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The consequences of gamma-ray burst jet opening angle evolution on the inferred star formation rate

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ABSTRACT

Gamma-ray burst (GRB) data suggest that the jets from GRBs in the high redshift universe are more narrowly collimated than those at lower redshifts. This implies that we detect relatively fewer long GRB progenitor systems (i.e. massive stars) at high redshifts, because a greater fraction of GRBs have their jets pointed away from us. As a result, estimates of the star formation rate (SFR; from the GRB rate) at high redshifts may be diminished if this effect is not taken into account. In this paper, we estimate the SFR using the observed GRB rate, accounting for an evolving jet opening angle. *We find that the SFR in the early universe ($z > 3$) can be up to an order of magnitude higher than the canonical estimates*, depending on the severity of beaming angle evolution and the fraction of stars that make long GRBs. Additionally, we find an excess in the SFR at low redshifts, although this lessens when accounting for evolution of the beaming angle. Finally, under the assumption that GRBs do, in fact, trace canonical forms of the cosmic SFR, we constrain the resulting fraction of stars that must produce GRBs, again accounting for jet beaming-angle evolution. We find this assumption suggests a high fraction of stars in the early universe producing GRBs – a result that may, in fact, support our initial assertion that GRBs *do not* trace canonical estimates of the SFR.

Key words: stars: formation – stars: general: gamma-ray bursts – cosmology: early Universe.

1 INTRODUCTION

Understanding the global star formation rate (SFR) density is a key factor in understanding galaxy formation and evolution throughout the history of our Universe; additionally, it provides a cosmic census of the many diverse astronomical objects in our Universe (e.g. see Hopkins & Beacom 2006; Kennicutt & Evans 2012; Krumholz 2014; Madau & Dickinson 2014, and references therein). However, accurately determining the cosmological SFR is difficult for a number of reasons. Many of these issues have to do with the assumptions invoked when trying to connect observations to a physical SFR density, as well as accurately accounting for observational selection effects (see e.g. Hopkins & Beacom 2006; Madau & Dickinson 2014 for a discussion of these issues). Furthermore, observations themselves are limited – classic techniques using ultraviolet and far-infrared measurements of galaxies are difficult at high redshifts; to get an accurate measurement of the SFR beyond a redshift of 3 or so, multiple techniques must be employed.

Because long gamma-ray bursts (lGRBs) are the most luminous explosions in the universe and because of definitive evidence of their association with massive star progenitors (Galama et al. 1998; Hjorth et al. 2003; Woosley & Bloom 2006; Hjorth & Bloom 2012), they have long been suggested as tools with which to estimate the high redshift SFR (Lloyd-Ronning, Fryer & Ramirez-Ruiz 2002; Jakobsson et al. 2005; Kistler et al. 2008, 2009; Yüksel et al. 2008; Wanderman & Piran 2010; Robertson & Ellis 2012; Trenti, Perna & Tacchella 2013; Lien et al. 2014; Petrosian, Kitanidis & Kocevski 2015; Chary et al. 2016; Le & Mehta 2017; Kinugawa, Harikane & Asano 2019; Elías-Chávez & Martínez 2020). However, there are a number of issues that make doing so difficult, essentially related to understanding exactly what types of stars and/or fractions of the global stellar population produce GRBs (including accounting for multiple GRB progenitors) and understanding how this relationship may change over cosmic time. In addition, the distribution of the GRB beaming angle plays an important role in relating the GRB rate to the SFR. And – finally and importantly – observational selection effects in the detection of high redshift GRBs must be taken into account.

Recently, Lloyd-Ronning, Aykutalp & Johnson (2019b) and Lloyd-Ronning et al. (2020) examined a large sample of lGRBs with redshifts (z, in the range $0.1 \lesssim z \lesssim 5$) and found that the estimates of the jet opening angle, θ_j, appear to be narrower at high redshifts than at low redshifts, with the best-fitting functional form of $\theta_j \propto (1+z)^{-0.8 \pm 0.2}$ (we chose a power-law fit as straightforward way to quantify this relationship and its scatter). Lloyd-Ronning et al. (2020) argue that this may be a result of lower metallicity, higher mass (and therefore denser) stars at high redshifts collimating the GRB jet more, compared to less dense stars at lower redshifts. Several recent studies support this framework – e.g. Klencki et al. (2020) show that low metallicity leads to more compact stars, while Chruslinska et al. (2020) show a higher rate of metal-poor star formation at high redshift, leading to a top-heavy IMF. Sharda, Federrath & Krumholz (2020) show that the presence of magnetic fields can suppress fragmentation in the early universe, leading to a top-heavy IMF at higher redshifts. Additionally, low metallicity stars

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at high redshifts undergo less mass (and angular momentum) loss, and therefore may rotate more rapidly. This may have an effect on the jet collimation, potentially leading to more collimated jets at high redshift [for example, for a magnetically launched jet (Blandford & Znajek 1977), the angular momentum and magnetic field of the central engine may play a role in the degree of collimation of the jet (Hurtado, in preparation)].

