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Protecting Life in the Milky Way: Metals Keep the GRBs Away

by

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ABSTRACT

The host galaxies of the five local, $z \leq 0.25$, long-duration gamma-ray bursts (GRBs 980425, 020903, 030329, 031203 and 060218), each of which had a well-documented associated supernova, are all faint and metal-poor compared to the population of local star-forming galaxies. We quantify this statement by using a previous analysis of star-forming galaxies ($0.005 < z < 0.2$) from the Sloan Digital Sky Survey to estimate the fraction of local star formation as a function of host galaxy oxygen abundance. We find that only a small fraction ($< 25\%$) of current star formation occurs in galaxies with oxygen abundance $12 + \log(\mathrm{O/H}) < 8.6$, *i.e.,* about half that of the Milky Way. However, all five low-z GRB hosts have oxygen abundance below this limit, in three cases very significantly so. If GRBs traced local star formation independent of metallicity, the probability of obtaining such low abundances for all five hosts would be $p \approx 0.1\%$. We conclude that GRBs trace only low-metallicity star formation, and that the Milky Way has been too metal rich to host long GRBs for at least the last several billion years. This result has implications for the potential role of GRBs in mass extinctions, for searches for recent burst remnants in the Milky Way and other large galaxies, for non-detections of late radio emission from local core-collapse supernovae, and for the production of cosmic rays in the local Universe. Our results agree with theoretical models that tie GRBs to rapidly spinning progenitors, which require minimal angular momentum loss in stellar winds. We also find that the isotropic energy release of these five GRBs, E_{iso}, steeply decreases with increasing host oxygen abundance. This might further indicate that (low) metallicity plays a fundamental physical role in the GRB phenomenon, and suggesting an upper metallicity limit for "cosmological" GRBs at $\approx 0.15\,Z_{\odot}$.

Key words: *Gamma rays: bursts*

1. Introduction

Special circumstances are required to produce a long gamma-ray burst (GRB). While it has now been firmly established that these events result from the death of very massive stars (*e.g.,* Galama *et al.* 1998, Stanek *et al.* 2003), there are two crucial features that distinguish progenitors of long GRBs from the vast majority of other core collapse supernovae. First, there is strong evidence that GRBs are highly beamed (*e.g.,* Stanek *et al.* 1999, Rhoads 1999). Second, the optically detected supernovae are all Type Ic, lacking both hydrogen and helium in their spectra (*e.g.,* Stanek *et al.* 2003, Modjaz *et al.* 2006, Mazzali *et al.* 2006, Mirabal *et al.* 2006). This combination of properties explains why they are so rare. The presence of a jet naturally implies rapid core rotation, which has been suggested by theoretical studies (*e.g.,* Woosley 1993) it is also easier for a jet to penetrate the thin envelope of a star that has experienced strong mass loss. However, the extensive mass loss (increasing with metallicity) required to produce Type Ic supernovae would normally also cause extensive angular momentum loss. In this paper, we directly assess whether such special circumstances exist by directly comparing GRB hosts' metallicity to the metallicity of star forming galaxies in the local Universe.

Studies of GRB hosts at $z \approx 1$ reveal that they are underluminous compared to the general population of star-forming galaxies (*e.g.,* Le Floc'h *et al.* 2003, Fruchter *et al.* 2006), suggesting that GRBs occur preferentially at low metallicities. In our analysis we study the five low redshift ($z \leq 0.25$) GRBs, a complete sample of "local" bursts identified so far. In all cases these GRBs were followed by well-documented supernovae. This sample now includes GRB 060218, whose host is fainter than the Small Magellanic Cloud (Modjaz *et al.* 2006). There are several reasons why this sample is worth a separate study. Good abundance information exists for the hosts of all five events, and it can be compared directly and using the same techniques to the sample of local star-forming galaxies from the Sloan Digital Sky Survey (SDSS) spanning approximately the same redshift range. The highest redshift in the sample, $z = 0.25$, corresponds to look back time of $\approx 2/3$ of the age of the Earth, about the time when life on Earth could be affected by GRB radiation. At these small distances we might also see other impacts of GRBs, such as production of cosmic rays and shell remnants. With five well-studied events at hand, for the first time there are enough data in this interesting redshift range to make a direct and statistically significant empirical study. This investigation complements the high-z studies and it directly addresses the properties of nearby GRBs and their hosts, in case they are different.

