Kilonova light curves from the disc wind outflows of compact object mergers

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ABSTRACT
We study the radioactively powered transients produced by accretion disc winds following a compact object merger. Based on the outflows found in two-dimensional hydrodynamical disc models, we use wavelength-dependent radiative transfer calculations to generate synthetic light curves and spectra. We show that resulting kilonova transients generally produce both optical and infrared emission, with the brightness and colour carrying information about the merger physics. In those regions of the wind subject to high neutrino irradiation, r-process nucleosynthesis may halt before producing high-opacity, complex ions (the lanthanides). The kilonova light curves thus typically have two distinct components: a brief (~2 d) blue optical transient produced in the outer lanthanide-free ejecta, and a longer (~10 d) infrared transient produced in the inner, lanthanide line-blanketed region. Mergers producing a longer lived neutron star, or a more rapidly spinning black hole, have stronger neutrino irradiation, generate more lanthanide-free ejecta and are optically brighter and bluer. At least some optical emission is produced in all disc wind models, which should enhance the detectability of electromagnetic counterparts to gravitational wave sources. However, the presence of even a small amount (10^{-4} M_{\odot}) of overlying, neutron-rich dynamical ejecta will act as a ‘lanthanide-curtain’, obscuring the optical wind emission from certain viewing angles. Because the disc outflows have moderate velocities (~10000 km s^{-1}), numerous resolved line features are discernible in the spectra, distinguishing disc winds from fast-moving dynamical ejecta, and offering a potential diagnostic of the detailed composition of freshly produced r-process material.

Key words: gravitational waves – hydrodynamics – nuclear reactions, nucleosynthesis, abundances – opacity – radiative transfer – gamma-ray burst: general.

1 INTRODUCTION
The ejection of radioactive material during, or immediately following, the merger of two neutron stars (or a neutron star and a black hole) can give rise to an optical/infrared transient similar to, but dimmer and briefer than, an ordinary supernova (Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010; Roberts et al. 2011; Barnes & Kasen 2013; Piran, Nakar & Rosswog 2013; Tanaka & Hotokezaka 2013; Grossman et al. 2014; Tanaka et al. 2014). These transients, called kilonovae, are promising electromagnetic counterparts to gravitational wave sources (Metzger & Berger 2012; Nis sanke, Kasliwal & Georgieva 2013), and may be diagnostic of the sites of heavy element nucleosynthesis (Lattimer & Schramm 1974; Freiburghaus, Rosswog & Thielemann 1999; Goriely, Bauswein & Janka 2011; Piran, Korobkin & Rosswog 2014).

Most studies of kilonovae have focused on material that becomes unbound during the merger itself. Simulations find that, on a dynamical time-scale of ~ milliseconds, around 10^{-4}–10^{-2} M_{\odot} of material may be flung out from the tips of the tidal tails or squeezed out from the contact interface between the two coalescing stars (e.g. Rosswog 2005; Duez et al. 2010; Bauswein, Baumgarte & Janka 2013; Hotokezaka et al. 2013). This dynamical ejecta is initially very neutron rich, with an electron fraction Y_e = n_e/(n_p + n_e) <\hspace{0.5cm}0.1, where n_p and n_e are the number density of protons and neutrons, respectively. Neutrinos emitted by the hot merger remnant can irradiate the outflowing material, perhaps raising the Y_e > 0.1 along the polar rotation axis (Wanajo et al. 2014).

Recently, more attention has focused on the possibility that a comparable or greater amount of mass may be expelled subsequent to the...
merger, as material in a rotationally supported disc accretes on to the central remnant on a viscous time-scale (∼1 s) (e.g. Beloborodov 2008; Metzger, Piro & Quataert 2009). Viscous and nuclear heating during accretion can drive winds that unbind a significant fraction of the disc (Lee, Ramirez-Ruiz & López-Cámara 2009; Fernández & Metzger 2013a; Just et al. 2015). Neutrino irradiation during this phase will change the composition of the outflows. If the central remnant is a black hole (BH), neutrinos emitted from the inner region of the disc will raise the mean electron fraction of the wind to \( Y_e \sim 0.2 \) (Surman, McLaughlin & Hix 2006; Metzger & Fernández 2014). If the BH is rapidly spinning, this neutrino irradiation is enhanced, leading to higher values of \( Y_e \) (Fernández et al. 2015; Just et al. 2015). If the central remnant survives for some period of time as a hypermassive neutron star (HMNS) before collapsing to a BH, the neutrino irradiation will be even stronger, and the electron fraction can be raised to yet higher values, \( Y_e \sim 0.3 \) (Metzger & Fernández 2014; Perego et al. 2014).

