An Explosion is Triggered by the Late Collapse of the Compact Remnant from a Neutron Star Merger

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Abstract

It is known that a binary neutron star (BNS) merger produces a hypermassive neutron star. The lifetime of this compact remnant depends on the total mass and the equation of state. The collapse of this compact remnant to a black hole torus system is expected to give rise to a powerful jet and a short gamma-ray burst. Nevertheless, if the collapse is delayed half a second or so, the surrounding matter would already be accreted and/or expelled, hence no significant torus is formed. However, the collapse itself gives rise to a quasi-isotropic magnetized fireball. This magnetic bomb dissipates much of its energy due to magnetic reconnection and produces the prompt emission. The energy range of such an explosion depends on the initial magnetic field strength and the amplification of the magnetic energy during merger. We briefly estimate the physical parameters at the time of collapse. We discuss the production of a quasi-isotropic magnetized fireball and its subsequent interaction with the ejected matter during merger as the outcome of the coalescence of a BNS system. We further suggest the radial stratification of the outflow, following the quasi-normal modes of the black hole.

Key words: gamma-ray burst; general – gravitational waves

1. Introduction

The dawn of the multi-messenger era was marked by the observation of GW170817 and GRB 170817A, with afterglow detection across the electromagnetic (EM) spectrum (The LIGO Scientific Collaboration & The Virgo Collaboration 2017; The LIGO Scientific Collaboration et al. 2017b). The simultaneous detection of gravitational waves and a short gamma-ray burst (GRB) made it clear that at least some short GRBs are produced by binary neutron star mergers (BNS). It was a longstanding conjecture that BNS are progenitors of short-duration GRBs (Eichler et al. 1989; Narayan et al. 1992).

One point of extreme interest is the overall low energetics of the prompt emission and the faint gamma-ray pulse, compared with the canonical short GRB, which pictures a highly relativistic outflow. After the merger of the BNS, a hypermassive neutron star (HMNS) is produced. The usual picture needs the collapse of this HMNS to produce a black hole and, together with the surrounding torus, it is expected to give rise to a relativistic jet. However, the isotropic energy of GRB 170817A observed to be $\sim 10^{56}$ erg. The main arguments for this low flux detection is picturing radiation from an off-axis jet, or radiation coming from a cocoon produced by the jet while drilling through the ejected matter\(^1\). The first to consider the interaction of a jet and the BNS ejecta was Nagakura et al. (2014) and Murguia-Berthier et al. (2014). They incorporated a density profile, inspired from BNS simulations, mimicking the BNS ejecta and the subsequent drilling of the jet through the ejecta. These can provide jet conditions that allow the outflow to break out from the ejecta or not.

In what follows, we describe the outcome of a BNS merger, where the merger remnant has a lifetime of seconds (or even a fraction of a second). At the time of the collapse, the surrounding matter consists of a negligible torus. Following this path, no jet is expected to form. We discuss the collapse of the merger remnant as the central engine of a magnetic explosion that drives a short GRB. Most of the amplified magnetic energy during the merger is released within a millisecond during collapse. This forms a magnetized fireball.

In Section 2, we estimate the physical parameters of the merger remnant and the surrounding torus at $\sim 1$ s, then present the main features of the collapse and discuss the energetics of such explosions. In Section 3, we discuss the imprint of this explosion. In Section 4, we provide our conclusions.

2. The Outcome of the Merger and the Collapse of the Supramassive Neutron Star (SMNS)

The outcome of the coalescence of a BNS can have different paths, which in turn would have different observational imprints. The difference in the collapse time of the HMNS, or a stable SMNS\(^2\) configuration could explain the short-GRB phenomenology (Ciolfi & Siegel 2015; Metzger et al. 2008; Rezzolla & Kumar 2015; Usov 1992).

