GRB 111005A at $z = 0.0133$ and the Prospect of Establishing
Long–Short GRB/GW Association

Yuan-Zhu Wang1,2, Yong-Jia Huang1,3, Yun-Feng Liang1, Xiang Li1, Zhi-Ping Jin1,3, Fu-Wen Zhang4, Yuan-Chuan Zou5, Yi-Zhong Fan1,3, and Da-Ming Wei1,3

1 Key Laboratory of dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Science, Nanjing 210008, China
2 University of Chinese Academy of Sciences, Yuquan Road 19, Beijing 100049, China
3 School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, China
4 College of Science, Guilin University of Technology, Guilin 541004, China
5 School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China

Received 2017 October 13; revised 2017 November 16; accepted 2017 November 20; published 2017 December 8

Abstract

GRB 111005A, a long-duration gamma-ray burst (GRB) that occurred within a metal-rich environment that lacks massive stars with $M_{\text{EAMS}} \geq 15 M_{\odot}$, is not coincident with supernova emission down to a stringent limit and thus should be classified as a “long–short” GRB (lsGRB; also known as an SN-less long GRB or hybrid GRB), like GRB 060505 and GRB 060614. In this work, we show that in the neutron star merger model the non-detection of the optical/infrared emission of GRB 111005A requires sub-relativistic neutron-rich ejecta with a mass of $\leq 0.01 M_{\odot}$, which is (significantly) less massive than that of GRB 130603B, GRB 060614, GRB 050709, and GRB 170817A. The lsGRBs are found to have a high rate density and the neutron star merger origin model can be unambiguously tested by the joint observations of the second-generation gravitational-wave (GW) detectors and the full-sky gamma-ray monitors such as Fermi-GBM and the proposed GECAM. If no lsGRB/GW association is observed in the 2020s, alternative scenarios have to be systematically investigated. With the detailed environmental information achievable for the nearby events, a novel kind of merger or explosion origin may be identified.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB 111005A) – gravitational waves

1. Introduction

Based on the duration of their prompt emission, the gamma-ray bursts (GRBs) are usually classified into two groups divided by $\sim 2$ s. The GRBs with a duration longer than 2 s are called long GRBs, while the events with a shorter duration are called short GRBs (Kouveliotou et al. 1993; Piran 2004). Long GRBs are believed to originate from collapsars that involve the death of massive stars and are expected to be accompanied by luminous supernovae (SNe; see Woosley & Bloom 2006), while the short GRBs are suspected to be from neutron star mergers and thus should not be coincident with luminous SNe (Eichler et al. 1989). Instead the short GRBs are likely associated with Li–Paczynski macronova (also called kilonova)—a novel kind of near-infrared/optical transient powered by the radioactive decay of heavy elements synthesized in the ejecta of a compact binary merger (e.g., Li & Paczynski 1998; Kasen et al. 2013; Tanaka & Hotokezaka 2013; Metzger 2017). The collapsar origin of most long GRBs has been confirmed by the SN detection in the afterglow follow-up observations (Woosley & Bloom 2006), while the neutron star merger model of short GRBs is supported by the observations of their afterglows and host galaxies (Berger 2014) as well as the detection of macronovae in GRB 130603B (Berger et al. 2013; Tanvir et al. 2013), GRB 050709 (Jin et al. 2016), and GRB 170817A (an event released after the submission of this work; see, e.g., Covino et al. 2017; Goldstein et al. 2017; Pian et al. 2017). Though the long and short classification has been widely adopted by the community, a few events, including GRB 060505 and GRB 060614 (Fynbo et al. 2006), share some characteristics of both groups (i.e., the so-called long–short GRBs or SN-less long GRBs, the events with apparent long duration but without luminous SN emission) and thus challenge the above simple scheme. The physical origin of these “outliers” attracted wide attention and was widely debated in the literature. The theoretical studies have shown that $\sim 40\%$ of Swift bursts shorter than 2 s may in fact be from collapsars, and alternatively, a non-negligible amount of non-collapsars may have durations longer than 10 s (e.g., Bromberg et al. 2013). The long–short GRBs may be such non-collapsars. The identification of a macronova signature in the late afterglow of GRB 060614 (Jin et al. 2015; Yang et al. 2015) provides direct support to the hypothesis that (some) long–short GRBs (lsGRBs) are intrinsically “short” (Gal-Yam et al. 2006; Gehrels et al. 2006; Ofek et al. 2007; Zhang et al. 2007). For GRB 060505, the situation is, however, less clear, and a novel massive star explosion origin is possible (Della Valle et al. 2006; Fynbo et al. 2006; Xu et al. 2009) since the properties of its host galaxy are consistent with those expected for canonical long-duration GRBs (Thöne et al. 2008). In view of these uncertainties, a more reliable probe of the nature of the progenitor stars of lsGRBs is crucial. The presence of an lsGRB at a very low redshift $z = 0.0133$ (i.e., GRB 111005A), as revealed very recently (Michalowski et al. 2016; Tanga et al. 2017), makes such a topic far more attractive than before.

