A CONSTANT LGRB METALLICITY DISTRIBUTION ACROSS REDSHIFTS $z < 2.5$

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ABSTRACT

Recent improvements in the population of Long-duration Gamma Ray Burst (LGRB) host galaxies with measured metallicities and host masses allows us to investigate how the distributions of both these properties change with redshift. First we exclude, out to $z < 2.5$, strong redshift dependent populations biases in mass and metallicity measurements. We then find a curious consistency in the metallicity distribution across different redshifts. This is at odds with the general evolution in the mass metallicity relation of typical galaxies, which become progressively more metal poor with increasing redshift at constant mass. By converting the measured LGRB host masses and redshifts to expected metallicities for a typical galaxy of each such mass and redshift, we further find that the increase in LGRB host galaxy mass distribution with redshift seen in the Perley et al. (2016) SHOALS sample is consistent with that needed to preserve the observed, non-evolving LGRB metallicity distribution. However the estimated LGRB host metallicity distribution is approximately a quarter dex higher than the measured metallicity distribution at all redshifts. This corresponds to about a factor of two in raw metallicity and resolves much of the difference between the LGRB formation metallicity cutoff of about a third solar in Graham & Fruchter (2017) with the cutoff value of solar claimed in Perley et al. (2016) in favor of the former. As LGRB hosts do not follow the general mass metallicity relation, there is no substitute for actually measuring their metallicities!

Keywords: gamma-ray burst: general

1. INTRODUCTION

Upon collecting the first samples of the galaxies hosting Long-softGamma-Ray Bursts (LGRBs) it was apparent that LGRBs occur in blue, highly starforming, and often irregular galaxies with a preponderance that clearly separated them from the general galaxy population (Fruchter et al. 1999, 2006; Le Floc’h et al. 2003, 2002; Christensen et al. 2004; Le Floc’h et al. 2006; Savaglio et al. 2009). The seminal work of Fruchter et al. (2006) compared the hosts of LGRBs with those of Core-Collapse Supernovae (CCSNe) found in the Great Observatories Origins Deep Survey (GOODS) and found that while half of the GOODS CCSNe occurred in grand design spirals (with the other half in irregulars), only one out of the 18 LGRB host galaxies of a comparable redshift distribution was in a grand design spiral. This comparison with SNe allowed Fruchter et al. (2006) to establish that this difference was beyond that expected from a sample of galaxies drawn randomly according to their rate of star formation.

As the Initial Mass Function (IMF) of blue irregular and spiral galaxies are thought to be largely similar (Bastian et al. 2010), massive stellar progenitors should be just as available per unit star-formation in both galaxy types. However, the much smaller size of blue irregulars would suggest, due to the galaxy mass-metallicity relation (Tremonti et al. 2004), that blue irregular galaxies are typically metal poor in comparison with grand design spirals. Thus Fruchter et al. (2006) postulated that LGRB formation is affected by the metallicity of their environments.

Stanek et al. (2007) showed that the very nearest LGRB hosts all have low metallicity when compared to similar magnitude galaxies in the Sloan Digital Sky Survey (SDSS). Furthermore, Kewley et al. (2007) found the LGRB host sample to be comparable to extremely metal-poor galaxies in luminosity-metallicity relation, star-formation rate (SFR), and internal extinction. Modjaz et al. (2008) dramatically strengthened this result by taking advantage of the fact that a broad-lined Type Ic (Ic-bl) supernova has been found underlying the light of nearly (Thöne et al. 2014) every LGRB in which a deep spectroscopic search was performed (Cano 2014; Hjorth & Bloom 2012; Hjorth 2013). The fact that LGRBs nearly always are associated with a Type Ic-bl SNe would suggest that LGRB progenitors probably have similar masses to those of regular Type Ic-bl SNe, thus largely eliminating the possibility that the observed LGRB metallicity bias is somehow a byproduct of a difference in the initial stellar mass functions. Modjaz et al. (2008) showed that Ic-bl SNe with associated LGRBs are observed to occur in host galaxies with much lower metallicities than either the hosts of Type Ic-bl SNe without associated LGRBs or the bulk of the star-forming galaxies in the SDSS. However, beginning with LGRB 051022 (Graham et al. 2009), some LGRBs were found to be located in host galaxies with a high metallicity (near-solar and above) but this accounted for only a small fraction of the LGRB population. The dramatic metallicity difference between both the star-formation weighted SDSS and non-engine driven SNe verses LGRB samples suggested a metallicity dependent step in either the formation of the gamma-ray jet or in its ability to escape the progenitor which has either burned or lost its outer hydrogen and helium layers (Woosley 1993; Woosley & Bloom 2006; Langer & Norman 2006).

To understand how LGRBs seem to have a metallicity aversion despite the existence of counterexamples, Graham & Fruchter (2013) compared the metallicity distribution of the hosts of LGRBs with that of the hosts of several similar indicators of star-formation: LGRBs, Type Ic-bl, and Type II SNe as well as with the metallicity distribution of star-formation in the general galaxy population of the local universe. Graham & Fruchter (2013) found that three quarters of the LGRB host population have metallicities below $12 + \log(O/H) < 8.6$ (in the Kobulnicky & Kewley 2004 KK04 metallicity scale),
while less than a tenth of local star-formation is at similarly low metallicities. However, the supernovae were statistically consistent with the metallicity distribution of star-formation in the general galaxy population. While the LGRB sample did extend to higher redshifts than the other populations the observed metallicity difference was far too great to be a product of metallicity evolution. Graham & Fruchter (2013) concluded that a low metallicity environment must be a fundamental component of the evolutionary process that forms LGRBs.

Graham & Fruchter (2017) expanded on the analysis of Graham & Fruchter (2013) by comparing the metallicity distribution of LGRB host galaxies to the that of star forming galaxies in the local universe. By effectively dividing one distribution by the other, Graham & Fruchter (2017) was able to directly determine the relative rate of LGRB formation as a function of metallicity in the low-redshift universe. They found a dramatic cutoff in the LGRB formation rate per unit star-formation above a metallicity of log(O/H) + 12 ≈ 8.3 (in the Kobulnicky & Kewley 2004 scale), with LGRBs forming between ten and fifty times more frequently per unit star-formation below this cutoff than above.

Krühler et al. (2015) performed a detailed analysis of 96 LGRB host galaxies with ESO Very Large Telescope (VLT) X-Shooter emission-line spectroscopy, providing the largest spectroscopic sample of LGRB host galaxies and comprising most of the publicly available data at the time. Krühler et al. (2015) finds that at $z < 1 \sim 20\%$ of their LGRB host galaxies have super-solar metallicities a result comparable with Graham & Fruchter (2013). Krühler et al. (2015) concludes that the properties of LGRB hosts can be explained by the tendency of LGRB events to avoid metal-rich environments.

Vergani et al. (2015) estimated the host stellar masses of the 14 $z < 1$ BAT6 (Salvaterra et al. 2012) host galaxies via spectral energy distribution (SED) fitting and found that those LGRBs tend to avoid massive galaxies in preference for faint low-mass star-forming galaxies typically below galaxy survey completeness limits. Vergani et al. (2015) estimates that with a metallicity threshold in LGRB production (of between $\frac{1}{2}$ to $\frac{1}{2}$ solar) the typical galaxy mass distribution would then reproduce that of the LGRB host galaxy population (i.e. primarily a reduction in the high-mass end of the distribution).

