Abstract
Recent follow-up observations of the binary neutron star (NS) merging event GW170817/SGRB 170817A reveal that its X-ray/optical/radio emissions are brightening continuously up to ~100 days post-merger. This late-time brightening is unexpected from the kilonova model or the off-axis top-hat jet model for gamma-ray burst (SGRB) afterglows. In this Letter, by assuming that the merger remnant is a long-lived NS, we propose that the interaction between an electron–positron-pair ($e^− e^+$) wind from the central NS and the jet could produce a long-lived reverse shock, from which a new emission component would rise and can interpret current observations well. The magnetic-field-induced ellipticity of the NS is taken to be $40^\circ$ in our modeling, so that the braking of the NS is mainly through the gravitational wave (GW) radiation rather than the magnetic dipole radiation, and the emission luminosity at early times would not exceed the observational limits. In our scenario, because the peak time of the brightening is roughly equal to the spin-down timescale of the NS, the accurate peak time may help constrain the ellipticity of the remnant NS. We suggest that radio polarization observations of the brightening would help to distinguish our scenario from other scenarios. Future observations on a large sample of short gamma-ray burst afterglows or detections of GW signals from merger remnants would test our scenario.

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

1. INTRODUCTION
Recently, the coincident detection of a gravitational wave (GW) event GW170817 (Abbott et al. 2017a) and its electromagnetic counterparts (i.e., a short gamma-ray burst (SGRB) SGRB 170817A and a kilonova; Arcavi et al. 2017; Drout et al. 2017; Goldstein et al. 2017; Kasen et al. 2017; Kasliwal et al. 2017; Pian et al. 2017; Smartt et al. 2017; Tanaka et al. 2017; Utsumi et al. 2017; Zhang et al. 2018) confirmed the hypothesis that binary neutron star (NS) mergers are at least the progenitors of some SGRBs. Early temporal and spectral observations in optical bands (within ~15 days) can be interpreted as the quasi-thermal radiation from a kilonova (Li & Paczyński 1998; Romswog 2005; Metzger et al. 2010; Metzger 2017). Chandra observations showed an X-ray source at location coincident with the kilonova transient at ~9 days after the burst (Troja et al. 2017). Continued monitoring revealed that the X-ray source brightened with time until 15.1 days post-merger (Haggard et al. 2017; Margutti et al. 2017). Most recently, this X-ray emission is found to be brightening according to the deep Chandra observations at 109.2 days post-burst (Ruan et al. 2018). In the radio band, it is showed that the radio emission is also brightening slowly up to 93 days post-burst (Hallinan et al. 2017; Mooley et al. 2017). Furthermore, it is found that the X-ray emission brightens at a similar rate as the radio emission, indicating that they share a common origin (Ruan et al. 2018). Late-time optical emission detected by the Hubble Space Telescope (HST; Lyman et al. 2018) at ~100 days also supports the theory that the optical brightening is from the same origin. The physical origin of the prompt emission and afterglow of SGRB 170817A has not yet been revealed. A uniform jet with a sharp edge (also called a top-hat jet) is usually considered to be responsible for the gamma-ray burst (GRB) prompt emission previously (e.g., Mészáros & Rees 1999; Panaitescu & Mészáros 1999). The low isotropic luminosity ($\sim 10^{47}$ erg s$^{-1}$) of the prompt emission of SGRB 170817A suggests that the GRB jet should be seen by an off-axis observer in this case (Granot et al. 2017a; Ioka & Nakamura 2017). However, the contradiction of the ratios of typical off-axis to on-axis photon energy and isotropic-equivalent energy does not support the theory that the prompt emission originates from such a top-hat jet (Granot et al. 2017b; Kasliwal et al. 2017). Moreover, the recently observed brightening X-ray/optical/radio afterglow also rules out the simple off-axis top-hat jet origin as it is not in agreement with the data. Alternative explanations, such as a structured off-axis jet (Lamb & Kobayashi 2017; Xiao et al. 2017; Kathirgamaraju et al. 2018; Meng et al. 2018), or the Thomson-scattered emission with a typical SGRB jet (Kisaka et al. 2017), or the breakout of a mildly relativistic wide-angle cocoon (Nakar & Sari 2010; Lamb & Kobayashi 2016; Gottlieb et al. 2017), were further suggested as being responsible for the prompt emission. The brightening afterglow is shown to be well interpreted by a structured outflow with a highly relativistic core (Lazzati et al. 2017c; Lyman et al. 2018; Margutti et al. 2018), which supports a jet-cocoon system produced in the NS merger (Murguia-Berthier et al. 2014; Nagakura et al. 2014; Lazzati et al. 2017a, 2017b; Nakar & Piran 2017; Wang & Huang 2017).

