ELECTROMAGNETIC TRANSIENTS POWERED BY NUCLEAR DECAY IN THE TIDAL TAILS OF COALESCING COMPACT BINARIES

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Received 2011 April 21; accepted 2011 June 10; published 2011 July 1

ABSTRACT

We investigate the possibility that long tidal tails formed during compact object mergers may produce optical transients powered by the decay of freshly synthesized r-process material. Precise modeling of the merger dynamics allows for a realistic determination of the thermodynamic conditions in the ejected debris. We combine hydrodynamic and full nuclear network calculations to determine the resultant r-process abundances and the heating of the material by their decays. The subsequent homologous structure is mapped into a radiative transfer code to synthesize emergent model light curves and determine how their properties (variability and color evolution) depend on the mass ratio and orientation of the merging binary. The radiation emanating from the ejected debris, though less spectacular than a typical supernova, should be observable in transient surveys and we estimate the associated detection rates. We find that it is unlikely that photometry alone will be able to distinguish between different binary mass ratios and the nature of the compact objects, emphasizing the need for spectroscopic follow-up of these events. The case for (or against) compact object mergers as the progenitors of short gamma-ray bursts can be tested if such electromagnetic transients are detected (or not) in coincidence with some bursts, although they may be obscured by on-axis afterglows.

Key words: black hole physics – gamma-ray burst: general – hydrodynamics – nuclear reactions, nucleosynthesis, abundances – radiative transfer – stars: neutron

Online-only material: color figures

1. INTRODUCTION

Merging compact binaries are primary candidates for direct detection of gravitational waves (GWs) by LIGO (Abbott et al. 2008), and are thought to be the progenitors of short gamma-ray bursts (SGRBs; cf. Lee & Ramirez-Ruiz 2007; Rosswog 2007; Nakar 2007; Gehrels et al. 2009). Observational limits now indicate that any supernova-like event accompanying SGRBs would have to be over 50 times fainter than normal Type Ia or Type Ic supernovae (SNe; Hjorth et al. 2005; Bloom et al. 2006), strongly constraining progenitor models for SGRBs (Lee & Ramirez-Ruiz 2007; Perley et al. 2009; Kocevski et al. 2010). Unless SGRBs are eventually found to be accompanied by telltale optical signatures like the SNe of long-duration GRBs (Hjorth et al. 2003), the only definitive understanding of the progenitors will come from possible associations to direct gravitational or neutrino signals (Rosswog & Liebendörfer 2003).

Merging compact binaries may produce optical or other long-wavelength phenomena following coalescence. Neutron-rich material can be dynamically ejected during a NS–NS (neutron star) or a NS–BH (black hole) merger, as tidal torques violently remove energy and angular momentum through the outer Lagrange point in the form of a large tidal tail. Its subsequent decompression may synthesize radioactive elements through the r-process (Lattimer & Schramm 1976; Freiburghaus et al. 1999), whose radioactive decay could power an optical transient (Li & Paczyński 1998; Metzger et al. 2010b). For double NS binaries there are one or two such structures, depending on the mass ratio and equation of state (EoS) of the NSs (Oechslin et al. 2007). Only one tail (or no tail) is formed in a BH–NS merger. The tails grow to a few thousand kilometers in size by the end of the disruption event, and some fluid (∼0.01 $M_\odot$) may become gravitationally unbound.

The most efficient conversion of radioactive energy to radiation is provided by those isotopes with a decay timescale comparable to the radiative diffusion time through the ejecta. In reality, there are likely to be a large number of nuclides with a broad range of decay timescales (Li & Paczyński 1998; Metzger et al. 2010b). Current observational limits thus place interesting constraints on the nuclear evolution of this material, as well as the total mass ejected.

In this Letter, we present the results of multi-dimensional hydrodynamic simulations of NS mergers for various binary mass ratios. The ejected material is then post-processed with a full nuclear network and a radiation transport code. Our goal is to investigate how radioactive r-process elements synthesized in the tidal tails could power electromagnetic transients, and how their properties depend on the mass ratio of the merging binary. We also discuss prospects for detection and implications for SGRBs.

