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The metallicity of the long GRB hosts and the fundamental metallicity relation of low-mass galaxies

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ABSTRACT

We investigate the metallicity properties of host galaxies of long gamma-ray bursts (GRBs) in the light of the fundamental metallicity relation (FMR), the tight dependence of metallicity on mass and star formation rate (SFR) recently discovered for Sloan Digital Sky Survey galaxies with stellar masses above $10^{9.2}$ $M_{\odot}$. As most of the GRB hosts have masses below this limit, the FMR can only be used after an extension towards lower masses. With this aim, we study the FMR for galaxies with masses down to $\sim 10^{8.3}$ $M_{\odot}$, finding that the FMR does extend smoothly at lower masses, albeit with a much larger scatter. We then compare the resulting FMR with the metallicity properties of 18 host galaxies of long GRBs. While the GRB hosts show a systematic offset with respect to the mass–metallicity relation, they are fully consistent with the FMR. This shows that the difference with the mass–metallicity relation is due to higher than average SFRs and that GRBs with optical afterglows do not preferentially select low-metallicity hosts among the star-forming galaxies. The apparent low metallicity is therefore a consequence of the occurrence of a long GRB in low-mass, actively star-forming galaxies, known to dominate the current cosmic SFR.

Key words: galaxies: abundances – galaxies: star formation.

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most energetic explosions in the Universe (see Zhang & Mészáros 2004, for a review) and detected in the γ-rays with a frequency of about one per day over the whole sky. The γ-ray emission is accompanied by a long-lasting tail, called afterglow, usually detected over the whole electromagnetic spectrum. Their extreme brightness easily overshines the luminosity of their host galaxy and makes them detectable up to extreme high redshift as shown by the discovery of GRB 090423 at $z = 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009). GRBs are usually divided into two, broad classes (Kouveliotou et al. 1993): short GRBs, which are believed to result from the merger of two compact objects, and long GRBs, associated with the collapse of the core of a massive star, such as a Wolf–Rayet star (Woosley & Heger 2006; Yoon, Langer & Norman 2006; Yoon et al. 2008). In this paper, we limit our analysis to the class of long GRBs.

Recent studies on the final evolutionary stages of massive stars (Fryer, Woosley & Hartmann 1999; Woosley & Heger 2006) have suggested that a Wolf–Rayet star can produce a long GRB if its mass-loss rate is small, which is possible only if the metallicity of the star is lower than ~ 0.1–$0.3\,Z_{\odot}$. In this case, the specific angular momentum of the progenitor allows the loss of the hydrogen envelope while preserving the helium core. In this view, GRBs may occur preferentially in galaxies with low metallicity (Fynbo et al. 2003; Prochaska et al. 2004; Fruchter et al. 2006; Stanek et al. 2006), although 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, GRBs could form from low-metallicity progenitors also in hosts with relatively high metallicities (Campisi et al. 2009).

Up to now, we have been able to detect the host galaxy of ∼70 long GRBs with known redshift. In more than half of the cases, the observations allowed us to determine the stellar mass and the star formation rate of the galaxy.[1] The observational information gathered so far indicates that long GRBs with optical afterglows are typically found to reside in low-mass, dwarf galaxies with average stellar masses $M_{\star} \sim 1$–5×10^{9} $M_{\odot}$ and a high specific star formation rate (SSFR = SFR/$M_{\star}$). Information about the chemical content of this objects is known only for a subsample of the hosts (Savaglio, Glazebrook & LeBorgne 2009; Levesque et al. 2010c; Levesque, Kewley & Larson 2010d). While most of the long GRBs are in low-metallicity galaxies, a few cases for which the galaxy metallicity is found to be quite high do exist (e.g. GRB 020819, Levesque et al.

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[1] Data taken from http://www.grbhosts.org/ (see Savaglio et al. 2007).

