IS THE METALLICITY OF THE PROGENITOR OF LONG GAMMA-RAY BURSTS REALLY LOW?

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ABSTRACT

Observations of long gamma-ray bursts (LGRBs) offer a unique opportunity to probe the history of cosmic star formation, although whether LGRBs are biased tracers remains highly debated. Based on an extensive sample of LGRBs compiled by Robertson & Ellis, we analyze various models of star formation rate, combining the possible effect of the cosmic metallicity evolution under the assumption that LGRBs preferentially occur in low-metallicity galaxies. The models of star formation rate tested in this work include empirical fits from observational data as well as a self-consistent model calculated from the hierarchical structure formation scenario. Comparing with the observational data, we find a relatively higher metallicity cut of $Z \gtrsim 0.6 \ Z_\odot$ for the empirical fits and no metallicity cut for the self-consistent model. These results imply that there is no strong bias toward low metallicity in LGRB host galaxies, in contrast to previous studies suggesting a cut of $Z \sim 0.1$–0.3 $Z_\odot$, and that the inferred low-metallicity dependencies of LGRBs are strongly related to the specific models of star formation rate. Furthermore, a significant fraction of LGRBs that occur in small halos down to $3 \times 10^8 \ M_\odot$ can provide an alternative explanation for the difference between the star formation rate and the LGRB rate.

Key words: galaxies: evolution – gamma-ray burst: general

Online-only material: color figures

1. INTRODUCTION

The time at which reionization was complete and the kinds of sources responsible for it still remain open questions. The optical depth of electron scattering constrained from the Wilkinson Microwave Anisotropy Probe (WMAP) infers that the universe has largely been reionized by $z \sim 10$ (Komatsu et al. 2011), which is somewhat in conflict with the Gunn–Peterson trough in the spectra of quasars at $z \gtrsim 6$ implying an end of the epoch of reionization at $z \sim 6$ (Fan et al. 2006). Models consistent with these constraints strongly suggest that the epoch of reionization is an extended process (Cen 2003; Choudhury & Ferrara 2006; Iliev et al. 2007). In addition, the galaxies observed at $z \sim 6$–10 infer that reionization is photon-starved (Bolton & Haehnelt 2007; Oesch et al. 2012). One solution to such a situation is that a significant fraction of ionizing photons are produced in low-mass galaxies forming in dark matter halos with mass below $\sim 10^9 \ M_\odot$ during the epoch of reionization. However, these galaxies are too faint to be observed by the current detectors. Even the future James Webb Space Telescope (JWST) will be incapable of reaching the required sensitivity to observe these sources. Fortunately, long gamma-ray burst (LGRB) observations offer a unique opportunity to probe the history of cosmic star formation at high redshifts, unlimited by the low brightness of their host galaxies.

As a result of the collapse of massive stars (MacFadyen & Woosley 1999), LGRBs are thought to be well suited to investigate cosmic star formation rate (CSFR; Porciani & Madau 2001; Bromm & Loeb 2002; Yüksel et al. 2008; Kistler et al. 2009). Still, this is challenging because detailed modeling is required to connect the LGRB rate to CSFR. In this respect, whether LGRBs are biased tracers remains highly debated (Daigne et al. 2006; Kistler et al. 2008). Earlier studies (e.g., Kistler et al. 2008) often modeled the relation between the LGRB rate and the CSFR using a redshift-dependent function in the form of a simple power law, $\Psi(z) \propto (1+z)^\beta$, with $\beta \approx 1.2$.

A possible physical explanation for such an enhancement is the cosmic metallicity evolution, because the collapsar model for LGRBs suggests that only massive stars with a metallicity of $Z \lesssim 0.1 \ Z_\odot$ can produce LGRBs (Woosley & Bloom 2006; Langer & Norman 2006; Salvaterra & Chincarini 2007). Observationally, Svensson et al. (2010) and Levesque et al. (2010a) found that LGRBs at $z \lesssim 1$ preferentially occur in relatively low-mass, low-metallicity galaxies. However, the scenario is more complex: several LGRB hosts with high metallicity have been found (Graham et al. 2009; Levesque et al. 2010a, 2010b, 2010c; Savaglio et al. 2012). Compiling a large sample of 46 LGRBs over $0 < z < 6.3$, Savaglio et al. (2009) found that the properties of their host galaxies are consistent with those expected for normal star-forming galaxies. Most recently, by analyzing a sample of 22 LGRB hosts with new radio data, Michałowski et al. (2012) found no difference between the properties of LGRB population and other star-forming galaxies. Hence, owing to the limited sample size, the metallicity dependencies of the LGRB hosts remain far from being well understood.