Electromagnetic (EM) outputs of merging objects have been considered in the literature. Especially after the collapse of the SMNS, where the strong magnetic field interaction with the black hole that lasts a considerable amount of time, can shape the afterglow of a short GRB (Lyutikov 2011). In this paper, we focus on the possibility that the SMNS produced during merger collapses within a few seconds after the merger. The important point is not exactly the lifetime of the SMNS itself, but the parameters of the torus surrounding it. The matter of the collapsing star itself quickly hides behind an event horizon, but the magnetic energy stored in the near zone magnetosphere of

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\(^1\) Numerical simulations of BNS systems, with a total mass above $\sim 3.2 M_\odot$, have shown that after the merger, a magnetic-jet structure from the black hole torus system is produced (Rezzolla et al. 2011; Kawamura et al. 2016; Ruiz et al. 2016). This is the starting point for a jet from a BNS merger (Aloy et al. 2005) and for off-axis radiation (Lazzati et al. 2017a, 2017b; Kathirgamaraju et al. 2018), as well as cocoon emission (Gottlieb et al. 2018).

\(^2\) A SMNS is a NS above the Tolman-Openheimer-Volkof (TOV) maximal mass, which can still be supported by rigid rotation.
the SMNS is released in a millisecond scale, producing an outward magnetic shock. The magnetic energy of the SMNS is expected to be more than $10^{50}$ erg, due to the magnetic field amplification during merger. Another meaningful point to note is the difference from the collapse of an isolated NS, which is expected to give rise to a short radio transient (Falccke & Rezzolla 2014). There are two major differences: on one hand, the enhanced magnetic energy due to amplification during merger; on the other hand, the fact that even if no torus is formed, the SMNS is not isolated. Rather, it lives inside a dust of leftover matter. It has been argued that this pollution may not allow the magnetar model to function (Murguia-Berthier et al. 2014). It is exactly this baryon pollution that contribute to the production of a fireball. Lehner et al. (2012) proposed that the collapse of the SMNS can produce an EM transient comparable in energy with a jet from a black hole torus when the SMNS collapses, and could contribute to the production of a short GRB. They performed simulations for the gravitational collapse of an isolated magnetized neutron star, and showed the instantaneous (millisecond scale) dissipation of the magnetic energy. They further discussed in detail how this picture would evolve in the presence of an accretion disk, which is the case for the remnant of a BNS merger. They compared the EM luminosity prior to merger with the post-merger phase where the SMNS has a large, but not coherent, magnetic field. Then, they estimated the EM transient produced from the collapse of the merger remnant and compared it with the subsequent jet produced by the trapped magnetic flux between the newly formed black hole and the accretion disk (Lehner et al. 2012).

Following this thinking and these estimations, we show that if the lifetime of the SMNS is longer than a second or so, then the limited amount of mass of the torus cannot result in a jet, but the collapse of the SMNS alone will power the short GRB.

The total mass (which, in the case of GW170817, was $\sim 2.74 M_\odot$; The LIGO Scientific Collaboration & The Virgo Collaboration 2017) and the EOS play the major roles for the SMNS. However, a study from Kaplan et al. (2012) showed that models with more thermal support are less compact, which makes them more stable in a longer timescale.

At this time, the structure of the surrounding torus has also changed significantly. The viscous accretion timescale estimated for the torus as

$$t_{\text{acc}} \approx 1 \text{ s} \left( \frac{R_T}{50 \text{ km}} \right)^2 \left( \frac{H_T}{25 \text{ km}} \right)^{-1} \times \left( \frac{\alpha}{0.01} \right)^{-1} \left( \frac{c_s}{0.1 \text{c}} \right)^{-1},$$

(3)

where $R_T$ is the radius of the torus, and $H_T$ is the typical vertical scale height of the torus. Then, the mass accretion rate onto the SMNS yields

$$M_{\text{SMNS}} \approx \frac{M_T}{t_{\text{acc}}} \sim 0.2 M_\odot s^{-1} \left( \frac{\alpha}{0.01} \right) \left( \frac{M_T}{0.2 M_\odot} \right) \times \left( \frac{R_T}{50 \text{ km}} \right)^{-2} \left( \frac{H_T}{25 \text{ km}} \right).$$

(4)

where $M_T$ is the mass of the torus. However, this accretion rate is not stationary, as the mass of the torus decreases in time and expands. The radius of the torus can reach $140 \text{ km}$ in 1 s. Nevertheless, it can account for a mass accretion of $\sim 0.12 M_\odot$ in 1 s (Fujibayashi et al. 2017).