Except for the scenarios mentioned above, it is still possible that the brightening is caused by a continued injection of energy from the central engine into the external jet (Pooley et al. 2017; Li et al. 2018). The energy injection has been frequently invoked in interpreting many nonstandard afterglow
3. The Astroparticle Scale

3.1. Neutrino Emission

The astrophysical neutrino flux is described by the density parameter of neutrinos, which is defined as $\Omega_{\nu}$, given by

$$\Omega_{\nu} = \frac{\rho_{\nu}}{\rho_{\text{crit}}}$$

where $\rho_{\nu}$ is the energy density of neutrinos and $\rho_{\text{crit}}$ is the critical density of the universe. The neutrino luminosity is given by

$$L_{\nu} = 4\pi r^2 \frac{dL_{\nu}}{dr}$$

where $r$ is the distance to the source and $dL_{\nu}/dr$ is the neutrino luminosity density. The neutrino energy spectrum is described by the spectral index $\gamma_{\nu}$, given by

$$\nu(E) = L_{\nu} E^{\gamma_{\nu}}$$

where $\nu(E)$ is the neutrino flux at energy $E$. The neutrino flux is given by

$$\nu(E) = \frac{L_{\nu}}{4\pi r^2} E^{-\gamma_{\nu}}$$

The neutrino energy spectrum is also described by the spectral index $\gamma_{\nu}$, given by

$$\gamma_{\nu} = \frac{d\ln \nu(E)}{d\ln E}$$

where $\nu(E)$ is the neutrino flux at energy $E$. The neutrino energy spectrum is given by

$$\nu(E) = L_{\nu} E^{\gamma_{\nu}}$$

and is determined by the source parameters, such as the energy and duration of the neutrino burst. The neutrino luminosity is given by

$$L_{\nu} = 4\pi r^2 \frac{dL_{\nu}}{dr}$$

where $r$ is the distance to the source and $dL_{\nu}/dr$ is the neutrino luminosity density.
where \( P_{v,i}^{\gamma} = \int \frac{dN}{d\epsilon} p_{v,i}^{\gamma} d\epsilon \), is the equivalent isotropic number distribution of electrons in the emitting shell, \( p_{v,i}^{\gamma} \) is the synchrotron emission power at frequency \( \nu' \) for an electron of Lorentz factor \( \gamma_{v,i} \). \( D = |I_0(1 - \beta_2 \cos \theta)|^{-1} \) is the Doppler factor, and \( D_{\gamma} \) is the luminosity distance of the burst. The corresponding integral limits are obtained according to virtue of spherical geometry (Wu et al. 2005), \( \Delta \phi = \arccos \left( \frac{\cos \theta - \cos \theta_i}{\sin \theta_i \sin \theta} \right) \), for case of \( |\theta_i - \theta_V| < \theta < \theta_i + \theta_V \) here. In our calculations, for the flux at \( t_{\text{obs}} \), the integration is performed over the equal arrival time surface (EATS; Waxman 1997; Granot et al. 1999; Huang et al. 2007; Geng et al. 2017), which is determined by

\[
 t_{\text{obs}} = (1 + z) \int_0^{R_\theta} \frac{1 - \beta_2 \cos \theta}{\beta_2 c} d\theta \equiv \text{const}, \tag{5}
\]

from which \( R_\theta \) (the radius for position at \( \theta \) on the surface) can be derived.

