Afterglows and Kilonovae Associated with Nearby Low-luminosity Short-duration Gamma-Ray Bursts: Application to GW170817/GRB 170817A

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Abstract

Very recently, the gravitational-wave (GW) event GW170817 was discovered to be associated with the short gamma-ray burst (GRB) 170817A. Multi-wavelength follow-up observations were carried out, and X-ray, optical, and radio counterparts to GW170817 were detected. The observations undoubtedly indicate that GRB 170817A originates from a binary neutron star merger. However, the GRB falls into the low-luminosity class that could have a higher statistical occurrence rate and detection probability than the normal (high-luminosity) class. This implies the possibility that GRB 170817A is intrinsically powerful, but we are off-axis and only observe its side emission. In this Letter, we provide a timely modeling of the multi-wavelength afterglow emission from this GRB and the associated kilonova signal from the merger ejecta, under the assumption of a structured jet, a two-component jet, and an intrinsically less-energetic quasi-isotropic fireball, respectively. Comparing the afterglow properties with the multi-wavelength follow-up observations, we can distinguish between these three models. Furthermore, a few model parameters (e.g., the ejecta mass and velocity) can be constrained.

Key words: gamma-ray burst: general – gravitational waves – radiation mechanisms: non-thermal

1. Introduction

Time-domain astronomy has entered a new era since the monumental discovery of gravitational waves (GWs) by the Advanced LIGO/Virgo observatories in the last two years (Abbott et al. 2016a, 2016b, 2017a, 2017b). Since then, searching for electromagnetic (EM) counterparts to GWs has become a very urgent issue in this field. Four confirmed detections, GW150914, GW151226, GW170104, and GW170814, are believed to originate from binary black hole (BBH) mergers with dozens of solar masses (Abbott et al. 2016a, 2016b, 2017a, 2017b). However, we generally would not expect any EM counterparts from BBH mergers, except for in the following specific situations (Connaughton et al. 2016; Loeb 2016; Perna et al. 2016; Yamazaki et al. 2016; Zhang 2016; de Mink & King 2017). Differing from BBH mergers, binary neutron star (BNS) mergers are expected to generate several EM signals, such as short gamma-ray burst (GRB) jet emission (e.g., Faber et al. 2006; Nakar 2007; Giacomazzo et al. 2013; Berger 2014; Ruiz et al. 2016; Kathirgamaraju et al. 2017), cocoon prompt emission (Gottlieb et al. 2018; Lazzati et al. 2017a, 2017b; Nakar & Piran 2017), jet/cocoon afterglows (e.g., Gottlieb et al. 2018; Lamb & Kobayashi 2017; Lazzati et al. 2017a; Nakar & Piran 2017), and kilonovae (also referred to as “macronovae”): Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010; Metzger & Berger 2012; Kasen et al. 2013; Hotokezaka & Piran 2015; Gottlieb et al. 2018; Nakar & Piran 2017). A late-time (year-scaled) radio signal might originate from the ejecta-medium interaction as the ejecta enters the Sedov–Taylor phase (Nakar & Piran 2011).

Although BNS mergers have been proposed as one of the possible progenitors of short GRBs over the past three decades (Paczyński 1986; Eichler et al. 1989; Narayan et al. 1992; Tutukov & Yungelson 1992; Mochkovitch et al. 1993; Bogomazov et al. 2007) and there is a plenty of indirect evidence for such a scenario (e.g., for reviews see Nakar 2007; Berger 2014), conclusive proof remains lacking. It is generally believed that the detection of GW emission can provide a unique way to verify this scenario. However, the Advanced LIGO/Virgo GW detection horizon of BNS mergers is only about 100 Mpc (Abadie et al. 2010; Martynov et al. 2016) and short GRBs rarely fall into this close distance range.