The previous estimate is another indication that collapse could be triggered at around 1 s after merger, due to accretion. Furthermore, the effective viscosity inside the torus results in the expansion of the torus. The density in the vicinity of the SMNS, at the time of collapse, is extremely important. As we show below, this is the parameter that designates the outcome of the collapse, a black hole torus magnetic jet or an induced magnetic explosion. The density of the torus at 1 s is estimated by its leftover mass and its expanded radius:

$$\rho_T \approx \frac{M_T}{2H_T \pi R_T^2} \sim 9.2 \times 10^9 \text{ g cm}^{-3} \left( \frac{M_T}{0.08 M_\odot} \right) \times \left( \frac{R_T}{140 \text{ km}} \right)^{-2} \left( \frac{H_T}{70 \text{ km}} \right)^{-1},$$

(5)

where all quantities are for the expanded torus at 1 s after merger. We should point out here, that if the collapse of the SMNS occurs even later, then there is the possibility that no debris disk is formed at all (Margalit et al. 2015).

Before discussing about the production of a jet or a magnetic explosion, we should first have an estimate of the mean

\[ t_{\text{eff}} \approx 3 \tau_r \frac{\Delta R}{c} \approx 0.8 \text{ s} \left( \frac{\tau_r}{10^7} \right) \left( \frac{\Delta R}{20 \text{ km}} \right). \]

(2)

The cooling of the SMNS due to neutrino diffusion can be estimated:

\[ \rho_T \approx \frac{M_T}{2H_T \pi R_T^2} \sim 9.2 \times 10^9 \text{ g cm}^{-3} \left( \frac{M_T}{0.08 M_\odot} \right) \times \left( \frac{R_T}{140 \text{ km}} \right)^{-2} \left( \frac{H_T}{70 \text{ km}} \right)^{-1}, \]

(5)

where $\Delta R$ is the local density scale height, and $\tau_r$ is the optical depth, with a mean value of $10^3$ for neutrinos of 10–100 MeV (Dessart et al. 2009). This means that in around 1 s, there is a 2% reduction of pressure, which could trigger the collapse of the SMNS. However, a study from Kaplan et al. (2014) showed that models with more thermal support are less compact, which makes them more stable in a longer timescale.

As an example, for the LS 220 EOS an equal mass BNS of total mass $M = 2.87 M_\odot$, collapses straight after merger, whereas for a total mass $M = 2.67 M_\odot$ does not collapse for some tens of milliseconds (Bovard et al. 2017).
magnetic field strength of the SMNS. It is expected that during the merger process, small-scale turbulence can amplify the magnetic field in values higher than $10^{16} G$ (Rasio & Shapiro 1999; Zrake & MacFadyen 2013; Giacomazzo et al. 2015). In such extreme conditions, the magnetic energy can reach as high as $\sim 10^{51}$ erg Kiuchi et al. (2015).

We check what happens if the SMNS collapses after 1 s. One of the most important points is the condition for the establishment of a magnetic jet. A stable configuration to be built by the black hole torus system needs at least that the torus pressure can balance the magnetic pressure. Following the above discussion, we assume that the mean magnetic field of the SMNS is $B \simeq 3 \times 10^{10} G$. This yields

$$\frac{B_{\text{SMNS}}^2}{8\pi} \simeq 3.5 \times 10^{31} \text{ dyn cm}^{-2} \left( \frac{B_{\text{SMNS}}}{3 \times 10^{10} G} \right)^2 \gg 9.2 \times 10^{29} \text{ dyn cm}^{-2} \left( \frac{\rho_T}{9.2 \times 10^9 \text{ g cm}^{-3}} \right) \simeq \rho_T \eta^2. \quad (6)$$

This is estimated at around 1 s post-merger. It is evident that at later times, when the torus has expanded more, the density decreases and the establishment of a magnetic jet becomes more difficult. A lower estimate that we get from the accretion rate at 1 s, which is $\sim 0.02 M_{\odot} \text{ s}^{-1}$ as reported in Fujibayashi et al. (2017). This yields

$$\frac{B_{\text{SMNS}}^2}{8\pi} \gg 2.6 \times 10^{28} \text{ dyn cm}^{-2} \sim \dot{M}_c/4\pi \rho_{\text{BH}}.$$  