3. Modeling the Afterglow

If a wind from the NS is due to magnetic dipole radiation (MDR), its luminosity is (Shapiro & Teukolsky 1983; Yu & Dai 2017)

\[
 L_w \approx 9.6 \times 10^{42} B_{NS,12}^2 R_{NS,6}^6 P_{NS,-3}^{-4} \left( 1 + \frac{t_{\text{obs}}}{T_{\text{sd}}} \right)^{-\alpha} \text{erg s}^{-1}, \tag{6}
\]

where \( B_{NS} \), \( R_{NS} \), \( P_{NS} \), \( T_{\text{sd}} \), and \( \alpha \) are the strength of the polar magnetic field, the radius, the initial spin period, the spin-down timescale, and the decay index of the NS. \( T_{\text{sd}} \) and \( \alpha \) are further determined by considering whether the spin-down of the NS is mainly due to the MDR or the GW radiation. The convention \( Q_i = Q/10^\alpha \) in cgs units is adopted hereafter. Within the scenario of \( e^+ e^- \) injection, it was revealed that the peak time of the brightening X-ray afterglow are roughly determined by \( T_{\text{sd}} \) (Geng et al. 2016). As a consequence, as required by the temporal observational data, we have

\[
 T_{\text{sd}} \geq 110 \text{ days} \approx 9.5 \times 10^6 \text{ s}. \tag{7}
\]

If the spin-down of the NS is due to MDR, then

\[
 T_{\text{sd,MDR}} = 2 \times 10^9 I_{45} B_{NS,12}^2 R_{NS,6}^6 P_{NS,-3}^2 \text{ s}, \tag{8}
\]

where \( I \) is the moment of inertia of the NS. Combining Equations (7) and (8) gives

\[
 B_{NS} \leq 1.5 \times 10^{13} I_{45}^{1/2} R_{NS,6}^{-3} P_{NS,-3}^2 \text{ G}, \tag{9}
\]

where typical values of \( I = 10^{45} \text{ g cm}^2 \), \( R_{NS} = 10^6 \text{ cm} \), and \( P_{NS} = 10^{-3} \text{ s} \) are taken.

On the other hand, GW radiation may also brake a newly born NS efficiently. The GW emission mechanism from the remnant NS may be due to magnetic-field-induced ellipticities (Bonazzolla & Gourgoulhon 1996; Palomba 2001; Cutler 2002; Dall’Osso et al. 2009), unstable bar modes (Lai & Shapiro 1995; Corsi & Mészáros 2009), or unstable r-modes oscillations (Andersson 1998; Lindblom et al. 1998; Dai et al. 2016). Here, we consider the first case to perform some representative estimates. The spin-down timescale due to an ellipticity of \( \epsilon \) can be expressed as (Shapiro & Teukolsky 1983; Osso et al. 2009)

\[
 T_{\text{sd,MDR}} = \frac{5 c^5 P_{NS}^4}{2048 \pi^4 G I^2} = 9.1 \times 10^5 \epsilon^{-3/2} I_{45}^{-1} P_{NS,-3}^4 \text{ s}, \tag{10}
\]

where \( G \) is the gravitational constant. Combining Equations (7) and (10), we derive that

\[
 \epsilon \leq 3.1 \times 10^{-5} I_{45}^{-1/2} P_{NS,-3}^2. \tag{11}
\]

How the NS spins down is uncertain, so the two cases with different braking mechanisms mentioned above are taken into account in our modeling. Due to the substantial angular momentum of the initial binary, an initial spin period of \( P_{NS} \sim 10^{-3} \text{ s} \) close to the centrifugal break-up limit is expected for the natal NS (e.g., Rezzolla et al. 2011; Giacomazzo & Perna 2013). We thus fix \( P_{NS} \) to be 1 ms for all our modeling. Model parameters making a good match to the data are given in Table 1 and the corresponding lightcurves are shown in Figure 1. The values for parameters like \( \theta_{i}, \theta_{V}, P_{2}, \rho_{2} \), and \( n_{1} \) adopted are consistent with those in other works (Lazzati et al. 2017; Lyman et al. 2018; Margutti et al. 2018). From Figure 1, it is seen that the multi-wavelength brightening is attributed to the emission from Region 3. The synchrotron frequency of \( \gamma_{m,3} \) (\( \theta_{m,3} \)) is below the radio band (3 GHz), while the cooling frequency \( \nu_{c,3} \) is above the X-ray band (1 keV) in our calculations, which is consistent with almost the same temporal indices for multi-wavelength brightening. In our modeling, we have supposed that the peak time (still unknown) of afterglows is roughly around 150 days. Because \( T_{\text{sd}} \) is sensitive to \( B_{NS} \) or \( \epsilon \) in two scenarios, respectively, a smaller \( B_{NS} \) or \( \epsilon \) would lead to a later peak time. The true peak time from future data would help us to determine the realistic

