain pockets of gas “particles” that can be sites to progenitors to LGRB events. Pockets have a metallicity Zpocket and age tage, and the host has metallicity Zhost computed as mean of the metallicity of all pockets present inside the simulated galaxy. According to Campisi et al. (2009), we create three host’s catalogues with different properties:

(i) HOST1, obtained by selecting galaxies containing stars with age tage < t∗ = 5 × 10^7 yr;
(ii) HOST2, including galaxies with stars of age tage < t∗ and metallicity Zpocket < 0.3 Z⊙;
(iii) HOST3, defined by selecting galaxies containing stars with age tage < t∗ and metallicity Zpocket < 0.1 Z⊙.

We computed the number of stars ending their lives as LGRBs, assuming a Salpeter Initial Mass Function (IMF), and on average (over all cosmic times) one LGRB event every 1000 supernovae (Porciani & Madau 2003, Campisi et al. 2011). The number of expected LGRBs in the k-th galaxy can be computed as 𝑁k,i ∝ 𝜂BH,i M∗,i,k(z), where 𝜂BH,i is the fraction of stellar mass that will produce black holes in case i (where i runs over the three catalogues, i = 1, 2, 3) and M∗,i,k is the stellar mass in the k-th galaxy that satisfies our selection criteria for the i-subsample (see Sec.3 in Campisi et al. 2009 for details). We point out that we select host galaxy candidates assuming constraints on the metallicity of LGRB progenitor stars, not on the overall metallicity Zhost of the host galaxy.

3.1 M* – Z and FMR of simulated LGRB hosts

In this Section, we focus on the position of LGRB hosts in the planes shown in Fig.1 and on the comparison with the observed LGRB hosts.

We first include the simulated galaxies belonging to the three samples HOST1-2-3 in the M* – Z and μ0,32 – Z planes. The metallicity, in this case, refers to the galaxy as a whole, and is extracted as Zhost from the catalogue. For each sample, we computed the median metallicity values as a function of the stellar mass M* and similarly, for FMR, as a function of μ0,32. In each sample, the median is obtained by weighting the host galaxies with the rate of occurrence of LGRBs in their pockets. In addition we restrict to galaxies at z ∼ 0.5 being the mean redshift of the observed sample of LGRB hosts.

Fig. 2 shows the results for HOST1-2-3 and the comparison with the LGRB’s data points. The left (right) panel refers to the M* – Z relation (FMR), and lines refer to the median computed for each sample as described in the figure caption. The black line in the right (left) panel refers to the M* – Z relation observed for galaxies at z ∼ 0.8 (to FMR as in Mannucci et al. 2011). The blue data points and blue dotted-line refer to the observed sample of 18 LGRB hosts.

In the left panel of Fig. 2, HOST1-2-3 show a systematic offset toward lower metallicities compared to the observed M* – Z relation for field galaxies. HOST2 and HOST3, corresponding to low cut-off in Zpocket, display a flat M* – Z relation. In these two samples, single simulated LGRB host galaxies with large M* may have high metallicities (i.e. high Zhost) as illustrated and discussed in the Appendix A. However, their contribution to the median, weighted for the rate of LGRB housed in the galaxy, is negligible as they are found to be site of only few LGRB events. In the right panel of Fig. 2, HOST1-2-3 are compared with the FMR. HOST1 reproduces the observed relation for field galaxies quite well. By contrast HOST2 and HOST3 show significant deviations from the FMR, as in the M* – Z plane.

The data of the 18 LGRB hosts are plotted in Fig. 2, and the blue-dotted line describes the best linear fit to the data (blue points with associated errors are as reported in Mannucci et al. 2011). In the M* – Z plane, GRB060218 is included in the fit though it lies at log(M*/M⊙) = 7.78 which is outside the range of mass accessible from the simulated volume.

In both planes, HOST1 is the sample providing the best description of the available data. In particular, this sample reproduces well the FMR for the observed LGRB hosts and the systematic offset in the M* – Z relation. This is due to the fact that in our simulation the probability to host a LGRB is higher in galaxies with higher SFRs.

