ON THE ORIGIN OF THE MASS–METALLICITY RELATION FOR GAMMA-RAY BURST HOST GALAXIES

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ABSTRACT

We investigate the nature of the mass–metallicity ($M-Z$) relation for long gamma-ray burst (LGRB) host galaxies. Recent studies suggest that the $M-Z$ relation for local LGRB host galaxies may be systematically offset toward lower metallicities relative to the $M-Z$ relation defined by the general star-forming galaxy (Sloan Digital Sky Survey, SDSS) population. The nature of this offset is consistent with suggestions that low-metallicity environments may be required to produce high-mass progenitors, although the detection of several GRBs in high-mass, high-metallicity galaxies challenges the notion of a strict metallicity cutoff for host galaxies that are capable of producing GRBs. We show that the nature of this reported offset may be explained by a recently proposed anticorrelation between the star formation rate (SFR) and the metallicity of star-forming galaxies. If low-metallicity galaxies produce more stars than their equally massive, high-metallicity counterparts, then transient events that closely trace the SFR in a galaxy would be more likely to be found in these low-metallicity, low-mass galaxies. Therefore, the offset between the GRB and SDSS defined $M-Z$ relations may be the result of the different methods used to select their respective galaxy populations, with GRBs being biased toward low-metallicity, high-SFR, galaxies. We predict that such an offset should not be expected of transient events that do not follow as closely the star formation history of their host galaxies, such as short duration GRBs and Type Ia supernova, but should be evident in core-collapse supernovae found through upcoming untargeted surveys.

Key words: galaxies: star formation – gamma rays: general

Online-only material: color figures

1. INTRODUCTION

Investigations of the environments in which gamma-ray bursts (GRBs) occur has long been an important path to understand the nature of their progenitors. The observations of long (LGRB) host galaxies show that they tend to be bluer, fainter, and later type than $M_*$ galaxies at similar redshifts. Spectroscopic observations of host galaxies have also shown that they tend to be metal poor. A detailed comparison between the metallicity at the sites of broad-lined Type Ic supernova (SN Ic) that have been associated with GRBs and the site of SN Ic with no detected gamma-ray emission found that the chemical abundance of SN-GRB hosts were systematically lower than the hosts of SN without GRBs (Modjaz et al. 2008). This metallicity difference raised the possibility of a upper limit to the metallicity of a galaxy that can produce a GRB.

Recently, Han et al. (2010) and Levesque et al. (2010) compared the mass–metallicity ($M-Z$) relation for long GRB host galaxies to samples from the Sloan Digital Sky Survey (SDSS) representative of the general star-forming galaxy population (Tremonti et al. 2004). Using a small sample of five host galaxies, Han et al. (2010) found that the metallicities of the host galaxies tended to fall below the low redshift $M-Z$ relation defined by SDSS catalog. Likewise, Levesque et al. (2010) compared a much broader sample of LGRB host galaxies and found a similar offset, with LGRB host galaxies exhibiting lower metallicities compared to SDSS galaxies of similar masses.

The relative nature of this metallicity offset for a given host mass, along with a small but growing number of high-mass, high-metallicity host galaxies presented by Levesque et al. (2010) and other studies (Fynbo et al. 2008), challenge the notion of a sharp metallicity threshold (Modjaz et al. 2006; Kocevski et al. 2009) for the host galaxies that are capable of producing LGRBs. Moreover, without such a strict low-metallicity criteria for the generation of GRB progenitors, the reason of the preference of GRBs to occur in environments with relatively lower chemical enrichment remains unclear.

In this Letter, we examine the $M-Z$ relation for GRB host galaxies by investigating the effects of a recently proposed anticorrelation between the galaxy’s star formation rate (SFR) and its metallicity. We show that such a connection between the SFR and chemical enrichment of a galaxy would naturally explain the systematic offsets reported by Han et al. (2010) and Levesque et al. (2010). If low-metallicity galaxies produce more stars than their equally massive, high-metallicity counterparts, then it would be expected that transient events that closely trace the star formation history of their host galaxies would be more likely to occur in these high-SFR, low-metallicity galaxies. We test this hypothesis by modeling the $M-Z$ relation for LGRBs using a combination of data from the SDSS-DR7 catalog and model prescription for the SFR–Z relation in Section 2. We compare our model predictions to published host mass data in Section 3 and we discuss the implications of our results in Section 4.