| Table 1 |
| Parameters Used in the Modeling of the Afterglow of SGRB 170817A |
| Parameters | MDR | GW Radiation |
| \( \theta_{i} \) | 15° | 10° |
| \( \theta_{V} \) | 20° | 20° |
| \( E_{K,iso} \) \((10^{50} \text{ erg})\) | 5 | 2 |
| \( t_{\text{sd}} \) | 100 | 100 |
| \( P_{2} \) | 2.12 | 2.15 |
| \( \xi_{c,2} \) | 0.012 | 0.05 |
| \( \xi_{B,2} \) | 0.003 | 0.002 |
| \( n_{1} \) \((\text{cm}^{-3})\) | \(8 \times 10^{-4}\) | \(8 \times 10^{-4}\) |
| \( B_{NS} \) \((G)\) | \(1.3 \times 10^{13}\) | \(10^{12}\) |
| \( T_{\gamma} \) | \(10^{4}\) | \(10^{4}\) |
| \( P_{3} \) | 2.17 | 2.17 |
| \( \xi_{B,3} \) | \(2 \times 10^{-7}\) | 0.02 |
| \( \sigma \) | \(2 \times 10^{-7}\) | 0.02 |
| \( \epsilon \) | 0 | \(4.4 \times 10^{-5}\) |

Notes.

In our calculations, we have considered two different models, in which the dominant braking mechanism for the spinning down of the pulsar is MDR or GW radiation, respectively.

\( a \) \( E_{K,iso} \) is the initial isotropic kinetic energy of the GRB jet ejecta.

\( b \) \( t_{\text{sd}} \) is the initial Lorentz factor of the GRB jet ejecta.

\( c \) \( t_{\gamma} \) is typically in range of \( 10^{2} \sim 10^{3}\) according to observations and theories of pulsar wind nebula (e.g., Rees & Gunn 1974; Lyubarsky & Kirk 2001; Bucciantini et al. 2011).

Usov 1992; Cutler & Jones 2001

\[
 T_{\text{sd,GR}} = \frac{5 c^5 P_{NS}^4}{2048 \pi^4 G I^2 c} = 9.1 \times 10^5 \epsilon^{-3/2} I_{45}^{-1} P_{NS,-3}^4 \text{ s}, \tag{10}
\]

where \( G \) is the gravitational constant. Combining Equations (7) and (10), we derive that

\[
 \epsilon \leq 3.1 \times 10^{-5} I_{45}^{-1/2} P_{NS,-3}^2. \tag{11}
\]

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This low radiation efficiency is to overcome the high peak flux density \( F_{\text{max},3} \approx 10^{3/2} \left( \frac{a_{B,3}}{10^{-3}} \right)^{1/2} B_{\text{NS}}^{1/2} \) caused by the relatively large \( B_{\text{NS}} \). Some other authors also found that the high spin-down luminosity from a magnetar remnant is much higher than the bolometric luminosity of the kilonova, which has been claimed to disfavor a long-lived magnetar remnant. This magnetar scenario is also not preferred in comparison with the GW spin-down scenario. In the case that the spin down of the NS is dominated by the GW radiation, the parameter \( B_{\text{NS}} \) is free to a fix \( T_{\text{sd}} \) so that \( \xi_B,3 \) and \( \sigma \) could be adjusted in a more plausible range under small \( B_{\text{NS}} \). But an ellipticity of \( 10^{-5} \) for the NS is needed. This ellipticity could be caused by an internal toroidal magnetic field of \( B_{\text{tor}} \approx 2 \times 10^{15} \frac{G}{\text{tor},\max} \) (Bonazzola & Gourgoulhon 1996; Cutler 2002; Dall’Osso et al. 2009; Mastrano et al. 2011; Gao et al. 2017). The strength of the polar magnetic field used in our fitting is \( B_{\text{NS}} = 10^{12} \text{G} \), which is much smaller than \( B_{\text{tor}} \). However, the analyses on the stability of a rotating NS with different configurations of the poloidal (surface) and the internal toroidal component by Akgün et al. 2013 and Dall’Osso et al. 2015 show that the magnetic configuration of the NS is stable, if the maximum toroidal field strength meets

\[
B_{\text{tor, max}} \leq 3 \times 10^{15} \frac{B_{\text{NS},12}^{1/2}}{\text{G}}.
\]

