

A magnetically driven origin for the low luminosity GRB 170817A associated with GW170817

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Abstract The gamma-ray burst GR170817A associated with GW170817 is subluminescent and subenergetic compared with other typical short gamma-ray bursts. It may be due to a relativistic jet viewed off-axis, or a structured jet or cocoon emission. Giant flares from magnetars may possibly be ruled out. However, the luminosity and energetics of GRB 170817A are coincident with those of magnetar giant flares. After the coalescence of a binary neutron star, a hypermassive neutron star may be formed. The hypermassive neutron star may have a magnetar-strength magnetic field. During the collapse of this hypermassive neutron star, magnetic field energy will also be released. This giant-flare-like event may explain the luminosity and energetics of GRB 170817A. Bursts with similar luminosity and energetics are expected in future neutron star-neutron star or neutron star-black hole mergers.

Key words: stars: magnetar — stars: neutron — gamma-ray bursts: individual (GRB 170817A) — gravitational waves

1 INTRODUCTION

GW170817 is the gravitational wave event of a binary neutron star inspiral (Abbott et al. 2017a). This event also has multi-wavelength electromagnetic counterparts (Coulter et al. 2017; Abbott et al. 2017b): a possible short gamma-ray burst (GRB), GRB 170817A (Abbott et al. 2017c; Goldstein et al. 2017; Savchenko et al. 2017); ultraviolet/optical/infrared emissions from a kilonova (Villar et al. 2017 and references therein); and delayed X-ray and radio emission, which may be the afterglow (Troja et al. 2017; Hallinan et al. 2017).

Detailed analysis shows that GRB 170817A is subluminescent and subenergetic compared with other cosmological short GRBs (Abbott et al. 2017c; Goldstein et al. 2017; Savchenko et al. 2017; He et al. 2018; Fong et al. 2017). Its isotropic energy and luminosity are: $E_{\text{iso}} = 3.1 \times 10^{46}$ erg and $L_{\text{iso}} = 1.6 \times 10^{47}$ erg s⁻¹, respectively, in the 1 keV–10 MeV range. It is 2 to 6 or-

ders of magnitude less energetic than other short GRBs (Abbott et al. 2017c). The physics related to its subluminescent aspects may be: (1) a relativistic jet viewed off-axis, (2) a structured jet or (3) cocoon emission (Abbott et al. 2017c; Murguia-Berthier et al. 2017; Kasliwal et al. 2017). For an off-axis jet, later deceleration may explain the delayed X-ray and radio afterglow emission (Troja et al. 2017; Hallinan et al. 2017). However, in order to see the prompt emission of the jet, a fine tuning of the line of sight may be required. The solid angle from which we can see this GRB is very small (Abbott et al. 2017c). A slightly off-axis jet (e.g., jet opening angle of 25° and viewing angle of 30°) may be ruled out by radio observations (Hallinan et al. 2017), while a widely off-axis jet (e.g., jet opening angle 10° and viewing angle 30°) can explain the X-ray and radio afterglow emissions. However, in the widely off-axis jet case, an independent mechanism for the prompt short GRB is required

(Hallinan et al. 2017). Furthermore, the energetics and luminosity of GRB 170817A are similar to those of the giant flare seen in a magnetar (Hurley et al. 2005; Palmer et al. 2005; Mereghetti 2008). This coincidence may be accidental. If not, it may suggest that GRB 170817A and magnetar giant flares share similar physical processes. The later probability is explored in the following.

The association of GRB 170817A with a binary neutron star merger event, soft spectrum and lack of tail emission may be used to argue against a magnetar giant flare origin (Abbott et al. 2017c; Goldstein et al. 2017). However, the remnant of the binary neutron star merger may be a hypermassive neutron star (Abbott et al. 2017c; Murguia-Berthier et al. 2017). The neutron star may have a magnetar strength magnetic field due to interactions between convection and differential rotation during the formation process. Subsequent collapse of the hypermassive neutron star to a black hole would also result in release of the neutron star’s magnetic energy. This giant-flare-like event may be responsible for the subluminal GRB 170817A, especially because of its similarity with magnetar giant flare energetics.

