Early Soft X-Ray to UV Emission from Double Neutron Star Mergers: 
Implications from the Long-term Observations of GW170817

Xiang-Yu Wang\textsuperscript{1,2} and Zhi-Qiu Huang\textsuperscript{1,2}

\textsuperscript{1} School of Astronomy and Space Science, Nanjing University, Nanjing 210093, People’s Republic of China; xywang@nju.edu.cn
\textsuperscript{2} Key laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, People’s Republic of China

Received 2017 December 13; revised 2018 January 4; accepted 2018 January 7; published 2018 January 23

Abstract
Recent long-term radio follow-up observations of GW170817 reveal a simple power-law rising light curve, with a slope of $\rho^{0.78}_{-0.05}$, up to 93 days after the merger. The latest X-ray detection at 109 days is also consistent with such a temporal slope. Such a shallow rise behavior requires a mildly relativistic outflow with a steep velocity gradient profile, so that slower material with larger energy catches up with the decelerating ejecta and re-energizes it. It has been suggested that this mildly relativistic outflow may represent a cocoon of material. We suggest that the velocity gradient profile may form during the stage that the cocoon is breaking out of the merger ejecta, resulting from shock propagation down a density gradient. The cooling of the hot relativistic cocoon material immediately after it breaks out should have produced soft X-ray to UV radiation at tens of seconds to hours after the merger. The soft X-ray emission has a luminosity of $L_{X} \sim 10^{45}$ erg s\textsuperscript{-1} over a period of tens of seconds for a merger event like GW170817. The UV emission shows a rise initially and peaks at about a few hours with a luminosity of $L_{UV} \sim 10^{42}$ erg s\textsuperscript{-1}. The soft X-ray transients could be detected by future wide-angle X-ray detectors, such as the Chinese mission Einstein Probe. This soft X-ray/UV emission would serve as one of the earliest electromagnetic counterparts of gravitation waves from double neutron star mergers and could provide the earliest localization of the sources.

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

1. Introduction
The recent detection of gravitational waves (GWs) from a double neutron star (DNS) merger, known as GW170817 (Abbott et al. 2017a), and the following detection of an electromagnetic counterpart marks a new era for studying DNS mergers (Abbott et al. 2017b). The $\gamma$-ray satellite \textit{Fermi} detected a sub-energetic short gamma-ray burst (GRB 170817A) about 2 s after the GW event (Goldstein et al. 2017; Lu et al. 2017; Zhang et al. 2017). A macronova/kilonova was detected in the IR to UV bands since about 10 hr after the merger (e.g., Coulter et al. 2017; Drout et al. 2017; Evans et al. 2017). \textit{Swift} began searching for a counterpart to GW170817 with its X-ray Telescope (XRT) from about 0.04 days after the merger (Evans et al. 2017), but no new X-ray source was found. The \textit{Chandra} X-ray satellite detected X-ray counterparts at about 9 and 15.1 days after the merger (Margutti et al. 2017a; Troja et al. 2017a). Later on, radio emission was detected by VLA at about 16, 19, and 39 days after the merger (Alexander et al. 2017; Hallinan et al. 2017). The X-ray and radio emissions are thought to arise from the synchrotron emission of an expanding blast wave, which is powered by some ejecta from the DNS merger (e.g., Kasliwal et al. 2017; Murguia-Berthier et al. 2017).