The value of \( Y_e \) in large part determines the final composition of the ejecta, and has a dramatic effect on the kilonova light curves. Unbound material will assemble into heavy elements via rapid neutron captures, or the r-process. The line opacity of some heavy elements differs significantly from that of ordinary astrophysical mixtures. In particular, for species with open f-shell valence electron configurations, namely the lanthanides (atomic number \( Z = 58–70 \)) and actinides (\( Z = 89–103 \)), the high atomic complexity leads to extremely high opacities (Kasen, Badnell & Barnes 2013). The high lanthanide opacity leads to a dimmer, longer duration kilonova light curve with emission peaking at infrared, rather than optical, wavelengths (Barnes & Kasen 2013).

For ejecta with low electron fraction, r-process nucleosynthesis proceeds all the way up to the third r-process peak, and a significant fraction of lanthanides, and perhaps actinides (de Jesús Mendoza-Temis et al. 2014), are produced. For higher electron fraction, nucleosynthesis stops at the second r-process peak, and the ejecta remains lanthanide free. The colour and brightness of kilonova light curves are therefore sensitive markers of the electron fraction of the ejecta, and can be used to gain insight into the physics of compact object mergers.

The predicted colours of disc winds will also impact strategies for finding electromagnetic counterparts to the gravitational wave sources detected by the advanced LIGO/VIRGO experiments. Most existing and upcoming wide-field surveys observe in optical bands; infrared surveys are less common and typically have much lower sensitivity and a smaller field of view. The presence of optical emission from a lanthanide-free disc wind would therefore enhance the prospect of finding a kilonova.

Here we present radiative transfer calculations of kilonova light curves that allow us to connect the observables to the merger physics, e.g. the relative mass of dynamical to wind ejecta, the lifetime of an HMNS, or the spin of a central BH. We begin with the two-dimensional hydrodynamical simulations from Metzger & Fernández (2014) and Fernández et al. (2015) which model the post-merger evolution (Section 2.1) and predict the distribution and electron fraction of unbound wind ejecta (Section 2.2). Additionally, we carry out r-process network calculations for parametrized wind outflows to estimate the critical electron fraction above which the ejecta is lanthanide free (Section 2.3). We then use a multidimensional radiative transfer code to generate synthetic kilonova spectra and light curves as a function of viewing angle (Section 3.1). We study several different models in order to explore the effects of the lifetime of an HMNS (Section 3.2), the spin of a BH (Section 3.3) and the presence of overlying dynamical ejecta (Section 3.4). We compare our wind light curves to observations of potential kilonova candidates (Section 3.5), and reflect on what implications our results have for detecting and interpreting kilonovae in future (Section 4).

2 PROPERTIES OF DISC WINDS

2.1 Hydrodynamical method

We make use of the hydrodynamical disc wind simulations from Metzger & Fernández (2014) and Fernández et al. (2015), as enumerated in Table 1. All calculations begun with an equilibrium disc torus surrounding a central remnant. The default disc mass was 0.03 M⊙, and models differ in the amount of time that the neutron star (NS) survived before collapse to a BH, with values of \( t_{\text{ns}} \) = {0, 30, 100, 300} ms. For one model (t0.8), the NS was assumed to survive indefinitely. Most models assume a non-rotating BH with the exception of four models (labelled by a0.8) for which we assumed prompt formation of a BH with spin parameter \( a = 0.8 \). For these cases, we also ran models with the disc mass increased to \( M = 0.1 \) and \( M = 0.3 \) M⊙ and the artificial viscosity parameter changed. We constructed several additional ejecta models, discussed in Section 3.4, by superimposing an outer shell or torus of dynamical ejecta upon the wind model t100.

The hydrodynamical simulations use the \textsc{flash}3.2 code (Dubey et al. 2009), with modifications that enable modelling the viscous evolution of merger remnant accretion discs (Fernández 2012; Fernández & Metzger 2013a,b). The code includes a Helmholtz equation of state (Timmes & Swesty 2000) with abundances in nuclear statistical equilibrium, charged-current neutrino rates including emission from an HMNS and disc self-irradiation via a neutrino leakage scheme, and viscous angular momentum transport via an \( \alpha \)-viscosity prescription (Shakura & Sunyaev 1973). Approximate general relativistic effects are included via the pseudo-Newtonian potential of Paczynski & Wiita (1980) for non-spinning BHs and HMNSs, and the potential of Artemova, Björnsson & Novikov (1996) for the spinning BH case. All models are evolved until 3000 orbits at the initial density maximum, or \( \sim 10 \) s.

To follow the unbound ejecta all the way to free expansion, we use a two-step process. First, in the original disc simulations we record all material leaving a sphere of radius 10¹⁷ cm, centred on the central remnant. This information is then used as an inner boundary condition for a calculation on a new, larger computational domain of radius 10¹⁴ cm. The hydrodynamics are then carried out without any source terms other than gravity and the equation of state.² The ambient density is reduced to 10⁻⁸ g cm⁻³ to prevent deceleration of the wind. By the time the ejecta reaches 10¹² cm, the material is very nearly homologous, i.e. the kinetic energy dominates and the velocity is proportional to radius. From this time on, the dynamics can be extrapolated analytically.