2010c; Küpcü Yoldaş et al. 2010, and GRB 050401, Watson et al. 2006), so that the role of metallicity in driving the GRB phenomena remains unclear and it is still debated (Fynbo et al. 2003; Prochaska et al. 2004; Fynbo et al. 2006; Stanek et al. 2006; Price et al. 2007; Wolf & Podsiadlowski 2007; Modjaz et al. 2008; Kocevski, West & Modjaz 2009; Graham et al. 2009a,b; Savaglio, Glazebrook & LeBorgne 2009; Fan, Yin & Matteucci 2010; Levesque et al. 2010a,c, e; Svensson et al. 2010).

Many recent studies have attempted to find similarities and differences between the GRB host population and the normal field galaxy one (see e.g. Fynbo et al. 2008). In particular, these studies compared the observed mass–metallicity relation (or the luminosity–metallicity relation) of the two populations obtaining contradictory results. From the analysis of a whole sample of known GRB hosts, Savaglio et al. (2009) concluded that there is no clear indication that GRB host galaxies belong to a special population. Their properties are those expected for normal star-forming galaxies, from the local to the most distant universe. On the other hand, the study of subsamples with well-determined chemical properties (e.g. Han et al. 2010; Levesque et al. 2010a,c) suggests that most of the long GRB host galaxies fall below the *M*–*Z* relation for the normal galaxy population.

The aim of this work is to further test the differences between the GRB hosts and field galaxies by taking advantage of the new fundamental metallicity relation (FMR) recently introduced by Mannucci et al. (2010). The FMR is a tight relation between stellar mass $M_\star$, SFR and gas-phase metallicity. Local SDSS galaxies define a surface in the 3D space of these three quantities, with metallicity being well determined by stellar mass and SFR. The residual metallicity scatter around this surface is very small, about 0.05 dex, similar to the expected uncertainties. Also, the same FMR defined locally by Sloan Digital Sky Survey (SDSS) galaxies is found to describe, without any evolution, the properties of high-redshift galaxies, up to $z = 2.5$. The origin of the strong, monotonic evolution of the mass–metallicity relation over the same redshift range (e.g. Tremonti et al. 2004; Erb et al. 2006b) is due to the increase in the target SFR with redshift, resulting in sampling different parts of the same FMR at different redshifts. At even higher redshifts, galaxies are found to evolve off the FMR (Maiolino et al. 2008; Mannucci et al. 2009), and this effect is under test with a larger number of observations (Troncoso et al., in preparation).

The ranges of mass and SFR over which the FMR was measured are limited by the number of galaxies in the SDSS Data Release 7 (DR7) sample used, which become rare at $\log(M_\star/\mathrm{M}_\odot)$ below 9.2 and above 11.4 and at $\log(\mathrm{SFR}/\mathrm{M}_\odot\ \mathrm{yr}^{-1})$ below −1.4 and above +0.8. For this reason, a comparison with the hosts of GRBs can only be done by extending this relation using lower mass galaxies, while a simple extrapolation of the FMR of massive galaxies could produce spurious effects.

2 EXTENDING THE FMR TOWARDS SMALLER MASSES

To derive the FMR, Mannucci et al. (2010) have split ∼140 000 SDSS-DR7 galaxies into bins of mass and SFR having a width of 0.15 dex in both quantities. To have a good estimate of both median and dispersion of the metallicity for each value of mass and SFR, only bins containing more than 50 galaxies have been used. This severely limits the range of mass and SFR over which the FMR has been measured, even if a significant number of galaxies outside these ranges are present in the original sample. Among the ∼140 000 SDSS-DR7 galaxies selected by Mannucci et al. (2010) requiring $0.07 < z < 0.30$ and signal-to-noise ratio $\mathrm{S/N(H\alpha)} > 25$, about 2000 (1.4 per cent) have masses below $10^{9.2}\ \mathrm{M}_\odot$. Here we intend to use these galaxies to extend the measured FMR.

