Faint Rapid Red Transients from Neutron Star - CO White Dwarf Mergers

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ABSTRACT

Mergers of neutron stars (NS) and white dwarfs (WD) may give rise to observable explosive transient events. We use 3D hydrodynamical (SPH) simulations, as well as 2D hydrodynamical-thermonuclear simulations (using the FLASH AMR code) to model the disruption of CO-WDs by NSs, which produce faint transient events. We post-process the simulations using a large nuclear network and make use of the SuperNu radiation-transfer code to predict the observational signatures and detailed properties of these transients. We calculate the light-curves (LC) and spectra for five models of NS - CO-WD mergers. The small yields of $^{56}\text{Ni}$ (few $\times 10^{-3} M_\odot$) result in faint, rapidly-evolving reddened transients (RRTs) with $B$ ($R$) - peak magnitudes of at most $\sim -12$ ($-13$) to $\sim -13$ ($-15$), much shorter and fainter than both regular and faint/peculiar type-Ia SNe. These transients are likely to be accompanied by several months-long, 1–2 mag dimmer red/IR afterglows. We show that the spectra of RRTs share some similarities with rapidly-evolving transients such as SN2010x, although RRTs are significantly fainter, especially in the I/R bands, and show far stronger Si lines. We estimate that the upcoming Large Synoptic Survey Telescope could detect RRTs at a rate of up to $\sim 10^{-70}$ yr$^{-1}$, through observations in the R/I bands. The qualitative agreement between the SPH and FLASH approaches supports the earlier hydrodynamical studies of these systems.

Key words: stars: neutron – white dwarfs – supernovae: general

1 INTRODUCTION

Mergers of neutron stars (NSs) or black holes (BH) with white dwarfs (WDs) have been explored through several hydrodynamical and nuclear-hydrodynamical simulations, e.g. Fernández & Metzger (2013a); Bobrick et al. (2017); Zenati et al. (2019); Fernández et al. (2019). All CO WD-NS mergers are expected to lead to unstable mass transfer (Bobrick et al. 2017) where the WD is tidally disrupted on dynamical timescales and forms an extended debris disk around the NS (Papaloizou & Pringle 1984; Fryer et al. 1999). The disc evolves mostly viscously but is also affected by nuclear burning. Disc viscosity and nuclear burning together power outflows throughout the disc (Metzger 2012). Nuclear burning in the disc proceeds steadily (with a possible weak detonation) and produces small amounts of $^{56}\text{Ni}$ (at most $10^{-2} M_\odot$), e.g. Zenati et al. (2019). Such a small amount of $^{56}\text{Ni}$ is expected to lead to optical transients which are much fainter than ordinary type Ia supernovae (SNe; which produce more than an order of magnitude more $^{56}\text{Ni}$). In this paper, we present the first synthetic LCs and spectra for CO WD-NS mergers and show that they may give rise to a novel class of faint, rapid transients (RRTs), with no evidence for hydrogen or helium.

To model the merger, we use two approaches. The first approach makes use of 2D coupled hydrodynamical-thermonuclear simulations with the FLASH code, similar to the method introduced by Fernández & Metzger (2013b). In these simulations, the NS-WD merger is followed only from the advanced stage at which the debris disk of the disrupted WD has already formed and given rise to an axisymmetric structure which can be explored in 2D (Zenati et al., hereafter Paper I). In the second approach, we applied a 3D SPH code to follow the full NS-WD merger, including the early pre-disruption phase, but with nuclear burning treated only in a post-processing step. As we discuss below, these two approaches are complementary and generally produce very similar results.