Very recently, long-term radio observations find that the radio flux continue to rise with a simple power-law in time, $F_{\nu} \propto \nu^{0.78_{-0.05}}$ (Mooley et al. 2017). The spectrum is consistent with optically thin synchrotron emission, with $E_{\nu} \propto \nu^{-0.61_{-0.05}}$. The latest X-ray detection with \textit{Chandra} of the source find that the X-ray emission is also brightening (Haggard et al. 2017; Margutti et al. 2017b; Troja et al. 2017b). The X-ray brightening suggests a temporal slope consistent with the radio light curve. Such a temporal slope cannot be produced by a single-velocity ejecta, which would produce a $\rho$ rising light curve or a decreasing light curve for the observed frequency $\nu$ located between the two break frequencies (i.e., $\nu_{\text{in}} < \nu < \nu_{\text{io}}$; Sari et al. 1998), as the ejecta is coasting or decelerating in a constant density interstellar medium (ISM; e.g., Xiao et al. 2017). Depending on the density of the circumburst medium, two velocity profiles of the outflow have been suggested to fit the radio data (Mooley et al. 2017). For a density of $n = 0.03$ cm\textsuperscript{-3}, the distribution of the kinetic energy is $E_{k}(\gamma/\beta) = 5 \times 10^{50}$ erg($\gamma/\beta^{3}$), with a maximum velocity of $\beta_{M} = 0.8$. While for a lower density of $n = 10^{-4}$ cm\textsuperscript{-3}, $E_{k}(\gamma/\beta) = 2 \times 10^{51}$ erg($\gamma/\beta^{3}$) with a maximum Lorentz factor of $\gamma_{M} = 3.5$. Such a velocity profile suggests that the energy in the blast wave is increasing with time, which may be due to that slower material with a larger energy catches up with the decelerating ejecta and re-energizes it (see also Pooley et al. 2017). To explain the emission of GRB 170817A in the meantime, a relativistic outflow with $\gamma \approx 2$ may be necessary (Gottlieb et al. 2017), so the low-density case is favored. The outflow then may represent the cocoon material (Gottlieb et al. 2017), which forms as the jet is propagating through the DNS merger ejecta (Nagakura et al. 2014; Lazzati et al. 2017a, 2017b; Nakar & Piran 2017).

This velocity profile may form at the stage when the cocoon breaks out of the merger ejecta. This profile reflects the structure of the outflow immediately after it breaks out, since after that the outflow matter simply undergoes free expansion. Such a self-similar velocity gradient profile is common in core-collapse supernovae. The supernova shock experiences acceleration in the steep density gradients of the progenitor
envelope, and the velocity gradient profile forms after the shock breaks out of the envelope (Matzner & McKee 1999). We suggest that the velocity gradient profile in the case of GW170817 forms when the cocoon breaks out of the DNS merger ejecta, resulting from shock propagation down a density gradient.

The cocoon is hot as it consists of mainly shock-heated material from the merger ejecta. After the DNS merger ejecta has been shocked, its thermal and kinetic energies are approximately equal. The next phase of evolution is postshock acceleration, in which heat is converted into outward motion and the cocoon material approaches a state of free expansion. The internal energy will be released once the cocoon expands to a radius where it becomes transparent to radiation (Nakar & Piran 2017). The physics is similar to that of a cooling envelope after the supernova shock breaks out. Recently, Piro & Kollmeier (2017) show that early $\leq 4$ day optical/infrared emission of GW170817 can be explained by shock cooling emission of the non-relativistic merger ejecta. Kisaka et al. (2015) show that the early macronova/kilonova emission of GRB 130603B could be due to shock cooling emission powered by a central engine. In this Letter, we calculate the cooling emission from the mildly relativistic shocked materials (i.e., the cocoon), taking into account the velocity gradient profile of the expanding materials. Due to that the cocoon material has a much higher velocity, compared with the bulk ejecta of the DNS merger, it becomes transparent much earlier, and thus the cooling emission constitutes the earliest electromagnetic counterpart of the DNS merger (only after the prompt $\gamma$-ray burst emission). In Section 2, we discuss the constraints on the cocoon properties placed by recent long-term radio and X-ray observations. Then, in Section 3, we calculate the light curves of the cocoon cooling emission and study the detectability by future wide-angle X-ray and UV missions. Finally, we give discussions and conclusions.

2. Constraining the Cocoon Properties with Long-term Radio and X-Ray Observations

The radio follow-up observations of GW170817 reveal a steady rise in the light curve with a slope $F_{\nu} \propto \nu^{0.78 \pm 0.05}$ (Mooley et al. 2017). Following the “refreshed” shock scenario of GRB afterglows (Rees & Mészáros 1998; Sari & Mészáros 2000), we study the velocity gradient of the outflow with this radio light curve. We assume that the source ejects shells of a range of Lorentz factors, with a mass profile of $m(>\gamma) \propto \gamma^{-3}$ in the range of $\gamma_m < \gamma < \gamma_M$, where $\gamma_m$ and $\gamma_M$ are, respectively, the minimum and maximum Lorentz factors of the ejected shells. For an observational frequency locating between the injection break frequency and the cooling frequency, i.e., $\nu_m \ll \nu \ll \nu_c$ (Sari et al. 1998), the light curve of the forward shock emission should be (Sari & Mészáros 2000)