To further investigate these findings, we consider the FMR of the simulated catalogues dividing galaxies in subsamples with SFRs in different bins. The results are shown in the left panels of Fig. A1 of Appendix A. We find that the FMR is well reproduced again by all subsamples of the HOST1 group, and by the subsample of galaxies with high SFR (log(SFR) > 0.9) of the HOST2 group. By contrast, none of the HOST3 subsamples reproduce the data since the constraint on metallicity in the progenitors Zpocket imposes also a severe cut in the metallicity of the host Zhost. Therefore, we can conclude that collapsar model predicting a strong metallicity bias can not be easily reconciled with the observational evidence that LGRB hosts do follow the FMR.

4 PROBABILITY DISTRIBUTIONS AND DARK LGRBS

It has been noted that observed LGRBs tend to occur in galaxies with high specific star formation rates (SSFRs) (Savaglio et al. 2009, Mannucci et al. 2011). The SSFR or its inverse, the so-called doubling time, are good markers of the ability of a galaxy to form stars in an efficient way. Mannucci et al. 2011 have shown that the observed LGRB hosts have always doubling times shorter than the Hubble time at the redshift of the object. This holds true for additional 17 LGRB hosts at z < 1 of unknown metallicity for...
The FMR of LGRBs hosts

5 Data are from the GHOST database (www.grbhosts.org)

which stellar mass \( M^* \) and SFR have been measured. We note that none of them has \( \log(\text{SSFR}) < -9.95 \) (with SSFR in units of yr\(^{-1}\)) confirming that all observed LGRB hosts have high SSFRs and doubling times shorter than the Hubble time, at the redshift of the burst. The position of LGRB hosts in the SSFR-\( Z \) plane may thus provide new hints on the host galaxy population.

In Fig. 3 we collect all observed data (blue dots) of the 18 LGRB in the SSFR-\( Z \) plane (the 17 SSFRs for the additional hosts with lack of \( Z \) measurement are plotted as black point at the top of the figure). In the same plane, the color-coded area gives the normalized probability map to have a LGRB event in galaxies of the HOST1 sample (see Appendix for our analysis on HOST1-2-3 in separated bins of SFR or mass \( M^* \)). The probability is computed normalizing the number of LGRB events of each galaxy for the total number of events. Most but not all observed LGRB hosts fall in the green zone where the expected probability for the HOST1 sample is the highest. The simulated galaxies cover a wide area in the SSFR-\( Z \) plane and extend also to low SSFRs. About 15% of all simulated LGRBs reside in galaxies with \( \log(\text{SSFR}) < -8.5 \), i.e. with doubling times longer than the Hubble time at \( z = 0.5 \). Therefore the model does not exclude hosts with low SSFR and we may still lack of LGRBs due to the low statistics related to the bias against identifying galaxies with low SFRs, or to dust extinction (see below).

Similarly, in the left panel of Fig. 4 we derive the color coded probability map of having a LGRB in a galaxy (with \( z \sim 0.5 \)) of the HOST1 sample with given metallicity and \( \mu_{0.32} \) (the lack of simulated galaxies with \( \mu_{0.32} < 8.2 \) is due to the resolution limit of the N-body simulation used). Data-points are also shown for the observed LGRB host galaxies. As in Fig. 3, most of the simulated hosts cluster in a very well defined region of the FMR, and these loci are populated by the observed data.

We note the existence of a region (i.e., the green area in the interval \( 10 < \mu_{0.32} < 10.5 \) corresponding to \( 8.6 < 12 + \log(O/H) < 9.1 \)) with high values of probability of LGRB occurrence that is underpopulated of observed LGRB hosts. The lack of observed hosts may be linked to the existence of dark LGRBs, i.e.
LGRBs with bright X-ray afterglow that are faint or not detected in optical. It has been shown (Perley et al. 2009) that most of these objects cannot be detected at optical wavelengths being strongly absorbed by dust in their host galaxies. Here, we argue that dark LGRBs may reside in hosts with high metal content (and therefore more dusty) that could populate the empty region in the $\mu_{0.32} - Z$ plane. Indeed the only point present in this region is relative to the host galaxy of GRB 020819, that is classified as a dark burst (Levan et al. 2003; Klose et al. 2003; Küpcü Yoldaş et al. 2010).