Luckily, the first strong evidence of GW170817 associated with GRB 170817A was discovered very recently (Abbott et al. 2017c), benefiting from its relatively close distance. It is undoubtedly a landmark in multi-messenger astronomy and can greatly enhance our understanding of BNS mergers. The host galaxy associated with GW170817/GRB 170817A is found to be NGC 4993 with a luminosity distance of DL ≈ 40 Mpc (Abbott et al. 2017d; Hjorth et al. 2017). Observationally, this GRB has a duration of T90 ≈ 2 s, an isotropic-equivalent γ-ray energy of Eiso ≈ 4.6 × 10^46 erg, and an isotropic-equivalent peak luminosity of Liso,peak ≈ 1.7 × 10^47 erg s⁻¹ (Goldstein et al. 2017; Zhang et al. 2017), which shows that this GRB is a few orders of magnitude less energetic than a typical (high-luminosity) short GRB (von Kienlin et al. 2017).

According to the statistic analysis of the luminosity function and burst rate of short GRBs (Sun et al. 2015; Ghiuranda et al. 2016), nearby low-luminosity short GRBs (with luminosity, e.g., Liso < 10^46 erg s⁻¹) may be much more numerous than normal ones and we have a greater chance to detect them. Generally, low-luminosity short GRBs could originate from less powerful central engines. Nevertheless, there is another possibility that we are off-axis and only observe the side emission of a normal short GRB since its detection probability should be higher than that of on-axis emission (Lazzati et al. 2017b). For instance, the side emission from an off-axis short GRB with a structured jet has been discussed as possible EM counterparts to GWs.
(Kathirgamaraju et al. 2017) and also several other radiation components such as the cocoon emission have been proposed as possible counterparts in previous works (Gottlieb et al. 2018; Jin et al. 2017; Lamb & Kobayashi 2017; Lazzati et al. 2017a, 2017b). This kind of side emission should be much fainter than the on-axis jet emission from an observational point of view (e.g., Yamazaki et al. 2002, 2003). The fact that GRB 170817A has a typical peak energy $E_p$ (Goldstein et al. 2017) would not conflict with these models, since the prompt emission mechanism is unknown and the observed gamma-rays could either arise from the emission of the jet scattered to a wide angle (Kisaka et al. 2017) or just from the emission produced as the cocoon breaks out of the ejecta (Gottlieb et al. 2018; Kasliwal et al. 2017).

Based on the above argument, we consider here several cases in which the viewing angle $\theta_\text{v}$ varies. We carry out calculations of multi-wavelength afterglow emission with different viewing angles under the assumption of a universally structured jet and a two-component jet, respectively, and then make a comparison with that of an intrinsically less-energetic quasi-isotropic fireball. Our results show that three such types of model are distinguishable and can be tested by multi-wavelength follow-up observations. We apply these models to GRB 170817A and find that the two-component jet model with reasonable parameters matches the observations better than the structured jet model does. Furthermore, we explore the kilonova emission from the BNS merger ejecta and constrain the ejecta parameters with the observations.

This Letter is organized as follows. In Section 2, we introduce the universally structured jet model and the two-component jet model and calculate the off-axis afterglow emission. Then, we present the method of calculations for the kilonova emission in Section 3. Section 4 shows our results for the two jet models and gives a comparison with an intrinsically less-energetic quasi-isotropic fireball. Section 5 is an application to the very recently discovered GW170817/GRB 170817A. Finally, we draw conclusions and provide a summary in Section 6.

2. Off-axis Afterglows

In this section, we consider a structured jet with a lateral distribution of kinetic energy per solid angle $\varepsilon(\theta)$. This kind of jet may form during the propagation of the jet inside the ejecta, which gives rise to shocks at the jet head (Nagakura et al. 2014; Nakar & Piran 2017). The relativistic shocked jet material forms an inner cocoon, which is wrapped by an outer cocoon composed of mildly relativistic shocked ejecta (Gottlieb et al. 2018; Lazzati et al. 2017a, 2017b; Nakar & Piran 2017). Although there is some mixing between them, the cocoon is far from isotropy (Lazzati et al. 2017b; Nakar & Piran 2017). Thus, the overall uniform jet core plus structured cocoon system can be named as a structured jet, of which the kinetic energy per solid angle and the initial Lorentz factor are assumed to be (Dai & Gou 2001; Zhang & Mészáros 2002a; Rossi et al. 2002; Kumar & Granot 2003)

