Chemical abundances and spatial distribution of Long Gamma-Ray Bursts

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ABSTRACT
We analyse the spatial distribution within host galaxies and chemical properties of the progenitors of Long Gamma Ray Bursts as a function of redshift. By using hydrodynamical cosmological simulations which include star formation, Supernova feedback and chemical enrichment and based on the hypothesis of the collapsar model with low metallicity, we investigate the progenitors in the range 0 < z < 3. Our results suggest that the sites of these phenomena tend to be located in the central regions of the hosts at high redshifts but move outwards for lower ones. We find that scenarios with low metallicity cut-offs best fit current observations. For these scenarios Long Gamma Ray Bursts tend to be [Fe/H] poor and show a strong α-enhancement evolution towards lower values as redshift decreases. The variation of typical burst sites with redshift would imply that they might be tracing different part of galaxies at different redshifts.

Key words: gamma-rays: bursts – galaxies: abundances, evolution

1 INTRODUCTION
Long gamma-ray bursts (LGRBs, see the reviews by Mészáros 2006; Atteia & Vedrenne 2009) are energetic radiation events, lasting between 2 and \(~\)1000 seconds, and with photon energies in the range of keV–MeV. Our current understanding of these sources indicates that the emission is produced during the collapse of massive stars, when the recently formed black hole accretes the debris of the stellar core. During the accretion, highly collimated ultrarelativistic jets consisting mainly of an expanding plasma of leptons and photons (fireball) are launched, which drill the stellar envelope. Internal shocks in the fireball accelerate leptons and produce the γ-radiation through synchrotron and inverse Compton processes. External shocks from the interaction of the jets with the interstellar medium produce later emission at lower energies, from X-rays to radio (afterglow). Optical afterglow spectra allowed the measurement of LGRB redshifts (Metzger et al. 1997), locating these sources at cosmological distances (z \(~\) 0.01 – 8.2), and revealing that their energetics is similar to that of Supernovae (SNe). Some LGRBs have indeed been observed to be associated to hydrogen-deficient, type Ib/c supernovae (e.g. Galama et al. 1998; Hjorth et al. 2003; Woosley & Bloom 2006; Starling et al. 2011). Afterglows allowed also the identification of LGRB host galaxies (HGs), which turned out to be mostly low-mass, blue and subluminous galaxies with active star formation (Le Floc’h et al. 2003; Christensen, Hjorth & Gorosabel 2004; Prochaska et al. 2004; Savaglio, Glazebrook & Le Borgne 2009).

Although the general picture is clear enough, its details are still a matter of discussion. Among other unanswered questions, the exact nature of the LGRB stellar progenitors is still being debated. Stellar evolution models provide a rough picture of the production of a LGRB in a massive star. According to the collapsar model (Woosley 1993; MacFadyen & Woosley 1999), LGRBs are produced during the collapse of single Wolf-Rayet (WR) stars. WR stars have massive cores that may collapse into black holes, and are fast rotators, a condition needed to support an accretion disc and launch the collimated jets. WRs have also large mass-loss rates, needed to lose their hydrogen envelope before collapsing, that would otherwise brake the LGRB jet. This model agrees with the observed association between LGRBs and hydrogen deficient SNe. However, WRs large mass-loss rates imply large angular momentum losses that would brake their cores, which would inhibit the production of the LGRB. To overcome this problem, Hirschi, Meynet & Maeder (2005) proposed low-metallicity WRs (WOs) as progenitors. WOs have lower mass-loss rates, diminishing the braking effect, but also preventing the loss of the envelope. Another possibility was proposed by Yoon, Langer & Norman (2006). According to these authors, low-metallicity, rapidly rotating massive stars evolve in a chemically homogeneous way, hence burning the hydrogen envelope, instead of losing it. Low-metallicity progenitor models are consistent with differ-
ent pieces of evidence. First, the works of Meynet & Maeder (2005) and Georgy et al. (2009) show that the collapse of high-metallicity stars produces mainly neutron stars, while those of low-metallicity stars form black holes. Second, LGRB HGs have been found to be low-metallicity systems (Fynbo et al. 2003; Le Floc’h et al. 2003; Christensen et al. 2004; Prochaska et al. 2004; Savaglio et al. 2009). Finally, the analysis of the statistical properties of the population of LGRBs suggests that their cosmic production rate should increase with respect to the cosmic star formation rate at high redshift, which could be explained as an effect of the low metallicity of the progenitors, combined with the cosmic metallicity evolution (Daigne, Rossi & Mochkovitch 2006; Salvaterra & Chincarini 2007). Another possibility for WR to lose the envelope without losing too much angular momentum is to be part of binary systems as proposed by Fryer & Hegue (2005).