We briefly analyze the simulated galaxies (HOST1) with high probability to host a LGRB in the empty region at high $\mu_{0.32}$, pointing out that they have higher stellar mass ($10 < \log(M_\odot/M_\odot) < 11$), and they show higher extinctions. In the right panel of Fig. 4 we show the color-coded map distribution of the total extinction coefficient $A_v$ in the V band (Buser V filter). The contours contain the 50% (smaller area) and the 99% (bigger area) of the entire population of simulated hosts showed in the left panel of Fig. 4. Again, the blue data points are the observed host galaxies. The principal result of this figure can be summarized as follows: despite the higher probability for galaxies with high $\mu_{0.32}$ to house a LGRB, their higher extinction prevents us from observing the optical afterglow of their LGRBs, instead the galaxies with lower extinction, and thus lower metallicity, are favorable to be observed. The white and yellow regions in the map refer to areas of low extinction where the bulk of the observed LGRBs are found. Similarly in the observation of core-collapse SNe, the missing in the Optical and IR observation is supposed to be correlated with the extinction of dust in the host galaxy Maiolino et al. (2002); Mannucci et al. (2003); Cresci et al. (2007).

However, we notice here that the present sample of observed LGRB hosts is not a complete or well controlled sample, and several selection effects could exist. In particular, we cannot use the present sample to investigate the relative fraction of LGRB hosts detected as function of $\mu_{0.32}$. Thanks to the unbiased simulated galaxy catalogues, we are able to predict the distribution on the FMR plane of host galaxies, waiting for future observations of dark GRB host galaxies.

5 CONCLUSIONS

In this paper, we studied the properties of LGRB host galaxies comparing 18 observed hosts with a catalogue of simulated galaxies constructed combining high-resolution N-body simulations with an up-to-date semi-analytic model of galaxy formation. The simulated catalogue reproduces the offset on the observed $M_* - Z$ relation and the tighter Fundamental Metallicity Relation (FMR) of the field galaxy populations (in the redshift interval $0.07 < z \leq 0.3$) with no need of introducing new free parameters.

Aim of our investigation was at studying the relative importance of metallicity and SFR in the characterization of a LGRB and of its host. To this purpose we studied the effects imposed by the presence of a metallicity threshold in the generation of a LGRB on the host galaxies. We extracted, from the main simulated catalogue, three samples of LGRB hosts, housing different pockets of gas particles with different metallicities $Z_{prog}$ that could be potential sites to LGRB formation. The first sample, denoted as HOST1, comprises galaxies undergoing star formation but with no threshold on the metallicity ($Z_{prog}$). HOST2 comprises instead star forming galaxies with lower metal content, i.e. a cut at $Z_{prog} = 0.3 Z_\odot$ and HOST3 at $Z_{prog} = 0.1 Z_\odot$.

Our analysis shows that HOST1 is the sample providing a very good description of the currently available LGRB host dataset. In particular, the simulated sample is able to reproduce, at the same time, the systematic offset of LGRB hosts toward lower metallicities in the $M_* - Z$ relation, and the tightness of the FMR in the $\mu_{0.32} - Z$ plane. In the simulated sample, the probability of housing a LGRB is higher in active star-forming galaxies. As a consequence, when weighted for this probability the simulated hosts tend to show lower metallicities at fixed stellar mass, in the $M_* - Z$
The FMR of LGRBs hosts