1 An important exception occurs if the outermost ejecta expands sufficiently rapidly for neutrons to avoid capture into nuclei. The high radioactive heating rate of free neutrons relative to r-process nuclei may power bright ultraviolet/blue emission on a time-scale of hours following the merger, despite the presence of lanthanides (Metzger et al. 2015).

2 Viscous and neutrino source terms operate on time-scales slower than the expansion time at these radii.
2.2 Ejecta properties

Fig. 1 shows the density and compositional structure of a representative model, t030, in the homologous phase. The ejecta is approximately spherical, with the bulk of the material moving at speeds of $\approx 10000$ km s$^{-1}$, or 0.03c. Such expansion velocities are substantially lower than that of the dynamical ejecta, which move at 0.1c–0.3c.

The outer layers of wind ejecta typically have a higher electron fraction than the inner regions, as the outer material is ejected at earlier times when the neutrino irradiation is higher due to the presence of an NS or a higher accretion rate on to the BH. In model t030, a low $Y_e$ plume is also seen along the equator. This feature forms out of the motion of the highly irradiated component of the wind, which originates in regions of small radius and high altitude above the disc mid-plane, and wraps around the back of the disc with near north–south symmetry (Fernández et al. 2015). The mass in this plume, however, is very small compared to the spherical core.

Fig. 2 shows, for each model, a histogram of the amount of mass ejected with various values of $Y_e$. Increasing the lifetime of an HMNS has two main consequences. First, a larger total amount of mass is ejected, due to higher neutrino heating and the presence of a hard boundary at the HMNS, which keeps disc material from being swallowed below the event horizon of a BH. Secondly, the mean value of $Y_e$ increases with $t_{\text{ns}}$ due to the greater level of neutrino irradiation from both the HMNS and the disc.

### Table 1

Disc wind model properties and summary of radiative transfer results. The first three columns from the left show model name, lifetime of the HMNS, and viscosity parameter, respectively. The following five columns show properties of the homologous ejecta: mass with $Y_e < 0.25$, mass with $Y_e > 0.25$, kinetic energy, mean velocity of material with $Y_e < 0.25$ and mean velocity of material with $Y_e > 0.25$. The last three columns give the peak luminosities averaged over the blue (3500–5000 Å), red (5000–7000 Å), and infrared (1–3 μm) bands, respectively.

| Model | $t_{\text{ns}}$ (ms) | $\alpha_{\text{visc}}$ | $M_{Y_e<0.25}$ (M$_\odot$) | $M_{Y_e>0.25}$ (M$_\odot$) | KE (erg) | $\bar{v}_{Y_e<0.25}$ (km s$^{-1}$) | $\bar{v}_{Y_e>0.25}$ (km s$^{-1}$) | $\nu L_b$ (B) (erg s$^{-1}$) | $\nu L_r$ (R) (erg s$^{-1}$) | $\nu L_i$ (IR) (erg s$^{-1}$) |
|-------|---------------------|------------------|---------------------|---------------------|--------|---------------------|---------------------|---------------------|---------------------|---------------------|
| t000  | 0                   | 0.03             | $1.5 \times 10^{-3}$ | $6.9 \times 10^{-3}$ | 1.6 $\times 10^{48}$ | 9297   | 18583              | 4.3 $\times 10^{40}$ | 2.1 $\times 10^{40}$ | 8.5 $\times 10^{40}$ |
| t030  | 0                   | 0.03             | $2.7 \times 10^{-3}$ | $5.4 \times 10^{-3}$ | 9.9 $\times 10^{48}$ | 7424   | 29518              | 5.8 $\times 10^{40}$ | 6.0 $\times 10^{40}$ | 1.0 $\times 10^{40}$ |
| t100  | 100                 | 0.03             | $7.3 \times 10^{-4}$ | $5.3 \times 10^{-3}$ | 2.5 $\times 10^{49}$ | 9805   | 15007              | 6.6 $\times 10^{40}$ | 1.3 $\times 10^{41}$ | 5.7 $\times 10^{40}$ |
| t300  | 300                 | 0.03             | $1.5 \times 10^{-2}$ | $6.9 \times 10^{-2}$ | $\alpha_{\text{visc}}$ | 16432  | 8.5 $\times 10^{40}$ | 2.4 $\times 10^{41}$ | 1.2 $\times 10^{40}$ | $\alpha_{\text{visc}}$ |
| t1nf  | +∞                  | 0.03             | $2.9 \times 10^{-2}$ | $1.9 \times 10^{-1}$ | $\alpha_{\text{visc}}$ | 21419  | 2.7 $\times 10^{41}$ | 3.9 $\times 10^{41}$ | 2.0 $\times 10^{40}$ | $\alpha_{\text{visc}}$ |
| a0.8, M0.03 | 0                | 0.03             | $4.9 \times 10^{-3}$ | $8.4 \times 10^{-4}$ | $\alpha_{\text{visc}}$ | 9996   | 21012              | 1.3 $\times 10^{41}$ | 7.5 $\times 10^{40}$ | 2.1 $\times 10^{40}$ |
| a0.8, M0.1 | 0                | 0.02             | $4.9 \times 10^{-3}$ | $7.1 \times 10^{-3}$ | $\alpha_{\text{visc}}$ | 11183  | 11840              | 1.7 $\times 10^{41}$ | 1.6 $\times 10^{41}$ | 2.6 $\times 10^{40}$ |
| a0.8, M0.3 | 0                | 0.02             | $1.3 \times 10^{-2}$ | $1.4 \times 10^{-2}$ | $\alpha_{\text{visc}}$ | 9135   | 15132              | 2.5 $\times 10^{41}$ | 3.0 $\times 10^{41}$ | 5.6 $\times 10^{40}$ |
| a0.8, M0.3v | 0               | 0.05             | $4.9 \times 10^{-2}$ | $3.2 \times 10^{-3}$ | $\alpha_{\text{visc}}$ | 12404  | 19945              | 1.7 $\times 10^{41}$ | 3.1 $\times 10^{41}$ | 1.4 $\times 10^{41}$ |