In this work, we investigate the influence of the evolution of cosmic metallicity placed on the CSFR–LGRB rate connection using an extensive sample of LGRBs compiled by Robertson & Ellis (2012) together with several CSFR models, including empirical models fitted from the observational data as well as a self-consistent model derived from the hierarchical structure formation scenario. This analysis could provide a better understanding of the high-redshift CSFR using the LGRB rate as the observational data. Moreover, this work makes a contribution to the study on the environments of LGRB host galaxies. This paper is organized as follows. The CSFR and LGRB rate models are explained in Section 2. In Section 3, we compare the predictions of the different models with the observed cumulative redshift distribution of LGRBs, and conclusions are presented in Section 4.
The cosmological parameters used in this paper are from the WMAP-7 results: $\Omega_m = 0.266$, $\Omega_\Lambda = 0.734$, $\Omega_b = 0.0449$, $h = 0.71$, and $\sigma_8 = 0.801$.

2. LGRB RATE

In order to successfully produce an LGRB with a collapsar, the progenitor star must be sufficiently massive to result in the formation of a central black hole (MacFadyen & Woosley 1999). Then the relationship between the intrinsic LGRB rate and the black hole formation rate can be parameterized as

$$\dot{n}_{\text{GRB}}(z) \propto \Phi(z) \dot{n}_{\text{BH}}(z),$$

where $\dot{n}_{\text{BH}}(z)$ is the black hole formation rate and $\Phi(z)$ is the redshift-dependent LGRB formation efficiency which is used to model possible discrepancies between $\dot{n}_{\text{BH}}$ and $\dot{n}_{\text{GRB}}$.

2.1. Model for $\Phi(z)$

Kistler et al. (2008) and Robertson & Ellis (2012) found that $\Phi \sim \text{constant}$ was inconsistent with the observational data, implying that there is an enhancement in the LGRB rate by some mechanism at high redshift. As suggested by the collapsar model (MacFadyen & Woosley 1999), the most likely physical explanation for this enhancement is the cosmic metallicity evolution, which has been explored by many authors (Langer & Norman 2006; Salvaterra & Chincarini 2007; Li 2008; Wang & Dai 2009; Butler et al. 2010; Virgili et al. 2011). For instance, Salvaterra & Chincarini (2007) explored a scenario in which LGRBs arise in metal-poor host galaxies, resulting in a metallicity cut of $Z \lesssim 0.1 Z_\odot$. Following Langer & Norman (2006, hereafter LN), in the scenario where LGRBs are biased to low-metallicity galaxies, the LGRB formation efficiency can be described by an analytical form for the fraction of stellar mass density in galaxies with metallicity below a given value of $Z_{\text{th}}$:

$$\Phi(Z_{\text{th}}, z) = \frac{\Gamma(a_1 + 2, (Z_{\text{th}}/Z_\odot)^{\beta} 10^{0.15(1+z)})}{\Gamma(a_1 + 2)},$$

where $\Gamma$ and $\Gamma$ are the incomplete and complete gamma functions, $a_1 = -1.16$ is the slope of the Schechter mass function of galaxies (Panter et al. 2004), and $\beta = 2$ is the power-law index of the galaxy mass–metallicity relation. It is worth stressing that this analytical form is based on the Schechter mass function of galaxies from Panter et al. (2004) and a linear bisector fit to the mass–metallicity relation obtained by Savaglio et al. (2005) of the form $M/M_\ast = K(Z/Z_\odot)^{0.5}$. LN did not address the redshift evolution of the galaxy mass function, and assumed that the average metallicity simply evolves as a function of the redshift according to $Z/Z_\odot \propto 10^{-0.15z}$, which is from the metallicity measurements of emission-line galaxies by Kewley & Kobulnicky (2005). The validity of these simplifications must be examined.