Mannucci et al. (2010) have introduced the new quantity μ_α defined as a linear combination of stellar mass and SFR:

$$\mu_\alpha = \log(M_*) - \alpha \log(\mathrm{SFR}) \tag{1}$$

and have demonstrated that, for $\alpha = 0.32$, all galaxies at $z < 2.5$ show the same dependence of metallicity on $\mu_{0.32}$ and the same range of values of $\mu_{0.32}$. In other words, the introduction of this quantity roughly defines a projection of the FMR that minimizes the scatter, i.e. corresponds to observing the FMR ‘edge-on’. From a physical point of view, metallicity is found to increase with mass and decrease with SFR. Therefore, a combination of these two quantities, with a negative factor for SFR, is expected (and actually found) to show a better correlation with metallicity. It is worth noting that the dependence of metallicity only on $\mu_{0.32}$ is not exact, as no part of the FMR is exactly a plane (see fig. 2 of Mannucci et al. 2010); nevertheless, this is a convenient approximation.

To avoid binning the limited number of galaxies with low mass into a large number of classes of mass and SFR, we extend the FMR directly by considering the combination $\mu_{0.32}$. We consider the ∼1400 galaxies in the Mannucci et al. (2010) sample with $8.3 < \mu_{0.32} < 9.4$. This is a small sample, side by side to the large sample of ∼140 000 galaxies with larger values of $\mu_{0.32}$, and problems with contamination are possible. Indeed, while ∼1300 galaxies with low $\mu_{0.32}$ show low metallicities, 86 of them, corresponding to 0.0007 of the full sample, have large values of metallicities, above $12+\log(\mathrm{O/H}) = 8.9$, with the same distribution of metallicity of the large population of massive, quiescent, metal-rich galaxies. Given the intrinsic uncertainties on mass and SFR, these 86 galaxies are likely to be metal-rich galaxies whose $\mu_{0.32}$ is incorrectly measured and scattered towards low values. We remove these galaxies from the sample and divide the remaining ∼1300 galaxies into bins of $\mu_{0.32}$, and for each bin we compute the median and standard deviation of metallicity. For comparison, we also compute the mass–metallicity relation considering the ∼1700 galaxies with masses between $10^{8.3}$ and $10^{9.4}\ \mathrm{M}_\odot$.

The results are shown in Fig. 1, where low-mass galaxies are compared to galaxies of larger $M_\star$. The left-hand panel shows the mass–metallicity relation. At masses above $\sim 10^{10}\ \mathrm{M}_\odot$ this is fully consistent with Tremonti et al. (2004), while it shows lower values of metallicity and a steeper slope at lower masses. This is probably due to the different selections: our requirement of a high S/N ($\mathrm{S/N} > 25$; see Mannucci et al. 2010) in the Hα line preferentially select galaxies with a high SFR and, as a consequence, lower metallicity, especially at low stellar masses.

The FMR is shown in the right-hand panel of Fig. 1. Low-mass galaxies appear to extend smoothly the FMR, with a linear relation between metallicity and $\mu_{0.32}$. The resulting FMR can be described by

$$\begin{aligned} 12 + \log(\mathrm{O/H}) &= 8.90 + 0.37m - 0.14s - 0.19m^2 \\ &\quad + 0.12ms - 0.054s^2 \quad \text{for } \mu_{0.32} \geq 9.5 \\ &= 8.93 + 0.51(\mu_{0.32} - 10) \text{ for } \mu_{0.32} < 9.5, \end{aligned} \tag{2}$$

where $m = \log(M_\star) - 10$ and $s = \log(\mathrm{SFR})$ in solar units.

