Journal of High Energy Astrophysics 9–10 (2016) 1–8

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap

Long GRBs as a tool to investigate star formation in dark matter halos

Jun-Jie Wei [a], Jing-Meng Hao [b,c], Xue-Feng Wu [a,d,*], Ye-Fei Yuan [e]

[a] Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China
[b] Center for Astrophysics, Guangzhou University, Guangzhou 510006, China
[c] Astronomy Science and Technology Research Laboratory of Department of Education of Guangdong Province, Guangzhou 510006, China
[d] Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing University-Purple Mountain Observatory, Nanjing 210008, China
[e] Key Laboratory for Research in Galaxies and Cosmology CAS, Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, China

A R T I C L E I N F O

Article history:
Received 5 June 2015
Accepted 13 November 2015

Keywords:
Gamma-ray burst: general
Galaxy: evolution
Stars: formation

A B S T R A C T

First stars can only form in structures that are suitably dense, which can be parametrized by the minimum dark matter halo mass $M_{\rm min}$. $M_{\rm min}$ must play an important role in star formation. The connection of long gamma-ray bursts (LGRBs) with the collapse of massive stars has provided a good opportunity for probing star formation in dark matter halos. We place some constraints on $M_{\rm min}$ using the latest *Swift* LGRB data. We conservatively consider that LGRB rate is proportional to the cosmic star formation rate (CSFR) and an additional evolution parametrized as $(1+z)^{\alpha}$, where the CSFR model is a function of $M_{\rm min}$. Using the χ^2 statistic, the contour constraints on the $M_{\rm min}$–α plane show that at the 1σ confidence level, we have $M_{\rm min} < 10^{10.5}$ $M_{\odot}$ from 118 LGRBs with redshift $z < 4$ and luminosity $L_{\rm iso} > 1.8 \times 10^{51}$ erg s^{-1}. We also find that adding 12 high-z ($4 < z < 5$) LGRBs (consisting of 104 LGRBs with $z < 5$ and $L_{\rm iso} > 3.1 \times 10^{51}$ erg s^{-1}) could result in much tighter constraints on $M_{\rm min}$, for which, $10^{7.7}$ $M_{\odot} < M_{\rm min} < 10^{11.6}$ $M_{\odot}$ (1σ). Through Monte Carlo simulations, we estimate that future five years of Sino–French spacebased multiband astronomical variable objects monitor (*SVOM*) observations would tighten these constraints to $10^{9.7}$ $M_{\odot} < M_{\rm min} < 10^{11.3}$ $M_{\odot}$. The strong constraints on $M_{\rm min}$ indicate that LGRBs are a new promising tool for investigating star formation in dark matter halos.

1. Introduction

Gamma-ray bursts (GRBs) are the most luminous explosive events in the cosmos, which can be detected even out to the edge of the Universe. To date, the highest redshift of GRBs is ∼9.4 (GRB 090429B; Cucchiara et al., 2011). So GRBs are considered as a powerful tool to probe the properties of the high-z Universe, including high-z star formation history (e.g., Chary et al., 2007; Yüksel et al., 2008; Kistler et al., 2009; Trenti et al., 2012; Wei et al., 2014), metal enrichment history (Wang et al., 2012), and the dark matter particle mass (de Souza et al., 2013). Theoretically, it is widely accepted that long bursts (LGRBs) with durations $T_{90} > 2$ s (where T_{90} is the interval observed to contain 90% of the prompt emission; Kouveliotou et al., 1993) are powered by the core collapse of massive stars (e.g., Woosley, 1993; Paczyński, 1998; Woosley and Bloom, 2006), which have been strongly supported by several confirmed associations between LGRBs and Type Ic supernovae (Stanek et al., 2003; Hjorth et al., 2003; Chornock et al., 2010). The collapsar model suggests that the cosmic GRB rate should in principle trace the cosmic star formation rate (CSFR; Totani, 1997; Wijers et al., 1998; Blain and Natarajan, 2000; Lamb and Reichart, 2000; Porciani and Madau, 2001; Piran, 2004; Zhang and Mészáros, 2004; Zhang, 2007).

