Revealing Physical Activity of GRB Central Engine with Macronova/Kilonova Data

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Abstract

The modeling of Li-Paczynski macronova/kilonova signals gives a reasonable estimate on the neutron-rich material ejected during the neutron star mergers. Usually the accretion disk is more massive than the macronova ejecta, with which the efficiencies of converting the disk mass into prompt emission of three merger-driven GRBs can hence be directly constrained. Supposing the macronovae/kilonovae associated with GRB 050709, GRB 060614, and GRB 130603B arose from radioactive decay of the r-process material, the upper limit on energy conversion efficiencies are found to be as low as \( \sim 10^{-6} \)–\( 10^{-4} \). Moreover, for all three events, neutrino annihilation is likely powerful enough to account for the brief gamma-ray flashes. Neutrino annihilation can also explain the “extended” emission lasting \( \sim 100 \) s in GRB 050709, but does not work for the one in GRB 060614. These progresses demonstrate that the macronova can serve as a novel probe of the central engine activity.

Key words: binaries: general – gamma-ray burst: general – radiation mechanisms: non-thermal – stars: neutron

1. Introduction

The research on mergers of a neutron star with either a neutron star or a stellar-mass black hole have attracted wider and wider attention since they are promising sources of significant gravitational-wave (GW) radiation that are expected to be detectable for the advanced detectors such as LIGO and Virgo in the near future (Abbott et al. 2016). Currently, the “related” observational data are mainly for short gamma-ray bursts (sGRBs), as favored by a broad range of observations (Berger 2014). With the sGRB data, our understanding of the rate and the launched relativistic outflow (including the subsequent radiation) of neutron star mergers has been significantly advanced (Nakar 2007; Berger 2014). The knowledge of the central engine, such as the accretion disk mass, the spin, and the mass of the newly formed black hole, and the energy extraction efficiency, however, is almost solely from the numerical simulations (Ruffert & Janka 1989; Rosswog et al. 1999; Kiuchi et al. 2009; Rezzolla et al. 2011) because the detectable photons were emitted at radii far from the central engine and usually the initial information of the GRB ejecta was lost. One exception is for the GRBs with a distinct thermal radiation component that the standard fireball acceleration and radiation apply to (Mészáros et al. 1993; Piran et al. 1993), for which the initial radius at which the fireball was launched or reformed can be reasonably inferred and a constraint on the mass of the central black hole is imposed (Pe’er et al. 2007; Fan & Wei 2011). However, no distinct thermal radiation component has been identified in prompt emission of sGRBs as of yet.

Thanks to the relatively narrow mass distribution of the double neutron star binaries observed in the Galaxy (Lattimer 2012), the mass of the nascent black hole (\( M_{\text{BH}} \)) and its spin parameter (\( a \)) can be reliably, reasonably evaluated, as demonstrated in both analytical approaches and numerical simulations (Lee et al. 2000; Kiuchi et al. 2009). Adopting these prior values of \( M_{\text{BH}} \) and \( a \), with the electromagnetic data, the mass of the accretion disk (\( M_{\text{disk}} \)) launching the sGRB ejecta can be estimated (Fan & Wei 2011). Not surprisingly, the estimated accretion disk masses are sensitively dependent on the energy extraction processes since the magnetic and neutrino mechanisms have rather different energy extraction efficiency (Fan et al. 2005). As a result, there is large divergence between the accretion disk masses inferred in different energy extraction models (Fan & Wei 2011; Giacomazzo et al. 2013; Liu et al. 2015) and it suffers from further uncertainties involved in the modeling. The other hope is that for some “nearby” (\( \sim 100 \) Mpc) binary neutron star mergers, with the GW data, the masses of the binaries as well as the formed accretion disk might be inferable in the 2020s (Kiuchi et al. 2010). A short summary of the current situation is that there is a lack of solid information about the central engine directly inferred from the observational data of sGRBs.