It is evident that the intrinsic scatter around the FMR increases towards lower values of $\mu_{0.32}$. The residual scatter is larger than the expected errors on metallicity, mass and SFR, even if the uncertainties on stellar masses from SED fitting could increase towards low masses. This increasing scatter towards dwarf galaxies is a well-known effect probably related to a large spread of histories and

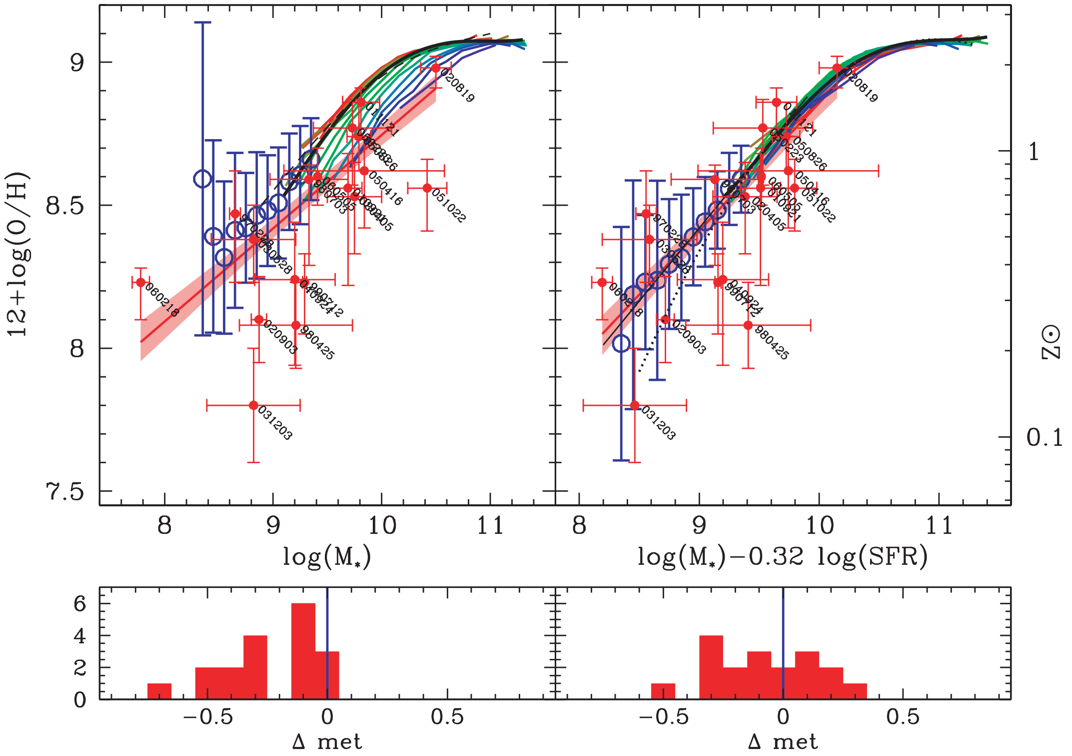

Figure 1. Left: mass–metallicity: metallicity of low-mass SDSS galaxies (blue open dots with 1σ dispersions) as a function of stellar mass. The coloured lines are local SDSS galaxies from Mannucci et al. (2010), colour-coded from red to blue according to an increasing SFR. The black thick line shows the polynomial fit to the mass–metallicity relation in Mannucci et al. (2010). The black dashed line is the mass–metallicity relation in Zahid et al. (2010), transformed to the same metallicity scale. The host galaxies of long GRBs are overplotted (red solid dots, labelled with the GRB date). The red thick line is a linear fit to these GRB host data, with $\pm 1\sigma$ bands shown in light red. It is clear that the GRB host follows a different relation and show systematically lower metallicities. The lower panel shows the difference between the metallicity of the GRB hosts and the mass–metallicity relation of SDSS galaxies, showing the systematic offset towards lower metallicities. Right: FMR: metallicity as a function of $\mu_{0.32} = \log(M_\star)-0.32\log(\mathrm{SFR})$ in solar units. The black solid line is the linear fit to the low-mass SDSS galaxies. For comparison, the black dotted line is the extrapolation of the second-degree fit to the FMR of the SDSS galaxies as defined in Mannucci et al. (2010) and plotted for $\log(\mathrm{SFR}) = 0$. The linear fit to the GRB host data (red line with the $\pm 1\sigma$ band) shows that GRB hosts are fully compatible with the FMR defined by local SDSS galaxies. This is also shown in the lower panel, where the metallicity difference of GRB hosts with the FMR is plotted.

current levels of star formation (Hunter & Hoffman 1999; Hunt, Bianchi & Maiolino 2005; Zhao, Gao & Gu 2010).

