Possible electromagnetic precursors from double neutron star mergers and their application

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ABSTRACT

Double neutron star (NS) mergers are powerful sources of gravitational waves (GWs). Meanwhile, electromagnetic interactions between the magnetospheres of the two NSs should also generate electromagnetic (EM) radiation during the coalescence. We investigate the signatures of this EM radiation and find a substantial amount of magnetic energy may be transformed into keV photons through synchrotron radiation and a giant radio pulse through coherent curvature radiation. Further, we show how to use this gravitational wave-electromagnetic wave (GW-EW) association to constrain the speed of GWs. An optimistic estimation gives that the uncertainty of the speed of GW is \( \frac{\delta v_{GW}}{c} \sim 1 \times 10^{-18} \left( \frac{D_L}{100 \text{ Mpc}} \right)^{-1} \left( \frac{\delta t}{10 \text{ ms}} \right) \), where \( c \) is the speed of light, \( D_L \) is the luminosity distance from the source to the earth, and \( \delta t \) is the uncertainty of the difference in emission time between the GW signal and the EW signal.

Subject headings: binaries: close - stars: neutron stars: magnetic field - gravitational waves

1. Introduction

Gravitational wave-electromagnetic wave (GW-EW) association (e.g., GW 170817/GRB 170817A/kilonova AT2017gfo association; Coulter et al. 2017; Arcavi et al. 2017; Abbott et al. 2017a) provides a new way to gain insight into some physical problems. The complementarity of the information derived from the GWs and EWs from the same source shows a strong potential in solving some long-standing problems about the source itself (Hayama et al. 2016; Du et al. 2018). More importantly, this association can also be used to constrain some problems in fundamental physics, for example, the speed of GWs (Fan et al. 2017; Abbott et al. 2017a).

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But limited by the properties of the observed electromagnetic counterparts, the existing constraint of the speed of GWs is imperfect. By comparing the arrival times of GWs and gamma-ray photons from the double neutron star (NS) merger, the speed of GWs is constrained as (Abbott et al. 2017a)

\[-3 \times 10^{-15} \leq \frac{\Delta v_{\text{GW}}}{c} \leq +7 \times 10^{-16},\]

where \(\Delta v_{\text{GW}}\) is the difference between the speed of GWs and the speed of light. However, the intrinsic difference in emission time between GWs and gamma-ray photons is uncertain and depends on the unknown jet physics of gamma-ray bursts. Therefore, this constraint is model dependent.

Fan et al. (2017) propose a model-independent method to measure the speed of GWs, which is based on strongly lensed GWs and their electromagnetic (EM) counterparts. From the viewpoint of practical application, the strong gravitational lens usually needs to be fine-tuned (e.g., appropriate deflection angles of photons and gravitons).

As a supplement to the above two strategies, other electromagnetic counterparts of GWs need to be searched. According to the unipolar inductor model of close binaries (Piddington & Drake 1968; Goldreich & Lynden-Bell 1969), the motion of the weakly magnetized companion relative to the magnetic field of the strongly magnetized primary will induce an electromotive force, and thus EM radiation can be generated by the accelerated charged particles. Piro (2012), Lai (2012), and Wang et al. (2016) studied this EM radiation in detail under the scenario that a NS binary in the later period of inspiral.

On the other hand, for two stars that are close to each other, if their magnetic fields have different orientations, there should be also a EM radiation due to magnetic reconnection mechanism (Uchida 1986). Here, this close binary system is also characterized as the NS binary (also mentioned in Wang et al. 2018). We will show that the signatures of the EM radiation may be useful to measure the speed of GW. This paper is organized as follows. In section 2, we investigate the properties of the EM radiation in the late-time inspiral phase of the NS binary system according to the magnetic reconnection mechanism. In section 3, we show how to further constrain the speed of GWs by using these GW-EW associated events. In Section 4, we present a brief discussion.

2. EM Radiation due to Magnetic Field Reconnection

As shown in Fig. 1, the two NSs have opposite dipole magnetic fields. The orbital separation between the two NSs is \(a\). For simplicity, the radiiuses of the two NSs \(R_*\) and the
dipole magnetic field strength on the two NSs surfaces $B_*$ are both assumed to be similar. According to the mechanism of magnetic reconnection, when the two NSs carry the plasma located in their magnetospheres to close to each other (inflows, see the blue solid arrows), the collision between these two inflows in the dissipation region (yellow region) will lead to the disruption and reconnection of magnetic lines of force. At the same time, magnetic energy will translate into kinetic energy and thermal energy of the plasma.