$$F_{\nu} \propto \nu^{-0.38},$$

where $\delta$ is the spectral index ($F_{\nu} \propto \nu^{-\delta}$). With an observed temporal slope of $F_{\nu} \propto \nu^{0.78}$ and a spectral slope of $\delta = 0.61 \pm 0.05$, we obtain $s \approx 7 \pm 0.5$. This value is roughly in agreement with $s = 6$ obtained by Mooley et al. (2017), who use numerical codes to calculate the light curve. The radio flux can be used to place constraints on the energy of the ejecta. The flux at 3 GHz is $F_{\nu} = 151 \pm 39 \, \mu$Jy at $t = 17.39$ days after the merger (Hallinan et al. 2017). We then obtain the kinetic energy of the blast wave

$$E_k \approx 10^{49} \, \text{erg} \epsilon_{e-1}^{-0.92} \epsilon_{B-2}^{-0.62} n^{-0.38} \left( \frac{F_{\nu}}{151 \, \mu \text{Jy}} \right)^{0.77} \left( \frac{t}{17.39 \, \text{day}} \right)^{3/8},$$

where $\epsilon_e$ and $\epsilon_B$ are the electron energy and magnetic energy equipartition factors in the shock, and $n$ is the number density of the surrounding medium. Here, we use the notations $\epsilon_{e-1} = \epsilon_e/10^{-1}$, $\epsilon_{B-2} = \epsilon_B/10^{-2}$, and $n^{-4} = n/(10^{-4} \, \text{cm}^{-3})$.

Chandra re-observed the source at about 109 days after the merger (Haggard et al. 2017; Margutti et al. 2017b; Troja et al. 2017b). The X-ray flux indicates a spectral slope $\delta \approx 0.6$ from radio to X-ray, which is consistent with the radio spectral slope (Margutti et al. 2017a). The spectrum of the X-ray emission alone is found to be $\delta = 0.62 \pm 0.27$, in agreement with the global spectrum from radio to X-ray. This indicates that the cooling break frequency $\nu_c$ is above the X-ray band at $t = 109$ days. Using the condition $\nu_c(t = 109 \, \text{d}) > 10^{18} \, \text{Hz}$ and the energy in the blast wave given by Equation (2), we get

$$n < 1.6 \times 10^{-3} \, \text{cm}^{-3} \epsilon_{e-1}^{0.57} \epsilon_{B-2}^{-1.46}.$$ (3)

A low density of $n < 0.04 \, \text{cm}^{-3}$ for the surrounding medium has also been inferred from the limit on the mass of neutral hydrogen (Hallinan et al. 2017). Note that the inverse Compton (IC) cooling is not taken into account in our estimate of $\nu_c$. IC cooling can become important if $\epsilon_e \gg \epsilon_B$ and depends on the ratio between $\nu_m$ and $\nu_c$. Since the observations of GW170817 suggest that $\nu_m$ is below the radio band and $\nu_c$ is above the X-ray, the Compton parameter is $Y < 1$ for reasonable values of $\epsilon_e$ and $\epsilon_B$ (Wang et al. 2010; Beniamini et al. 2015). Thus, the IC cooling does not introduce a significant change to our Equation (3). Then, we find a lower limit on the blast wave kinetic energy at $t = 17.39$ days,

$$E_k > 3.5 \times 10^{48} \, \text{erg} \epsilon_{e-1}^{-1} \epsilon_{B-2}^{-0.38},$$ (4)

The single power-law temporal behavior since $t = 17.39$ days after the merger requires that the fastest shell has been decelerated before this time. From this, we obtain

$$\gamma_M \gtrsim 3E_{b,49}^{1/8}n^{-1/8} \left( \frac{t}{17.39 \, \text{day}} \right)^{-3/8}.$$ (5)

In the above, we have assumed that the forward shock dominates the flux from the possible reverse shock in the refreshed shock scenario. This assumption is valid in our case since the injection break frequency $\nu_m$ of the reverse shock emission is much lower than that of the forward shock and the observed frequency is above $\nu_m$ of the forward shock emission (Sari & Mészáros 2000). Kumar & Piran (2000) have shown that the Lorentz factor of the inner shell with respect to decelerating outer shell is about 1.25 when the collision takes place.\(^3\) So the Lorentz factor of the reverse shock is expected to be $\gamma_R < 1.25$. Then, we expect that the ratio of thermal Lorentz factors of electrons in the reverse shock and forward shock is