The above discussion is summarized in Figure 1. So far, we have estimated that if the collapse is triggered around or after $\sim 1$ s after merger, the magnetic energy of the SMNS is released and will induce a powerful explosion of $E_{\text{exp}} \sim 10^{51}$ erg, contrary to an expected magnetic jet. The energetics for this magnetic bomb follow from the properties of the remnant (SMNS) itself. The absence of a jet was discussed by Sala et al. (2018), where instead a flare produced during the magnetic field amplification gave rise to a relativistic isotropic fireball, which could explain the prompt emission of GRB 170817A (Salafia et al. 2017, see also Tong et al. 2018), whereas what we discussed here comes after merger, and the absence of a jet is due to the physical conditions that come around or after $\sim 1$ s.

The amount of baryons in this magnetic bomb is subject to the leftover matter exterior to the SMNS and the neutrino-driven wind. This magnetic bomb very quickly catches up the relatively slow-moving ejecta and crashes onto them. This matter, expelled dynamically or secularly, is responsible for the appearance of a kilonova (The LIGO Scientific Collaboration et al. 2017a), and moves with velocities $u \approx 0.1$–0.2$c$ (Metzger et al. 2010; Bovard et al. 2017).

The matter ejected during merger depends on the EOS; nevertheless, its averaged distribution on a sphere far from the merger point shows that above the equator, the overall ejected matter may be three orders of magnitude less than what was ejected in the equatorial plane (roughly $\sim 10^{-6} M_{\odot}$, Bovard et al. 2017). The magnetic bomb finds it easier to pass through the ejecta from higher latitudes. This means that it may have a wide-angle jet structure, or rather that it is quasi-isotropic with a big opening angle from the orbital axis.

We have to stress that what was discussed in this section is not at all any kind of a proof that the collapse of the merger remnant came at $\sim 1$ s post-merger. The major point here was that if the collapse comes after $\sim 1$ s, then it is extremely difficult to produce a magnetic jet.

### 3. The Imprint of the Magnetic Bomb

The formation of a magnetized fireball that crashes on the ejecta is established if the collapse of the SMNS happens at $\sim 1$ s (Figure 2). In this section, we discuss the evolution of this magnetic bomb. We show that after the explosion, a relativistic outflow is produced. We further discuss how this outflow can push matter from the polar region and surpass the BNS ejecta. The amplified magnetic field in the SMNS is favored in the toroidal direction and could produce a magnetically driven plasma gun (Contopoulos 1995). At the time of collapse, all of this energy is released in a millisecond scale. This explosion induces a shock to the surrounding matter. The shock front is perpendicular to the radial direction and parallel to the predominantly toroidal magnetic field. We assume that the upstream pressure is small, as the SMNS has collapsed when the magnetic explosion is produced. Analysis of the jump conditions across the shock can yield useful estimations for the parameters of the post-shock region and have been widely used for astrophysical purposes (e.g., Kennel & Coroniti 1984). We
define the magnetization parameter as

\[ \sigma = \frac{B^2}{4\pi pc^2}, \]  

(7)

then the corresponding downstream Lorentz factor is

\[ \gamma \approx \sqrt{\sigma}. \]  

(8)

In Figure 3, we plot the magnetization parameter for the relevant values of the magnetic field and the density, where the density values can be viewed as an angular distribution of the matter from the equator till the polar region, where density falls significantly.

It is evident, that for a polar density of \(10^7 \text{ g cm}^{-3}\) (as reported in Fujibayashi et al. 2017), an outflow with a Lorentz factor of 10 is formed.