Regardless of the physical origin of the jet angle-redshift anti-correlation, a consequence of this relationship is that there exists a smaller fraction of *observable* GRB jets at high redshift, compared to those at lower redshifts. In other words, because of the narrower collimation at high redshifts, there will be a higher fraction of GRBs with jets pointed away from Earth. This leads to a higher density of GRB progenitors at high redshift than we would infer if we use a constant, non-evolving jet opening angle. This effect must be taken into account when using GRBs to estimate the high redshift SFR.

To estimate the SFR from the GRB rate, one must assume something about the fraction of stars that produce GRBs and whether this fraction evolves through cosmic time (e.g. see Kistler et al. 2008, 2009; Yüksel et al. 2008 for a straightforward summary of this issue). Alternatively, one can assume a one-to-one correspondence between the GRB rate and the SFR measured by other techniques and then infer the fraction of stars that produce GRBs. Once again, GRB jet beaming angle evolution will affect this result and must be accounted for.

In this paper, we examine both approaches with the novel addition of accounting for beaming angle evolution through cosmic time. Our aim is twofold: (1) assuming the fraction of stars that produce lGRBs, *estimate the SFR* from the GRB rate accounting for the fact that lGRB beaming angle appears to evolve with redshift and (2) under the assumption that lGRBs trace previously determined parametrization of the global SFR, *estimate the fraction of stars that must produce lGRBs* in order to be consistent with the GRB rate (again, accounting for jet beaming angle evolution).

Our paper is organized as follows. In Section 2, we summarize the data sample and results of Lloyd-Ronning et al. (2019b, 2020), who showed lGRBs appear to exhibit cosmic beaming angle evolution, with higher redshift lGRBs more narrowly beamed than low redshift ones. In Section 3, we describe the method used to estimate the SFR and/or fraction of stars that are progenitors for lGRBs, based on the methods described in Kistler et al. (2008, 2009) and Yüksel et al. (2008) and present our results. We show that lGRB beaming angle evolution leads to an SFR at high redshifts that is higher than canonical estimates (Madau & Dickinson 2014) for both a constant and evolving fraction of stars that produce GRBs. Alternatively, under the assumption that the lGRB rate density follows the Madau & Dickinson (2014) SFR density, we calculate the *inferred* fraction of stars that make GRBs (and its evolution). These results indicate that a higher fraction of stars produce GRBs at both low ($(1 + z) < 3$) and high ($(1 + z) > 3$) redshifts relative to the peak of star formation – a counter-intuitive result that we argue may emphasize the inaccuracy of assuming that GRBs trace the global SFR. Our conclusions are summarized in Section 4.

2 DATA

Our data sample is described in detail in Lloyd-Ronning et al. (2019b, 2020), who use data compiled in Wang et al. (2020); this latter reference contains all publicly available observations of 6289 GRBs from 1991 to 2016. For the 376 GRBs with redshifts (and therefore isotropic energy) estimates, Lloyd-Ronning et al. (2019b) found that certain intrinsic lGRB properties appear to evolve with redshift, even when accounting for Malmquist-type biases and selection effects in the observed data. However, in the hundred or so bursts where jet opening angle estimates are available and for which one can compute beaming angle corrected (that is, the actual emitted) gamma-ray energy and luminosity, Lloyd-Ronning et al. (2019b) found these variables (i.e. gamma-ray luminosity and emitted energy) are *not* correlated with redshift. This suggests that jet opening angle *is*, and indeed they found a significant anticorrelation between jet opening angle and redshift, with a functional form $\theta_j \propto (1 + z)^{-0.8 \pm 0.2}$. Such an anticorrelation between jet angle and redshift was originally suggested in Lloyd-Ronning et al. [2002; e.g. see their Section 5.1.2; they suggested the faster rotation of stars at high redshift could be consistent with lower mass (and angular momentum) loss due to lower metallicity]. Observational evidence for this anticorrelation has also been put forth by Lü et al. (2012) and Laskar et al. (2014, 2018a,b). An explanation for this correlation in terms of collimation by a massive star stellar envelope is given in Lloyd-Ronning et al. (2020).

2.1 The role of selection effects

As mentioned above, the analysis of Lloyd-Ronning et al. (2019b) accounts for gamma-ray flux-limit selection effects in the data. However, we might ask what other types of selection effects could potentially contribute to the $\theta_j - (1 + z)$ anticorrelation. In this case, it is important to consider jet opening angle estimate techniques and whether there is a selection against higher opening angles at larger redshifts. Indeed, since opening angles are measured by breaks in afterglow light curves, when the relativistic beaming angle $1/\Gamma$ reaches the physical "edge" of the jet, larger opening angles cannot be detected until later times (for a given Γ for the outflow) and the afterglow may have faded below detector sensitivity by that point.