\(^3\) The values of 1.25 corresponds to a case that the outer, decelerating shell has a constant energy. For the case of re-energized, decelerating outer shell, the relative Lorentz factor is even lower (see Equation (3) in Rees & Mészáros 1998).
is the Doppler factor. Although the number of electrons in the reverse shock is larger than that of the forward shock by a factor of $\Gamma_f$, the synchrotron flux of the forward shock at the frequency $\nu_m < \nu < \nu_c$ dominates over that of the reverse shock.

Mooley et al. (2017) obtain $E(>\gamma \beta) = 2 \times 10^{51}(\gamma \beta)^{-5}$ with a maximum Lorentz factor of $\gamma_M = 3.5$ by fitting the radio data. Our simple analytic result is well consistent with their result. In the following calculations, we assume that the fastest shell has a Lorentz factor of $\gamma_M = 3.5$ and an energy of $E_M = 4 \times 10^{48}$ erg, and that the shells have a velocity gradient profile of $m(>\gamma \beta) \propto (\gamma \beta)^{-4}$ in the velocity range of $1 \lesssim \gamma \beta \lesssim 3.5$.

3. Soft X-Ray and UV Emission from the Cooling Cocoon

This velocity profile reflects the structure of the cocoon material immediately after it breaks out of the merger ejecta, since after that the cocoon material simply undergoes free expansion. When the cocoon material becomes transparent, the cooling of the cocoon material will produce an electromagnetic signal.

Assuming a cocoon has a self-similar mass distribution $m(>\gamma \beta) = m_M (\gamma \beta/\gamma_M)^{-2}$. For $E_M = 4 \times 10^{48}$ erg and $\gamma_M = 3.5$, the mass of the maximum velocity ejecta is $m_M = 1.2 \times 10^{27}$ g. The highest-velocity shell in the outermost region becomes transparent at the earliest time. The shell with mass $m$ becomes transparent when its optical depth satisfies the condition

$$\tau(m) = \frac{\kappa m}{4\pi r^2} = \frac{c}{\nu_{sh}} \approx 1.$$  

With $r = 2(\gamma \beta)^2 ct$, we can obtain the mass and Lorentz factor of the shell that becomes transparent at a given time $t$, i.e.,

$$m = m_M \left(\frac{t}{t_M}\right)^{-\frac{2}{\gamma_M}},$$  

and

$$\gamma \beta = \gamma_M \left(\frac{t}{t_M}\right)^{-\frac{\gamma_M}{2}},$$  

where

$$t_M = \left(\frac{\kappa m}{16\pi \gamma_M^4 c^2}\right)^{1/2} = 12 s E_{M,48.6}^{-1/2} \gamma_M^{-2.5} k_{i,1}^{1/2}$$

is the characteristic timescale, corresponding to the time when the fastest shell becomes transparent. Here, we use the notations of $k_i = \kappa/1.0$ cm$^2$ g$^{-1}$, $E_{M,48.6} = E_M/10^{48.6}$ erg, and $\gamma_{M,3.5} = \gamma_M/3.5$.

The initial internal energy within each shell is roughly half of the final kinetic energy of the shell for mildly relativistic shocks (Tan et al. 2001), so we assume $E_0(\gamma) = \frac{1}{2} \gamma mc^2$. The internal energy $E$ decreases due to adiabatic expansion. Since $E = \gamma \varepsilon' V'$ and the comoving volume is $V' \propto r^2 r'/\gamma$, $E \propto \varepsilon' r^3$, where $\varepsilon'$ is the comoving energy density. As the energy density scales as $\varepsilon' \propto n^{4/3} \propto r^{-3}$, where $n$ is the comoving baryon number density, we have $E \propto r^{-1}$. Thus, at a given time $t$, the internal energy is

$$E(t) = E_0 \frac{R}{r} = \frac{1}{2} \frac{mcR}{\gamma \beta t},$$

where $R$ is the initial radius of the cocoon at which it breaks out of the merger ejecta. The value of $R$ is not well known. A breakout radius of $\sim 10^{40} – 10^{41}$ cm is estimated from the duration and lag of the prompt GRB (Gottlieb et al. 2017). Kasliwal et al. (2017) find a breakout radius of $\sim 3 \times 10^{41}$ cm in their numerical simulations of the DNS merger. The bolometric luminosity is roughly