Figure 2. The amount of mass ejected with different values of the electron fraction, for disc wind models of different NS lifetimes, $t_{\text{ns}}$. A longer-lived NS leads to a larger total ejected mass and a higher mean electron fraction. The shaded area shows the region $Y_e > 0.25$ where the ejecta is likely lanthanide free.

2.3 Nucleosynthesis and lanthanide fraction

Knowledge of the compositional structure of the wind ejecta is needed to predict the resulting kilonova light curves. A full calculation of the ejecta abundances would require detailed nuclear-reaction network post-processing of thermodynamic trajectories along the wind. Here we approximate the composition by a one-to-one mapping from the electron fraction. This mapping is obtained by evolving parametrized trajectories with the nuclear-reaction network code TORCH (Timmes 1999). Trajectories begin with abundances in nuclear statistical equilibrium at a temperature $T = 5 \times 10^{9}$ K and entropy $s \approx 20 k_{\text{B}}$baryon. The density decays exponentially in time, with expansion time $t_{\exp} = 100$ ms and the entropy is held constant, assuming that radiation dominates the pressure. The chosen values of entropy and expansion time correspond to mass-flux-weighted averages from disc wind simulations at the point where the average temperature is $5 \times 10^{9}$ K (Fernández & Metzger 2013a). TORCH lacks a treatment of fission, which is
Figure 3. Nucleosynthesis results for parametrized wind models. Top panel: final mass fractions of the wind for an expansion time $t = 0.1$ s, entropy = 20 $k_B$/baryon and varying values of electron fraction, $Y_e$. For higher values of $Y_e$, the $r$-process fails to produce lanthanides (shaded grey region). Bottom panel: integrated mass fraction of all lanthanides as a function of electron fraction assuming different values of entropy and expansion time. For conditions typical of disc wind ejecta ($s = 20 k_B$/baryon, $t = 0.1$ s), no lanthanides are produced if $Y_e \gtrsim 0.25$. an important physical effect in low-$Y_e$ outflows, but should not be significant around the critical $Y_e$ at which lanthanides first appear.

The top panel of Fig. 3 shows the final mass fraction distributions for a few sample wind trajectories of different $Y_e$. We find that the lanthanide mass fraction decreases sharply above $Y_e \approx 0.25$. For electron fractions above this value, the neutron density is too low for the $r$-process to proceed past the long beta-decay lifetimes associated with the $N = 82$ closed shell nuclei, and nucleosynthesis halts at atomic numbers of $Z \approx 58$. For lower electron fractions, however, the flow is able to move past this point and proceeds rapidly to the next closed shell at $N = 126$.

The bottom panel of Fig. 3 shows that the transition to a lanthanide-free composition is fairly abrupt in $Y_e$, and not overly sensitive to the value of the entropy chosen, so long as it is a few times $10$ $k_B$/baryon. The threshold for producing lanthanides varies from $Y_e = 0.2$ to 0.3 depending on the conditions. We therefore consider $Y_e \approx 0.25$ to be a good rule of thumb for distinguishing between the presence and absence of lanthanides, recognizing that the exact value of the critical $Y_e$ depends to some extent on the properties of each fluid element.

3 LIGHT CURVES AND SPECTRA

3.1 Radiative transfer method

We input the homologous wind profiles from the hydrodynamical simulations of Section 2.2 into the multidimensional radiative transfer code SEDONA (Kasen, Thomas & Nugent 2006) to calculate synthetic light curves and spectra. The calculation setup was similar to that discussed in Kasen et al. (2013) and Barnes & Kasen (2013), and assumed local thermodynamic equilibrium for the atomic level populations and ionization state.