Thanks to the great contribution of the *Swift* satellite (Gehrels et al., 2004), the number of GRBs with measured redshifts has increased rapidly over the last decade. Surprisingly, the *Swift* data seem to indicate that the rate of LGRBs does not strictly trace the CSFR, but instead implying some kind of additional evolution (Daigne et al., 2006a; Guetta and Piran, 2007; Le and Dermer, 2007; Salvaterra and Chincarini, 2007; Kistler et al., 2008, 2009; Li, 2008; Salvaterra et al., 2009, 2012; Campisi et al., 2010; Qin et al., 2010; Wanderman and Piran, 2010; Cao et al., 2011; Virgili et al., 2011; Elliott et al., 2012; Lu et al., 2012; Robertson and Ellis, 2012; Wang, 2013; Wei et al., 2014). The observed discrepancy between the LGRB rate and the CSFR is used to be described by an enhanced evolution parametrized as $(1+z)^{\alpha}$ (e.g., Kistler et al., 2008). Many mechanisms have been proposed to explain the enhancement,

* Corresponding author at: Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China.
E-mail addresses: xfwu@pmo.ac.cn (X.-F. Wu), yfyuan@ustc.edu.cn (Y.-F. Yuan).

http://dx.doi.org/10.1016/j.jheap.2015.11.001
2214-4048/

such as cosmic metallicity evolution (Langer and Norman, 2006; Li, 2008), an evolution in the stellar initial mass function (Xu and Wei, 2009; Wang and Dai, 2011), and an evolution in the GRB luminosity function (Virgili et al., 2011; Salvaterra et al., 2012; Tan et al., 2013; Tan and Wang, 2015).

However, it should be emphasized that the prediction on the LGRB rate strongly relates to the star formation rate models. With different star formation history models, the results on the discrepancy between LGRB rate and CSFR could change in some degree (see Virgili et al., 2011; Hao and Yuan, 2013). There are many forms of CSFR available in the literature. Most previous studies (e.g., Kistler et al., 2008, 2009; Li, 2008; Salvaterra et al., 2009, 2012; Robertson and Ellis, 2012; Wei et al., 2014) adopted the widely accepted CSFR model of Hopkins and Beacom (2006), which provides a good piecewise-linear fit to the ultraviolet and far-infrared observations. But, it is obviously that the empirical fit will vary depending on both the functional form and the observational data used. Hao and Yuan (2013) confirmed that LGRBs were still biased tracers of the CSFR model derived from the empirical fit of Hopkins and Beacom (2006). While, using the self-consistent CSFR model calculated from the hierarchical structure formation scenario, they found that large number of LGRBs occur in dark matter halos with mass down to $10^{8.5}$ $M_\odot$ could give an alternative explanation for the CSFR–LGRB rate discrepancy.

The fact that stars can only form in structures that are suitably dense, which can be parametrized by the minimum mass $M_{\rm min}$ of a dark matter halo of the collapsed structures where star formation occurs. Structures with masses smaller than $M_{\rm min}$ are considered as part of the intergalactic medium and do not take part in the star formation process. Thus, the minimum halo mass $M_{\rm min}$ must play an important role in star formation. Some observational data have been used to constrain $M_{\rm min}$ in several instance, including the following representative cases: Daigne et al. (2006b) showed that with a minimum halo mass of 10^7–10^8 $M_\odot$ and a moderate outflow efficiency, they were able to reproduce both the current baryon fraction and the early chemical enrichment of the intergalactic medium; Bouché et al. (2010) found that a minimum halo mass $M_{\rm min} \simeq 10^{11}$ $M_\odot$ was required in their model to simultaneously account for the observed slopes of the star formation rate–mass and Tully–Fisher relations; Muñoz and Loeb (2011) found that the observed galaxy luminosity function was best fit with a minimum halo mass per galaxy of $10^{9.4^{+0.3}_{-0.9}} M_\odot$.

The collapsar model suggests that LGRBs constitute an ideal tool to investigate star formation in dark matter halos. The expected GRB redshift distributions can be calculated from the self-consistent CSFR model as a function of the minimum halo mass $M_{\rm min}$. Thus, $M_{\rm min}$ can be constrained by directly comparing the observed and expected redshift distributions. In this paper, we extend the work of Hao and Yuan (2013) by presenting robust limits on $M_{\rm min}$ using the latest *Swift* GRB data. Since the latest data have many redshift measurements, a reliable statistical analysis is now possible. This analysis not only provides a better understanding of the high-z CSFR using the LGRB data, but also indicates that LGRBs can be a new tool to constrain the minimum halo mass. The outline of this paper is as follows. In Section 2, we will briefly describe the star formation model we have adopted and demonstrate the impact of the minimum halo mass $M_{\rm min}$ on the CSFR. In Section 3, we will present the method for calculating the theoretical GRB redshift distribution, and then in Section 4 show direct constraints on the numerical value of $M_{\rm min}$ from the latest *Swift* GRB data. In Section 5, we will discuss possible future constraints using a mock sample. Finally, we will end with our conclusions in Section 6.

