EFFECT OF A HIGH OPACITY ON THE LIGHT CURVES OF RADIOACTIVELY POWERED TRANSIENTS FROM COMPACT OBJECT MERGERS

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ABSTRACT

The coalescence of compact objects is a promising astrophysical source of detectable gravitational wave signals. The ejection of \( r \)-process material from such mergers may lead to a radioactively powered electromagnetic counterpart signal which, if discovered, would enhance the science returns. As very little is known about the optical properties of heavy \( r \)-process elements, previous light-curve models have adopted opacities similar to those of iron group elements. Here we consider the effect of heavier elements, particularly the lanthanides, which increase the ejecta opacity by several orders of magnitude. We include these higher opacities in time-dependent, multi-wavelength radiative transport calculations to predict the broadband light curves of one-dimensional models over a range of parameters (ejecta masses \( \sim \) \( 10^{-3} \)–\( 10^{-1} M_\odot \)) and velocities \( \sim \) \( 0.1 \)–\( 0.3 c \)). We find that the higher opacities lead to much longer duration light curves which can last a week or more. The emission is shifted toward the infrared bands due to strong optical line blanketing, and the colors at later times are representative of a blackbody near the recombination temperature of the lanthanides (\( T \sim 2500 \) K). We further consider the case in which a second mass outflow, composed of \( ^{56}\text{Ni} \), is ejected from a disk wind, and show that the net result is a distinctive two component spectral energy distribution, with a bright optical peak due to \( ^{56}\text{Ni} \) and an infrared peak due to \( r \)-process ejecta. We briefly consider the prospects for detection and identification of these transients.

Key words: atomic data – nuclear reactions, nucleosynthesis, abundances – opacity – radiative transfer – stars: neutron – supernovae: general

Online-only material: color figures

1. INTRODUCTION

A deeper understanding of compact object binary mergers has the potential to shed light on several important and unresolved questions in astrophysics. Binary neutron star mergers (NSMs) may be the central engines of short-duration gamma-ray bursts (Paczynski 1986; Narayan et al. 1992), and heavy-element nucleosynthesis in merger ejecta undergoing decompression from nuclear densities (Lattimer & Schramm 1974, 1976) may contribute to the production of \( r \)-process elements in the universe (e.g., Eichler et al. 1989; Rosswog et al. 1998, 2000; Freiburghaus et al. 1999; Rosswog 2005; Goriely et al. 2005). With the LIGO (Abramovici et al. 1992) and VIRGO experiments preparing to upgrade to advanced status, compact object mergers provide the most likely source of kHz gravitational waves (GWs). The science returns from detected GW signals can be enhanced by the identification of a coincident electromagnetic signature (e.g., Schutz 1986, 2002; Stubbs 2008; Bloom et al. 2009).

There are several possible Electromagnetic (EM) transients associated with NSMs, including short-duration gamma-ray bursts, orphan radio and optical afterglows, and optical “kilonova” light curves (Nissanke et al. 2013; Metzger & Berger 2012). The kilonovae are optical transients powered by the radioactive decay of material ejected in the merger. Simulations suggest that somewhere in the range of \( 10^{-3} \)–\( 10^{-1} M_\odot \) may be ejected either by tidal stripping during the merger itself or later by a disk wind driven in the evolution of a post-merger remnant. The tidally ejected material is very neutron-rich and should form heavy elements via the \( r \)-process, while the subsequent outflows could be less neutron-rich, in which case nucleosynthesis may not extend much beyond the iron peak. In either case, the brightness of the resulting light curves will be set by the mass of radioisotopes ejected, while the duration depends on the effective diffusion time through the ejecta, and hence on mass, velocities, and opacities. While the nucleosynthesis and radioactive heating have been modeled with a fair degree of detail (Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011), the unknown opacities of \( r \)-process elements remain a major challenge to predicting kilonova light curves and spectra. Li & Paczyński (1998) were the first to study the \( r \)-process transients from NSM. Their simplified one-zone model assumed spherical symmetry and a blackbody spectrum and absorbed much of the physical complexity of the system into a set of input parameters. Assuming opacities on the order of the electron scattering opacity, they predicted that the light curves would peak in the optical/ultraviolet and rise to peak bolometric luminosities of \( \sim 10^{35} - 10^{36} \) erg s\(^{-1}\) on a timescale of a day. More recent, more detailed models (Metzger et al. 2010; Roberts et al. 2011) have used nuclear reaction networks to determine the radioactive heating rate and Monte Carlo radiation transport to calculate merger light curves, under the assumption that the opacities of heavy \( r \)-process elements could be approximated by those of iron. These newer models found qualitatively similar results, with peak bolometric luminosities \( \sim 10^{41} - 10^{42.5} \) erg s\(^{-1}\) and rise times around 1 day, with the colors rapidly reddening post-peak.

In this paper, we show that using more realistic opacities of \( r \)-process material has a dramatic effect on the predicted kilonova light curves. We use improved estimates of the atomic data and opacities of heavy elements derived from ab initio atomic structure models (Kasen et al. 2013, hereafter K13). The \( r \)-process opacities are orders of magnitude higher than those of iron group elements; as a consequence, we predict
light curves that are longer, dimmer, and redder than previously thought. Rather than peaking sharply at \( t \approx 1 \) day, the duration of the bolometric light curves can last \( \sim 1 \) week. The spectral energy distribution (SED) is highly suppressed in the optical, with the bulk of the energy emitted in the infrared. Such findings can inform observational searches for an EM counterpart to a GW trigger by clarifying the transient timescales, the bands in which EM emission will be strongest (or have the most distinct signature), and the distances out to which we might expect a successful EM detection.

