BRIGHT “MERGER-NOVA” FROM THE REMNANT OF A NEUTRON STAR BINARY MERGER: A SIGNATURE OF A NEWLY BORN, MASSIVE, MILLISECOND MAGNETAR

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ABSTRACT

A massive millisecond magnetar may survive the merger of a neutron star (NS) binary, which would continuously power the merger ejecta. We develop a generic dynamic model for the merger ejecta with energy injection from the central magnetar. The ejecta emission (the “merger-nova”) powered by the magnetar peaks in the UV band and the peak of the light curve, progressively shifts to an earlier epoch with increasing frequency. A magnetar-powered merger-nova could have an optical peak brightness comparable to a supernova, which is a few tens or hundreds times brighter than the radioactive-powered merger-novae (the so-called macro-nova or kilo-nova). On the other hand, such a merger-nova would peak earlier and have a significantly shorter duration than that of a supernova. An early collapse of the magnetar could suppress the brightness of the optical emission and shorten its duration. Such millisecond-magnetar-powered merger-novae may be detected from NS–NS merger events without an observed short gamma-ray burst, and could be a bright electromagnetic counterpart for gravitational wave bursts due to NS–NS mergers. If detected, it suggests that the merger leaves behind a massive NS, which has important implications for the equation-of-state of nuclear matter.

Key words: gamma-ray burst: general – stars: neutron – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Mergers of double neutron stars (NSs) or a NS with a stellar-mass black hole are the primary targets of direct detections of gravitational waves (GWs). It is expected that, by the end of this decade, the second generation of ground-based GW detectors will extend the detection horizons of the mergers to a few hundred Mpc or even 1 Gpc (Abadie et al. 2010; Nissanke et al. 2013). Electromagnetic (EM) transients that are spatially and temporally coincident with the GW bursts due to the mergers, could play a crucial role in the discovery and identification of the GW signals by providing position, time, redshift, and astrophysical properties of the sources.

The brightest EM emission during the compact binary mergers is probably short-duration gamma-ray bursts (SGRBs; e.g., Gehrels et al. 2005; Fox et al. 2005; Fong et al. 2013; cf. Virgili et al. 2011). However, since they are usually beamed into a small opening angle (e.g., Burrows et al. 2006; De Pasquale et al. 2010), most GW bursts would not be detected together with SGRBs (e.g., Metzger & Berger 2012). Numerical simulations show that a more isotropic, sub-relativistic \((v_\text{e} \sim 0.15–0.25c)\) outflow could be ejected during a merger, which could include the tidal tail matter during the merger and the matter from the accretion disk (e.g., Rezzolla et al. 2011; Bauswein et al. 2013; Rosswog et al. 2013). The typical mass of the ejecta is in the range \(M_\text{ej} \sim 10^{-3}–10^{-2} M_\odot\) (Hotokezaka et al. 2013). Somewhat higher mass could also exist (Fan et al. 2013). The ejecta is expected to be neutron-rich and thus heavier radioactive elements could be synthesized via the \(r\)-process. Li & Paczyński (1998) suggested that the ejecta could produce a thermal UV–optical transient powered by radioactive decay, which is more isotropic than SGRBs. In the past few years, much effort has been invested in determining the details of merger dynamics, nuclear synthesis, radiative transfer, etc. (e.g., Kulkarni et al. 2005; Rosswog 2005; Metzger et al. 2010; Goriely et al. 2013; Roberts et al. 2013; Barnes & Kasen 2013; Bauswein et al. 2013; Grossman et al. 2013; Piran et al. 2013; Rosswog et al. 2013; Takami et al. 2013; Tanaka & Hotokezaka 2013). The interaction between the merger ejecta and the ambient medium is also expected to produce a long-lasting afterglow emission (Nakar & Piran 2011; Metzger & Berger 2012; Piran et al. 2013). Nevertheless, the brightness of the afterglow emission is typically low, and strongly depends on the ambient density.

