PROCEEDINGS OF SCIENCE

Cocoon emission in neutron star mergers

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In the neutron star (NS) merger events the short gamma-ray burst (sGRB) jet heats up part of the merger ejecta producing the cocoon component. The cocoon is expected to give a bright early electromagnetic (EM) counterpart. However, in GW170817, sky localization took ∼10 hours and early EM counterparts were missed. Here, in anticipation of future GW170817-like events, we analytically model the cocoon, from the early prompt phase, and from later engine phases (i.e., extended and plateau). Then, we calculate its EM cooling emission. We find that the cocoon outshines the r-process powered kilonova/macronova at early times (10–1000 s), peaking at UV bands. In particular, later engine activity makes the cocoon emission brighter and longer. We show that the relativistic velocity of the cocoon's photosphere is measurable with instruments such as Swift, ULTRASAT and LSST. Also, we show that energetic cocoons, including failed jets, can be detected as X-ray flashes. Our model clarifies the physics and parameter dependence, enabling the extraction of important physical information (about the jet and the merger ejecta) with future multi-messenger observations of NS mergers.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)1455

1. Introduction

Binary Neutron Star mergers have been proposed to explain *short* Gamma-Ray Bursts (*s*GRBs) [1–3]. In 2017, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo Consortium (LVC) detected the first gravitational wave (GW) signal from the BNS merger event, GW170817 [4]. ∼ 1.7 s later, Fermi telescope recorded a *s*GRB, *s*GRB 170817A [5]. About 10 hours later, the merger site was localized and follow-up observation across the electromagnetic (EM) spectrum started. This enabled the discovery of the a red component; i.e, kilonova/macronova (KN hereafter); indicating presence of r-process nucleosynthesis [6, 7] as previously predicted in [8–10]. Follow-up observations were also able to find clear evidence of a relativistic jet [11] viewed off-axis. All these discoveries were perfectly consistent with the scenario of *s*GRBs.

In this scenario, the merger powers relativistic jets though mass accretion [1–3]). However, the expanding merger ejecta surrounds the jet birth place. Therefore, the jet-ejecta interaction is inevitable [12, 13]. During this interaction, the jet outflow is continuously mixed with the ejecta, creating a hot and turbulent component in the surroundings of the jet called the “cocoon" ([14]). And once the outer edge of ejecta is reached, both of the jet and the cocoon can escape to the outside of the ejecta, i.e., breakout powering a unique astrophysical transient [15–18].

Here, we are interested in the EM cocoon emission as a counterpart to GW signal from NS mergers (NS-NS and BH-NS) as in GW170817. Our goal is to model the cocoon emission so that we can directly link the observational features with the physical properties of central engine jets and ejecta in NS mergers, *s*GRBs, KNe, and r-process nucleosynthesis.

In this paper, we use numerical simulations of hydrodynamical jets propagating in the dynamical ejecta of NS mergers. We found that most of the cocoon is “trapped" inside the ejecta. We focus on the“escaped" cocoon part (that breaks out of the ejecta) that is relevant to the cocoon emission. For simplicity we categorize the escaped cocoon into the “relativistic cocoon" and “non-relativistic cocoon", and model it analytically. We then analytically estimate the observed cocoon emission.

2. Numerical simulations of sGRB-jet's cocoon

We use the same numerical code as in [21], [22], and [20]. We investigate the jet propagation in *s*GRB – NS merger context where the medium is expanding (see Figure 1). Table 1 shows the representative subsample of jet models simulated: “narrow", “wide", and “failed" (for more information see [17, 18]).

Simulations are set to start at $t = t_0$. The jet is launched (injected) at the same time, for a duration of $t_e - t_0 = 2$ s. The delay between the merger time and the jet launch time is set as $t_0 - t_m = 0.160$ s. All simulations are run, through the jet breakout, until $t - t_0 = 10$ s. This is considerably a much longer simulation time compared to previous studies (e.g. [20]) and requires a large computational domain.