2. OPACITY OF \( r \)-PROCESS EJECTA

Supernova (SN) calculations suggest that at blue wavelengths bound–bound transitions from complex iron group elements dominate other forms of opacity, such as electron scattering, free–free, and photoionization (see, e.g., Pinto & Eastman 2000). Literally millions of lines, Doppler-broadened by the remnant’s differential velocities, contribute to a pseudo-continuum bound–bound opacity. Photons traveling through the ejecta are continually Doppler-shifted with respect to the co-moving frame, and come into resonance with multiple transitions one by one. The velocity gradient of the remnant thus enhances the effective line opacity, an idea introduced by Karp et al. (1977) and further developed in subsequent studies (Friend & Castor 1983; Eastman & Pinto 1993; Hoeftlich et al. 1993).

We use here the formalism given by Eastman & Pinto (1993) where the extinction coefficient is given by

\[
\alpha_{\exp}(\lambda_c) = \frac{1}{c t_{\exp}} \sum_i \frac{\lambda_i}{\Delta \lambda_c} (1 - e^{-\tau_i}).
\]

This formula represents an average over discrete wavelength bins, where \( t_{\exp} \) is the time since mass ejection, \( \lambda_c \) is the central wavelength of the bin, \( \Delta \lambda_c \) is the bin width, \( \tau_i \) is the Sobolev optical depth of a line (Sobolev 1960), and the sum runs over all lines in the bin. The extinction coefficient is related to the expansion opacity by \( \kappa_{\exp} = \alpha_{\exp}/\rho \), where \( \rho \) is the gas density. In applying the Sobolev formalism, we make two important assumptions: first, that the intrinsic (Doppler) width of lines is small compared to the velocity scale over which the ejecta properties vary, and second, that the intrinsic profiles of strong lines do not overlap with other lines. While the first condition is easily satisfied in rapidly expanding NSM ejecta, the second may not be (see K13), and a non-Sobolev treatment may ultimately be necessary for a fully rigorous treatment of the radiation transport.

To calculate Sobolev line optical depths, we assume that the atomic level populations are set by local thermodynamic equilibrium (LTE). This approximation should be reasonable in the optically thick regions of ejecta, where the radiation field tends toward a blackbody distribution. Baron et al. (1996), for example, show that in Type Ia SN models the atomic level populations acquire their LTE values near and below the SN photosphere. Jack et al. (2011) have quantified the impact of non-LTE (NLTE) effects on the theoretical light curves of Type Ia SNe in the \( \sim \)month following explosion. They find moderate \((\lesssim 30\%)\) differences in the broadband fluxes in the optical \( U, B, V, \) and \( R \) bands (wavelengths for which the ejecta is optically thick) and larger effects \((\sim 50\%)\) in the longer wavelength \( I \) band (at which the ejecta becomes transparent). While the density of NSM ejecta is lower than that of ordinary SNe, the opacity is much higher in both the optical and the infrared; we therefore expect that errors in our predicted fluxes due to NLTE effects will be at similarly moderate levels, at least during the optically thick phases that we focus on here (i.e., before and just after the light-curve peak). Such errors, while deserving of further study, are likely less significant than the uncertainties related to the atomic line data and ejecta model geometry. At later times \((\sim 1 \) week after peak), when the remnant becomes optically thin, LTE breaks down completely and our predicted colors become unreliable.

The expansion opacity takes a simplified form in atmospheres where most lines are extremely optically thick \((\tau \gg 1)\). As \( \tau \) increases, the dependence of \( \kappa_{\exp} \) on optical depth is eliminated \((1 - e^{-\tau_i} \approx 1)\), and the expression for expansion opacity simplifies to a sum of optically thick lines. The dependence on density and other determinants of optical depth are concomitantly reduced. Under these conditions, the number of distinct optically thick lines in each bin becomes the most important predictor of ejecta opacity. An exhaustive tally of lines is therefore essential to accurately modeling ejecta opacity. Unfortunately, there are relatively few line data available for the heavy elements \((Z > 28)\) expected to be synthesized in NSM ejecta. We compiled the line data calculated by the Mons group (Biémont et al. 1999; Palmeri et al. 2000; Quinet & Biémont 2004) and included in the VALD database (Heiter et al. 2008), which includes moderately extensive data for a couple heavy ions (e.g., \( \text{Ce}^{2+}, \text{Ce}^{3+} \)), but very little for most other species.

On theoretical grounds, we expect the lanthanides (atomic numbers \( Z = 58–72 \)) to contribute significantly to ejecta opacity, due to the complicated structure of their valence \( f \) shells. This argument is illustrated with a simple combinatorics heuristic. The number of substates corresponding to a given electron orbital is roughly

\[
C = \frac{g!}{n!(g-n)!} \quad \text{with } g = 2(2l+1),
\]

where \( n \) is the number of valence electrons and \( l \) is the angular momentum quantum number of the valence shell. The number of lines should scale as \( C^2 \), and will be much greater for ions with electrons in an open \( f \) \((l = 3)\) shell. Assuming lines from the two species are equally likely to be optically thick, we expect atmospheres containing lanthanides to have a much higher opacity than atmospheres of pure iron. A similar argument could be applied to elements of the actinide series, which may also be produced in the merger ejecta. However, the mass fractions of most actinides are predicted to be low, and can likely be ignored.