Following Li (2008), we estimate the redshift evolution of the average metallicity below. Given the scaling $12 + \log(O/H) = \log(Z/Z_\odot) + 8.69$ (Allende Prieto et al. 2001), the redshift-dependent mass–metallicity relation derived by Savaglio et al. (2005) can be written as

$$\log(Z/Z_\odot) = -16.2803 + 2.5315 \log M - 0.09649 \log^2 M + 5.1733 \log t_H - 0.3944 \log^2 t_H - 0.403 \log t_H \log M,$$

where $t_H$ is the Hubble time in units of Gyr and $M$ is the galaxy stellar mass in units of $M_\odot$. Equation (3) then can be used to calculate the average metallicity, which is given by

$$\langle Z/Z_\odot \rangle = \frac{\int_0^\infty Z(M, z) M \Phi(M) dM}{\int_0^\infty M \Phi(M) dM}.$$

By adopting a redshift-evolving galaxy mass function from Drory & Alvarez (2008),

$$\Phi(M, z) dM = \Phi_\ast \left(\frac{M}{M_\ast}\right)^{\gamma} \exp\left(-\frac{M}{M_\ast}\right) \frac{dM}{M_\ast},$$

$$\gamma(z) \approx -1.3,$$

$\langle Z/Z_\odot \rangle$ is calculated and shown in Figure 1 and compared to the measurements from Kewley & Kobulnicky (2005). The result of $\langle Z/Z_\odot \rangle$ with the non-evolving galaxy mass function from Panter et al. (2004) is also shown in Figure 1. As can be seen, the redshift evolution of the metallicity according to $Z/Z_\odot \propto 10^{-0.15z}$ evolves more rapidly to lower metallicity with increasing redshift than that of $\langle Z/Z_\odot \rangle$ with both the evolving and non-evolving galaxy mass functions. This is because the contribution to $\langle Z/Z_\odot \rangle$ is dominated by galaxies with mass around $M_\ast \sim 10^{11}$, whereas faster evolution of metallicity is primarily due to low-mass galaxies (Savaglio et al. 2005; Li 2008). However, due to the small number of LGRBs with well-determined redshifts and many uncertain biases, such as their selection effects, evolving luminosity function, and the evolving stellar initial mass function (IMF), for our purpose, it is enough to adopt the analytical form of LN in this paper.

In addition to LN, Robertson & Ellis (2012) extended the model of Kocevski et al. (2009) to calculate $\Phi(z)$ from the star formation fraction below some metallicity cut. They found that star formation proceeding in galaxies with metallicity below the value $12 + \log(O/H)_{\text{crit}} \approx 8.7$, which corresponds
to $z \sim 0.6-1.0 \ Z_\odot$ depending on the solar abundance value (Modjaz et al. 2008) and metallicity scale used, tracks the LGRB rate with high consistency and parameterized it as

$$\Psi_m(z) = 0.5454 + (1-0.5454) \times [\text{erf}(0.324675z)]^{1.45}. \quad (6)$$

In Figure 2, we show a comparison of Equation (2) with different values in metallicity cut ($Z_{th} = 0.1-0.6 \ Z_\odot$) and the parameterized best-fit from Robertson & Ellis (2012). As can be seen, the best-fit of Robertson & Ellis (2012) is similar to the $Z = 0.6 \ Z_\odot$ case of LN.

### 2.2. The CSFR Models

The black hole formation rate $\dot{n}_{BH}(z)$ is calculated by

$$\dot{n}_{BH}(t) = \int_{m_{BH}}^{m_\text{up}} \Phi(m) \dot{\rho}_s(t - \tau_m) \ dm, \quad (7)$$

where the lower limit of the integral, $m_{BH}$, represents the minimum mass of a star that could collapse to a black hole, which is taken to be 25 $M_\odot$ (Bromm & Loeb 2002). $\Phi(m)$ is the stellar IMF, and $\dot{\rho}_s(t - \tau_m)$ represents the CSFR at the retarded time $(t - \tau_m)$, where $\tau_m$ is the lifetime of a star with mass $m$.