The merger products are usually considered to be a black hole. Alternatively, given the uncertainties of nuclear matter equation-of-state and NS mass distributions of the merger systems, it is possible that at least some NS–NS mergers would leave behind a stable (for hours to days), rapidly rotating NS (e.g., Dai et al. 2006; Fan & Xu 2006; Zhang 2013; Giacomazzo & Perna 2013). This is indirectly supported by the fact that some SGRBs are followed by an X-ray plateau with an abrupt ending, which is best interpreted as emission from a spinning down magnetar (e.g., Rowlinson et al. 2010, 2013). More directly, the present lower limit of the mass of Galactic NSs is precisely set by PSR J0348+0432 to 2.10 ± 0.04 M_\odot (Antoniadis et al. 2013). The permitted equations of state usually lead to a maximum mass close to or higher than 2.5 M_\odot for a non-rotating NS, which is comparable to the sum of the masses of some Galactic NS–NS binaries. Zhang (2013) proposed that if a NS–NS merger leaves behind a millisecond magnetar, a GW burst would be associated with a bright X-ray early afterglow due to magnetar wind dissipation, regardless of whether there is an associated SGRB. Gao et al. (2013) studied the multi-wavelength afterglows of such a magnetar-powered merger ejecta.

Following the above considerations, we suggest in this Letter that the magnetar wind would first heat up the neutron-rich merger ejecta before powering its afterglow and consequently...
produce a bright “merger-nova.” A similar process could have been observed in the so-called superluminous supernovae (Kasen & Bildsten 2010), the light curves of which can be explained by having a millisecond magnetar wind heating the ejecta more than radioactive processes (Inserra et al. 2013). In this Letter, we develop a dynamic model for the evolution of the merger ejecta including acceleration, cooling, and deceleration. We then study the emission properties of the millisecond-merger ejecta including acceleration, coasting, and deceleration.

An obvious difference between a merger-nova and a supernova would be their distinct ejecta masses. We use \( E_{\text{rot}}/M_{\text{ej}}c^2 = 1 \) to define a critical ejecta mass as \( M_{\text{ej, cr}} = 0.01 \ P_{1,-3}^{-2} \ M_{\odot} \), below which the ejecta can be accelerated to a relativistic speed \(^5\) by the magnetar wind (Gao et al. 2013). The predicted range of the ejecta masses, \( M_{\text{ej}} \sim 10^{-4} \cdots 10^{-2} \ M_{\odot} \), indicates that a complete description of the dynamical evolution of a merger-nova, which covers both the non-relativistic and high-relativistic phases, is desirable. The total energy of the ejecta excluding the rest energy can be expressed by \( E_{\text{ej}} = (\Gamma - 1)M_{\text{ej}}c^2 + \Gamma E_{\text{int}} \), where \( \Gamma \) is the Lorentz factor and \( E_{\text{int}} \) is the internal energy measured in the comoving rest frame. Energy conservation gives \( dE_{\text{ej}} = (\xi L_{\text{sd}} + L_{\text{ra}} - L_{\text{c}}) \, dt \), where a fraction \( \xi \) of the spin-down luminosity is assumed to be injected into the ejecta, \( L_{\text{ra}} \) is the radioactive power, and \( L_{\text{c}} \) is the radiated bolometric luminosity. The dynamic evolution of the ejecta can be determined by

\[
\frac{d\Gamma}{dt} = \frac{\xi L_{\text{sd}} + L_{\text{ra}} - L_{\text{c}} - \Gamma D(dE_{\text{int}}/dt')}{M_{\text{ej}} c^2 + E_{\text{int}}},
\]

where \( D = 1/[(\Gamma - 1) - \beta] \) is the Doppler factor with \( \beta = \sqrt{1 - 1/\Gamma^2} \). The comoving time \( dt' \) can be connected with the observer’s time by \( dt' = D \, dt \). The variation of the internal energy in the comoving frame can be expressed by (e.g., Kasen & Bildsten 2010)

\[
\frac{dE_{\text{int}}}{dt'} = \xi L_{\text{sd}} + L_{\text{ra}} - L_{\text{c}} - \mathcal{P} \frac{dV'}{dt'},
\]

where the comoving luminosities read \( L'_{\text{sd}} = L_{\text{sd}}/D^2 \), \( L'_{\text{c}} = L_{\text{c}}/D^2 \), and

\[
L'_{\text{ra}} = \frac{L_{\text{ra}}}{D^2} = 4 \times 10^{39} M_{\text{ej, -2}}
\]

\[
\times \left[ \frac{1}{2} - \frac{1}{\pi} \arctan \left( \frac{t' - t_0}{t'_{\sigma}} \right) \right]^{1.3} \text{erg s}^{-1}
\]