2. TIDAL TAIL EVOLUTION

2.1. Ejection

To calculate the ejected mass and structure of the tidal tails, we used a three-dimensional smoothed particle hydrodynamics (SPH) method (Lee & Ramirez-Ruiz 2007; Lee et al. 2010). A Lagrangian method like SPH is well suited to follow tidal disruption processes for which the geometry, densities, and timescales change violently (cf. Rasio & Shapiro 1994; Lee 2000; Rosswog et al. 2003). We used a hybrid EoS, which combined the cold Friedman–Pandharipande–Skyrme (FPS) nuclear EoS with an ideal thermal component as described
by Shibata et al. (2005). This more accurate treatment of the low-density EoS prevents the formation of hydrodynamic instabilities in the ejecta seen in previous studies (Lee & Ramirez-Ruiz 2007), but does not significantly alter the ejected mass. Once the fluid in the tidal tails became unbound, we stopped the SPH calculations and followed particles on ballistic trajectories in the potential of the central remnant until the expansion became homologous.

To explore the dependence on the physical parameters of the binary system, we considered four models: three NS–NS mergers with mass ratios \( q = M_2/M_1 = 1, 0.95, \) and 0.88 and one BH–NS merger with \( q = 0.31 \). Around 0.05 \( M_0 \) of material was ejected in all four models. Figure 1 shows the final density structures of the tails at homology, and Table 1 summarizes the relevant properties of the simulations. The thermodynamic trajectories of individual SPH particles did not vary significantly between the four models, but there are significant differences in the final ejecta geometry. The relative mass of the two tails depends on the mass ratio and the nature of the merging objects, as well as the underlying EoS (which has not been explored in this work). There is a clear progression from equal mass tails in the \( q = 1.0 \) case to almost no secondary tail in the \( q = 0.88 \) NS–NS case. It is of interest to determine if different tail geometries can be distinguished using optical observations, as this would constrain the nature of the system producing a GW signal.

2.2. Nuclear Evolution

We follow the evolution of the composition of the tails using a 6312 isotope nuclear reaction network which extends past uranium. Density histories of particles from the SPH simulations are employed. The charged particle and neutron capture rates in the network up to \( \text{At} = 85 \) are taken from Rauscher & Thielemann (2000). Past \( \text{At} \), the neutron capture rates of Panov et al. (2010) are used. The network terminates at \( Z = 102 \). We use experimental values of nuclear masses where available; otherwise, theoretical masses are taken from Möller et al. (2003). Neutron-induced fission rates are taken from Panov et al. (2010) and the simple approximation of Frankel & Metropolis (1947) is used to calculate spontaneous fission rates. Fission barriers are taken from Mamdouh et al. (2001). We use the empirical fits of Wahl (2002) for the fission fragment distributions.

The nuclear network is evolved in time using a variant of the XNet code (Hix & Thielemann 1999). We have implemented the PARDISO sparse matrix solver (Schenk et al. 2008), which makes calculations of large networks with implicitly coupled fission interactions feasible. The energy released by nuclear reactions is self-consistently added back to the material, similar to Freiburghaus et al. (1999).

The material ejected in the tails is initially near the surface of the NS, making it challenging to determine the initial electron fraction and entropy. Therefore, we assume the initial conditions to be \( Y_e = 0.2, \rho = 10^{11} \text{ g cm}^{-3}, \) and \( T_0 = 1 \). The initial composition is then determined by nuclear statistical equilibrium (NSE). This results in an initial distribution of nuclei near the \( N = 50 \) and 82 closed shells, with \( Z \approx 26 \) and 38, respectively, similar to that employed by Freiburghaus et al. (1999). As was pointed out by Goriely et al. (2005), if tidally ejected material is un-shocked, the initial temperature of the material is likely much less than \( T_0 = 1 \). To test the dependence,
we ran calculations varying the initial temperature down \(T_0 = 0.2\), and found that the nuclear heating rate was not substantially altered.