The main result of our analysis is to show that the oxygen abundances of the five hosts, which range from ≈ 0.1 to ≈ 0.5 of the Solar value, are much lower than would be expected if local GRBs traced local star formation independently of metallicity. We conclude that GRBs are restricted to metal-poor stellar populations, in agreement with recent theoretical models of their progenitors (*e.g.,* Yon and Langer 2005, Woosley and Heger 2006), and that the Milky Way and other large spirals have been too metal-rich to host GRBs for the last several billion years (see also Langer and Norman 2006). We discuss several implications of this result. We also find that the γ-ray isotropic energy release, $E_{\rm iso}$, for these five GRBs declines with increasing oxygen abundance of the host galaxy, and suggest that the oxygen abundance threshold for a "cosmological" GRB (visible at high redshifts) may be as low as 0.15 of the Solar value.

2. Comparison of GRB Hosts with Local Star-Forming Galaxies

Are the properties of long duration GRB hosts unusual compared with the properties of normal galaxies in the local Universe? We can address this question by comparing the physical characteristics of local GRB hosts directly to the same quantities for local galaxies in the SDSS.

Tremonti *et al.* (2004) determine metallicities for a large sample of SDSS galaxies from their spectra. The redshifts of that sample are restricted to $0.005 < z < 0.2$, providing a good comparison sample to the local GRB hosts. The metallicities are derived by a likelihood analysis which compares multiple nebular emission lines ([O II], Hβ, [O III], Hα, [N II], [S II]) to the predictions of the hybrid stellar-population plus photoionization models of Charlot and Longhetti (2001). A particular combination of nebular emission line ratios arises from a model galaxy that is characterized by a galaxy-averaged metallicity, ionization parameter, dust-to-metal ratio, and 5500 Å dust attenuation. For each galaxy, a likelihood distribution for metallicity is constructed by comparison to a large library of model galaxies. The median of this distribution is taken to be the galaxy metallicity, and the width of the distribution is taken to be the error on the metallicity. Fig. 1 shows the galaxies from the extended sample of 73 000 star-forming SDSS galaxies studied by Tremonti *et al.* (2004) in the metallicity-luminosity plane. We now add to this diagram the local GRB hosts.

The large filled dots in Fig. 1 mark the locations of three previous GRB/SN hosts (SN 1998bw, SN 2003dh, SN 2003lw) with values of M_B and $12+\log({\rm O/H})$ taken mostly from Sollerman *et al.* (2005) (see Table 1 for references). In addition, we show the host of a very recent GRB 060218/SN 2006aj, whose host galaxy has $12+\log({\rm O/H}) = 8.0$ and sub-SMC luminosity (Modjaz *et al.* 2006). We also add a host of GRB 020903 (Soderberg *et al.* 2005, Bersier *et al.* 2006), which had a clear supernova signature in its light curve, and was at fairly low redshift $z = 0.25$. Oxygen abundance for the host of GRB 020903 has been recently measured by Hammer *et al.* (2006). The symbol areas for the GRB points in Fig. 1 are scaled with isotropic γ-ray energy release $\log E_{\rm iso}$ for each burst (see Table 1), ranging from $\approx 1.0\times10^{48}$ ergs for GRB 980425 to $\approx 2.0\times10^{52}$ erg for GRB 030329. There seems to be a progression of $E_{\rm iso}$ towards lower energies with increasing oxygen abundance, which we will discuss later in the paper. As discussed in Sollerman *et al.* (2005) the applied R_{23} metallicity diagnostic (fol-