The neutron-rich sub-relativistic matter ejected in the neutron star mergers are the ideal sites to synthesize the r-process material (Lattimer & Schramm 1974; Eichler et al. 1989). The radioactive decay of these heavy elements gives rise to the near-infrared/optical transients, i.e., the so-called Li-Paczynski macronova/kilonova (Li & Paczynski 1998; Metzger et al. 2010; Kasen et al. 2013). Recently macronova/kilonova signals have been identified in a few events (Berger et al. 2013; Tanvir et al. 2013; Jin et al. 2015, 2016; Yang et al. 2015). Such new transients, in addition to labeling the birth sites of the very heavy elements, are promising electromagnetic counterparts of gravitational sources that are expected to be detectable by advanced LIGO/Virgo in the near future. In this work, we show that the macronova observations also serve as a novel probe of the central engine activity of sGRBs.

2. The Method

Throughout this work, we assume that the macronovae/kilonovae associated with GRBs arose from the radioactive...
decay of the $r$-process material launched by neutron star mergers, which is particularly motivated by the fact that an NS–BH merger model can reasonably reproduce the multi-epoch/band light curve of the macronova associated with GRB 060614 (see Figure 1 of Jin et al. 2015). An independent/important support for the scenario of generating $\sim 0.1 \, M_\odot$ $r$-process material in a neutron star merger event is the heavy element enrichment detection of the ancient dwarf galaxy Reticulum II (Ji et al. 2016). Alternatively, the current GRB-associated macronova/kilonova signals could be, for example, the thermal-like radiation of the sub-relativistic ejecta heated by the central engine-generated X-rays (Kisaka et al. 2016). In such a model the sub-relativistic ejecta mass can be much less than that found in the $r$-process material modeling and the progenitor stars may be double NSs. Nevertheless, as long as the ejecta mass is found in a given macronova/kilonova origin model, the approaches outlined in this work can be straightforwardly applied. Hence, in this work, we focus on our “fiducial” case.

Within the $r$-process material radioactive decay scenario, the modeling of the macronova/kilonova light curve can yield a reasonable estimate of the mass of the neutron-rich ejecta ($M_{ej}$) and possibly also distinguish between the progenitor stars, either binary neutron stars or neutron star–black hole binaries. The major differences of the ejecta from these two kinds of progenitors include (Hotokezaka et al. 2013; Tanaka et al. 2014): (a) some NS–BH mergers eject much more material than the NS binary mergers; (b) NS–BH merger ejecta are launched predominantly along the orbital plane. Consequently, the macronova powered by some NS–BH mergers are much more luminous, bluer, and last longer than the macronovae powered by NS binary mergers. Such a goal likely has already been achieved in the studies of some GRB/macronova events and NS–BH merger origin is favored (Hotokezaka et al. 2013; Yang et al. 2015; Jin et al. 2016; Kawaguchi et al. 2016). Below, we focus on probing the central engine activity with $M_{ej}$ within the NS–BH merger scenario.

The central engine activity is “governed” by $M_{disk}$. Previously, the $M_{disk}$ can only be inferred with the electromagnetic data within the double neutron star merger scenario (Fan & Wei 2011; Giacomazzo et al. 2013; Liu et al. 2015), which is strongly model dependent. Such a puzzle, fortunately, can be solved in a new way. As found in the advanced numerical simulations on neutron star mergers (including both the double neutron star mergers and the neutron star–stellar-mass black hole mergers; see Fouchart et al. 2014; Dietrich et al. 2015; Just et al. 2015; Kawaguchi et al. 2015; Kyutoku et al. 2015 and the references therein), there is a general conclusion that “the accretion disk mass $M_{disk}$ is (significantly) larger than $M_{ej}$” (see Figure 1 for illustration; where the triangles represent the mergers of equal- and unequal-mass neutron stars assuming several different equations of state, while the squares are the black hole–neutron star mergers with various initial parameters). One exception is in the case of tidal disruption of a star with a hyperbolic orbit, half the material is ejected and the other half is bound (i.e., $M_{disk} = M_{ej}$; K. Hotokezaka 2016, private communication). Therefore, we have $M_{disk} \geq M_{ej}$ if a black hole was promptly formed in the mergers. For the neutron star–stellar-mass black hole mergers this is always the case. If instead a hypermassive neutron star was formed in the binary neutron star mergers, it will take a time of $\sim 100$ ms or longer to collapse into a black hole, during which most of the disk material likely has accreted onto the central remnant and $M_{ej}$ cannot be taken as a robust lower limit of $M_{disk}$. That is why we focus on the NS–BH mergers favored in current macronova/kilonova modeling. According to Figure 1, it is also reasonable to assume $M_{disk} \leq 0.3 \, M_\odot$.

