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# ON THE COLLAPSAR MODEL OF LONG GAMMA-RAY BURSTS: CONSTRAINTS FROM COSMIC METALLICITY EVOLUTION

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## ABSTRACT

We explore the consequences of new observational and theoretical evidence that long gamma-ray bursts (GRBs) prefer low-metallicity environments. Using recently derived mass-metallicity correlations and the mass function from SDSS studies, and adopting an average cosmic metallicity evolution from Kewley & Kobulnicky and Savaglio et al., we derive expressions for the relative number of massive stars formed below a given fraction of solar metallicity, $\epsilon$, as a function of redshift. We demonstrate that about 1/10 of all stars form with $\epsilon < 0.1$. Therefore, a picture in which the majority of GRBs form with $\epsilon < 0.1$ is not inconsistent with an empirical global SN/GRB ratio of 1/1000. It implies that (1) GRBs peak at a significantly higher redshift than supernovae; (2) massive star evolution at low metallicity may be qualitatively different; and (3) the larger the low-metallicity bias of GRBs, the less likely binary evolution channels can be significant GRB producers.

*Subject headings:* galaxies: evolution — gamma rays: bursts — stars: Wolf-Rayet

*Online material:* color figures

## 1. INTRODUCTION

It become clear in the last few years that long GRBs are associated with the endpoints of massive star evolution. They occur in star-forming regions at cosmological distances (Jakobsen et al. 2005) and are associated with supernova-type energies. The collapsar model explains GRB formation via the collapse of a rapidly rotation massive iron core into a black hole (Woosley 1993). The short timescale of gamma-ray emission requires a compact stellar size, on the order of light-seconds. This constraint leaves only massive Wolf-Rayet stars as possible progenitors. However, this poses a difficulty: Wolf-Rayet stars in the local universe are known to have strong stellar winds (Nugis et al. 1998), which lead to a rapid spin-down (Langer 1998), in agreement with the absence of signatures of rapid rotation in the Galactic Wolf-Rayet sample (Eenens 2004).

It is the current understanding that the ratio of GRBs to supernovae is about 1/1000, based on about $(1–2) \times 10^{-6}$ observed bursts per supernova in the BATSE sample (Porciani & Madau 2001), and a beaming factor of ~500 (Frail et al. 2001; Yonetoku et al. 2005). This implies that about 1 out of 100 Wolf-Rayet stars produces a GRB (van Putten 2004). These low values are thought to support the idea that rather exotic binary evolution channels might constitute the main evolutionary paths towards GRBs (Podsiadlowski et al. 2004; Fryer & Heger 2005), corroborated by the two basic problems of single-star models in producing collapsars (Petrovic et al. 2005): (1) the spin-down of the stellar core due to magnetic core-envelope coupling (Heger et al. 2005; Petrovic et al. 2005), which is required to understand the slow rotation of young pulsars (Ott et al. 2005) and white dwarfs (Berger et al. 2006), and (2) the spin-down due to Wolf-Rayet winds mentioned above.

However, recent single-star models have overcome both problems for suitable initial conditions. The models by Woosley

& Heger (2006) and Yoon & Langer (2005) avoid problem 1 by rapid rotation, which keeps the stars nearly chemically homogeneous and thus avoids the formation of a massive envelope, and problem 2 by choosing a low enough metallicity, which according to recent evidence (Crowther et al. 2002; Vink & de Koter 2005) reduces the Wolf-Rayet mass-loss rates. These are the first single-star evolution models fulfilling the requirements of the collapsar model that are at the same time fully consistent with the slowly rotating stellar remnants in our Galaxy. However, they predict long GRBs only for metallicities of about $Z/Z_\odot \lesssim 0.1$.

In this context, the growing empirical evidence that the long bursts indeed prefer a low-$Z$ environment is remarkable. While indirect evidence from GRB host galaxies is pointing toward low metallicity (Fynbo et al. 2003; Conselice et al. 2005; Fruchter et al. 2006), direct metallicity determinations yield subsolar values down to 1/100 of the solar metallicity (Gorosabel et al. 2005; Chen et al. 2005; Starling et al. 2005). While the observational and the theoretical evidence for long GRBs occurring at low metallicity needs further confirmation, we are motivated by the findings reported above to explore the consequences of such a possibility.