Figure 2 shows the total heating rate and final abundance distribution for a selection of fluid elements. Similar to Metzger et al. (2010b), we find that the late time heating rate is insensitive to the exact initial conditions and is statistical in nature, as predicted by Li & Paczyński (1998). One day after disruption, the top five beta-decays contributing to the heating are \(^{125}\)Sb, \(^{126}\)Sb, \(^{132}\)I, \(^{127}\)Te, and \(^{197}\)Pt.

### 2.3. Radiative Transfer

We calculated the optical emission of the mergers using the SEDONA three-dimensional time-dependent LTE Monte Carlo radiative transfer code (Kasen et al. 2006). The output of the hydrodynamic simulations at the time of homology was mapped onto a Cartesian grid for post-processing by the transport code. A global nuclear heating rate based on a fit to the nuclear network calculations was used. We accounted approximately for neutrino losses by assuming 75% of the nuclear network energy generation was deposited in the material (Metzger et al. 2010b). Of the energy that is left, we assumed 50% was deposited as gamma-rays from decays while the other 50% was deposited thermally.

The opacity of \(\nu\)-process material at the relevant densities and temperatures is not well known. The main contribution to the opacity is presumably due to millions of atomic lines, which are Doppler broadened by the high differential velocities in the ejecta. Unfortunately, complete atomic line lists for these high-

\(Z\) species are not available. Given the uncertainty, we adopted here a constant gray opacity of \(\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}\) which is characteristic of the line expansion opacity from iron group elements (e.g., Kasen & Woosley 2007). This is in contrast to the approach of Metzger et al. (2010b), who used oscillator strengths for pure Fe with ionization potentials from Pb. Considering that neither approach will yield accurate spectral information, we feel that our simple gray opacity scheme is a reasonable approximation.

We calculated the spatial distribution of gamma-ray heating by following the transport of gamma-rays and determining the fraction of their energy thermalized by Compton scattering and photoelectric absorption. Since the dominant Compton opacity has only a weak wavelength dependence, the exact spectrum of gamma-ray emission from the radioactive source does not strongly affect the results. We therefore simply assumed all gamma-rays were emitted at 1 MeV. We found that the gamma-ray thermalization rate was greater than 80% for the first two days after disruption.

### 3. Detailed Properties of the Electromagnetic Counterparts

The top panel of Figure 3 shows the \(R\)-band light curves for the four models in Table 1. As expected from the simple models of Li & Paczyński (1998), the peak luminosity correlates with the total ejected mass of radioactive elements and the time of the peak scales inversely with mass and velocity. Because the total mass ejected in these mergers is not very sensitive to \(q\), the nature of the merger cannot easily be determined solely from the peak time or luminosity. Additionally, the peak luminosity varies with viewing angle within a single model by a factor of \(\approx 3\), which is as large as the variation in the angle-averaged peak luminosity between models. This further complicates our ability to distinguish between different mass ratios and progenitor models based only on luminosities.\(^5\)

Still, it may be possible to determine if one or two tails are present based on the color evolution of the light curves. In NS–NS mergers which produce two tails, the luminosity of the transient will be given by the sum of the luminosities of the tails, each of which can be approximated as a Li & Paczyński (1998) expanding sphere. We denote here the heavier and lighter tails with the subscript 1 and 2, respectively. Li & Paczyński (1998) find that at late times, the evolution of the effective temperature is given by \(T_{\text{eff,1}} \approx 4.7 \times 10^3 \text{ K} (M/0.01 \text{ M}_\odot)^{1/4}(c/v)^3((\text{day}/t)^3/4(f/3 \times 10^{-7}))^{1/4}\). The ratio of the effective temperatures in the tails at late times is then

\[
\frac{T_{\text{eff,1}}}{T_{\text{eff,2}}} \approx \left( \frac{M_1}{M_2} \right)^{1/4} \left( \frac{v_2}{v_1} \right)^{3/4}.
\]

Significant variation in color from the single tail case is then expected only for a considerable difference between velocities. In this case, tail 2 will shift the total light blueward if it makes an important contribution to the total luminosity at any time. The time of peak luminosity for a single tail is given by \(t_{\text{eq}} \approx 1 \text{ day} (M/0.01 \text{ M}_\odot)^{1/2}(3v/c)^{1/2}\). If the velocity of the second tail is much lower, it contributes more to the total luminosity at late times and the light will be bluer compared to the more massive tail emitting radiation alone.