As we and others have already found (Fernández & Metzger 2013b; Zenati et al., 2019), the evolution of the merger and the evolution of the WD debris disk are dominated by the viscous evolution and the gravitational energy, with nuclear burning playing only a minor role in the structural evolution of the disk and the outflows, but playing an impor-
The initial parameters of the simulated NS-WD merger models. The columns show the names of the models, the masses of the WDs ($M_{\text{WD}}$) in solar masses, the maximum density in the torus in our FLASH simulations ($\rho_{\text{max}}$), the torus radius in units of the tidal radius ($R_0/r_t$) and the initial mass fractions of He, C and O. The last three columns show the kinetic energy at the end of the FLASH simulations and the total mass of iron-group ejecta (IGE) and all of the ejecta ($M_{\text{tot}-\text{ij}}$). The energy powering the outflows comes almost entirely from accretion and not the nuclear processes involved, e.g. Zenati et al. (2019).

| # | $M_{\text{WD}}[M_\odot]$ | $\rho_{\text{max}}[g/cm^3]$ | $R_0/r_t$ | $\%\text{He}_4$ | $\%\text{C}_{12}$ | $\%\text{O}_{16}$ | $E_{\text{K}}[\text{erg}]$ | $\text{IGE}_[10^{-3}M_\odot]$ | $M_{\text{tot}-\text{ij}}_[10^{-3}M_\odot]$ |
|---|-----------------|-----------------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C | 0.55 | $8.5 \times 10^6$ | 0.8 | -- | 50 | 50 | $2.8 \times 10^{45}$ | 9.0 | 19 |
| D | 0.63 | $6.4 \times 10^6$ | 1 | 9 | 50 | 41 | $3.6 \times 10^{49}$ | 9.6 | 210 |
| E | 0.63 | $8.5 \times 10^6$ | 0.8 | 4 | 49 | 47 | $1.4 \times 10^{49}$ | 6.1 | 90 |
| F | 0.63 | $2.3 \times 10^6$ | 1.1 | -- | 50 | 50 | $1.5 \times 10^{48}$ | 8.1 | 10 |
| * | 0.8 | $4.4 \times 10^6$ | 0.8 | -- | 50 | 50 | $3.2 \times 10^{49}$ | 45 | 94 |

Table 1.

2. METHODS

Our original FLASH simulations and their results are described in detail in Zenati et al. (2019) (Paper I). Here we briefly summarize the main ingredients of the model: the WD profiles produced with the MESA stellar evolution code, the simulations of the debris disk evolution with the FLASH code, and the nuclear post-processing - all of which we already described in Paper I. We then focus on the new FLASH simulations using the Water code and then describe our radiation-transfer modelling with the SuperNu code and the resulting observational signatures (light-curves and spectra), which are the main focus of the current paper.

2.1 The neutron star and white dwarf models

We describe the properties of each of the NS-WD models we simulated in Table 1. We obtained the structural properties of the WDs through detailed stellar evolution models of single and binary stars using the MESA code (Paxton et al. 2011, 2013, 2015). In all cases, we considered only stellar progenitors of solar metallicity. Our models include both typical CO WDs as well as hybrid HeCO WDs. The former are the outcomes of regular evolution of single stars, which results in WDs composed of ~ 50% carbon and ~ 50% oxygen. The hybrid WDs, containing both CO and He, are the outcomes of binary stellar evolution, as described in Zenati et al. (2018). Subsequently, we used these stellar profiles to set up our WD models in the SPH code and their bulk compositions to set up the disrupted WD’s in the FLASH code.

We do not resolve the NSs in our simulations and model them as point masses. We considered two NS masses, 1.4 $M_\odot$ and 2 $M_\odot$, which corresponds to the typical range of NS masses observed in binary radio pulsars, e.g. Lattimer (2012).

2.2 FLASH simulations

During the early stages of disruption, the NS tidally shreds the WD into a debris disc, e.g. Papaloizou & Pringle (1984); Fryer et al. (1999). The detailed initial conditions and the structure and evolution of the modelled disc can be found in Paper I.

We simulate the evolution of such a disc using the publicly available FLASH code v4.2 (Fryxell et al. 2000). We employ the unsplit PPM solver of FLASH hydrodynamics code in 2D axisymmetric cylindrical coordinates on a grid of size $1 \times 10^{10}$ cm using adaptive mesh refinement. We follow the approach similar to the one adopted in other works on thermonuclear SNe (e.g. Meakin et al. 2009). We handle detonations by the reactive hydrodynamics solver in FLASH without the need for a front tracker, which is possible since unresolved Chapman–Jouguet detonations retain the correct jump conditions and propagation speeds.