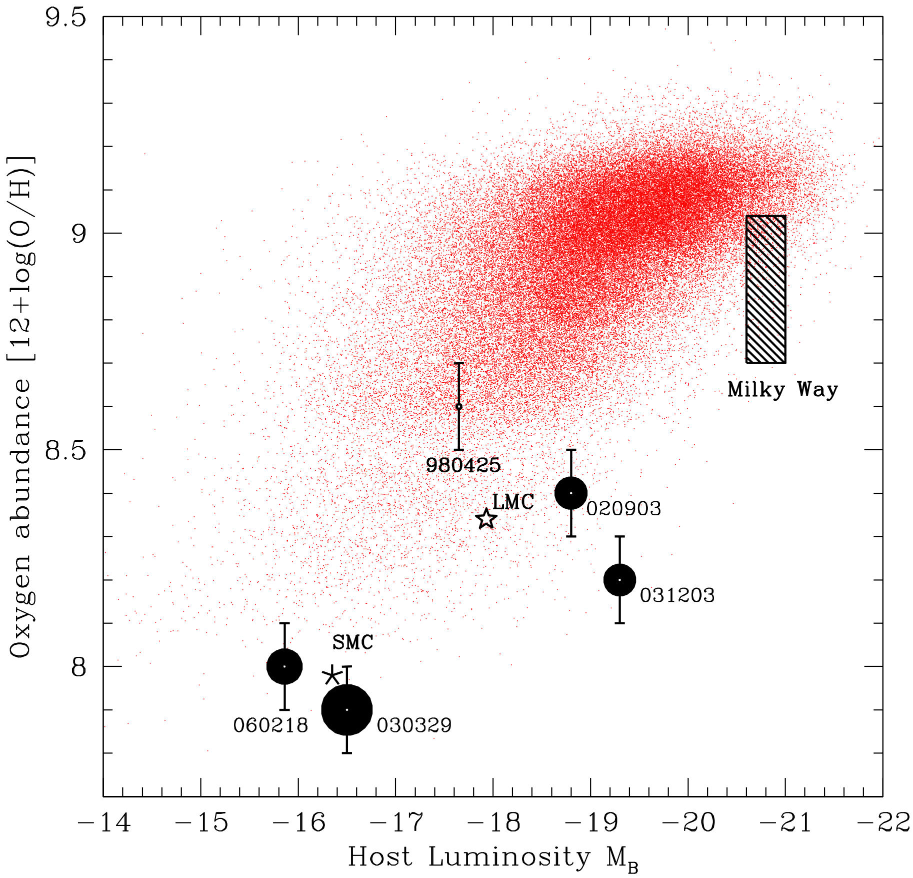

Fig. 1. Five low-z GRB/SN hosts (filled circles) and local star forming galaxies (small points: Tremonti *et al.* 2004, Tremonti 2006, private communication) in the host luminosity-oxygen abundance diagram. For comparison we also show the Milky Way, the LMC and the SMC. It is clear that local GRB hosts strongly prefer metal-poor and therefore low-luminosity galaxies. The circle areas for the GRB hosts are proportional to the log of the isotropic γ-ray energy release, $\log E_{\rm iso}$, for each burst, ranging from $\approx 1.0\times10^{48}$ erg for GRB 980425 to $\approx 2.0\times10^{52}$ erg for GRB 030329.

lowing Kewley and Dopita 2002), which employs emission line ratios of [O II], [O III] and Hβ, is double-valued. The degeneracy between the lower and upper oxygen abundance branch can be broken by taking into account other emission lines, *e.g.*, [N II]. For the host of GRB 030329, Sollerman *et al.* (2005) could not break the degeneracy due to the non-detection of [N II], so they stated two possible values for $12+\log(\mathrm{O/H})$, namely 8.6 and 7.9. Using the published line ratios by Sollerman *et al.* (2005) and Gorosabel *et al.* (2005), we consult Nagao, Maiolino and Marconi (2006) who point to another emission line diagnostic, namely [O III]λ5007 / [O II]λ3729, that can give leverage in distinguishing between the two branches. According to Nagao, Maiolino and Marconi (2006) when that ratio is above 2, the lower branch is favored, and we find a value of 2.11 for that ratio. The lower value of $12+\log(\mathrm{O/H})$ for the host of GRB 030329 is also preferred by Gorosabel *et al.* (2005) and seems more likely given its low luminosity – the upper branch would predict a much brighter host galaxy according to the luminosity-metallicity relationship. For GRB 020903 Hammer *et al.* (2006) derive $12+\log(\mathrm{O/H})=8.0$, using the effective temperature method. That method has a significant offset from the Kewley and Dopita (2002) scale, so using the published values of line fluxes in Table 1 of Hammer *et al.* (2006) we apply the prescription of Kewley and Dopita (2002) and obtain $12+\log(\mathrm{O/H})=8.4$. If we were instead to use the formula from the very recent work of Kewley and Ellison (in preparation) to convert from the effective temperature method to the Kewley and Dopita (2002) method, we would add an offset of $+0.4$ dex, in excellent agreement with the previous value. We therefor adopt the final value of oxygen abundance of 8.4 for the host of GRB 020903.

