GW170817: A Neutron Star Merger in a Mass-Transferring Triple System

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ABSTRACT

The light curve of GW170817 is surprisingly blue and bright. Assuming that the event is a binary neutron star merger, we argue that blueness and brightness of the light curve is the result of ejecta that contains a substantial amount of thermal energy. To achieve this, the ejecta must be reheated at a substantial distance (1 to 2000 solar radii) from the merger to avoid losing the energy to adiabatic cooling. We show that this reheating can occur if the merger occurs in a hierarchical triple system where the outer star has evolved and filled its Roche lobe. The outer star feeds mass to the inner binary, forming a circumbinary disc, driving the inner binary to merge. Because the outer star fills its Roche lobe, a substantial fraction of the dynamical ejecta collides with the evolved star, reheating the ejecta in the process. We suggest that the process of mass transfer in hierarchical triples tends to form coplanar triple systems such as PSR J0337+1715, and may provide electromagnetic counterparts to binary black hole mergers.

Key words: gravitational waves — stars: neutron — radiative transfer — gamma-ray burst: short

1 INTRODUCTION

The recent detection of gravitational waves (GWs) from binary black hole mergers (Abbott et al. 2016a,b, 2017; The LIGO Scientific Collaboration et al. 2017a) was a triumph of GW astrophysics. However, the lack of detection in other wavebands did not allow the source to be well localized, due to the low spatial resolution of current GW detectors. The lack of an EM counterpart was not too surprising, as binary black holes in vacuum do not produce robust electromagnetic signals.

Binary neutron star (BNS) mergers or neutron-star black hole mergers can unbind significant amounts of matter and may be bright electromagnetically. Kilonova emission is one possible electromagnetic counterpart that may be detected by optical or near infrared observations (see for instance Smartt et al. 2016a; Abbott et al. 2016c; Kasliwal et al. 2016; Smartt et al. 2016b) though the area of sky that needs to be search following a GW detection is formidable ($\sim 1000$ deg$^2$)(see for instance Abbott et al. 2016c). The search area is reduced by an order of magnitude with three detectors (e.g. The LIGO Scientific Collaboration et al. 2017a,b).

Kilonova emission from a BNS merger may arise from two sources (for recent reviews, see Fernández & Metzger 2016 and Tanaka 2016). First, the dynamical ejecta of the merger would produced a peak luminosity of $10^{40} - 10^{41}$ ergs s$^{-1}$ a few days to a week after the initial merger. Due to the high opacities of the ejecta, the emission is expected to be mainly in the near infrared. (Kasen et al. 2013; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Tanaka et al. 2017; Fontes et al. 2017). Second, outflows from the merger disc from viscous heating, neutrino heating, and/or nuclear recombinations would produce high $Y_e$ outflows that are mainly Lanthanide-free (Fernández & Metzger 2013; Metzger & Fernández 2014; Martin et al. 2015; Tanaka et al. 2017). As a result of the substantially lowered opacity, the resulting light curve from these outflows would peak earlier (at about 1 day) and be bluer (Kasen et al. 2015; Metzger & Fernández 2014; Tanaka et al. 2017).

Up until recently, claims of kilonova detections have been associated with short gamma-ray bursts. These detections were at best a single detection in the near infrared (Tanvir et al. 2013; Berger et al. 2013; Jin et al. 2013; Yang et al. 2015; Jin et al. 2016). This situation changed with the GW detection of GW170817 which was detected in both LIGO and the Virgo detectors (The LIGO Scientific Collaboration et al. 2017b). The detection triggered a worldwide
follow-up campaign. The relative closeness of GW170817 of ≈ 40 Mpc and superior localization of three detectors allowed rapid EM follow-up of galaxies in the 31 square degree field (Kasliwal et al. 2017). A number of instruments around the world were able to track the lightcurve of the electromagnetic counterpart, GW170817, from its early detection in the near-UV and optical at 0.5 days to its rapid fade, and the transition of the peak intensity from the optical to the infrared (Kasliwal et al. 2017).