In the cases of NS - HeCO-WD mergers (models D and E), we identify the ignition and detonation of helium in the accretion disk. The helium ignition occurs at sufficiently high accretion rates at densities of $\rho \gtrsim 8 \times 10^6 g/cm^3$, which, through supersonic burning, gives rise to a (weak) He-detonation in the HeCO mixed layer.

In the cases of NS - CO-WD mergers, the required pressure and density for a weak detonation are $P \gtrsim 2 \times 10^{25}$ erg cm$^{-3}$ and $\rho \gtrsim 2.5 - 3 \times 10^6 g/cm^3$, respectively, which is higher than in the case of NS-He CO mergers. The timescale for $C_{12}$ burning is also much longer, in effect leading to a different and delayed (by about one second) detonation compared to the HeCO WD cases.

In this work, we have also checked the resolution convergence following Fisher et al. (2019) and have not observed
any changes in the evolution of the disk. We evolved our simulations for (175-270) s. In one test case, we ran a lower-resolution model for up to 400 s. In comparison, the orbital timescale at the circularisation radius in case of model D, is about 40 seconds. The viscous timescale at the circularisation radius $R_\text{0}$, given by:

$$t_{\text{visc}} \sim 260 \left( \frac{0.1}{\alpha} \right) \left( \frac{R_0}{10^{10} \text{ cm}} \right)^{3/2} \left( \frac{1.4 M_\odot}{M_c} \right)^{1/2} \left( \frac{H_0}{0.5 R_0} \right)^{2} \text{ s},$$

is about 260 seconds, assuming the alpha-disc model parameter $\alpha = 0.1$, as adopted in our FLASH simulations. In the equation, $M_c$ is the central mass of the NS and $H_0$ is the scale height in the disc. In the inner regions of the disc, where most nuclear burning takes place, due to a smaller radius, the viscous timescale is only a few tens of seconds, which is well covered by our runs.

While our FLASH simulations do not capture all the de-
Figure 2. The evolution of the WD debris for model E based on FLASH simulations. The panels show the colour coded density distribution and velocity fields (black arrows) throughout the simulation. The velocity scale is $4500 \text{ km} \cdot \text{sec}^{-1}$. Magenta lines show the surfaces of constant temperature.
talls of the initial 3-dimensional onset phase of mass transfer in the binaries, the orbital and viscous timescales of the disc are well captured by our models. The simulation timescales also agree with the timescales of our SPH simulations, which also last for several hundreds of seconds. The overall similarity of the nuclear abundance patterns and a reasonable, typically up to 1 dex, agreement of the nuclear yields supports the picture that both codes capture the phase which is most relevant to nuclear burning.

As discussed in detail in Paper I, we use the Helmholzt EOS (Timmes & Swesty 2000), and account for self-gravity of the disk. We employ a 19-isotope reaction network with correct treatment of the burning front (Fryxell et al. 1989). To prevent the production of artificial unrealistic early detonation that may arise from insufficient numerical resolution, we applied a limiter approach following Kushnir et al. (2013). Further details of these simulations can be found in Paper I. The initial conditions and the outcomes of the simulations we use in the current paper are summarized in Table 1.

### 2.3 SPH simulations

We have complemented and verified our modelling with theFLASH code using by using a smoothed particle hydrodynamics (SPH) code Water (Bobrick et al. 2017). We set up the SPH simulations and their post-processing aiming to reproduce the same physical mergers like the ones modelled by the FLASH method. The SPH approach allows us to evolve the models from early stages of mass transfer in 3D and follow the disruption of the WD and the formation of the disc, while our 2D FLASH simulations can only be initiated at a late stage when a WD debris disk is already assumed to have formed. On the other hand, our SPH models only include nuclear burning as a post-processing step. The two approaches, therefore, are different and complement each other.