3 METALLICITY OF THE HOSTS OF GRB

The formation of long GRBs is thought to be related to the collapse of a very massive, low-metallicity star (Fryer et al. 1999; Woosley & Heger 2006). Thus, it has been argued that the occurrence of a long GRB may be linked to an overall low metal content of its host galaxy, making GRB hosts a biased galaxy sample with respect to the normal field population. In order to check whether this bias exists, we consider the properties of the GRB hosts in the light of the observed FMR for normal field galaxies. To this extent, we collect all the GRB host galaxies at $z < 1$ with available observations to measure and, at the same time, stellar mass, SFR and gas-phase metallicity.

Line fluxes of long GRB hosts have been published by several authors (Savaglio et al. 2009; Han et al. 2010; Levesque et al. 2010b). We have used these compilations to measure gas-phase metallicities, using the method described in Maiolino et al. (2008) and Cresci et al. (2010), and expressing them in the same scale as in Nagao, Maiolino & Marconi (2006), Kewley & Ellison (2008) and Mannucci et al. (2010), where solar metallicity is $12 + \log(\mathrm{O/H}) = 8.69$. Many metallicity indicators have been proposed that are based on line ratios (e.g. Pettini & Pagel 2004; Nagao et al. 2006; Kewley & Ellison 2008), but none of them is without problem. For example, R23 has two branches, with two different metallicities associated with each value of R23. Both Hα/[N II]λ6584 and [O II]λ3727/[Ne III]λ3869 have monotonic variations with metallicity and no dependence on extinction, but they include fainter lines, especially for very high or very low metallicities. [O III]$\lambda\lambda$4958, 5007/[O II]λ3727 and [O III]$\lambda\lambda$4958,5007/[N II]λ6584 are sensitive to extinction, which is usually poorly known. Following Nagao et al. (2006), we measure metallicities by simultaneously considering all the flux ratios among the relevant emission lines, fitting these values with two free parameters, metallicity and extinction. Usually this method can obtain a reliable value of metallicity, avoiding or mitigating the intrinsic problems of each individual line ratio. In contrast, extinction is usually very poorly constrained, because most of the line ratios used involve a line with similar wavelengths. For this reason, when flux ratios between different hydrogen Balmer lines are available and give consistent results, we measure extinction from these Balmer decrement (assuming intrinsic line ratios of Hα/Hβ = 2.87, Hγ/Hβ = 0.466, Hδ/Hβ = 0.256; Osterbrock 1989), considerably reducing the uncertainties on A_V. The SFR is then obtained, as in Mannucci et al. (2010), from Hα corrected for extinction, using the calibration in Kennicutt (1998). Uncertainties on the SFR are computed taking into account the errors on both line

Table 1. Properties of the GRB hosts.