2 DESCRIPTION OF THE SCENARIO

The binary neutron star merger for GW170817 could result in a remnant with mass $2.7\text{--}2.8 M_{\odot}$ (Abbott et al. 2017a). This mass lies in the hypermassive range for many neutron star equations of state (Abbott et al. 2017c). The presence of a blue kilonova may also indicate the presence of a hypermassive neutron star (Murguia-Berthier et al. 2017). A hypermassive neutron star has mass larger than the maximum mass of a uniformly rotating neutron star. It is supported by differential rotation. Subsequent dissipation of the differential rotation will result in a collapse of the hypermassive neutron star to a black hole (Baumgarte et al. 2000; Hotokezaka et al. 2013). The associated magnetic braking or viscous dissipation timescale is about 100 ms (Hotokezaka et al. 2013). However, for a nascent hypermassive neutron star, collapse can happen only when its thermal energy is carried away by neutrinos (Sekiguchi et al. 2011). The typical neutrino cooling timescale is on the order of seconds. This may correspond to the 1.7 s delay of GRB 170817A and the merger time of GW170817. The footpoints of magnetic field lines are initially anchored to the neutron star’s crust. After collapse of the hypermassive neutron star to a black hole, there is no solid crust to which the field lines can be anchored.

The magnetic field may thus be ejected. Reconnection may occur during this process, similar to solar coronal mass ejection and magnetar giant flares (Lyutikov 2006; Elenbaas et al. 2016).

According to Hotokezaka et al. (2013) (their figure 2 and references therein), the nascent hot neutron star may be $0.1 M_{\odot}$ heavier than the maximum mass of a cold supramassive neutron star. The maximum mass of a cold supramassive neutron star is about 1.2 times the maximum mass of a cold nonrotating neutron star. Assuming a remnant mass of $2.75 M_{\odot}$ (Abbott et al. 2017a), the above scenario results in the maximum mass of a cold non-rotating neutron star of about $2.2 M_{\odot}$. This rough estimation is consistent with results of more detailed analysis (Margalit & Metzger 2017; Shibata et al. 2017; Rezzolla et al. 2018; Ruiz et al. 2018).

Prior study on the double pulsar system shows that a binary neutron star may be made up of a normal neutron star and a recycled one (Lyne et al. 2004). For a merger timescale of 10 Gyr (Blanchard et al. 2017), the magnetic field of the two neutron stars may have decayed significantly. During the birth of a hypermassive neutron star, it may acquire rapid rotation and a strong magnetic field (Zrake & MacFadyen 2013; Giacomazzo & Perna 2013; Ciolfi et al. 2017). The turbulent dynamo process for normal magnetars may also take place in the case of nascent hypermassive neutron stars (Duncan & Thompson 1992). Its magnetic field can be as high as that of a magnetar magnetic field, e.g. up to $10^{15}\text{--}10^{16}$ G. For a volume about the size of a cube with the neutron star radius $\Delta V \sim 10^{18} \text{ cm}^3$, the stored magnetic energy is about

$$E_{\text{mag}} \sim B^2 / (8\pi) \Delta V \sim 4 \times 10^{46} - 4 \times 10^{48} \text{ erg}.$$

This energy is enough to power the soft gamma-ray emissions of GRB 170817A (Abbott et al. 2017c; Goldstein et al. 2017). The spike of magnetar giant flares lasts about 0.5 s (Hurley et al. 2005; Palmer et al. 2005; Mereghetti 2008). The magnetic field may be dragged by the expanding ejecta and lead to formation of a current sheet (Lyutikov 2006; Yu & Huang 2013). When the ejecta escapes, magnetic dissipation inside the current sheet would give rise to flares and the duration timescale is determined by the escape velocity of the expanding ejecta, which closely depends on the magnetic reconnection inflow velocity. Our detailed calculation shows that an inflow Mach number $M_A = V_{\text{inflow}}/V_A \sim V_{\text{inflow}}/c$ less than 10^{-3} can reproduce the observed flare duration timescale well (Yu et al. in prep.). This may also

explain why the initial pulse of GRB 170817A also lasted about 0.5 s (Goldstein et al. 2017; Savchenko et al. 2017). In this case, the luminosity of the initial pulse should be around $10^{47} \text{ erg s}^{-1}$. Therefore, a giant-flare-like origin can explain the subluminal and subenergetic GRB 170817A associated with GW170817.

Relativistic reconnection is believed to be operating in GRBs. Magnetars, originally proposed to account for GRBs (Duncan & Thompson 1992), share similar behaviors with low luminosity GRBs. Observations of GRB 080916C indicate that the GRB central engine likely launched magnetically-dominated plasma and magnetic reconnection led to prompt emissions of the GRB (Zhang & Yan 2011; McKinney & Uzdensky 2012), which provide a promising mechanism to facilitate rapid conversion of magnetic energy to radiation. The reconnection inflow velocity is roughly