Understanding the nature of LGRB progenitors is beyond the interest of only stellar evolution, black hole formation, and high energy astrophysics. The visibility of LGRBs up to very high redshifts ($z > 8$), allows their use as tools to explore star formation and galaxy evolution in the early Universe. On the other hand, observations of the environment and HGs of LGRBs could reveal important clues about the progenitors of these phenomena. Given that star formation shifts outward within a galaxy due to the depletion of gas in the central regions as the galaxy evolves, that the interstellar medium of galaxies is not chemically homogeneous, and that the chemical enrichment is affected by variations of the star formation rate and the production of different types of SNe, it is expected that both the LGRB positions within a galaxy and the chemical properties of the environment in which LGRBs occur depend on redshift and on the metallicity of the LGRB progenitors.

Using high-precision astrometry, Bloom, Kulkarni & Djorgovski (2002) and Blinnikov et al. (2005) have measured the positions of $\sim 35$ LGRBs with respect to the centres of their hosts, supporting the collapsar model against the (now disproved) neutron star merger model. The question of the metallicity dependence of LGRB progenitors could also be investigated comparing these data with model predictions. The chemical abundances of LGRB circumburst and HG environments were investigated by several authors (Prochaska et al. 2007; Niino, Totani & Kobayashi 2009; Savaglio, Glazebrook & Le Borgne 2009; Schady et al. 2010). However, only in a few cases of low-redshift bursts a direct measure of the metallicity of the star-forming region that produced the LGRB is available. At intermediate redshift observers usually measure the mean HG metallicity, while at high redshift they must resort to GRB-DLA techniques, which give the metallicity of galactic clouds intercepting the line of sight to the LGRB, but not necessarily associated with the burst itself (Prochaska et al. 2007; Rau A. et al. 2010).

In this paper, we use cosmological hydrodynamical simulations which include star formation and SN feedback to investigate the predictions of different progenitor scenarios regarding the positions of LGRBs and the chemical abundances of their environment. Since galaxy formation is a highly non-linear process, cosmological numerical simulations (Katz & Gunn 1991; Navarro & White 1993; Mosconi et al. 2001; Springel & Hernquist 2003; Scannapieco et al. 2005, 2006) are the best tools to investigate these LGRB properties. In the past, this method has been used by several authors to investigate different aspects of the LGRB properties. Swierkowski et al. (2004) have shown that requiring HGs to have high star formation efficiency, the observed HG luminosity function can be reproduced. Nuza et al. (2007) developed a Monte Carlo simulation to synthesize LGRB and HG populations in hydrodynamical simulations of galaxy formation, in the framework of the collapsar model. They have found that a bias to low-metallicity progenitors ($Z < 0.3Z_\odot$) is needed to explain the observed properties of HGs. Campisi et al. (2009) and Chisari, Tissera & Pellizza (2010) used semi-analytical models of galaxy formation to study the properties of HG populations. Particularly Chisari et al. (2010) developed a new approach to model the detectability of the LGRBs. Both teams explored models with mass and metallicity cut-offs for LGRB progenitors, finding that models with a metallicity cut-off could explain the HG properties, and hence supporting previous claims that LGRBs are biased tracers of star formation. However in these semi-analytical models, the spatial distribution of individual stellar populations within HGs cannot be investigated. The chemical abundances of LGRB-DLAs were investigated using numerical simulations by Pontzen et al. (2010), finding that the clouds producing the absorption lie at galactocentric distances of the order of 1 kpc.