$$L = \frac{E(t)}{t} = \frac{m_M c R}{2g \gamma_M^2 t_M^2} \left(\frac{t}{t_M}\right)^{-\frac{2}{\gamma_M}},$$

$$= 3 \times 10^{45} \text{erg s}^{-1} \gamma_{M,3.5}^{-3/2} \left(\frac{t}{t_M}\right)^{-\frac{2}{\gamma_M}}.$$  

The photosphere radius is

$$r_{ph} = \left(\frac{\kappa M}{4\pi}\right)^{1/2} = 9 \times 10^{12} \text{cm}^{1/2} E_{M,48.6}^{1/2} \gamma_{M,3.5}^{1/2} \left(\frac{t}{t_M}\right)^{1/2}.  \tag{12}$$

Then, we obtain the effective photosphere temperature

$$T_{eff} = \left(\frac{\gamma^2 L}{4\pi \sigma^4 r_{ph}^4}\right)^{1/4},$$

$$= 10^8 K R_{L,1}^{1/4} \gamma_{M,3.5}^{3/2} k_{i,1}^{1/2} E_{M,48.6}^{-1/4} \left(\frac{t}{t_M}\right)^{-1/2} \gamma_{M,3.5}^{1/2},  \tag{13}$$

where $\sigma$ is the Stephan–Boltzmann constant. Assuming a blackbody spectrum for the cooling emission, the observed luminosity at a given frequency $\nu$ is

$$L_{\nu} = \frac{8 \pi^2 h\nu^3}{c^2} \left(\frac{1}{\exp\left(\frac{h
u}{k T_{eff}}\right) - 1}\right) \left(\frac{v_{ph}}{D}\right)^2,$$  

where $D = 1/(\gamma \beta)$ is the Doppler factor (Gao et al. 2017). The cooling emission of relativistic matter lasts until the low velocity shell with $\gamma \beta = 1$ becomes transparent, which is

$$t_{rel} = t_M \left(\frac{\gamma \beta}{\gamma_M}\right)^{1/2} = 6 \times 10^3 s E_{M,48.6}^{-1/2} \gamma_{M,3.5}^{5/2} \kappa_{i,1}^{1/2} (\gamma \beta)^{-5},$$  

where we have taken $s = 6$ in the last step. Note that the lowest value of $\gamma \beta$ is not known, as the radio and X-ray flux are still rising up to the present. However, $\gamma \beta$ should be greater than 1, otherwise the energy in cocoon would be too large. After the time $t_{rel}$, macronova/kilonova emission from sub-relativistic material of the bulk merger ejecta becomes dominated. The bulk merger ejecta may also have some velocity gradient profiles, as has been suggested in Piro & Kollmeier (2017) and Waxman et al. (2017).

Using the above formulas, we calculate the light curves of the soft X-ray emission in the energy range of 0.5–4 keV and UV light curves in the range of 200–240 nm. The energy ranges are selected according to the future wide-angle X-ray and UV missions, respectively, such as Einstein Probe (EP) and...
Figure 1. Light curves of soft X-ray emission in 0.5–4 keV from the cooling of a cocoon, which has a velocity profile of \( E_\gamma (\gamma \beta) = 2 \times 10^{51} \text{erg} (\gamma \beta)^{-5} \) with a maximum Lorentz factor of \( \gamma_M = 3.5 \). The black dashed line represents the sensitivity curve of the Einstein Probe telescope for a source at the same distance of GW170817 (i.e., \( d = 40 \text{Mpc} \)). The black solid straight line represents the sensitivity curve of Swift/XRT for a source at \( d = 40 \text{Mpc} \). The start time of XRT observation is taken to be 45 s (the average slew time for XRT) after a possible BAT trigger (note, however, that GRB 170817A did not trigger Swift/BAT).

Figure 2. Light curves of the UV emission in the range of 200–240 nm from the cooling of the cocoon. The parameter values of the cocoon used in the calculation are the same as those used in Figure 1. Note that the cocoon emission lasts only until the lowest velocity shell with \( \gamma \beta > 1 \) becomes transparent. See Equation (15) in the text for the estimate of this time.

