REVEALING THE HIGH-REDSHIFT STAR FORMATION RATE WITH GAMMA-RAY BURSTS

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ABSTRACT

While the high-\(z\) frontier of star formation rate (SFR) studies has advanced rapidly, direct measurements beyond \(z \sim 4\) remain difficult, as shown by significant disagreements among different results. Gamma-ray bursts, owing to their brightness and association with massive stars, offer hope of clarifying this situation, provided that the GRB rate can be properly related to the SFR. The Swift GRB data reveal an increasing evolution in the GRB rate relative to the SFR at intermediate \(z\); taking this into account, we use the highest-\(z\) GRB data to make a new determination of the SFR at \(z = 4–7\). Our results exceed the lowest direct SFR measurements and imply that no steep drop exists in the SFR up to at least \(z \sim 6.5\). We discuss the implications of our result for cosmic reionization, the efficiency of the universe in producing stellar-mass black holes, and “GRB feedback” in star-forming hosts.

Subject headings: galaxies: evolution — gamma rays: bursts — stars: formation

1. INTRODUCTION

The history of star formation in the universe is of intense interest to many in astrophysics, and it is natural to pursue pushing the boundary of observations to as early of times as possible. Our understanding of this history is increasing, with a consistent picture now emerging up to redshift \(z \sim 4\), as summarized in Figure 1. The cosmic star formation rate (SFR) measurements from the compilation of Hopkins & Beacom (2006) are shown, along with new high-\(z\) measurements based on observations of color-selected Lyman break galaxies (LBGs) (Bouwens et al. 2008; Mannucci et al. 2007; Verma et al. 2007) and Ly\(c\) emitters (LAEs) (Ota et al. 2008). Much current interest is on this high-\(z\) frontier, where the primeval stars that may be responsible for reionizing the universe reside. Due to the difficulties of making and interpreting these measurements, different results disagree by more than their quoted uncertainties.

Instead of inferring the formation rate of massive stars from their observed populations, one may directly measure the SFR from their death rate, since their lives are short. While it is not yet possible to detect ordinary core-collapse supernovae at high \(z\), long-duration gamma-ray bursts (GRBs), which have been shown to be associated with a special class of core-collapse supernovae (Stanek et al. 2003; Hjorth et al. 2003), have been detected to \(z = 6.3\). The brightness of GRBs across a broad range of wavelengths makes them promising probes of the star formation history (SFH) (see, e.g., the early works of Totani 1997; Wijers et al. 1998; Lamb & Reichart 2000; Blain & Natarajan 2000; Porciani & Madau 2001; Bromm & Loeb 2002). In the last few years, Swift (Gehrels et al. 2004) has spearheaded the detection of GRBs over an unprecedentedly wide redshift range, including many bursts at \(z \gtrsim 4\). Surprisingly, examination of the Swift data reveals that GRB observations are not tracing the SFH directly, instead implying some kind of additional evolution (Daigne et al. 2006; Le & Dermier 2007; Yüksel & Kistler 2007; Salvaterra & Chincarini 2007; Guetta & Piran 2007; Kistler et al. 2008; Salvaterra et al. 2008).

GRBs can still reveal the overall amount of star formation, provided that we know how the GRB rate couples to the SFR. In this study, we use the portion of the SFH that is sufficiently well determined to probe the range beyond \(z = 4\). We do this by relating the many bursts observed in \(z = 1–4\) to the corresponding SFR measurements and by taking into account the possibility of additional evolution of the GRB rate relative to the SFR. This calibration eliminates the need for prior knowledge of the absolute conversion factor between the SFR and the GRB rate and allows us to properly relate the GRB counts at \(z = 4–7\) to the SFR in that range. Additionally, we make use of the estimated GRB luminosities to exclude faint low-\(z\) GRBs that would not be visible in our high-\(z\) sample, i.e., to compare “apples to apples.”