The early (0.5 d) emission of GW170817 was surprisingly bright (≈ 10^{32} ergs s^{-1}) and surprisingly blue, but rapidly faded to the infrared by day 2 (Kasliwal et al. 2017). The discovery paper modeled the light curve of GW170817 with a “concordant” cocoon breakout model that depends on a delayed jet colliding with the dynamical ejecta, thereby generating the later-time kilonova emission (Kasliwal et al. 2017). The delayed jet accelerates lower opacity (κ ∼ 1 cm^2 g^{-1}) material to velocities that causes it to peak early and is followed by slower (0.1c) higher opacity (κ ∼ 10 cm^2 g^{-1}) material that forms the bulk of the ejecta. This “concordant” model requires an ejecta mass of ≈ 0.05 M⊙, which is significantly higher than the maximum ejecta mass of 0.01 M⊙ predicted by state of the art numerical simulations of BNS mergers (see for instance Goriely et al. 2011; Hotokezaka et al. 2013; Dietrich et al. 2015).

In this Letter, we propose an alternative to the “concordant” model of Kasliwal et al. (2017). Here we argue that a combination of substantially preheated ejecta and kilonova emission explains the light curve of GW170817 in §2. In §3, we argue that for this preheated emission to be comparable to kilonova emission at about 0.5 days, the preheating must occur at a distance of between 1 - 2000 R⊙ from the initial merger. We then argue that this preheating may be a natural consequence if the BNS is in a hierarchical triple where the outer star evolves up the RGB or AGB phase and fills its Roche-lobe in §4. Mass loss from this outer giant creates a circumbinary disc around the BNS, driving it to merge. After merger, the dynamical ejecta collides with the star, with the resultant shock reheating the adiabatically cooled ejecta material. We close with a discussion in §5 where we speculate on the implications of this scenario for PSR J0337+1715 and electromagnetic counterparts of binary black hole mergers.

2 ANALYTIC LIGHT CURVES

We model the ejecta as a constant density expanding sphere. The expansion adiabatically cools the thermal energy, and does not affect the latent heat of radioactive decay. As a result, the thermal energy from the latter dominates at when the shell reaches large radii, where photons are able to readily escape. Radiation in an optically thin medium diffuses outward at an effective speed of v_{diff} = c/τ, where τ = κρR is the optical depth, κ is the opacity, ρ is the density, and R = vt is the radius of the sphere, and v is the expansion velocity. For a constant density sphere where ρ = M_{ej}/(4πR^2/3) and M_{ej} is the ejecta mass, the optical depth scales like

\[ τ \sim κρR \propto R^{-2} \propto v^{-2}t^{-2}. \]  

As a result, the bulk of the radiation is trapped at early times when τ ≫ 1 and c/τ ≪ v. At late times, when v_{diff} ≫ v, the radiation can escape. For radioactive heating that follows an exponential decay law, e.g., for supernovae, this gives a late time luminosity:

\[ L_{\text{late}} = \dot{q}M_{ej} = \dot{q}_0M_{ej}\exp\left(-\frac{t}{\tau}\right), \]  

where \( \dot{q} \) is the heating rate per unit mass and \( \tau \) is the decay timescale.

To derive the early time light curve, we consider t ≪ τ so that \( \dot{q} \approx \dot{q}_0 \) and τ(R) ≫ 1. As noted earlier, the bulk of the radiation is trapped, but radiation near the surface escapes. So radiation escapes from an optical depth of c/τ(ΔR) = v, which corresponds a physical depth of

\[ ΔR = \frac{c}{vκρ}. \]  

Radiation down to this depth can escape which gives a total luminosity of

\[ L_{\text{early}} = \dot{q}ΔM_{ej} = 4\pi R^2ρΔR\dot{q} \propto t^2. \]  

This t^2 power law has been used to fit the early rise of SN2011fe (Nugent et al. 2011). Here, we have assumed a constant density distribution and an uniform distribution of radioactive material. Deviations from these assumptions yield different power laws (Piro & Nakar 2013, 2014; Piro & Morozova 2016).

Finally, setting ΔR = R and \( \tau \approx vt \) in equation (3) gives the time of peak light:

\[ t_{\text{peak}} = \sqrt{\frac{\kappa M_{ej}}{\dot{q}_0}} = 5 \times 10^5 \frac{\sqrt{\kappa_1}}{\nu_1} M_{ej}^{1/2} v^{-1/2} t_1^{-1/2}, \]  

where \( M_{ej} = M_{ej}/10^{-2} M_⊙, \nu_1 = ν/0.1c \) and \( \kappa_1 = \kappa/1 \text{ cm}^2 \text{ g}^{-1} \).

