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

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ABSTRACT

The host galaxies of the four local, $z < 0.17$, long-duration gamma-ray bursts (GRBs 980425, 030329, 031203 and 060218), each of which had an associated hypernova studied with optical spectroscopy, 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 ($< 20\%$) of current star formation occurs in galaxies with oxygen abundance $12 + \log{(O/H)} < 8.6$, i.e., about half that of the Milky Way. However, all four 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 four hosts would be $P \approx 0.15\%$. 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 four GRBs, E_{iso}, steeply decreases with increasing host oxygen abundance, further indicating that (low) metallicity plays a fundamental physical role in the GRB phenomenon, and suggesting an upper metallicity limit for "cosmological" GRBs at $\sim 0.15\ Z_\odot$.

Subject headings: gamma-rays: bursts

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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 $z \sim 1$ 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 four low redshift ($z < 0.17$) GRBs that have been directly identified with Type Ic 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 four 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, $z = 0.17$, corresponds to about half 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 four 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 four 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., Woosley & 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 & Norman 2006). We discuss several implications of this result. We also find that the $\gamma-$ray isotropic energy release, $E_{\rm iso}$, for these four 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 & Longhetti (2001). These models cast the nebular line strengths in terms of effective galaxy properties. In other words, 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 5500Å 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

Table 1: Properties of the Local GRBs/SNe and their Hosts

GRB	980425	030329	031203	060218
SN	1998bw	2003dh	2003lw	2006aj
z (redshift)	0.0085^f	0.1685^f	0.1055^f	0.0335^d
$E_{\rm iso}$ (10^{50} erg)	0.010 ± 0.002^a	180 ± 21^a	0.26 ± 0.11^e	0.62 ± 0.1^b
M_B (host)	-17.65^f	-16.5^c	-19.3^e	-15.86^d
$12+\log[{\rm O/H}]$	8.6^f	$7.9^{c,g}$	8.2^f	8.0^d

References: (a) Amati (2006); (b) Campana et al. (2006); (c) Gorosabel et al. (2005); (d) Modjaz et al. (2006); (e) Prochaska et al. (2004); (f) Sollerman et al. (2005); (g) this work
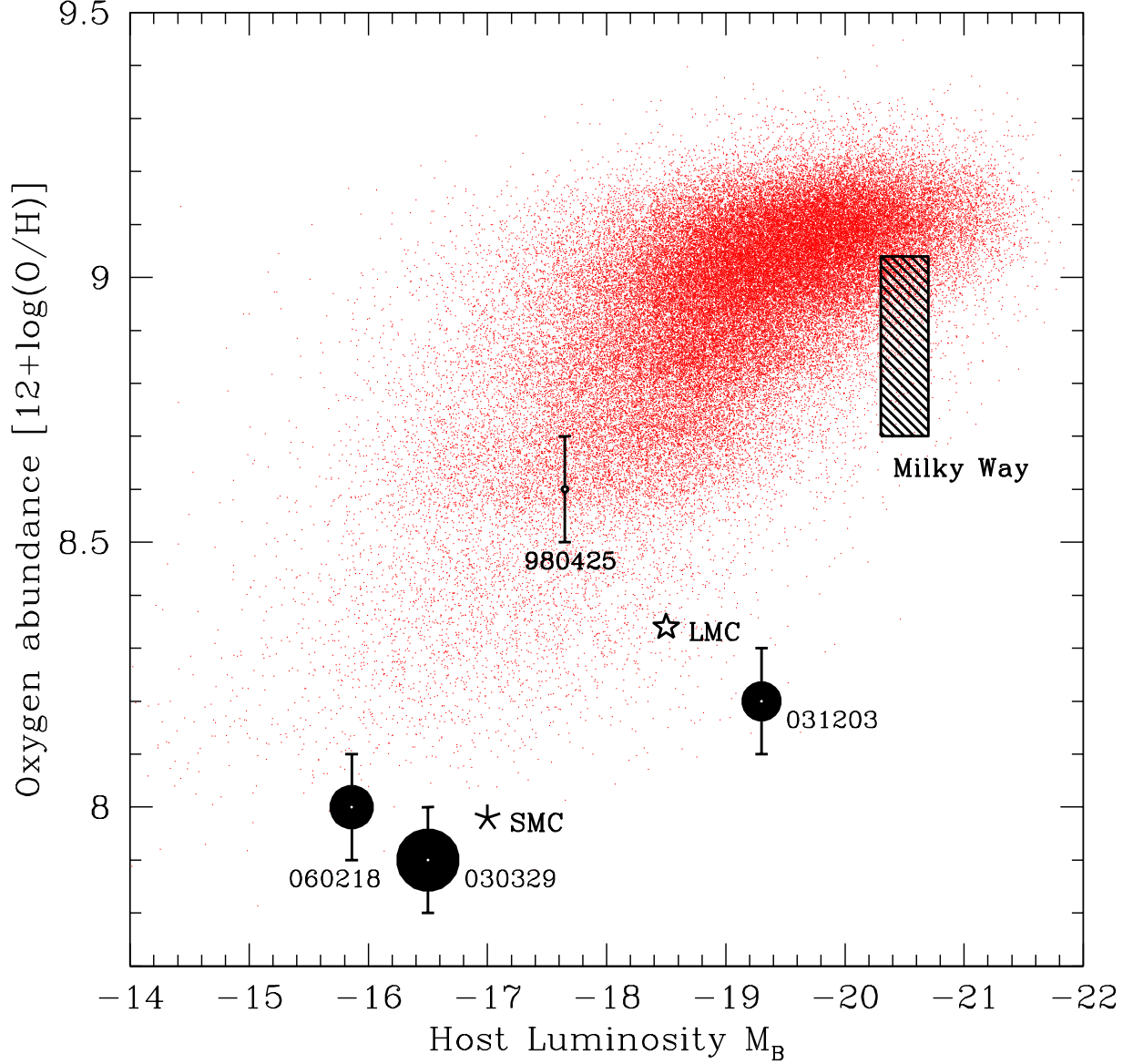
Fig. 1.— Four low-z GRB/SN hosts (filled circles) and local star forming galaxies (small points: Tremonti et al. 2004; Tremonti 2006, private communication) in the host luminosity-oxygen abundance diagram. For comparison we also show the Milky Way, the LMC and the SMC. It is clear that local GRB hosts 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 $\sim 1.0 \times 10^{48}$ erg for GRB 980425 to $\sim 2.0 \times 10^{52}$ erg for GRB 030329.