Our results show that the SFR must be relatively high in the range \(z = 4–7\) when compared to SFR measurements made using more conventional techniques. While the GRB statistics at high \(z\) are relatively low, they are high enough, permitting an approach complementary to other SFR determinations, which themselves must contend with presently unknown extinction corrections, cosmic variance, and selection effects, most importantly that flux-limited surveys necessarily probe the brightest galaxies, which may contain only a small fraction of the star formation activity at early epochs. We discuss the implications these results in the context of reionization and broader applications.

2. THE GRB TECHNIQUE

The relationship between the comoving GRB and star formation rate densities can be parameterized as \(\dot{n}_{\text{GRB}}(z) = \dot{\xi}(z) \times \dot{\rho}(.)(z)\), where \(\dot{\xi}(z)\) reflects the fraction of stars that produce long-duration GRBs and any additional evolutionary effects. Importantly, the SFH is well known for \(z \leq 4\), and we use the Hopkins & Beacom (2006) fit in this range. The expected (all-sky) redshift distribution of GRBs can be cast as

\[
\frac{d\dot{N}}{dz} = F(z) \frac{\dot{\xi}(z) \dot{\rho}(.)(z) \, dV \, dz}{f_{\text{mean}}} \frac{1}{1 + z},
\]

where \(0 < F(z) < 1\) summarizes the ability both to detect the...
initial burst of gamma rays and to obtain a redshift from the optical afterglow and includes observational factors such as instrumental sensitivities. Beaming rendering some fraction of the prompt GRB emission. Using another quantity, such as the peak isotropic equivalent flux ($N_{iso}$ Butler, private communication), yields quantitatively similar results.

The shaded boxes in Figure 2 show three groups of GRBs defined by this $L_{iso}$ cut in $z = 1–4, 4–5,$ and $5–7$ (the high-$z$ boxes chosen to have equal counts). The GRBs in $z = 1–4$ act as a “control group” to base the GRB to SFR conversion, since this range has both good SFR measurements and GRB counting statistics. We calculate the “expected” number of GRBs in this range as

$$N_{i=1}^{exp} \delta \Omega = A \frac{\Delta r}{4\pi} \int_{z}^{z} \frac{dS}{dz} F(z) \mathcal{E}(z) \frac{dV}{dz} \frac{1}{1+z},$$

in which $A = \Delta r \Delta \Omega \mathcal{E}_0 F_0 / 4\pi \langle f_{beam} \rangle$, an unknown normalization, depends on the total live time, $\Delta r$, and the angular sky coverage, $\Delta \Omega$. Using the average SFR density, $\langle \dot{\rho}_* \rangle_{z_1,z_2}$, a similar relation can be written for $z = 4–5$ and $5–7$ as

$$N_{i=1}^{exp} = A \frac{\Delta r}{4\pi} \int_{z}^{z} dz \frac{dS}{dz} (1+z)^n \frac{dV}{dz} \frac{1+z}{1+z}.$$

Our interest is in $\langle \dot{\rho}_* \rangle_{z_1,z_2}$ which we find by dividing out $A$, using equation (3). Taking the observed GRB counts, $N_{i=1}^{obs}$ to be representative of the expected numbers, $N_{i=1}^{exp}$, we find

$$\langle \dot{\rho}_* \rangle_{z_1,z_2} = \frac{N_{i=1}^{obs}}{N_{i=1}^{exp}} \int_{z_1}^{z_2} dz \frac{dS}{dz} \frac{dV}{dz} \frac{1+z}{1+z}.$$

written in terms of the data for the groups of GRBs. The de-
crease of $(dV/dz)/(1 + z)$ at $z \geq 1.5$ increasingly amplifies the significance of distant observed GRBs.