In a similar analysis, Perley et al. (2016) used Spitzer rest-frame near-IR (NIR) luminosity observations to calculate masses for 82 LGRB host galaxies from the Swift GRB Host Galaxy Legacy Survey (SIOALS) and also use the distribution of these masses to estimate a metallicity threshold. However Perley et al. (2016) estimates the metallicity threshold to be much higher at “approximately the solar value.” They also find that dust-obscured LGRBs dominate the massive host population while little dust is seen in low-mass hosts and that host metallicity has little impact on LGRB production at $z > 1.5$ while preventing most LGRB events at lower redshifts.

Here (in subsubsection 3.2.1) we will fully exploit the new larger emission-line metallicity LGRB host galaxy sample of Krühler et al. (2015) (in concert with the Graham & Fruchter 2013 sample) to examine how the LGRB metallicity distribution changes with redshift. First however (in subsection 3.1) we will analyze and address the redshift biases of the different LGRB populations as this is necessary to validate our samples. Also (in subsubsection 3.2.2), in order to test the validity in the general approach of using galaxy mass to estimate LGRB host metallicities, we will compare our observed LGRB metallicity distributions (as a function of redshift) with the expected metallicity distribution for galaxies with the mass and redshift the LGRB population.

2. METHODS

2.1. Sample selection

2.1.1. Host Metallicities

The vast majority of LGRB host galaxy emission-line metallicity measurements are contained in either the Graham & Fruchter (2013) sample or the X-Shooter observations compiled in Krühler et al. (2015). The objects of the later sample are heavily dominated by observations of Hjorth et al. (2012): The Optically Unbiased Gamma-Ray Burst Host Survey (TOUGHS). TOUGHS is a homogeneous sample of 69 Swift GRB hosts selected via their bursts high-energy properties and locations on the sky and not dependent on the optical properties of the galaxies observed. Krühler et al. (2015) was able to obtain hosts metallically measurements for 44 objects [count again], or about 3 times the previous sample of Graham & Fruchter (2013). Furthermore the X-Shooter’s integrated IR spectroscopic channel extends the redshift overage of the LGRB host metallicity sample out to $z = 2.47^1$. In combination Krühler et al. (2015) and Graham & Fruchter (2013) provide a sample of sufficient size and redshift range to allow division into different redshift bins as necessary to study the evolution of the LGRB metallicity distribution with redshift as we will do here.

Two objects overlap between the samples (LGRBs 050824 and 051022) whose measured metallicity values differ by 0.23 and 0.31 dex between the Graham & Fruchter (2013) and Krühler et al. (2015) estimates respectively. In the combined sample the duplication has been removed and the flux measurements from the Krühler et al. (2015) spectroscopy used. Note that the metallicity values and relative measured line fluxes for the host of LGRB 051022 have been noted to be significantly different before, potentially due to as yet unresolved differences in the metallicity across the galaxy (Graham et al. 2015). We have removed LGRB 020819B from our sample due to the revised host galaxy association of Perley et al. (2017) and the poor metallicity constraint on the now correctly associated host galaxy.

2.1.2. Host Masses

While neither the Graham & Fruchter (2013) or Krühler et al. (2015) provide host galaxy masses or even have the required IR observations required for such mass measurements, the Perley et al. (2016) SIOALS sample does. Unfortunately the Perley et al. (2016) SIOALS sample has a paucity of objects at low redshift (only 3 at $z < 0.5$) so we supplement it with the Svensson et al.

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1 This is discounting GRB 120118B with a redshift of $z = 2.94$ due to use of the [Ne III] method for breaking R21 metallicity degeneracy which should never be applied to LGRB hosts (Graham & Fruchter 2013)
population which is predominately at $z < 1$ and also has mass values based on deep IR observations. Two objects overlap between the samples (LGRBs 060218 and 080319B) whose log masses differ by 0.24 and -0.43 between the Svensson et al. (2010) and Perley et al. (2016) estimates respectively. In our combined sample the duplication has been removed and the Perley et al. (2016) values used.

2.2. Metallicity Determination

Here we use metallicities determined via the $R_{23}$ diagnostic in the Kobulnicky & Kewley (2004) (KK04) scale. The $R_{23}$ method is the primary metallicity diagnostic for galaxies at $z > 0.3$ (especially those where the faint [O III] 4363 Å line is not measurable). The $R_{23}$ diagnostic is based on the electron temperature sensitivity of the oxygen spectral lines, achieved via using the ratio of the oxygen line strength to a spectral feature independent of oxygen spectral lines, achieved via using the ratio of the measured line ratios (using $R_{23} = \frac{I_{[OIII]} + I_{[OII]} + I_{H\beta}}{I_{[NII]} + I_{H\beta}}$) and then compared along an [O III] to [O II] line ratio contour against the best calibration data available. This classical application however treats ionization as a parameter independent of metallicity and ignores the feedback the latter has on the former. Kewley & Dopita (2002) solve this issue by using iterative fitting to dynamically factor the effects of the metallicity on the ionization parameter.$^2$

2.3. Distribution Analysis

One of the most powerful tools for understanding the behavior of GRBs and SNe is to study the distribution of such events with respect to a physical property. Fruchter et al. (2006) compared the location distribution of LGRB and ccSNe events on their host galaxies with the distribution of the blue light in their hosts. The result was that, while core collapse supernovae follow the blue light distribution of their host galaxies, LGRBs showed a strong preference for occurring in the brightest regions of their hosts. This suggested that, while ccSNe are unbiased tracers of the available star-formation, LGRBs likely favor very massive progenitors which are concentrated in the most star forming regions of their host galaxies. Stanek et al. (2007) compared the metallicity distribution of LGRBs and SDSS galaxies to show that nearby LGB hosts have low metallicities when compared to similar magnitude Sloan galaxies.

These methods employ normalized cumulative evenly spaced step-functions to track the distributions of the objects. This approach works well for objects such as LGRBs and SNe whose detection is proportionate to their event rate. Galaxy samples however have massive Malmquist biases and the individual galaxies are themselves dissimilar. To allow for direct meaningful comparison between the metallicity distribution of LGRBs and galaxies Graham & Fruchter (2013) first converted the SDSS to a volume limited sample with a tight redshift cut and then weighted the galaxies by their star-formation rate. The result was a weighted step-function for the galaxy population with a varying step height. The LGRBs showed a strong preference for low metallicities while the SNe populations tracked the star-formation weighted volume limited galaxy sample.

Here we are tasked with the need to compare a variety of different LGRB populations (composed of LGRB samples with different measured physical properties) to

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$^2$ For a more detailed description of our metallicity calculation methodology we refer the reader to Graham & Fruchter (2013). For a more detailed description of the advantages and accuracy of the iterative fitting approach we refer the reader to Kewley & Dopita (2002). For readers who wish to calculate their own metallicities we refer them to the excellent newer metallicity code of Bianco et al. (2016) which is capable of determining metallicities using a range of different diagnostics and scales (note that this code is not used in this paper due solely to our desire to retain full constancy with Graham & Fruchter 2013). For the solar metallicity value in the KK04 scale we refer the reader to the Allende Prieto et al. (2001) estimated of log(O/H)+12 = 8.69 ± 0.05 based on solar 6300 Å [O I] line measurement. It should be noted that while the emission line diagnostics can be cross calibrated due to the large number of H II regions upon which multiple diagnostics can be applied (Kewley & Ellison 2008) this is not true of the density-sensitive 6300 Å [O I] line measurement where the line strength is insufficient for widespread application. Thus any absolute reference to the solar value should be considered very approximate and detailed scientific comparisons to emission line metallicities in terms of solar fractions should be avoided. For conversions to other metallicity scales and a discussion of associated issues we refer the reader to the transforms of Kewley & Ellison (2008). For a general introduction to the $R_{23}$ diagnostic we refer the reader to Pagel et al. (1979, 1980).
excluded redshift dependent selection biases from contaminating our further analysis. Normalized cumulative distribution plots would ordinarily be ideal for such a task except that the differing physical properties have different redshift ranges where they can be observed and different rates of observation (e.g. metallicity measurement requires spectroscopy of certain lines thus having redshift limitations and spectroscopy is an expensive use of telescope time). To examine the extent to which the samples we consider in this paper suffer from different selection effects we therefore employ cumulative distribution plot with a manual weighting for each population so as to scale the populations to an arbitrary level at a designated redshift. In this work, we will adopt $z \approx 2.5$ for such a designated redshift as it is the approximate end of the redshift range for which we have metallicity measurements. For populations that do not reach the designated redshift we scale the weighting to achieve the best congruence with the other populations. We also adjust the weightings of all the populations as needed to favor a common congruence.