4. Summary and Discussions

We have suggested that soft X-ray to UV emission may be produced by cocoons in DNS mergers at very early times after the merger, arising from the cooling of the hot cocoon, similar to the cooling envelope emission in core-collapse supernovae. As cocoons have wide angles, these soft X-ray and UV transients also have wide angles and thus they have a much better chance to be detected than the jet emission. Such soft X-ray and UV transients, if detected, would serve as very early electromagnetic counterparts to the GW sources. As X-ray and UV detectors have much better localization ability than the \( \gamma \)-ray detectors, they could provide accurate spatial positions of GW events within minutes to hours. This will be important for further follow-up observations of the GW source.

We have assumed that the outflow powering the long-term radio and X-ray emission are relativistic with a maximum Lorentz factor of \( \gamma_M \gtrsim 3 \), consistent with the cocoon scenario. It has been pointed out that a semi-relativistic outflow with a maximum velocity of \( \beta_M = 0.8 \) (Mooley et al. 2017), arising from the dynamic ejecta of the DNS merger, can also explain the long-term radio and X-ray emission. In this case, we would not expect soft X-ray emission at early time because the effective photosphere temperature decreases as the maximum velocity decreases. However, we would still expect bright UV radiation from the cooling of this semi-relativistic ejecta on a timescale of hours after the merger.

The prompt emission of GRB 170817A has a main pulse, followed by a weak and soft component with a low signal-to-noise ratio (Goldstein et al. 2017; Lu et al. 2017; Zhang et al. 2017). The soft component has a luminosity of \( L_s = 10^{46} \text{erg s}^{-1} \) lasting for \( \approx 1.1 \text{s} \). The spectrum of this soft component can be fit by a blackbody with a temperature of \( kT = 10.3 \pm 1.5 \text{keV} \) (Goldstein et al. 2017; Zhang et al. 2017). It was suggested that this thermal component could be due to the photosphere emission from a cocoon (Goldstein et al. 2017). However, a straightforward calculation of the

ULTRASAT (Sagiv et al. 2014; Yuan et al. 2015). The mostly poorly known parameters in the calculation are the opacity \( \kappa \) and the breakout radius \( R \), thus we consider various combinations of these two parameters. The light curves of the soft X-ray emission are shown in Figure 1. To study the detectability of this emission, we also plot the sensitivity curve of the EP telescope in the figure. For a wide range of parameter spaces of \( \kappa \) and \( R \), the soft X-ray emission lasts at least tens of seconds above the sensitivity of the EP telescope if a similar event to GW170817 occurs in the future. As this emission lags only a few seconds behind the merger, this would represent the soft X-ray transient from the cooling cocoon could be detected by XRT.

The UV light curves for the same parameter values are shown in Figure 2. The flux shows a monotonic rise in time because the peak frequency of the blackbody spectrum is above the UV frequency range at such early time. The luminosity in the range of 200–240 nm at the peak is above \( 10^{42} \text{erg s}^{-1} \), even for the conservative parameter values. The UV emission from the cocoon could be detected to distances above \( \sim 1\text{Gpc} \) by ULTRASAT, considering that the limit magnitude of ULTRASAT is \( m = 21 \) (Sagiv et al. 2014). Such early UV emission could also be detected by Swift/UVOT, if UVOT slews quickly enough to the target. At later time, the UV emission will transit to the phase where the bulk ejecta of macronovae/kilonovae become dominated (Metzger 2017; Piro & Kollmeier 2017; Waxman et al. 2017; Yu & Dai 2017).
photosphere radius gives $r_{ph} = \gamma_c (L/4\pi c T^4)^{1/2} = 3 \times 10^8(\gamma_c/3)\text{cm}$, which is too small for a cocoon with a mildly relativistic Lorentz factor of $\gamma_c = 3$.

The spectrum of the soft X-ray emission in our case should be thermal in the absence of dissipation below the photosphere, which can be distinguished from non-thermal X-ray emission predicted in some models. For example, Zhang (2013) suggests that if the post-merger product of DNS is a highly magnetized, rapidly rotating neutron star, the dissipation of a proto-magnetar wind after the merger could produce non-thermal X-ray emission (see also Sun et al. 2017).