For kilonova, a major difference is that the exponential decay law of equation (2) no longer holds, as there are a large number of different lanthanides with different radioactive decay timescales. Metzger et al. (2010) found that this gives a heating rate of

\[ \dot{q}_{kn} = \dot{q}_{kn,0}t_{td}^{-1.3}, \]  

where \( \dot{q}_{kn,0} = 2 \times 10^{10} \text{ ergs s}^{-1} \text{ g}^{-1} \) and \( t_{td} = t/1 \text{ day} \) (see also Wanajo et al. 2014; Hotokezaka et al. 2017; Tanaka et al. 2017). As a result of equation (6), equations (2) and (4) are modified and become

\[ L_{\text{kn,late}} = 4 \times 10^{11} M_{ej,-2}^{1.3} M_{td}^{-1} v^{-1} M_{\odot} \text{ ergs s}^{-1}, \]  

\[ L_{\text{kn,early}} = 2 \times 10^{11} \kappa_1 M_{td}^{-1} v^{-1} M_{\odot} \text{ ergs s}^{-1}. \]  

To smoothly join the early and late-time kilonova light curves, we assume a kilonova light curve of the form

\[ L_{\text{kn}} = \left( L_{\text{kn,early}} \right)^{-1/2} L_{\text{kn,late}}^{1/2} = L_0 \left( η_{\text{e}}^{-1} t_{td}^{-1.4} + t_{td}^{2.6} \right)^{-1/2}, \]  

where \( L_0 \) and \( η_{\text{e}} \) parameterize the uncertainties in \( \kappa, M_{ej}, \dot{q}, \) and \( v \). Here the peak in the light curve is given by dL/dt = 0 or \( t_{p} ≈ 0.7 η_{\text{e}}^{-1/2} \text{ days} \).

We now assume that the thermal energy of the ejecta is substantial. This is in contrast to supernova Ia where the early time shock heated light curve (Piro et al. 2010) is rapidly swamped by the rising radioactive nickel luminosity.
We begin with an estimate of the energy budget of the trapped radiation, then a lower limit on the radius at which preheating occurs is:

$$t_{\text{inj}} > \frac{E_{\text{Th}}}{E_{\text{km}}} t = 22 L_{42} \left( \frac{M_{\odot}}{10^{-2} M_{\odot}} \right)^{-1} v_{\text{ej}}^{-2} \left( \frac{1d}{0.5} \right) s,$$

(15)

which works out to be a distance of

$$R_{\text{inj}} > R_{\text{inj}}^*= v t_{\text{inj}} = 7 \times 10^{10} L_{42} \left( \frac{M_{\odot}}{10^{-2} M_{\odot}} \right)^{-1} v_{\text{ej}}^{-2} \text{ cm}.$$

(16)

The fact that any shock that produces the radiation visible at 0.5 days must occur on a scale greater than 1 solar radii eliminates any injection during the formation of the initial ejecta, i.e., from shocks during the merger process.

The observation of preheated material at 0.5 days sets an upper limit on the preheating radius of:

$$R_{\text{inj}} < R_{\text{inj}}^* = v t_{\text{inj}} = 1.3 \times 10^{14} v_{\text{ej}}^{-1} \left( \frac{1d}{0.5} \right) \text{ cm},$$

(17)

which is approximately 2000 solar radii.

There are a number of ways to reheat the ejecta at these radii. First, the ejecta can be reheat by a substantially delayed (in local dynamical times) jet (Gottlieb et al. 2017; Kasliwal et al. 2017). Second, the ejecta can collide with material around the merging neutron star. The mass of material required would be substantial, i.e., similar to the mass of ejecta itself, which precludes any sort of stellar outflow from a progenitor. However, we discuss another possibility, that the ejecta collides with a Roche filling third body which both provides a target, and a mechanism that produces the merging BNS.

### 4 GIANTS IN A TRIPLE SYSTEM

Red Giant Branch (RGB) and Asymptotic Giant Branch (AGB) stars have scales up to 1000 solar radii. If a BNS merger occurs in a triple system, then the ejecta from the merger would impact the third star, shock, and reinject thermal energy into the ejecta. The kinetic energy and momenta carried by the ejecta, as estimated above, are similar to those carried by supernova ejecta, although the mass of the ejecta in the latter case is much larger than in a neutron star merger. Three dimensional hydrodynamic simulations of the interaction between high velocity ejecta and stars, e.g., Liu et al. (2012), show that while the companion or target star, with mass $M_\ast$ and radius $R_\ast$, will survive, it will lose a significant amount of mass. The simulations agree with simple scaling models for the amount of mass loss (Colgate 1970; Wheeler et al. 1975). The energetics and timing of the optical emission seen in GW170817 require that some of the stripped and ablated material is accelerated to velocities comparable to that of the ejecta ($v_{ab} \sim 0.1c$). The ratio of the ablated mass that reaches $v_{ab}$ to initial mass of the companion star is $F_{\text{last}} = (\Sigma_{ej} / \Sigma_{ab}) (v_{ej} / v_{ab}) - 1$, where $\Sigma_{ej}$ is the surface density of the ejecta when it encounters the companion star, and $\Sigma_{ab}$ is the surface density of the material ablated from the companion that reaches $v_{ab}$.