The energy extraction efficiency ($\epsilon$) of the sGRB central engine is

$$\epsilon = E_{\gamma,j}/M_{disk} c^2,$$

where $E_{\gamma,j} = E_{\gamma}(1 - \cos \theta_j) \approx E_{\gamma} \theta_j^2/2$ is the geometry-corrected prompt emission energy of the sGRB, $\theta_j \ll 1$ is the half-opening angle of the GRB ejecta, and $E_{\gamma}$ is the isotropic-equivalent energy of the prompt emission. With the good-quality prompt and afterglow emission data of some sGRBs, $E_{\gamma}$ can be directly measured and the $\theta_j$ can be yielded in the numerical modeling of the afterglow emission, with which $E_{\gamma,j}$ is obtained. The main challenge is how to measure or estimate $M_{disk}$ reliably. Fortunately, we have shown that $M_{disk} \geq M_{ej}$ with which $\epsilon$ can be constrained.

Thanks to the great efforts of the GRB follow-up observation community, three macronova signals have been identified in sGRB 130603B (Berger et al. 2013; Tanvir et al. 2013), hGRB 060614 (Berger et al. 2013; Tanvir et al. 2013), and sGRB 050709 (Tanvir et al. 2013). The numerical modeling of the signal in sGRB 130603B in the binary neutron star merger scenario suggests $M_{ej} \sim 0.03$–$0.08 \, M_\odot$ (Berger et al. 2013), which might be a challenge since usually the binary neutron star mergers are not expected to be able to eject such massive outflow. On the other hand, a neutron star–black hole merger model (Tanaka et al. 2014) can reasonably reproduce the macronova signal in sGRB 130603B with $M_{ej} \sim 0.05 \, M_\odot$ (Hotokezaka et al. 2013; Jin et al. 2016; Kawaguchi et al. 2016). For hGRB 060614, the macronova modeling gives a
Table 1
The Estimate of the Energy Extraction Efficiency

| GRB 050709a | GRB 060614b | GRB 130603B
|-------------|-------------|-------------|
| $E_\nu (10^{51} \text{ erg})$ | 0.069 | 2.1 | 2.1 |
| Duration (s)$^3$ | 0.07%(+130) | 5(±97) | 0.18 |
| $\theta_1$ (rad) | 0.10 | 0.08 | 0.085 |
| $M_{\text{eq}}(M_\odot)$ | ~0.05 | ~0.10 | ~0.05 |
| $M_{\text{disk}}(M_\odot)$ | $\geq 0.05$ | $\geq 0.10$ | $\geq 0.05$ |
| $\epsilon$ | $\leq 3.9 \times 10^{-6}$ | $\leq 3.8 \times 10^{-5}$ | $\leq 6.4 \times 10^{-5}$ |
| $L_{\text{es}}$ for initial spike | Possible | No | Possible |
| $L_{\text{es}}$ for extended emission | Possible | No | Possible |

Notes:
- $^a$ Villasenor et al. (2005) and Jin et al. (2016).
- $^b$ Gehrels et al. (2006) and Xu et al. (2009).
- $^c$ Tanvir et al. (2013), Berger et al. (2013), and Fan et al. (2013).
- $^d$ The durations include that of the hard spike and the “extended emission” (in the brackets).
- $^e$ The value of $M_{\text{eq}}$ is estimated within the neutron star–black hole merger model.
- $^f$ The value of $\epsilon$ is derived with Equation (1).

$M_{\text{eq}} \sim 0.1 M_\odot$ in the neutron star–black hole merger scenario and $\sim 0.2 M_\odot$ in the case of the binary neutron star merger (Yang et al. 2015). The I/F814W-band macronova signal of sGRB 050709 is rather similar to (though a bit dimmer than) that of hGRB 060614, and the neutron star–black hole merger modeling suggests a $M_{\text{eq}} \sim 0.05 M_\odot$ (Jin et al. 2016). Other physical parameters of these three macronova-associated GRBs, including $E_\nu$, and $\theta_1$, are also summarized in Table 1. With Equation (1) and the fact that $M_{\text{disk}} \geq M_{\text{eq}}$, it is thus straightforward to get the constraint on $\epsilon$, which is found to be very low.