with \( t'_0 \sim 1.3 \text{ s} \) and \( t'_{\sigma} \sim 0.11 \text{ s} \) (Korobkin et al. 2012). For typical parameters \( L_{\text{ra}} \ll L_{\text{sd}} \) unless the magnetar only lives for a few hundred seconds, \( \mathcal{P} \, dV' \) represents the work due to free expansion of the ejecta which converts internal energy into bulk kinetic energy. The pressure \( \mathcal{P} = E_{\text{int}}/3V' \) is dominated by radiation, and the evolution of the comoving volume can be determined by

\[
\frac{dV'}{dt'} = 4\pi R^2 \beta c,
\]

together with

\[
\frac{dR}{dt} = \frac{\beta c}{(1 - \beta)},
\]

where \( R \) is the radius of the ejecta. The radiated bolometric luminosity can be derived approximately from the diffusion equation in the comoving frame (Kasen & Bildsten 2010; Kotera et al. 2013)

\[
L'_c = \frac{E'_{\text{int}}/c}{\tau R/\Gamma} = \frac{E'_{\text{int}}}{t'^2_{\sigma}}, \quad \text{for } t < t'_{\sigma},
\]

\[
= \frac{E'_{\text{int}}}{R/\Gamma}, \quad \text{for } t > t'_{\sigma},
\]

\(^4\) The thermal emission of the merger ejecta (Li & Paczyński 1998) was named as “macro-nova” by Kulkarni (2005) due to its sub-supernova luminosity, or as “kilo-nova” by Metzger et al. (2010) due to its luminosity of \( \sim 10^{35} \) times than the Eddington luminosity. In this Letter, we use a more general word “merger-nova” to reflect a wider range of predicted luminosities.

\(^5\) The impact of a magnetar wind on a merger-nova was considered by Kulkarni (2005), who adopted a relatively long spin period of a few hundred milliseconds, so that the dynamics is still in the non-relativistic regime.
In our calculations, a constant opacity $\kappa = 0.2 \text{ cm}^2 \text{ g}^{-1}$ is adopted for simplicity, which is appropriate for electron scattering in a plasma with an ionization degree of 0.5. However, for $r$-process elements, Kasen et al. (2013) found that the bound–bound, bound–free, and free–free transitions could provide more important contributions to the opacity, which makes the opacity higher and strongly energy-dependent. As a result, the merger-nova emission could be extended, weakened, and shifted toward softer bands (Barnes & Kasen 2013). Additionally, the ionization of the ejecta by the wind X-ray emission (Zhang 2013) could also affect the opacity.
band (∼1 eV), a luminous flash with a peak luminosity of ∼10^{43} \text{erg s}^{-1} appears in the day–week timescale. This was the reason why we did not adopt the word “macro-nova” or “kilo-nova.” Nevertheless, such a bright optical emission could be significantly suppressed by an early collapse of the magnetar (t_{\text{col}} \ll t_{\text{md}}) due to an extra angular momentum loss (e.g., via strong gravitational radiation), as shown by the dotted lines in Figure 2 for an optionally taken t_{\text{col}} = 10^4 \text{s}. Of course, in a more detailed calculation, the influence on the spin-down behavior of the extra angular momentum loss before this collapsing time should also be taken into account (Fan et al. 2013, submitted).

For a direct impression of the merger-nova optical emission, in Figure 3 we present the optical light curve of the magnetar-powered merger-nova in a linear timescale, in comparison with the bolometric light curves of two supernovae (SN 1998bw and SN 2006gy) and a light curve of radioactive merger-nova (as labeled). The dash-dotted (blue) and solid (orange) lines represent M\text{\gamma} = 10^{-2} M_{\odot} and 10^{-4} M_{\odot}, respectively. The thick and thin lines correspond to a magnetar collapsing time as t_{\text{col}} = 10^3 \text{s} \ll t_{\text{md}} and t_{\text{col}} = 2 t_{\text{md}}, respectively. The zero-times of the supernovae are set at the first available data.

(A color version of this figure is available in the online journal.)

where the energy loss due to shock emission is ignored, an approximation usually adopted in GRB afterglow modeling. As shown in Figure 4, for a reasonable range of the ambient density, deceleration could not start before acceleration is complete. Therefore, the acceleration and deceleration processes can in principle be investigated independently, as treated in Section 2. The light curves of the afterglow synchrotron emission for a typical ambient density n = 0.1 \text{cm}^{-3} are presented in Figure 2 along with the merger-nova light curves. As shown, the afterglow emission could be much weaker than that of the merger-nova in a wide frequency range, although a noteworthy fraction of the injected energy is also transferred to the shock.