The Water code is based on the most up-to-date SPH prescriptions available and derived from the Oil-on-Water code used to model the onset stages of mass transfer (Bobrick et al. 2017), see also Church et al. (2009). We refer to Bobrick et al. (2017) for full implementation details and summarise the key components of the code below.

We solve the Navier-Stokes equations by discretizing the Lagrangian as done in Springel (2010). This way, we ensure exact energy and momentum conservation, only limited by the accuracy of the graviy solver, which we implement as in Benz et al. (1990). We limit the maximum radius of SPH particles in a Lagrangian and continuous way, thus partially mitigating the so-called fall-back problem when ejected particles become large and acquire too many neighbours upon falling back on the donor. We use Wendland W6 kernels (Dehnen & Aly 2012), which prevent pairing instability by falling back on the donor. We use Wendland W6 kernels throughout the WD-debris disk with a core radius of 0.1 $R_{\text{WD}}$ and have checked the convergence by simulating models in 20 K, 50 K and 100 K resolution.

### 2.4 Nuclear post-processing

We use a 19-isotope $\alpha$-chain network in the FLASH simulations and do not evolve chemical compositions in the SPH simulations. The $\alpha$ network can adequately capture the energy generated during nuclear burning (Timmes & Swesty 2000). To verify the abundances produced by the FLASH code and to calculate the detailed nuclear yields for the SPH runs, we applied a nucleosynthetic post-processing step with a large network. For the grid-based FLASH simulations, we made use of 4000-10000 tracer particles to follow the evolution and to track the composition, velocity, density, and temperature of the WD debris. These particles were evenly spaced throughout the WD-debris disk with a step of $2 \times 10^4$ cm. The detailed histories of density and temperature from tracer particles (from FLASH) and SPH particles (from the SPH Water code) were post-processed with MESA (version 10390) one-zone burner (Paxton et al. 2015). We employed a 125-isotope network that includes neutrons and composite reactions from JINA REACLIB (Cyburt et al. 2010). We subsequently used the outputs of the original $\alpha$ network in the FLASH case, to correctly weigh the nuclear abundances over the material, and the outputs of the $\alpha$ network in the SPH case.
detailed MESA PPN network in the SPH case for further analysis.

2.5 Radiation transfer modeling using SuperNu

Following the nuclear post-processing, we mapped the physical properties from this step as inputs for the openly available radiation transfer code SuperNu (Wollaeger et al. 2013; Wollaeger & van Rossum 2014) in order to calculate the light-curves (LC) and spectra expected from the mergers. SuperNu uses Implicit Monte Carlo (IMC) and Discrete Diffusion Monte Carlo (DDMC) methods to stochastically solve the special-relativistic radiative transport and diffusion equations to first order in \( v/c \) in three dimensions. The hybrid IMC and DDMC scheme used in SuperNu makes it computationally efficient in regions with high optical depth. This approach allows SuperNu to solve for energy diffusion with very few approximations, which is very relevant for supernova light curves.

SuperNu code follows the free-expansion phase of supernovae using a velocity grid. We map the 3D velocities of the FLASH material and the SPH particles to a 1D-spherical light-curves (LC) and spectra expected from the mergers in SuperNu, as they are, at the end of simulations. In other words, we set the masses in each of the grid cells of SuperNu equal to the sum of the masses of the corresponding elements (grid cells for FLASH, particles for SPH). We set the chemical compositions and electron fractions \( Y_e \) as the mass-weighted average compositions in each cell. Unlike the Eulerian-based FLASH code, SuperNu can handle true vacuum within cells. Consequently, zero-mass grid cells containing no mapped particles require no special treatment, although the velocity distributions did not contain any significant gaps.