Our calculations of opacities using line data from VALD demonstrate that the lanthanides have a much higher expansion opacity than iron (see Figure 1). However, the limited line data available in the VALD database are inadequate for calculating \( r \)-process opacities over the wavelength and temperature range needed for a realistic transport calculation. For example, VALD includes virtually no line data for ionization states greater than doubly ionized. Thus, at early times (one or two days after the merger) when the ejecta is rather hot and highly ionized, the VALD data severely underestimate the opacity and result in unrealistic light curves and colors. A more serious and persistent issue is that VALD contains almost no lines with wavelengths greater than \( 1 \) \( \mu \)m and so cannot be used at any epoch to calculate a sensible infrared opacity or emissivity (see Figure 1). We will find that most of the emission from NSMs is in fact radiated at wavelengths \( \gtrsim 1 \) \( \mu \)m, which means that more extensive infrared line data are needed to reliably predict the broadband light curves and colors.
Given the limitations of the VALD line data, we instead use the theoretical lanthanide line data of K13 derived from the atomic structure modeling code Autostructure (Badnell 2011). This supplies approximate radiative data for neodymium (Z = 60) and a few other elements over the entire wavelength range of interest (~100–10000 Å). We tested the reliability of the Autostructure data by comparing predicted expansion opacities of select species, including Fe and Ce, to those calculated using existing line data for a few heavy elements. The boosted r-process opacity takes into account the diversity of species in an r-process mixture by assuming that all lanthanides have an opacity comparable to Nd.

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

Figure 1. Wavelength-dependent expansion opacities for ejecta with $\rho = 10^{-13}$ g cm$^{-3}$, $T = 5000$ K, and $t_{\text{exp}} = 1$ day. The opacity of iron is calculated using both the VALD and Autostructure linelists to demonstrate the reliability of the latter approach. The r-process opacity calculated using Autostructure data for Nd is in fairly good agreement with that using the VALD linelist (which only includes extensive line data for a few heavy elements). The boosted r-process opacity takes into account the diversity of species in an r-process mixture by assuming that all lanthanides have an opacity comparable to Nd.

The remainder of the composition is taken to be calcium, which serves as a low-opacity filler with an appropriate ionization potential.

Since each ion species in the ejecta has a unique set of strong lines, and since $k_{\text{exp}}$ increases with the number of strong lines, mixtures with a greater diversity of elements will have higher opacity. Since both Nd and Fe have intermediate complexity for their respective blocks, their opacities can presumably be taken as representative of other elements in the same region of the periodic table. We therefore assume that each lanthanide or d-block element in the original compositions provides an opacity equal to that of Nd or Fe, respectively, and arrive at a generalized expression for the extinction coefficient

$$a_{\text{exp}} = \frac{1}{c_{\text{exp}}} \sum_{Z} N_{Z} \sum_{i} \frac{\lambda_{i}}{\Delta \lambda_{i}} (1 - e^{-\tau_{i}}),$$

where $Z$ runs over the representative elements (here Fe and Nd), $N_{Z}$ is the number of elements in the block represented by $Z$, and $\rho_{Z} = \chi_{Z} \rho_{r}$, with $\chi_{Z}$ the mean mass fraction of the representative elements. Since lanthanide contributions dominate the opacity, the boosting procedure effectively increases the opacity by a factor of $14$, the number of lanthanide species.

Figure 1 shows the expansion opacity calculated for typical parameters of NSM ejecta ($\rho = 10^{-13}$ g cm$^{-3}$, $T = 5 \times 10^{3}$ K, and $t_{\text{exp}} = 1$ day). The values vary with temperature and density, but in general our calculations indicate r-process opacities many orders of magnitude higher than those calculated for iron group elements. The r-process elements also have a greater density of strong lines at long wavelengths; thus, the bound–bound opacity in NSM ejecta remains relatively high even in the infrared and provides the dominate source of opacity over the relevant range of the electromagnetic spectrum.

3. LIGHT CURVES OF R-PROCESS TRANSIENTS

The surprisingly high opacity of r-process material, discussed in Section 2, has important implications for the EM emission from NSMs. In this section, we present radiation transport calculations using our refined opacity estimates to determine the bolometric and broadband light curves of r-process outflows. Our predictions diverge from those of earlier studies, which assumed that the opacities were similar to those of iron.

3.1. Ejecta Model

We model the NSM ejecta as a spherically symmetric outflow undergoing homologous expansion. In reality, the ejecta may have a highly asymmetric, “tidal tail” geometry (Rosswog 2005). Three-dimensional transport calculations suggest that this asphericity makes the emission moderately anisotropic but does not qualitatively change the shape of the light curves (Roberts et al. 2011). We describe the density of the ejecta using the broken power-law profile introduced by Chevalier & Soker (1989), in which density decreases as $r^{-2}$ in the inner layers of the atmosphere and as $r^{-n}$ (with $n > 3$) in the outer layers. The shift from $n$ to $\delta$ occurs at the transition velocity

$$v_{t} = 7.1 \times 10^{3} \xi_{v} (E_{51}/M)^{1/2} \text{ cm s}^{-1},$$

where $E_{51}$ is the explosion energy $E/10^{51}$ erg, $M$ is the ejecta mass $M_{\odot}$ in units of $M_{\odot}$, and $\xi_{v}$ is a numerical constant. For $v < v_{t}$, the density is given by

$$\rho(r, t) = \xi_{\rho} \frac{M_{\odot}}{v_{t}^{3}} \left( \frac{r}{v_{t} t} \right)^{-\delta},$$

and an analogous expression describes the outer layers. The constants $\xi_{v}$ and $\xi_{\rho}$ satisfy the requirement that the density profile integrates to the specified mass and energy. We also tried using an exponentially decreasing density profile, but found that the light curves were mostly insensitive to the details of the density structure. The results presented here were generated using the broken power-law profile with $(\delta, n) = (1, 10)$. 