This is a manual process, as the goal is to produce a distribution plot where deviation of congruence is reflective of redshift dependent selection biases. While a program to estimate a scaling values that minimizes the area between two curves could be used instead, the advantage of doing the scaling by hand it that when the samples agree to a point and then diverge this can be shown in a physically meaningful way. This human touch allows for choosing scaling values that work sensibly, and where a best fit area minimizing value is not ideal for comparison, the author can adjust accordingly.

For a more strict comparison we also calculate KS values (which do not require such a scaling factor). However the graphical manually scaled approach allows us to know where biases are present in our data, and after achieving an understanding of their causes we can estimate their effects on our analysis. One critical limitation of this process is it requires having redshift data and is therefore insensitive to biases in measuring the redshifts of our targets. To attempt to correct for this we also include a similar scaling of a theoretical LGRB distribution using the results of Graham & Schady (2016). Since we cannot exclude a redshift bias in the Graham & Schady (2016) results (i.e. inducing an error in the metallicity evolution history of the universe) this is not a perfect solution.

We then also use normalized cumulative distribution plots with a uniform step height to track the metallicity distribution of LGRB hosts within various redshift bins. This ability to break the sample into different redshift bins is enabled by the enlarged LGRB host metallicity galaxy population, however this analytical method has been used previously.

3. ANALYSIS

3.1. Redshift Distribution

Before we can explore the metallicity distribution of LGRBs as a function of redshift we need to account for the effect of redshift on the completeness of the differing LGRB populations. To achieve this we cumulatively plot the redshifts of the different LGRB populations scaled by an arbitrary factor such that the distributions agree as best as possible with the Krühler et al. (2015) distribution. As we will later focus on analyzing the LGRB metallicity distribution we thus chose to normalize our scaling analysis here to the LGRB metallicities. The degree of scaling is of particular interest as it merely indicates the size of the populations (out to a their redshift limit) which tracks general trends in the degree of observational followup (i.e. $\sim 1/4$ of LGRBs with spectroscopic redshifts have measured metallicities). Thus were a population of LGRBs to exist with exactly the same distribution as Krühler et al. (2015) but with half the number of objects it would be given a scaling factor of 2. What is of interest is any differences in the distributional shape of the different populations as this indicates redshift dependent biases. By comparing populations of galaxies with different observed properties we can thus identify redshift biases in how samples of those properties are collected and measured.

To investigate the potential of redshift dependent sample biases on our metallicity distributions we therefore compare the following populations for the described reasons:

- We begin by plotting the redshift distributions of the LGRB host galaxy populations for which we have host metallicity measurements. Since Krühler et al. (2015) has approximately three times as many objects, we use this as the numeric baseline and scale the sample of Graham & Fruchter (2013) by a factor of 0.7 to match.

- To address concerns about a metallicity dependent redshift bias we also plot the subset of Krühler et al. (2015) hosts with metallicities above solar. As this is only about a third of the total Krühler et al. (2015) host population, it is scaled by a factor of three. The Graham & Fruchter (2013) high metallicity sample is omitted due to its small size of only two objects (after the removal of LGRB 020819B).

- To address concerns about a bias in metallicity measurement as a function of redshift we plot the entire Krühler et al. (2015) host population including the objects without a metallicity. As this makes an approximate 50% increase in the sample size (at $z < 2.5$ before the slope noticeably changes) we scale it down by a factor of $\frac{2}{3}$. As the slope of this, and some other distributions, noticeably changes at $z \approx 2.5$, and since $z \approx 2.5$ is the limit of the redshift range for which we have measured metallicities, we adopt this redshift, along with the matching ordinate of this distribution (a value of $\sim 60$), as the reference point for scaling the remaining distributions.

- Next we compare it with the general burst population by plotting all known LGRB host galaxy redshifts as conveniently compiled in the GRB table of Jochen Greiner\(^3\) (excluding for this and all other samples those objects with no or only photometric redshifts), as of UTC noon March 15\(^{st}\) 2019. As this sample is undoubtedly subject to a variety

\(^3\) http://www.mpe.mpg.de/~jcg/grbgen.html
of complex selection effects, its use provides a reasonable assessment of the degree that such unmitigated effects have on our analysis. Again and subsequently the sample is scaled to match the other distributions.

- To address biases in host redshift measurement with redshift we plot the Perley et al. (2016) SHOALS and Salvaterra et al. (2012) BAT6 samples, which claim to be unbiased in their selections.

- To also sample bias in host galaxy mass measurement we also plot the subset of Perley et al. (2016) SHOALS galaxies with mass values (excluding limits) as well as the sample of Svensson et al. (2010).

We also consider a theoretical curve for the LGRB event rate. Graham & Schady (2016) estimated the LGRB progenitor rate using the Graham & Fruchter (2017) results in concert with SNe statistics via an approach patterned loosely off the Drake equation. Beginning with the cosmic star-formation history, Graham & Schady (2016) took the expected number of broad-line Type Ic events that are in low metallicity host environments as potential LGRB progenitor candidates. They then adjusted this number by adding the contribution of broad-line Type Ic SNe in high metallicity host environments at a much reduced weighting of $\sim 1/100$ (the Graham & Fruchter 2017 estimate on the relative suppression of LGRB formation in high metallicity environments). A comparison of this estimate of potential LGRB progenitor candidates to the observed LGRB rate corrected for instrumental selection effects (estimated by Lien et al. 2014 and Graff et al. 2015), provided a combined estimate of the fraction of broad-line Type Ic SNe residing in metal poor environments that produce an LGRB and the fraction of such LGRBs that are beamed in our direction. Thus Graham & Schady (2016) estimated that, in a low metallicity environment, an aligned LGRB occurs out of approximately every 4000 $\pm$ 2000 broad-lined Type Ic Supernovae. Therefore if one assumes a semi-nominal beaming factor of 100 then 1 out of $\sim 40$ low metallicity Ic-bl SNe give rise to an LGRB.

Using the process described above, we derive an expected LGRB event rate as follows: Beginning with the cosmic star-formation rate history of Hopkins & Beacom (2006) and the Graham & Schady (2016) estimates of the metallicity distribution of the universe as a function of redshift we obtain an estimate of the amount of star-formation above and below the Graham & Fruchter (2017) metallicity cutoff. The expected number of LGRBs formed is thus estimated after applying the Graham & Fruchter (2017) estimate of the effect of metallicity on the LGRB formulation rate per unit of available star-formation. The result is an expected LGRB event rate as a function of redshift which can then be scaled in the same manner as the observed LGRB populations described previously.