We have explored these issues in Lloyd-Ronning et al. (2019b, 2020; see also the recent paper by Le, Ratke & Mehta 2020, who look at biases in redshift distributions and jet opening angles between different subsets of GRB data.). In particular, in Lloyd-Ronning et al. (2020), we implemented a strong artificial truncation in the $\theta_j - (1 + z)$ plane, which mimics a selection against large opening angles at high redshifts. Even when accounting for this selection bias using established non-parametric statistical techniques (Efron & Petrosian 1992, 1999), we find that there is still a significant anticorrelation between θ_j and $(1 + z)$. We also note that the redshift distribution of GRBs with jet opening angle estimates is not different from that of the entire sample of GRBs. A Kolmogorov–Smirnov (KS) test comparing the two distributions gives a p value of 0.64 that they are drawn from the same parent distribution – in other words, the redshift distributions of GRBs with jet opening angle measurements and the entire sample of GRBs are statistically the same (histograms of the two samples are shown in Fig. 1). Because there is roughly same relative fraction of jet opening angle measurements at low and high redshifts ($\sim$1/3), this suggests that we may not be missing a large fraction of large opening angle GRBs at high redshift and that the anticorrelation between jet opening angle and redshift may indeed have a physical origin.

In what follows, we assume the jet opening angle-redshift anti-correlation is physical and explore how this relationship can affect estimates of the high redshift SFR.

3 RESULTS

Because of the strong evidence that lGRBs are associated with the deaths of massive stars (e.g. see Woosley & Bloom 2006; Hjorth

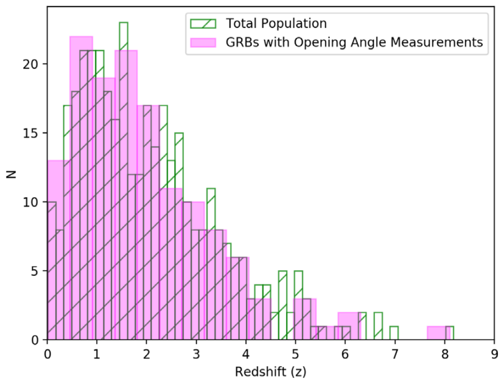

Figure 1. Redshift distribution of GRBs with jet opening angle distributions (magenta) compared to the entire population There is no statistically significant difference between the shapes of the two distributions.

& Bloom 2012 for summaries) and because they are so luminous and can be detected to such high redshifts, many authors have attempted to use GRBs to estimate the high redshift SFR (Lloyd-Ronning et al. 2002; Kistler et al. 2008, 2009; Yüksel et al. 2008; Wanderman & Piran 2010; Robertson & Ellis 2012; Trenti et al. 2013; Lien et al. 2014; Petrosian et al. 2015; Kinugawa et al. 2019). However, as mentioned in the introduction, there are a number of complicating issues in understanding exactly how lGRBs track or trace the global SFR. One must address a host of issues in accurately determining the lGRB rate – flux sensitivity selection effects and other observational biases must be accounted for (e.g. Lloyd-Ronning et al. 2002, 2019b; Petrosian et al. 2015) to get an accurate measure of the true, underlying lGRB rate. Additionally, because we will in general only observe a fraction $d\Omega/4\pi$ of those GRBs whose jets are directed toward us [where $d\Omega = 2\pi(1 - cos(\theta_j))$ is the jet solid angle], an understanding of the behaviour of GRB beaming angle distribution is necessary to correct for the true underlying number of GRB progenitor systems. Finally, we need to get a handle on the GRB progenitor system – exactly what fraction of stars make lGRBs and how does this fraction evolve as a function of redshift?

3.1 Obtaining the SFR from the lGRB rate

There are several possible approaches to tackling this problem. One straightforward approach is laid out in Kistler et al. (2008), (2009) and Yüksel et al. (2008). One can essentially parametrize the various unknowns mentioned above to estimate the SFR from the lGRB rate

$$\dot{\rho}_{\rm SFR}(z) = ({\rm d}\dot{N}/{\rm d}z)({\rm f_{beam}}(z))\left(\frac{(1+z)}{{\rm d}V/{\rm d}z}\right)\frac{1}{\epsilon(z)}, \quad (1)$$

where ${\rm d}\dot{N}/{\rm d}z$ is the true, underlying lGRB rate (accounting for the GRB luminosity function and detector trigger selection effects), $\epsilon(z)$ parametrizes the fraction of stars that make GRBs (and in principle can evolve with redshift), and $f_{\rm beam}(z)$ is a factor ($>$1) that accounts for the number of GRBs missed due to beaming. The factor dV/dz is the cosmological volume element given by