As the line data of high-$Z$ elements is still incomplete, we used an approximate method to construct effective opacities of $r$-process mixtures. The opacity of all d-shell species was calculated using the atomic data for iron (Kurucz & Bell 1995), while the opacity of all f-shell species (the lanthanides) was calculated using the detailed atomic structure calculations for neodymium ($Z = 60$ Kasen et al. 2013). Atomic structure calculations have shown that this proxy approach provides a reasonable approximation of the pseudo-continuum opacities, although it fails to produce the proper line features. To estimate the abundance of lanthanides, we used the wind nucleosynthesis calculations of Section 2.3 with an assumed entropy of $s = 20 k_B$/baryon and expansion time-scale of $t_{\text{exp}} = 0.1$ s. This mapping is only a rough approximation, as fluid elements with entropies greater than 20 or 30 $k_B$/baryon and with faster expansion times are present in the hydrodynamical models. The lack of detailed nucleosynthetic yield calculations therefore limits the quantitative accuracy of our predicted light curves.

For the radioactive heating rate, $\epsilon_{\text{rad}}(t)$, of the wind, we use the results given in Roberts et al. (2011), which we assume to be the same in all regions of ejecta with $Y_e < 0.4$. In reality, the heating rate will depend on the local electron fraction. Grossman et al. (2014) show that, on day time-scales, the heating rate of $Y_e \sim 0.1$ has a factor of $\sim 2$ greater than that of the $Y_e < 0.1$ outflows calculated by Roberts et al. (2011). Our calculations may therefore underestimate the radioactive heating and kilonova luminosities. For $Y_e > 0.4$, the heating rate is lower (Grossman et al. 2014) and so we take $\epsilon_{\text{rad}}(t) = 0$ in these regions. Since most of the ejecta have $Y_e < 0.4$, this choice has little impact on the final light curves.

The SEDONA calculations generate the spectral time series every 0.1 d after merger, within a wavelength range of 200–30 000 Å, and from 20 different viewing angles equally spaced in the cosine of the polar angle $\theta$. From the spectra, we constructed broad-band light curves by averaging the emission over three different wavelength ranges: 3500–5000 Å (‘blue’), 5000–7000 Å (‘red’) and 1–3 μm (‘infrared’). Table 1 gives the peak luminosity of all models in each of these bands.

3.2 Effect of NS lifetime

Fig. 4 shows the predicted light curves, from all viewing angles, of four models with different NS lifetimes. Fig. 5 shows angle-averaged light curves for the same models. Because the wind outflows are roughly spherically symmetric, the variation of the light curves with viewing angle is generally small. The exception is model t10n, where the ejecta have a significant prolate elongation, and the blue light curve is a factor of $\sim 3$ brighter for an equatorial viewing angle, at which the projected surface area of the ejecta is maximal.

The light curves of model t000 – which assumes prompt formation of a BH – show two distinct components: a brief ($\sim 2$ d) blue optical transient and a longer ($\sim 10$ d) infrared transient. The infrared emission is generated within the central ejecta, where the electron fraction is $Y_e < 0.25$ and heavy line blanketing from the lanthanides suppresses the optical flux. This light curve is qualitatively similar to that found in the parametrized models calculated by Barnes & Kasen (2013). The blue component of the light curve is produced by the small amount of high $Y_e$ (lanthanide-free) material in the outer layers of ejecta. The production of even a small ($\sim 10^{-4}$ $M_\odot$) amount of high-$Y_e$ in the exterior ejecta therefore has important implications for the detectability of kilonovae with optical facilities.

As the lifetime of the HMNS is increased, the optical light curves become brighter. This is because neutrino irradiation converts a larger fraction of the wind to $Y_e > 0.25$, and a greater total mass is ejected due to the hard boundary of the HMNS. For the extreme case of a stable NS (model t10n), the entire wind is lanthanide free.
Figure 4. Synthetic light curves of models t000, t030, t100 and tInf. Blue lines denote blue optical emission (averaged over 3500–5000 Å), red lines denote red optical emission (5000–7000 Å) and black lines infrared emission (1–3 µm). Lines are overplotted for 20 different viewing angles, equally spaced in $\cos \theta$. A small amount of Monte Carlo noise is apparent in the calculations.

Figure 5. Left-hand panel: angle-averaged synthetic light curves of various wind models at optical blue wavelengths (3500–5000 Å). The closed circles show $r$-band observations of the possible kilonova following GRB 080503 (Perley et al. 2009). The triangle symbol denotes an upper limit. As the redshift of 080503 is unknown, we adopt a value $z = 0.25$ and neglect $k$-correction effects. Right-hand panel: model light curves of the same models at infrared wavelengths (1–3 µm). The square shows the Hubble Space Telescope observations of the possible kilonova associated with GRB130603B (Berger, Fong & Chornock 2013; Tanvir et al. 2013).
and the blue optical emission peaks at $vF_e \approx 2.8 \times 10^{41}$ erg s$^{-1}$, a factor of 10 brighter than that of the prompt BH model t000. The optical light curves roughly follow analytic expectations that the duration should scale as $t \propto M^{1/2}$ and the peak optical luminosity as $L \propto M^{1/2}$ (Metzger et al. 2010), where $M$ is the ejected mass of high $Y_e$ material given in Table 1.

