

# On the Optical Transients from Double White-dwarf Mergers: A Neutron Star Remnant

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**Abstract.** Recent discoveries of ultra-massive magnetic white dwarfs and peculiar pulsars have renewed interest in non-explosive outcomes of double white dwarf (DWD) mergers. In particular, some mergers may result in the prompt or delayed collapse to a neutron star (NS). In this work, we investigate the optical transient powered by the spindown luminosity of a highly magnetized, rapidly rotating NS remnant. We model the thermal emission from the dynamical ejecta, accounting for energy injection, thermalization efficiency, and photon leakage as the ejecta expands and becomes optically thin. Using a semi-analytic model, we simulate light curves in the LSST and ZTF bands and estimate detection rates under optimistic merger scenarios. Bright transients ( $M_g \sim -15$ ) with durations of days to months are predicted for high dipole factors ( $\log D \gtrsim 32$ , with  $D = B^2/P^4$ ), detectable out to  $\sim 1$  Gpc. We find that the  $g$  and  $r$  bands offer the highest detection prospects, with potential rates up to  $\sim 10^5$  events per year for LSST under extreme assumptions. These transients provide a direct electromagnetic signature of non-explosive DWD mergers and could constrain remnant properties, progenitor masses, and the fraction of explosive versus non-explosive channels.

**Resumo.** Descobertas recentes de anãs brancas ultra-massivas e magnéticas, assim como pulsares peculiares, renovaram o interesse por desfechos não explosivos de fusões de anãs brancas duplas (DWDs). Em particular, algumas fusões podem colapsar diretamente a estrelas de nêutrons (NS). Neste trabalho, investigamos o transiente óptico impulsionado pela luminosidade de *spindown* de uma NS remanescente altamente magnetizada e de alta rotação. Modelamos a emissão térmica do ejecta dinâmico, levando em conta injeção de energia, eficiência de termalização e vazamento de fótons à medida que o ejecta se torna ópticamente fino. Usando um modelo semi-analítico, simulamos curvas de luz nas bandas do LSST e ZTF e estimamos taxas de detecção sob cenários otimistas. Transientes brilhantes ( $M_g \sim -15$ ) com durações de dias a meses são previstos para altos fatores dipolares ( $\log D \gtrsim 32$ , com  $D = B^2/P^4$ ), detectáveis até  $\sim 1$  Gpc. Encontramos que as bandas  $g$  e  $r$  oferecem as melhores perspectivas, com taxas potenciais de até  $\sim 10^5$  eventos/ano no LSST. Esses transientes constituem uma assinatura eletromagnética direta de fusões não explosivas de DWDs e podem restringir propriedades do remanescente, massas progenitoras e a fração de canais explosivos *versus* não explosivos.

**Keywords.** white dwarfs – neutron stars – transients – double degenerate mergers – optical emission

## 1. Introduction

Double white dwarf (DWD) mergers are among the most common compact binary coalescences in the Universe. While some lead to thermonuclear explosions such as Type Ia supernovae (Iben & Tutukov 1984; Paczyński 1985), others may avoid detonation and leave behind a compact remnant: either a white dwarf (WD) or, under sufficient total mass and central compression, a neutron star (NS) (Saio & Nomoto 1985; Nomoto & Iben 1985; Becerra et al. 2018). The detection of ultra-massive white dwarfs and fast-spinning, highly magnetized pulsars has recently strengthened the plausibility of the latter channel.

Electromagnetic counterparts to non-explosive DWD mergers have been proposed in several forms. Sousa et al. (2023) explored optical transients powered by fallback accretion onto a central WD, predicting peak luminosities of  $\sim 10^{41}$  erg s<sup>-1</sup>. However, if the merger leads instead to a NS, the energy reservoir changes dramatically. Conservation of angular momentum and magnetic flux during collapse implies the birth of a millisecond, magnetar-strength neutron star, whose dipole spindown can inject up to  $10^{48}$ – $10^{50}$  erg into the surrounding ejecta.

Here, we focus on this NS-powered channel. We improve upon previous treatments by explicitly modeling the time-dependent thermalization and leakage of injected radiation as the ejecta expands. This allows us to compute realistic light curves

across optical bands and estimate detection prospects for current and upcoming surveys like ZTF and LSST.