Fascinatingly, as shown in Figure 1, we find that there does not appear to be any particularly significant differences in the redshift distributions of the different LGRB samples aside from the following:

1. Graham & Fruchter (2013) sample shows a considerably reduced rate of LGRB observation at redshifts high enough ($z \geq 0.5$) to require a separate IR spectrograph to observe some of the lines required for determining a metallicity. As X-shooter contains an integrated IR spectrograph, the Krühler et al. (2015) sample is not subject to this effect.

2. The Krühler et al. (2015) metallicity sample has a gap from $1.7 < z < 2.1$ which is due to observational difficulties in obtaining all the lines needed for metallicity measurement (see text). As measuring the redshift does not require observing specific lines this gap is not seen in the Krühler et al. (2015) redshift sample. We also compare these LGRB samples with our predicted LGRB rate estimate from Graham & Schady 2016 (thick grey line) and find it to be in good agreement with the samples at $z < 2.5$ and with the Perley et al. (2016) SHOALS sample in particular at higher redshifts. KS test results for the lines in this figure are shown in Table 2 in the appendix.
redshift distributions as expected since the cause of this gap is not dependent on the metallicity of the objects. However this gap in the Krührler et al. (2015) metallicity sample is not seen in the Krührler et al. (2015) redshift sample (of which the Krührler et al. 2015 metallicity sample is a sub-sample) as any distinct combination of emission lines is sufficient to identify the redshift whereas the consistent metallicity diagnostic used here requires a specific set of lines (see as described in subsection 2.2). After correcting for this gap (i.e. artificially scaling the post gap metallicity sample lines back up to the other distributions) the metallicity populations continue to track the other distributions for the (limited) remainder of their redshift ranges.

3. The samples diverge at \( z \geq 2.5 \) due to different completeness rates for high redshift objects. As this is beyond the redshift range of our host metallicity sample, it does not impact our subsequently metallicity distribution analysis. It is worth noting that the Perley et al. (2016) SHOALS sample does not show a change of slope in these regions unlike the other samples and instead agrees quite closely with our predicted LGRB event rate curve from the Graham & Schady (2016) formulation of LGRB formation rate as a function of the cosmic star-formation rate and the metallicity distribution of the universe as a function of redshift. Since the BAT6 sample is flux limited, as they go higher in redshift, their sensitivity to the lower end of the GRB luminosity function decreases. This results in an underrepresentation of high redshift objects, which is consistent with the underrepresentation in the sample of all LGRBs with spectroscopically measured redshifts (private communications). Given that the BAT6 sample tracks the Greiner table sample of all known LGRB redshifts after the \( z \sim 2.5 \) diverge point with the other samples, this suggests that the "variety of complex selection effects" in the full LGRB redshift sample is dominated by the same flux limited selection effect as the BAT6 sample.

To analyze this more rigorously we calculate Kolmogorov–Smirnov (KS) probabilities comparing all of our samples with each other in Table 2. To address the issues noted above we introduce some additional subsets of our samples as follows. (1) We subdivide the Graham & Fruchter (2013) sample into objects with \( z < 0.5 \) and \( z > 0.5 \) so as to assess the fit of the sample with and without the application of a separate IR spectrograph. (2) We subdivide the Krührler et al. (2015) metallicity sample into objects with \( z < 2 \) and \( z > 2 \) so as to allow us to assess the fit of the sample without the gap at \( z \approx 2 \). For the same reason, we also add a \( z < 2 \) Krührler et al. (2015) high metallicity sample but can not add a matching high metallicity \( z > 2 \) sample as we have fewer than 4 such objects. (3) For all samples that extend to \( z > 2.5 \) we add a subset of values with \( z < 2.5 \) to compare only those regions before the \( z > 2.5 \) divergence.

To compare with the our Graham & Schady (2016) based theoretical curve for the LGRB event rate, we create a simulated population of about 3000 objects using an appropriately weighted random generation approach. Specifically we create a redshift array corresponding to million year increments since \( z = 4 \). We then calculate an LGRB rate estimate for each redshift normalized such that the maximum value at any redshift is 1. Then we exclude bins where the rate estimate is lower than a random number, unique for each redshift, uniformly distributed in the 0 to 1 range. The result is a set of redshifts with the same distribution as expected for the theoretical LGRB event rate. This simulated population is then treated like any other population for the KS analysis.

Calculating KS values for comparison has the notable advantage that the values do not need to be scaled but can be compared directly (therefore the scaling factors from Figure 1 are not used is the KS analysis). Critical to our KS analysis is that samples must be matched across a common redshift range. To achieve this, for any two samples being compared, we take the sample with the smallest redshift range, set a redshift cutoff at 0.05 \( z \) higher than the highest redshift in that sample, and remove all objects (in the other sample) with redshifts above this cutoff. (This additional 0.05 \( z \) redshift grace allows us to utilize both samples in full if their maximum redshifts are similar, otherwise one sample would always have its highest redshift object removed.) Samples are compared without a lower redshift cut, unless a lower redshift range is specified for the sample, in which case the same process is used but in reverse (again with a 0.05 \( z \) grace). Since some samples are redshift subsets of others, and the redshift ranges are matched, some comparisons will be of a set of objects with itself, those are thus marked as having a KS probability of “1” (values of “1.00000” are the result of rounding). Some comparisons have fewer than the 4 objects in each sample needed for the KS test and are marked as NaN. The KS values calculated for the populations shown in Figure 1 are given in Table 2 in the appendix.

This consistency of redshift distributions between different LGRB samples, aside from the perviously enumerated effects, suggests that there are no unknown significant deviations in the redshift completeness of our sample (at least that correlate with redshift) and that we have a good understanding of the causes for the deviations that are present. The consistency with our theoretical curve further suggests that the observed populations are unbiased and that there are unlikely to be effects caused by systematic bias in population of all LGRB with spectroscopically measured redshifts. This validates the integrity of our LGRB samples and allows us to proceed with studying the how the metallicity distributions vary as a function of redshift.

3.2. Metallicity Distribution as a Function of Redshift

3.2.1. From Observations

We begin, in Figure 2, with a standard normalized cumulative metallicity distribution plot of LGRBs with measured host metallicities divided across five redshift bins with a width of 0.5 \( z \). This gives a series of 5 distributions for the Krührler et al. (2015) and 2 for the Graham & Fruchter (2013) samples (since all objects in the latter sample are \( z < 1 \)). A distribution for both the Graham & Fruchter 2013 & Krührler et al. 2015 samples across all redshifts is also provided for reference. The
Figure 2. Cumulative distribution of measured LGRB host metallicities binned by redshift. The original Graham & Fruchter (2013) sample and the newer larger Krühler et al. (2015) sample are used. As described in Graham & Fruchter (2013), all metallicities are calculated using the R23 diagnostic and Kobulnicky & Kewley 2004 (KK04) scale via a version of the Kewley & Dopita (2002) metallicity code re-calibrated to the Kewley & Dopita (2002) scale. To maintain consistency across both samples, and with the analysis of Graham & Fruchter (2013), the metallicities for the Krühler et al. (2015) objects were recalculated from the line strength tables given in Krühler et al. (2015). Naturally, these metallicity values are almost identical to the R23 KK04 metallicity values given in Krühler et al. (2015). Surprisingly, the data does not show any statistically significant evolution in the LGRB host metallicity distribution with redshift.