In this work, we use cosmological numerical simulations of galaxy formation to construct synthetic LGRB populations, which allow us to investigate the properties of individual stellar populations within HGs. Our simulations are similar to those of (Nuza et al. 2007), but with a higher resolution, and include the effects of the energy feedback of SNe into the interstellar medium. The metallicities of each stellar population can be estimated, and used to construct different metallicity-dependent scenarios for LGRB production within the collapsar model. As stated by Chisari et al. (2010), the detectability of LGRBs and their HGs is an important aspect that should not be disregarded for a proper comparison with the observed samples, hence we included it in our population synthesis in the same way as these authors.

This work is organized as follows. In Sections 2 and 3 we describe the cosmological simulations of galaxy formation used, and our LGRB population synthesis models, respectively. We present our results and compare the to available observational data in Section 4. Finally, in Section 5 we present our conclusions.

2 SIMULATIONS

We analyse hydrodynamical cosmological simulations performed with a version of GADGET-3 which includes star formation, metal-dependent cooling, chemical enrichment, multiphase gas and Supernova feedback (for further details see Scannapieco et al. 2005, 2006). The simulated regions represent periodic volumes of 10 $\text{Mpc} h^{-1}$ side and are consistent with a $\Lambda$-CDM universe with the following cosmological pa-
The feedback model considers Type II and Type Ia Supernovae (SNIII and SNIa, respectively). The energy per SN event released into the interstellar medium is $0.7 \times 10^{51}$ erg. The model assumes that stars with masses greater than $8 M_\odot$ end their life as SNIII with lifetime $\approx 10^8$ yr. Lifetimes for the progenitors of SNIa are randomly selected in the range $0.1 - 1$ Gyr. The chemical yields for SNIII are given by Woosley & Weaver (1995) while those of SNIa correspond to the W7 model of Thielemann et al. (1993). Initially gas particles are assumed to have primordial abundances of $X_H=0.76$ and $X_H=0.24$. The chemical algorithm follows the enrichment by 12 isotopes: $^1$H, $^2$He, $^{12}$C, $^{15}$O, $^{25}$Mg, $^{28}$Si, $^{56}$Fe, $^{14}$N, $^{20}$Ne, $^{32}$S, $^{40}$Ca and $^{62}$Zn (Mosconi et al. 2001).

We would like to stress that this model has proven to be successful at regulating the star formation activity and at driving powerful mass-loaded galactic winds without the need to introduce mass-depend parameters (Scannapieco et al. 2008).

We analyse two simulations: S230 and S320, which have been also used by De Rossi et al. (2010) to study the Tully-Fisher relation obtaining very good agreement with observations. S230 has initially $2 \times 230^3$ with dark matter masses of $5.93 \times 10^6 M_\odot h^{-1}$ and initial gas mass of $9.1 \times 10^5 M_\odot h^{-1}$. S230 initially has $2 \times 320^3$ with dark matter of $2.20 \times 10^6 M_\odot h^{-1}$ and initial gas mass of $3.4 \times 10^5 M_\odot h^{-1}$. S320 was only run to $z \approx 2$ because of lack of computational power. We use this simulation to assess possible numerical resolution problems.

From the general mass distribution, we select virialized structures by using the friends-of-friends technique and then identify all substructures within the virial radius by applying the SUBFIND algorithm (Springel et al. 2001). We select as simulated galaxies those substructures sampled with more than 3000 particles.

De Rossi & Tissera (2010) found that the mass-metallicity relation (MZR) of galaxies in these simulations differs at low redshifts from that reported by Tremonti et al. (2004) so that galaxies have lower mean metallicity than observed although the shape of the observed MZR is very well reproduced. Because of this, we renormalized the simulated abundances to make them consistent with observations. For that purpose, we adopted the results of Maiolino et al. (2008) who proposed a model to describe the evolution of observed MZR which matched available observations at $z=0.07$, 0.7 and 2.2. With this adjustment, our simulated MZR reproduce observations at different redshifts. For illustration purposes, we show our analysis at four redshifts: $z=0, 1, 2$ and 3.