We consider that the IMF follows the Salpeter (1955) form $\Phi(m) = Am^{-2.35}$ and this function is normalized as $\int_{m_{up}}^{m_{inf}} Am^{-2.35} \ dm = 1$, where we take $m_{inf} = 0.1 M_\odot$ and $m_{up} = 140$ for lower and upper mass limits, respectively.

The stellar lifetime $\tau_m$ as a function of mass $m$ is given by the fit of Scalo (1986) and Copi (1997):

$$\log_{10}(\tau_m) = 10.0 - 3.6 \log_{10}\left(\frac{M}{M_\odot}\right) + \left[\log_{10}\left(\frac{M}{M_\odot}\right)\right]^2. \quad (8)$$

For CSFR $\dot{\rho}_s$, there are many forms available in the literature. Kistler et al. (2008, 2009) and Robertson & Ellis (2012) adopted the piecewise-linear model of Hopkins & Beacom (2006), which provides a widely accepted empirical fit to the available multiband observations. However, it should be stressed that the empirical fit will obviously vary depending on the functional form as well as the adopted observational data. As a comparison, the model of Cole et al. (2001) is also considered, which is given by the parametric form:

$$\dot{\rho}_s = \frac{(a + bz)h}{1+(z/c)^d}, \quad (9)$$

where $h = 0.7$, $a = 0.017$, $b = 0.13$, $c = 3.3$, and $d = 5.3$ (Hopkins & Beacom 2006).

In addition, we utilize a self-consistent model derived by Pereira & Miranda (2010) from the hierarchical structure formation scenario. Using the Press–Schechter formalism, Pereira & Miranda (2010) obtained the CSFR by means of solving the evolution equation of the total gas density that takes into account the baryon accretion rate and the lifetime of the stars produced in the halos. Two predictions of this model are shown under different assumptions on the threshold dark matter halo mass below which star formation is suppressed: $M_{min} = 3 \times 10^8 M_\odot$ and $M_{min} = 3 \times 10^9 M_\odot$. The lower value assumes that the star formation proceeds in the halos down to the limit of H I cooling ($T_{vir} \sim 2 \times 10^4$ K), while the higher value corresponds to a fit to the observed high-redshift CSFR, which successfully reproduces the CSFR from $z = 5$ to $z = 8$.

All these different CSFRs are summarized in Figure 3, compared to the data from Hopkins (2004, 2007) and Li (2008). As can be seen, all of these models are similar and consistent with observations at redshift $z < 4$. At high redshifts, the Pereira & Miranda (2010) CSFR remains much flatter than the two empirical fits from Hopkins & Beacom (2006) and Cole et al. (2001), which are already beginning to drop exponentially.

### 3. COMPARISON WITH THE OBSERVATIONAL DATA

To compare with observations, we calculate the expected cumulative redshift distribution of LGRBs as

$$N(<z) = A \int_{0}^{z} \Psi(z) \dot{n}_{BH}(z) \frac{dV}{dz} \ dz, \quad (10)$$

where $A$ is a constant that depends on the observing time, the sky coverage, the survey flux limit, and so on. $dV/dz$ is the comoving volume element per unit redshift, computed by

$$\frac{dV}{dz} = \frac{4 \pi c d_L^2}{1+z} \left| \frac{dt}{dz} \right|, \quad (11)$$

where $d_L$ is the luminosity distance and $dt/dz$ is given by (Pereira & Miranda 2010)

$$\frac{dt}{dz} = \frac{9.78 \ h^{-1} \ Gyr}{(1+z) \sqrt{\Omega_m + \Omega_k (1+z)^3}}. \quad (12)$$