distribution is taken to be the error on the metallicity. Figure 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 Figure 1 mark the locations of three previous GRB/SN hosts (SN 1998bw, SN 2003dh, SN 2003lw) with values of M_B and $12 + \log{(\mathrm{O/H})}$ 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 $12 + \log{(\mathrm{O/H})} = 8.0$ and sub-SMC luminosity (Modjaz et al. 2006). The symbol areas for the GRB points in Figure 1 are scaled with isotropic γ-ray energy release $\log{E_{\mathrm{iso}}}$ for each burst (see Table 1), ranging from $\sim 1.0 \times 10^{48}$ ergs for GRB 980425 to $\sim 2.0 \times 10^{52}$ erg for GRB 030329. There seems to be a progression of E_{iso} towards lower energies with increasing oxygen abundance, which we will discuss later in the paper. As discussed in Sollerman et al., the applied R_{23} metallicity diagnostic (following Kewley & 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. and Gorosabel et al. (2005), we consult Nagao, Maiolino & Marconi (2006) who point to another emission line diagnostic, namely [O III]$\lambda 5007$/[O II]$\lambda 3729$, that can give leverage in distinguishing between the two branches. According to Nagao et al., 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 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 & Hodge 1989) based on measurements of individual HII regions. 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. 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 & 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 the next Section.

Note that we use the oxygen abundance values as derived from the R_{23} relationship by Kewley & Dopita (2002), to be consistent with the literature. 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), we decided to consistently use the same technique in comparing the GRB hosts amongst themselves and to the local galaxies in the Tremonti et al. sample. We should stress that our conclusions do not depend on the choice of R_{23} calibration, and were we to use the Nagao et al. (2006) prescription, the oxygen abundances for GRB 030329 and 060218 would be even lower, and our result even more significant.

3. Star Formation and Stellar Mass of GRB Hosts

How improbable are the low oxygen abundances of the four low-redshift GRB hosts, under the "null hypothesis" that GRBs trace star formation or stellar mass 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), respectively.

The distribution of stellar masses, M, of galaxies in the local Universe can be fit by a Schechter (1976) function, $\phi(M)dM \propto (M/M^*)^{\alpha} \exp{(-M/M^*)}dM$, with the slope $\alpha = -1.1$ and characteristic mass $M^* \approx 10^{10.85} M_{\odot}$. This distribution is measured for galaxy masses $M > 10^9 M_{\odot}$. We have converted Bell et al.'s 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^{-1} Mpc^{-1}.