GRB 111005A triggered the Swift-BAT at 08:05:14 UT on 2011 October 5 (Saxton et al. 2011). This burst has a duration of $T_{90} = 26 \pm 7$ s. Its fluence in the 15–150 keV band is of $(6.2 \pm 1.1) \times 10^{-7}$ erg cm$^{-2}$ and the spectrum is best fit by a single power-law with index $\Gamma = 2.4 \pm 0.2$ (Tanga et al. 2017). Therefore, GRB 111005A is likely a typical long–soft GRB. Due to Sun site constraint, no quick X-ray or optical follow-up observations were carried out. Near-infrared images taken during twilight and close to the horizon did not reveal any variable source, ruling out the presence of any bright SN
emission (Michalowski et al. 2016). However, the follow-up radio observations located GRB 111005A very accurately and thus established the association of GRB 111005A and the galaxy ESO 580-49 (Michalowski et al. 2016). With such a low redshift, GRB 111005A is the second closest long GRB ever detected, making it the closest lGRB and enabling the nearby environment to be studied at an unprecedented resolution of 100 pc. From the analysis of the MUSE data cube, Tanga et al. (2017) found GRB 111005A to have occurred within a metal-rich environment with little sign of ongoing star formation. Their spectral analysis at the position of the GRB indicates the presence of an old stellar population (\(\geq 10\) Myr), which limits the mass of the GRB progenitor to \(M_{\text{ZAMS}} < 15 M_{\odot}\), in direct conflict with the collapsar model. The deep limits on the presence of any SN emission combined with the environmental conditions at the position of GRB 111005A thus favor the non-collapsar origin (i.e., the merger origin). Among the possible non-collapsar scenarios, the neutron star merger possibility is very attractive since the detection of one such nearby event by Swift in about 10 years performance points to a high rate and the second-generation gravitational-wave (GW) detectors, for example, the Advanced LIGO/Virgo (Abadie et al. 2010), can catch the signals. The main purpose of this work is to examine whether the binary neutron star merger scenario really meets the infrared/optical upper limits and evaluate the prospect of establishing or ruling out the neutron star merger origin of lsGRBs in the Advanced LIGO/Virgo era.

2. Limits on the Macronova Emission Associated with GRB 111005A

As a result of the Sun site constraint, the optical/infrared observations of GRB 111005A were very rare. Benefiting from its very low redshift, the optical/infrared upper limits still impose interesting bounds on the macronova model. We focus on the double neutron star merger model since the neutron star–black hole merger rate is widely expected to be much less frequent, i.e., about one order of magnitude lower than the double neutron star mergers (Abadie et al. 2010; Li et al. 2017). In Figure 1, we compare the \(r\), \(i\), \(J\), \(K\) band upper limits of GRB 111005A to the macronova emission predicted in the NSM-all model of Tanaka & Hotokezaka (2013). Note that the extinction of the host with \(A_V = 2\) mag (Michalowski et al. 2016) has been corrected. The sub-relativistic outflow has a rest mass of 0.01 \(M_\odot\) and a velocity of 0.12c (where \(c\) is the speed of the light). Interestingly, the predicted macronova emission is roughly consistent with the upper limits. We thus set a bound on the neutron-rich ejecta mass of GRB 111005A, i.e., \(M_{\text{ej}} \leq 0.01 M_\odot\).