$$
\begin{aligned}
{\rm d}V/{\rm d}z = 4\pi\left(\frac{c}{H_o}\right)^3\left[\int_1^{1+z}\frac{{\rm d}(1+z)}{\sqrt{\Omega_\Lambda+\Omega_m(1+z)^3}}\right]^2 \\
\times\frac{1}{\sqrt{\Omega_\Lambda+\Omega_m(1+z)^3}}, \quad (2)
\end{aligned}
$$

where we use $\Omega_m = 0.286$, an $\Omega_\Lambda = 0.714$ and an $H_o = 69.6\,{\rm km\,s^{-1}\,Mpc^{-1}}$. Lloyd-Ronning et al. (2019b) describe how they obtained the differential rate distribution of long GRBs as a function of redshift, ${\rm d}\dot{N}/{\rm d}z$, using the non-parameteric methods of Lynden-Bell (1971) and Efron & Petrosian (1992), (1999). In particular, this quantity reflects the underlying GRB rate distribution, accounting for observational selection effects. We refer the reader to Lloyd-Ronning et al. (2019b) for a discussion of how this distribution is obtained. The factor we focus on here is $f_{\rm beam}(z)$. In previous studies, this was assumed to be a constant. The results of Lloyd-Ronning et al. (2019b, 2020), however, suggest that this function evolves with redshift. This factor – a number greater than one, which parametrizes the number of GRBs missed due to jets being pointed away from us – is proportional to the inverse of the solid angle of the jet. Therefore, because the solid angle is proportional to θ_j^2 for small jet opening angles, if the jet opening angle θ_j evolves as $(1+z)^{-\alpha}$, the function $f_{\rm beam} \propto (1/\theta_j^2) \propto (1+z)^{2\alpha}$.

Lloyd-Ronning et al. (2019b) found $\alpha \sim 0.8$, which leads to $f_{\rm beam}(z) \propto (1+z)^{1.6}$. Fig. 2 shows the SFR derived from equation 1 above, given the functional form of beaming angle evolution seen in the data (magenta line, with the error indicated by the grey region). Here, we have assumed that the fraction of stars $\epsilon(z)$ that produce lGRBs remains relatively constant throughout cosmic time. The green line in this figure shows the inferred SFR assuming no beaming angle evolution (but still a constant $\epsilon(z)$). As expected, if lGRBs are more narrowly beamed in the high redshift universe, then – for a given fraction of stars that make lGRBs – there is a relatively higher SFR in the early universe.

Because of the uncertainties in associating the lGRB rate with the global SFR, there is some freedom in how to normalize our SFR curves in Fig. 2. One possibility is to normalize the SFR derived from the lGRB rate with that of the Madau & Dickinson (2014; hereafter MD14) rate at a redshift of $(1 + z) \approx 3$, where star formation appears to peak. This is shown in the left-hand panel of Fig. 2. However, the SFR is better determined observationally at lower redshifts (see e.g. fig. 1 of Hopkins & Beacom 2006) and therefore normalizing our curves to the MD14 rate at $(1 + z) \approx 2$ (or even lower) is also justifiable. We show this normalization in the right-hand panel of Fig. 2. Note that there appears to be an excess at low redshifts (particularly when beaming angle evolution is *not* taken into account), which we discuss further in Section 3.3 below.

Regardless of normalization, Fig. 2 indicates that the shape or functional form of the SFR throughout cosmic time, as inferred from the GRB rate, is different from the MD14 rate (given a constant fraction of stars that make lGRBs). In particular, when beaming evolution is accounted for, the peak of the SFR appears at redshifts of $z \sim 3$ (or higher) and there is a higher rate of SFR in the early universe than predicted by other estimates (on which the MD14 rate is based).

Of course, there is no reason to expect that the fraction of stars that make lGRBs should be constant throughout cosmic time. Given the conditions of low metallicity (and, relatedly, high angular momentum) necessary to launch a GRB jet (MacFadyen & Woosley 1999; Hirschi, Meynet & Maeder 2005; Yoon & Langer 2005; Woosley & Heger 2006; Yoon, Langer & Norman 2006), we might expect that a higher fraction of stars in the early universe make lGRBs compared to those in the lower redshift universe. How exactly to parametrize or account for this is unclear, however. In Fig. 3, we show the SFR assuming two different functions for the evolution of the fraction of stars that make GRBs: $\epsilon(z) \propto (1+z)^{0.1}$ (green curve) and $\epsilon(z) \propto (1+z)^{1.0}$ (cyan curve). In these figures, we use a beaming evolution consistent with the relationship found in Lloyd-Ronning et al. (2019b, 2020), $f_{\rm beam} \propto (1+z)^{1.6}$. Our results indicate, again, that – whether or not the fraction of stars that make GRBs evolves through cosmic time – the SFR derived from the GRB rate