Table 1

Properties of the local GRBs/SNe and their hosts

GRB SN	980425 1998bw	020903 ...	030329 2003dh	031203 2003lw	060218 2006aj
z (redshift)	0.0085[i]	0.251[b,h]	0.1685[i]	0.1055[i]	0.0335[f]
E_{iso} $[10^{50}$ erg]	0.01 ± 0.002[a]	0.28 ± 0.07[a]	180 ± 21[a]	0.26 ± 0.11[g]	0.62 ± 0.1[c]
M_B (host)	-17.65[i]	-18.8[b]	-16.5[d]	-19.3[g]	-15.86[f]
12+log(O/H)	8.6[i]	8.4[e,j]	7.9[d,j]	8.2[i]	8.0[f]

References: (a) Amati (2006), (b) Bersier *et al.* (2006), (c) Campana *et al.* (2006), (d) Gorosabel *et al.* (2005), (e) Hammer *et al.* (2006), (f) Modjaz *et al.* (2006), (g) Prochaska *et al.* (2004), (h) Soderberg *et al.* (2005), (i) Sollerman *et al.* (2005), (j) this work

For comparison, we also mark the locations of the Milky Way (including a box to indicate the range due to the metallicity gradient, Carigi *et al.* 2005, Esteban *et al.* 2005) and the Small and Large Magellanic Clouds (Skillman, Kennicutt and Hodge 1989) based on measurements of individual H II regions (we use the values of M_B from Arachnids 2005). According to Esteban *et al.* (2005), the value of $12+\log(\mathrm{O/H})$ for the Solar circle is 8.70 ± 0.05. While in our main analysis we directly compare nebular oxygen abundance between the Tremonti *et al.* (2004) sample and the GRB hosts, when referring to "Solar metallicity", we adopt the Solar oxygen abundance of $12+\log(\mathrm{O/H})=8.86$ (Delahaye and Pinsonneault 2006).

It is indeed striking, that all of the local GRB hosts lie at substantially lower metallicity than the vast majority of local galaxies in the SDSS sample. We quantify this result in Section 3.

Note that we use the oxygen abundance values as derived from the R_{23} relationship by Kewley and Dopita (2002), to be consistent with the literature and to obtain the best relative values of the oxygen abundance. Since different calibrations of the R_{23} diagnostic have systematic differences of up to 0.2 dex at these low abundances (see *e.g.*, Nagao *et al.* 2006, Kewley and Ellison, in preparation), we decided to consistently use the same technique in comparing the GRB hosts amongst themselves. In addition, the recent work by Kewley and Ellison (in preparation) shows that applying the method of Kewley and Dopita (2002) to the Tremonti *et al.* (2004) SDSS sample results in very good agreement between the two methods, *i.e.*, basically the Tremonti *et al.* (2004) sample is effectively on the Kewley and Dopita (2002) abundance scale. We should stress that our overall conclusion that the local GRBs only occur in metal-poor galaxies does not depend on the exact choice of R_{23} calibration, because the GRB hosts so clearly happen only in low-metallicity galaxies.

3. Star Formation and Stellar Mass of GRB Hosts

How improbable are the low oxygen abundances of the five low-redshift GRB hosts? We test that under two "null hypothesis", one that GRBs trace star formation, second that stellar GRBs trace star mass, in both cases independently of metallicity. We address this question with a Monte Carlo test, by combining the Bell *et al.* (2003) measurement of the galaxy stellar mass function from the 2MASS and SDSS surveys with the correlations of stellar mass with metallicity and star formation rate (SFR) measured for SDSS galaxies by Tremonti *et al.* (2004) and Kauffmann *et al.* (2004), Brinchmann *et al.* (2004), respectively.

The distribution of stellar masses, M, of galaxies in the local Universe can be fit by a Schechter (1976) function, $\phi(M)\,\mathrm{d}M \propto (M/M^*)^{\alpha} \exp(-M/M^*)\,\mathrm{d}M$. This distribution is measured for galaxy masses $M > 10^9$ $\mathrm{M}_{\odot}$. We have converted Bell *et al.*'s (2003) M^* value from their "diet Salpeter" IMF to the Kroupa (2001) IMF used in the SDSS analysis, and we have adopted the value of the Hubble constant $H_0 = 70$ km/(s·Mpc). All galaxies in the sample have the characteristic mass $M^* \approx 10^{10.85}$ $\mathrm{M}_{\odot}$ and the slope $\alpha = -1.1$, while late-type only galaxies have $M^* \approx 10^{10.65}$ $\mathrm{M}_{\odot}$ and $\alpha = -1.27$. The latter galaxies are closer match to the star-forming galaxies considered in the other studies that we use below. This sample of late-type galaxies is also appropriate for testing the hypothesis that GRBs trace star formation.