The ejecta mass $m_{ej} \approx 0.01M_{\odot}$, so only the outer layers of the companion star, comprising a mass comparable to $m_{ej}$,
can be accelerated to $v_{ab}$. The corresponding initial dimensionless cylindrical radius (or impact parameter) $r_{ab} \equiv b/R_c$ of the high velocity ablated material is of order unity. Then the fraction of ablated mass is

$$F_{\text{fast}} \approx \frac{1}{4} \frac{M_2}{M_c} \frac{R^2}{a_{\text{fast}}^2}$$

where $a_{\text{triple}}$ is the separation between the center of mass of the binary and the companion star. We will argue that $a_{\text{triple}} \approx 2R_c$, so that $F_{\text{fast}} \approx 10^{-3}$.

How might a configuration of a merging BNS with a RGB or AGB star companion in such a tight orbit arise? The binary fraction of massive stars is large, i.e., of order 70% (see for instance Duchêne & Kraus 2013; Sana et al. 2012). Moreover, a substantial fraction of these stars are in triple or higher multiplicity systems. Hence it is likely that many BNS may have initially formed in a triple system, and there are a number of known neutron stars that are currently in triple systems, e.g., Thorsett et al. 1999; Ransom et al. 2014.

Hierarchical triple systems may be subject to secular effects such as the Kozai oscillation (Kozai 1962; Lidov 1962). However, the fraction of triples with the required high inclinations is small, so instead, let us consider the evolution of a third star around a BNS. As the star goes up the RGB or the AGB, it will fill its Roche lobe and begin to transfer mass to the BNS. For stars between 1-3 solar masses, this mass transfer is stable, as the donor is lower mass than the accreting BNS. For stars larger than ~ $M_{\odot}$, mass transfer is unstable and the system enters a common envelope phase, shrinking the orbit of the BNS and the third star.

For stable mass transfer, a circumbinary disc would form around the BNS. The rate at which angular momentum is transported through the disc is then

$$\dot{L} = \dot{M} \sqrt{GM_{\odot}d},$$

where $M$ is the mass accretion rate onto the disc, $M$ is the total mass of the BNS, $r_d \lesssim R_{\text{RGB}}$ is the size of the disc, and $R_{\text{RGB}}$ is the size of the RGB or AGB star, which is similar to the size of the disc assuming that the star fills its Roche lobe.

When the gas in the disc gets down to $r \approx 2a$, where $a \ll r_d$ is the semimajor axis of the BNS, the disc is truncated (Armitage & Natarajan 2002; MacFadyen & Milosavljević 2008; Chang et al. 2010) and the gas piles up at that radius. As a result the orbit of the BNS shrinks on a timescale given by

$$t_{\text{ins}} \approx \frac{M}{M_{\odot}} \frac{a}{r_d} = 3 \times 10^7 \left( \frac{M}{3 M_{\odot}} \right) M_{\odot} \left( \frac{a}{r_d} 10^{-2} \right)^{1/2} \text{yrs},$$

where $M_{\odot} = M/10^{-8} M_{\odot} \text{yr}^{-1}$. Another way to interpret this is that the total mass accreted, $M_{\text{acc}}$, to drive the BNS to merge is

$$M_{\text{acc}} M = \sqrt{\frac{a}{r_d}} = 0.1 \left( \frac{a}{r_d} 10^{-2} \right)^{1/2}.$$

In any case, the timescale to merger or amount of mass loss

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1 D’Orazio et al. (2013) (see also Farris et al. 2015) showed that accretion is not completely arrested, but is reduced by a factor of a few compared to a system without a central binary. Required to drive a BNS to merge is shorter than the lifetime of the RGB or AGB star or the total mass of the RGB or AGB envelope.