2. MODEL PRESCRIPTIONS

In order to investigate the nature of the metallically offset in the $M-Z$ relation for LGRB host galaxies, we must consider the difference between the probability distributions for the metallicity of a galaxy drawn from the general star-forming population and a galaxy that is likely to harbor an LGRB. For the general star-forming population, the metallicity probability distribution $P(Z)$ for a galaxy of a given stellar mass $M_*$ is simply the normalized metallicity distribution $\phi(Z, M_*)$ of all star-forming galaxies at that mass. Therefore, the most likely metallicity of a galaxy drawn randomly from the star-forming population will reflect the peak of $\phi(Z, M_*)$. The most likely metallicity of a galaxy selected because of the
occurrence of an LGRB is quite different. For host galaxies, any metallicity dependence on the probability of the transient event, \( P_{\text{LGRB}}(Z, M_*) \), must be taken into consideration. In such a case, the resulting LGRB metallicity distribution would reflect the product of the metallicity distribution for all star-forming galaxies and this metallicity dependent probability distribution, \( P_{\text{Host}}(Z) \sim \phi(Z, M_*) \cdot P_{\text{LGRB}}(Z, M_*) \).

The metallicity dependence on the probability of the transient event can represent a number of different theoretical considerations. It could reflect, for example, the metallicity dependence on the likelihood that a star would possess the physical conditions required to produce a GRB. Conversely, it could even reflect a hypothetical, metallicity-dependent, observational bias. In this Letter, we focus on the metallicity dependence of a galaxy’s SFR as the primary contributor to \( P_{\text{LGRB}}(Z, M_*) \).

Because the production (and death) of massive stars is closely linked to the ongoing star formation in a galaxy, we assume that a higher SFR in a galaxy will result in a greater likelihood for the occurrence of an LGRB. Therefore we set \( P_{\text{LGRB}}(Z, M_*) \sim \text{SFR}(Z, M_*) \). Here we are assuming that an equal fraction of stars being produced, in both low- and high-SFR galaxies, contribute to the production of massive LGRB progenitors. Likewise, for the purposes of this analysis, we make the explicit assumption that galaxies of all metallicities are equally likely to produce a GRB.

In order to model the \( M-Z \) relation for GRB host galaxies, we must convolve the \( \phi(Z) \) and \( P_{\text{LGRB}}(Z) \) probability distributions and find the peak of the resulting \( P_{\text{Host}}(Z) \) distribution for a range of galaxy masses. This requires adopting prescriptions for both \( \phi(Z) \) and \( \text{SFR}(Z) \) as a function of galaxy mass. We can measured \( \phi(Z) \) directly through the use of data from the MPA/JHU catalog\(^3\) from SDSS-DR7.\(^4\) This catalog includes stellar masses and emission-line estimates for over 927,552 galaxies, providing a wealth of information regarding galaxy demographics in the local universe. The metallicity values presented in the catalog reflect oxygen abundance estimates based on a statistical method discussed in Tremonti et al. (2004). We also utilize the catalog’s stellar masses, obtained through broadband fits SDSS photometry, and SFR estimates based on the technique discussed in Brinchmann et al. (2004).

For the purposes of our model, we selected emission-line galaxies with a redshift cut of 0.005 < \( z < 0.30 \) for which stellar mass estimates were possible. For the remaining galaxies, we set a threshold to the signal-to-noise ratio \((S/N)\) of H\(\alpha\) of \(S/N > 5\) in order to insure reliable metallicity estimates. Metallicities for active galactic nuclei are not reported in the catalog and hence are not included in our sample. Our final sample contains 155564 galaxies.

For an analytic description of \( \text{SFR}(Z) \), we turn to Mannucci et al. (2010), where the authors quantified a trend between SFR and metallicity using the SDSS-DR7 MPA/JHU catalog at redshifts between 0.07 and 0.30 (see Lara-López et al. 2010 for a similar result). They find that for all \( \log(M_*) < 10.7, \) SFR increases with decreasing metallicity at constant mass (e.g., see their Figure 1, Mannucci et al. (2010)). They provide a 4th-order polynomial fit to the observed SFR–\( Z \) relation, although for the purposes of our analysis we have reworked their expression into a power-law model attenuated by an exponential in order to extrapolate their original fit below \( \log(\text{SFR}) < -1 \) and above \( \log(\text{SFR}) > 1 \). Our empirical model for the prescription of \( Z(\text{SFR}, M_*) \) can be expressed as