After submitting this work, the data of AT 2017gfo (e.g., Coulter et al. 2017) were released. In Figure 1, we compare AT 2017gfo to the upper limits of GRB 111005A (see also Yue et al. 2017). In all bands, the macronova emission associated with GRB 111005A should be dimmer than AT 2017gfo by a factor of 3–10. Such a difference may be mainly caused by the large amount of \(r\)-process material (\(M_{\text{ej}} \sim 0.04 \pm 0.01 M_\odot\)) ejected from GRB 170817A. The presence of some lanthanide-free material in the directions surrounding the rotational axis of the remnant (Kasliwal et al. 2017; Pian et al. 2017) is needed to explain the early bright multi-wavelength of AT 2017gfo. While for GRB 111005A the tight constraints on the early optical emission may favor the absence of the lanthanide-free material, indicating the central engine collapsed promptly (or one of the pre-merger object is a stellar mass black hole) and the disk wind outflow component did not play an important role (Kasen et al. 2015).

The numerical modeling of the macronova signal of sGRB 130603B yields \(M_{\text{ej}} \sim 0.03 M_\odot\) (Berger et al. 2013; Tanvir et al. 2013). For GRB 060614 and GRB 050709, the macronova modeling gives \(M_{\text{ej}} \sim (0.1, 0.05) M_\odot\), respectively (Jin et al. 2015, 2016; Yang et al. 2015). In Figure 2, we summarize these results together with the upper limits for GRB 111005A. Interestingly, Hotokezaka et al. (2015) showed that for the current neutron star merger rate inferred from the short GRB data, each event should eject \(\sim 10^{-2}–10^{-1} M_\odot\) \(r\)-process material to reproduce that observed in the Galaxy (see also Wang et al. 2017). The analysis of the \(r\)-process material in
ultrafaint dwarf galaxies suggests there are $\sim 6 \times 10^{-3} - 4 \times 10^{-2} M_\odot$ heavy elements in each neutron star merger (Beniamini et al. 2016a, 2016b). We therefore conclude that the ejecta masses of neutron star mergers are diverse and GRB 111005A may have launched a relatively small amount of sub-relativistic neutron-rich outflow (otherwise AT 2017fgo is atypical). Indeed, the ejecta mass depends sensitively on the equation of state and on the mass ratio of the pre-merger compact objects (e.g., Hotokezaka et al. 2013; Dietrich et al. 2015; Kawaguchi et al. 2015; Kyutoku et al. 2015). In particular, for neutron star–black hole mergers, the black hole spin also plays an important role and $M_{ej}$ can be in a very wide range, from $\sim 0.5 M_\odot$ to $\sim 0.2 M_\odot$ (see, e.g., Figure 1 of Shen et al. 2017 for a summary; please note that the data of GW170817 favor the equation of state models that predict a compact star, Abbott et al. 2017a, for which the neutron star–black hole mergers launch less massive ejecta than that believed before). One potential challenge for the neutron star–black hole merger model is the relatively low rate of such an event (usually it is lower than the neutron star merger rate by a factor of 10; Abadie et al. 2010). As for double neutron star mergers, the mass ratios are expected to be much more narrowly distributed, as observed in the Galaxy, and $M_{ej}$ is mainly governed by the equation of state. One may thus expect a narrow distribution of $M_{ej}$ as well. However, the disk wind as well as the neutrino-driven wind from the surface of the nascent hypermassive/supramassive neutron star formed in the merger can also enhance the neutron-rich outflow (Metzger 2017). Therefore, a wide distribution of $M_{ej}$ for double neutron star mergers is still possible. For a neutron star merger rate of $\mathcal{R}_{nsm} \sim 10^9 \text{Gpc}^{-3} \text{yr}^{-1}$, as inferred from the successful detection of GW170817 in the second observational run of advanced LIGO (Abbott et al. 2017a) and from the data of “local” sGRBs (Jin et al. 2017), a reasonably large neutron star merger sample will be available in the near future and the dedicated macronova/kilonova observations and modeling will yield a reliable distribution of $M_{ej}$, with which the double neutron star merger origin possibility of GRB 111005A will be directly tested.