The motivation behind this longer computation time is to follow the late time evolution of the cocoon, until the free expansion phase is reached and the system is fully ballistic, i.e., interaction between the jet/cocoon/ejecta becomes negligible. We refer to this time, the time at which the system is ballistic, as $t_1 \lesssim 10$s (for more information see [17, 18]).

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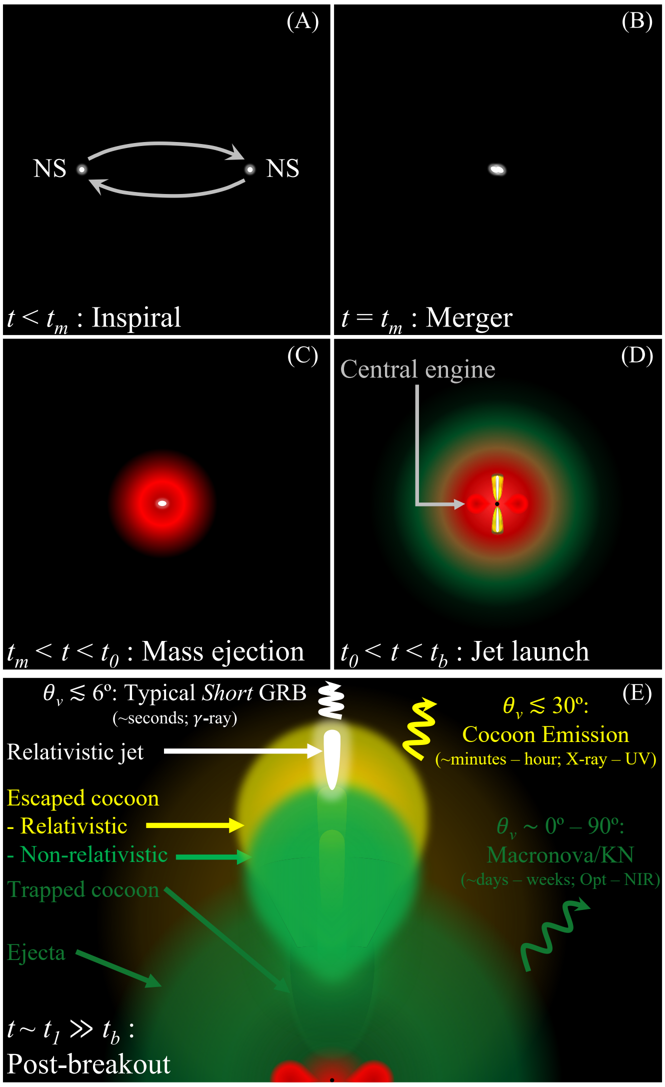

Figure 1: Schematic illustration of the timeline and key phases in NS mergers, with the observational perspective. Initially, a pair of compact objects in the inspiral phase [NS-NS here; applies also for a NS-BH system] (A) . The two objects merge into one compact object (B). This interaction triggers mass ejection [$\sim 0.01 M_\odot$ expanding at $\langle\beta\rangle \sim 0.2c$; [19]] (C). Soon after ($\sim 0.1 - 1$ s in the case of GW170817; see [20]), a system of a central compact object with an accretion disk is formed (D). This system (i.e., central engine) powers two polar jets (D) [white]. Each jet propagates through the surrounding dense ejecta (D) [red and dark green]. This forms a bubble of hot gas, “cocoon", around the jet (D) [yellow]. Soon after the jet/cocoon breaks out of the ejecta, the system enters the free-expansion phase (E). Only a small fraction of the cocoon escapes from the ejecta and expands in the conical manner [with an opening angle $\theta_c^{es} \sim 20° - 30°$] (E) [see [17]]. This escaped cocoon contains a relativistic component, and a non-relativistic component (E) [yellow (mostly shocked jet cocoon), and light green (mostly shocked ejecta cocoon), respectively]. Three EM transients are highlighted; from hard to soft, short to long, and narrow to wide emission’s opening angle: *s*GRB [white], cocoon emission [yellow], and KN [dark green] (E).