## 3 SCENARIOS FOR LGRBS

To construct synthetic LGRB populations from the stellar populations described by the simulations we adopt the collapsar model, in which LGRB progenitors are massive stars possibly with low metallicity. We investigate four scenarios in which progenitors have a mass greater than a certain minimum $m_{\text{min}}$. For scenario 1 this is the only condition, while for the others a maximum metallicity $Z_c$ is assumed for the progenitors. The values of $m_{\text{min}}$ and $Z_c$ were taken from Chisari et al. (2010), who derived them by fitting the LGRB rate observed by BATSE, and are listed in Table 1.

We estimate the number of massive stars in each simulated galaxy at each analysed redshift by assuming a Initial Mass Function given by Salpeter (1955). We included all stars born within $\tau_c=100$ Myr. This time interval is larger than the mean lifetime of SNIII progenitors but it allow us to minimize numerical fluctuations and it is small compared to SFR variations. The selected progenitors define the scenario 1. For scenarios 2, 3, and 4 we impose a requirement on the mean metallicity, considering only new born stars with $Z < Z_c=0.6, 0.3, 0.1$, respectively.

Following Chisari et al. (2010), for each stellar population represented by a particle $p$ with mass $m_p(p,z)$ at redshift $z$ satisfying the above requirements, we calculated the number of LGRBs produced as the number of stars with $m > m_{\text{min}}$.

\[
N(p,z) = m_p(p,z) \int_{m_{\text{min}}}^{100M_\odot} \frac{\xi(m) dm}{\int_{0.1M_\odot}^{100M_\odot} m \xi(m) dm}, \tag{1}
\]

where $\xi(m)$ is the Initial Mass Function with $0.1 M_\odot$ and $100 M_\odot$ its lower and upper mass cut-offs, respectively. The intrinsic LGRB rate for a stellar population in any scenario is then

\[
r(p,z) = \frac{N(p,z)}{\tau_c}, \tag{2}
\]

We are interested in computing observable properties of the stellar populations selected by LGRB observations, such as metallicities, $\alpha$-elements abundances, and distances to their HG centre. As discussed by Chisari et al. (2010), selection effects introduced by observations can be modeled by weighting the properties of simulated stellar populations by their contribution to the total observed LGRB rate at the Earth. We applied the method developed by Chisari et al. (2010) to estimate the probability that a certain LGRB produced at a given $z$ could be observed at Earth. However, there might be other biases introduced by observations which are difficult to model because of their dependence on sensitivity and spectral bands of the detectors and telescopes. Particularly, the afterglow observations, on which the precise positioning of LGRBs is based, are usually made in the optical range and could be affected by dust absorption, biasing the samples towards low metallicity systems. As claimed by Fynbo et al. (2009), about 40 per cent of LGRBs might be dust obscured. Dust effects have not been included in our scenarios hence, caution should be taken when comparing our results with observations. We will point out possible dust effects when appropriate.
At fixed redshift, the weights depend only on the intrinsic LGRB rate of the corresponding stellar population, becoming

\[ p_{\text{det}}(p, z) = \frac{r(p, z)}{\sum_{p'} r(p', z)}, \]

(3)

where the sum extends over all the stellar populations \( p' \) producing LGRBs at a given redshift. For any observable property \( X(p, z) \) of these stellar populations, its mean observed value at \( z \) must then be

\[ \langle X(z) \rangle = \sum_{p'} p_{\text{det}}(p, z) X(p', z). \]

(4)

4 RESULTS AND ANALYSIS

4.1 Spatial distribution of LGRBs

We first investigate the spatial distribution of LGRBs in our scenarios. For this purpose, we calculate the distance between the LGRB and the centre of mass of its galaxy \( b \). To eliminate the effects produced by the growth of galaxies as the structure in the Universe assembles, we normalize \( b \) by taking the ratio \( b/r_{\text{opt}} \), where \( r_{\text{opt}} \) is the optical radius of the galaxy, defined as the radius encompassing 83 per cent of its baryonic mass (Tissera & Domínguez-Tenreiro 1998).