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characteristic velocity by \( \beta = \frac{v}{c} \sim 0.1 \). We adopt these parameters as our fiducial model, but vary the mass and velocity scales over the range \( M = 10^{-3} - 10^{-1} M_\odot \) and \( \beta_{\text{char}} = 0.1 - 0.3 \), where we define the characteristic velocity by

\[
E = \frac{1}{2} M_\odot (\beta_{\text{char}})^2.
\]

We assume the ejecta to be homogenous and composed of either pure \( r \)-process material or pure \( ^{56}\text{Ni} \). For models with \( r \)-process elements, all zones are assumed to have the same radioactive decay rate given by Roberts et al. (2011). Of the decay energy, 10% is taken to be in fission fragments, and 90% in beta decays. Of the beta decay energy, 25% is assumed to be lost to neutrinos, with the remaining 75% split equally between leptons and gamma rays. Leptons and fission fragments are assumed to be thermalized locally, while we use a radiation transport scheme to follow the propagation and absorption of gamma rays. This approximate apportioning of the decay energy is based on the physical considerations given in Metzger et al. (2010).

### 3.2. Light Curves

We generate synthetic observables of our ejecta models using the time-dependent multi-wavelength radiation transport code Sedona (Kasen et al. 2006). Beginning at an initial time of 0.1 days after mass ejection, the code follows the temperature and density evolution of the expanding ejecta, taking into account radiative and radioactive heating as well as cooling by expansion. The wavelength-dependent \( r \)-process and iron opacities are calculated in each zone using the Autostructure and Kurucz & Bell (1995) line data, respectively. The ionization and excitation state of the gas are set by LTE, and lines are taken to be completely absorbing. Sedona synthesizes the emergent spectral time series, from which we construct bolometric and broadband light curves. Table 1 summarizes the EM properties of the models we investigated.

![Figure 2](image)

**Figure 2.** Synthetic bolometric light curves of \( r \)-process transients with different ejecta masses (top panel) and velocities (bottom panel). For comparison, we also show the light curve of a model with fiducial ejecta parameters (\( \beta = 0.1 \) but calculated assuming iron-like opacities (dashed lines). The higher opacities of \( r \)-process ejecta lead to significantly broader light curves. The models with higher ejecta velocities correspond to shorter rise times and steeper declines, while those with higher masses have greater luminosities and longer durations.

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

### Table 1

| \( M_\odot \) (\( M_\odot \)) | \( \beta \) | Composition | \( L_{\text{bol}}(\text{erg} \text{s}^{-1}) \) | \( t_{\text{bol}}(\text{d}) \) | \( M_\gamma \) | \( M_\tau \) | \( M_\beta \) | \( M_\chi \) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 10\(^{-3}\)   | 0.1            | \( r \)-proc   | \( 1.2 \times 10^{51} \) | 0.65            | \(-9.3\)        | \(-11.2\)      | \(-12.0\)      | \(-14.0\)      |
| 10\(^{-3}\)   | 0.2            | \( r \)-proc   | \( 1.6 \times 10^{51} \) | 0.75            | \(-9.1\)        | \(-11.3\)      | \(-12.6\)      | \(-14.1\)      |
| 10\(^{-3}\)   | 0.3            | \( r \)-proc   | \( 3.5 \times 10^{51} \) | 0.15            | \(-9.3\)        | \(-12.4\)      | \(-13.6\)      | \(-14.7\)      |
| 10\(^{-2}\)   | 0.1            | \( r \)-proc   | \( 5.2 \times 10^{51} \) | 0.25            | \(-11.2\)       | \(-12.7\)      | \(-13.3\)      | \(-15.8\)      |
| 10\(^{-2}\)   | 0.2            | \( r \)-proc   | \( 8.5 \times 10^{51} \) | 0.85            | \(-11.4\)       | \(-12.8\)      | \(-14.2\)      | \(-15.9\)      |
| 10\(^{-2}\)   | 0.3            | \( r \)-proc   | \( 1.7 \times 10^{51} \) | 0.25            | \(-11.8\)       | \(-14.1\)      | \(-15.2\)      | \(-16.5\)      |
| 10\(^{-1}\)   | 0.1            | \( r \)-proc   | \( 2.4 \times 10^{51} \) | 0.65            | \(-12.9\)       | \(-14.1\)      | \(-14.6\)      | \(-17.5\)      |
| 10\(^{-1}\)   | 0.2            | \( r \)-proc   | \( 4.1 \times 10^{51} \) | 0.35            | \(-13.4\)       | \(-14.3\)      | \(-15.4\)      | \(-17.5\)      |
| 10\(^{-1}\)   | 0.3            | \( r \)-proc   | \( 7.2 \times 10^{51} \) | 0.25            | \(-14.0\)       | \(-15.5\)      | \(-16.7\)      | \(-18.1\)      |
| 10\(^{-3}\)   | 0.1            | \( ^{56}\text{Ni} \) | \( 3.5 \times 10^{51} \) | 0.25            | \(-13.0\)       | \(-12.6\)      | \(-12.6\)      | \(-11.8\)      |
| 10\(^{-2}\)   | 0.1            | \( ^{56}\text{Ni} \) | \( 3.7 \times 10^{51} \) | 0.75            | \(-15.4\)       | \(-14.9\)      | \(-14.5\)      | \(-14.8\)      |

Notes.