The dissipation rate of magnetic energy $\dot{E}_B$ depends on the velocity of inflow $v_{in}$. But since the magnetosphere environment is uncertain, $v_{in}$ is an unknown parameter. Second best, if only for rough estimation, one can use the characteristic parameters of the NS binary system to estimate $\dot{E}_B$ through dimension analysis. Assuming a steady-state magnetic reconnection that magnetic flux dissipated in the dissipation region is balanced by the inflow, one simply has

$$\dot{E}_B \sim \frac{1}{2u_0} \left[ B_* \left( \frac{a}{2R_*} \right)^{-3} \right]^2 (\dot{a}R_*^2), \quad (2)$$

where $u_0$ is the permeability of vacuum, and $v_{in} \sim \dot{a}$ is adopted. The time evolution of $a$ is

$$a = 20 (1 - 1695t)^{1/4} \text{ km}, \quad (3)$$

where $a = 20$ km at $t = 0$ is set when the surfaces of the two NSs just touch with each other. Combining equations (2) and (3), one has

$$\dot{E}_B \sim 10^{44}(1 - 1695t)^{-9/4} \left( \frac{B_*}{10^{12} \text{ Gs}} \right)^2 \text{ erg} \cdot \text{s}^{-1}, \quad (4)$$

here $R_* = 10$ km is adopt[1].

The dissipation of magnetic energy will accelerate electrons (In this paper, electrons and positrons are not distinguished and are collectively referred to electrons.). The energy of electrons can be converted to EM radiation through, e.g., synchrotron radiation. The peak frequency of synchrotron radiation is

$$\nu_m \approx 1.3 \times 10^{18} \left( \frac{\Gamma}{10^2} \right)^2 \left( \frac{B}{10^8 \text{ Gs}} \right) \text{ Hz}, \quad (5)$$

where $\Gamma$ is the Lorentz factor of electrons, and $B$ is the magnetic field strength at the region where the electrons begin to radiate. Here, $\Gamma \sim 10^2$ and $B \sim 10^8$ Gs are adopted for estimates. The reasons are: 1) the acceleration of electrons is suppressed by synchrotron

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[1] This result is consistent with that of Wang et al. (2018), but we use a different method.
radiation, which makes $\Gamma$ not very high (see, e.g., Wang et al. 2016); 2) whether or not there is a residual magnetic field after the magnetic reconnection, small scale secondary magnetic fields on the NSs always exists, and hence $B$ should not be too small; 3) even though the electrons have higher lorentz factors that $\gamma$-ray emission can be produced, the cascade processes $e + B \rightarrow \gamma + B$ and $\gamma + B = e + e^+$ will convert $\gamma$-ray photons to keV photons. As a consequence, it is expected that a keV radiation can be emitted\(^2\). This keV radiation can be detected at (McWilliams & Levin 2011)

$$D_L \approx 120 \left( \frac{\eta E_B}{10^{43} \text{erg} \cdot \text{s}^{-1}} \right) \left( \frac{\Delta \Omega}{4 \times 10^4 \text{deg}^2} \right)^{-1/2} \text{Mpc},$$

where $\eta$ is the efficiency of the transformation of magnetic energy into keV radiation, and $\Delta \Omega$ is the beaming angle of the keV radiation.

In addition to synchrotron radiation, curvature radiation can also cool the electrons. The cooling timescale due to curvature radiation is

$$t_{\text{cur}} \approx 2 \times 10^8 \left( \frac{\rho}{10 \text{ km}} \right)^2 \left( \frac{\Gamma}{10^2} \right)^{-3} \text{s},$$

where $\rho$ is the curvature radius of magnetic lines of force. For comparison, the synchrotron-radiation lifetime of electrons is

$$t_{\text{syn}} \approx 5 \times 10^{-10} \left( \frac{\Gamma}{10^2} \right)^{-1} \left( \frac{B}{10^8 \text{ Gs}} \right)^{-2} \text{s}.$$  

It is clear that the cooling of electrons is dominated by the synchrotron radiation.