Krühler et al. (2015) z < 0.5 and both the Graham & Fruchter (2013) 0 < z < 0.5 and 0.5 < z < 1 bins seem to deviate slightly towards a more metal poor distribution than the remaining z > 0.5 Krühler et al. (2015) populations, however the statistical significance of this is tenuous. The z > 2.0 Krühler et al. (2015) population also appears to a little more metal rich than the 0.5 < z < 2.0 Krühler et al. (2015) populations but this is not statistically significant. This is counter intuitive, as due to both the typically smaller masses of star-forming galaxies and the less time available for metal enrichment, one would expect the metallicity of any typical galaxy sample to decrease with redshift. The result is a markedly constant metallicity distribution across the different redshift bins, indicative of far less metallicity evolution than is present in the typical star-forming galaxy population across the same redshift range (Zahid et al. 2013). Since LGRBs are formed in star-forming galaxies this discrepancy is perplexing.

Ideally we would next compare the metallicity distribution of LGRB hosts with a sample of typical star-forming galaxies at the same redshifts selected in a star-formation weighted manner (i.e. the sample methodology of the Graham & Fruchter (2013) SDSS population but at higher redshifts). Unfortunately, a suitable galaxy sample does not exist. The SDSS metallicity sample only extends (with a large sample size) out to z < 0.3 and even out to that redshift range there are completeness issues with faint galaxies. While using the z = -0 SDSS population and subtracting the expected metallicity shift from the mass metallicity relation would provide a crude metallicity distribution, this would not provide a suitable enough estimate for the star-formation weighting. Therefore our ability to quantify the expected metallicity distribution evolution for the LGRB hosts from the typical star-forming galaxy population is lacking. Still, the absence of any apparent evolution can be reasonably excluded from being due to mass metallicity relation evolution across the redshift range in question.

Although we cannot create a suitable comparison sample of star-forming galaxies (i.e. galaxies of the same redshift distribution selected in a star-formation weighted manner), we can compare our sample of LGRB host metallicities with a sample of typical metallicities for galaxies with the masses and redshifts of an actual LGRB host galaxy population. Fortunately, we have already assessed the redshift distribution (subsection 3.1) of our LGRB host galaxy mass samples and found to to be consistent with that of our host metallicity samples.

3.2.2. Expected Metallicity Distribution From Mass & Redshift

To compare the metallicities which have been measured with the typical metallicity expected for a galaxy of a given mass at a specific redshift we must use the mass metallicity relation to estimate a metallicity. However, the mass metallicity relation itself varies with redshift. Therefore, we estimate the mass metallicity relation for the redshift of the galaxy in question by interpolating from the mass metallicity relations measured at different redshifts. While Mannucci et al. (2010) claim a fundamental mass, metallicity, & star-formation rate relation that remains independent of redshift, we found (for the local universe) this to be mostly a mass metallicity relation, with a small but statistically significant star-formation rate perturbation, that is not independent of redshift. The applicability of the Mannucci et al. (2010) relation beyond the local universe is dubious at best with Wuyts et al. (2014) and Sanders et al. (2015) finding no SFR dependance on the mass-metallicity relation, and Yates et al. (2012); Yates & Kauffmann (2014) finding a slight positive correlation for high mass objects, all contrary to the Mannucci et al. (2010) claim of a strong anti-correlation. As this clearly invalidates the fundamental relation being invariant with redshift, we therefore do not use the Mannucci et al. (2010) relation here.

While Zahid et al. (2013) provide a series of mass metallicity relation fits across the redshift range of interest, we apply our own 2-dimensional fit to the Zahid et al. (2013) Figure 1 data so such that we can estimate the metallicity for a galaxy of any given mass and redshift. Care was taken to avoid over-fitting the Zahid et al. (2013) data and a number of fitting procedures were trialed with fitting a minimum curvature spline surface using the MIN_CURVE_SURF procedure adopted. Our estimated metallicity results for a continuous range of galaxy masses are plotted against the individual redshift fits of Zahid et al. (2013) in Figure 3.

We therefore apply this methodology to estimate
the expected metallicities for the Perley et al. (2016) SHOALS sample. We show the estimated metallicity distribution of this sample in Figure 4 right, using the same redshift binning as in Figure 2. For comparison we show a simplified version of our measured LGRB host metallicities on the left side of this figure (Figure 4). The upper half of the expected metallicity distributions shows a lack of metallicity evolution with redshift consistent with that seen in the measured metallicity distributions. Since the mass metallicity relation decreases with redshift, to therefore maintain a consistent metallicity distribution the LGRB mass distribution would have to increase with redshift. Perley et al. (2016) claims that this in indeed the case. To illustrate this we plot the combined Perley et al. (2016) and Svensson et al. (2010) mass distributions with the same redshift binning and colors in an inset of Figure 4. While an increase in observed host galaxy masses with redshift could potentially be due to Malmquist bias it seems unlikely that such a bias would exactly match that needed to correct for mass metallicity evolution so as to maintain a consistent metallicity distribution. Moreover, Perley et al. (2016) claims that their observed mass distribution increase is not caused by observational biases in their sample.

Comparing between the right and left sides of Figure 4, the estimated metallicity distributions have higher metallicities for a given redshift than the measured metallicity distributions. We overplot these metallicity distributions (simplified to show only the full 0 < z < 2.5 redshift range) in Figure 5. This distributional offset of, on average, approximately a quarter dex is roughly constant across the distributions interquartile range. Therefore, the LGRB host galaxy population is systematically lower in metallicity than typical galaxies of comparable mass and redshift. This suggests that the LGRBs are biased towards the lowest metallicities within any galaxy population and can not be correctly modeled using the general mass metallicity relation.

We find an absence of large differences in the LGRB redshift distribution out to z of 2.5 between different samples studying different physical properties of bursts. The minor exceptions are that the Graham & Fruchter (2013) LGRB metallicity sample shows an expected bias against LGRB metallicities where a separate IR instrument is required to observe the reddest required lines. This bias is not repeated in the Krühler et al. (2015) X-Shooter survey since X-Shooter can observe all required spectral lines for determining metallicity out to z = 2.5, however a gap in the X-Shooter metallicity redshift coverage is seen between approximately 1.7 < z < 2.1 due to some of the required lines falling out of observable spectral regions. We also find that the observed LGRB redshift distribution agrees well the distribution predicted in Graham & Schady (2016) and that the Perley et al. (2016) SHOALS redshift distribution particularly matches predictions at redshifts above z of 2.5 where the redshift distributions of the different LGRB samples (which extent to these high redshifts) diverge.

We then proceed to look for evolution in the metallicity distribution as a function of redshift and find surprisingly little. There appears to be curious consistency in the metallicity distribution across different redshifts. This is at odds with the general evolution in the mass metallicity relation, which becomes progressively more metal poor with increasing redshift. As the average mass, redshift, and metallicity are related (by an evolving mass metallicity relation) we can thus use any two properties to estimate the third.

By converting the measured LGRB host masses and redshifts from Perley et al. (2016) to expected metallicities, using a fitting of the mass-metallicity-redshift relation of typical galaxies from Zahid et al. (2013), we further find that the LGRB host galaxy mass distribution increase with redshift seen in the Perley et al. (2016) SHOALS sample is consistent with that needed to preserve the LGRB metallicity distribution because the mass metallicity relation decreases with redshift. Furthermore we find that these estimated LGRB host metallicities consistently overestimate the actual measured host metallicities by approximately a quarter dex. This corresponds to about a factor of two in raw metallicity and resolves much of the difference between the LGRB formation metallicity cutoff of about a third solar in Graham & Fruchter (2017) with the cutoff value of just under solar claimed in Perley et al. (2016) in favor of the former. As LGRB hosts do not follow the general mass metallicity relation, there is no substitute for actually measuring their metallicities!