The \( B_{\text{tor}} \) required for the ellipticity in our result could be still below the \( B_{\text{tor, max}} \). Moreover, our adopted \( \epsilon \) of less than a few times \( 10^{-5} \) is consistent with current upper limits on the GW emission (Abbott et al. 2017b). It is well below the LIGO detectability, as would be any higher, yet plausible value.

It was argued that high X-ray emission from the central NS with \( B_{\text{NS}} \geq 10^{12} \text{G} \) could be detected in the early afterglow (e.g., Zhang 2013; Sun et al. 2017). This early high X-ray emission may be in contradiction with the upper limits of X-ray flux for SGRB 170817A (Margutti et al. 2018). Indeed, the wind luminosity of \( L_w = 9.6 \times 10^{32} \text{erg s}^{-1} \) (\( B_{\text{NS}} = 10^{12} \text{G} \)) is higher than the X-ray upper limit of \( 7 \times 10^{38} \text{erg s}^{-1} \) at \( \sim 2.2 \text{days} \) (Troja et al. 2017). However, the radiation efficiency of converting wind luminosity to X-ray luminosity (\( \eta_X \)) needs to be taken into account when we are using this upper limit to constrain the parameters of the NS. If the wind from the NS is dissipated via some mechanisms such as gradual magnetic reconnection (Spruit et al. 2001; Drenkhahn 2002; Beniamini & Giannios 2017), \( \eta_X \) will increase monotonously with \( L_w \) for a specific \( \Gamma_4 \) and will be inversely dependent on \( \Gamma_3 \) (see Figure 4 of Xiao & Dai 2017). For the case of \( \Gamma_4 = 10^4 \) and \( B_{\text{NS}} = 10^{12} \text{G} \) adopted in our paper, \( \eta_X \) is less than \( 10^{-4} \) according to Xiao & Dai 2017, which ensures that the X-ray emission (if it exists) from the NS wind would not exceed the observational limit. On the other hand, the energy of the NS wind may be absorbed by the merger ejecta, so the NS wind is a further energy source for the kilonova in addition to the radioactivity. In the scenario proposed by Metzger & Piro 2014, a nebula of \( e^+e^- \) and non-thermal photons is produced from the dissipation of the NS wind behind the ejecta. A fraction of the nebula energy would be absorbed by the ejecta (non-thermal photons get thermalized via their interaction with the ejecta wall), and a range of 0.01–0.1 is generally expected for the absorption efficiency (Metzger & Piro 2014; Yu & Dai 2017). The remaining fraction of the nebula energy will be lost by the PdV work, which affects the evolution of the ejecta radius. Considering the absorption efficiency of 0.01 – 0.1 for the NS wind here, the resulting power is lower than the bolometric luminosity of the kilonova (\( \sim 5 \times 10^{41} \text{erg s}^{-1} \); Cowperthwaite et al. 2017). Therefore, the NS wind would not affect the temporal behavior of the kilonova significantly.

In our calculations, we have only considered the \( e^+e^- \) wind that is injected into the GRB jet (along the jet direction). Observations of more slowly rotating pulsars (e.g., Crab) indicate that the jet-and-torus morphology is common for the pulsar wind nebula (e.g., Kargaltsev & Pavlov 2008; Reynolds et al. 2017). If the \( e^+e^- \) wind is isotropic or toroidally
dominated (such as the Crab Nebula), the effect of its injection into the kilonova ejecta may be more significant. However, simulations show that it is still possible that the $e^+e^-$ wind would be dominated in the jet direction when the magnetic obliquity angle is small (see Figure 5 of Porth et al. 2017). At the same time, we are still lacking knowledge about the preferred wind direction of the newly born NS studied here. Our calculations still make sense as long as there is an $e^+e^-$ wind injected in the jet direction.