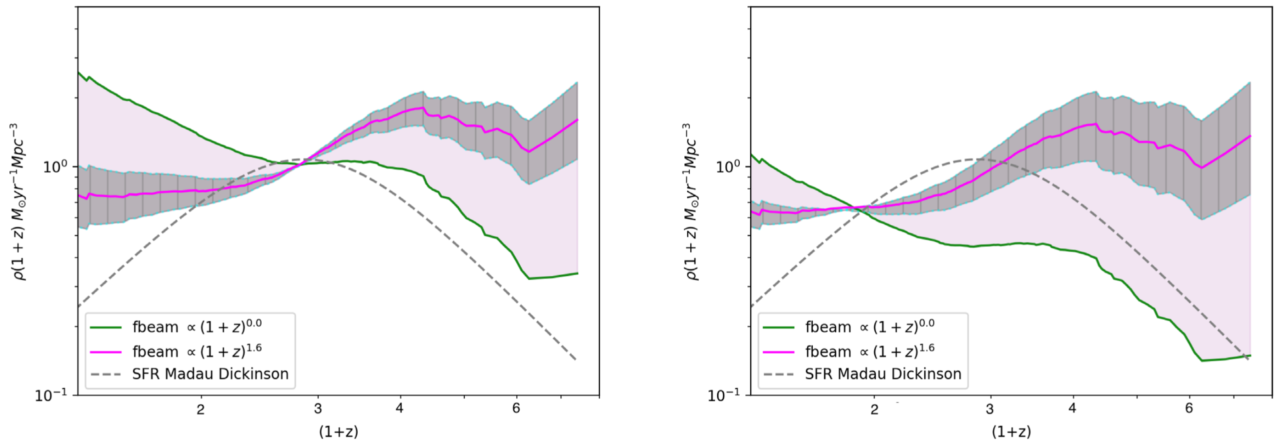

Figure 2. Left-hand panel: SFR density $\rho(1+z)$ as a function of redshift $(1+z)$ assuming a constant fraction of stars produce GRBs and accounting for beaming angle evolution, according to the best fit to the data, $\theta_j \propto (1+z)^{-0.8\,\pm\,0.2}$ (with the grey region denoting the error on the fit). The green line shows the inferred SFR assuming no beaming angle evolution. Curves are normalized to the MD14 SFR at a peak at $(1+z) = 3$. Right-hand panel: Same as left-hand panel, but curves are normalized to the MD14 SFR at a redshift $(1+z) = 2$.

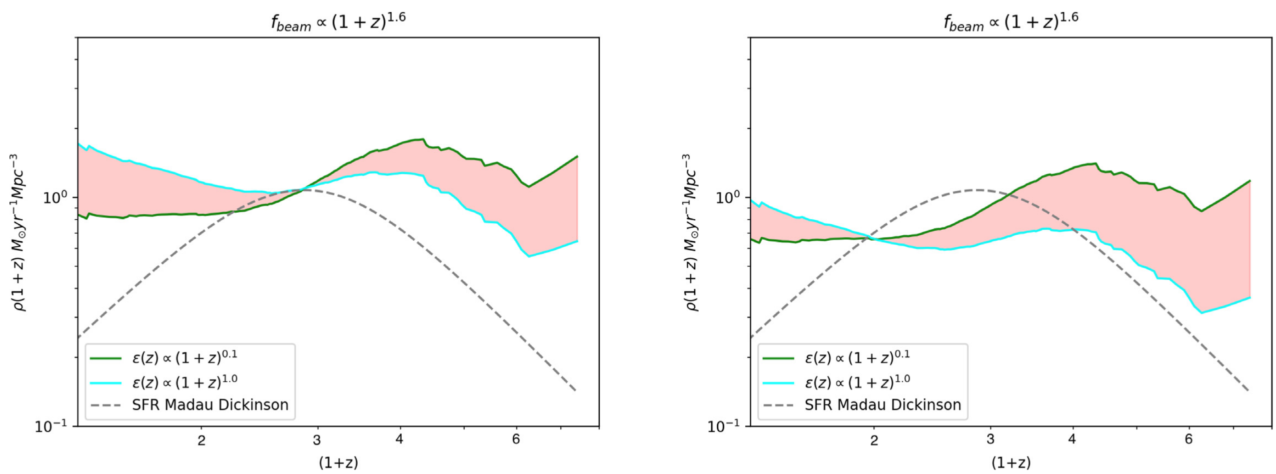

Figure 3. Left-hand panel: SFR density $\rho(1+z)$ as a function of redshift $(1+z)$ assuming the fraction of stars $\epsilon(1+z)$ that produce GRBs evolves with redshift, with $\epsilon(1+z) \propto (1+z)^{0.1}$ (green line) and $\epsilon(1+z) \propto (1+z)^{1.}$. (cyan line). We take a beaming angle evolution of $f_{\mathrm{beam}} \propto (1+z)^{1.6}$, consistent with the anticorrelation we find in the data between jet opening angle and redshift. Curves are normalized at the peak of the MD14 SFR. Right-hand panel: Same as left-hand panel, but with the curves normalized to the MD14 SFR at a redshift of $(1+z) \sim 2$.

is different from the MD14 rate and higher at large redshifts, when beaming angle evolution is accounted for.