The next question to address is whether this outflow can break out from the ejecta. In the case of a relativistic flow interacting with an external medium, the Sedov length signals the radius where deceleration begins. The Sedov length is generally defined as the radius where the energy of the swept up matter, \(E = m_e c^2 \int_0^r 4\pi r^2 \rho^2 dr\), equals the energy of the explosion. The polar regions with less density are favored as a pathway for the explosion. As mentioned before, the ejected mass from the polar regions is on the order of \(\sim 10^{-5} M_\odot\) (Bovard et al. 2017). Thus, the rest-mass energy of the matter in the polar region is \(E_{\text{mpolar}} \sim 10^{48} \text{ erg}\). Because the energy of the explosion is \(E_{\text{exp}} \sim 10^{51} \text{ erg}\), the deceleration radius is reached further out in the interstellar medium and the outflow can successfully surpass the BNS ejecta from the polar region.

The prompt gamma-ray emission consists of a nonthermal pulse produced by accelerated particles through magnetic reconnection that will follow the collapse and the release of the magnetic energy of the SMNS. During the expansion of the fireball, further dissipation of the magnetic energy can contribute more to this. This will be followed (or accompanied) by a thermal high-energy pulse produced almost with the fireball itself, due to the pressure and the high temperatures in the post-shock region. When the fireball reaches the photosphere \(r_{ph} \sim 10^{12} \text{ cm}\), it is already further beyond the slow-moving ejecta (at a similar time, the ejecta is almost an order of magnitude closer to the source) and thus photons will not find any other obstacle (Figure 2).

The duration of the high-energy pulse, which in the case of GRB 170817A was \(\sim 2\) s (Goldstein et al. 2017),

\[ \text{The duration of the emission from the spherical cap is } dt \sim h/c = r_{ph} \times (1 - \cos(\theta))/c \approx 2r_{ph}\theta_f^2/c. \]  

For a mildly relativistic outflow with \(\Gamma > 1/\theta_f\), the relevant timescale of the pulse is \(dt \sim r_{ph}/2c \Gamma^2\) (Piran 2005), which for a range of \(\Gamma \approx 7-10\), the duration is \(dt \sim 1-2\) s. We should also mention here that even in the canonical short-GRB picture, the \(\sim 2\) s duration may be a problem if the disk is not massive enough and is accreted in less than a second.

Another point that we want to touch is a way of radially stratifying the fireball. It is known that the production of a black hole is followed by the “ringing down” of the black hole (Kokkotas & Schmidt 1999). The first burst from the collapse is followed by further pulses with almost an order of magnitude of less intensity and a millisecond duration (Lehner et al. 2012; Dionysopoulou et al. 2013; Most et al. 2018). Every pulse will be accompanied by a production of a slower fireball, due to the reduced magnetic pressure injected by the pulse. The quasi-normal modes of the black hole are exponentially decaying, but can contribute to the radial stratification of the fireball. The fireball may also form a cocoon-like structure at the intersection with the high-density ejecta and may have a similar EM signature with a cocoon produced by a jet (Gottlieb et al. 2018).

There is no need to speculate more about the radiation imprint of such fireball, as this should follow from a complete study of such a process. Nevertheless, we should add that several observational facts that followed GW170817 and GRB 170817A can accommodate the production of such a wide-angle mildly relativistic outflow. The rising X-ray emission \(\sim 3\) days after the event and the radio observations \(\sim 20\) days can be explained with a quasi-isotropic outflow, and in the case we discussed, the kinetic energy can be up to the order of \(10^{50}\) erg (Alexander et al. 2017; Margutti et al. 2017). Furthermore, it was stated that the observed radio data have no direct indication of the presence of a jet, and can be explained by a wide-angle mildly relativistic outflow (Mooley et al. 2018). Observations (radio, optical, and X-ray) cannot rule out one or the other choice (Margutti et al. 2018).

4. Conclusions

The aim of this paper is to present and discuss the possibility that the outcome of a BNS merger follows a path that produces a quasi-spherical fireball behind the BNS ejecta rather than a jet. The main outcome of a merger discussed in the literature is
the production of a black hole together with a surrounding torus or a stable magnetar, both of which are used to explain short GRBs. In light of these new observations, we propose that it is equally possible to follow a third path: namely, that the compact remnant produced after merger collapses and no significant torus is produced. As a consequence, all of the magnetic energy of the SMNS will be released in a millisecond scale. The important point here is that this energy can be as much as $10^{50}$ erg, due to magnetic field amplification during merger. Thus, its energy could, in principle, power a short GRB (Fong et al. 2015).

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