5. DISCUSSION

The absence of evolution in the LGRB metallicity distribution is quite puzzling and does not seem to conform to our general expectations of galaxy evolution. The simplest explanation of the known LGRB preference for low metallicity environments (Graham & Fruchter 2013, 2017; Perley et al. 2016; Levesque et al. 2010a,b) is that this effect is caused by a difference in the LGRB formation rate per unit star-formation at different metallicities (c.f. Graham & Fruchter 2017). However, this explanation would not produce an LGRB metallicity distribution with no redshift evolution, as seen here, since the underlying star-formation from which the LGRBs are formed.
Figure 4. Left: Measured metallicities binned by redshift. This is the sample from Figure 2 but no longer showing the Graham & Fruchter (2013) and Krühler et al. (2015) samples separately. Right: Binned metallicities estimated from host galaxy mass and redshift using a 2-dimensional fit of Zahid et al. (2013) Figure 1. This is generated from the sample of host masses and redshifts in Perley et al. (2016). Inset: The masses of these objects binned by redshift. All redshift bins use the same color scheme (the black lines show the combined metallicities across the entire $z < 2.5$ redshift range). Note the much tighter correlation of estimated metallicities in the upper half of the figure than measured masses. This suggests that the metallicities are indeed tightly correlated as seen in the measured data (left plot) and this is what is actually driving the mass distribution seen in the Perley et al. (2016) masses (inset plot). The lack of a similar tight correlation on the bottom half of the plot is likely due to these host galaxies being significantly off the typical mass-metallicity relation for their redshift. KS test results for the lines in this figure are given in appendix tables.

One possible explanation might be that the high metallicity LGRB hosts are not representative of the general galaxy population and may have recently been low metallicity galaxies that have undergone a sudden burst of enrichment. This could also explain the existence of high metallicity LGRBs as the gas that formed the progenitor may have been segregated from this enrichment process and thus allowing the LGRB to form in a low metallicity environment.

The recent discovery of host association confusion leading to the spurious high metallicity host measurement of LGRB 020819B (Perley et al. 2017) and potentially also LGRB 050826 (C. Thöne private communication) demands a closer vetting of the high metallicity LGRB host population. Perhaps then claims of high metallicity LGRB hosts being dominated by merger induced starbursts could be validated and the disproportionate (with respect to the underlaying star-formation) association of high metallicity LGRB hosts with dynamical systems shown. At the moment this remains speculative as, while the high metallicity LGRB 051022 is clearly such a system (Graham et al. 2015, 2009), an extensive study of a well vetted representative population will be needed to establish this trend beyond mere anecdotal cases.

Were merger induced starbursts (of low metallicity galaxies) the cause of the high metallicity LGRB host population then the rate of such mergers would likely not depend on the fraction of high metallicity galaxies and their high metallicity star-formation. Therefore the general galaxy metallicity distribution (and its evolution) would largely be irrelevant, as it is thus not producing LGRBs, and therefore the LGRB metallicity distribution (at least for all but the low metallicity end) would be a function of the distribution in the metallicity enrichment timescale and the timescale distribution between LGRB progenitor gas segregation and the LGRB explosion. Essentially this reduces the problem to a race between how fast the host galaxy metallicity can increase and how long the LGRB can wait to explode. Such a race condition would be expected to produce a static LGRB metallicity distribution.

While LGRB progenitors are certainly massive stars it remains an open question of whether they are the most massive and thus if, in a starburst scenario, they are the first stars to explode. The question then becomes one of timing and a full prior generation of stars would actually be problematic as we need to enrich the host galaxy ISM without enriching the LGRB progenitor itself. Assuming it is possible to enrich the host galaxy ISM in the interval between when the gas that will form the LGRB progenitor becomes segregated from that of the host to when the LGRB progenitors lifespan ends in an LGRB event,
et al. (2013) galaxy populations this could also simply be caused by uncertainty in the requisite extrapolation. It is worth noting that the highest redshift galaxy population in Zahid et al. (2013), that of Erb et al. (2006) at a redshift of $z = 2.26$, still expects a mean metallicity of only $\log(O/H)+12 \approx 8.5$ (after conversion into the KK04 scale) for a billion solar mass galaxy at that redshift whereas Graham & Fruchter (2017) found the metallicity cutoff to be $\log(O/H)+12 \approx 8.3$ for the LGRB formation per unit star-formation rate. Even if such an extrapolation of the Zahid et al. 2013 fit could be trusted outside of its observed redshift range, it would still be unwise to draw too heavily on inferring host metallicity behavior from host masses as one of the significant results of this paper is that the former are not a typical representation of the latter. We must stress again that there is no substitute for actually measuring galaxy metallicities.

The metallicity distribution of the LGRB host galaxy population does not seem to evolve with redshift as would be expected given the cosmological metallicity enrichment of the universe, in particular the lower average metallicity of star-forming environments with redshift. The expected LGRB host metallicity distribution (the metallicity of typical galaxies with the same mass and redshift as the LGRB hosts) also does not seem to evolve but is systematically approximately twice that of the measured metallicities. The LGRB host galaxy mass distribution slowly increases with redshift as is required to correct for cosmological metallicity enrichment and maintain a constant metallicity distribution. While we cannot fully exclude the possibility of Malmquist bias contributing to our results, we have analyzed in detail possible redshift biases between our samples and find no such unexplained effects. We also would not expect Malmquist bias to reproduce either consistent observed metallicity distributions or the mass increase with redshift needed to exactly maintain consistent estimated metallicity distributions. Therefore we conclude that something more complicated is occurring than the simple relative rate difference in LGRB formation as a function of metallicity proposed in Graham & Fruchter (2017).

One potential explanation is that the LGRB events seen in high metallicity environments do not actually originate from high metallicity progenitors. Instead these
events may originate from low metallicity star formation and the metallicity of their environments is otherwise enriched (e.g. the enrichment happening after the progenitor was formed). Were this the case, then an absence of evolution in the LGRB metallicity distribution would be expected since LGRBs would form at a consistent rate (regardless of redshift) in the abnormally low metallicity galaxy population (remember the typical LGRB host metallicity range is below the mass-metallicity range of typical galaxies throughout our redshift range of galaxies with observed metallicities). About 20% of the time (per unit star-formation) the low metallicity galaxy undergoes a rapid metallicity enrichment phase (perhaps induced by a merger or near merger tidal disruption) and thus becomes a high metallicity host by the time the LGRB occurs. This process would thus potentially result in a fixed ratio of different LGRB environments (at the time of observation), irrespective of changes in the metallicity distribution of typical star-forming galaxies (i.e. their typical metallicity evolution / enrichment) since typical star-forming galaxies are too high metallicity to form LGRBs.

Unfortunately, the required understanding of rapid, perhaps collisionally induced, starburst metallicity enrichment is lacking. The limitations of rapid enrichment are not observationally constrained and the simulations not yet sufficient to address the issue directly. A detailed study of high metallicity LGRB host galaxies to compare their properties in detail against a matching typical star forming galaxy population (i.e. investigating anecdotal claims of merger over representation) and extending our study of the LGRB host metallicity distribution out to redshifts where the metallicity of typical star forming galaxy population is consistent with or lower than the typical LGRB population (perhaps at $z \sim 4$) is essential to continuing this investigation.