$$\varepsilon(\theta) \equiv \frac{dE}{d\Omega} = \begin{cases} \varepsilon_0, & \text{if } \theta \leq \theta_c, \\ \varepsilon_0 (\theta/\theta_c)^{-k}, & \text{if } \theta_c < \theta < \theta_m, \end{cases}$$

$$\Gamma_0(\theta) = \begin{cases} \Gamma_0, & \text{if } \theta \leq \theta_c, \\ \Gamma_0 (\theta/\theta_c)^{-s}, & \text{if } \theta_c < \theta < \theta_m, \end{cases}$$

where the typical half-opening angle of short GRBs $\theta_c \approx 0.1$ (which is marginally consistent with the median opening angle given by Fang et al. 2015) and the maximum angle $\theta_m = 4\theta_c$ are assumed. The index $k$ can be deduced from the luminosity distribution of local event rate density $\rho_0(L)$. On the one hand, the local event rate density of short GRBs can be fitted by a power-law $\rho_0(L) \propto L^{-\lambda}$ with $\lambda \sim 0.7$ (Sun et al. 2015). Since $\rho_0(L) \propto \Omega(\theta_E) \approx \pi \theta^2$ for similar durations of prompt emission, we can get $L \propto \theta^{-2/\lambda}$. On the other hand, the isotropic-equivalent luminosity $L \propto 4\pi \times dE/d\Omega \times \theta^{-k}$. Therefore, $k = 2/\lambda \approx 2.86$. In this Letter, we adopt $k = 3$ as a nominal value. Generally, the relationship of indices $s$ and $k$ can be deduced from some empirical relations. Observationally, the relationship between the initial Lorentz factor and isotropic-equivalent energy is approximated by $\Gamma_0 \propto E_{\gamma,\text{iso}}^{1/4}$ (e.g., Zhang & Mészáros 2002b; Liang et al. 2010; Lü et al. 2012). Thus, since $L \propto E_{\gamma,\text{iso}}$, we have $s \approx k/4$ in this work.

Similarly, a two-component jet can be described by the following angular distributions (e.g., Vlahakis et al. 2003; Huang et al. 2004; Lamb & Kobayashi 2017):

$$\varepsilon(\theta) = \begin{cases} \varepsilon_{\text{in}}, & \text{if } \theta \leq \theta_c, \\ \varepsilon_{\text{out}}, & \text{if } \theta_c < \theta < \theta_m, \end{cases}$$

$$\Gamma_0(\theta) = \begin{cases} \Gamma_{\text{in}}, & \text{if } \theta \leq \theta_c, \\ \Gamma_{\text{out}}, & \text{if } \theta_c < \theta < \theta_m, \end{cases}$$

where $\varepsilon_{\text{in}}$ and $\varepsilon_{\text{out}}$ and $\Gamma_{\text{in}}$ and $\Gamma_{\text{out}}$ represent the kinetic energies and Lorentz factors of the inner fast spine and outer slow sheath, respectively.

For an off-axis viewing angle $\theta_\text{v}$, the infinitesimal patch of the emission region at $(r, \theta, \phi)$ makes an angle $\alpha$ with respect to the observer, which is given by (Kathirgamaraju et al. 2017)

$$\cos \alpha = \cos \theta_\text{v} \cos \theta + \sin \theta_\text{v} \sin \theta \cos \phi.$$  (5)