GRB	z	$\log(M_\star)$ ($\mathrm{M}_\odot$)	SFR ($\mathrm{M}_\odot\ \mathrm{yr}^{-1}$)	12+log(O/H)	A_V
970228	0.695	8.65 ± 0.05	1.95 ± 0.22	$8.47^{+0.15}_{-0.24}$	$0.0^{+0.7}_{-0.0}$
980425	0.0085	9.21 ± 0.52	0.24 ± 0.05	$8.08^{+0.15}_{-0.15}$	$1.9^{+0.1}_{-0.1}$
980703	0.966	9.33 ± 0.36	4.20 ± 0.17	$8.59^{+0.05}_{-0.30}$	$0.0^{+0.7}_{-0.0}$
990712	0.434	9.29 ± 0.02	2.62 ± 0.05	$8.23^{+0.10}_{-0.18}$	$0.5^{+0.1}_{-0.1}$
010921	0.451	9.69 ± 0.13	3.60 ± 0.32	$8.56^{+0.12}_{-0.34}$	$1.6^{+1.0}_{-1.0}$
011121	0.362	9.81 ± 0.17	3.30 ± 0.05	$8.86^{+0.05}_{-0.13}$	$0.9^{+0.1}_{-0.1}$
020405	0.691	9.75 ± 0.25	14.1 ± 0.29	$8.53^{+0.12}_{-0.20}$	$1.9^{+0.6}_{-0.6}$
020819B	0.411	10.50 ± 0.14	12.5 ± 0.17	$8.98^{+0.07}_{-0.07}$	$1.8^{+0.5}_{-0.5}$
020903	0.251	8.87 ± 0.07	3.00 ± 0.08	$8.05^{+0.16}_{-0.15}$	$0.8^{+0.2}_{-0.2}$
030528	0.782	8.82 ± 0.39	5.40 ± 0.19	$8.38^{+0.12}_{-0.15}$	$0.0^{+0.8}_{-0.0}$
031203	0.1055	8.82 ± 0.43	13.1 ± 0.05	$7.80^{+0.20}_{-0.20}$	$0.0^{+0.2}_{-0.0}$
040924	0.858	9.20 ± 0.37	1.02 ± 0.58	$8.23^{+0.20}_{-0.30}$	$0.0^{+1.2}_{-0.0}$
050223	0.584	9.73 ± 0.36	4.20 ± 0.64	$8.77^{+0.10}_{-0.20}$	$1.5^{+1.4}_{-1.3}$
050416	0.6528	9.84 ± 0.74	2.00 ± 0.43	$8.62^{+0.12}_{-0.20}$	$0.7^{+1.1}_{-0.7}$
050826	0.296	9.79 ± 0.11	1.60 ± 0.10	$8.74^{+0.12}_{-0.12}$	$0.1^{+0.2}_{-0.1}$
051022	0.8070	10.42 ± 0.18	89.6 ± 0.15	$8.56^{+0.10}_{-0.15}$	$1.0^{+0.3}_{-0.3}$
060218	0.0334	7.78 ± 0.08	0.052 ± 0.10	$8.23^{+0.05}_{-0.13}$	$0.5^{+0.3}_{-0.3}$
060505	0.0889	9.41 ± 0.01	0.46 ± 0.05	$8.60^{+0.10}_{-0.10}$	$0.8^{+0.1}_{-0.1}$

fluxes and dust extinction. Finally, stellar masses are taken from Savaglio et al. (2009).Table 1 lists the resulting properties of the host galaxies in terms of stellar mass, SFR, gas-phase metallicity and intrinsic dust extinction.

These data are plotted in Fig. 1 and compared with both the mass–metallicity relation (left-hand panel) and the FMR (right-hand panel) of local SDSS galaxies. We computed a linear fit to the GRB host data taking into account the errors on metallicity, mass and SFR. The comparison with the mass–metallicity relation shows that, as already obtained by Levesque et al. (2010b) and Han et al. (2010), GRB host galaxies have lower metallicity than galaxies of the same mass both in the local universe (SDSS galaxies) and at intermediate redshift (Savaglio et al. 2005; Zahid, Kewley & Bresolin 2010). In contrast, we also found that GRB hosts do follow the FMR and its extension towards low masses, without any significant discrepancy. In other words, when the dependence on SFR is properly taken into account, the metallicity properties of long GRB hosts do not differ substantially from those of the typical field population. As explained in the discussion, this means that the low metallicities are associated with both low masses and high SFR, i.e. with a high SSFR.

We stress that such a good agreement is only obtained when the original FMR is extended using low-mass galaxies. The use of an extrapolation of the original second-order fit would produce a spurious difference in metallicity, with GRB hosts being more metal rich than field galaxies.