We thank Yunwei Yu, Zhuo Li, and Bing Zhang for valuable discussions. This work is supported by the 973 program under grant 2014CB845800 and the NSFC under grant 11625312.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, PhRvL, 119, 161101
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, ApJL, 848, L13
Alexander, K. D., Berger, E., Fong, W., et al. 2017, ApJL, 848, L21
Beniamini, P., Nava, L., Duran, R., & Piran, T. 2015, MNRAS, 454, 1073
Coulter, D. A., Foley, R. J., Kilpatrick, C. D., et al. 2017, Sci, doi:10.1126/science.aap9811
Drout, M. R., Piro, A. L., Shappee, B. J., et al. 2017, Sci, doi:10.1126/science.aap9049
Evans, P., Cenko, S., Kennea, J. A., et al. 2017, Sci, doi:10.1126/science.aap9580
Gao, H., Cao, Z., & Zhang, B. 2017, ApJL, 851, L45
Goldstein, A., Veres, P., Burns, E., et al. 2017, ApJL, 848, L17
Gottlieb, O., Nakar, E., & Piran, T. 2017, Hotokezaka, arXiv:1710.05896
Haggard, D., Ruan, J. J., Nynka, M., et al. 2017, GCN, 2220
Hallinan, G., Corsi, A., Mooley, K. P., et al. 2017, Sci, doi:10.1126/science.aap9585
Kasliwal, M. M., Nakar, E., Singer, L. P., et al. 2017, Sci, doi:10.1126/science.aap9455
Kisaka, S., Ioka, K., & Takami, H. 2015, ApJ, 802, 119
Kumar, P., & Piran, T. 2000, ApJ, 532, 286
Lazzati, D., Deich, A., Morsony, B. J., & Workman, J. C. 2017a, MNRAS, 471, 1652
Lazzati, D., López-Cámara, D., Cantiello, M., et al. 2017b, ApJL, 848, L6
Lu, R. J., et al. 2017, arXiv:1710.06979
Margutti, R., Berger, E., Fong, W., et al. 2017a, ApJL, 848, L20
Margutti, R., Fong, W., Effekhari, T., et al. 2017b, GCN, 22203
Matzner, C. D., & McKee, C. F. 1999, ApJ, 510, 379
Metzger, B. D. 2017, arXiv:1710.05931
Mooley, K. P., Nakar, E., Hotokezaka, K., et al. 2017, arXiv:1711.11573
Murguia-Berthier, A., Ramirez-Ruiz, E., Kilpatrick, C. D., et al. 2017, ApJL, 848, L34
Nagakura, H., Hotokezaka, K., Sekiguchi, Y., Shibata, M., & Ioka, K. 2014, ApJL, 784, L28
Nakar, E., & Piran, T. 2017, ApJ, 834, 28
Piro, A. L., & Kollmeier, J. A. 2017, arXiv:1710.05822
Pooley, D., Kumar, P., & Wheeler, J. C. 2017, arXiv:1712.03240
Rees, M. J., & Meszaros, P. 1998, ApJL, 496, L1
Sagiv, I., Gal-Yam, A., Ofek, E. O., et al. 2014, AJ, 147, 79
Sari, R., & Meszaros, P. 2000, ApJL, 535, L33
Sari, R., Piran, T., & Narayan, R. 1998, ApJL, 497, L17
Sun, H., Zhang, B., Gao, H., et al. 2017, ApJL, 835, 7
Tan, J. C., Matzner, D., & McKee, C. F. 2001, ApJL, 551, 946
Troja, E., Piro, L., Ryan, G., et al. 2017b, GCN, 22201
Wang, X. Y., He, H. N., Li, Z., Wu, X., & Dai, Z. G. 2010, ApJL, 712, 1232
Waxman, E., Ofek, E., Kushnir, D., & Gal-Yam, A. 2017, arXiv:1711.09638
Xiao, D., Liu, L. D., Dai, Z. G., & Wu, X. F. 2017, ApJL, 850, L41
Yu, Y. W., & Dai, Z. G. 2017, arXiv:1711.01898
Yuan, W., Zhang, C., Feng, H., et al. 2015, arXiv:1506.07735
Zhang, B. 2013, ApJL, 763, L22
Zhang, B.-B., Zhang, B., Sun, H., et al. 2017, arXiv:1710.05851