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

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

and the estimated scatter about the mean is only 0.1 dex. According to Tremonti et al., this fit is valid in the stellar mass range $8.5 < \log M/M_{\odot} < 11.5$. We fit Kauffmann et al.'s (2004) relation between SFR and M by the broken power-law form

$$\log \mathrm{SFR}(M) = -0.1 + \beta \, (\log M - 10.5), \qquad (2)$$

with slope $\beta = +0.5$ for $\log M < 10.5$, and $\beta = -0.6$ for $\log M > 10.5$, where SFR is in units of $M_{\odot}$ yr^{-1}. Equation (2) is an eyeball fit to the data in Fig. 7 of Kauffmann et al. (2004) in the mass range $9.3 < \log M/M_{\odot} < 11.3$, from which we also estimate a 1σ scatter of 0.15 dex about the mean relation.
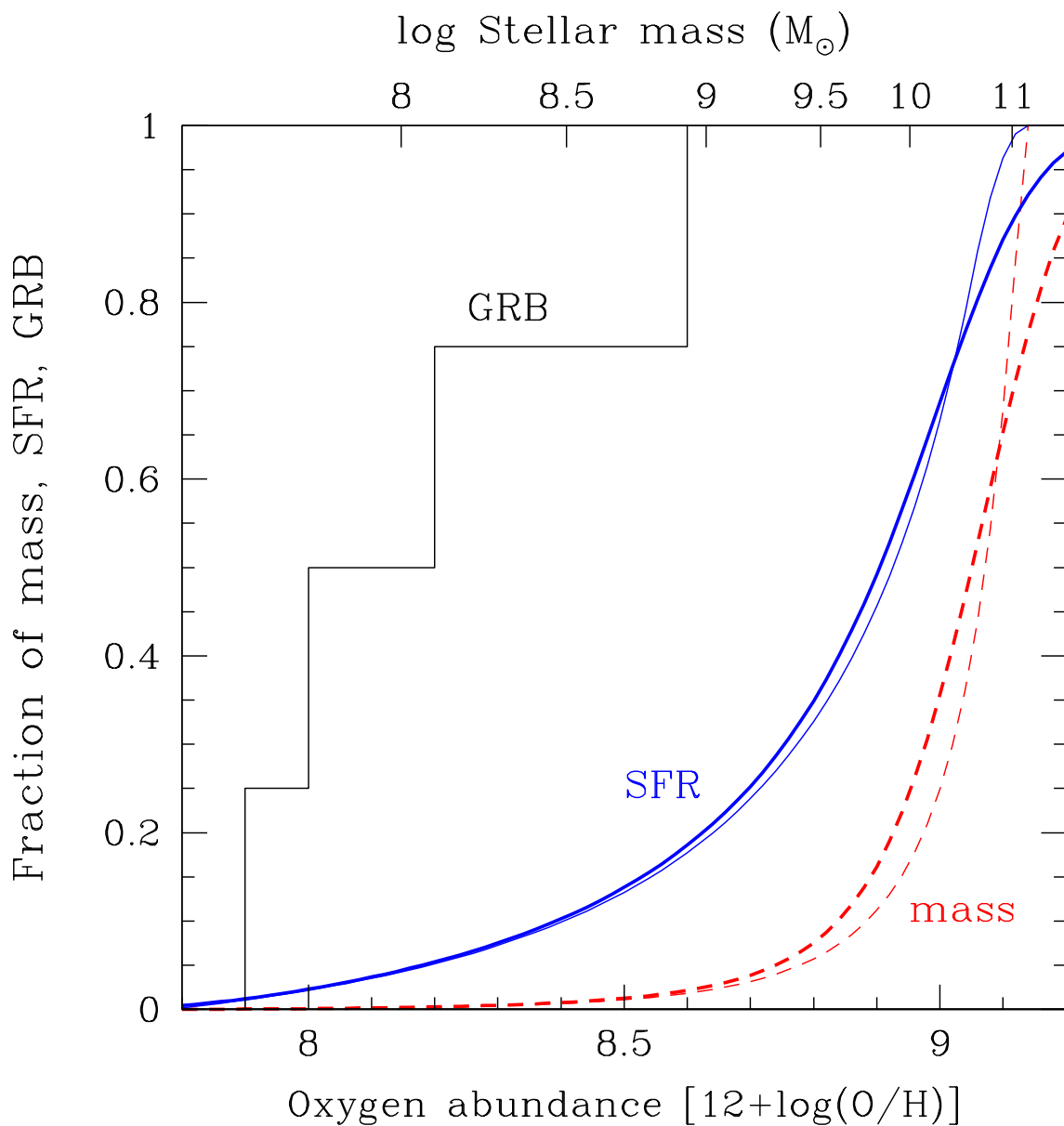
Fig. 2.— Cumulative fractions of total stellar mass (dashed lines) and total star formation (solid lines) in galaxies below a given oxygen abundance $12 + \log{(O/H)}$. The thick lines show the results of Monte Carlo realizations that include the estimated intrinsic scatter of the mass-metallicity and mass-SFR relations. The thin lines show the results if there was no scatter. The solid histogram is the cumulative metallicity distribution of the four GRBs. The top horizontal axis shows the corresponding scale of the galaxy stellar masses (Eq.1).