$$V_{\text{inflow}} = M_A V_A,$$

where V_A is the Alfvén velocity. In the magnetically dominated environment, the Alfvén velocity is approximately the speed of light. The magnetic reconnection model for GRBs indicates that, in the vicinity of the central engines, Sweet-Parker reconnection dominates and the magnetic reconnection rate is rather low. Fast reconnection switches on at a rather distant radius of $\sim 10^{13} \text{ cm}$, where the ion skin depth becomes larger than the Sweet-Parker layer thickness, and fast Petschek-like reconnection takes place (McKinney & Uzdensky 2012). We also note that fast reconnection would also inhibit jet formation by the Blandford-Znajek mechanism (Blandford & Znajek 1977). For these reasons, we adopt a small value of Alfvén Mach number, less than 10^{-3} . The toroidal electric field E_ϕ inside the current sheet is approximately

$$E_\phi \sim B_{\text{dipole}} \times (V_{\text{inflow}}/c).$$

In Figure 1, we illustrate our scenario for a magnetically driven low luminosity GRB. The radiative emission comes from the Poynting flux associated with the current sheet and the energy dissipation rate is written as

$$\dot{E}_{\text{diss}} = c \int_{r_1}^{r_2} r E_\phi B_r dr,$$

where r_1 and r_2 are the two tips of the current sheet. Note that both B_r and E_ϕ vary with radius between r_1 and r_2 . The luminosity can be roughly estimated to be

$$M_A c \times (B/10^{14} \text{ G})^2 (r/15 \text{ km})^2 \sim 10^{47} \text{ erg s}^{-1}.$$

Here the magnetic field we adopt is the average magnetic field.

The magnetic field is so strong that the dynamics are dominated by the magnetic field. Under such circumstances, the mass of the ejecta can be estimated as

$$\sim 10^{30} \times (B/10^{16} \text{ G})^2 (R/15 \text{ km})^3 \text{ g},$$

where we assume that the ejecta is generated in the vicinity of the central neutron star and the strength of the magnetic field is adopted as $B \sim 10^{16} \text{ G}$. Our simulations show that the ejecta is magnetically driven and can be accelerated to a speed of about $\sim 0.1c$. This is consistent with observational constraints about the ejecta of the kilonova (Villar et al. 2017). A detailed description of our model and simulation results will be reported elsewhere (Yu et al. in prep.).

The initial pulse of GRB 170817A has peak energy of about 200 keV (Goldstein et al. 2017). It is not detected in the 0.2 – 5 MeV energy range (Li et al. 2018). The emission following the initial pulse of GRB 170817A has even lower peak energy, about 30 keV (for a thermal spectrum, Goldstein et al. 2017). The giant flare of magnetar SGR 1806–20 has peak energy of about 0.5 – 1 MeV (Hurley et al. 2005; Palmer et al. 2005). If the hard X-ray photons are due to resonant inverse Compton scattering¹ (other radiation mechanisms are also possible, Elenbaas et al. 2017), the hard X-ray photons can only escape when the magnetic field is smaller than 10^{13} G , in order to avoid photon splitting or pair production (Beloborodov 2013). The electron cyclotron energy is about $\hbar\omega_B \approx 100 \text{ keV} (B/10^{13} \text{ G})$. The resonant condition requires that the seed photons should have typical energy $\gamma 3kT \approx \hbar\omega_B$ (You et al. 2003, where γ is the electron Lorentz factor and assuming thermal seed photons). The scattered photons have typical energy of about $\gamma \hbar\omega_B$. For a Lorentz factor of $\gamma \sim 5$, the scattered photons have an energy of about 0.5 MeV. The seed photons have typical energy of about 20 keV. In the case of giant flares from magnetars, the central neutron star is always there. The large scale strong dipole magnetic field is always present. This may ensure that magnetar giant flares can have hard spectra, especially for the initial spike (Elenbaas et al. 2017). However, in the magnetically driven origin for GRB 170817A, the central

¹ In the case of a strong magnetic field, the Thomson scattering cross section is significantly reduced (Herold 1979). Non-magnetic Thomson scattering and inverse Compton scattering are changed to resonant cyclotron scattering and resonant inverse Compton scattering, respectively.

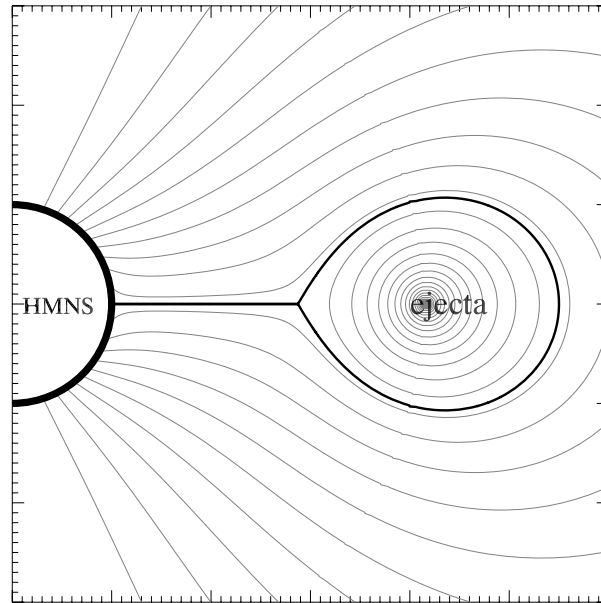


Fig. 1 An illustrative scenario of our magnetic reconnection driven low luminosity GRBs. The *thick horizontal line* represents the current sheet caused by the escape of ejecta, where the Poynting flux inside the current sheet supports the low luminosity of GRB 170817A. Here HMNS means hypermassive neutron star.