In the Fig. 1 we present the distribution of \( b/r_{\text{opt}} \) for the LGRBs at different redshifts \( (z = 0, 1, 2, 3) \), weighted by their detectability as explained in section 3. We observe that LGRB progenitors tend to reside in the inner regions galaxies at high redshift, and to be progressively located at larger distances from the centre as redshift decreases. This is consistent with the fact that the main sites of star formation shift outwards as time evolves and the galactic structure gets assembled in a hierarchical fashion. This effect is stronger in our scenarios with higher \( Z_c \), because low metallicity populations tend to be formed in the outer regions of galaxies which are less enriched since all simulated systems exhibit metallicity gradients.

In Fig. 2, we plot the median values of \( b/r_{\text{opt}} \) in our scenarios as a function of redshift, together with the available observations of the LGRBs positions within their hosts (Bloom et al. 2002; Blinnikov et al. 2005). These authors measure the distance of LGRB to the centre of their hosts, projected onto the plane of the sky, and normalised by the galaxy half-light radius \( r_h \). As these authors point out, this normalisation is a crude way of deprojecting the values of \( b \). To transform them into \( b/r_{\text{opt}} \), we assume that LGRB hosts can be modeled by an exponential disc, for which \( r_h = 0.52r_{\text{opt}} \). Fig. 2 shows that our scenarios are consistent with observations, except at very low redshifts in which the observed median value of \( b/r_{\text{opt}} \) drops abruptly, while our scenarios remain almost constant. By analysing the LGRBs contributing to the lowest-\( z \) point in Fig. 2, we find that almost half of them (3 out of 7) have \( b/r_{\text{opt}} \) values consistent with zero. Interestingly, the hosts of these LGRBs show evidence of interaction or close companions. Hence, the presence of nuclear star formation activity could be explained as triggered by galaxy interactions as suggested by observations (Lambas et al. 2003) and numerical simulations (Barnes & Hernquist 1996; Milos & Hernquist 1996; Tissera 2000; Perez et al. 2006). Then, the discrepancy can be attributed to the fact that our simulated galaxy sample does not reflect the effects of this mode of star formation at low redshift since our analysed galaxies are dominated by systems with low gas reservoir (De Rossi & Tissera 2010; De Rossi, Tissera & Pedrosa 2011). A further piece of evidence for this explanation is provided by a recalculation of the lowest-\( z \) point, excluding the three quoted LGRBs (filled circle in Fig. 2). The new point lies within 3\( \sigma \) of our scenarios, showing a better agreement than the original one.

The large error bars of the observations, which originate in the low number of LGRBs with precise positions, prevent us from using a goodness-of-fit estimator to determine the scenario that better fits the observations. However the fact that the observed values are always higher than the predictions of scenarios Sc1 and Sc2 implies that it is very improbable that these scenarios could explain the observations. Hence our results suggest that LGRB progenitors would have low metallicities \( (Z < 0.3Z_\odot) \). In the case that dust effects introduce important biases in the impact parameter distribution, the preference for low metallicity progenitors obtained from Fig. 2 would have to be re-considered. Observations providing new insights on the location of dark GRBs may help to resolve this issue.

4.2 Chemical abundances

To analyse the chemical abundances of the LGRB progenitors in our scenarios, we use the ratio [Fe/H] as a measure of the iron abundance, and [Si/Fe] as a measure of the relative abundance of \( \alpha \) elements to iron. In Fig. 3 we present the distribution of [Fe/H] for the LGRB progenitors in our scenarios at different redshifts, weighted by the detectability in the same way as in the previous section. We observe that the abundance of iron increases as redshift decreases in...
all scenarios. This can be understood in terms of the chemical evolution of the interstellar medium. As time evolves SNe contribute to the enrichment of the medium with iron, hence stellar populations born at low redshifts exhibit higher iron abundances. This enrichment is stronger in scenarios Sc1 and Sc2, where the metallicity cut-offs are not so restrictive.