## 2. Model Overview

We model the optical transient produced when a NS formed as the remnant of a DWD merger injects rotational energy into the surrounding dynamical ejecta. The thermalization of this energy and the subsequent radiative cooling of the ejecta generate a detectable optical signal. The model combines a geometric description of the ejecta with a treatment of energy injection, thermalization, and leakage.

### 2.1. Geometry of the Ejecta and Radiative Transfer

The dynamical ejecta is assumed to be spherically symmetric, unbound, and described by a power-law density profile  $\rho \propto r^{-m}$ . Following Sousa et al. (2023), we discretize the ejecta into  $N$  non-interacting, homologously expanding mass shells, indexed from  $i = 0$  (innermost) to  $i = N$  (outermost). Each shell evolves independently as:

$$r_i(t) = \tilde{r}_i \left( \frac{t}{t_*} \right)^n, \quad v_i(t) = \tilde{v}_i \left( \frac{t}{t_*} \right)^{n-1},$$

where  $\tilde{r}_i$  and  $\tilde{v}_i$  are the initial radius and velocity of shell  $i$ ,  $n \approx 1$  is the expansion index (homologous flow), and  $t_* = n\tilde{r}_0/\tilde{v}_0$  is a characteristic expansion timescale.

The density of each shell is:

$$\rho_i(t) = \tilde{\rho}_0 \left( \frac{\tilde{r}_0}{\tilde{r}_i} \right)^m \left( \frac{t}{t_*} \right)^{-3n},$$

with normalization

$$\tilde{\rho}_0 = \frac{3-m}{4\pi} \frac{m_{\text{ej}}}{\tilde{r}_0^3} \left[ \left( \frac{\tilde{r}_N}{\tilde{r}_0} \right)^{3-m} - 1 \right]^{-1},$$

where  $m_{\text{ej}}$  is the total ejecta mass.

Assuming a gray opacity  $\kappa = 0.2 \text{ cm}^2 \text{ g}^{-1}$ , the optical depth of shell  $i$  is:

$$\tau_i(t) = \int_{r_i}^{\infty} \kappa \rho(r, t) dr = \tilde{\tau}_i \left( \frac{t}{t_*} \right)^{-2n},$$

with

$$\tilde{\tau}_i = \frac{m-3}{m-1} \frac{\kappa m_{\text{ej}}}{4\pi \tilde{r}_0^2} \left[ \frac{(\tilde{r}_0/\tilde{r}_i)^{m-1} - (\tilde{r}_0/\tilde{r}_N)^{m-1}}{1 - (\tilde{r}_0/\tilde{r}_N)^{m-3}} \right].$$

The total optical depth seen by photons from the central engine is  $\tau_0(t) \equiv \tau_{i=0}(t)$ .

The radial depth from which photons escape freely is, defined by the photospheric radius  $R_{\text{ph}}(t)$  defined by  $\tau(R_{\text{ph}}, t) = 1$ . When the ejecta becomes optically thin ( $\tau_0 \ll 1$ ), we set  $R_{\text{ph}} = r_0$  (the innermost shell radius).

## 2.2. Energetics: Central Engine, Thermalization, and Radiation

The central NS is characterized by an initial spin period  $P_0$  and surface dipole magnetic field  $B_d$ . Assuming conservation of angular momentum and magnetic flux during collapse, plausible post-merger values are  $B_d \sim 10^{10}\text{--}10^{14} \text{ G}$  and  $P_0 \sim 1 \text{ ms--}1 \text{ s}$ . This yields a large rotational energy reservoir<sup>1</sup>:

$$E_{\text{rot}} \approx 2 \times 10^{50} \left( \frac{P_0}{1 \text{ ms}} \right)^{-2} \text{ erg}.$$

This energy is released via magnetic dipole braking. Over the relevant timescales for optical transients ( $t \ll t_{\text{sd}}$ ), the spindown luminosity is nearly constant:

$$H_{\text{sd}}(t) = \frac{H_{\text{sd},0}}{(1+t/t_{\text{sd}})^2}, \quad H_{\text{sd},0} = \frac{B_d^2 R^6 8\pi^4}{3c^3 P_0^4},$$

where  $R \approx 10^6 \text{ cm}$  and the spindown timescale is

$$t_{\text{sd}} = \frac{3Ic^3 P_0^2}{4\pi^2 B_d^2 R^6} \approx 2400 \text{ yr} \quad (\text{for } B_d = 10^{12} \text{ G}, P_0 = 1 \text{ ms}).$$