Fruchter A. S., Levan A. J., Strolger e. a., 2006, Nature, 441, 463
Fryer C. L., Woosley S. E., Hartmann D. H., 1999, ApJ, 526, 152
Fynbo J. P. U., Watson D., Thöne C. C., Sollerman J., Bloom J. S., Davis T. M., Hjorth J., Jakobsson P., Jørgensen U. G., Graham J. F., Fruchter A. S., Bersier D., Kewley L., Cassan A., Castro Cerón J. M., Foley e. a., 2006, Nature, 444, 1047
Galama T. J., Vreeswijk P. M., van Paradijs J., Kouveliotou C., Augusteijn T., Bönnardt H., Brewer J. P., Dombvier V., Gonzalez J.-F., Leibundgut B., Lidman C., Hainaut O. R., Patat F., Heise J., in’t Zand J., Hurley e. a., 1998, Nature, 395, 607
Han X. H., Hammer F., Liang Y. C., Flores H., Rodrigues M., Hou J. L., Wei Y. J., 2010, A&A, 514, A24+
Jabran Zahid H., Kewley L. J., Bresolin F., 2010, ArXiv e-prints
Klose S., Henden A. A., Greiner J., Hartmann D. H., Cardiel N., Castro-Tirado A. J., Castro Cerón J. M., Gallego J., Gorgosbel J., Stecklum B., Tanvir N., Thiele U., Vrba F. J., Zeh A., 2003, ApJ, 592, 1025
Küpcü Yoldas A., Greiner J., Klose S., Krühler T., Savaglio S., 2010, A&A, 515, L2+
Levan A., Fruchter A., Rhoads J., Burud I., Rol E., Salamanca I., Kaper L., Tanvir N., 2003, GRB Coordinates Network, 1844, 1
Levesque E. M., Kewley L. J., Berger E., Jabran Zahid H., 2010, AJ, 140, 1557
Levesque E. M., Kewley L. J., Graham J. F., Fruchter A. S., 2010, ApJ, 712, L26
Li L.-X., 2006, MNRAS, 372, 1357
Li L.-X., Paczyński B., 1998, ApJ, 507, L59
MacFadyen A. I., Woosley S. E., 1999, ApJ, 524, 262
MacFadyen A. I., Woosley S. E., Heger A., 2001, ApJ, 550, 410
Maiolino R., Nagao T., Grazian A., Cocchia F., Marconi A., Mannucci F., al. 2008 Vol. 488, AMAZE. I. The evolution of the mass-metallicity relation at z > 3. pp 463–479
Maiolino R., Vanzi L., Mannucci F., Cresci G., Ghinassi F., Della Valle M., 2002, A&A, 389, 84
Mannucci F., Cresci G., Maiolino R., Marconi A., Gnerucci A., 2010, MNRAS, 408, 2115
Mannucci F., Cresci G., Maiolino R., Marconi A., Pastorini G., Pozzetti L., Gnerucci A., Risaliti G., Schneider R., Lehner M., Salvati M., 2009, MNRAS, 398, 1915
Mannucci F., Maiolino R., Cresci G., Della Valle M., Vanzi L., Ghinassi F., Ivanov V. D., Nagar N. M., Alonso-Herrero A., 2003, A&A, 401, 519
Mannucci F., Salvaterra R., Campisi M. A., 2011, MNRAS, pp 439–45
O’Shaughnessy R., Belczynski K., Kalogera V., 2008, ApJ, 675, 566
Perley D. A., Cenko S. B., Bloom J. S., Chen H., Butler N. R., Kocevski D., Prochaska J. X., Broadwin M., Glazebrook K., Kasliwal M. M., Kulkarni S. R., Lopez S., Ofek E. O., Pettini M., Soderberg A. M., Starr D., 2009, AJ, 138, 1690
Poričian C., Madau P., 2001, ApJ, 548, 522
Price P. A., Songaila A., Cowie L. L., Bell Burnell J., Berger E., Cucchiara A., Fox D. B., Hook L., Kulkarni S. R., Penprase B., Roth K. C., Schmidt B., 2007, ApJ, 663, L57
Prochaska J. X., Bloom J. S., Chen H.-W., Hurley K. C., Melbourne J., Dressler A., Graham J. R., Osip D. J., Vacca W. D., 2004, ApJ, 611, 200
Savaglio S., 2006, New Journal of Physics, 8, 195
Savaglio S., Fall S. M., Fiore F., 2003, ApJ, 585, 638
Savaglio S., Glazebrook K., Le Borgne D., 2009, ApJ, 691, 182
Spergel D. N., Bean R., Doré O., Nolta M. R., Bennett C. L., Dunkley J., Hinshaw e. a., 2007, ApJS, 170, 377
APPENDIX A: DETAILS ON THE HOSTS' SAMPLES