3.2 The high redshift SFR

Accounting for potential lGRB beaming angle evolution has a significant effect on the inferred high redshift SFR, leading to estimates that are up to an order of magnitude higher than the MD14 rate. Interestingly, the peak of the inferred SFR (even without accounting for beaming angle evolution) appears to be around $(1+z) \sim 4$, compared with $(1+z) \sim 3$ of the MD14 rate. This may be a reflection of the lGRB rate tracing the evolution of a specific progenitor (e.g. low metallicity, massive stars) rather than the global stellar population. In addition, our SFR curve is fairly flat from redshifts between $3.5 < (1+z) < 6$. A similarly flat curve was found in the analyses of Kistler et al. (2008), Petrosian et al. (2015), and Lloyd-Ronning et al. (2019b), without accounting for beaming angle evolution (although their inferred SFRs are flat between slightly different redshift ranges).

It is possible that the lGRB rate at high redshifts more closely follows galactic nuclear star formation, leading to a different redshift peak compared to MD14 rate. For example, Hopkins & Beacom (2006) suggest that the accretion of gas on to central supermassive black holes, triggered by mergers and/or interactions of galaxies, leads to starbursts [and active galactic nuclei (AGN) activity]. This AGN activity is expected to peak around $(1+z) \sim 4$ (Miyaji et al. 2015), closer to the peak of the SFR we derive from the lGRB rate. Indeed, numerical simulations have shown that the gravitational tidal torques excited during major mergers lead to rapid inflows of gas into the centres of galaxies (Barnes & Hernquist 1996), which can be a mechanism to trigger starbursts in galaxies. In addition, Hopkins & Quataert (2010) find that AGN activity is more tightly coupled to nuclear star formation than the global SFR of a galaxy. This is also seen in numerical simulations of Aykutalp et al. (2014), (2019). Finally, Hocuk & Spaans (2010) found that in the X-ray irradiated case, fewer stars are formed but *with a higher initial masses*. Therefore, again, the lGRB rate may align more with this channel of star formation and will lead to an SFR peak that occurs earlier than the MD14 rate.

3.3 On the excess rate at low redshifts

The SFR that we derive from the lGRB rate shows an excess at low redshifts compared to the MD14 rate. The effect is less pronounced when we account for beaming angle evolution (but still there to some extent). We note that at very low redshifts [as $(1 + z) \rightarrow 1$], the volume element (e.g. equation 2) goes to zero faster than the observed lGRB rate ($\mathrm{d}\dot{N}/\mathrm{d}z$) does and this causes the SFR in equation 1 to diverge at low redshifts. This effect comes into play around a redshift of $z \sim 0.3$; as a result, we show our results down to that limit, before the divergence becomes too severe (see also the discussion in Lloyd-Ronning et al. 2019b, of this issue).

However, even before this numerical effect comes into play, an excess at low redshifts appears to exist. This was also noted in Petrosian et al. (2015), Yu et al. (2015) and Lloyd-Ronning et al. (2019b). We emphasize that these analyses account for the greater probability of detecting low luminosity GRBs at low redshifts (i.e. Malquist biases) through non-parametric statistical techniques that account for the GRB luminosity function (although we caution a single – albeit conservative – detector flux limit was used in our analysis; in reality, the detector trigger criteria are more complicated). Another approach is to impose a minimum luminosity cutoff as in Kistler et al. (2008) – this will eliminate the excess of low luminosity GRBs at small redshifts (and as a result mitigate the excess in the inferred SFR at these redshifts).

Again, this effect is more pronounced when beaming angle evolution is *not* accounted for. Therefore, it may be that beaming angle evolution is stronger than we have estimated and the low redshift SFR in fact roughly matches the MD14 rate at low redshifts (as in the lower part of the grey region in Fig. 2; in this case, the high redshift SFR is then vastly larger than that of the MD14 rate).

Another possibility for the mismatch at low redshifts could result from the array of progenitors that potentially contribute to lGRB rate (Levan et al. 2016), which may be more pronounced at low redshifts. That is, there may exist a greater number lGRB progenitor systems that are viable at lower redshifts. For example, certain binary merger systems proposed for lGRBs – which require more cosmic time to form and merge – may play a larger role in the lGRB rate at low redshifts. Additionally, they do not necessarily need the low metallicity conditions required of single star progenitors (Hao et al. 2020; Metha & Trenti 2020). Meanwhile, single star progenitors may become less viable at low redshifts due to the higher metallicity and accompanying higher mass loss (Chrimes, Stanway & Eldridge 2020; Klencki et al. 2020; Metha & Trenti 2020; Price-Whelan et al. 2020).