However, the ejecta does not absorb all of this power. The thermalization efficiency is determined by the total optical depth:

$$\eta(t) = 1 - e^{-\tau_0(t)}.$$

Thus, the effective heating rate is:

$$H_{\text{eff}}(t) = \eta(t) H_{\text{sd}}(t),$$

<sup>1</sup> Using a typical NS moment of inertia  $I \approx 10^{45} \text{ g cm}^2$ .

and the leaked luminosity (unabsorbed, potentially observable in X-rays or radio) is:

$$L_{\text{leak}}(t) = e^{-\tau_0(t)} H_{\text{sd}}(t).$$

Energy is distributed among shells proportionally to their mass:

$$H_{\text{eff},i}(t) = \frac{m_i}{m_{\text{ej}}} H_{\text{eff}}(t), \quad m_i = \int_{r_i}^{r_{i+1}} \rho(r, t) 4\pi r^2 dr.$$

The internal energy of each shell evolves as:

$$\frac{dE_i}{dt} = -P_i \frac{dV_i}{dt} - L_{\text{cool},i} + H_{\text{eff},i},$$

with a radiation-dominated equation of state ( $E_i = 3P_i V_i$ ). The cooling luminosity due to photon diffusion is:

$$L_{\text{cool},i} = \frac{cE_i e^{-\tau_i}}{r_i}.$$

While the total thermal (blackbody) luminosity is:

$$L_{\text{rad}}(t) = \sum_{i=0}^N L_{\text{cool},i}(t),$$

and the bolometric luminosity is  $L_{\text{bol}} = L_{\text{rad}} + L_{\text{leak}}$ .

Using the Stefan–Boltzmann law, the effective temperature is:

$$L_{\text{rad}}(t) = 4\pi R_{\text{ph}}^2(t) \sigma T_{\text{eff}}^4(t).$$

Finally, absolute magnitudes in LSST *ugrizy* bands are computed by integrating the Planck function over each filter's transmission profile. Because  $H_{\text{sd},0} \propto B_d^2/P_0^4$ , we introduce the dipole factor  $D \equiv B_d^2/P_0^4$  (with  $\log D \in [24, 40]$  in cgs units) as the key parameter governing the transient's peak luminosity and duration.

## 3. Results

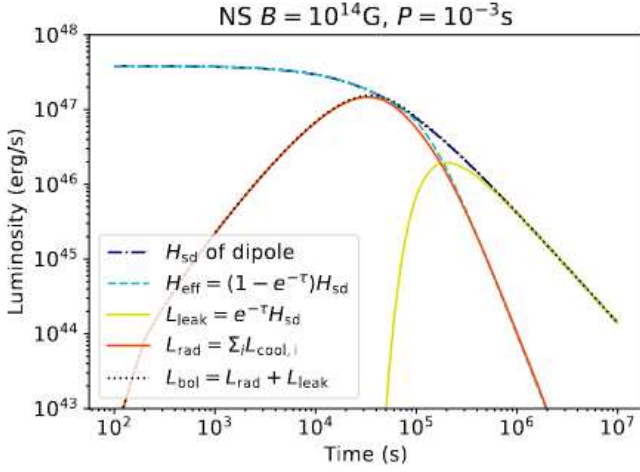
### 3.1. Light Curves, Spectra, and Parameter Dependence

We simulate the optical transient produced by the interaction between a newborn NS and the dynamical ejecta from a DWD merger. The NS is characterized by a dipole magnetic field  $B_d = 10^{10}\text{--}10^{14} \text{ G}$  and initial spin period  $P_0 = 0.1\text{--}10 \text{ ms}$ , consistent with angular momentum and magnetic flux conservation during collapse. The ejecta mass is fixed at  $m_{\text{ej}} = 0.1 M_{\odot}$ , with velocity  $v_{\text{ej}} \sim 10^8 \text{ cm s}^{-1}$ , representative of hydrodynamical simulations (Dan et al. 2014).