The mean stellar mass-metallicity relation of Tremonti *et al.* (2004) has the form

$$12 + \log(\mathrm{O/H}) = -1.492 + 1.847 \log M - 0.08026\,(\log M)^2 \qquad (1)$$

with the quoted scatter about the mean of 0.1 dex. According to Tremonti *et al.* (2004) this fit is valid in the stellar mass range $8.5 < \log M/\mathrm{M}_{\odot} < 11.5$. We fit Brinchmann *et al.*'s (2004) relation between SFR and M by the broken power-law

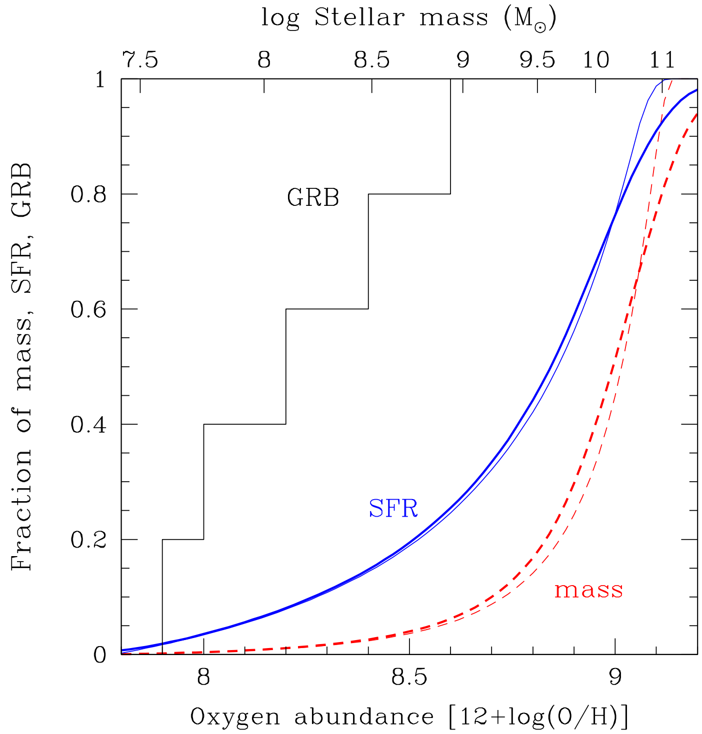

Fig. 2. Cumulative fractions of total star formation (solid lines) and total stellar mass (dashed lines) in late-type galaxies with the oxygen abundance below a given $12+\log(\mathrm{O/H})$. Thick lines show the results of Monte Carlo realizations that include the estimated intrinsic scatter of the mass-metallicity and mass-SFR relations. Thin lines show the results if there was no scatter. Solid histogram is the cumulative metallicity distribution of the five GRBs. Top horizontal axis shows the corresponding scale of the galaxy stellar masses (Eq. 1).

form

$$\log \mathrm{SFR}(M) = 0.7 + \beta\,(\log M - 10.5) \qquad (2)$$

with slope $\beta = +0.6$ for $\log M < 10.5$, where SFR is in units of $\mathrm{M}_\odot$/yr. Eq. (2) is an eyeball fit to the data in Fig. 17 of Brinchmann *et al.* (2004) in the mass range $7 < \log M/\mathrm{M}_\odot < 11$, from which we also estimate a 1σ scatter of 0.3 dex about the mean relation. At higher masses, $10.5 < \log M < 11.5$, Brinchmann *et al.* (2004) find approximately constant SFR ($\beta \approx 0$), while Kauffmann *et al.*'s (2004) Fig. 7 indicates a significant downturn ($\beta \approx -0.6$). In the following, we consider the high-mass slope $\beta = -0.6$ as standard and the other ($\beta = 0$) as a variation, and treat the difference in inferred results as a systematic uncertainty associated with the mass-metallicity modeling.

We use the above relations to calculate a fraction of stellar mass and star formation rate contained in galaxies with metallicities below those of the GRB hosts. We generate Monte Carlo realizations of 10^6 galaxies with stellar masses drawn from the Bell *et al.* (2003) mass function. We have extrapolated this mass function below its last measured point, down to $10^{7.4}$ $\mathrm{M}_\odot$, which corresponds to the average metallicity $12+\log(\mathrm{O/H}) \approx 7.8$, in order to include all GRBs in our sample. However, this is a conservative assumption since without this extrapolation the mass and SFR fractions at low metallicity would be even smaller. For each galaxy, we draw a metallicity and an SFR from Eq. (1) and Eq. (2), assuming log-normal scatter of 0.1 dex and 0.3 dex, respectively. Note that we assume uncorrelated scatter between these two quantities at fixed M. To the extent that the observational inputs are correct, this sample should have the same joint distribution of mass, star formation rate, and metallicity as real galaxies in the low-z Universe.