Throughout we use the cosmological parameters from the *Wilkinson Microwave Anisotropy Probe* (WMAP) nine-year data release (Hinshaw et al., 2013), namely $\Omega_{\rm m} = 0.286$, $\Omega_\Lambda = 0.714$, $\Omega_{\rm b} = 0.0463$, $\sigma_8 = 0.82$ and $h = 0.69$.

2. The cosmic star formation

In the framework of hierarchical structure formation, the self-consistent CSFR model can be obtained by solving the evolution equation of the total gas density that takes into account the baryon accretion rate, the ejection of gas by stars, and the stars formed through the transfer of baryons in the dark matter halos (see Pereira and Miranda, 2010). The baryon accretion rate stands for the process of structure formation, which governs the size of the reservoir of baryons available for star formation (Daigne et al., 2006b). In this section, we will briefly summarize how to obtain the CSFR from the hierarchical model, which is developed by Pereira and Miranda (2010).

In the hierarchical formation scenario, the comoving abundance of collapsed dark matter halos can be determined based on the Press–Schechter (P–S) like formalism (Press and Schechter, 1974). We adopt the most popularly used halo mass function, named the Sheth–Tormen mass function (Sheth and Tormen, 1999), which is similar to the form of the P–S mass function:

$$f_{\rm ST}(\sigma) = A\sqrt{\frac{2a_1}{\pi}}\left[1+\left(\frac{\sigma^2}{a_1\delta_c^2}\right)^p\right]\frac{\delta_c}{\sigma}\exp\left(-\frac{a_1\delta_c^2}{2\sigma^2}\right) , \qquad (1)$$

where the parameter $\delta_c = 1.686$ could be explained physically as the linearly extrapolated overdensity of a top-hat spherical density perturbation at the time of maximum compression. The choice of values $A = 0.3222$, $a_1 = 0.707$, and $p = 0.3$ gives the best fit to mass functions derived from numerical simulations over a broad range of redshifts and masses. The number density of dark matter halos with mass M, $n_{\rm ST}(M, z)$, can be related to $f_{\rm ST}(\sigma)$ by

$$\frac{{\rm d}n_{\rm ST}(M,z)}{{\rm d}M} = \frac{\rho_{\rm m}}{M}\frac{{\rm d}\ln\sigma^{-1}}{{\rm d}M} f_{\rm ST}(\sigma) , \qquad (2)$$

where $\rho_{\rm m}$ is the mean mass density of the Universe. The variance of the linearly density field $\sigma(M, z)$ is given by

$$\sigma^2(M,z) = \frac{D^2(z)}{2\pi^2}\int_0^\infty k^2 P(k) W^2(k,M){\rm d}k , \qquad (3)$$

where the primordial power spectrum $P(k)$ is smoothed with a real space top-hat filter function $W(k, M)$, $D(z)$ is the growth factor of linear perturbations normalized to $D = 1$ at the present epoch and the redshift dependence enters only through $D(z)$.

The baryon distribution is considered to be tracing the dark matter distribution without any bias, which means the baryons density is completely proportional to the density of dark matter. Note that first stars can form only in structures that are suitably dense, which can be parametrized by the minimum dark matter halo mass $M_{\rm min}$. Thus, star formation will be suppressed when the halo mass below $M_{\rm min}$. In fact, the suppression in star formation is time dependent, i.e., the minimum mass $M_{\rm min}$ should evolve with z as the cooling processes of the hot gas in structures depend on the chemical composition and ionizing state of the gas (see Daigne et al., 2006b). However, the process of evolution is very complex. It is beyond the scope of this study to consider the detailed analysis on evolution, so we would like to keep $M_{\rm min}$ as a constant and set it as a free parameter in this model, as those authors did in their works (see, e.g., Daigne et al., 2006b; Pereira and Miranda, 2010; Muñoz and Loeb, 2011). Therefore, the fraction of baryons inside collapsed halos at redshift z is given by

$$f_{\rm b}(z) = \frac{\int_{M_{\rm min}}^\infty n_{\rm ST}(M,z)M\,{\rm d}M}{\int_0^\infty n_{\rm ST}(M,z)M\,{\rm d}M} . \qquad (4)$$