Assuming that the jet expands outward in a homogeneous medium with a typical number density $n \sim 10^{-2} \text{ cm}^{-3}$ for short GRBs (Fong et al. 2015), the evolution of the bulk Lorentz factor $\Gamma$ can be obtained in the same way as in previous works (e.g., Blandford & McKee 1976; Huang et al. 1999; Dai & Gou 2001). In this Letter, we adopt the generic dynamics of a jet following Huang et al. (2000) without considering any lateral expansion of the jet. The radius and the time $t'$ in the jet’s comoving frame can be expressed as

$$\frac{dR}{dt} = \frac{c\beta}{1 - \beta \cos \alpha},$$  (6)

and

$$\frac{dt'}{dt} = \frac{1}{\Gamma(1 - \beta \cos \alpha)},$$  (7)

where $\beta \equiv (1 - 1/\Gamma^2)^{1/2}$ and $t$ is the observed time.

Now we can calculate synchrotron radiation of the electrons accelerated by a forward shock produced due to an interaction of the jet with its ambient medium. Assuming the electrons have a power-law distribution $d\eta_e / d\varepsilon_e \propto \varepsilon_e^{-p}$, the minimum electron Lorentz factor is then $\gamma_m = [(p - 2)/(p - 1)] \varepsilon_e (m_p/m_e) \Gamma$, where $\varepsilon_e$ is a fraction of the post-shock energy density converted
to electrons and the spectral index of the electron energy distribution $p = 2.5$ is adopted as a nominal value. The cooling Lorentz factor is $\gamma_e = 6\pi m_e c / (\sigma_T B^2 \Gamma^2)$, where the magnetic field strength in the shocked medium is given by $B' = [32\pi \epsilon_B \Gamma (1 - \Gamma^2)]^{1/2}$ with $\epsilon_B$ being a fraction of the post-shock energy density converted to a magnetic field. In this Letter, we adopt typical equipartition factors $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$ for short GRBs (Fong et al. 2015). With these parameters, we can calculate the typical frequency $\nu'_m$ and the cooling frequency $\nu'_c$. According to the relative values of the two frequencies, the spectrum without synchrotron self-absorption (SSA) can be written (Sari et al. 1998). The SSA frequency $\nu'_c$ can be obtained by equating the blackbody luminosity at the Rayleigh–Jeans end with the synchrotron luminosity. At last, we can write down the complete differential luminosity $dL'_v / d\Omega'$ in the jet’s comoving frame (e.g., Dai & Gou 2001; Xiao & Dai 2017).

The observed total flux density of the off-axis afterglow is then given by (Dai & Gou 2001; Granot et al. 2002; Kathirgamaraju et al. 2017)

$$F_v = \int_0^{\nu_m} d\nu_0 \int_0^{2\pi} d\phi_0 \frac{dL'_v / d\Omega'}{4\pi D_L^2 \Gamma^3 (1 - \beta \cos \alpha)^3},$$  

(8)

where $D_L$ is the luminosity distance of the source to an observer. Note that we should integrate on the equal arrival time surface that is determined by $t = \int \left[ (1 - \beta \cos \alpha) / (c \beta) \right] dR \equiv$ constant (Waxman 1997; Panaiteescu & Mészáros 1998; Sari 1998; Huang et al. 2000; Moderski et al. 2000).

### 3. Kilonovae

The neutron-rich ejecta produced during a BNS merger undergoes rapid neutron capture ($r$-process) nucleosynthesis. The radioactive decay of these heavy nuclei is able to power a day-to-week-long kilonova (Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010; Kasen et al. 2013; Tanvir et al. 2013; Metzger 2017).