In this Appendix, we illustrate further findings obtained from the analysis of HOST1-2-3 in selected SFR and $M_\ast$ intervals. Figure A1 show in the $\mu_{0.32} - Z$ and SSFR$-Z$ plane the relations for our subsamples of host galaxies. The contribution of hosts with different SFRs are shown with different colors. The same color coding is adopted for the observed data. Finally, the short-long dashed line is the best-fit to the observed data obtained by Mannucci et al. (2011). The FMR is well reproduced by all subsamples of galaxies belonging to the HOST1 group, and they are also in agreement with observations (top panel of Fig. A1). For the HOST2 sample (middle panel of Fig. A1) simulated galaxies seem to provide a reasonable description of the data: both highly star forming objects (blue-dot-dashed lines and data) and less active galaxies (yellow-short-dashed and red-dotted lines) and data are well reproduced. However this model predicts a systematic shift of the LGRB host population with $0 < \log(SFR) < 0.9$ (green-dashed lines) to-ward low metallicities with respect to the FMR. This shift is not observed in the present sample of LGRB host data (green points) that represent the bulk of the LGRB host population in the observed sample. This is reflected in the behavior of the total FMR of simulated galaxies (solid line) that falls below the observed FMR of LGRB hosts. This effect is amplified in the HOST3 sample (bottom panel of Fig. A1), where only a few highly star forming galaxies with high metallicities are present. The shift in metallicity for middle and low star forming objects is more evident with the simulated curves always below the observed data points.

Fig. A1 shows the distribution of simulated LGRB hosts at $z \sim 0.5$ in the SSFR$-Z$ (right panels). The lines refer to the median weighted relations in different stellar mass bins, the data and lines of the same color refer to the same $M_\ast$ range. Again, we find that HOST1 provides a good description of the data. In particular, HOST1 galaxies are found to have decreasing metallicities for increasing SSFRs and decreasing stellar masses similarly to the observed trends. This is a direct consequence of the fact that HOST1 follow the FMR. Galaxies with higher SFR and lower stellar masses have lower metallicities; also higher stellar masses correspond higher metallicities.

In addition, as shown in Fig. A1, HOST2 and HOST3 sample provide a poor description of the distribution of observed LGRB hosts in the SSFR$-Z$ plane. In these cases, the simulated galaxies show a flat or inverted behavior with respect to the data. Indeed, the metallicities of simulated hosts are found to increase with SSFR. This fact provide further evidence that models requiring a metallicity threshold for LGRB formation seems at odd with the properties of the observed LGRB host sample.
The FMR of LGRBs hosts

Figure A1. Left column: $\mu_{0.32} - Z$ plane for the host simulated galaxies (with $z \sim 0.5$), the colored lines are the median values in different bins of SFR. Data points refer as in Fig.4 to the observed LGRB hosts and black-dashed line is their best fit. Finally black-solid line is the FMR Mannucci et al. 2010a. Right column: SSFR (in units of yr$^{-1}$) versus metallicity $Z$. Points are the data as in the right panels. Triangles at the top of the figure refer to 17 LGRBs for which the metallicity is not measured yet. The lines are the median values for HOST1-2-3 in different bin of $M_*$. 

© 2011 RAS, MNRAS 000