The dependence of the infrared brightness on $t_{\text{ns}}$ is non-monotonic. The mass of low $Y_e$ ejecta in model t030 ($t_{\text{ns}} = 30$ ms) is greater than that of model t000, and hence the infrared light curve brighter. A turnover point, however, is reached around $t_{\text{ns}} \approx 100$ ms, at which point the neutrino irradiation is sufficient to convert nearly the entire wind to high-$Y_e$, reducing the infrared emission. The kilonova colours thus correlate with the degree of neutrino irradiation. For $t_{\text{ns}} \lesssim 30$ ms, the ratio $vL_{\nu}(B)/vL_{\nu}(\text{IR}) \approx 5$, whereas for $t_{\text{ns}} > 30$ ms the colour is much bluer, with $vL_{\nu}(B)/vL_{\nu}(\text{IR}) \approx 10$.

The origin of the infrared emission in models with $t_{\text{ns}} \gtrsim 100$ ms is distinct origin from those with $t_{\text{ns}} < 100$ ms. In the latter cases, the infrared emission arises in low-$Y_e$, lanthanide-blanketed regions of ejecta. In the former, there is no low-$Y_e$ ejecta, and the infrared emission is simply the long wavelength tail of the thermal spectrum that peaks in the optical. Such infrared light curves display two distinct maxima, separated by about 10 d. The origin of the secondary maximum is similar to that studied for Type Ia SN, and results from an enhancement in infrared emissivity that occurs when the ejecta transitions from doubly to singly ionized (Kasen et al. 2006). The clear separation of the two maxima in these models may be an artefact of our approximate opacity prescription, which uses iron group atomic data as a proxy for all d-shell elements. In reality, the change in ionization state occurs at a different time for different elements, depending on the ionization potential, which for complex mixtures may have the effect of smearing the two peaks together.

Fig. 6 shows the spectra evolution of model t100 over 10 d. The colour of the continuum rapidly evolves from blue emission produced in the outer high-$Y_e$ layers of ejecta to infrared emission produced in the inner, low-$Y_e$ ejecta. The spectra show numerous line absorption features that, given the moderate ejecta velocities (5000–10 000 km s$^{-1}$), are fairly well resolved. This differs from the spectra of dynamical ejecta, where the line features are highly blended due to the fast (0.1c–0.3c) ejecta velocities (Kasen et al. 2013). However, given our approximate line opacities, the position of individual lines cannot be trusted, and as line data from more species are added, line blending may become more prevalent. Although more work is needed to make quantitative spectral predictions, our results suggest that the relative slowness of the wind may be discernible in the line features, providing a way to distinguish a wind from dynamical ejecta. The presence of resolved lines also provides hope that the detailed composition of outflows could be estimated from spectral analysis.

### 3.3 Effect of disc mass and BH spin

The models discussed so far have all assumed a non-spinning BH. It is more likely, however, that the BH remnant of a compact object merger is a rapidly rotating (Oechslin, Janka & Marek 2007; Kiuchi et al. 2009; Rezzolla et al. 2010). We have therefore also calculated several models representing immediate formation of a BH with Kerr parameter $a = 0.8$. The general relativistic effects were only approximately captured via a pseudo-Newtonian potential (see Section 2.1).

As discussed in Fernández et al. (2015), a higher BH spin leads to a deeper potential well and a higher neutrino irradiation from the inner regions of the disc. As a result, the fraction of high-$Y_e$ material in the wind is greater compared to the non-spinning BH case. In the spinning BH model a0.8_M0.03, about 15 per cent of the ejecta has $Y_e > 0.25$. This is significantly larger than the $\sim 4$ per cent high-$Y_e$ mass fraction found in the non-spinning BH model t000, and comparable to the fraction found in model t030 (for which an HMNS collapses to a non-rotating BH after $t_{\text{ns}} = 30$ ms). As seen in Fig. 5, the light curves of models a0.8_M0.03 and t030 are indeed quite similar. This degeneracy represents a challenge in using kilonova observations to diagnose the lifetime of an HMNS.

We have also explored the effect of increasing the mass of the disc from our default value $M = 0.03 \, M_\odot$ to $M = 0.1 \, M_\odot$ and $M = 0.3 \, M_\odot$. In these models (a0.8_M0.1, a0.8_M0.3 and a0.8_M0.3v), the remnant was assumed to be a BH with $a = 0.8$. As expected, a greater disc mass produces a larger ejected mass and a brighter kilonova. In our model with the most massive winds (a0.8_M0.3v), the total ejected mass is about 0.05 $M_\odot$ and the kilonova light reaches infrared luminosities in excess of $10^{41}$ erg s$^{-1}$.