The density distribution of the ejecta can be obtained from numerical simulations. The geometry structure of the ejecta can be modeled as a partial sphere in the latitudinal and longitudinal direction (Kyutoku et al. 2013, 2015). We assume a homologous expansion inside the ejecta, so the density of the ejecta is (Kawaguchi et al. 2016)

$$\rho(v, t) = \frac{M_{ej}}{2 \phi_{ej} \theta_{ej} (v_{max} - v_{min})} v^{-2} t^{-3},$$  

(9)

where $v_{min}$ and $v_{max}$ are the minimum and maximum velocities of the ejecta, respectively, $\theta_{ej}$ is the polar opening angle, and $\phi_{ej}$ is the azimuthal opening angle. Here, we adopt $v_{min} = 0.02c$ and $v_{max} = 2\theta_{ej} - v_{min}$. For a BNS merger, there exists a linear correlation between $\theta_{ej}$ and $\phi_{ej}$ (Dietrich & Ujevic 2017):

$$\phi_{ej} = 4\theta_{ej} + \frac{\pi}{2}.$$  

(10)

We assume that the kilonova is powered radioactively, without an additional energetic engine such as a stable strongly magnetized millisecond pulsar as suggested in the literature (e.g., Dai et al. 2006; Yu et al. 2013). The heating rate of $r$-process ejecta can be approximated by a power law (Korobkin et al. 2012; Tanaka & Hotokezaka 2016)

$$\dot{Q} \approx M_{ej} \epsilon_0 \left( \frac{t}{t_{day}} \right)^{-\alpha},$$  

(11)

where we adopt $\epsilon_0 = 1.58 \times 10^{40}$ erg s$^{-1}$ g$^{-1}$ and $\alpha = 1.3$ following Dietrich & Ujevic (2017).

The bolometric luminosity of kilonova is approximated by (Kawaguchi et al. 2016; Dietrich & Ujevic 2017)

$$L_{MN} = (1 + \theta_{ej}) \epsilon_{th} \times \begin{cases} t/t_c, & \text{if } t \leq t_c, \\ 1, & \text{if } t > t_c, \end{cases}$$  

(12)

where the factor $(1 + \theta_{ej})$ indicates the contribution from an effective radial edge. $\epsilon_{th}$ is the thermalization efficiency introduced in Metzger et al. (2010), and we adopt $\epsilon_{th} = 0.5$ as a nominal value. The critical time $t_c$ at which the expanding ejecta becomes optically thin (Kawaguchi et al. 2016) is

$$t_c = \left[ \frac{\theta_{ej} \kappa M_{ej}}{2 \phi_{ej} (v_{max} - v_{min}) c} \right]^{1/2}.$$  

(13)

For $t < t_c$, the mass of the photon-escaping region is $M_{obs}(t) = M_{ej}(t/t_c)$. At $t = t_c$, the whole region of the ejecta becomes transparent. Kasen et al. (2013) and Barnes & Kasen (2013) found that the opacity of $r$-process ejecta, particularly lanthanides, is much higher than that for Fe-peak elements, with $\kappa \sim 10–100$ cm$^2$ g$^{-1}$. Kawaguchi et al. (2016) and Dietrich & Ujevic (2017) found that the bolometric light curve of a kilonova in the analytic model mentioned above can well match the results of radiation-transfer simulations performed in Tanaka & Hotokezaka (2013).

Assuming that the spectrum of the kilonova emission is approximated by a blackbody, the effective temperature can be written as

$$T_{eff} = \left( \frac{L_{MN}}{\sigma_{SB} S} \right)^{1/4},$$  

(14)

where $\sigma_{SB}$ is the Stephan–Boltzmann constant and $S = R_{ej}^2 \phi_{ej}$ is the emitting area with $R_{ej} \sim v_{max} t$ being the radius of the latitudinal edge. The observed flux at photon frequency $\nu$ can be calculated by

$$F_{\nu, MN} = \frac{2\pi h \nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T_{eff}) - 1} \frac{R_{ej}^2}{D_L^2},$$  

(15)

where $h$ is the Planck constant and $k_B$ is the Boltzmann constant.