## 2. METHOD AND RESULTS

In order to quantify the amount of star formation at a given metallicity, we use the Schechter distribution function of galaxy masses and then substitute in it the well-defined mass-metallicity relation. We use the mass function and metallicity-mass correlation determined in comprehensive SDSS studies and deep surveys. For the mass function there are fine studies by Cole et al. (2001), Bell et al. (2004), and Panter et al. (2004), and we use the latter here. For the mass-metallicity relation we use the classic studies of Tremonti et al. (2004) and Savaglio et al. (2005). From equation (1) of Panter et al. (2004), we have

$$\Phi(M) = \Phi_* \left(\frac{M}{M_*}\right)^\alpha e^{(-M/M_*)}, \tag{1}$$

where $\alpha = -1.16$ and $\Phi_* = 7.8 \times 10^{-3} \, h^3 \, \mathrm{Mpc}^{-3}$. The frac-

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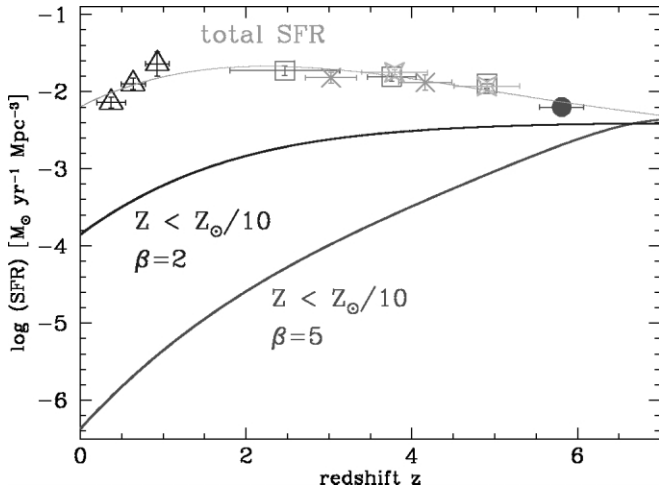[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

Fig. 1.—Formation rate of stars with a metallicity below $Z_\odot/10$ ($\epsilon = 0.1$) for a fiducial galaxy mass-metallicity relation $M \sim Z^\beta$ for $\beta = 2$ (*middle curve*) and $\beta = 5$ (*bottom curve*). These curves have been obtained by multiplication of the fit to the total star formation rate as function of redshift (*top curve*) obtained from the empirical data presented by Bouwens et al. (2004; *points with error bars*) with the fraction $\Psi$ of stars born with a metallicity below a specified value. [*See the electronic edition of the Journal for a color version of this figure.*]

tion $\Psi(M)$ of the mass density in galaxies with a mass less than $M$ is then

$$\Psi(M) = \frac{\int_0^M M\Phi(M)\,dM}{\int_0^\infty M\Phi(M)\,dM} = \frac{\hat{\Gamma}(\alpha + 2,\, M/M_*)}{\Gamma(\alpha + 2)}, \quad (2)$$

where $\hat{\Gamma}$ and $\Gamma$ are the incomplete and complete gamma functions. We then choose the galaxy mass-metallicity relation of the form $M/M_* = K(Z/Z_\odot)^\beta$, where $K$ and $\beta$ are constants. For simplicity we choose to use the linear bisector fit to the mass-metallicity relation derived by Savaglio et al. (2005) at redshift $z = 0.7$. This is parallel to the quadratic fit of Tremonti et al. (2004) at the low masses and metallicities that we consider here. The form we derive is very close to $\beta = 2$ and $K = 1$, and we assume these values. This gives a pleasing Gaussian form to the metallicity function, which may be of more general applicability. We now derive the fractional mass density belonging to metallicities below metallicity $Z$ at a given redshift $z$ as

$$\Psi\left(\frac{Z}{Z_\odot}\right) = \frac{\hat{\Gamma}[\alpha + 2,\, (Z/Z_\odot)^\beta 10^{0.15\beta z}]}{\Gamma(\alpha + 2)}, \quad (3)$$

where we use the average cosmic metallicity scaling as $d[Z]/dz = -0.15$ dex per unit redshift from Kewley & Kobulnicky (2005) and L. Kewley & H. A. Kobulnicky (2006, in preparation). We use this scaling since the mean metallicity is given by

$$\langle Z \rangle = \frac{\int_0^\infty Z(M)M\Phi(M)\,dM}{\int_0^\infty M\Phi(M)\,dM} = K^{-1/\beta}Z_\odot \frac{\Gamma(2 + \alpha + 1/\beta)}{\Gamma(\alpha + 2)}, \quad (4)$$

and thus the mean metallicity is linearly proportional to $Z_\odot$, $\langle Z \rangle = \text{constant} \times Z_\odot$. The ratio of the gamma functions in the above equation gives 0.80 for $\beta = 5$ and 0.73 for $\beta = 2$, assuming $\alpha = -1.16$ in both cases. Our scaling simply gives

self-consistently $\langle Z \rangle = Z_\odot 10^{-\gamma z}$, where from Kewley & Kobulnicky (2005, 2006 [in preparation]) we have $\gamma = 0.15$, which we adopt here. The $\gamma$-value found by Savaglio et al. (2005) is approximately $\gamma \sim 0.3$–0.4 (S. Savaglio 2005, private communication).