In Fig. 2, we plot the relation between the SSFR and metallicity for the 18 GRB host galaxies of our sample compared to the local SDSS galaxies. Here the colour code shows different values of stellar mass. The solid lines show the relation between mass and SSFR for field galaxies, and the shaded area accounts for the intrinsic scatter of the observed relation for SDSS galaxies. GRB hosts populate the plot similarly to normal field galaxy population, with more (less) massive hosts lying in the upper (lower) bound of the observed relation. As already discussed, host metallicities are in line with those expected for star-forming, field objects, apart from GRB 980425. Notably, all the GRB hosts are found to present a relatively high SSFR, with log (SSFR) ≥ −10. Their growth time, i.e. the time required by the galaxy to form its observed stellar mass at the present level of SFR, i.e. 1/SSFR, is shorter than the Hubble

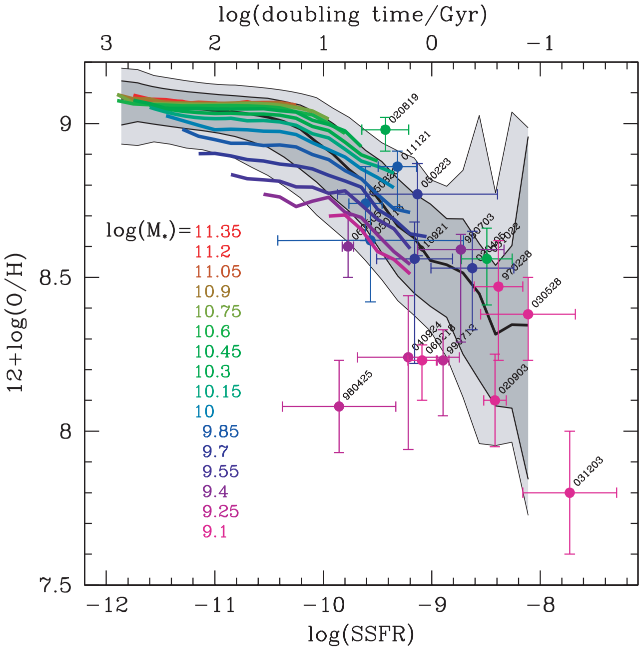

Figure 2. Metallicity of GRB hosts as a function of the SSFR. The grey-shaded area shows the relation for all SDSS galaxies, irrespective of mass, with the areas containing 68 and 90 per cent of the galaxies. The coloured lines are the median metallicity of SDSS galaxies with the listed values of stellar mass. Dots are GRB hosts, colour coded with stellar mass. A broad agreement between the two distributions is found.

time at the redshift of the GRB, for all objects in our sample. This indicates that GRB hosts are forming quite efficiently their stars similarly to local starbursts.

4 DISCUSSION

We have compared the metallicity properties of a sample of 18 GRB host galaxies with those of the local field population. In particular, we have found that GRB hosts do follow the FMR recently found by Mannucci et al. (2010). This fact implies that GRB hosts do not differ substantially from the typical galaxy population. The typical low, sub-solar metallicity found in many recent studies (e.g. Savaglio et al. 2009; Levesque et al. 2010b and references therein) does not necessarily mean that GRBs occur in special, low-metallicity galaxies, as the exception of GRB 020819 clearly shows, and that a direct link between low metallicity and GRB production exists. Indeed, this observation can be explained as a consequence of the well-known link between the GRB event and the death of very massive stars, which produces a relation between long GRBs and star formation (Totani 1997; Mao & Mo 1998; Wijers et al. 1998; Porciani & Madau 2001). In the local universe, about 70 per cent of all star formation activity occurs in galaxies with masses between $10^{9.5}$ and $10^{10.2}$ $\mathrm{M}_{\odot}$ (Mobasher et al. 2009), where most of the GRBs of our sample are also found. Low stellar mass means low metallicities at all redshifts (e.g. Tremonti et al. 2004; Savaglio et al. 2005; Erb et al. 2006a; Maiolino et al. 2008; Mannucci et al. 2009; Zahid et al. 2010); therefore, low metallicities are expected for GRB hosts. Also, the FMR shows that galaxies with a higher SFR have lower metallicities than more quiescent galaxies of the same mass. As a consequence, a star formation selected galaxy sample, such as the present GRB host sample, is expected to fall below the mass–metallicity relation, but follow the FMR. This is what is observed in Fig. 1.