Finally, it may also be that the functional form of the parametrization in equation 1 (particularly $f_{\mathrm{beam}}(z)$ and $\epsilon(z)$) are not simple power laws, but are more complicated than what we have assumed. We argue (here and in Lloyd-Ronning et al. 2019b, 2020) that the data are reasonably parametrized by a power law for $f_{\mathrm{beam}}(z)$. However, $\epsilon(z)$ could potentially be a very complicated function and indeed as we show below, when the GRB rate is assumed to follow the MD14 SFR, an interesting function for $\epsilon(z)$ emerges.

3.4 Estimating the fraction of stars producing lGRBs

In our prescription above, we have assumed that some given fraction of stars (parametrized by the function $\epsilon(z)$) produces GRBs. However, metallicity plays a strong role in stellar evolution, affecting the stellar structure, as well as the mass and angular momentum loss of a massive star – quantities that are all crucially connected to whether or not a GRB will be successfully produced in its collapse. And because

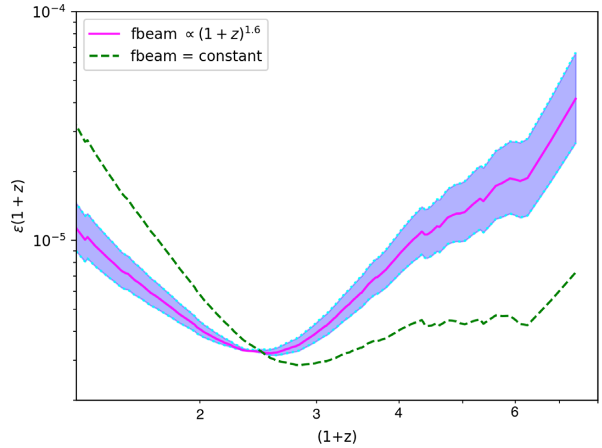

Figure 4. Fraction of stars $\epsilon(1 + z)$ that make lGRBs assuming the lGRB rate density directly traces the MD14 SFR density. The magenta line and purple region show this quantity accounting for jet beaming angle evolution seen in the data $\theta_j \propto (1 + z)^{-0.8 \pm 0.2}$. The green dashed line shows $\epsilon(1 + z)$ assuming no beaming angle evolution.

metallicity evolves through cosmic time (e.g. Pettini et al. 1997; Lara-López et al. 2009; Yuan, Kewley & Richard 2013), we therefore might reasonably expect that the fraction of stars that produce GRBs will evolve with redshift, with more stars able to produce GRBs at lower metallicities (higher redshifts). This is the motivation behind our parametrization of $\epsilon(z)$ in Fig. 3, where we assumed a power-law evolution of the fraction of stars that produce GRBs. We note that an important consideration in all of this is whether the star is in a binary system and how this (along with metallicity) plays a role in the evolving fraction of stars that produce GRBs (Metha & Trenti 2020).

Therefore, another approach we may take in using the lGRB rate to learn something about star formation history, is to assume that the lGRB rate roughly traces the MD14 functional form of the global SFR and solve for the fraction of stars that produce lGRBs. In other words, one can take an assumed SFR, and – given the observed GRB rate – estimate the fraction of stars that make GRBs as a function of redshift

$$\epsilon(z) = (\mathrm{d}\dot{N}/\mathrm{d}z)(\mathrm{f_{beam}}(z)) \left(\frac{(1+z)}{\mathrm{d}V/\mathrm{d}z}\right) \frac{1}{\dot{\rho}_{\mathrm{SFR}}(z)}, \tag{3}$$

where we use

$$\dot{\rho}_{\mathrm{SFR}}(z) = .0015 \frac{(1+z)^{2.7}}{(1+[(1+z)/2.9]^{5.6})} \mathrm{M_{\odot} yr^{-1} Mpc^{-3}}, \tag{4}$$

for our SFR (Madau & Dickinson 2014).

We show this estimate for $\epsilon(z)$ in Fig. 4, where the magenta line (and purple region) indicates our estimate accounting for jet opening angle evolution and the green dashed line assumes no beaming angle evolution with redshift. We choose to conservatively normalize the curves to a value of $\sim$5 x 10^{-6} at a redshift of $(1 + z) \sim 3$, where star formation peaks. We obtained this value by assuming roughly 0.1 per cent of stars result in a supernova – of these supernovae, only about $\sim$15 per cent (Smith et al. 2011) are of Type Ib/c, the type associated with lGRBs. Of this subset of Type Ib/c supernovae, only about 10 per cent (Chapman et al. 2007; Kanaan & de Freitas Pacheco 2013) successfully launch a GRB jet (due to conditions such as sufficient angular momentum and magnetic flux to launch a jet powerful enough to pierce through the progenitor envelope; a discussion of some of these issues can be found in Lloyd-Ronning et al. 2019a). This normalization is a big uncertainty, of course, and there is room for a range of values given our current state of knowledge.