Let us check if either the neutrino/anti-neutrino annihilation process or the magnetic process is needed to account for the data. Note that in typical neutron star–black hole mergers, an initial spin $a > 0.6$ and a $M_{\text{BH}} < 10 M_\odot$ (the observed Galactic black holes likely have a typical mass $\sim 6–8 M_\odot$) are needed to eject massive neutron-rich outflow. Therefore, in the following discussion, we take $a = 0.7$ and $M_{\text{BH}} = 7 M_\odot$. An empirical relation of the luminosity of such a hot ejecta reads (Zalamea & Beloborodov 2011)

$$L_{\text{es}} \approx 5 \times 10^{52} \text{ erg s}^{-1} \left(\frac{\theta_1}{0.1}\right)^{-2} \left(\frac{x_{\text{ms}}}{1.7}\right)^{-4.8} \times \left(\frac{M}{1 M_\odot}\right)^{9/4} \left(\frac{M_{\text{BH}}}{7 M_\odot}\right)^{-3/2},$$

which holds for $M_{\text{igm}} < M < M_{\text{tap}}$, where $x_{\text{ms}} = (3 + Z_2 + [(3 - Z_2)(3 + Z_2 + 2Z_2)]^{1/2})^2 / 2$ (where $Z_2 = 1 + (1 - a^2)^{1/3} [(1 + a)^{1/3} + (1 - a)^{1/3}]$ and $Z_2 = (3a^2 + Z_2^2)^{1/2}$). For $a = (0.8, 0.9, 0.95)$ we have $x_{\text{ms}} = (1.45, 1.16, 1.00)$, respectively; $M$ is the accretion rate, $M_{\text{igm}} = K_{\text{igm}} (a/0.1)^{5/3}$, $M_{\text{tap}} = K_{\text{igm}} (a/0.1)^{1/3}$, and $\alpha$ is the viscosity. Both $K_{\text{igm}}$ and $K_{\text{igm}}$ are functions of $a$, and for $a = (0.95, 0.95)$, $K_{\text{igm}} = (0.071, 0.021) M_\odot$ s$^{-1}$ and $K_{\text{igm}} = (9.3, 1.8) M_\odot$ s$^{-1}$, respectively (Zalamea & Beloborodov 2011). The corresponding

The efficiency of “energy extraction” is

$$\epsilon_{\text{es}} \equiv \frac{\theta_1^2}{2Mc^2} L_{\text{es}} \approx 7 \times 10^{-6} \left(\frac{x_{\text{ms}}}{1.7}\right)^{-4.8} \times \left(\frac{M}{0.1 M_\odot}\right)^{5/4} \left(\frac{M_{\text{BH}}}{7 M_\odot}\right)^{-3/2}.$$  

The smaller $M$ is, the less efficient the energy extraction we have.

In the Blandford–Znajek mechanism (Blandford & Znajek 1977; Lee et al. 2000), the luminosity of the electromagnetic outflow can be estimated by

$$L_{\text{BZ}} \approx 1.5 \times 10^{52} \text{ erg s}^{-1} \epsilon_{\text{BZ}} \left(\frac{a}{0.7}\right)^2 \left(\frac{M}{0.01 M_\odot}\right) \times \left(\frac{\theta_1}{0.1}\right)^{-2} \left[(1 + \sqrt{1 - a^2})/2\right]^{-2},$$

where $\epsilon_{\text{BZ}} \sim O(1)$ is a dimensionless parameter that describes the ratio between the ordered magnetic field energy density and the total energy density of the accreting material. The energy extraction efficiency is thus

$$\epsilon_{\text{BZ}} \equiv \frac{\epsilon_{\text{es}}}{\epsilon_{\text{BZ}}} \approx 3.8 \times 10^{-4} \epsilon_{\text{BZ}} \left(\frac{a}{0.7}\right)^2 \times \left(\frac{\theta_1}{0.1}\right)^{-2} \left[(1 + \sqrt{1 - a^2})/2\right]^{-2}.$$  

In the case of $M \ll 1 M_\odot$ s$^{-1}$, we have $\epsilon_{\text{es}} \ll \epsilon_{\text{BZ}}$ (see Equations (3) and (5)).