### 4. Theoretical Results

Figure 1 shows our theoretical light curves of the structured jet model for different viewing angles. We consider a typical short GRB with jet core energy $\epsilon_0 = 10^{50}$ erg/sterad and Lorentz factor $\Gamma_0 = 300$, located at a close distance $D_L = 40$ Mpc. With the increase of the viewing angle, the peak luminosity decays and the X-ray light curve shifts to earlier times until $\theta_e$ becomes larger than $\theta_{min}$, which is different from previous works that assume $s = k$ (e.g., Huang et al. 2000; Moderski et al. 2000; Granot et al. 2002; Lamb & Kobayashi 2017). The reason for this result is that the light curves peak when the break frequencies $\nu'_m$ and $\nu'_c$ cross the observed
frequency (Sari et al. 1998). Since $\nu'_m = \gamma^2_m eB'/(2\pi m_e c) = 1.95 \times 10^9 n^{-1/2} \Gamma (\Gamma - 1)^{5/2} \text{Hz}$ and $\nu'_c = \gamma^2_c eB'/(2\pi m_e c) = 2.85 \times 10^9 n^{-3/2} \Gamma^{-3/2}(\Gamma - 1)^{-3/2} \nu'^{-2} \text{Hz}$ for the parameters taken in Section 2, we find that $\nu'_m < \nu'_c$ is always satisfied so the synchrotron emission is in the slow cooling regime. After converting the observed frequencies into the comoving frame, we see that $\nu'_m < \nu'_X < \nu'_c$ is always established, while initially $\nu'_\text{r,band} < \nu'_m < \nu'_c$ but soon turns into $\nu'_m < \nu'_\text{r,band} < \nu'_c$, and initially $\nu'_\text{radio} < \nu'_m < \nu'_c$ but turns into $\nu'_m < \nu'_\text{radio} < \nu'_c$ at a much later time. This gives rise to different peak times of different bands. The light curves of the r band are shown in Figure 1(b). Solid lines correspond to afterglow emission, and dashed and dotted lines to kilonova emission. The theoretical flux of the kilonova signal depends on the kinetic energy and velocity of the ejecta. Numerical simulations have suggested that the ejecta have typical masses of $10^{-4} - 10^{-2} M_\odot$ and velocities of 0.1–0.3 c (e.g., Nagakura et al. 2014). Thus, we consider two masses $10^{-3} M_\odot$ (magenta) and $10^{-2} M_\odot$ (red), and velocities 0.1 c (dotted) and 0.3 c (dashed), so we have four combinations. For large viewing angles, the kilonova signal probably dominates over the afterglow. Therefore, if the kilonova component can be extracted in optical–infrared follow-up observations, it will help constrain parameters such as the viewing angle and the ejecta mass and velocity. For completeness, we plot the light curves of the radio band ($\nu = 5 \text{GHz}$) in Figure 1(c). Since the wide-angle structured jet (including its cocoon) sweeps up its ambient medium at early times, there might be no medium left over, and thus the ejecta will possibly expand freely with a nearly constant velocity. Thus, we neglect any emission from an interaction of...
the ejecta with its ambient gas in a year-scale period after the merger (Nakar & Piran 2011). The time evolution of the afterglow spectrum is shown in Figure 1(d) for the $q_v = 4c$ case. The theoretical results in the two-component jet model shown in Figure 2 are very different from those of the structured jet model. The line styles in this figure are the same as those in Figure 1. For an off-axis observer, the afterglow emission is dominated by the wide component at early times. The relevant parameters are $\Gamma_{in} = 300$, $\Gamma_{out} = 30$, $\varepsilon_{in} = 10^{30}$ erg/sterad, and $\varepsilon_{out} = 10^{48}$ erg/sterad. The emission from the narrow component generally shows up at times later than $10^5$ s. The ratio of peak luminosities between the wide and narrow component depends on the ratio of their energy and viewing angle. With the increase of $\theta_v$, the peak time delays and the peak luminosity decays.