For these spinning BH models, we also explored the effect of varying the viscosity parameter $\alpha$. A higher value of $\alpha$ generally leads to greater viscous heating and stronger winds. For the models with disc mass $M = 0.3 \, M_\odot$, increasing the viscosity from $\alpha = 0.02$ to $\alpha = 0.05$ gives a factor of $\sim 2$ more ejected mass. In addition, the viscosity parameter has a significant effect on the composition.
of the disc winds, with higher values of $\alpha$ leading to lower mean values of $Y_e$. For the $\alpha = 0.8$ BH models, using $\alpha = 0.02$ results in $\sim 60$ per cent of the ejecta having $Y_e > 0.25$, while for $\alpha = 0.03$ and $\alpha = 0.05$ the high-$Y_e$ mass fraction is $\sim 15$ per cent and $\sim 6$ per cent, respectively. A similar dependence on $\alpha$ can be seen in the semi-analytical calculations of Metzger, Piro & Quataert (2008a) and the numerical models of Fernández & Metzger (2013a). This dependence is presumably due to the fact that increasing the viscous heating rate leads to a faster time-scale for matter ejection, and hence less time for the fluid $Y_e$ to be raised by weak interactions within the disc. The dependence on the $\alpha$ parameter represent an important uncertainty in our calculations and highlight the need for studies that abandon the $\alpha$-viscosity prescription and treat the full 3D magnetohydrodynamical evolution of the disc.

### 3.4 Effect of dynamical ejecta

Prior to the ejection of disc winds, neutron rich material may be dynamically expelled in the merger, producing an overlying layer of rapidly expanding, presumably low-$Y_e$ material. This dynamical ejecta likely moves faster than the wind, and may act as a ‘lanthanide curtain’, obscuring our view of the optical emission originating with the wind ejecta.

To explore this effect, we created several models in which we superimposed a spherical shell of $Y_e < 0.25$ material on to the outer region of the 2D wind model t100. We took the radial density profile of the shell to be a Gaussian with central velocity $v = 0.2c$ and a width of $\Delta v = 0.1c$ and varied the mass of dynamical ejecta between $M_{\text{dyn}} = 10^{-5}$ and $10^{-2} M_\odot$.

Fig. 7 shows the angle-averaged light curves for models with different values of $M_{\text{dyn}}$. Due to the extremely high lanthanide opacities, we find that only a small mass of dynamical ejecta ($M_{\text{dyn}} \approx 10^{-4} M_\odot$) is required to suppress the blue optical flux by more than an order of magnitude. For models with $M_{\text{dyn}} \gtrsim 10^{-3} M_\odot$, the wind emission is completely invisible, and the optical and infrared light curves arise entirely within the dynamical ejecta. In these cases, the brief peak and subsequent tail of blue flux are due to the small fraction of optical radiation that is produced in and manages to escape from the heavily line-blanketed dynamical ejecta.

In realistic merger simulations, the dynamical ejecta is not completely spherical, and may possess some lanthanide-free ‘windows’ through which we can see the wind ejecta. In the NS + NS simulations of Bauswein et al. (2013), the outflows have a torus-like anisotropy, with less material ejected along the polar axis. Neutrino irradiation of the dynamical ejecta may also raise the $Y_e$ in the polar region, reducing the abundance of lanthanides in that material (Wanajo et al. 2014). In BH–NS mergers, mass ejection occurs mainly through the tidal tail of the NS, forming a single thick arm confined to the equatorial plane. However, Foucart et al. (2015) find that in BH–NS mergers a small amount ($\sim 3 \times 10^{-3} M_\odot$) of low-$Y_e$ material can be ejected along the polar regions during the early disc formation and circularization.

To explore the possible geometrical effects, we constructed an additional model in which $M_{\text{dyn}} = 10^{-3}$ of dynamical ejecta was distributed in a torus about the equator. Here we took the density profile in both the $r$ and $z$ directions to be Gaussian with width of $\Delta v = 0.1c$, a distribution that closely resembles the ejecta seen in the Newtonian NS–NS simulations of Rosswog (2005). Fig. 8 shows the resulting light curves as seen from different viewing angles. For pole-on orientations ($\theta = 90^\circ$), an observer can see most of the wind ejecta through the hole of the dynamical torus, and the blue optical flux is only reduced by factor of $\sim 2$ at peak. For orientations closer to edge-on ($\theta = 0^\circ$), however, the dynamical torus obscures the wind optical flux by an order of magnitude or more.