\[
12 + \log(O/H)_{\text{T84}} = \log_{10} \left[ \text{SFR}^\alpha \exp(-\tau \cdot \text{SFR}) \right] + \beta, \quad (1)
\]

where \( \alpha, \beta, \) and \( \tau \) represent an \( M_*/M_\odot \) dependent power-law index, metallicity offset, and attenuation coefficient, respectively. These parameters can be expressed as

\[
\alpha = (M_*/M_\odot - \alpha_{\text{offset}})/\alpha_{\text{norm}}, \quad (2)
\]

\[
\beta = \ln(M_*/M_\odot - \beta_{\text{offset}})/\beta_{\text{norm}}, \quad (3)
\]

\[
\tau = (M_*/M_\odot - \tau_{\text{offset}})/\tau_{\text{norm}}, \quad (4)
\]

where \( \alpha_{\text{offset}} = 11.45, \alpha_{\text{norm}} = 11.15, \)

\[
\beta_{\text{offset}} = 7.90, \beta_{\text{norm}} = 10.20, \quad (6)
\]

\[
\tau_{\text{offset}} = 11.10, \tau_{\text{norm}} = -46.67. \quad (7)
\]

With such a prescription, the power-law index \( \alpha \), metallicity offset, and the attenuation coefficient all decrease with increasing \( M_*/M_\odot \), matching the results presented in Mannucci et al. (2010). Our analytic model is presented in Figure 1 for several different values of \( \log(M_*/M_\odot) \) between 9.25 \( \leq \) \( \log(M_*/M_\odot) \leq 11.35 \).

3. RESULTS

Using the subset of data from MPA/JHU catalog, we can obtain \( \phi(Z) \) for effectively a constant mass by selecting all galaxies within a narrow \( M_*/M_\odot \) range. For example, in Figure 2, we show the normalized \( \phi(Z) \) (blue histogram) selected for all galaxies between \( 9.9 < \log(M_*/M_\odot) < 10.1 \) \( \phi(Z) \), totaling 20450 galaxies. The peak of this distribution represents the median metallicity for a star-forming galaxy in the MPA/JHU catalog for \( \log(M_*/M_\odot) \sim 10.0 \pm 0.1 \). We can then calculate the median metallicity of a galaxy likely to host a GRB by weighting \( \phi(Z, M_*) \) by \( \text{SFR}(Z, M_*) \) and finding the peak of the resulting probability distribution \( P_{\text{Host}}(Z, M_*) \). The normalized \( P_{\text{Host}}(Z, M_*) \) distribution is shown in Figure 2 (red histogram). The peak of the \( P_{\text{Host}}(Z, M_*) \) distribution has shifted to lower metallicities because of the greater weight given to low-metallicity galaxies due to their higher SFR compared to their higher metallicity counterparts.

We calculate the median of the \( \phi(Z) \) and \( P_{\text{Host}}(Z) \) distributions for a range of \( \log(M_*/M_\odot) \) values between 8.0 < \( \log(M_*/M_\odot) < 11.0 \) and plot the results in Figure 3. The red circles represent the predicted median GRB host galaxy metallicity as a function of \( \log(M_*/M_\odot) \), effectively producing an SFR weighted \( M-Z \) relation that is shifted to lower metallicities compared to the \( M-Z \) relation for the general star-forming galaxy population. The vertical error bars represent the 1σ spread in the underlying \( P_{\text{Host}}(Z) \) distribution. The offset between the SFR weighted and general \( M-Z \) relations is roughly \( \sim 0.3 \) at \( \log(M_*/M_\odot) \sim 9.0 \) and \( \sim 0.15 \) at \( \log(M_*/M_\odot) \sim 11.0 \).

We compare our modeled SFR weighted \( M-Z \) relation to the mass and metallicity of a subset of GRB host galaxies selected from Levesque et al. (2010). Because Levesque et al. (2010) report their metallicity values in the diagnostic presented in Kobulnicky & Kewley (2004, KK04), we convert their reported

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\(^3\) http://www.mpa-garching.mpg.de/SDSS

\(^4\) http://www.sdss.org/dr7
values to the T04 system using the conversion tables provided in Kewley & Ellison (2008). Since this conversion is not defined for all metallicities, we selected a subsample of four host galaxies below \( z < 0.3 \) that fell within the metallicity range for which this conversion was possible.