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 a Monte Carlo realization 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 $10^{7.4} M_\odot$, which corresponds to the average metallicity of $12 + \log{(O/H)} \approx 7.8$, in order to include all GRBs in our sample. 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 the relations (1) and (2), assuming log-normal scatter of 0.1 dex and 0.15 dex, respectively. Note that we assume uncorrelated scatter between these two quantities at fixed M. To the extent that the observational inputs are correct (they are also extrapolated beyond the measured mass range), 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 Figure 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 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 relations (1) and (2). In this case, the mean fractions can be expressed analytically as $f_{\mathrm{SFR}} = \int_0^{M_{O/H}} \mathrm{SFR}(M)\,\phi(M)dM / \int_0^\infty \mathrm{SFR}(M)\,\phi(M)dM$ and $f_{\mathrm{mass}} = \int_0^{M_{O/H}} M\phi(M)dM / \int_0^\infty M\phi(M)dM$, where $M_{O/H}$ is the average mass corresponding to the metallicity $12 + \log{(O/H)}$ via relation (1). Our Monte Carlo sample without the intrinsic scatter gives identical results to these analytical expressions.

The histogram in Figure 2 shows the cumulative oxygen abundance distribution of the four 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 10^6 trials of selecting four "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 four selected hosts satisfies $12 + \log{(O/H)} \leq 8.6$ only 0.15% of the time. We also find that the median abundance of the four hosts (more precisely, the average of the two central values) satisfies $12 + \log{(O/H)} \leq 8.1$ only 0.05% of the time. While the median test yields the strongest result, it may be sensitive to our extrapolation of the Tremonti et al. (2004) and Kauffmann et al. (2004) relations below the range $12 + \log{(O/H)} \gtrsim 8.5$ 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. Finally, we have used a standard Kolmogorov-Smirnov test with a sample size $N = 4$. The KS probability of the observed GRB metallicities being drawn from the SFR distribution is 0.24%, while the
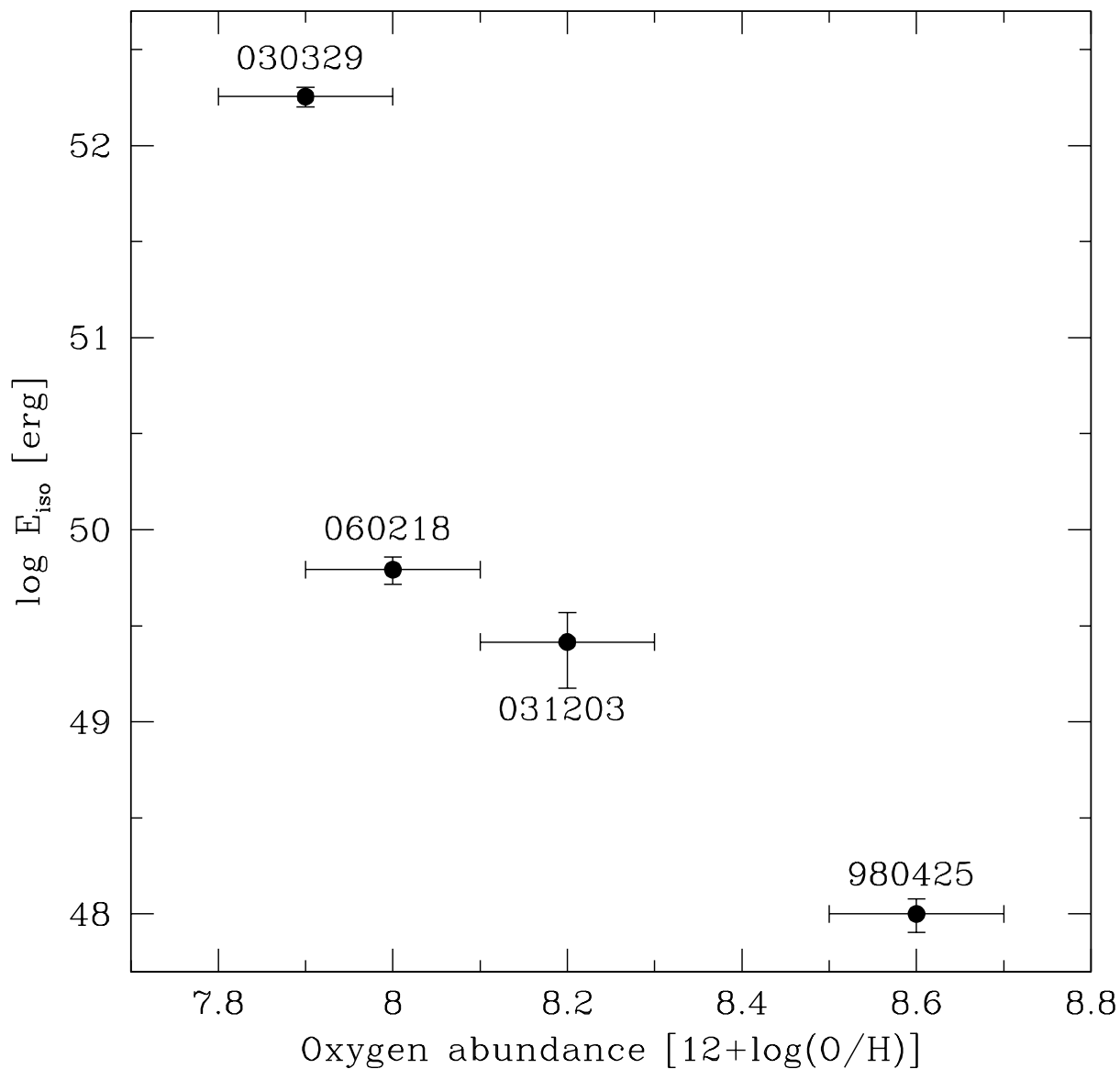
Fig. 3.— Isotropic energy release in γ-rays, E_{iso}, for the four local GRBs plotted vs. the oxygen abundance of their hosts. A strong dependence of E_{iso} on $12 + \log{(\mathrm{O/H})}$ seems to be present, with a possible threshold for making "cosmological" GRBs at $12 + \log{(\mathrm{O/H})} = 8.0$, i.e., about 0.15 of the Solar oxygen abundance.