The thick solid curve in Fig. 2 shows the cumulative relation between star formation rate and oxygen abundance in the Monte Carlo sample, *i.e.*, the fraction of star formation in late-type galaxies with oxygen abundance below the value on the x-axis. The thick dashed curve shows the corresponding cumulative relation for stellar mass instead of star formation. The thin solid and dashed curves show the star formation and stellar mass relations, respectively, if we ignore scatter and use just the mean Eq. (1) and Eq. (2). In this case, the fractions can be written analytically as $f_{\mathrm{SFR}} = \int_0^{M_{\mathrm{O/H}}} \mathrm{SFR}(M)\,\phi(M)\,\mathrm{d}M / \int_0^{\infty} \mathrm{SFR}(M)\,\phi(M)\,\mathrm{d}M$ and $f_{\mathrm{mass}} = \int_0^{M_{\mathrm{O/H}}} M\phi(M)\,\mathrm{d}M / \int_0^{\infty} M\phi(M)\,\mathrm{d}M$, where $M_{\mathrm{O/H}}$ is the average mass corresponding to the metallicity $12+\log(\mathrm{O/H})$ *via* Eq. (1). Our Monte Carlo sample without the intrinsic scatter gives identical results to these analytical expressions.

The histogram in Fig. 2 shows the cumulative oxygen abundance distribution of the five low-z GRBs, which is clearly very different from that of star-forming galaxies. In order to quantify the statistical significance of this discrepancy, we have generated new 10^6 trials of selecting five "hosts" randomly from the metallicity distribution function given by the SFR fraction (thick solid line). To their chosen metallicities we add an estimated observational error, assuming it to be log-normal with the standard deviation of 0.1 dex. The maximum abundance among the five selected hosts satisfies $12+\log(\mathrm{O/H})) \leq 8.6$ only $p_{\mathrm{max}} = 0.13\%$ of the time. We also find that the median abundance of the five hosts satisfies $12+\log(\mathrm{O/H}) \leq 8.2$ only $p_{\mathrm{med}} = 0.5\%$ of the time. Note that the median test may be sensitive to our extrapolation of the Tremonti *et al.* (2004) relation below the range $12+\log(\mathrm{O/H}) \geq 8.5$ constrained by the data. Had we not taken into account the scatter of the mass-metallicity or mass-SFR relations, the resulting probabilities would be even lower. If we draw model galaxies from the mass function of all (not only late-type galaxies), the probabilities are at least a factor of 10 lower. We have also used a standard Kolmogorov-Smirnov test with a sample size $N=5$. The KS probability of the observed GRB metallicities being drawn from the SFR distribution is 0.32%, consistent with our Monte Carlo result, while the probability of being drawn from the mass distribution is only 0.008%.

Our results are not sensitive to the variation of the high-mass slope of the mass-star formation rate relation. If we take $\beta = 0$ at $\log M > 10.5$, the probabilities