The constant $A$ can be removed by normalizing the cumulative redshift distribution of LGRBs to $N(0, \ z_{max})$ as

$$N(<z|z_{max}) = \frac{N(0, z)}{N(0, z_{max})}. \quad (13)$$

Our LGRB sample is taken from Robertson & Ellis (2012), which consists of 152 LGRBs with well-determined redshifts. Robertson & Ellis (2012) chose the sample from Butler et al. (2007, 2010), Perley et al. (2009), Sakamoto et al. (2011), Greiner et al. (2011), and Krühler et al. (2011), including only LGRBs detected before the end of the Second Swift BAT GRB Catalog. To remove the influence of the Swift threshold
Figure 3. Cosmic star formation rate (CSFR) vs. redshift $z$. The solid line represents the empirical fit of Hopkins & Beacom (2006, HB) and the dashed line corresponds the empirical fit of Cole et al. (2001, C). The short-dashed line and dot-dashed line represent the model of Pereira & Miranda (2010) with a threshold mass: $\log M_{\text{min}} = 8.5$ and $\log M_{\text{min}} = 9.5$, respectively. The observational data are taken from Hopkins (2004, 2007) and Li (2008).

 owing to which low-luminosity bursts cannot be observed at higher redshift, as in Kistler et al. (2008) and Robertson & Ellis (2012), we only use bursts with isotropic-equivalent luminosities $L_{\text{iso}} > 10^{51}$ erg s$^{-1}$ which is computed by

$$L_{\text{iso}} = \frac{E_{\text{iso}}}{T_{90}(1+z)},$$

where $E_{\text{iso}}$ is the isotropic-equivalent energy and $T_{90}$ is the time interval containing 90% of the prompt emission. This culling leaves us with 87 LGRBs over $0 < z < 4$.

Figure 4 shows the comparison between the cumulative redshift distribution of the observed LGRBs and the expectations $N(<z|z_{\text{max}} = 4)$ with the adoption of the Hopkins & Beacom (2006) CSFR, for three different metallicity cuts using Equation (2) and the parameterized best-fit of Robertson & Ellis (2012). We then use the one-sample Kolmogorov–Smirnov (K-S) test to assess the consistency between the redshift distribution of the observed and expected LGRBs. In agreement with previous studies (Kistler et al. 2008; Robertson & Ellis 2012), the model with no metallicity cut shows little consistency with the observations, with $P \approx 0.1$. However, in contrast to previous studies that suggest a metallicity cut of $Z_{\text{th}} \lesssim 0.3 Z_\odot$ (Woosley & Heger 2006; Langer & Norman 2006; Salvaterra & Chincarini 2007; Li 2008; Campisi et al. 2010), the model with a cut of $Z_{\text{th}} = 0.3 Z_\odot$ shows little consistency with the data. Only the intermediate model adopting the value of $Z_{\text{th}} = 0.6 Z_\odot$ shows high consistency with the data, similar to the model from the best-fit of Robertson & Ellis (2012). On the other hand, when assuming the Cole et al. (2001) model for the star formation rate, even the model with no metallicity cut is fully consistent with the data at the probability level of 0.78 (Figure 5). The K-S test gives the probability 99% of a more relaxed cut of $Z_{\text{th}} = 0.9 Z_\odot$. Note that this higher cut is also more consistent with recent studies of the LGRB host galaxies (Graham et al. 2009; Levesque et al. 2010a, 2010b; Michałowski et al. 2012). The test statistics and probability for the relevant models are summarized in Table 1.

We now consider the self-consistent CSFR model of Pereira & Miranda (2010). Figure 6 shows the comparison with the cumulative redshift distribution of the 62 LGRBs with $z < 5$ and $L > 3 \times 10^{51}$ erg s$^{-1}$, normalized over the range $0 < z < 5$. As can be seen, provided that the star formation proceeds in the halos down to the limit of H$\upgamma$ cooling ($T_{\text{vir}} \sim 2 \times 10^4$ K
and $M_{DM} \sim 3 \times 10^{9} M_\odot$, the calculated LGRB redshift distribution $N(z < z_{\text{max}} = 5)$ fits the observational data very well even without considering the extra evolution effect of metallicity ($P \approx 0.96$), implying that LGRBs are produced in all types of star-forming galaxies. This result also implies an alternative explanation for the CSFR–LGRB rate discrepancy, i.e., there is significant star formation in faint galaxies, as suggested by Trenti et al. (2012). To illustrate this, we utilize this CSFR model to calculate the LGRB distributions for different threshold masses of dark matter halos. The results are shown in Figure 7 and demonstrate that the LGRB redshift distribution is consistent with a threshold halo mass of $M_{\text{min}} = 3 \times 10^{9} M_\odot$ at the 96% level (and $M_{\text{min}} = 3 \times 10^{8} M_\odot$ at the 39% level). This is also in agreement with that found by Muñoz & Loeb (2011), in which the minimum mass halo capable of hosting galaxies is suggested to be around $2.5 \times 10^{9} M_\odot$.