We find that both the predicted SFR weighted \( M-Z \) relation and the GRB host data are shifted toward lower metallicities than the general \( M-Z \) when considering the errors in both mass and metallically. In addition, the decrease in the offset between the SFR weighted and general \( M-Z \) relations is consistent with the trend reported by Levesque et al. (2010) in which the metallicities of high-mass host galaxies are more consistent with the general \( M-Z \) relation compared to their low-mass counterparts. Although we point out that this trend is characterized by a single galaxy presented in Levesque et al. (2010) and requires additional detections of GRBs in massive galaxies to confirm.

Nonetheless, all four galaxies systematically fall below our predicted model. We return to the implications of this discrepancy in the next section.

4. DISCUSSION

The possibility of a correlation between the chemical enrichment and the rate of star formation in a galaxy may begin to explain the relative nature of the offset reported by Levesque et al. (2010), without the need of an absolute metallicity cutoff. If low-metallicity galaxies tend to produce more stars than their high-metallicity counterparts for a given stellar mass, then the likelihood of detecting a transient event linked to a massive, short lived progenitor from within a low-metallicity galaxy will increase accordingly. Therefore the nature of the offset of the GRB defined \( M-Z \) relation toward lower metallicity could largely be explained as a bias toward finding transient events in galaxies with relatively higher SFRs.

Several studies have already indicated that LGRBs do tend to occur in galaxies with higher specific star formation than typical star-forming galaxies at similar redshifts (Christensen et al. 2004; Savaglio et al. 2009). We illustrated this in Figure 4, where we plot the SFR versus \( M_\star/M_\odot \) for all 155,564 galaxies in...
Figure 3. $M-Z$ relation for the general star-forming population between $0.005 < z < 0.30$, with the color coding representing the absolute SFR. The blue diamonds represent the median $M-Z$ relation presented in Tremonti et al. (2004) with the dashed and dotted lines representing the contours which include 68% and 95% of the data, respectively. The red circles represent our predicted median GRB host galaxy metallicity as a function of $\log(M_*)$, effectively producing an SFR weighted $M-Z$ relation which is shifted to lower metallicities. The vertical error bars represent the $1\sigma$ spread in the underlying $P_{\text{host}}(Z)$ distribution. The blue circles represent the mass and metallicity of GRB host galaxies selected from Levesque et al. (2010) for which a conversion between the KK04 and T04 metallicity diagnostics was possible.

(A color version of this figure is available in the online journal.)

Figure 4. SFR vs. $M_*/M_\odot$ for all 155564 galaxies in our SDSS sample along with six galaxies presented in Levesque et al. (2010) and two galaxies from (Savaglio et al. 2009) that fell below $z < 0.3$. The color gradient represents the galaxy metallicities.

(A color version of this figure is available in the online journal.)

our SDSS sample along with six galaxies presented in Levesque et al. (2010) and two galaxies from (Savaglio et al. 2009) that fell below $z < 0.3$. The color gradient represents the metallicity of the SDSS galaxies and the expected trend of increasing SFR and metallicity as a function of galaxy mass is clearly evident. All eight of the low redshift LGRB hosts under consideration occupy the upper left of the SFR–$Z-M_*/M_\odot$ plot, having SFRs that are substantially larger than the mean SDSS sample for their galaxy mass. These few galaxies illustrate the degree to which these host galaxies have SFRs that exceed the star formation activity of similar galaxies.

A bias toward finding transient events in high-SFR galaxies alone does not explain why LGRBs occur in small to intermediate size galaxies as opposed to the most massive galaxies, which typically have much higher absolute rates of star formation. To understand the mass distribution of LGRB host galaxies, we must consider the number of galaxies as a function of mass (the galaxy mass function). Although high-mass galaxies produce far more stars than their low-mass counterparts, it has long been known that dwarf galaxies represent the largest fraction of galaxies in the local universe (Bell et al. 2003). As a result, the SFR weighted galaxy mass function, i.e., the galaxy mass at which most of the star formation is occurring at a given redshift, peaks at intermediate masses. Therefore the fact that we do not see LGRBs occurring predominately in the most massive, highly star forming, galaxies is not in contradiction to the
suggestion that transient selected galaxies are biased toward high-SFR environments.

In Kocevski et al. (2009) we compared the mass distribution of GRB host galaxies to the SFR weighted galaxy mass function. Using a similar argument as we have in this Letter, we modeled the SFR weighted galaxy mass function for a variety of redshifts by convolving prescriptions for the galaxy mass function $\phi(M_*/M_\odot)$ at a given redshift with the SFR as a function of stellar mass. We found that the SFR weighted mass function at $z = 1$ peaks at roughly $\log(M_*/M_\odot) \sim 10.3$. The measured median stellar mass of LGRB host galaxies reported by Savaglio et al. (2009) for the same redshift is slightly lower, roughly $\log(M_*/M_\odot) \sim 9.3$.