Since most of the material is gravitationally bound at the end of the simulations, both in FLASH and SPH, mapping the 3D velocities directly to SuperNu represents fast dynamical ejecta and is an approximation, as we discuss in Section 4. To check for the effect of the additional ejecta released as a slow wind, we additionally initialised SuperNu by randomly assigning the element velocities typical spread of 200 km/s with a 1-\( \sigma \) spread of 200 km/s. As we discuss in Section 4 the true fractions of material in fast and slow ejecta are uncertain, and thus we obtain the characteristic signal expected from both types of ejecta.

We initialised the SuperNu code at 0.5d after the merger. The homologously expanding material adiabatically cools down by at least six orders of magnitude in temperature by this point. We set the temperature of the material initialised in SuperNu to upper estimate value of \( 10^5 \) K. Setting initial temperatures to values lower than \( 10^5 \) K led to essentially the same lightcurves or spectra. We have also verified that the input distributions for SuperNu from SPH and FLASH simulations broadly looked similar.

Figure 3. The bolometric lightcurves. Top: The bolometric lightcurves for all models based on the FLASH and SPH simulations. The subplot shows the light curves for all the models based on the FLASH simulations. Bottom: Comparison of the bolometric lightcurves from the SPH and the FLASH models for models D and E.

3 RESULTS

3.1 Merger dynamics

We infer the three-dimensional picture of the merger and its long-term behaviour from our SPH simulations (see Fig. 1). Initially, the mass-transfer rates are low, and the evolution resembles that of stably transferring binaries. However, as the Roche lobe gradually cuts off increasingly large fractions of the donor, the mass transfer rate grows over time. At a certain point, the mass transfer rate is so high, that the donor effectively becomes gravitationally unbound and enters a free fall onto the accretor Margalit & Metzger (2016). During this phase, the tidal forces stretch the white dwarf (see figure 1), causing it to self-intersect, thus producing shocks and circularising the material into a disc. The density and temperature rise in the shocked regions, which leads to, initially mild, nuclear burning. Due to the limitations of the 2D models, our 2D FLASH models (see Fig. 2) begin only after the formation of the debris disk and subsequently follow its nuclear-hydrodynamic evolution.

In the FLASH models, we see that as the density and temperature increase in the inner regions, they attain critical conditions for thermonuclear burning, which leads to a weak explosive detonation. We discuss this in more detail in Paper I. However, only a small fraction of the accreting material participates in thermonuclear burning. As a result, this produces only small amounts of nuclear by-products. Both the FLASH and the post-processing of the
NS-WD mergers

| # | \(M_{\text{WD}}[M_\odot]\) | \(^{56}\text{Ni} \times 10^{-3}[M_\odot]\) | \(B_{\text{peak}}\) | \(\Delta B_{15}\) | \(R_{\text{peak}}\) | \(\Delta R_{15}\) | \(I_{\text{peak}}\) | \(\Delta I_{15}\) |
|---|---|---|---|---|---|---|---|---|
| C | 0.55 | 5.25 (6.51) | -12.81 (12.68) | 4.50 (2.85) | -14.70 (14.66) | 3.29 (1.81) | -14.93 (14.89) | 2.04 (1.78) |
| D | 0.62 | 6.16 (10.03) | -12.80 (12.66) | 3.41 (2.68) | -14.72 (15.11) | 2.75 (1.54) | -14.98 (15.26) | 2.01 (1.57) |
| E | 0.62 | 2.84 (10.14) | -12.92 (12.92) | 3.48 (1.95) | -14.25 (14.90) | 2.82 (1.44) | -14.75 (15.01) | 2.10 (1.40) |
| F | 0.62 | 3.88 (8.82) | -12.19 (12.40) | 3.64 (2.47) | -14.36 (14.79) | 2.77 (1.36) | -14.80 (14.91) | 2.02 (1.49) |
| J | 0.8 | 1.78 (20.16) | -10.88 (12.28) | 3.55 (2.67) | -13.21 (14.35) | 1.91 (1.52) | -13.87 (14.85) | 1.82 (1.42) |

Table 2. The outcomes of the merger models explored in this study, based on FLASH simulations and SPH results in close brackets. The columns correspond to: model number (1); the white dwarf mass (2); the amount of \(^{56}\text{Ni}\) produced (3); the B-peak luminosity (4); the decrease in B-magnitude over 15 days since the peak (\(\Delta B_{15}\)) (5); the R-peak luminosity (6); the decrease in R-magnitude over 15 days since the peak (\(\Delta R_{15}\)) (7); the I-peak luminosity (8) and the decrease in I-magnitude over 15 days since the peak (9).