- Peak bolometric luminosity, in erg s\(^{-1}\).
- Rise time to bolometric light-curve peak, in days.
Figure 3. Synthetic broadband light curves calculated for the fiducial ejecta model calculated using iron-like opacities (left) and $r$-process opacities (right). The effect of $r$-process opacities is to suppress the optical emission and shift the radiation toward redder bands, in particular the infrared $J$, $H$, and $K$ bands. (A color version of this figure is available in the online journal.)

\[ t_d \simeq \left( \frac{M_{\text{ej}} \kappa}{v_c} \right)^{\frac{1}{2}} \]

through the ejected material (Arnett 1979),

where $v$ is a characteristic ejecta velocity and $\kappa$ an appropriately wavelength-averaged opacity. Because the $r$-process opacities are 10–100 times larger than those of iron, the diffusion time is significantly lengthened. The longer diffusion time also leads to a dimmer luminosity at peak, as a greater fraction of the radioactive energy is lost due to expansion before it can be radiated. The models roughly obey Arnett’s law—i.e., the emergent luminosity and instantaneous radioactive energy input are approximately equal at peak (Arnett 1979, 1982).

The $r$-process-powered bolometric light curves vary with the ejecta properties in predictable ways. Higher mass ejections give a greater luminosity and longer duration, due to their larger radioactive mass. Ejecta models with higher kinetic energies have shorter rise times, reach greater peak luminosities, and decline more rapidly than their lower energy analogs. Over the reasonable range of ejecta parameters considered here, the light curves exhibit significant diversity—the peak luminosities vary by more than an order of magnitude, and the durations range from $\lesssim 1$ day to as long as two weeks.

The broadband magnitudes of the models also differ significantly from previous expectations. Figure 3 shows that, compared to a model that uses iron-like opacities, $r$-process transients output much more energy in red and infrared bands, with a strong suppression of the optical emission. We find bright, broad peaks in the $J$, $H$, and $K$ bands, while the $U$, $B$, and $V$ bands are heavily line blanketed and decline sharply at early times. Figure 4 shows that the colors of the fiducial $r$-process model redden rapidly over the first day or two, and afterward become remarkably constant, with the SED peaking in the infrared at around $\sim 1 \mu m$. Other than the very red color, the spectra at these phases resemble those of other high-velocity SNe, with a pseudo-blackbody continuum and broad ($\sim 200$ Å) spectral features (see K13 for further discussion).

The behavior of the broadband light curves can be understood by examining the photospheric properties of $r$-process transients, since the observed SED roughly corresponds to a blackbody at the photospheric temperature and radius. In Figure 5, we plot the velocity and temperature evolution of the photosphere, the surface defined by

\[ \tau(r_{\text{phot}}) = -\int_{r_{\text{phot}}}^{\infty} \bar{\kappa}_P(r) \rho(r) dr = 1, \]

where $\bar{\kappa}_P(r)$ is the Planck mean opacity, computed from our $r$-process line data. In the initial phases, the photospheric...
velocity and temperature decline steadily, reflecting the decrease in density and the cooling of the ejecta due to expansion. At $\sim 2$ days, however, the photospheric temperature stabilizes at $T \approx 2500$ K. Since this is close to the first ionization temperature of the lanthanides, this plateau probably reflects the sharp drop in opacity that occurs when these elements recombine to neutral (K13). Recombination occurs in the cooler outer layers first, and a sharp ionization front forms in the ejecta. Photons pass easily through the cooler, neutral outer layers, but are trapped in the ionized inner regions—the photosphere thus forms at the ionization front. During this phase, the emergent colors are roughly constant in time and resemble those of a blackbody at the lanthanide recombination temperature. Over time, the recombination front recedes inward, reaching the center at around 14 days. At this point, the ejecta is nearly entirely neutral and transparent.

3.3. Uncertainties in the Opacities

Though our $r$-process opacities represent an improvement over previously available data, the Autostructure models of Nd are subject to uncertainties. In particular, the structure models rely on an ab initio optimization, such that the predicted atomic level energies and line wavelengths generally differ from the experimental values. To explore the effects of these uncertainties, we calculated bolometric and broadband light curves using two different Autostructure models of Nd ($opt2$ and $opt3$ from K13) each with a somewhat different energy level structure. The $opt3$ model reproduces the low-lying energy levels of NdII quite well, while the $opt2$ model has generally higher excitation energies which are harder to populate under our assumption of LTE. The result is fewer strong lines and a lower overall opacity for the $opt2$ case.

In Figure 6, we plot bolometric light curves for ejecta models with $\beta_{\text{char}} = 0.1$ and a variety of masses. The light curves calculated using the $opt2$ line data have somewhat sharper, more luminous peaks and swifter declines, consistent with the expected lower opacities. The differences, however, are fairly modest, and the bolometric luminosity never differs by more than a factor of $\sim 3$. The effects are more noticeable in the broadband light curves (Figure 7). In particular, the $R$-band light curves are $\sim 1$–$2$ mag brighter for the $opt2$ data, which could have important implications for detectability. Based on comparison to experiment, we expect the $opt3$ data to be more reliable; however, further work refining the opacities is clearly warranted.