3. Case Studies

Below, we discuss these three GRBs and their “extended emission” case by case. In particular, we focus on whether the neutrino process can work or not since all the $\epsilon$ reported in Table 1 are sufficiently small to be well matched (see Equation (5)). To be able to account for the data within the neutrino process, the requests of $L_{\text{es}} \geq L_\nu$, (equally, $\epsilon_{\text{es}} \geq \epsilon_{\text{BZ}}$) and $M \leq M_{\text{disk}} / r$ should be satisfied, where $r$, $L_\nu$, $\epsilon_{\text{es}}$, are the duration after the redshift correction, luminosity, energy extraction efficiency of the prompt emission or alternatively the extended emission, respectively. Note that $M_{\text{ig}} \leq M_{\text{disk}} \leq 0.3 M_\odot$ and $\epsilon_{\text{es}}$ are different from $\epsilon$ in the case of the presence of extended emission.

GRB 050709. It is a short burst lasting $\sim 0.07$ s followed by the extended X-ray emission with a duration of $\sim 130$ s. At a redshift of $z = 0.16$, the initial hard spike has an $E_\nu \sim 2.8 \times 10^{50}$ erg and a corresponding luminosity of $L_{\nu=0.065} \sim 4.5 \times 10^{50}$ erg s$^{-1}$ (Villasenor et al. 2005). With Equation (2) we find out that with the other fiducial parameters, for $M \sim 0.15 M_\odot$ s$^{-1}$, the neutrino/anti-neutrino process is energetic enough to generate the hard spike. The corresponding accretion disk mass is $\sim 0.01 M_\odot$, significantly smaller than $M_{\text{ig}} \sim 0.5 M_\odot$. Therefore, most of the accretion disk mass might have been consumed to yield the $\sim 112 (1 + z)$ s long-tail X-ray emission. The time-averaged luminosity of the extended X-ray emission is $L_{\text{es}} = 112 \times 3 \times 10^{37}$ erg s$^{-1}$, the neutrino process may be able to work with a high spin parameter $a \sim 0.9$ (i.e., $x_{\text{ms}} = 1.16$) and $M \sim 2 \times 10^{-3} M_\odot$ s$^{-1}$. The disk mass for the extended emission is $\sim 0.22 M_\odot$, which may be possible in some neutron star–black
hole merger models (see Figure 1). The $\sim 100$ s duration of the “steady extended” accretion process for the disk formed in the compact object mergers requires $\alpha \sim 10^{-3}$ (see also Lee et al. 2009), which is at the low end of the distribution discussed in the literature (note that this request also holds for the magnetic energy extraction process). As far as the energy budget is concerned, the neutrino process seems to be plausible for GRB 050709.

GRB 130603B. The burst was at a redshift of $z = 0.356$ and the prompt emission lasted for $\sim 0.12(1+z)$ s with a luminosity of $L_{\gamma} = 1.8 \times 10^{52}$ erg s$^{-1}$ (Tanvir et al. 2013). With Equation (2) we find that with other adopted fiducial parameters, for $M = 0.6 M_\odot$, the neutrino/anti-neutrino process is energetic enough to generate the brief but intense gamma-ray flash (see also Equation (3)). This requires an $M_{\text{disk}} \sim 0.07 M_\odot$, which seems possible with an inferred $M_{\text{ej}} \sim 0.05 M_\odot$ (see Figure 1).