Table 1: The subsample of the simulated models and their corresponding parameters. From the left: The model name; the ejecta mass, assuming polar densities; the jet initial opening angle; and the engine's isotropic equivalent luminosity. All the other parameters are the same for the three jet models [17, 18].

Jet models	M_e [$M_\odot$]	θ_0 [deg]	$L_{iso,0}$ [erg s^{-1}]
Narrow	0.002	6.8	5×10^{50}
Wide	0.002	18.0	5×10^{50}
Failed	0.010	18.0	1×10^{50}

3. Analytic modeling of the cocoon

3.1 Jet propagation and breakout

The jet propagation through the expanding ejecta can be solved analytically following the same arguments used by [23] for the collapsar case. Detailed calculations in [20, 22] give a full description of the cocoon properties as a function of time until the jet breakout.

3.2 Cocoon escape from the ejecta

As explained in [17] the cocoon escape from the ejecta is very modeled by the parameter α which is defined as the ratio of energy density between the cocoon and the ejecta, and can be found analytically (as a function of the jet, ejecta, and cocoon parameters) at the breakout time.

Results are shown in Figure 2 and indicate that our simple analytic model reproduces well the numerical results [for more information see [17]].

3.3 Freely expanding cocoon

From our late time numerical simulations (up to $\sim$ 10s), we analysed the escaped cocoon and measured its mass density, internal energy density and morphology. In our analysis we divide the escaped cocoon into two parts: relativistic cocoon ($10 > \Gamma\beta > \Gamma_t\beta_t \sim 1.33$) and the non-relativistic cocoon ($\beta_t > \beta > \beta_m$); and found that mass and internal energy density for each of these cocoon components can be fitted with simple power-law functions (with indices respectively; for the mass density as $l = 0$, and $m \approx 8$; and for the internal energy density as: 2, and -3) (for more details see [18]).

4. Analytic modeling of the cocoon emission

4.1 Optical depth

After finding the mass and internal energy distribution for the escaped cocoon, we analytically solve the radiation transfer using a sharp diffusion shell (see [24]). We follow a relativistic treatment. We calculate the optical depth using the mass density profile. Then, we calculate luminosity using the internal energy density's profile. we find that the classical radiation diffusion criteria $\tau \sim c/v_d$ does not apply for the non-relativistic cocoon due the steep density profile, and found the $\tau \sim 20/\beta_d$ is more reasonable. For the photospheric radius we use $\tau_{ph} = 1$. Then we solve the Stefan-Boltzmann equation in the relativistic limit to find the blackbody temperature.

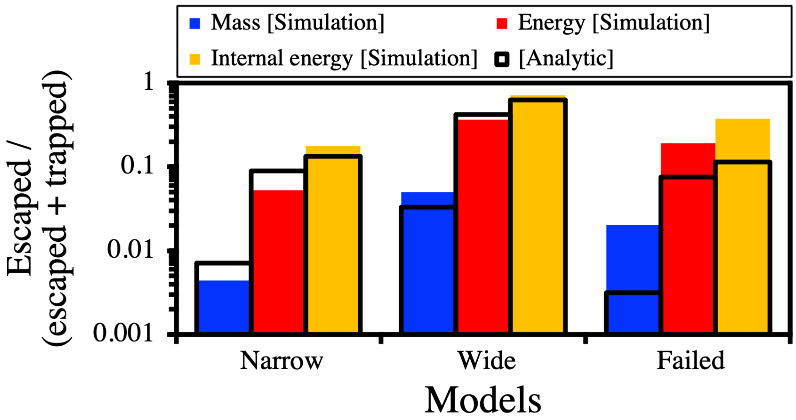

Figure 2: Mass (blue), energy (red), and internal energy (orange) fractions of the escaped cocoon as measured from simulations (in the laboratory frame), for the narrow, wide, and failed jet models, at the free expansion phase (t_1). Histograms with black borders indicates the fractions found using our fully analytic model [see Section 3.2.