3. The Rate Density of lsGRBs and the Gravitational-wave Detection Prospect

GRB 111005A has an $E_{iso} \sim 10^{57}$ erg and an $E_p < 15$ keV, which could well be an off-beam (if the GRB outflow is uniform) or off-axis (if the GRB outflow is structured) short GRB (as shown in Yue et al. 2017 some bright sGRBs could reproduce the characters of the prompt emission of GRB 111005A if viewed off-beam). GRB 060505 has an $E_{iso} \sim 10^{49}$ erg and a $T_\\text{iso} \sim 4$ s, but a hard spectrum (Ofek et al. 2007). Therefore, the off-beam/off-axis GRB scenario is disfavored. As for GRB 060614, it is so bright/long that it is very unlikely to be an off-beam/axis event. We thus conclude that not all of the lsGRBs are off-beam/axis sGRBs, and it is thus necessary to pin down their progenitors. For such a purpose, the rate of lsGRBs is needed. The lack of jet half-opening angle information of GRB 060505 and GRB 111005A does not hamper us since in this work we are keen on the lsGRB/GW association events, for which only the progenitors of lsGRBs can be directly revealed.

Inspired by the method utilized in Abbott et al. (2016) to determine the binary black hole merger rates, we estimate the lsGRB rate in the same way. The main point of the procedure is to relate the rate and the observation with $\Lambda = R(\langle VT \rangle)$, where $\Lambda$ is the Poisson mean number of the astrophysical trigger (our current approach is much simpler than that for GWs since the three lsGRBs are well identified as gamma-ray bursts and we do not need to consider a terrestrial trigger) and $\langle VT \rangle$ is the population-averaged sensitive spacetime volume of the search. Generally, $\langle VT \rangle$ can be calculated with (Liang et al. 2007)

$$\langle VT \rangle = \frac{\Omega T}{4\pi} \int_{F_{\text{min}}}^{F_{\text{max}}} \Phi(L) dL \int_0^{z_{\text{max}}} \frac{1}{1+z} \frac{dV(z)}{dz} dz,$$

(1)

where $\Omega$ is the field of view of the instrument, $\Phi(L)$ is the luminosity function of lsGRBs, and $z_{\text{max}}$ corresponds to the maximum detection range for a burst with luminosity $L$ and is determined by the instrument flux threshold. Having the fact that the luminosity function cannot be well constrained since there are just three identified lsGRBs so far, the result of the integration in Equation (2) is model dependent. To avoid the large uncertainties in the luminosity function, we calculate the rate based upon the properties of individual events (event based), i.e., GRB 111005A, GRB 060505, and GRB 060614 are treated as three distinct classes that together stand for the whole population of lsGRBs, and their $\langle VT \rangle$ are obtained independently by

$$\langle VT \rangle_i = \frac{\Omega T}{4\pi} \int_0^{z_{\text{max},i}} \frac{1}{1+z} \frac{dV(z)}{dz} dz,$$

(2)

(see the following discussion for the choice of $z_{\text{max},i}$ for each burst). The total event rate is then the sum of the individual values derived from each $\langle VT \rangle_i$. Such an approach is different from that used in previous GRB rate estimates (e.g., Liang et al. 2007). Assuming a Poisson fluctuation on the observed number events (in our case the observed number is one for each class), the likelihood for the rate $\mathcal{R}$ of a given class is

$$\mathcal{L}(1|\mathcal{R}) = \Lambda e^{-\Lambda} \mathcal{R}(\langle VT \rangle) \exp[-\mathcal{R}(\langle VT \rangle)].$$

(3)

The posterior over $\mathcal{R}$ is then obtained by multiplying the likelihood with a prior $P(\mathcal{R})$ and normalized over the possible range of $\mathcal{R}$. Two kinds of functions are chosen as our prior: a Uniform distribution of $\mathcal{R}$ and a Poisson Jeffreys prior that is proportional to $1/\sqrt{\mathcal{R}}$.