More generally we find that estimating the metallicity of LGRB hosts from their mass and redshift, while reproductive of some observed trends, is not accurate and should not be attempted. (Even a specific LGRB-calibrated mass-metallicity relation is not practical since there is no universal correspondence between LGRB host mass and metallicity, regardless of redshift, at the low metallicity end of the population.) Actually measuring galaxy metallicities in emission beyond $z > 2$ becomes increasing difficult due to the required spectral lines being redshifted out of the observable range. X-shooter with the K band blocking filter in place is limited to observations at $z < 2.15$, and without it, observations are only practical out to $z < 2.6$ which is also the limit of what can be reasonably expected from the ground. JWST will be able to brute force these observations at high redshifts however a more efficient approach would be to use absorption metallicities at such higher redshifts. Fortuitously, LGRB host galaxies themselves are uniquely suited to absorption metallicity measurement as the GRB afterglow itself provides a bright background source clean of intrinsic spectral features (as present in QSOs) and LGRB hosts are also star-forming galaxies with typically robust emission lines. Absorption metallicities however are practically limited to galaxies at $z > 1.6$ due to requiring observations of the Ly$\alpha$ line. The lack of much overlap between these redshift ranges has deterred a direct comparison of measured values leaving great uncertainty in their respective cross-calibration. Once such a cross-calibration between emission and absorption metallicities (similar to the cross-calibration between different emission line diagnostics of Kewley & Ellison 2008) is achieved, extending our analysis out to a higher redshifts in absorption will allow us to directly probe the critical region where the mass metallicity relation of the typical galaxy population transits the optimal metallicity range for LGRB formation. Such analysis is critical to understand how metallicity shapes the formation process of the LGRBs seen in high metallicity host galaxies and thus how LGRBs form in general. To say it again: as LGRB hosts do not follow the general mass metallicity relation and thus there is no substitute for actually measuring their metallicities!

We thank Thomas Krühler for many useful discussions and assisted assistance. His omission as a co-author is due solely to his personal preference since leaving academia. He is missed.

We thank the BAT6 team for a detailed explanation of their $z \geq 2.5$ selection effects.

John Graham acknowledges support through the National Science Foundation of China (NSFC) under grant 11750110418.

**APPENDIX A**

**DATA AND KS TABLES**

Here we provide a data table of our combined LGRB sample (Table 1) and KS test result tables for Figures 1 (Table 2) and 4. Figure 4 has KS test results for the left (measured host metallicity – Table 3), inset (host mass – Table 4), and right (estimated host metallicity – Table 5) plots as well as another KS test (Table 6) on only the upper half of the values in each redshift bin of Figure 4 left. These KS test result tables are computed (for each figure) by calculating the KS probabilities of every line in the figure against every other line.

Table 2 shows that the redshift distribution of the different observed LGRB populations are in reasonable agreement with each other except as noted in section 3.1. By further dividing the populations (into subpopulations not separately shown in 1) we can validate that these exceptions are due the reasons claimed in the text. Specifically we divide the Graham & Fruchter (2013) sample into objects with redshift above and below $z = 0.5$ and find that both of these subpopulations are much more consistent with the other lines, while the combined population is not, due to a lower observing rate at $z > 0.5$ where a separate IR spectrograph is required. We also divide the Krühler et al. (2015) metallicity into objects with redshift above and below $z = 2$ and again find that both of these subpopulations are much more consistent than the other lines, while the combined population, due to a gap in the Krühler et al. (2015) metallicity sample from $1.7 \lesssim z \lesssim 2.1$ caused by a line measurement difficulty. (Note that the sample redshift matching process results in these this redshift gap being trimmed from the comparison samples as well.) Finally for those samples who’s redshift range exceed $z < 2.5$ we create a $z < 2.5$ subpopulation so as to compare them without being subject to the gamma-ray flux limited selection effects present at higher redshifts and find that these populations are indeed more consis-
tent at lower redshifts.

Table 3 shows that the different LGRB redshift bins indeed have the same metallicity distribution as appears in Figure 1 left. Table 4 shows however that there is a strong difference in the host mass distribution of the different LGRB redshift bins (see Figure 1 inset). It is thus surprising that when these mass and redshift values are used to estimate a host metallicity values for these objects the LGRB redshift bins have a much more consistent metallicity distribution (Table 5), particularly on the upper half of the distributions (Table 6).

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Table 2

| All LGRBs | All LGRBs | GF13 Metalicites | GF13 Metalicites | GF13 Metalicites | Svensson Masses | Kruehler Redshifts | Kruehler Metalicites | Kruehler Metalicites | Kruehler Metalicites | Kruehler Metalicites | Kruehler Metalicites | Kruehler High Metalicity | Kruehler High Metalicity |
|-----------|-----------|------------------|------------------|------------------|------------------|------------------|-------------------|-------------------|-------------------|-------------------|-------------------|------------------------|------------------------|
| Redshifts | Redshifts | z < 2.5          | z < 0.5          | z > 0.5          |                  |                  |                   |                   |                   |                   |                  |                        |                        |
| All LGRBs | z < 2.5   |                  |                  |                  |                  |                  |                   |                   |                   |                   |                  |                        |                        |
| GF13 Metalicites | z < 2.5 | 0.1748           | 0.1748           |                  |                  |                  |                   |                   |                   |                   |                  |                        |                        |
| GF13 Metalicites | z < 0.5 | 0.6164           | 0.6164           |                  |                  |                  |                   |                   |                   |                   |                  |                        |                        |
| GF13 Metalicites | z > 0.5 | 0.9806           | 0.9806           |                  |                  |                  |                   |                   |                   |                   |                  |                        |                        |
| Svensson Masses |          | 0.7626           | 0.7626           | 0.3700           | 0.9748           |                  |                   |                   |                   |                   |                  |                        |                        |
| Kruehler Redshifts | z < 2.5 | 0.5915           | 0.8123           | 0.0371           | 0.3129           | 0.9518           | 0.9432           |                  |                   |                   |                   |                  |                        |                        |
| Kruehler Redshifts | z < 0.5 | 0.8123           | 0.8123           | 0.0371           | 0.3129           | 0.9518           | 0.9432           |                  |                   |                   |                   |                  |                        |                        |
| Kruehler Metalicites | z < 2  | 0.8080           | 0.8080           | 0.1341           | 0.3713           | 0.6024           | 0.6950           | 0.0989           | 0.0989           | 1                 |                  |                  |                        |                        |
| Kruehler Metalicites | z > 2  | 0.8379           | 0.8379           |                  | 0.0116           | 0.9886           | 0.6808           | 0.0180           | 0.6300           | 0.1443           | 0.8397           |                        |                        |
| Kruehler High Metalicity |          | 0.9621           | 0.9621           | 0.3000           |                  |                  | 0.9096           |                  | 0.0045           | 0.9974           | 0.9751           |                        |                        |
| Kruehler High Metalicity | z < 2  | 0.6429           | 0.6429           | 0.3000           |                  |                  |                  |                  | 0.0920           | 0.9230           | 0.9659           |                        |                        |
| BAT6 sample | z < 2.5 | 0.6587           | 0.3157           | 0.0377           |                  |                  |                  |                  |                  |                   |                   |                  |                        |                        |
| BAT6 sample | z < 0.5 | 0.3157           | 0.3157           | 0.0377           |                  |                  |                  |                  |                   |                   |                   |                  |                        |                        |
| BAT6 sample | z > 0.5 | 0.6587           | 0.3157           | 0.0377           |                  |                  |                  |                  |                   |                   |                   |                  |                        |                        |
| SHOALS Masses |          | 0.0804           | 0.0801           | 0.0116           |                  |                  |                  |                  |                   |                   |                   |                  |                        |                        |
| SHOALS Masses | z < 2.5 | 0.0801           | 0.0801           | 0.0116           |                  |                  |                  |                  |                   |                   |                   |                  |                        |                        |
| SHOALS Masses | z < 0.5 | 0.0801           | 0.0801           | 0.0116           |                  |                  |                  |                  |                   |                   |                   |                  |                        |                        |
| SHOALS Masses | z > 0.5 | 0.0801           | 0.0801           | 0.0116           |                  |                  |                  |                  |                   |                   |                   |                  |                        |                        |
| SHOALS Redshifts | z < 2.5 | 0.9331           | 0.0331           | 0.0102           | 0.4746           | 0.9543           | 0.6901           | 0.0604           |                  |                  |                   |                  |                        |                        |
| SHOALS Redshifts | z < 0.5 | 0.9331           | 0.0331           | 0.0102           | 0.4746           | 0.9543           | 0.6901           | 0.0604           |                  |                  |                   |                  |                        |                        |
| SHOALS Redshifts | z > 0.5 | 0.9331           | 0.0331           | 0.0102           | 0.4746           | 0.9543           | 0.6901           | 0.0604           |                  |                  |                   |                  |                        |                        |
| SHOALS High Metalicity |          | 0.0000           | 0.0002           | 0.0341           | 0.3374           | 0.9682           | 0.5185           | 0.5096           |                  |                   |                   |                  |                        |                        |
| SHOALS High Metalicity | z < 2  | 0.0000           | 0.0002           | 0.0341           | 0.3374           | 0.9682           | 0.5185           | 0.5096           |                  |                   |                   |                  |                        |                        |
| SHOALS High Metalicity | z > 2  | 0.0000           | 0.0002           | 0.0341           | 0.3374           | 0.9682           | 0.5185           | 0.5096           |                  |                   |                   |                  |                        |                        |
| GS16 Prediction | z < 2.5 | 0.9854           | 0.5496           | 0.8525           | 0.0748           | 0.8911           | 0.6113           | 0.4173           | 0.1706           |                  |                   |                  |                        |                        |
| GS16 Prediction | z < 0.5 | 0.9854           | 0.5496           | 0.8525           | 0.0748           | 0.8911           | 0.6113           | 0.4173           | 0.1706           |                  |                   |                  |                        |                        |
| GS16 Prediction | z > 0.5 | 0.9854           | 0.5496           | 0.8525           | 0.0748           | 0.8911           | 0.6113           | 0.4173           | 0.1706           |                  |                   |                  |                        |                        |