Typical RGB or AGB stars reach scales up to a few hundred solar radii, but spend a majority of their time at smaller radii. This would give a semimajor axis of the outer orbit $a_{\text{triple}} \approx 2R_c \sim 100 - 1000 R_{\odot}$. As it is Roche-filling, only 1/16 of the ejecta hits the star. We can also expect a dilution of the thermal energy of factor of about 10 when it is observed at 0.5 days at a radii of about 2000 $R_{\odot}$. Thus, we expect an upper limit for the preheated emission of $10^{-2}$ of the kinetic energy. Finally, while it may seem surprising that a hierarchical triple remains bound given the typically high natal kicks of young pulsars (~ 500 km s$^{-1}$), double NSs typically favor small kicks ($\lesssim 50 - 100$ km s$^{-1}$ Tauris et al. 2017).

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5 DISCUSSION AND CONCLUSIONS

In this Letter, we argue that appropriately preheated ejecta produces a rapidly falling light curve that is initially blue and bright. Combined with the radioactively heated material from a kilonova, we model the entire light curve of GW170817. We estimate the scale where this preheating occurs to be between 1 – 2000 $R_{\odot}$, which excludes any process during the BNS merger. We argue that a Roche filling RGB or AGB star at this scale is a plausible scenario. We also argue that mass loss from the RGB or AGB star would form a circumbinary disc that drives the system to merge in the first place. Therefore, Roche-lobe filling giants in a hierarchical triple may be an important channel for producing merging BNSs and modifying their lightcurves.

Such a triple system is reminiscent of PSR J0337+1715, a millisecond pulsar in a hierarchical triple system (Ransom et al. 2014). PSR J0337+1715 is a coplanar system, which we suggest may be the result of the outer star having filled its Roche lobe, producing a circumbinary disc that drove the inner binary to align with the outer orbital plane. In fact, Tauris & van den Heuvel (2014) argue at one point in the history of the system, the outer star overflowed its Roche lobe, transferring mass to the inner binary. However, Tauris & van den Heuvel (2014) do not comment on the possibility that this mass transfer could explain the coplanarity of the inner and outer orbits.

Circumbinary discs have been proposed in several contexts to produce binaries that are interesting from the viewpoint of GWs. For instance, they have been used to solve the “final parsec” problem for supermassive binary black hole (SMBBH) mergers (Armitage & Natarajan 2002; MacFadyen & Milosavljević 2008; Chang et al. 2010). More recently, they have been proposed to solve the “final AU” problem for merging stellar mass black holes (Stone et al. 2017). Stone et al. (2017) proposed that stellar mass binary black holes in AGN discs would develop circumbinary discs that would drive the pair to merge. Our proposed scenario would be an example of such a circumbinary disc that forms in the field, not in a gas rich environment like an AGN disc, and that produces an observable that is associated with the merger.

Finally, we comment on the circumbinary disk scenario for binary black hole mergers. The presence of a circumbi-
At this radius, the order of magnitude luminosity is $L \approx 3 \times 10^9 M_500^{0.2} H_1^{-0.8}$ cm$^{-2}$. (22)

where $H_1 = (h/r)/0.1$, $a_{\perp} = a/10^{-2}$, and $M_{500} = M/500 M_{\odot}$. At this radius, the order of magnitude luminosity is

$$L = \frac{\Delta M}{M} \frac{GM}{r} t_{\text{visc}}^{-1} \pi \Sigma^2$$

$$\approx 10^{39} M_500^{-2.2} H_1^{-1} \Sigma \left(\frac{\Delta M}{M} \left(\frac{\Sigma}{0.05}\right)\right) \text{ ergs s}^{-1}$$

(23)

where $t_{\text{visc}} = a_{\perp}^{-1} \sqrt{\Sigma / GM}$ is the thermal time of the disc and $\Sigma = 10^{25}$ g cm$^{-2}$ is the surface density of the disc. The effective temperature would be a few $10^9$ K.

For the second possibility, the luminosity would be approximately Eddington, $L \approx 7 \times 10^{39} M_{500}$ ergs s$^{-1}$, with a delay of the viscous time at decoupling, $t_{\text{visc,dec}} = \tau_{\text{disc}}(r = 2a_{\perp}) \approx 2M_{500}^{-2} H_1^{-1} r_{\text{dec}}$, which is about a day. The effective temperature of the emission would be akin to a X-ray binary accreting at Eddington, $T_{\text{eff}} \sim 3 \times 10^6 - 10^7$ K.

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