probability of being drawn from the mass distribution is less than 10^{-6}.

We conclude that even this small sample of low-z GRB hosts is sufficient to show that GRBs do not trace star formation, or the stellar mass, in the local Universe. Instead, GRBs appear to arise preferentially in the lowest metallicity systems. In Figure 1, it is striking that GRB 031203, which has by far the brightest host galaxy, resides in a system that is extremely metal-poor compared to other galaxies of its luminosity. Equally intriguing is the trend for brighter GRBs to occupy the lowest metallicity hosts. Figure 3 illustrates this point directly, plotting the isotropic $\gamma-$ray energy release $E_{\rm iso}$ against $12 + \log{(\rm O/H)}$. 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 $E_{\rm iso}$ 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 $E_{\rm iso}$ is reasonably representative of the true energetics of these low-z GRBs, then Figure 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 $12 + \log{(\rm O/H)} \sim 8.0$, roughly 0.15 of the Solar abundance.

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 §2 and §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 & 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 (Woosley & 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 & 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 & Woosley 2002). Woosley & Heger (2006) estimate that an iron abundance of about 0.1 Solar is a maximum threshold for their 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, & Kudritzki 1986). Our use of oxygen as a proxy for metallicity may threfore 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 & 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 & Conti 1994). Since normal Type Ib/Ic supernovae are associated with Wolf-Rayet progenitors, the low metallicity of the four local GRB hosts is even more significant, as Type Ib/c 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 & 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 $z \sim 1$ 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 & Prochaska 2006). In addition, planet-hosting stars are on average even more metal rich than the Sun (e.g., Santos, Israelian & 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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