3. The Inferred High-$z$ Star Formation Rate

We show our new determinations of the high-$z$ SFR in Figure 1 and how they compare with most of the conventional SFR results in this range. While evolution with $\alpha = 3$ (0) would decrease (increase) these values by a factor $\sim 2$, it would also disagree with $z < 4$ data. Other changes in the details of our analysis, while changing the results somewhat, do not change the important point that the high-$z$ SFR must be relatively large to accommodate the several observed high-$z$ GRBs. These details include the exclusion of a particular GRB or changes in redshift assignments or ranges. Taking into account the Poisson confidence interval for four observed events and slightly enlarging it, we assign a statistical uncertainty of a factor of 2 up or down. As the number of GRBs increases, this uncertainty will correspondingly decrease, and more attention will need to be placed on systematics. Our luminosity cut happens to re-  

provide an update of the SFH fit of Hopkins & Beacom (2006) based on our GRB results (solid line in Fig. 1). Here we adopt a continuous form of a broken power law,  

$$\dot{\rho}_*(z) = \rho_0 \left[ (1 + z)^{a+b} \left( \frac{1 + z}{B} \right)^{b} + \left( \frac{1 + z}{C} \right)^{c} \right]^{1/2},$$  

where $a = 3.4$ ($b = -0.3$, $c = -3.5$) is the logarithmic slope of the first (middle, last) piece, and the normalization is $\rho_0 = 0.02 M_\odot$ yr$^{-1}$ Mpc$^{-3}$. Using $\eta = -10$ smooths the transitions, while $\eta \rightarrow -\infty$ would recover the kinkiness of the original form. The breaks at $z_1 = 1$ and $z_2 = 4$ correspond to $B = (1 + z_1)^{a+b} = 5000$ and $C = (1 + z_2)^{b} = 9$.

4. Comparison to Other SFR Results

Our SFR results, particularly the $z = 5–7$ point, are at the high end of SFR results obtained with more conventional methods, which show significant differences among themselves. Likely, these methods are measuring different populations of galaxies, with the GRBs probing low-luminosity galaxies that are otherwise not accounted for fully. As detailed, the statistics of the GRB data are adequate, and it is unlikely that our GRB results are overestimated, and if anything, the true SFR is even larger. We assume that a steep drop in the SFR is not being hidden by a steep rise in the fraction of stars that produce GRBs, beyond the evolution already taken into account; that would be even more interesting.

The extent of extinction by dust on high-$z$ SFR measurements is not yet strongly constrained. There are a number of indications that dust is ubiquitous over the range $4 \leq z \leq 6$ (e.g., Chary et al. 2005; Ouchi et al. 2004; Ando et al. 2006), and the dust correction in this range can be up to a factor of $\sim 2–3$. At higher redshift, there are no strong observational constraints. The dust corrections assumed in Bouwens et al. (2007, 2008) are generally small at high $z$; on the other hand, observations verify the existence of at least one heavily obscured galaxy at $z \sim 6.6$ (Chary et al. 2005), and UV-selected samples would be expected to be biased against such objects. We also note that the recent mid-IR detection of the progenitor of SN 2008S implies that some short-lived stars do produce dust (Prieto et al. 2008). For all of the LBG-based SFR results in Figure 1, we have included the dust corrections indicated by the respective authors. While the true dust corrections may be larger, it seems likely that an additional factor of several is implausible.

The LBG surveys are most sensitive to the brightest galaxies, and great efforts are made to define the UV galaxy luminosity function (LF) and how well it is sampled at the faint end. For example, the results shown in our Figure 1 from Bouwens et al. (2008) are integrated down $0.2L_\star$, for $L_\star$ defined at $z = 3$. For the three lowest-$z$ points, they also integrate down to $0.04L_\star$, yielding SFR results of a factor of a few higher. Correcting these measurements to account for the contributions from even fainter galaxies is necessary but difficult due to the poor observational constraints on the faint-end slope of the LF. Depending on the value of this slope and the lower limit of the integration, the necessary correction may be as little as a factor of 2 or as much as an order of magnitude (see Hopkins 2006). It also seems that Ly$\alpha$ emitters do not contribute significantly to the total SFR.