5. Results and Discussion

The isotropic luminosity from jet-shock heating in the different phases [calibrating to the parameters of the wide (successful) jet model; see Table 1] can be estimated reasonably well as

$$\begin{aligned} L^{j}_{bl} &\sim 3.3\times 10^{43}\ \mathrm{erg\ s^{-1}} \\ &\left(\frac{L_{iso,0}}{5\times 10^{50}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{t_b - t_0}{0.46\ \mathrm{s}}\right)\left(\frac{t_b}{0.62\ \mathrm{s}}\right)\left(\frac{E^{es}_{c,i,r}/E^{es}_{c,i}}{0.52}\right) \\ &\left(\frac{E^{es}_{c,i}/E_{c,i}}{0.63}\right)\left(\frac{\theta_0}{18^\circ}\right)^2\left(\frac{\kappa}{1\ \mathrm{cm^2\ g^{-1}}}\right)^{\frac{p-2}{2}}\left(\frac{t_{obs}}{75\ \mathrm{s}}\right)^{-p}, \end{aligned} \tag{1}$$

where, $L_{iso,0}$ is the central engine's isotropic luminosity, θ_0 is the initial jet opening angle, $t_b - t_0$ is the breakout time since the jet launch, t_b is the breakout time since the merger, $\frac{E^{es}_{c,i}}{E_{c,i}}$ is the fraction of escaped cocoon internal energy, $\frac{E^{es}_{c,i,r}}{E^{es}_{c,i}}$ is the fraction of escaped cocoon internal energy in the relativistic cocoon, and κ is the opacity in the escaped cocoon. The the time index p has been introduced to reproduce the temporal properties of the luminosity [$p = 4/3$ for $t_{obs} < t_{obs}(\Gamma_d = 1/\theta^{es}_c)$, and $p = 2$ for $t_{obs} > t_{obs}(\Gamma_d = 1/\theta^{es}_c)$]; and one can find the timescale $t_{obs}(\Gamma_d = 1/\theta^{es}_c) \sim \left[\frac{\kappa M^{es}_{c,r}(\theta^{es}_c)^6}{12c^2\Omega\Gamma_t^{-2}}\right]^{1/2}$ ($\sim$ 75 s here for the wide jet case; and $\sim$ 6 s for the narrow jet case) (for more details see [18]).

6. Conclusion

We presented numerical simulations of the cocoon breakout in NS mergers, for three different types of jets: narrow, wide, and failed. We followed the cocoon evolution for timescales much longer than the breakout time (up to $\sim$ 10 s $\gg t_b - t_0$). We analysed the distribution of mass and energy in the cocoon, finding that, contrary to previous considerations, only a tiny fraction of