neutron star collapses to a black hole. During the magnetic reconnection process, the magnetic field will decrease with time. This may explain why the initial pulse of GRB 170817A has a soft spectrum compared with that of magnetar giant flares. The softer emission following the initial pulse may be the seed thermal emission. It may come from photospheric emission of the fireball generated during the giant-flare-like event. Here the “fireball” should be similar to that generated during magnetar giant flares (Thompson & Duncan 1995; Elenbaas et al. 2017). This situation is different from the “fireball” in canonical GRBs, although the terminology “fireball” is used in both cases.

During the collapse of the hypermassive neutron star to a black hole, both matter and magnetic field can be ejected. The ejection of magnetic field energy is also employed to explain the energy of fast radio bursts (see Falcke & Rezzolla 2014 for a description of the collapse of a supramassive neutron star). However, the possibility that a fast radio burst is also generated during the collapse of a hypermassive neutron star cannot be excluded.

A general picture for GW170817/GRB 170817A may be that: The merger of the binary neutron star could result in the birth of a hypermassive neutron star. After about one second, the hypermassive neutron star collapses to a black hole. During this process, a relativis-

tic jet and a subrelativistic outflow may be generated by the central engine. At the same time, the collapse of the hypermassive neutron star will also trigger the release of magnetic energy. Since the jet is seen widely off-axis, its prompt emission may be missed. Instead, the magnetic energy release may be responsible for the low luminosity GRB 170817A. Subrelativistic outflow is responsible for the kilonova emissions. The relativistic jet may be successful or fail during its drill through ambient matter. A cocoon may be generated during this process. An off-axis structured jet or near isotropic outflow (e.g., cocoon or outflow generated by the magnetic energy release) may be responsible for the X-ray/radio afterglow (D’Avanzo et al. 2018).

3 DISCUSSION

Here we provide an alternative explanation for the low luminosity GRB 170817A associated with GW170817. Compared with other explanations (off-axis jet, structured jet, cocoon), a magnetically driven origin naturally results in a burst luminosity similar to that of magnetar giant flares. The giant-flare-like event may not have strong beaming, similar to magnetar giant flares (Lyutikov 2006). Bursts with similar luminosities may also be observed in future binary neutron star merger

events, provided that they are close enough. On the other hand, if future observations find that this case of the GRB 170817A event is singular, then the magnetically driven origin may be ruled out.

If we are lucky in that prompt emission of the jet is also seen, then we should see two bursts following a gravitational wave event. The internal collision of shocks may result in a delay between the prompt emission and magnetic energy release. This will result in a precursor (which is due to a giant-flare-like event), followed by a classical GRB. Previous observations found some feasible precursors of short GRBs (Troja et al. 2010). It is possible that these precursors are also due to magnetic energy release of the central engine. During the merger of a neutron star/black hole system, a giant-flare-like event may also happen if a strong magnetic field can also be generated (Wan 2017).

The possible contribution of a hypermassive neutron star to GRB 170817A is explored in this paper. The magnetic energy release of a hypermassive neutron star may also contribute to X-ray/radio afterglows (Salafia et al. 2017; D’Avanzo et al. 2018). The central compact object of a binary neutron star merger may also be a long lived neutron star, instead of a short lived hypermassive neutron star (Dai et al. 2006; Fan & Xu 2006; Lü et al. 2015). For GW170817/GRB 170817A, a long lived neutron star cannot be ruled out (Ai et al. 2018) and it may contribute to kilonova emissions (Yu & Dai 2017). In the case of a long lived neutron star, a giant-flare-like event is also possible. However, this may not correspond to the case of GRB 170817A. This possibility could be revealed in future observations.

During the preparation process, we noted the paper of Salafia et al. (2017), who employed a fireball powered by a giant flare to explain both GRB 170817A and the X-ray/radio afterglow. This is different from our scenario. In our scenario, (1) the time delay between GRB 170817A and GW170817 is due to delayed collapse of the hypermassive neutron star, (2) the giant-flare is triggered by collapse of the hypermassive neutron star to a black hole and (3) we focus on the giant-flare-like origin for the low luminosity GRB 170817A.

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