### 3.5 Comparison to observations

One week following the gamma-ray burst (GRB) 130603B, Tanvir et al. (2013) and Berger et al. (2013) detected an excess infrared emission that they attributed to a kilonova. In the right-hand panel of Fig. 5, we compare that Hubble Space Telescope infrared data point to our models. The luminosity of the 130603B excess is brighter than most of the wind models. The exception is model a0.8.0.M3.3v, which assumed a large initial disc mass of 0.3 $M_\odot$ (and a higher viscosity $\alpha = 0.05$) and therefore ejected the largest mass of lanthanides ($0.05 M_\odot$). The relatively large implied disc mass may be consistent with the high luminosity of the GRB itself, and...
4 SUMMARY AND CONCLUSIONS

We have shown how material ejected in disc winds subsequent to a compact object merger can give rise to both optical and infrared kilonova emission. We considered the dependences on key parameters such as the delay until BH formation, BH spin, and the presence of neutron-rich dynamical ejecta. In Fig. 9, we summarize schematically the range of possible kilonova properties, and illustrate how they roughly map to the progenitor binary and remnant type. Our main findings are as follows.

(1) For the characteristic entropies and expansion times of disc winds, we find that the abundance of lanthanides cuts off sharply when the electron fraction $Y_e > 0.25$ (Fig. 3). The electron fraction in turn is very sensitive to the level of neutrino irradiation of the wind and hence acts as a diagnostic of the physical conditions in the aftermath of the merger (Metzger & Fernández 2014).

(2) The presence of optical emission is a ubiquitous feature of the disc wind ejecta, even in the case of non-spinning, promptly formed BH remnants (Fig. 4). The magnitude and duration of this optical component is a sensitive function of the lifetime of an HMNS or the spin of the promptly formed BH. In the limit of a very long lived HMNS, photons emerge primarily in the optical, reaching luminosities up to $10^{45} \, \text{erg s}^{-1}$ for moderate disc masses ($0.03 \, M_\odot$).

(3) The ratio of the optical to infrared luminosity from a kilonova provides a powerful measure of the relative mass of high-$Z$ to low-$Z$ ejecta. Using this information to infer the underlying physical scenario, however, may be difficult given the degeneracies. For example, the wind ejecta from a promptly formed, rapidly spinning BH produces a similar kilonova light curve to that of a long-lived HMNS (Fig. 5).

(4) Because the expansion velocities of the wind are moderate ($\sim 10000 \, \text{km s}^{-1}$), numerous line absorption features are discernible in the spectra (Fig. 6). This distinguishes the spectra of disc winds from those of fast-moving dynamical ejecta, for which the line features are broader and heavily blended. Observing the spectra of wind ejecta may thus allow us to study the detailed composition of freshly produced r-process material. At present, however, the atomic data are not good enough to predict all line wavelengths, and additional atomic structure calculations are needed.

(5) The optical emission from a disc wind can be easily obscured by even a small amount ($10^{-4} \, M_\odot$) of neutron-rich dynamical ejecta, causing most of the flux to emerge in the near-infrared. In the case of NS–NS mergers, this dynamical ejecta is expected to be nearly isotropic, reducing the likelihood of observing an optical component (Fig. 7). For BH–NS mergers, the confinement of the dynamical ejecta to the equatorial plane makes the detection of optical emission more promising from polar viewing angles (Fig. 8).

(6) The infrared emission observed following GRB 130603B can be explained by a disc wind only if the merger formed a rather massive disc ($\sim 0.3 \, M_\odot$). The optical bump observed following GRB 080503 (with a redshift of $z = 0.25–0.5$) can be nicely explained by a wind from a moderately massive disc ($\sim 0.03 \, M_\odot$) irradiated by a long-lived HMNS.

Our calculations have illustrated the key dependences of kilonova light curves from disc winds; however, several improvements are needed to generate reliable, quantitative theoretical predictions. On the wind dynamics side, a more advanced neutrino transport scheme is required to better quantify the distribution of electron fraction in the ejecta. Inclusion of magnetohydrodynamics (as opposed to an $\alpha$-viscosity) and full general relativity is also very important to quantify the amount and composition of the ejected mass. Using more realistic initial conditions, taken from an actual merger simulation, would provide a better description of the relative size and spatial distribution of the dynamical ejecta and accretion disc. An accurate determination of the final composition of the wind requires post-processing of multiple fluid elements with nuclear-reaction networks, as opposed to the single entropy mapping used in this paper. On the radiative transport side, better line data for the high-$Z$ elements, in particular the lanthanides and actinides, is necessary to calculate the pseudo-continuum opacity and line features.
Kilonova light curves from disc winds

Figure 9. Schematic illustration of the mapping between mergers and kilonova light curves. The top panel shows the progenitor system, either an NS–NS or an NS–BH binary, while the middle plane shows the final merger remnant (from left to right: an HMNS that collapses to a BH after time \( t_{ns} \), a spinning magnetized NS, a non-spinning BH and a rapidly spinning BH). The bottom panel illustrates the relative amount of UV/blue emission from an n-precursor (purple), optical emission from lanthanide-free material (blue) and IR emission from lanthanide containing ejecta (red).

We also need a better understanding of the radioactive decay energy rate, and the thermalization efficiency of decay products (electrons, gamma-rays and fission fragments). Work along many of these lines is progressing, and will eventually allow for more robust predictions of kilonova light curves.

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