However, there is still a possibility that an observed low-luminosity burst is not due to a large viewing angle, and instead it arises from an intrinsically less-energetic quasi-isotropic fireball. We need to consider its afterglow emission for completeness. The structured jet model can be easily generalized to an isotropic fireball case if we set index $k = 0$ and opening angle $\theta_{in} = \pi$ in Equation (1). Since the kinetic energy per solid angle along the line of sight in the structured jet model can be estimated by $\varepsilon_{0}/\varepsilon_{obs} = (\theta_{v}/\theta_{\theta})^{-3}$, to make a direct comparison with one of the previous cases (e.g., $\varepsilon_{0} = 10^{50}$ erg/sterad, $\theta_{v} = 4\theta_{\theta}$), we assume a fireball with isotropic kinetic energy $E_{iso} \sim 4\pi \times 10^{50} \times 4^{-3}$ erg $\sim 2.0 \times 10^{49}$ erg. The corresponding X-ray, r-band, radio light curves and spectral evolution are shown in Figure 3. Different lines represent different medium densities, ranging from $n = 10^{-4} - 1$ cm$^{-3}$. As expected, the flux level drops with the decrease of $n$. Note that the radio light curve shape varies with medium density because there is a crossing between $\nu_{\alpha}$ and $\nu_{\text{radio}}$ for higher densities (in the cases of $n = 1$ and 0.1 cm$^{-3}$), while $\nu_{\alpha} < \nu_{\text{radio}}$ always holds for densities lower than $10^{-2}$ cm$^{-3}$. We can clearly

![Figure 2. Theoretical results in the two-component jet model. Panel (a): the X-ray light curves for different viewing angles. The line styles are the same as in Figure 1(a). Panel (b): the r-band magnitude for different viewing angles. The line styles are the same as in Figure 1(b). Panel (c): the radio ($\nu = 5$ GHz) light curves for different viewing angles. The line styles are the same as in Figure 1(c). Panel (d): the spectrum evolution for the viewing angle $\theta_v = 4\theta_{\theta}$ case. The line styles are the same as in Figure 1(d).](image-url)
see that the observed afterglow emission of an intrinsically less-energetic fireball is very different from that of an intrinsically powerful off-axis short GRB discussed above. In particular, comparing the yellow solid line in Figure 1(a) with the blue solid line in Figure 3(a), we can see that the peak time and peak luminosity differ (about two orders of magnitude) for these two types of model. Similar differences can be found in the r band and radio band. Also, the quasi-isotropic kilonova signal may be different since intrinsically fainter short GRBs are likely accompanied by less-energetic ejecta, so the kilonova should be dimmer. The spectral evolution with time is also different from each other in the two types of model if we compare Figure 3(d) with Figure 1(d). All of these results would be testable by multi-wavelength follow-up observations.

5. Application to GW170817/GRB 170817A

In this section, we try to fit the multi-wavelength observational data (for a complete collection, see Abbott et al. 2017d) with the above models and the results are shown in Figures 4 and 5. The relevant fitting parameters are given in Tables 1 and 2. The X-ray upper limits are given by Swift-XRT and NuSTAR (Evans et al. 2017), while the two detections of Chandra are indicated by the red data points (Troja et al. 2017). For the optical band, we choose the r band to fit, and the data are collected in the literature (Andreoni et al. 2017; Arcavi et al. 2017; Coulter et al. 2017; Drout et al. 2017; Kilpatrick et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017). The six radio data points ($\nu = 3$ GHz) are taken from Hallinan et al. (2017) and could give tight constraints on models. The quasi-isotropic fireball model is ruled out because the early X-ray flux is overestimated if the X-ray light curve is required to pass through the Chandra data point. The structured jet model can account for the Chandra X-ray data without violating the Swift-XRT and NuSTAR upper limits only if $\theta_v > \theta_m$. Obviously, the two-component model works well for X-ray emission. For the