In addition to errors inherent in the individual structure models, a perhaps larger uncertainty in our $r$-process opacities arises from the fact that we represent all lanthanides with the radiative data of Nd. In fact, the lanthanides with a nearly half open $f$ shell (in particular gadolinium) will be significantly more complex, with perhaps $\sim 10$ times as many lines of Nd. We therefore suspect that our current calculations underestimate the true opacity. The light curves we present here suggest that increasing the opacity further will lead to an even greater suppression of optical emission.

3.4. A $^{56}$Ni-powered Transient

Given that the radioactive light curves of NSMs depend strongly on the composition of the ejecta, it is worth considering whether any elements lighter than the lanthanides may be produced in these events. While the material dynamically ejected in the merger itself (the tidal tails) is thought to undergo robust $r$-process nucleosynthesis, it is plausible that a comparable amount of mass may subsequently be blown off in winds from an accretion disk surrounding the merged
different ratios of the $^{56}\text{Ni}$ wind mass ($r$ lines. We show the fiducial model and light curves for two different masses of ejected $^{56}\text{Ni}$ in solid lines.

Ye fraction to remain uncertain, neutrino irradiation may drive the electron remnant. Though the physical properties of the disk winds remain uncertain, neutrino irradiation may drive the electron fraction to $Y_e \gtrsim 0.4$, in which case the nucleosynthesis may not extend past $Z \sim 50$ (Surman et al. 2006, 2008; Metzger et al. 2008; Darbha et al. 2010). If $Y_e$ is very close to 0.5, the composition will be primarily $^{56}\text{Ni}$. In this case, the EM signature of a merger may be a superposition of a $^{56}\text{Ni}$- and an $r$-process-powered transient.

To address this possibility, we consider a simplified scenario where $10^{-3} - 10^{-2} M_\odot$ of pure $^{56}\text{Ni}$ is blown off in a wind immediately post-merger. Consistent with our use of spherical symmetry thus far, we model this wind as a spherical outflow, with $\beta_{\text{cha}} = 0.1$ and the same broken power-law density profile with $(n, \delta) = (1, 10)$. We consider the tidal tails and disk wind to be two separate, non-interacting components, which is perhaps not unreasonable given that the winds are likely collimated in the polar regions, while the tidal tails are largely confined to the orbital plane. Ignoring viewing angle effects, we take the two-component light curve to simply be the superposition of the individual $^{56}\text{Ni}$-powered and the $r$-process-powered light curves.

Figure 8 shows the two-component light curves, for two different ratios of the $^{56}\text{Ni}$ wind mass ($M_{\text{ni}}$) to the $r$-process tidal tail mass ($M_{\text{rp}}$). For $M_{\text{ni}} \ll M_{\text{rp}}$, the primary effect of the $^{56}\text{Ni}$ wind is to raise the early-time luminosity, creating a very short peak at $t \sim 1$ day, which blends into a long, flat, $r$-process light curve. The cumulative light curve thus appears to have a faster rise time and longer plateau. If $M_{\text{ni}} \approx M_{\text{rp}}$, the $^{56}\text{Ni}$ emission dominates the $r$-process emission for the first $\sim 5$ days post-merger, with the two components contributing roughly equally thereafter. The net effect is a gradually declining light curve, with the long $r$-process plateau obscured by the $^{56}\text{Ni}$-powered light curve.

The addition of a $^{56}\text{Ni}$ component also affects the SED of the transient, as shown in Figure 9 for the case $M_{\text{ni}} = M_{\text{rp}} = 10^{-2} M_\odot$. Given the much lower iron group opacities, the SED of the $^{56}\text{Ni}$ ejecta is much bluer than that of the $r$-process ejecta. The emission in the optical bands ($U, B, V, R$) is relatively bright and set by $^{56}\text{Ni}$ mass, while the $r$-process material establishes the behavior in the infrared bands. Such an unusual SED may serve as an EM fingerprint that could improve the prospects for positively identifying an NSM. In particular, as shown in Figure 10, the spectrum of a two-component outflow is, to first approximation, the superposition of two blackbodies—a sharply peaked bluer blackbody, corresponding to the $^{56}\text{Ni}$ ejecta, and a lower, redder one, corresponding to the $r$-process material.

The aggregate light-curve model we present here glosses over some of the more complex physical processes. Our model assumes spatially distinct regions of pure $^{56}\text{Ni}$ and pure $r$-process material. In reality, the nucleosynthetic yields are highly sensitive to the conditions in the wind, and it is possible that disk outflows contain some elements heavier than $^{56}\text{Ni}$. Contamination of the outflows with even a small mass fraction of lanthanides ($\sim 10^{-3}$) can significantly increase the opacities and the optical line blanketing. Even if our simplified compositions turn out to be reasonable, our model does not account for the geometry of the ejecta and any possible mixing of the wind and tidal tail components. Given the presumably high level of asymmetry, the net (tails + wind) EM output may depend heavily on orientation, making our simple superposition procedure valid only along certain lines of sight.