However, it is worth noting that there may be a giant radio pulse due to the curvature radiation. According to the Ruderman-Sutherland model (Ruderman & Sutherland 1975), the electrons with $\Gamma \sim 10^2 - 10^3$ will make contribution to the radio emission through the coherent curvature radiation in the region where the magnetic field lines are open (see Fig. 1). The location of the radio radiation is $\rho_c \sim 10^8 \text{ cm} - 10^9 \text{ cm}$ away from the NS surface. If the opening angle of the outflow satisfies $\theta > \rho_c/R_\ast > 10^{-3} \text{ rad}$, some of the accelerated electrons in the outflow will enter this region and generate radio emission. Following the

\(^2\)This conclusion seems somewhat arbitrary. As a corroboration, there are some signs indicate that magnetic reconnection under a similar environment can result in X-ray flares (Dai et al. 2006)
method of Totani (2013), the flux in observed frequency \( \nu_{\text{obs}} \) is

\[
F_\nu = \frac{1}{\nu_{\text{obs}}} \frac{\epsilon_r |\dot{E}|}{4\pi D_L^2}
\]

\[
\approx 0.2 \left( \frac{\epsilon_r}{10^{-3}} \right) \left( \frac{\nu_{\text{obs}}}{1.4 \, \text{GHz}} \right)^{-1} \left( \frac{D_L}{300 \, \text{Mpc}} \right)^{-2}
\]

\[
\times \left( \frac{\dot{E}_B}{10^{44} \, \text{erg} \cdot \text{s}^{-1}} \right) \, \text{Jy},
\]

where \( \epsilon_r \) is the efficiency of converting magnetic energy into radio radiation. So this pulse may also be detected at cosmological distance.

3. Constraining the speed of GW

To measure the speed of GWs, one needs to define the speed first. Under the Robertson-Walker metric

\[
ds^2 = -c^2 dt^2 + a(t)^2 \left( dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right),
\]

the definition of velocity with practical physical meaning is proper velocity \( v_p \). Taking the line of sight as the radial direction, there is

\[
v_p = \frac{a(t) dr}{dt}.
\]

For a photon, \( ds = 0 \), it is easy to verify that the speed of light is \( c \) under this definition. Since the co-moving coordinate of the GW-EW source \( r \) is an invariant, according to equation (11), the speed of GWs \( v_{\text{GW}} \) and the speed of light satisfy

\[
\int_{t_{e2}}^{t_{\text{mer}}} v_{\text{GW}} \frac{dt}{a(t)} = \int_{t_{e1}}^{t_{\text{tou}}} \frac{dt'}{a(t')}.
\]

where \( t_{e1} \) and \( t_{\text{tou}} \) is the emission time and arrival time of EWs, and \( t_{e2} \) and \( t_{\text{mer}} \) is the the emission time and arrival time of GWs, respectively. Equation (12) also can be rewritten as

\[
\int_{t_{e2}}^{t_{e1}} (...) + \int_{t_{\text{tou}}}^{t_{\text{mer}}} (...) = \int_{t_{e1}}^{t_{\text{tou}}} (c - v_{\text{GW}}) \frac{dt}{a(t)},
\]

where

\[
(...) \equiv v_{\text{GW}} \frac{dt}{a(t)}.
\]
Now the difficulty is that $t_{e1}$ and $t_{e2}$ are uncertain, as well as $\Delta t = t_{e2} - t_{e1}$. This is exactly the difficulty confronted the first strategy mentioned in the introduction. But in any case, according the unipolar inductor model and magnetic reconnection model, the EWs are emitted during the late-time inspiral phase of NS binary. Therefore, $\Delta t$ should be much smaller than the travel times of GWs and EWs ($t_{\text{mer}} - t_{e2}$ and $t_{\text{tou}} - t_{e1}$). On the other hand, the observation (Abbott et al. 2017a) shows that $t_{\text{mer}} - t_{\text{tou}}$ should be also a small quantity when compared to the travel times of GWs and EWs. Therefore, equation (13) is approximatively given by

$$\frac{v_{GW}}{1 + z_e}(t_{e1} - t_{e2}) + v_{GW}(t_{\text{mer}} - t_{\text{tou}}) = (c - v_{GW}) \int_0^{z_e} \frac{dz}{H(z)},$$

