Cosmic $\gamma$-Ray Bursts as a Probe of Star Formation History

Enrico Ramirez-Ruiz*,†, Edward E. Fenimore† & Neil Trentham*

*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom.
†D-436, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, U.S.A.

Abstract.
The cosmic $\gamma$-ray burst (GRB) formation rate, as derived from the variability-luminosity relation for long-duration GRBs, is compared with the cosmic star formation rate. If GRBs are related to the collapse of massive stars, one expects the GRB rate to be approximately proportional to the star formation rate. We found that these two rates have similar slopes at low redshift. This suggests that GRBs do indeed track the star formation rate of the Universe, which in turn implies that the formation rate of massive stars that produce GRBs is proportional to the total star formation rate. It also implies that we might be able to use GRBs as a probe of the cosmic star formation rate at high redshift. We find that the cosmic star formation rate inferred from the variability-luminosity relation increases steeply with redshift at $z > 3.0$. This is in apparent contrast to what is derived from measurements of the cosmic star formation rate at high redshift from optical observations of field galaxies, suggesting that much high-$z$ star formation is being missed in the optical surveys, even after corrections for dust extinction have been made.

THE COSMIC STAR FORMATION RATE

The variation of the total cosmic star formation rate with redshift $z$ — the SFR plot — is conventionally determined by measurements of the H$\alpha$ luminosity of galaxies at $z < 0.2$ and of UV luminosities at $z > 0.2$ (Madau et al. 1996).

Two major complications in constructing the SFR plot at any $z$ are (i) the need to correct UV luminosities for dust extinction, and (ii) the need to assume a stellar IMF. However, both of these seem to have been addressed with considerable success: (i) by adopting the corrections of Calzetti (1997), which when applied to the CFRS data of Lilly et al. (1996) produce a SFR plot similar to that generated from infrared ISO observations (Flores et al. 1999), which are sensitive to the absorbed and re-radiated UV flux, and (ii) by using an IMF that flattens below 1 $M_\odot$ e.g. that of Kroupa et al. 1993, which seems to be universal (Gilmore & Howell 1998). The SFR plot constructed with both of these assumptions, when integrated over cosmic
time, reproduces the correct local stellar density of $\Omega_* \sim 0.005$ that we derive from a number of methods. We can therefore have considerable confidence in current determinations of the SFR plot at $z < 3$ (Somerville et al. 2000).

At $z > 3$, there are additional, potentially more serious, complications. The only types of high-$z$ galaxies whose contributions to the SFR plot have been unambiguously determined are the Lyman-break galaxies (LBGs; Steidel et al. 1999). Lyman-$\alpha$ (Ly$\alpha$) emitters may contribute too, but current indications are that their contribution is small ($10^{-2} \, M_\odot \, yr^{-1} \, Mpc^{-3}$ compared to $10^{-1} \, M_\odot \, yr^{-1} \, Mpc^{-3}$ for the LBGs; Hu et al. 1998). However, these Ly$\alpha$-emitters and other galaxies which might exist but cannot be found by the selection techniques used to find either Ly-break or Ly$\alpha$ galaxies, could have their contributions systematically underestimated. Such galaxies might be lost due to $(1 + z)^{-4}$ surface-brightness dimming (Lanzetta et al. 2000), or the detectability of a small fraction of the members of a population might be enhanced by supernovae that happened to go off in those members causing us to miss the bulk of the sources representing that population (the supernovae are not dimmed by $(1 + z)^{-4}$ and can affect detectability if $10 \log(1 + z) > \text{mag}_{\text{SN}} - \text{mag}_{\text{gal}}$). Therefore, indirect constraints are important at such high $z$. The constraint from $\Omega_*$ is weak since the contribution to the total integral of the SFR plot is small at high $z$ since $dt/dz$ is small there. Another constraint is that all the star formation at $z > 3$ must produce enough metals to enrich the Ly$\alpha$ forest at $z = 3$ (Cowie & Songaila 1998), but this is also of limited use here, since it is unclear what fraction of metals escape from the galaxies in which the stars form. A potentially more powerful probe is given by the $\gamma$-ray burst (GRB) formation rate plot, which must track the SFR plot closely if the majority of GRBs originate from the collapse of massive stars. This is what we investigate here.