In our detailed models, the velocity difference between the tails is not significant enough compared to the mass difference between the tails in either of the asymmetric NS–NS merger models for the tails to be easily discernible in their color evolution, as shown in Figure 3. There is thus no significant distinguishing characteristic between ejecta geometries in their

\(^5\) We also do not observe the non-smooth structures seen in the light curves of Metzger et al. (2010b), which are due to their use of approximate non-gray opacities.
colors. All four models show similar reddening as a function of time. Without knowing the detailed line opacity of the $r$-process elements, it is difficult to predict the spectroscopic signatures of NS mergers. We expect that high-$Z$ atoms will have a very large number of lines in the optical, perhaps exceeding the large number known for the iron group elements. Because the ejecta velocities in the tidal tails are a factor of $\sim$2–3, larger than ordinary SNe, the absorption features in the photospheric phase ($\lesssim$15 days) should be very broad. The likely outcome is a blending together of the lines into a relatively featureless continuum, not unlike the early time observations of broad line Type Ic SNe (cf. Galama et al. 1998).

More detailed information about the ejecta geometry could be inferred from spectroscopic observations taken at late times ($\gtrsim$15 days) when the ejecta has entered the nebular phase and emission features begin to appear. Assuming relatively unblended lines (or line complexes) are present at these epochs, the spectral features should show double-peaked emission profiles, at least for equatorial viewing angles. The relative strength of the peaks could be used to estimate the relative masses of the two tails.

In brief, the inclusion of realistic ejecta geometries does not significantly alter the predictions made by simple spherical “tail” models which include realistic nuclear physics. This can be attributed to the fact that the ejecta does not deviate strongly from a spherical geometry, the relative masses and velocities of the two tails do not induce significant differences in the peak temperatures of the two tails, and we have assumed a gray opacity. Therefore, we have shown that the main uncertainties do not involve the structure of the ejecta, but rather the total ejected mass, its velocity structure, and the opacity of pure $r$-process material. The ejected mass and velocity are dependent on the nuclear EoS (Lee 2000; Oechslin et al. 2007) and the treatment of gravity (Rosswog 2005), both of which we have not studied in detail here. Also, heating from $r$-process nucleosynthesis may affect the dynamics of the material and the total ejected mass (Metzger et al. 2010a). The opacity of pure $r$-process material is unknown at these low densities, so its relevance cannot be accurately assessed at this time.

4. IMPLICATIONS FOR SGRBs, GW OBSERVATIONS, $r$-PROCESS

If compact object mergers are indeed the progenitors of SGRBs, these optical transients could possibly be seen alongside their more spectacular prompt gamma-ray display. In the second panel of Figure 3, we compare our synthetic optical light curves to optical afterglow observations and upper limits of SGRBs taken from Berger (2010). Clearly, the optical observations are all for on-axis SGRBs. We also show two synthetic on-axis SGRB optical afterglow light curves taken from van Eerten & MacFadyen (2011), and for comparison, the light curves of two standard SNe. It seems that the optical observations can be reasonably explained by afterglow models, but, interestingly, they also do not rule out the possible contribution of an $r$-process-powered SN. It is also expected that in a sizeable fraction of events, these $r$-process-powered SNe may dominate the optical light at timescales of a day.