Figure 4. The UBVRI light curve (LC) for model D (left) and model E (right). The top panels show the results from the radiative transfer processing of the SPH simulations. The bottom panels show for the same models from based 2D FLASH simulations.

SPH modelling show that the mergers produce only up to \(\sim 10^{-3} - 10^{-2} M_\odot\) of intermediate or even iron group elements. In particular, the amount of \(^{56}\text{Ni}\) is always at most \(10^{-2} M_\odot\). The bulk of the nuclear material is produced in the developed disc stages, well represented both by SPH and FLASH. The total released nuclear energy, as reported from the 19-isotope network in FLASH simulation, reaches only up to \(\sim 10^{49} - 10^{51}\) erg. For comparison, the amount of the released gravitational energy, calculated as the total increase in the kinetic and internal energies minus the total generated nuclear energy, see, e.g. (Fernández & Metzger 2013a; Zenati et al. 2019; Fernández et al. 2019), is a few times \(10^{47}\) to \(10^{49}\) erg. Thus, the released gravitational energy is 10 to 100 times larger than the released nuclear energy. Hence, gravitational dynamics drives most of the outflows and heats most of the material in the systems.

Figure 5. Spectra for models C, F and J from the FLASH simulations shown at different times (top panel), spectra for model F superposed with spectra from SN2010xs and SN2005ek (middle panel) and a comparison of the FLASH- and SPH-based spectra for model D (bottom panel).

Our models do not follow the long-term evolution of the NS-WD mergers and, in particular, the evolution of the fallback material that could potentially contribute to the transient luminosity. Nevertheless, we briefly discuss a simplified analytical model for the possible fallback contribution in the Appendix. We find that the fallback material is unlikely to contribute significantly to the transient energetics and the observable lightcurves.

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the range $3.35 \pm 4.5$) and rapid decline in the redder bands ($\Delta B_{15}$ in the range $1.8 \pm 2.34$). Such rapid red transients (RRTs), as predicted by our models, are difficult to observe in current surveys, and have not been observed yet to the best of our knowledge. Nevertheless, next-generation surveys such as the upcoming Large Synoptic Sky Survey (LSST), might be able to observe tens of such events every year (see the next section). An observational feature specific to these transients may be a faint (up to mag $-13$) $^{56}$Ni-powered several-months long secondary red afterglow transient. Due to lower ejection velocities compared to RRTs, the expansion happens on roughly 10 times longer timescales, resulting in larger diffusion time, later nebular phase and several month-long peak half-times. The peak luminosity of these secondary transients are an upper estimate and are likely lower, depending on the fraction of the mass lost through the disc wind ejecta.

Our results show comparable ranges of ejected masses, velocities, and $^{56}$Ni production as found in the simplified 1D models by Margalit & Metzger (2017a). These earlier models provided basic estimates for the bolometric light curves which are broadly in agreement with our detailed bolometric light curves.