**THE $\gamma$-RAY BURST RATE**

GRBs are detectable out to the farthest reaches of the observable Universe, and provide information about processes occurring at all cosmic epochs. Recent observations suggest that the long-duration GRBs and their afterglows are produced by highly relativistic jets emitted in core-collapse supernova explosions. Hence the redshift distributions of GRBs should track the cosmic star formation rate of massive stars accurately (Lamb & Reichart 2000; Blain & Natarajan 2000). At present, however, there are too few redshift measurements with which to estimate the global GRB formation rate. Nonetheless, these few measured redshifts can be used to calibrate properties of GRBs that might let them serve as standard candles. Fenimore & Ramirez-Ruiz (2000) have suggested that the spikiness of the burst time structure is correlated with luminosity, with smooth bursts being intrinsically less luminous. In principle, the measured spikiness combined with the observed flux can be used to obtain distances much like Cepheid observations give distance estimates from the pulsation period. Using a sample of 220 bright BATSE
bursts for which high-resolution light curves were available, Fenimore & Ramirez-Ruiz (2000) estimated the evolution of the GRB formation rate from parameters measured solely at $\gamma$-ray energies.

![Figure 1](image.png)

**FIGURE 1.** A summary of the current state of knowledge of the star formation history of the Universe. The data points plotted are described in Somerville et al. (2000). The open stars are the GRB formation rate obtained by Fenimore & Ramirez-Ruiz (2000) normalized to the SFR at $z=1$ ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $H_o = 65$ km s$^{-1}$ Mpc$^{-1}$). The error bars represent the systematic uncertainty in the burst formation rate calculated from the uncertainty in the variability-luminosity relationship, and are clearly larger than the statistical uncertainty on each data point.

**THE SFR PLOT AT $z < 3.0$**

At low redshift, the GRB formation rate (BFR) plot tracks the SFR plot in shape (see Figure 1). This is the redshift regime where we have considerable confidence in the SFR plot (see § 1). This concordance suggests:

(i) the idea that GRBs do indeed track the SFR of the Universe. This would imply that the formation rate of massive stars that produce GRBs is proportional to the total SFR, as would follow if the IMF does not vary substantially over this $z$ range;

(ii) that we can use GRBs as a high-$z$ probe. They are not affected by extinction or surface-brightness dimming. So one might therefore expect the high-$z$ BFR plot to track the high-$z$ SFR plot.
THE SFR PLOT AT $z > 3.0$

The high-$z$ BFR plot has a steep slope. This is different from the much flatter slope of the SFR plot as derived from LBG observations (Steidel et al. 1999). If the BFR plot does indeed track the SFR plot at high-$z$ (as it does at low-$z$), then this would suggest that much high-$z$ star formation is being missed in the optical surveys, even after corrections for dust extinction have been made.

Interestingly, Lanzetta et al. (2000) find evidence for a very steep SFR plot based on an analysis of high-$z$ galaxies in the Hubble Deep Fields in which they consider selection effects that can arise from surface-brightness dimming. An additional source of star-formation at high-$z$ could come from luminous SCUBA galaxies (Blain et al. 1999) which could be missing from optical surveys (e.g. Smail et al. 1999) because they are heavily extinguished by dust.

One important caveat is that the redshift range ($z < 3.0$) in which the BFR plot tracks the SFR plot is similar to the redshift range in which GRBs were used to calculate the variability-luminosity relation (there is only one event with $z > 3.0$). The application of this relation to faster variabilities and therefore higher luminosities (as is required to derive the BFR plot at $z > 3.0$) depends on an extrapolation of this relation. If the extrapolation fails, this weakens our conclusion about the steep slope of the BFR at high-$z$. Also, if the fraction of massive stars that produce GRBs is a strong function of metallicity, then this could create a redshift-dependence of the normalization of the BFR plot relative to the SFR plot, which would also weaken the assertion that the SFR plot is steep at high-$z$.

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