GRB 060614. The prompt emission of hGRB 060614 at $z = 0.125$ consisted of two epochs. The first is a hard spike lasting $\sim 4.4(1+z)$ s with an $E_\gamma \sim 3.7 \times 10^{50}$ erg (Xu et al. 2009), suggesting a corresponding luminosity $L_{\gamma} \sim 8 \times 10^{46}$ erg s$^{-1}$. The neutrino/anti-neutrino process can marginally give rise to the initial gamma-ray flash with an $M_{\text{disk}} \sim 0.2 M_\odot$ and $\alpha \sim 0.8$. In view of the rather massive ejecta with $M_{\text{ej}} \sim 0.1 M_\odot$, an $M_{\text{disk}} \sim 0.2 M_\odot$ is possible. However, for the $\sim 86 (1+z)$ s long-tail emission of hGRB 060614 with an averaged luminosity of $L_{\gamma} \sim 2 \times 10^{49}$ erg s$^{-1}$, the neutrino process is hard to contribute to. This is because the total accretion disk is not expected to be more massive than $0.3 M_\odot$ (see Figure 1), with which the averaged accretion rate $\dot{M} < 3 \times 10^{-3} M_\odot$ s$^{-1}$. In the most promising case (i.e., a very high $\alpha = 0.95$ and a sufficiently small $\alpha \leq 0.01$ to render $M_{\text{ej}} \sim 10^{-3} M_\odot$ s$^{-1}$), we have a luminosity of $L_{\gamma} \sim 10^{48}$ erg s$^{-1}$, one order of magnitude lower than the observed value. On the other hand, we have $L_{\text{HZ}} \sim 1.5 \times 10^{51}$ erg s$^{-1} \varepsilon_\gamma (a/0.7)^2 (M/10^{-3} M_\odot)$ s$^{-1}$, which can match the observation data as long as $\varepsilon_\gamma > 0.01 (a/0.7)^2 (M/10^{-3} M_\odot)$ s$^{-1}$). The initial magnetization degree (i.e., the initial ratio between the magnetic field energy density and the thermal energy density) of the outflow powering the long-tail emission is expected to be approximately tens. Again, the $\sim 100$ s duration of the accretion process for the disk formed in the compact object mergers requires $\alpha \sim 10^{-3}$.

All these results/constraints in the case of neutrino anti-neutrino annihilation are summarized in Figure 2. Clearly, the neutrino process may be able to account for some but not all data, and the magnetic process is in principle sufficient for all the data.

If $M_{\text{ej}} \sim 10^{-3} - 10^{-2} M_\odot$, as suggested in Kisaka et al. (2016), the limits on the efficiencies of the central engines will be 1–2 orders of magnitude higher, leading to looser constraints. For $M_{\text{BH}} \sim 3 M_\odot$ (i.e., within the double neutron star merger scenario), with a reasonable $a \sim 0.7$ the accretion disk masses $M_{\text{disk}}$ are required to be $\sim 0.005, 0.04, 0.12 M_\odot$ for the hard spikes of GRB 050709, GRB 060614, and GRB 130603B, respectively; otherwise, the neutrino process is not efficient enough. Though in some binary neutron star mergers $M_{\text{disk}}$ can be as massive as $\sim 0.2 M_\odot$ (see the triangles in Figure 1), the inferred rather low $M_{\text{ej}}$ hampers us from drawing a reliable conclusion on the role of the neutrino process. For the extended X-ray emission of GRB 050709 and GRB 060614, the required $M_{\text{disk}} \sim 0.38, 1.6 M_\odot$ even for a somewhat “optimistic” $a = 0.8$. We thus suggest that the neutrino process is hard to account for in the extended emission.

4. Conclusion and Discussion

We show in this work the macronova data provide a novel probe of the GRB central engine activity. The conversion efficiency of the disk mass into the GRB prompt emission is found to be rather low, and the neutrino processes are likely able to generate the brief gamma-ray flashes in all three events (see Table 1 and Figure 2). The situation is less clear for the extended emission found in GRB 050709 and GRB 060614. For the former, the neutrino process may work thanks to the low luminosity of the extended X-ray emission. While for the latter, the magnetic process is necessary. Note that these conclusions are based on the NS–BH merger model for current GRB-associated macronova/kilonova events. Interestingly, all three current macronova-associated GRBs have small offsets from the host Galaxy centers, in agreement with the NS–BH merger model prediction (Troja et al. 2008). In other scenarios that yield a much lower $M_{\text{ej}}$, the constraints are weaker (see Section 3). Nevertheless, the NS–BH merger scenario is well testable in the era of GW astronomy (Mandel et al. 2015). GRB 060614, if it is indeed from an NS–BH merger, is within the expected advanced LIGO/Virgo sensitivity range (Li et al. 2016a), and a further examination reveals a very promising detection prospect of NS–BH merger events (Li et al. 2016b). Though the GRB/GW events are expected to be rare in the next decade, the macronova/GW events are expected to be much more frequent. The statistical study can be helpful in revealing the macronova nature and hence yield a better understanding of the GRB central engine.

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