Computed Kolmogorov–Smirnov (KS) probabilities comparing the lines in the Figure 1 redshift distributions (and some additional subsets thereof). This was affected by, for each paring, removing the objects of each line outside the redshift range of the other (with a grace of 0.05 z) and then running a normal KS test on the remaining values. NaN values indicate KS test failure due to having fewer than 4 objects in a redshift matched comparison sample. Values of “1” are exact and indicate a sample which, due to redshift range matching cuts, is being evaluated with itself, values of “1.0000” are the result of rounding. Note: The KS values in this table are not dependent on the line scaling factors used in Figure 1.
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Table 3
KS probabilities for Figure 4 left

| z region | 0.5 < z < 1 (blue) | 0.5 < z < 1.5 (cyan) | 1 < z < 1.5 (orange) | 1.5 < z < 2 (red) | 2 < z < 2.5 (black) |
|----------|--------------------|-----------------------|----------------------|-------------------|---------------------|
| 0 < z < 0.5 | 0.3407             | 0.3167                | 0.3167               | 0.3167            | 0.3167              |
| 1 < z < 1 | 0.4227             | 0.9764                | 0.9764               | 0.9764            | 0.9764              |
| 1.5 < z < 2 | 0.3964             | 1.0000                | 0.9588               | 0.9588            | 0.9588              |
| 2 < z < 2.5 | 0.0920             | 0.8272                | 0.8787               | 0.8938            | 0.9925              |
| All z < 2.5 | 0.0920             | 0.8272                | 0.8787               | 0.8938            | 0.9925              |

Computed Kolmogorov–Smirnov probabilities comparing the lines in the Figure 4 left measured host metallicity distributions.

Table 4
KS probabilities for Figure 4 inset

| z region | 0.5 < z < 1 (blue) | 0.5 < z < 1.5 (cyan) | 1 < z < 1.5 (orange) | 1.5 < z < 2 (red) | 2 < z < 2.5 (black) |
|----------|--------------------|-----------------------|----------------------|-------------------|---------------------|
| 0 < z < 0.5 | 0.2851             | 0.2851                | 0.2851               | 0.2851            | 0.2851              |
| 1 < z < 1 | 0.0908             | 0.0060                | 0.0060               | 0.0060            | 0.0060              |
| 1.5 < z < 2 | 0.1755             | 0.0534                | 0.9795               | 0.9795            | 0.9795              |
| 2 < z < 2.5 | 0.0204             | 0.0005                | 0.4232               | 0.4232            | 0.4232              |
| All z < 2.5 | 0.0204             | 0.0005                | 0.4232               | 0.4232            | 0.4232              |

Computed Kolmogorov–Smirnov probabilities comparing the lines in the Figure 4 inset mass distributions.

Table 5
KS probabilities for Figure 4 right

| z region | 0.5 < z < 1 (blue) | 0.5 < z < 1.5 (cyan) | 1 < z < 1.5 (orange) | 1.5 < z < 2 (red) | 2 < z < 2.5 (black) |
|----------|--------------------|-----------------------|----------------------|-------------------|---------------------|
| 0 < z < 0.5 | 0.9875             | 0.9875                | 0.9875               | 0.9875            | 0.9875              |
| 1 < z < 1 | 0.5809             | 0.2584                | 0.2584               | 0.2584            | 0.2584              |
| 1.5 < z < 2 | 0.3081             | 0.1685                | 0.6553               | 0.6553            | 0.6553              |
| 2 < z < 2.5 | 0.2270             | 0.0558                | 0.5099               | 0.5099            | 0.5099              |
| All z < 2.5 | 0.4801             | 0.3402                | 0.6359               | 0.6359            | 0.6359              |
| z > 2.5 (dashed) | 0.3597             | 0.0310                | 0.4050               | 0.2275            | 0.1949              |

Computed Kolmogorov–Smirnov probabilities comparing the lines in the Figure 4 right estimated metallicity distributions. The metallicities are estimated based on the mass metallicity relation for their redshifts.

Table 6
Upper KS probabilities for Figure 4 right

| z region | 0.5 < z < 1 (blue) | 0.5 < z < 1.5 (cyan) | 1 < z < 1.5 (orange) | 1.5 < z < 2 (red) | 2 < z < 2.5 (black) |
|----------|--------------------|-----------------------|----------------------|-------------------|---------------------|
| 0 < z < 0.5 | 0.7038             | 0.7038                | 0.7038               | 0.7038            | 0.7038              |
| 1 < z < 1 | 0.4428             | 0.0166                | 0.0166               | 0.0166            | 0.0166              |
| 1.5 < z < 2 | 0.8471             | 0.2231                | 0.7001               | 0.7001            | 0.7001              |
| 2 < z < 2.5 | 0.9719             | 0.1785                | 0.4232               | 0.4232            | 0.4232              |
| All z < 2.5 | 0.5224             | 0.4285                | 0.1258               | 0.9018            | 0.2753              |
| z > 2.5 (dashed) | 0.1019             | 0.0002                | 0.0646               | 0.0110            | 0.0646              |

Computed KS probabilities comparing the upper half of the lines in Figure 4 right estimated metallicity distributions. This was affected by removing the lower half of the metallicity values of each line and then running a normal KS test on the remaining values.