5. Discussion and Conclusions

We developed an empirical method for estimating the high-$z$ SFR using GRB counts, improving on earlier estimates of the high-$z$ SFR using GRB data (e.g., Berger et al. 2005; Natarajan et al. 2005; Jakobsson et al. 2006; Le & Dermer 2007; Chary et al. 2007) in several ways, not least of which by using significantly updated SFR (Hopkins & Beacom 2006) and/or GRB (Butler et al. 2007) data. Taking advantage of the improved knowledge of the SFR at intermediate $z$, we were able to move beyond the assumption of a simple one-to-one correspondence between the GRB rate and the SFR, accounting for an increasing evolutionary trend. The higher statistics of the recent Swift GRB data allowed the use of luminosity cuts to fairly compare GRBs in the full $z$ range, eliminating the uncertainty of the unknown GRB luminosity function. By comparing the counts of GRBs at different $z$ ranges, normalized to SFR data at intermediate $z$, we based our results squarely on data, eliminating the need for knowledge of the absolute fraction of stars that produce GRBs.

Our GRB-based SFR value in $z = 4–5$ is comparable to more conventional results, which may be taken as a validation of our method, i.e., possible selection effects have been adequately controlled for (see Kistler et al. 2008 for more details), while our SFR value in $z = 5–7$ is larger, which has important implications. A significant population of low-luminosity star-forming galaxies picked out by GRBs but missed in other surveys could reconcile these differences (searches utilizing cluster lensing, e.g., Richard et al. 2008, may help, if cosmic variance can be understood). Yan & Windhorst (2004) argue that the correction for the faint end of the LF should be large to correct for dwarf galaxies missed in LBG surveys. Since GRBs are observed to favor subluminous host galaxies (Fynbo et al. 2003; Le Floc’h et al. 2003; Fruchter et al. 2006), they may be probing such faint galaxies.

The universe was fully reionized by $z = 6$ (Wyithe et al. 2005; Fan et al. 2006), and it appears that AGN could not have been responsible (Hopkins et al. 2008). Can stars have reionized...
the universe? In Madau et al. (1999) the SFR density required to produce a sufficient ionizing photon flux is parameterized by two factors; the photon escape fraction ($f_{\text{esc}}$) and the clumpiness of the IGM ($C$). These enter as a ratio, $Cf_{\text{esc}}$, which is not known precisely. For $Cf_{\text{esc}} \lesssim 30$, the required SFR at $z = 6$ is $\dot{\rho}_*(z = 6) \approx 0.03 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$, just at the level of our GRB-based SFR.

This ratio may be higher (due to either $C$ or $f_{\text{esc}}$), however, which would render our measured value of $\dot{\rho}_*(z = 6)$ too low, reintroducing the concern that star formation may be insufficient to achieve reionization (e.g., Gnedin 2008). If there is a maximum metallicity for forming a GRB, then the evolutionary trend may saturate at high enough redshift; arbitrarily assuming no evolution beyond $z \approx 4$ would give an additional factor of $\approx 2$. Finally, requiring a minimum amount of metals in a star for a successful GRB would suppress the GRB rate at increasingly high $z$, necessitating a higher underlying SFR. A similar argument could be made concerning whether early, metal-poor stars possessed sufficient angular momentum. Overall, more data are needed concerning the varying ionization fraction with redshift to establish if star formation is quantitatively acceptable as an explanation for reionization, instead of simply by default if AGN have been eliminated.

The possibility of continuing evolution in the GRB rate relative to the SFR invites some astrophysical speculations. While the overall black hole production rate in core-collapse supernovae is poorly understood empirically (Kochanek et al. 2008), bright GRBs might be regarded as tracing the large angular momentum end of the black hole birth distribution (e.g., for collapsars; MacFadyen & Woosley 1999). Evolution would mean that the high-$z$ universe was more efficient at producing such black holes than usually considered. This may have implications for the nucleosynthetic yields from these explosions (e.g., Nomoto et al. 2006). The effect of supernovae on the gas in high-$z$ galaxies is an ongoing field of research (e.g., Whalen et al. 2008). Following from the considerations above, it may be that small galaxies had a disproportionately large rate of GRBs relative to normal supernovae. In this case, it would be interesting to examine the fate of such galaxies after including multiple injections of highly asymmetric, relativistic ejecta, as well as implications for enrichment of the IGM (i.e., “GRB feedback”).

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