In Fig. 4 we present the distribution of [Si/Fe] for LGRB progenitors. We observe that, for all our scenarios, they exhibit a higher [Si/Fe] as redshift increases, indicating an enhancement in \( \alpha \) elements at high redshifts. This is consistent with the fact that SNII enrich the interstellar medium. Due to the fact that SNII progenitors have lifetimes \( \sim 10 \text{Gyr} \) while those of SNII live only \( \sim 10 \text{Myr} \), at high redshift only the contribution of the latter to the interstellar medium enrichment is significant, rendering stellar populations rich in \( \alpha \) elements. As redshift decreases, the contribution of SNII becomes important, decreasing the abundance of \( \alpha \) elements relative to iron.

The trend of [Si/Fe] to decrease towards lower redshift is also observed in Fig. 5 (right panel), where we plot the median value of the ratio [Si/Fe] as a function of redshift. In this figure we also observe that the values of [Si/Fe] of the LGRB progenitors is lower and evolve more strongly with redshift in the scenarios where the metallicity cut-off is more restrictive. In the left panel of Fig. 5 we show the median value of the ratio [Fe/H] as a function of redshift. We find that the median value of [Fe/H] decreases with \( Z_c \) as expected for cut-offs progressively more restrictive in metallicity. These results indicate that the metallicity cut-off tends to eliminate old stellar populations highly enriched by SNII, located mainly in the central regions of galaxies and originated in first outbreaks of star formation.

5 CONCLUSIONS

Aiming at understanding the relation between LGRBs and star formation, we analysed the spatial distribution and chemical abundances of stellar populations producing these phenomena. We investigated four different scenarios for the progenitors of LGRBs based on the collapsar model with different metallicity cut-offs.

We compared the spatial distribution of LGRBs within their HGs in our scenarios and with the available observations. We found that in all our scenarios LGRB progenitors reside on average in the outer regions of their galaxies at low redshifts, shifting toward the centre as redshift increases.
Scenarios favouring low metallicity progenitors tend to produce LGRBs further out from the central regions than those allowing high metallicity progenitors. The confrontation of our models with available observations supports scenarios with low metallicity cut-offs, in agreement with previous results (Nuza et al. 2007; Campisi et al. 2009; Chisari et al. 2010). Particular we best reproduce current available observations for a model where LGRB progenitors are massive stars with $Z < 0.3$. Further precise LGRB position measurements would help to confirm these trends.

Regarding [Fe/H] abundances of the stellar populations producing LGRBs, we found that in all our scenarios [Fe/H] increases as redshift decreases. This effect is less conspicuous in the scenarios with low metallicity progenitors, as in these cases the metallicity cut-off restricts the chemical abundances of the stellar populations producing LGRBs. The $\alpha$-enhancement decreases with redshift in all our scenarios, as a result of the different contributions of SNII and SNIa. Contrary to the detected trend in [Fe/H], the $\alpha$-enhancement shows a stronger evolution with redshift as $Z_{\odot}$ decreases. As previously discussed, these chemical trends can be understood within the context of chemical evolution in hierarchical clustering scenarios.

Considering that the results on the spatial distribution of LGRB progenitors favours low-metallicity progenitor models, one would expect that the iron abundance of the stellar populations producing LGRBs remains low at all redshifts with little variations ([Fe/H] $\sim -1$). On the other hand, one would expect that the $\alpha$-enhancement strongly decreases with redshift (by 0.2 dex between $z = 3$ and $z = 0$). This means that, if LGRBs are produced by low metallicity massive stars, their location will be shifted on average from the central regions to the outskirts of galaxies. If LGRBs can trace the chemical properties of the interstellar medium, they may map different regions of galaxies at different redshifts. A test of these predictions could be set up as further dust-corrected measurements of the chemical abundances of the stellar populations producing LGRBs become available.

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