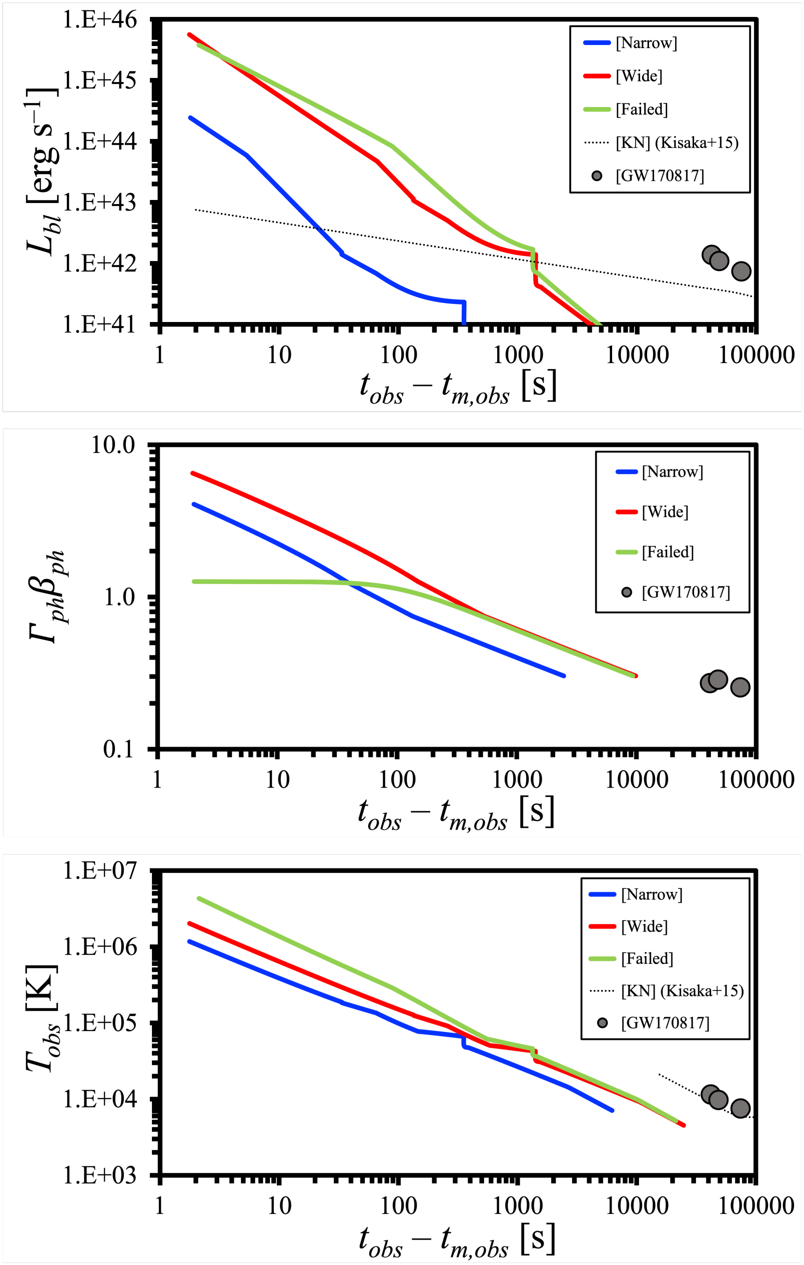

Figure 3: Bolometric isotropic luminosity (top), photospheric four-velocity (middle), and observed temperature (bottom), for three representative jet models [narrow (blue), wide (red), and failed (green) in Table 1], as a function of the observed time since the merger. The predicted early KN is shown (dotted black; following the analytic model by [25]), as well as the recorded measurements on GW170817 (grey circles [6, 7]). This illustrates the expected imprint of the cocoon depending on the jet model in future GW170817-like events (NS mergers with or without a *s*GRB).

the cocoon manages to escape from the ejecta ($\sim 0.5 - 5\%$ in terms of mass). We then modeled the escaped cocoon mass and internal energy distribution, and estimated its emission using the approximation of a sharp diffusion shell, as a function of the parameters of the jet and the ejecta.

Our results indicates that , with the new generation of GW detectors (the upcoming LIGO O4; also with ET, and CE), the cocoon emission is detectable in future GW170817-like events if early localization is achieved. And with its observational features (luminosity, temperatures, and photospheric velocity) understood (with our analytic model), the cocoon emission can potentially be used to better understand NS mergers, *s*GRBs, and KNe (together with the other EM counterparts: prompt emission, KN emission, and afterglow emission); practically, the cocoon emission can be used to indirectly measure the escaped cocoon's mass and relate it to the mass of the dynamical ejecta, infer the type of jet, and indirectly trace r-process nucleosynthesis.

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