This *Ansatz* includes various simplifications. Because the parameter we need here is a ratio of two moments of the mass function, the evolution of the normalization of the mass function (the cosmic stellar mass density) cancels. The remaining evolutionary term is essentially the mean cosmic metallicity evolution. Since we are dealing here with massive star formation from the interstellar medium and since the metallicity constraint is from the physics of line-driven winds, we use the scaling with redshift derived from emission-line studies by Kewley & Kobulnicky (2005, 2006 [in preparation]) for [O/H]. The study of Gallazzi et al. (2005) derives stellar metallicities and gives in their Figure 6 the distribution of stellar metallicity in galaxies at low redshift. As they note, in general the stellar metallicity is always lower than the gas-phase metallicity, and our use of Kewley & Kobulnicky's gas-phase evolution is conservative. We are assuming in these star-forming galaxies that the evolving metallicity distribution we have derived also applies to the ISM in which the stars are forming.

For our fiducial numbers $\alpha = -1.16$, $\beta = 2$, and $K = 1$, we thus obtain

$$\Psi\left(\frac{Z}{Z_\odot}\right) = \frac{\hat{\Gamma}[0.84,\, (Z/Z_\odot)^2 10^{0.30z}]}{\Gamma(0.84)}, \quad (5)$$

where $\Gamma(0.84) \simeq 1.122$.

The result of folding $\Psi$ with the total star formation rate history is shown in Figure 1. Here the total star formation rate $r_{\rm SFR}(z)$ is derived from a fourth-order polynomial fit to the data presented in Bouwens et al. (2004).

In order to be able to compare with observations, we convolve the fraction $\Psi$ of stars born with a metallicity of less than $Z_\odot\epsilon$ with the comoving volume element of the Friedman-Robertson-Walker metric. The quantity $d_m(z)$ used below is the proper-motion distance for our cosmological parameters. We are using the standard cosmological parameters of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

Including the time dilation effect due to redshift that slows the rates with redshift, the unbiased observed rate of core-collapse supernovae from stars with a metallicity below $Z_\odot\epsilon$ then becomes

$$R_{\rm SN}(\epsilon) = f_{\rm SN} 4\pi \int_0^{z_{\rm max}} \frac{\Psi(z, \epsilon)r_{\rm SFR}(z)}{z + 1} d_M^2(z) \left\{\frac{d[d_M(z)]}{dz}\right\}, \quad (6)$$

where

$$f_{\rm SN} = \int_{8\,M_\odot}^{100\,M_\odot} a\varphi(m)\,dm \simeq 0.0074 \quad (7)$$

is the number of core-collapse events per solar mass of stars formed, where $a = 1\,M_\odot / \int \varphi(m)\,dm$, $\varphi(m)$ is the Salpeter initial stellar mass function (IMF), and $f_{\rm SN}$ is the number of core-collapse events per solar mass of star formation. Figure 2 shows the resulting supernova rates, and their integrated value, for various values of $\epsilon$.

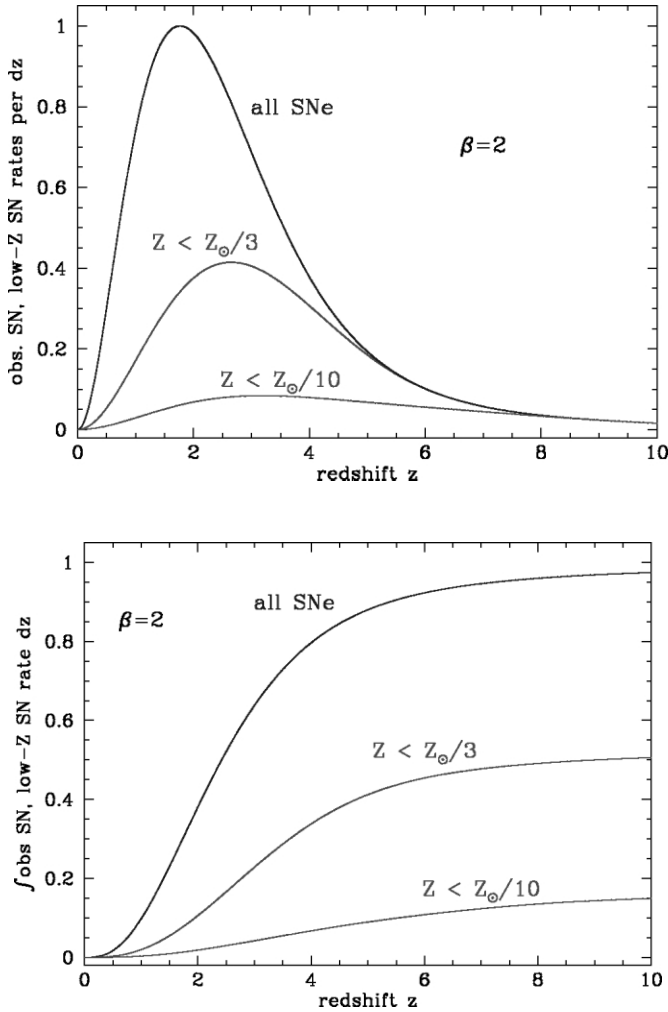In Table 1 we derive the perceived global and local ratios