4. CONCLUSION

The connection of LGRBs with the collapse of massive stars has provided a unique opportunity to probe the history of star formation at high redshifts. In this case, how the LGRB rate is connected to the CSFR needs to be known. In this work, we have investigated the idea that LGRBs as biased indicators of the CSFR occur preferentially in low-metallicity galaxies. We tested various CSFR models together with the metallicity considerations of Langer & Norman (2006) using the constraints from newly discovered bursts.

Comparing the cumulative redshift distribution of luminous ($L_{iso} > 10^{51}$ erg s$^{-1}$) Swift LGRBs compiled by Robertson & Ellis (2012) over $0 < z < 4$, we find a relatively higher metallicity cut of $Z_{th} = 0.6$–0.9 $Z_\odot$ for both star formation rate models of Hopkins & Beacom (2006) and Cole et al. (2001), in contrast to previous studies which suggest a strong metallicity cut of $<0.1–0.3 Z_\odot$ (Salvaterra & Chincarini 2007; Campisi et al. 2010; Virgili et al. 2011). Especially when considering a self-consistent star formation model of Pereira & Miranda (2010) which takes into account a hierarchical structure formation scenario, the calculated expectations show strong consistency with the observational data over $0 < z < 5$, requiring no metallicity cut at all. These results imply that
LGRBs are tracers of a significant fraction of the total star formation with no biases, which is consistent with recent studies on LGRB hosts (Michałowski et al. 2012; Elliott et al. 2012). Therefore, we conclude that LGRBs populate all types of star-forming galaxies, with no strong metallicity preference, which means that LGRBs are less biased tracers of the star formation than previously suggested. Moreover, using the self-consistent CSFR model, we also find that the scenario that a significant fraction of LGRBs occur in small halos down to $3 \times 10^8 M_\odot$ can provide an alternative explanation for the difference between the CSFR and LGRB rate. Our results also show that the inferred low-metallicity dependencies of LGRBs are strongly related to the specific CSFR model one adopts, suggesting that detailed observations of individual LGRB host galaxies are essential to provide a better understanding of the metallicity cut for LGRB production. If numbers of similar observations are confirmed, it could mean that the key role that metallicity plays in producing LGRBs, which is suggested by the traditional collapsar model, needs reconsideration in future studies or it may need alternative progenitor pathways in which a low-metallicity environment is not necessarily required.