4. CONCLUSION

We have shown that the radioactive powered light curves associated with NSMs are greatly modified when more realistic values for the opacities of $r$-process material are taken into account. The $r$-process opacities are much higher than those of
other sorts of dim transients. In particular, the SED of provides signatures that may allow us to distinguish NSMs from components—lanthanide recombination. If the merger ejects two separate mass peaks in the infrared, with a color temperature set by more importantly, the uniquely high opacity of may not require quite as high a cadence of observations. Perhaps the other hand, the light curves are of longer duration, and so challenges to observational surveys at optical wavelengths. On the one hand, the light curves are broader and dimmer than those calculated assuming iron—due to both the complexity of heavy elements (in particular the lanthanides) and the diversity of atomic species present. Refining our understanding of the atomic structure of these elements is an important step toward a more rigorous model of transients from merging compact objects.

In accordance with theoretical expectations, the extremely high opacity results in bolometric light curves that are broader and dimmer than those calculated assuming iron-like opacities. Our calculations indicate that the light curves are likely to last at least a few days, and may endure as long as a week or two in certain cases. The broadband magnitudes are also significantly impacted; we find heavy line blanketing in the optical and UV bands, with most of the radiation emitted in the near-infrared. The colors at later times are fairly constant in the optical and UV bands, with most of the radiation emitted in the near-infrared. The colors at later times are fairly constant, improving detection capabilities in the near-infrared. Discovery of such a two-component light curve and the peak at blue wavelengths is due to the $^{56}$Ni, while the $r$-process material supplies the red and infrared emission. The best-fit blackbody curves to the individual spectra are overplotted in dashed black lines ($T_{\text{eff}} \approx 5700$ K, $T_{\text{eff}} \approx 2400$ K). The combined spectrum generally resembles a superposition of two blackbodies at different temperatures.

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

These findings have important, if mixed, consequences for the detectability of EM counterparts to NSMs. On the one hand, we predict dimmer bolometric luminosities and SEDs largely shifted into the infrared, both of which pose serious challenges to observational surveys at optical wavelengths. On the other hand, the light curves are of longer duration, and so may not require quite as high a cadence of observations. Perhaps more importantly, the uniquely high opacity of $r$-process ejecta provides signatures that may allow us to distinguish NSMs from other sorts of dim transients. In particular, the SED of $r$-process ejecta peaks in the infrared, with a color temperature set by lanthanide recombination. If the merger ejects two separate mass components—$r$-process tidal tails and a $^{56}$Ni wind—the dual spectrum may be quite distinctive, with discernible infrared and optical components.

The SEDs we predict can be used to roughly estimate the detectability, given the varying depths and wavelength coverage of different observing facilities (e.g., Nissanka et al. 2013). For example, Pan-STARRS (see http://pan-starrs.ifa.hawaii.edu) and Palomar Transient Factory (PTF; Law et al. 2009) achieve an $R$-band depth of $M_R \approx 21$ mag, while LSST reaches a depth of $M_R \sim 24$ (LSST Science Collaborations 2009). We find that an $r$-process transient with fiducial model parameters will peak at $M_R = -13$, which, under ideal observing conditions, would be observable to Pan-STARRY or PTF out to a distance of $\sim 60$ Mpc. This is an interesting but rather small fraction of the volume probed by advanced LIGO/VIRGO. The case with LSST is more promising, with sensitivity in the $R$ band out to $\sim 250$ Mpc. Discovery of $r$-process ejecta in the $U$ or $B$ bands with any facility would appear to be quite difficult, given the heavy line blanketing at these wavelengths.

Given that our models predict that most of the emission is at longer wavelengths, improving detection capabilities in the near-infrared may greatly aid in future searches for EM counterparts. Ground-based facilities with sensitivity in the $I$ or $Y$ bands ($0.8–1.1 \mu m$) may want to make use of these capabilities, as the $r$-process transients are generally $\sim 1$ mag brighter in these bands than in $R$ band. The construction of space-based facilities such as WFIRST (Green et al. 2012) and Euclid (Amendola et al. 2012) would be of particular interest. WFIRST is proposed to have an $H$-band depth of $\sim 25$ mag, with Euclid achieving a similar sensitivity. As our fiducial model is much brighter in the infrared ($M_H \approx -15$) than in the optical bands, such facilities could potentially make a detection out to a distance of $\sim 1000$ Mpc, encompassing the entire LIGO/VIRGO volume.

Discovering the EM counterparts to NSMs would be made significantly easier if, in addition to $r$-process elements, these events also separately eject some significant amount of $^{56}$Ni or lower mass ($Z < 58$) radioactive isotopes. Our models predict that such “lanthanide-free” light curves are reasonably bright in the optical bands ($M_R \approx M_R \approx -15$) and would be within range for many upcoming optical transient surveys. It is possible that winds from a post-merger accretion disk may produce such lighter element outflows, although more detailed simulations are needed to constrain the mass and composition of the material ejected. Clearly any detection of a short-lived optical transient should, if possible, be immediately followed up at infrared wavelengths to look for a coincident $r$-process transient from the tidal tails. Discovery of such a two-component light curve and spectrum would be a very strong signature of an NSM. It would also provide insight into the merger and post-merger physics by constraining the mass ejected by different mechanisms.