Fig. 2.—Normalized differential and cumulative core-collapse supernovae rates as a function of redshift as perceived by an unbiased observer (see eq. [6]) for all stars and for stars with metallicities less than $Z_\odot/3$ and $Z_\odot/10$. [*See the electronic edition of the Journal for a color version of this figure.*]

of low-metallicity to all supernovae for various metallicity thresholds and for two galaxy mass-metallicity exponents. From these, we compute formation rates of low-metallicity black holes by assuming supernovae to form from stars above $8\,M_\odot$, but black holes to form only from stars above $30\,M_\odot$, which—for a Salpeter IMF—gives a BH/SN ratio of 0.14. Since black hole formation is only one out of three criteria for GRB production within the collapsar frame, our derived numbers

give an upper limit to the GRB production rate from low metallicities, independent of the stellar evolution scenario considered. For $\epsilon = 0.1$, this corresponds to less than 22 GRBs per 1000 SNe globally in the universe, and to less than 3/1000 at low redshift. This is what stars with a metallicity of $Z_\odot/10$ and below can provide maximally. Table 1 shows further that the constraint of achieving 1 GRB per 1000 SNe globally in the universe results in about 1 GRB per 10,000 SNe in the local universe.

We note that these numbers seem to be remarkably insensitive to details of the star formation history. The last row in Table 1 is computed by using the star formation history shown by Firmani et al. (2006), which is similar to the one used here up to redshift 2, but which remains at the top level until about $z = 6$ (see their Fig. 2). However, Table 1 also shows that the redshift at which the GRB rate peaks does depend on the star formation history and thus cannot yet be predicted reliably.

### 3. DISCUSSION AND CONCLUSIONS

To produce a GRB, Wolf-Rayet stars at core collapse are required to have sufficient angular momentum. Stellar evolution models that include magnetic fields predict too slowly rotating cores for models that develop an extended, massive envelope after the main sequence. Current evolutionary models that include rotation predict extended envelopes for the vast majority of massive stars in the Galaxy or Magellanic Clouds, in agreement with the number of blue and red supergiants (Maeder & Meynet 2001, 2005). Only the fastest rotators are thought to be able to avoid extended envelopes for metallicities below about $Z_\odot/10$ or $\epsilon = 0.1$ (Yoon & Langer 2005; Woosley & Heger 2006).

Most importantly, the numbers derived for $\epsilon = 0.1$ in Table 1 appear not to be in conflict with observations. Per 1000 supernovae in the universe, 160 are predicted to occur from stars with $Z > Z_\odot/10$, out of which 22 would produce a black hole. Thus, producing one GRB per 1000 supernovae globally in the universe (see § 1) seems possible.

On the other hand, a large fraction of the 22 black holes may be born without producing a GRB: not all of them may occur in W-R stars but rather in more extended stars (Maeder & Meynet 2005), and the most massive ones would lose too much angular momentum in a wind, even for metallicities as low as $Z > Z_\odot/10$ (Yoon & Langer 2005). While within the chemically homogeneous evolution scenario for GRB formation (Yoon & Langer 2005; Woosley & Heger 2006) a GRB/BH fraction of 1/20 can certainly be obtained (Yoon & Langer 2006), this is therefore unlikely for exotic binary channels for