We first calculate the rate of GRB 111005A class GRBs following the procedure described above. We collect the 1 s peak energy flux in the 15–150 keV band of GRB 111005A from the Swift-BAT GRB Catalog (Lien et al. 2016). At a redshift of 0.0133, the luminosity in this band is $2.8 \times 10^{46}$ erg s$^{-1}$. As the Swift-BAT threshold is $\sim 10^{38}$ erg s$^{-1}$ cm$^{-2}$, such a low-luminosity event can only be seen within $z = 0.035$, implying a very small search volume and thus a very high astrophysical rate density. By applying Equation (3), considering Swift has a field of view $\sim 1.4$ sr and 11 years of observation (Gehrels et al. 2004), a rate for the GRB 111005A class is found to be $\mathcal{R}_{\text{GRB 111005A}} = 58_{-13}^{+219}$ Gpc$^{-3}$ yr$^{-1}$ (using the Uniform prior, the errors are reported at the 90% confidence level), or $29_{-18}^{+199}$ Gpc$^{-3}$ yr$^{-1}$.
GRB 111005A is the closest lsGRB reliably identified so far. This burst, with $E_{\text{iso}} \sim 10^{47}$ erg and $E_p < 15$ keV, could well be an off-beam or off-axis short GRB, while for GRB 060505 and GRB 060614, such a possibility is strongly disfavored. The infrared/optical upper limits of GRB 111005A, though rare, still impose tight constraints on the mass of the neutron-rich outflow expected in the neutron star merger scenario. The inferred bound (i.e., $M_\odot \lesssim 0.01 M_\odot$) is significantly smaller than that found in macronova modeling of GRB 130603B, GRB 060614, and GRB 050709. A neutron star–black hole merger can just eject a tiny amount of neutron-rich material. Their merger rate, however, is usually expected to be significantly lower than the neutron star mergers, hence such an event should be less frequent. On the other hand, a wide distribution of $M_{\text{ns}}$ for double neutron star mergers is still possible and reliable measurements are expected in the advanced LIGO/Virgo era, with which the binary neutron star merger origin of GRB 111005A will be directly tested. The successful identification of three nearby lsGRBs among Swift events suggests a high rate of $59^{+226}_{-36}$ Gpc$^{-3}$ yr$^{-1}$ (for the Uniform prior) and $30^{+305}_{-18}$ Gpc$^{-3}$ yr$^{-1}$ (for the Poisson Jeffreys prior); note that no jet opening angle correction is made since the latter can be detected up to a distance of $\sim 400$ Mpc (e.g., Li et al. 2016).

Different from GRB 111005A, the events of GRB 060614 and GRB 060505 are more luminous and can be detected by Swift up to $\sim 0.63$ and $\sim 1.4$, respectively. However, the reliable identification of lsGRBs at relatively high redshifts is quite a challenge. So far, the farthest lsGRB candidate is XRF 040701 at a redshift of 0.21 (Soderberg et al. 2005). Therefore the corresponding $\langle \mathcal{V} \rangle$ is limited by the identification probability, rather than their luminosities. We assume a “valid” identification horizon for lsGRBs as $\sim 0.25$ and present the resulting posterior distribution for the GRB 060505 class and the GRB 060614 class in Figure 3 (they share the same distribution since their identification horizons are assumed to be the same), and the inferred rate is $\mathcal{R}_{\text{GRB060505}} \sim 0.22^{+0.82}_{-0.14}$ Gpc$^{-3}$ yr$^{-1}$ (the Uniform prior) or $0.11^{+0.75}_{-0.05}$ Gpc$^{-3}$ yr$^{-1}$ (the Poisson Jeffreys prior). $\mathcal{R}_{\text{GRB111005A}}$ is about two orders of magnitudes lower than $\mathcal{R}_{\text{GRB111005A}}$, implying that GRB 111005A may be different from the other two, as already speculated in the previous paragraph. Finally, the posterior distribution of the total rate density of lsGRBs is calculated by convoluting the posterior distributions of the three classes, and the rates for uniform and Jeffreys prior are $59^{+226}_{-36}$ Gpc$^{-3}$ yr$^{-1}$ and $30^{+305}_{-18}$ Gpc$^{-3}$ yr$^{-1}$, respectively. As expected, the total rate density is dominated by the GRB 111005A class (see Figure 3).

4. Summary

The Astrophysical Journal Letters, 851:L20 (5pp), 2017 December 10

Wang et al.