(15)

where $z_e$ is the redshift of the NS binary, and $H(z)$ is the Hubble parameter. Since co-moving distance is

$$D_c = c \int_0^{z_e} \frac{dz}{H(z)},$$

(16)

following from equation (13), one has

$$v_{GW} = \frac{c}{1 + \frac{c}{D_c} \left[ (t_{\text{mer}} - t_{\text{tou}}) - \frac{t_{e2} - t_{e1}}{1 + z_e} \right]} \approx c \left\{ 1 - \frac{c}{D_c} \left[ (t_{\text{mer}} - t_{\text{tou}}) - \frac{\Delta t}{1 + z_e} \right] \right\}.$$  

(17)

Assuming that the measurement error of arrival times is much less than the uncertainty of $\Delta t$ (i.e., $\delta t$ in equation (18)), according to equation (17), the uncertainty of the speed of GWs $\delta v_{GW}$ is

$$\frac{\delta v_{GW}}{c} = \frac{1}{c} \frac{\partial v_{GW}}{\partial \Delta t} \delta t = \frac{c}{D_c} \frac{\delta t}{1 + z_e}.$$  

(18)

It is clear that one should reduce the value of $\delta t$ to improve the measurement accuracy.

Note that when the surfaces of the two NSs contact, the gap between the two NSs disappears and the magnetic reconnection occurs in the two stars. The radiation of the accelerated electrons after this contact will be blocked by the dense star matter. And the electrons that were accelerated before the collision quickly lose energy due to the keV radiation (see equation (8)). Therefore, the luminosity of keV radiation will sharply decay, which will appear as a peak on the light curve. But the same cannot be true for the gravitational radiation, the luminosity of gravitational radiation will keep increasing until the ringdown
of merger remnant begins. From now on, we use the original $t_{e1}$ and $t_{e2}$ to represent the emission times of these two peak signals. Then $\Delta t = t_{e2} - t_{e1}$ is roughly the duration time of NS binary merger ($R_*/\dot{a}(t = 0) \sim 10$ ms). The uncertainty $\delta t$ should not be larger than the duration time of NS binary merger itself, i.e., $\max(\delta t) \sim O(10$ ms). Since these GW and EW signals can only be detected at low redshifts, i.e., $z_e < 1$, equation (18) finally can be reduced to

$$
\frac{\delta v_{GW}}{c} \sim 1 \times 10^{-18} \left( \frac{D_L}{100 \text{ Mpc}} \right)^{-1} \left( \frac{\delta t}{10 \text{ ms}} \right). \quad (19)
$$

4. Discussion

In this paper, we show the possible signatures of the EM precursors of NS binary mergers, and discussed their application in constraining the speed of GWs. Admittedly, there is somewhat arbitrary in the argument of the properties of the keV radiation. Here, our aim is to provide a possible strategy to measure the speed of GWs. The event rate of NS binary merger is $1540^{+3200}_{-1220}$ Gpc$^{-3}$yr$^{-1}$ (Abbott et al. 2017b). There are enough sources to test our method in the range of $\sim 100$ Mpc. In the future, space-GW detectors (e.g., LISA and Taiji (Stroer & Vecchio 2006; Wu 2012), and TianQin (Luo et al. 2016) ) are able to search for NS binary systems and provide early forecasts for EW detectors and high-frequency GW detectors, such that the follow-up observations can determine $t_{\text{tou}}$ and $t_{\text{mer}}$.

In addition, in the above argument, the measuring errors of $t_{\text{tou}}$ and $t_{\text{mer}}$ are assumed to be secondary. This is not always the case. If the luminosity is low and the sensitivity of the instruments is not high enough, the measurement is not necessarily accurate. But to say the least, there is always an opportunity to improve the technology to achieve higher time resolution. Furthermore, when $t_{\text{tou}}$ and $t_{\text{mer}}$ are measured accurately, there is another intriguing implication. Assuming that $v_{GW} = c$, one has $t_{\text{mer}} - t_{\text{tou}} = t_{e2} - t_{e1}$. The value of $t_{e2} - t_{e1}$ is only depend on the radiuses of the two NSs under tidal deformation, such that it may be useful to constrain the equation of state of NSs.

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Fig. 1.— A schematic diagram to the magnetic reconnection of NS binary system. Left panel: Carried by the inflows (blue solid arrows), the magnetic lines of force with opposite directions come into contact at X point. Right panel: Magnetic field lines break and reconnect in the dissipation region (yellow region), which then produces outflows (black solid arrows).