![Figure 3. Theoretical results in the quasi-isotropic fireball model. Panel (a): the X-ray light curves for different medium densities. The black solid, dashed, blue solid, dashed, and green solid lines represent $n = 1, 10^{-2}, 10^{-3}, 10^{-4}$ cm$^{-3}$, respectively. Panel (b): the r-band magnitude for different medium densities. The line styles are the same as in Figure 3(a). Panel (c): the radio ($\nu = 5$ GHz) light curves for different medium densities. The line styles are the same as in Figure 3(a). Panel (d): the spectrum evolution for the $n = 0.01$ cm$^{-3}$ case. The line styles are the same as in Figure 1(d).](image-url)
optical band, we use a Markov Chain Monte Carlo (MCMC) approach and the r-band data can be well fitted by the kilonova component, while the afterglow emission is always sub-dominant, which is shown in Figures 4(b) and 5(b). The MCMC best-fitting parameters obtained from the corner plot shown in Figure 6 for the kilonova component are $M_{\text{ej}} = 0.026 \pm 0.0016$ (2$\sigma$) and $v_\text{ej} = (0.12 \pm 0.015)c$ (2$\sigma$), where $M_{\text{ej}} = (\kappa/10 \text{ cm}^2 \text{ g}^{-1}) \times (M_{\text{ej}}/M_\odot)$ is defined. The radio data can provide the tightest constraint on the models. The comparisons of the fitting results with radio observations are given in Figures 4(c) and 5(c). Generally, the two-component jet model gives the better-fitting quality than the structured jet model. However, the radio data are still dimmer than model predictions in all of the cases, indicating that there might be an extra component leading to the delayed X-ray emission (e.g., the contribution of a reverse shock). Note that there are some degeneracies in parameters (energy, medium density, viewing angle, etc.) and better-fitting quality can be achieved through fine tuning.

6. Conclusions

The discovery of multi-wavelength EM signals associated with GW170817 marks the beginning of a new era in multi-messenger time-domain astronomy. In this work, we have first re-investigated both an afterglow and a kilonova that are associated with a nearby low-luminosity short GRB from a BNS merger, under the assumption of a universally structured jet and a two-component jet. We then tried to apply the models to GW170817/GRB 170817A. In general, the isotropic fireball model is ruled out because it is fully inconsistent with the early X-ray upper limits and radio data. The structured jet model may
explain the late-time X-ray emission but predict a radio flux much higher than observed. The multi-wavelength observational data could be well fitted by the two-component jet model and all the relevant parameters are within their reasonable ranges, although further fine tuning is needed.

Generally, detecting a low-luminosity short GRB is estimated to be much easier in our local universe than a normal one because the former has a much greater occurrence rate than the latter does. With the upgrade of the Advanced LIGO/Virgo detectors and the improvement of the all-sky transient survey, this kind of association will become more and more common in the future. We have considered two possibilities that either a faint short GRB (like GRB 170817A)
is intrinsically low-luminosity and quasi-isotropic or it is just due to off-axis jet emission. We have shown that the properties of afterglow emission in these cases are obviously different. The light curves rise slower and peak at a later time for the off-axis case (e.g. Murguia-Berthier et al. 2017). The spectrum is also different at any given time. Furthermore, if we assume the kinetic energy of the ejecta is proportional to that of the jet, the kilonova signal in the less-energetic fireball case should be much fainter than that of the off-axis powerful short GRB case. With multi-wavelength follow-up observations of a local low-luminosity short GRB, we can distinguish between these models very soon if such an association is confirmed again in the future. In addition, several key parameters can be constrained such as the viewing angle, the ejecta mass, the ejecta velocity, and the ambient medium density, all of which would help reveal the mystery of short GRBs. For GW170817/GRB 170817A, the ejecta parameters obtained in this Letter are \((\kappa/10 \text{ cm}^2 \text{ g}^{-1}) \times (M_\text{ej}/M_\odot) = 0.026 \pm 0.0016 \) \((2\sigma)\) and \(v_\text{ej} = (0.12 \pm 0.015)c \) \((2\sigma)\) by considering the kilonova component. These parameters are well consistent with numerical simulations of BNS mergers.

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Figure 6. Parameter corner in the modeling of r-band data. The contours are 1\(\sigma\), 2\(\sigma\), and 3\(\sigma\) uncertainties, respectively.
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