### 3.3 Rate estimates

Despite the relatively small peak luminosities of such transients, upcoming synoptic surveys such as LSST will observe them frequently. With the $5\sigma$ magnitude limits for single-visit detections of 24.0 and 24.7 in I and R bands, respectively (LSST Science Collaboration et al. 2009), LSST will be able to detect such transients within 15 days past the peak up to a distance of 250 Mpc. In order to estimate the detection rates, we assume that the merger rates of CO WD-NS binaries scale with the blue luminosity (total luminosity, e.g. of galaxies, in the B-band). By using the galactic merger rate of $1 \pm 2 \times 10^{-4}$ yr$^{-1}$ from our population synthesis studies of NS-WD mergers (Toonen et al. 2018), the galactic blue luminosity of $1.7 \times 10^{10} L_{B,\odot}$ (Kalogera et al. 2001) and the blue luminosity for the local universe $1.98 \times 10^{8} L_{B,\odot}$/Mpc$^3$ (Kopparapu et al. 2008), we find that LSST will detect between 10 and 70 transients per year within its field of view. The detection efficiency is similar for R and I bands. In comparison, the ongoing ZTF survey is expected to observe between 0.05 and 0.3 such transients per year, assuming R-band detection limit of 21, consistent with the current null-detection of such transients by ZTF.

### 3.4 Composition

The detailed composition yields from our FLASH models have already been presented in detail in Paper I. The results from the post-processing of the SPH simulations show overall agreement with the FLASH results. The nuclear yields for most alpha-elements, as well as $^{56}$Ni, are within 1 dex, as produced by the two codes, and the abundance patterns look similar, although suggesting systematically somewhat lesser production of burned material in FLASH. The detailed comparison for 17 elements can be seen in Fig. 7.

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**Figure 6.** Light curve (top panel), BVRI bands (middle panel) and spectra (bottom panel) for the largest possible secondary transient for model D, in which all the material is ejected as a slow wind $v = 400$ km/s, and a 1-$\sigma$ spread of 200 km/s. The upper panel: the light curve zoom on the first 240 days, the middle panel shows the light curve for up to 372 days. The middle panel: lightcurves in the B, V, R, I bands. U band is not shown since its luminosity is below mag $-8$. The lower panel: the spectra at $-1$, 50, 100, 150 days after peak. The secondary red transient is expected to have a wide peak with half-time of $\sim 50$ d, while its peak magnitude is expected to be no larger than in this example.

**3.2 Light curve and spectra properties**

Figures 3 and 4 show the resulting bolometric and UBVRI lightcurves from our models, while Fig. 5 shows the predicted spectra from these models. Table 2 summarizes the basic properties of the transients. Figure 6 shows the lightcurve and spectra for the possible secondary transient from the disk-wind material.

As can be seen, our models predict that NS - CO-WD mergers give rise to vary faint transients with absolute B magnitudes in the range between $-10.9$ and $-12.8$. These transients are far brighter in the I/R bands, with peak I magnitudes in the range between $-13.9$ and $-15$. These transients show extremely fast decline in the B-band ($\Delta B_{15}$ in
DISCUSSION AND SUMMARY

In our study, we explored the observable manifestation of transients from NS-WD mergers. We have made use of AMR and SPH hydrodynamical simulations to model the mergers of NSs with CO WDs, followed their thermonuclear evolution through concurrent and post-process analysis and then used radiative-transfer models to predict the expected lightcurves and spectra of such transients. We generally find that NS-WD mergers give rise to ultra-faint, rapidly evolving reddened transients (RRTs), likely observable with next-generation surveys such as the LSST.

In our study, we have qualitatively confirmed, for the first time with a 3D code, the nuclear yields in NS-WD mergers obtained in earlier axisymmetric simulations, e.g. (Fernández & Metzger 2013a; Zenati et al. 2019; Fernández et al. 2019). As discussed in Section 2.5, the fraction of the fast material ejected dynamically, is the major uncertainty in our model, and our synthesised lightcurves provide the maximal expected signal expected for RRT. The FLASH simulations, dominated by α-viscosity, may be representative of the MRI-dominated disc stage following the merger and produce up to 0.1-0.2 $M_\odot$ of fast ejecta, thus supporting the idea that the amount of fast ejecta may be significant. The slow disc ejecta produced later on may result in a faint red several months-long afterglow. The subsequent evolution of the remnant object has been studied in detail by Margalit & Metzger (2017b).