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REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJL, 556, L63
Bolton, J. S., & Haehnelt, M. G. 2007, MNRAS, 382, 325
Bromm, V., & Loeb, A. 2002, ApJ, 575, 111
Butler, N. R., Bloom, J. S., & Poznanski, D. 2010, ApJ, 711, 495
Butler, N. R., Kocevski, D., Bloom, J. S., & Curtis, J. L. 2007, ApJ, 671, 656
Campisi, M. A., Li, L.-X., & Jakobsson, P. 2010, MNRAS, 407, 1972
Cen, R. 2003, ApJ, 594, 12
Choudhury, T. R., & Ferrara, A. 2006, MNRAS, 371, L55
Cole, S., Norberg, P., Baugh, C. M., et al. 2001, MNRAS, 326, 255
Copi, C. J. 1997, ApJ, 487, 704
Daigne, F., Rossi, E. M., & Mochkovitch, R. 2006, MNRAS, 372, 1034
Drory, N., & Alvarez, M. 2008, ApJ, 680, 41
Elliott, J., Greiner, J., Khochfar, S., et al. 2012, A&A, 539, A113
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Graham, J. F., Fruchter, A. S., Kewley, L. J., et al. 2009, in AIP Conf. Ser. 1133, Gamma-ray Burst: Sixth Huntsville Symposium, ed. C. Meegan, C. Kouveliotou, & N. Gehrels (Melville, NY: AIP), 269
Greiner, J., Krühler, T., Klose, S., et al. 2011, A&A, 526, A30
Hopkins, A. M. 2004, ApJ, 615, 209
Hopkins, A. M. 2007, ApJ, 654, 1175
Hopkins, A. M., & Beacom, J. F. 2006, ApJ, 651, 142
Iliev, I. T., Mellema, G., Shapiro, P. R., & Pen, U.-L. 2007, MNRAS, 376, 534
Kewley, L., & Kobulnicky, H. A. 2005, in Starbursts: From 30 Doradus to Lyman Break Galaxies, ed. R. de Grijs & R. M. González Delgado (Astrophysics and Space Science Library, Vol. 329; Dordrecht: Springer), 307
Kistler, M. D., Yüksel, H., Beacom, J. F., Hopkins, A. M., & Wyithe, J. S. B. 2009, ApJL, 705, L104
Kistler, M. D., Yüksel, H., Beacom, J. F., & Stanek, K. Z. 2008, ApJL, 673, L119
Kocevski, D., West, A. A., & Modjaz, M. 2009, ApJ, 702, 377
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Krühler, T., Greiner, J., Schady, P., et al. 2011, A&A, 534, A108
Langer, N., & Norman, C. A. 2006, ApJL, 638, L63
Levesque, E. M., Kewley, L. J., Berger, E., & Zahid, H. J. 2010a, AJ, 140, 1557
Levesque, E. M., Kewley, L. J., Graham, J. F., & Fruchter, A. S. 2010b, ApJL, 712, L26
Levesque, E. M., Soderberg, A. M., Kewley, L. J., & Berger, E. 2010c, ApJL, 725, 1337
Li, L.-X. 2008, MNRAS, 388, 1487
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Michałowski, M. J., Kamble, A., Hjorth, J., et al. 2012, ApJ, 755, 85
Modjaz, M., Kewley, L., Krishner, R. P., et al. 2008, AJ, 135, 1136
Muñoz, J. A., & Loeb, A. 2011, ApJ, 729, 99
Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2012, ApJ, 745, 110
Panter, B., Heavens, A. F., & Jimenez, R. 2004, MNRAS, 355, 764
Pereira, E. S., & Miranda, O. D. 2010, MNRAS, 401, 1924
Perley, D. A., Chen, S. B., Bloom, J. S., et al. 2009, AJ, 138, 1690
Pforr, N., & Madau, P. 2001, ApJ, 548, 522
Robertson, B. E., & Ellis, R. S. 2012, ApJ, 744, 95
Sakamoto, T., Barthelmy, S. D., Baumgartner, W. H., et al. 2011, ApJS, 195, 2
Salpeter, E. E. 1955, ApJ, 121, 161
Salvaterra, R., & Chincarini, G. 2007, ApJL, 656, L49
Savaglio, S., Glazebrook, K., & Le Borgne, D. 2009, ApJL, 691, 182
Savaglio, S., Glazebrook, K., Le Borgne, D., et al. 2005, ApJ, 635, 260
Savaglio, S., Rau, A., Greiner, J., et al. 2012, MNRAS, 420, 627
Scalo, J. M. 1986, FCPb, 11, 1
Svensson, K. M., Levan, A. J., Tanvir, N. R., Fruchter, A. S., & Strolger, L.-G. 2010, MNRAS, 405, 57
Trenti, M., Perna, R., Levesque, E. M., Shull, J. M., & Stocke, J. T. 2012, ApJL, 749, L38
Virgili, F. J., Zhang, B., Nagamine, K., & Choi, J.-H. 2011, MNRAS, 417, 3025
Wang, F. Y., & Dai, Z. G. 2009, MNRAS, 400, L10
Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507
Woosley, S. E., & Heger, A. 2006, ApJ, 637, 914
Yüksel, H., Kistler, M. D., Beacom, J. F., & Hopkins, A. M. 2008, ApJL, 683, L5