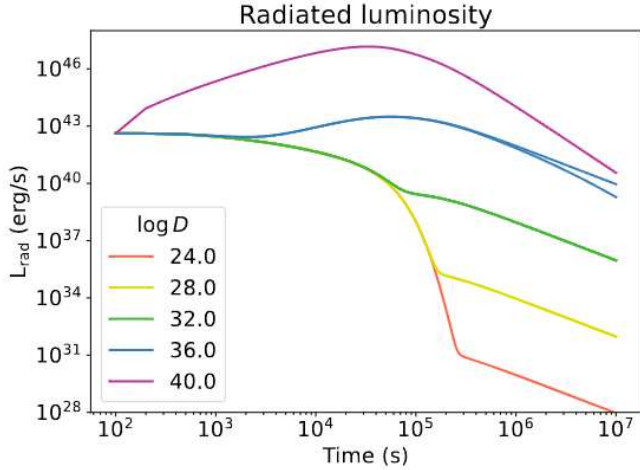
The bolometric light curve (Figure 1) for a representative case reveals three key phases:

1. Trapping phase: The ejecta is optically thick, so nearly all spindown power is thermalized.
2. Peak phase: The ejecta becomes marginally transparent, and  $L_{\text{rad}}$  reaches its maximum.
3. Leakage-dominated phase: The ejecta is optically thin, most energy escapes unthermalized, and the optical transient fades rapidly.

The diversity of transients is governed almost entirely by the dipole factor  $D \equiv B_d^2/P_0^4$ . Figure 2 shows that the peak luminosity and duration scale monotonically with  $D$ : low- $D$  systems produce faint, fast transients (peaking in hours), while high- $D$  systems yield bright events lasting weeks to months.



**FIGURE 1.** Time evolution of heating by the source ( $H_{\text{inj}} = H_{\text{sd}}$ , dark-blue, dot-dashed line), the effective injection into the ejecta ( $H_{\text{eff}}$ , blue dashed line), and the thermal radiation emitted ( $L_{\text{rad}}$ , black dotted line).  $L_{\text{bol}}$  is the sum of the radiated luminosity from the cooling of the ejecta ( $L_{\text{rad}}$ , red solid line) and the leaked luminosity ( $L_{\text{leak}}$ , green solid line).



**FIGURE 2.** Isotropic luminosity radiated by the ejecta powered by remnant NSs with varying dipole factors  $\log D = 24\text{--}40$ , illustrating the strong dependence of brightness and duration on the NS parameters.

A near-perfect degeneracy exists between different  $(B_d, P_0)$  pairs that share the same  $D$ . However, this degeneracy breaks at late times due to differences in the spindown timescale  $t_{\text{sd}} \propto P_0^2/B_d^2$ .

The spectral energy distribution evolves from blue (UV/optical) at early times to redder wavelengths as the ejecta cools. The  $g$  and  $r$  bands are expected to provide the strongest signal due to the effective temperature evolution of the ejecta.

### 3.2. Observational Prospects with LSST

We estimate that the brightest transients corresponding to highly magnetized, rapidly rotating NS remnants could reach optical magnitudes within the detection range of deep surveys such as LSST, with durations of weeks to months. In contrast, transients

from less energetic remnants fade within hours, posing a challenge for surveys with typical cadences of 2–3 days.

Assuming optimistic but plausible rates for non-explosive DWD mergers that form NS remnants, we find that LSST could detect a non-negligible number of such events per year, particularly in the  $g$  and  $r$  bands. A detailed quantification of detection rates, including band-by-band sensitivities, will be presented in the forthcoming publication.

## 4. Discussion and Outlook

NS-powered DWD transients occupy a luminosity–timescale niche between novae and supernovae, but with distinctive multi-wavelength signatures. Unlike fallback-powered WD cases (Sousa et al. 2023), the NS channel can produce significantly brighter events due to the larger rotational energy reservoir.

These transients offer a rare opportunity to probe the non-explosive DWD merger pathway. Their detection would:

- Confirm the existence of prompt or delayed NS formation from DWDs;
- Constrain the remnant’s dipole factor  $D$ , and thus  $B_d$  and  $P_0$ ;
- Provide ejecta mass estimates, linked to progenitor mass ratios (Dan et al. 2014);
- Help quantify the branching ratio between explosive (SNe Ia) and non-explosive channels.

The unthermalized spindown radiation ( $L_{\text{leak}}$ ) may produce detectable X-ray or radio counterparts, aiding identification. Furthermore, DWD binaries are prime LISA sources (Perego et al. 2025), and electromagnetic identification of post-merger transients could enable full reconstruction of progenitor parameters (Carvalho et al. 2022).

While current surveys like ZTF lack the depth and cadence for low- $D$  transients, LSST will be transformative—especially in  $g$  and  $r$ . Realistic rates depend on the (yet unknown) distribution of  $D$  among merger remnants, but even a handful of detections would open a new window into the final fate of white dwarf binaries.

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