The work we have presented here is an important step toward improving our predictions of the radioactive transients from NSMs. However, much remains to be done. The opacities we have used, while more realistic than previous estimates, are still subject to important uncertainties. In particular, we need comprehensive structure calculations to derive radiative data for all lanthanides. In addition, more detailed simulations of the dynamics and nucleosynthesis of the mass ejection are needed to better predict the mass, composition, and geometry of the ejecta. Of special interest are the properties of the disk wind and any mixing of these outflows with the tidal tail material. Finally, three-dimensional radiative transfer calculations will be needed to predict the light curves of multi-component mass ejections and to determine their dependence on viewing angle. Such theoretical work should improve our understanding of the EM counterparts to GW sources and the heavy elements they produce.
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REFERENCES

Abramovici, A., Althouse, W. E., Drever, R. W. P., et al. 1992, Sci, 256, 325
Amendola, L., Appleby, S., Bacon, D., et al. 2012, arXiv:1206.1225
Arnett, W. D. 1979, ApJ, 230, L37
Arnett, W. D. 1982, ApJ, 253, 785
Badnell, N. R. 2011, CoPhC, 182, 1528
Baron, E., Hauschildt, P. H., Nugent, P., & Branch, D. 1996, MNRAS, 283, 297
Bauswein, A., Goriely, S., & Janka, H.-T. 2013, ApJ, 773, 78
Biémont, E., Palmeri, P., & Quinet, P. 1999, Ap&SS, 269, 635
Bloom, J. S., Holz, D. E., Hughes, S. A., et al. 2009, arXiv:0902.1527
Chevalier, R. A., & Soker, N. 1989, ApJ, 341, 867
Darbha, S., Metzger, B. D., Quataert, E., et al. 2010, MNRAS, 409, 846
Eastman, R. G., & Pinto, P. A. 1993, ApJ, 412, 731
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Natur, 340, 126
Freiburghaus, C., Rosswog, S., & Thielemann, F.-K. 1999, ApJL, 525, L121
Friend, D. B., & Castor, J. I. 1983, ApJ, 272, 259
Goriely, S., Bauswein, A., & Janka, H.-T. 2011, ApJL, 738, L32
Goriely, S., Demetriou, P., Janka, H.-T., Pearson, J. M., & Samyn, M. 2005, NuPhA, 758, 587
Green, J., Schechter, P., Baltay, C., et al. 2012, arXiv:1208.4012
Heiter, U., Barklem, P., Fossati, L., et al. 2008, JPhCS, 130, 012011
Hoeflich, P., Mueller, E., & Khokhlov, A. 1993, A&A, 268, 570
Hotokezaka, K., Kiuchi, K., Kyutoku, K., et al. 2013, PhRvD, 87, 024001
Jack, D., Hauschildt, P. H., & Baron, E. 2011, A&A, 528, A141
Janka, H.-T., Eberl, T., Ruffert, M., & Fryer, C. L. 1999, ApJL, 527, L39
Karp, A. H., Lasher, G., Chan, K. L., & Sulpeter, E. E. 1977, ApJ, 214, 161
Kasen, D., Badnell, N. R., & Barnes, J. 2013, ApJ, 774, 25
Kasen, D., Thomas, R. C., & Nugent, P. 2006, ApJ, 651, 366
Kurucz, R., & Bell, B. 1995, Atomic Line Data, Kurucz CD-ROM No. 23 (Cambridge, MA: Smithsonian Astrophysical Observatory)
Lattimer, J. M., & Schramm, D. N. 1974, ApJ, 192, L145
Lattimer, J. M., & Schramm, D. N. 1976, ApJ, 210, 549
Law, N. M., Kulkarni, S. R., Dekany, R. G., et al. 2009, PASP, 121, 1395
Lee, W. H. 2001, MNRAS, 328, 583
Li, L.-X., & Paczyński, B. 1998, ApJL, 507, L59
LSST Science Collaborations 2009, arXiv:0912.0201
Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48
Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Metzger, B. D., Piro, A. L., & Quataert, E. 2008, MNRAS, 390, 781
Narayan, R., Paczynski, B., & Piran, T. 1992, ApJ, 395, L83
Nissanke, S., Kasliwal, M., & Georigieva, A. 2013, ApJ, 767, 124
Oechslin, R., Janka, H.-T., & Marek, A. 2007, A&A, 467, 395
Paczynski, B. 1986, ApJL, 308, L43
Palmeri, P., Quinet, P., Wyart, J.-F., & Biémont, E. 2000, PhyS, 61, 323
Pinto, P. A., & Eastman, R. G. 2000, ApJ, 530, 757
Quinet, P., & Biémont, E. 2004, ADNDT, 87, 635
Roberts, L. F., Kasen, D., Lee, W. H., & Ramirez-Ruiz, E. 2011, ApJL, 736, L21
Rosswog, S. 2005, ApJ, 634, 1202
Rosswog, S., Davies, M. B., Thielemann, F.-K., & Piran, T. 2000, A&A, 360, 171
Rosswog, S., Liebendörfer, M., Thielemann, F.-K., et al. 1999, A&A, 341, 499
Rosswog, S., Thielemann, F. K., Davies, M. B., Benz, W., & Piran, T. 1998, in Proc. of 9th Workshop on Nuclear Astrophysics, ed. W. Hillebrandt & E. Muller, 103
Schutz, B. F. 1986, Natur, 323, 310
Schutz, B. F. 2002, in Lighthouses of the Universe: The Most Luminous Celestial Objects and Their Use for Cosmology, ed. M. Gilfanov, R. Sunyeav, & E. Churazov (Berlin: Springer-Verlag), 207
Sobolev, V. V. 1960, Moving Envelopes of Stars (Cambridge, MA: Harvard Univ. Press)
Stubbs, C. W. 2008, CoGra, 25, 184033
Surman, R., McLaughlin, G. C., & Hix, W. R. 2006, ApJ, 643, 1057
Surman, R., McLaughlin, G. C., Ruffert, M., Janka, H.-T., & Hix, W. R. 2008, ApJL, 679, L117