We interpreted this discrepancy as evidence for a metallicity cutoff in which the SFR weighted galaxy mass function would be truncated due to the relationship between a galaxy’s mass and metallicity. This would result in a host mass distribution which would be shifted to lower masses. Such a metallicity cutoff may not be necessary if in fact low-mass, low-metallicity galaxies produce more stars than their high-metallicity counterparts. In such a scenario, the SFR weighted galaxy mass function would be shifted to lower masses without the need of a metallicity cutoff due to the additional weight given to low-mass, low-metallicity galaxies. The effects of a SFR–$Z$ relation for low-mass galaxies was not taken into account in the analysis performed by Kocevski et al. (2009) and a full examination of the effects of the correlation on the resulting joint mass and metallicity distributions will be reserved for a future paper.

Although we have shown that a metallicity dependance on the SFR of low-mass galaxies can in fact produce an $M$–$Z$ relation offset to lower metallicities, the mass and metallicity data taken from Levesque et al. (2010) nonetheless systematically fall below our modeled $M$–$Z$ relation. Within the context of our model, this discrepancy may be evidence for a further bias in the probability of LGRBs to occur in relatively low-metallicity environments beyond the metallicity dependent SFR that we have considered. This would indicate that $P_{\text{LGRB}}(Z, M_*)$ may be more complex than we had originally assumed. An additional metallicity bias, such as a sharp increase in $P_{\text{LGRB}}(Z, M_*)$ with decreasing metallicity due to a metallicity dependance on the physical conditions required to produce a GRB, could account for the discrepancy between our modeled $M$–$Z$ relation and the observed host galaxies. In the framework of the collapsar model, low-metallicity progenitors would retain more of their mass due to the reduction of line-driven stellar winds (Vink & Koter 2005), and hence preserve more of their angular momentum and stellar mass at the time of collapse (Woosley & Heger 2006). This mechanism may play an important role to the production of collimated emission that is thought to be required to produce LGRBs, although the observation of GRBs associated with SN Ib/c events certainly complicates the general collapsar model, e.g., Woosley & Bloom (2006).

Therefore, although the observations of several high-mass, high-metallicity LGRB host galaxies may rule out a strict metallicity “cutoff,” the discrepancy between the host galaxy data measured by Levesque et al. (2010) and our modeled $M$–$Z$ relation may point to further metallicity biases in the LGRB sample. These biases need only to reflect a decreasing likelihood of a GRB occurrence as a function of increasing metallicity in order to provide a mechanism to further shift the LGRB defined $M$–$Z$ relation to lower metallicities. Such biases would compound the effect introduced through the simple metallicity-dependent SFR prescription that we have assumed in our model and as such there would be no need for a strict metallicity “cutoff” to explain the relative preference for LGRBs to occur in low-metallicity environments.

Finally, our work predicts that core-collapse SNe found through untargeted surveys such as the Palomar Transient Factory, Pan-Starrs, and the Large Synoptic Survey Telescope should also define an $M$–$Z$ relationship that is shifted to lower metallicities compared to the general star-forming galaxy population. Such an effect should not be expected of transient events that do not follow as closely the star formation history of their host galaxies, such as short duration GRBs and SN Ia events. If subsequent observations of SN II and Ibc host galaxies found through these surveys do not show such an offset, then the shift in the GRB defined $M$–$Z$ relation would necessarily be a physical effect intrinsic to GRBs and not due to the SFR–$Z$ selection bias that we propose.

Addendum: The authors would like to note that Mannucci et al. (2011) have also reported on the implications of the SFR–$Z$ correlation on the metallicity distribution of long GRB host galaxies. Their work largely draws the same conclusions as those presented here. Using a broad sample of 18 GRB host galaxies with $z < 1.0$ and measured metallicities, they confirm that long GRB host galaxies systematically lie below the $M$–$Z$ relation for SDSS selected galaxies. They find that this trend can be explained by the increased SFR exhibited by lower metallicity galaxies compared to higher metallicity galaxies of the comparable mass and that GRB hosts need not be drawn from a special, low-metallicity, population of galaxies. Our results differ in that the we show that an additional bias must be present to explain the degree of offset between the GRB host galaxies and the $M$–$Z$ relation.

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Kocevski & West