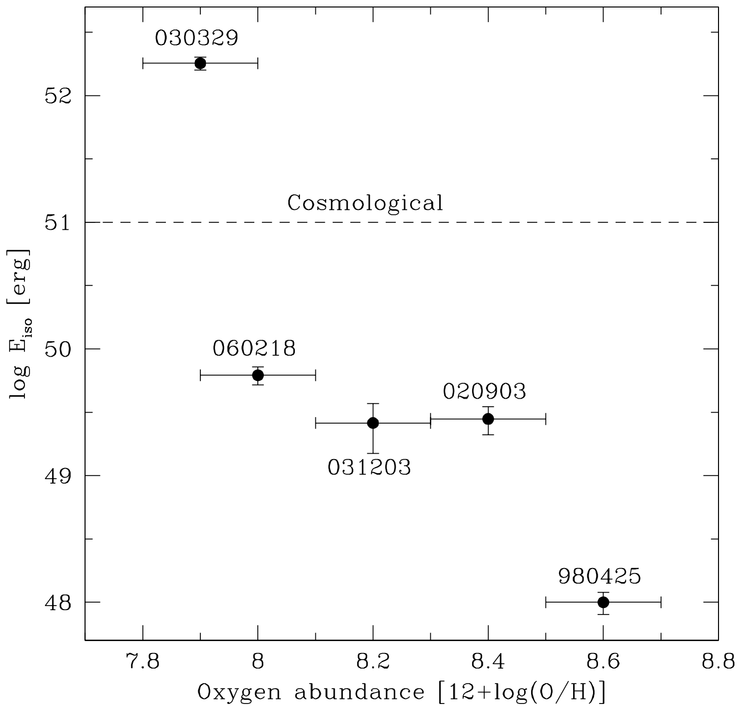

Fig. 3. Isotropic energy release in γ-rays, $E_{\rm iso}$, for the five local GRBs plotted *vs.* the oxygen abundance of their hosts. A strong dependence of $E_{\rm iso}$ on $12+\log(\mathrm{O/H})$ seems to be present, with a possible threshold for making "cosmological" GRBs at $12+\log(\mathrm{O/H})=8.0$, *i.e.,* about 0.15 of the Solar oxygen abundance. With dashed line at $E_{\rm iso}=10^{51}$ erg we indicate the approximate limit for "cosmological" long GRBs (see Table 1 in Amati 2006).

change only slightly and shift only towards smaller values. The results of our models are summarized in Table 2.

Finally, we consider the most conservative scenario that our oxygen abundance determination of GRB hosts is systematically off by up to 0.2 dex with respect to Tremonti *et al.*'s (2004) values. We add $+0.2$ dex to the maximum and median GRB metallicities (now 8.8 and 8.4, respectively) and recalculate the Monte Carlo probabilities. These new probabilities are of course not as small as for our fiducial metallicities, but nevertheless low. The maximum abundance is satisfied only in 2% of the cases and the median in less than 3% of the cases. Note that we consider this arbitrary shift as an extreme scenario and that we believe our GRB metallicities to be correct as described in Section 2 and given in Table 1.

We conclude that even this fairly small sample of low-z GRB hosts is sufficient to show that GRBs do not trace the overall star formation in the local Universe (and do no trace mass at extremely high confidence). Instead, GRBs arise preferentially in the lowest metallicity systems. In Fig. 1 it is striking that GRB 031203, which has the brightest host galaxy, resides in a system that is extremely metal-poor com-

Table 2

Monte Carlo probabilities

Model	p_{max}	p_{med}
"standard"	0.0013	0.0051
flat SFR	0.0012	0.0047
+0.2 dex shift	0.020	0.028

Probabilities of the GRB hosts tracing overall star formation (independently of metallicity).

pared to other galaxies of its luminosity. Equally intriguing is the trend for brighter GRBs to occupy the lowest metallicity hosts. Fig. 3 illustrates this point directly, plotting the isotropic $\gamma-$ray energy release E_{iso} against $12+\log(O/H)$ (for an earlier, indirect attempt to correlate E_{iso} with host metallicity see Fig. 1 in Ramirez-Ruiz *et al.* 2002). The low energies of the low-z GRBs have been discussed by many authors ever since the discovery of GRB 980425. In principle the low values of E_{iso} could arise from beaming effects, with the proximity of the bursts allowing us to see them further off-axis, but Cobb *et al.* (2006) argue persuasively against this interpretation. If E_{iso} is reasonably representative of the true energetics of these low-z GRBs, then Fig. 3 suggests that there may be a threshold for producing truly "cosmological" GRBs that are bright enough to be seen to high redshift, at an oxygen abundance $12+\log(O/H)\approx 8.0$, roughly 0.15 of the Solar abundance. We caution that this trend is rather speculative given the current data, unlike the main result of our of paper, *i.e.*, that local GRBs occur only in metal-poor galaxies.

4. Discussion

Our findings for local GRBs are in qualitative agreement with the studies showing that high-redshift GRBs reside in underluminous galaxies (*e.g.*, Le Floc'h *et al.* 2003, Fruchter *et al.* 2006). The advantage of studying the local sample is that we can focus directly on metallicity, which appears to be the critical physical parameter, and we can compare the GRB host metallicities to those measured in local star-forming galaxies. The arguments in Section 2 and Section 3 indicate that long GRBs occur only in low metallicity environments, and therefore do not occur in "normal" galaxies that are comparable to the Milky Way in mass and metallicity. This has a number of implications, some of which have been discussed independently by Langer and Norman (2006) based on an entirely different line of argument involving higher-z GRBs.