Some warnings apply, which are related to the nature of the present GRB host galaxy sample. Our sample consists mostly of long GRBs whose position has been provided by the detection of their optical afterglow. It is known that a population of GRBs with a bright X-ray afterglow and lacking of optical counterpart does exist, the so-called dark GRBs, and most of them reside in dusty environments (e.g. Perley et al. 2009; Küpcü Yoldaş et al. 2010). It is still not known if this dust is spread across the host galaxy, which thus is likely to be metal-rich (Fynbo et al. 2009), or is directly associated with the GRB itself (Perley et al. 2009), may be without a clear dependence on metallicity. In all cases, it is difficult to access with the available data whether the inclusion of dark GRBs could change our main conclusions. Indeed, it is possible that dark GRB hosts would populate the region of the FMR at a high value of μ_α. This kind of studies will require the collection of an unbiased GRB-selected galaxy sample (see e.g. Malesani et al. 2009).

Such a complete or well-controlled sample is also needed to address the role of the several selection effects that could exist even within the class of GRBs with an optical bright afterglow. For example, it is very probable that galaxies with a high SFR are over-represented in this sample because they are easier to detect. For this reason, for example, the present sample of GRB hosts does not allow us to study if a direct correspondence exists between the fraction of GRB and the fraction of SFR as a function of stellar mass of the hosts. Despite this problem, it is likely that the present sample represents the metallicity properties of the population of host of GRBs with optical bright afterglows because none of the main selection effects within this class of GRBs is directly related to metallicity.

5 CONCLUSIONS

Our main findings can be summarized in the following two points.

(1) The average low metallicity observed in long GRB host galaxies is an outcome of the observed relation between stellar mass, SFR and metallicity: since the long GRB hosts are generally low-mass and high star-forming galaxies, i.e. objects characterized by a low value of μ_α, their metallicity is expected to be sub-solar; the metallicity observed in GRB hosts is exactly what is expected on the basis on their mass and SFR, with no apparent bias towards lower metallicities.

(2) Long GRBs does not necessarily explode in galaxies with a low metallicity (and indeed GRB 020819 is one of such cases). The condition for a galaxy to host a GRB seems indeed related to its ability to form stars in an efficient way. Our conclusions, based on a sample of GRB hosts at $z < 1$, are similar to what has been found by Fynbo et al. (2008) at high redshift.

Also, since GRB hosts follow the FMR, the relation can be used to predict the properties of those hosts for which one of the parameters ($M_\star$, SFR or metallicity) is not known.

Finally, our results also suggest that larger samples of GRB hosts can be used to study the FMR of normal starburst galaxies. This is in particular exciting since GRBs may allow us to extend current studies of the FMR both towards low values of μ_α and towards higher redshift, in principle up to extremely high redshifts (at least up to $z \sim 8$ as shown by GRB 090423). Thanks to their brightness, GRBs can be used as a background light to study the metal content of its parent galaxy even at very high-z as demonstrated by the case of GRB 050904 at $z = 6.3$ for which an estimate of the metallicity has been derived by Totani et al. (2006) and Kawai et al. (2006). The study of the metal enrichment history at these early cosmic epochs is of uttermost importance to better understand the first stages of galaxy formation in the Universe and to constrain the properties of those galaxies that have reionized the intergalactic medium (see Salvaterra, Ferrara & Dayal 2010).

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