The current and next generation of wide-field surveys (such as Palomar Transient Factory (PTF), The Synoptic All Sky InfraRed Survey (SASIR), The Panoramic Survey Telescope and Rapid Response System (Pan STARRS), and The Large Synoptic Survey Telescope (LSST)) will be sensitive to very subtle changes in flux on timescales of more than a few days. In Table 2, we show the detection rates expected for three transient surveys given the low, recommended, and high merger rates in Abadie et al. (2010), calculated assuming a cosmology given by Komatsu et al. (2009) and a constant merger rate per volume. The rates are corrected for the effects of a finite cadence. For the PTF and Pan STARRS, the detection rate is significantly lower than that expected for advanced LIGO.
whereas the inverse is true for SASIR and LSST. This suggests that the electromagnetic counterparts of compact object mergers may be more readily detectable than the associated gravity waves, which could help focus GW searches and better constrain merger rates.\footnote{We note that even if all compact mergers are associated with SGRBs, the $r$-process-powered SNe will still dominate the off-axis optical afterglow.} Additionally, we find that LSST will potentially be able to detect these events out to $z > 0.3$, giving a handle on the evolution of the merger rate with cosmic time.

It is clear from this and previous work (Freiburghaus et al. 1999; Goriely et al. 2005) that large amounts of $r$-process material will be ejected in these events, which may contribute significantly to the total $r$-process budget of the galaxy. There may be problems, however, explaining the low metallicity halo $r$-process abundance data within this scenario (Argast et al. 2004). Because the production of $r$-process elements is robust in the tails (i.e., the production of material with $A > 120$ is insensitive to the initial conditions of the material), the major uncertainty in this model lies in the amount of mass material will be ejected in these events, which may contribute significantly to the total $r$-process budget of the galaxy. There may be problems, however, explaining the low metallicity halo $r$-process abundance data within this scenario (Argast et al. 2004). Because the production of $r$-process elements is robust in the tails (i.e., the production of material with $A > 120$ is insensitive to the initial conditions of the material), the major uncertainty in this model lies in the amount of mass ejected and how this material is spread throughout individual galaxies (Zemp et al. 2009; Kelley et al. 2010). Given these considerations, it seems likely that observations, or lack thereof, of the transients produced in these mergers will give significant insight into the evolution of $r$-process material in the universe.

Useful discussions with C. Fryer and S. Woosley are gratefully acknowledged. L.R. thanks Raph Hix for allowing us to use his nuclear network code and for many useful discussions concerning its use. We acknowledge support from an NNSA/DOE Stewardship Science Graduate Fellowship (L.R.) (DE-FC52-08NA28752), the University of California Office of the President (L.R.) (09-IR-07-117968-WOOS), the DOE SciDAC Program (D.K.) (DE-FC02-06ER41438), CONACYT (W.H.L.) (83254, 101958), and the David and Lucille Packard Foundation (E.R.-R.) (2004). Because the production of $r$-process-powered SNe will still dominate the off-axis optical afterglow.

### Table 2

Detection Rates for Various Blind Transient Searches

| Model  | PTF | Pan STARRS | LSST | SASIR |
|--------|-----|------------|------|-------|
|        | $R_{\text{low}}$ | $R_{\text{ce}}$ | $R_{\text{high}}$ | $R_{\text{low}}$ | $R_{\text{ce}}$ | $R_{\text{high}}$ | $R_{\text{low}}$ | $R_{\text{ce}}$ | $R_{\text{high}}$ |
| NS–NS  | 0.1 | 10 | 100 | $1.3 \times 10^{-3}$ | 0.13 | 1.3 | $2.3 \times 10^{3}$ | $2.3 \times 10^{3}$ | $2.3 \times 10^{4}$ | 1.2 | 1.2 | $10^{3}$ |
| BH–NS  | $7.3 \times 10^{-3}$ | 0.36 | 12 | $8.4 \times 10^{-5}$ | $4.2 \times 10^{-3}$ | 0.14 | 1.6 | 79 | $2.6 \times 10^{3}$ | 0.083 | 4.1 | 140 |

Notes. Properties of the surveys are assumed to be the same as those given in Strubbe & Quataert (2009). All rates are in detections per year.