In both scenarios, we can see that the resulting multi-wavelength afterglows are observable within $\sim1000$ days, which could help to test our modeling in the future. However, one should notice that, due to the spin down, the NS, if supramassive, may collapse into a black hole at some late time $\geq T_{\text{sd}}$. After the collapse, the $e^+e^-$ wind injection may be terminated and a steeper decay in the lightcurves after the peak is expected. We have not included this possibility in our current calculations. An abrupt decay signature (if it exists) in the late observational data would correspond to this possibility.

It may be difficult to distinguish our model from the structured jet/cocoon model merely based on the lightcurves. Both our model and the structured jet/cocoon model can well interpret the data in the brightening phase until now. For the upcoming decay phase, the decay index of the optical lightcurves ranges from $-0.5$ to $-1.1$ in the structured jet model, depending on different $n_{\text{i}}$ used (Margutti et al. 2018). The decay index in our model is $\sim-0.7$, which does not deviate much from the former. Nevertheless, observations of the polarization during the brightening phase may help to judge which model is preferred. According to Lan et al. (2016), the magnetic field frozen in the relativistic wind may be large-scale ordered, and synchrotron radiation from the shocked wind region should be highly polarized. While the magnetic field of the emission region in the structured jet/cocoon model may be random, a relatively low polarization degree would be expected. Thus we suggest radio polarimeter facilities should be used to detect the polarization evolution of the radio afterglow of SGRB 170817A.

5. Conclusions

As shown by deep Chandra, HST, and Very Large Array (VLA) observations of GW170817, the multi-wavelength brightening has ruled out the model of a simple off-axis top-hat jet. Here we have proposed that the $e^+e^-$ wind injection from a central NS into a top-hat jet could yet provide an explanation for current observations. The brightening is attributed to the synchrotron emission from electrons accelerated by the RS in our scenario. The peak time observed in the future would mark the spin-down time of the central NS.

In our modeling, we invoked the GW radiation as the main braking mechanism of the NS. An ellipticity of $4.4 \times 10^{-5}$ and a polar magnetic field of $10^{12}$ G are required to match current data. Other relevant parameters are generally consistent with those adopted in other works. Current observations cannot distinguish our scenario from other models such as the cocoon model and the structured jet model (Gottlieb et al. 2017; Lazzati et al. 2017c; Margutti et al. 2017; Mooley et al. 2017; Lyman et al. 2018). Further detailed observations of lightcurves and polarization evolution may help to discriminate these models.

The observations on afterglows of long GRBs have shown some features that are beyond the standard model, such as the X-ray plateau and optical rebrightening. Lessons from modeling these (on-axis) special afterglows tell us that it is still uncertain whether the optical rebrightening is caused by the late activities of a central engine or detailed characteristics of the jet (like the two-component jet model, a kind of simple structured jet). This situation may also exist for SGRB afterglows, as in the case of SGRB 170817A here. No such deep multi-wavelength follow-ups of SGRBs has been carried out before SGRB 170817A, hence the sample of SGRBs with high quality data for late-time afterglows is still rare. In the future, there are two potential ways to distinguish our $e^+e^-$ scenario from the structured jet scenario. The first is an indirect way. For late-time afterglows of an on-axis jet from a double NS merger, the lightcurves are thought to gradually decline in the scenarios of the structured jet or the jet-cocoon system. This gradual decline is a natural result of the smooth distribution of $\Gamma$ and $E_{\text{iso}}$ from simulations when the jet is viewed on axis. However, for the $e^+e^-$ wind injection scenario, the flux from the RS should be able to exceed that from the FS. Therefore, significant optical rebrightening at late times may occur in the sample of on-axis afterglows from a double NS merger. In fact, the clear optical rebrightening has been observed in SGRB 090426 (Nicuesa Guelbenzu et al. 2011; Geng et al. 2016), although some authors argued that GRB 090426 may be associated with a collapsar event, rather than the merger of double NSs (Antonelli et al. 2009; Levesque et al. 2010; Xin et al. 2011). Second, the post-merger remnant could be confirmed by searching the GW signals from the remnant. The identification of a central long-lived NS or others would support or rule out our scenario. This could be done when the advanced GW detectors reach their designed sensitivity or with the next-generation detectors (Abbott et al. 2017b).

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