4. CONCLUSION AND DISCUSSION

By describing the dynamic evolution of a merger ejecta powered by a millisecond magnetar, we calculate the thermal emission of the merger-nova and the non-thermal emission of the external shock. The optical brightness of the millisecond-magnetar-powered merger-nova is found to be comparable to or even higher than that of supernovae, which is a few tens or hundreds times brighter than the radioactive-powered kilonova, if the magnetar remains stable before t_{\text{md}}. Nevertheless, early GW loss and an earlier collapsing time could suppress the optical emission significantly. The magnetar collapse due to losing most centrifugal support could also restrict the duration of the merger-nova within the order of (at most) a few days, which is considerably shorter than the supernovae duration lasting months and years. Detecting such a unique EM transient associated with a GW burst would unambiguously confirm the astrophysical origin of the GW burst and robustly suggest a massive millisecond magnetar formed during the merger.

So far, no bright optical merger-nova have been detected in association with SGRBs. This may be understood as follows. Along the spin axis, a strong magnetar jet could break out by propelling ejecta sideways (Bucciantini et al. 2012; Quataert & Kasen 2012), so that there could be no merger-nova emission toward the observer in the SGRB direction. A bright merger-nova may still be observable in the equatorial direction, but...
it is relativistically Doppler de-boosted in the direction of the SGRB. We expect that bright merger-nova tend to be discovered in NS–NS mergers without a SGRB association. For the detectability of the millisecond-magnetar-powered merger-novae, a detailed Monte Carlo simulation could be desirable. Here we give a rough estimate. In the survey mode, the detection efficiency of merger-novae by an optical telescope may be estimated by

\[ \eta \sim \frac{(1+z)T_{\text{mn}} \text{FOV}}{T_{\text{exp}} 4\pi} \sim 2 \times 10^{-4} (1+z), \quad (11) \]

where \( z \) is redshift, \( T_{\text{mn}} \) is days is the merger-nova duration above the detector sensitivity limit, \( T_{\text{exp}} \) is hours is the exposure time, \( \text{FOV} \sim 10^{-4} \) is the field of view of the telescope. The detection rate of millisecond-magnetar-powered bright optical merger-novae without a SGRB association may be estimated as

\[ R_{\text{mn}} = \frac{\dot{\rho}_{\text{NS-NS}}}{3} \left[ \frac{L_{\text{mn}}}{4\pi S (1+z)^2} \right]^{3/2} \eta f \]

\[ = 0.06(1+z)^{-2} L_{\text{mn},42.5}^{3/2} S_{13}^{-3/2} \eta^{-4} f^{-1} \]

\[ \times \left( \frac{\dot{\rho}_{\text{NS-NS}}}{500 \text{Gpc}^{-3} \text{yr}^{-1}} \right) \text{yr}^{-1}, \quad (12) \]

where \( \dot{\rho}_{\text{NS-NS}} \) is the NS–NS merger rate density normalized to beaming-corrected SGRB rate density, \( L_{\text{mn}} \) is the merger-nova luminosity, \( S \) is the telescope sensitivity which is normalized to a V-band magnitude \( -22.5 \) and should strongly depend on the exposure time, and \( f \) is the fraction of NS–NS mergers that give rise to a millisecond magnetar. One can see that the short duration of the merger-novae (small \( \eta \)) could make them easily to evade from the current supernova surveys, even though they are very luminous. A shorter lifetime of the magnetar (e.g., due to strong gravitational radiation) would reduce \( L_{\text{mn}} \) and \( T_{\text{mn}} \), which lead to a lower observed event rate of the optical merger-novae. Future wide-field optical telescope surveys (e.g., the Ground-based Wide-Angle Camera array) would detect these events or pose important constraints on the unknown parameters such as \( \dot{\rho}_{\text{NS-NS}}, \eta, \) and \( f \).

Finally, while this Letter only focuses on the effect of energy injection into the merger ejecta, a large fraction of the spin-down luminosity carried in the magnetar wind could be dissipated directly. The internal dissipation may arise from turbulent magnetic reconnection due to internal collisions of the magnetar wind (Zhang & Yan 2011) or from the termination shock of the wind (Dai 2004). These internal dissipations could produce an emission typically in a higher-energy band, e.g., in X-rays (Yu et al. 2010; Zhang 2013). This X-ray transient is also expected to ionize the entire ejecta, similar to the case of superluminous supernovae (Metzger et al. 2013).

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