Our results agree well with recent theoretical work on GRB progenitors. The collapsar model, where the GRB is created by an accretion disk around a rotating black hole, requires the core angular momentum of the progenitor to be dynamically important at the time of collapse. This requirement sets severe limits on core angular momentum loss, which would normally accompany the substantial mass loss associated with the Wolf-Rayet stars thought to be the progenitors of typical Type Ic supernovae. Two viable channels have been proposed, both of which avoid the red supergiant phase. First, interactions with a close binary companion can strip the envelope too rapidly for the core to be spun down (see Podsiadlowski *et al.* 2004 for a detailed discussion). Second, a single star that rotates rapidly enough can experience fully mixed evolution (Yoon and Langer 2005, Woosley and Heger 2006) and avoid the red supergiant phase entirely. The latter mechanism also avoids core contraction during the hydrogen and helium burning phases, which would further shield the core from angular momentum loss associated with magnetic fields (Spruit 2002, however, see Denissenkov and Pinsonneault 2006). With either of these mechanisms, however, GRBs would not be expected for high iron abundances because of strong mass and angular momentum loss during either the main sequence or the Wolf-Rayet phase (Heger and Woosley 2002). Yoon and Langer (2005) and Woosley and Heger (2006) estimate that an iron abundance of about 0.1 Solar is a maximum threshold for such a mechanism. The existence of a strong metallicity threshold therefore provides support for recent theoretical models of the formation of long GRBs, and with better statistics we may be able to distinguish between the different formation channels.

The iron abundance is more important than the oxygen abundance in this regard because iron provides much of the opacity for radiation-driven stellar winds (*e.g.,* Pauldrach, Puls and Kudritzki 1986). Our use of oxygen as a proxy for metallicity may therefore underestimate the significance of the abundance trends that we observe. The earliest generations of stars are known to be enhanced in [O/Fe] relative to the Solar mixture (Lambert, Sneden and Ries 1974). It is therefore likely that the GRB host galaxies are even more iron-poor than they are oxygen-poor. The specific frequency of Wolf-Rayet stars relative to O stars is an order of magnitude higher in high metallicity spirals than it is in systems such as the SMC (Maeder and Conti 1994). Since normal Type Ic supernovae are associated with Wolf-Rayet progenitors, the low metallicity of the five local GRB hosts is even more significant, as Type Ic supernovae in general trace metal-rich star formation.

An upper limit on metallicity for long GRBs has a number of other consequences. GRBs are unlikely to be a source of cosmic rays in the Milky Way (a possibility discussed by, *e.g.,* Dermer 2002), and they can play only a limited role in cosmic ray production in the low-redshift Universe. Searches for GRB remnants in nearby large galaxies (*e.g.,* Loeb and Perna 1998) are expected to yield few, if any, detections. We also argue that asymmetric supernovae remnants observed in the Milky Way did not result from recent GRB explosions (*e.g.,* Fesen *et al.* 2006, Laming *et al.* 2006). It also follows that late-time non-detections of radio emission from local core-collapse supernovae (*e.g.,* Soderberg *et al.* 2006), while providing interesting constraints on their physics, do not provide information on the beaming or circumstellar environments of GRBs. These core-collapse SNe are most likely located in higher metallicity galaxies that are unlikely to produce a GRB.

A GRB occurring in the last billion years within a few kiloparsecs from Earth has been invoked as a possible cause for a mass extinction episode (*e.g.,* Thomas *et al.* 2005a,b). Our results make this scenario most unlikely – by the time the Earth formed, the Milky Way disk was already too metal-rich to host a long GRB. SN 1998bw/GRB 980425, the only local event to happen in a fairly metal-enriched galaxy, was also by far the weakest localized GRB ever, with at least 10 000 times lower energy than a typical $z \approx 1$ GRB. As such, it would not cause mass extinction at several kpc from Earth. The same can be said about short GRBs, which are not only less frequent than long GRBs (*e.g.,* Kouveliotou *et al.* 1993), but also less energetic and less beamed (*e.g.,* Grupe *et al.* 2006, Panaitescu 2006). Short GRBs are also not concentrated to star-forming regions, thus on average they are much further away from any life-hosting planets (*e.g.,* Bloom and Prochaska 2006). In addition, planet-hosting stars are on average even more metal rich than the Sun (*e.g.,* Santos, Israelian and Mayor 2004), making long GRBs an even less likely source of life extinction events in the local Universe. So to finish with a bit of good news, we can probably cross GRBs off the rather long list of things that could cause humankind to "join the dinosaurs" on the extinct species list.

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