Regardless of the normalization, we can try to understand the resulting shape of the curves in Fig. 4. There is a counter-intuitively large dip in the fraction of stars that make GRBs right at the peak of star formation, when we take this approach. The increase in $\epsilon(z)$ at high redshifts may be plausible due to decreasing metallicity and possibly a top-heavy IMF at higher redshifts. The increase in $\epsilon(z)$ at lower redshifts is uncertain and may, again, be a reflection of the breakdown between single star collapsar progenitors and lGRBs (see Section 3.3 above on the excess at low redshifts). However, ultimately, the curve we find for $\epsilon(z)$ – under the assumption that the GRB rate traces the MD14 SFR – may be emphasizing that GRBs, in fact, do *not* trace the global SFR.

It is important to note, however, that the relative fraction of stars that produce lGRBs changes significantly *when accounting for beaming angle evolution of the GRB jet*. As seen in Fig. 4, there is a much higher fraction of stars that make GRBs at high redshifts and relatively less at low redshift, when accounting for the change in average jet beaming angle over cosmic time. Regardless of the validity of the underlying assumption of the lGRB rate tracing the global SFR, this emphasizes the importance of accounting for jet opening angle evolution when trying to understand the relationship of lGRBs to their progenitor systems.

4 CONCLUSIONS

Observations suggest that the jet opening angles of lGRBs evolve over cosmic time, with lGRBs at higher redshifts more narrowly beamed than those at lower redshifts. In this paper, we have: (1) estimated the SFR from the GRB formation rate, accounting for the evolution of the distribution of GRB jet opening angles (and given an assumption about the fraction of stars that make lGRBs) and (2) estimated the fraction of stars that make lGRBs under the assumption that lGRBs trace the global SFR as parametrized by MD14.

Our main results are as follows:

(i) When accounting for beaming angle evolution – with lGRBs more narrowly beamed at higher redshifts – we find a higher relative SFR at high redshifts. *Depending on the strength of the beaming angle evolution and the normalization of the inferred SFR, the SFR can be up to an order of magnitude higher than the canoncial MD14 estimate.* Our inferred SFRs from the GRB rate may be indicating a specific metallicity dependent SFR (see e.g. Björnsson 2019; Chruslinska et al. 2020), given the low-metallicity requirements for succesfully launching a GRB jet in a massive star.

(ii) There appears to be an excess in our SFR estimates at *low redshifts* relative to the MD14 rate (again, depending on the normalization we choose). Accounting for beaming angle evolution lessens this excess, which may suggest the importance of accounting for the evolution. Alternatively, this could be a reflection of the breakdown of a one-to-one correspondence between lGRBs and massive star progenitor systems at low redshifts. In other words, if multiple systems (including binary merger systems) contribute significantly to the GRB rate at low redshifts, this may lead to such an excess at low redshifts.

(iii) Under the assumption that GRBs trace the MD14 SFR, we estimate the fraction of stars that produce lGRBs (in order to be consistent with the observed GRB rate), once again accounting for beaming angle evolution. Although the overall normalization of this curve is uncertain, we find that this approach implies a higher fraction of stars in the early universe produce GRBs. This result is plausible in light of the fact that low metallicity conditions are conducive to launching a successful GRB. We also find, using this approach, that a higher fraction of stars produce GRBs at lower redshifts than at the peak of star formation (although less so when beaming angle evolution is accounted for). As discussed above, this somewhat unexpected result could reflect the breakdown of a one-to-one correspondence between lGRBs and massive star progenitors at low redshifts, and may also indicate the implausibility of assuming that the lGRB rate density follows the SFR as parametrized by MD14.

Because of the extreme luminosity of lGRBs, they remain powerful probes of the early universe and potentially important tools with which to measure the SFR at redshifts that are inaccessible by other methods. That the jet opening angle of lGRBs may evolve over cosmic time, with jets in the early universe being more narrowly beamed than those at lower redshifts, has important implications on estimates of the SFR from the lGRB rate – implying it has perhaps, up until now, been largely underestimated. As the next generation of telescopes is launched – including deep space optical and infrared probes such as the *James Webb Space Telescope* and *Nancy Grace Roman Telescope,* as well as transient detectors such as *Theseus* and the *Space Variable Objects Monitor* – we will get a more extensive probe into the early universe. In addition, new methods employing measurements of the neutrino flux (Riya & Rentala 2020), for example, could enable us to more securely ascertain star formation during these epochs, allowing us to test our predictions of the SFR at high redshift, and gain a better understanding of the history of star formation throughout our Universe.

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DATA AVAILABILITY

The data underlying this article are publicly available at https://iopscience.iop.org/article/10.3847/1538-4357/ab0a86.

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