Our predicted RRTs are much fainter and faster evolving than both typical Ia SNe as well as other peculiar faint and/or rapid transients observed to date. Over the last two decades several classes of fast-evolving SNe had been identified (de Vaucouleurs & Corwin 1985; Poznanski et al. 2010; Tutukov et al. 1992; Kasliwal et al. 2010; Perets et al. 2011; Drout et al. 2013, 2014; Ruiter 2020). However, RRTs are too faint and typically redder than these SNe. Even the faintest rapidly evolving SNe differ significantly from our predicted RRTs, as can be seen in the lightcurve in figure 8 comparing SN 2010X and SN 2005ek with the RRTs. Moreover, their helium and aluminium content may be too small to explain the He and Al lines identified in these SNe (Kasliwal et al. 2010), and they show much stronger Si lines. Other faint
type Ia SNe such as Ca-rich 2005E-like SNe (Perets et al. 2010) or SN 2008ha-like SNe (Foley et al. 2009) are still much brighter in the blue bands, are not as red and decline much slower than our predicted RRTs.

Transients from NS-WD mergers may, therefore, represent a completely different class of SNe that might be observed mostly in close-by galaxies using large telescopes or possibly with next-generation surveys such as LSST, as discussed above. As we show in Toonen et al. (2018) and discuss above, the rates of NS-WD mergers could be sufficiently high as to be observed by LSST. The delay-time distribution for such mergers peaks at early times of hundreds of Myr up to one Gyr, and they are therefore expected to occur preferentially in late-type host galaxies.

Finally, as we noted in Paper I, the total masses accreted onto the NS in our models appear to be small, and we, therefore, expect that NS-WD mergers are unlikely to produce regular GRBs. Nevertheless, one cannot exclude ultra-faint long GRBs lasting over timescales comparable to accretion timescales; in this case, an ultra-long GRB accompanied by an RRT would provide a very clear smoking-gun signature for the origin of both these types of transients.

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APPENDIX: LATE-TIME FALLBACK AND FALLBACK-Powered LIGHTCURVE

A significant fraction of the mass of the disrupted WD remains bound during the entire merger. The fallback material may, therefore, accrete onto the NS and potentially contribute to the emission from the merger over long timescales after the initial disruption of the WD. However, our radiative transfer models assume a homologous expansion of the material and therefore do not account for any contribution from the fallback material.

To test how sensitive are our predictions to the way we initialize the ejecta properties in SuperNu, we, therefore, considered a simplified analytical model following Dexter & Kasen (2013). It describes how the longer-term fallback of material onto the accretor powers the evolution of the light-curve, and predicts

\[ L_{\text{fallback}}(t) = L_0 \left( \frac{t_0}{2d} \right)^n e^{-t^2/2d^2} \left( -\frac{1}{2} \right)^{n/2} \times \]

\[ \times \left[ \gamma \left( 1 - \frac{n}{2}, -\frac{t_0^2}{2d^2} \right) - \gamma \left( 1 - \frac{n}{2}, -\frac{c^2}{2d^2} \right) \right], \]

where \( \gamma(\alpha, \beta) \) is the incomplete gamma-function, \( t_0 = t_{\text{dyn}}, \) \( n = 5/3, \) and \( t_d \) follows from Arnett (1979):

\[ t_d = \sqrt{\frac{3}{4\pi} \left( \frac{M_{\text{ejecta}} + M_{\text{fallback}}}{\eta_{\text{final-ejecta}} \cdot c} \right) \kappa} \]

where \( \kappa \) is speed of light; for the complete solution see Dexter & Kasen (2013). Using this model we find that the potential contribution to the light-curves from the fallback model are \( 3 \sim 7 \) orders of magnitude smaller in luminosity compared to the ones predicted by our SuperNu modelling, or by our \( E_{\text{SN}} \) model in Zenati et al. (2019). Given these results, we believe it is safe to neglect the contribution from the emission from the fallback accretion.

In the longer term, the remnants form a stable thick disk-like puffy structure around the NS. In the yet longer-term, the leftover debris produce a more spherical cloudy structure around the NS. Its detailed evolution is beyond the scope of our models and is to be studied elsewhere.

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