TABLE 1
Ratios of Low-Metallicity Supernovae and Black Holes and GRBs

| $\epsilon$ | $\beta$ | $\langle$low-Z SNe/1000 SNe$\rangle$ | $\langle$low-Z BHs/1000 SNe$\rangle$ | (low-Z SNe/1000 SNe)$_{z=0}$ | (low-Z BHs/1000 SNe)$_{z=0}$ | (GRB/1000 SNe)$_{z=0}$ | $z_{SN}$ | $z_{GRB}$ |
|---|---|---|---|---|---|---|---|---|
| 0.3 ....... | 2 | 520 | 73 | 130 | 18 | 0.25 | 1.8 | 2.7 |
| 0.1 ....... | 2 | 160 | 22 | 20 | 3 | 0.13 | 1.8 | 3.2 |
| 0.03 ...... | 2 | 34 | 5 | 3 | 0.4 | 0.09 | 1.8 | 5.3 |
| 0.01 ...... | 2 | 7 | 1 | 0.5 | 0.07 | 0.08 | 1.8 | 9.8 |
| 0.3 ....... | 5 | 380 | 53 | 7 | 1 | 0.02 | 1.8 | 3.7 |
| 0.1 ....... | 5 | 60 | 8 | 0.007 | 0.001 | 0.0001 | 1.8 | 7.0 |
| 0.1 ....... | 2 | 160 | 22 | 20 | 3 | 0.13 | 2.0 | 5.3 |

Notes.—For various upper metallicity limits $\epsilon$ and galaxy mass-metallicity exponents $\beta$, we show the number of supernovae with $Z/Z_\odot < \epsilon$ (or "low-Z supernovae") per 1000 supernovae in the universe as seen from an unbiased observer (see eq. [6] and Fig. 2), the corresponding number of "low-Z black holes" per 1000 supernovae, both numbers at redshift $z = 0$, the local ($z = 0$) number of GRBs per 1000 supernovae required to have a global GRB/SN ratio of 1/1000, and the redshifts at which the SN and GRB rates are perceived as maximum by an unbiased observer (see Fig. 2). For the bottom row, a different underlying star formation history has been assumed (see text).

GRB production, i.e., for channels through which only a small fraction of stars of any initial mass evolve. Clearly, the more the long GRBs are confined to low metallicities, the more unlikely it is that binary evolution is needed to explain the majority of events.

The empirical cosmic GRB-to-SN ratio of about 1/1000 (see § 1) cannot directly rule out more extreme values of $\epsilon$, i.e., $\epsilon = 0.1$–0.01 (see Table 1); in fact, for $\epsilon = 0.01$, about 10% of all massive stars with $Z < Z_\odot/100$ would need to produce a GRB. However, this would imply that the formation of *every* black hole would be accompanied by a GRB. Furthermore, the GRB rate would peak only at a redshift of about $z = 10$. A value of $\epsilon = 0.01$ thus appears unlikely. Furthermore, our models with $\beta = 5$ produce such a small local GRB/SN ratio that they seem to be ruled out.

We find that a restriction of GRBs to low metallicities ($Z < Z_\odot/10$; i.e., $\epsilon = 0.1$) has the following consequences:

1. GRBs do not follow star formation in an unbiased manner. For example, for an overall star formation rate that predicts a perceived SN peak at a redshift of $z_{SN} \simeq 1.8$, we find for $\epsilon = 0.1$ that the GRB rate peaks at a redshift of $z_{GRB} \simeq 3.2$ (Fig. 2 and Table 1; see also Firmani et al. 2006).

2. Local massive galaxies, such as our Milky Way, are not expected to host long GRBs. The last long GRB in our Galaxy should have occurred several gigayears ago.

3. The global and local GRB-to-SN ratios appear to be insensitive to the details of the cosmic star formation history, while the redshift of the peak GRB rate can vary appreciably (Table 1).

4. The local GRB/core-collapse ratio is much smaller than the one obtained from averaging over the universe, i.e., by 1 order of magnitude for $\epsilon = 0.1$ (Table 1).

5. We obtain the expected result that the number of massive stars in the universe with a metallicity below a critical value $\epsilon$ does roughly scale with $\epsilon$. That is, for $\epsilon = 0.1$ we find a ratio of low-metallicity ($Z < Z_\odot/10$) to total global supernova rates of 0.16. Furthermore, the probability that a randomly chosen burst has a metallicity of $Z_\odot/100$ is about 10%.

6. We derive the most likely redshift for GRBs of specified metallicity for unbiased observations. For example, for a metallicity of $Z_\odot/100$, as found for GRB 050730, we find GRBs to occur most likely at redshifts of $z > 6$. Locally, the ratio of GRBs with a metallicity of $Z_\odot/100$ to all GRBs is about 0.02 (Table 1).

7. The larger the low-metallicity bias of long GRBs, the less likely can binary scenarios explain the major fraction of them.

8. A confirmation of the low-metallicity bias of long GRBs to values of the order of $\epsilon = 0.1$ would imply that fast rotation may be much more common at low metallicity among massive stars.

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