Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Consequences of Jet-Ejecta Interaction in Neutron Star Mergers

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Abstract. In the first observed neutron star merger, GW170817, two dynamical components, mildly- and ultra-relativistic outflows were detected independently. The first component triggered a rapidly evolving thermal transient named macronova (kilonova), while the second caused an observed short GRB where the early gamma-ray signal was followed by a multi-wavelength afterglow. These two distinct components are typically modelled independently and the observational consequences of their interplay are hardly explored. Here we summarize the results of 3D special-relativistic simulations that we have used to investigate the consequences of jet propagation through a realistic environment. We show how the presence of a jet can lead to the macronova being brighter and bluer for on-axis observers in the first few days. Then we show the consequences on the interaction on the shape of the emerging jet. Finally, we will discuss how small scale features in the emerging jet structure can impact the best-fit afterglow parameters.

Keywords. methods: numerical, hydrodynamics, ISM: jets and outflows, gamma rays: bursts

1. Introduction

On 2017, August 17, a new era for multimessenger astrophysics started when the gravitational wave GW170817 produced by a binary neutron star (BNS) merger was detected together with the short gamma-ray burst GRB 170817A (Abbott et al. 2017a, Goldstein et al. 2017). These two independent detections proved the long suspected connection between BNS merger and short GRBs. Moreover the event was followed by several detections that covered the whole electromagnetic spectrum (Abbott et al. 2017b). The following observations delivered strong evidence for an ultrarelativistic jet and mildly-relativistic ejecta. Both the multi-wavelength afterglow (Troja et al. 2019) and the VLBI detection of superluminal motion (Mooley et al. 2018) are naturally explained by a jet that successfully broke out from the ejecta. The follow-up campaign also discovered a thermal transient detectable from UV to Optical and NIR, that emerged already a few hours after the merger and faded on the time scale of weeks (see e.g. Abbott et al. 2017b). The properties of this signal were found consistent with those of a thermal transient powered by the radioactive decay of freshly synthesized r-process nuclei, named macronova (or kilonova, see e.g. Metzger 2010). The powering of a macronova requires the release of neutron-rich material after the merger. In these events mass ejection occurs via several channels, each one characterized by different masses, velocities and nuclear compositions. In this framework the amount of free neutrons within the ejecta plays a key role in shaping the observations. This quantity can be expressed in terms of electron fraction Y_e.

However both the remnant and the surrounding torus are very efficient in producing neutrinos, by reaching neutrino luminosities $> 10^{53}$ erg s^{-1}. Such neutrino abundance makes weak interactions occurring efficiently in the surroundings, changing locally the amount of free neutrons available for the r-processes (see e.g. Perego et al. 2014). For a more detailed description of the different kinds of ejecta, their properties and the way they result in a macronova the reader can refer to Metzger (2019) for a recent review on the subject.

The observations following GW170817 allowed to model the properties of both the jet and the ejecta independently. The two dynamical components are however expected to interact before becoming visible and such interaction might affect the observed features. Here I present the results of a work involving special relativistic numerical simulations to investigate the observational consequences of the interaction between different jets and a realistic post-merger environment, represented by the neutrino-driven wind from Perego et al. (2014). In Nativi et al. (2021) is investigated how jets propagating through a neutrino-driven wind can impact the broad-band light curves of a macronova. To compare with observations the hydrodynamic evolution is followed by 3D Monte Carlo radiative transfer simulations performed with the Possis code (Bulla 2019). Nativi et al. (2022) focuses instead on the complementary problem i.e., the impact that a realistic environment has on the observations of the jet. Every real jet is expected to have a structure, meaning that its energy per unit solid angle $\mathrm{d}E/\mathrm{d}\Omega$ and Lorentz Factor Γ are a function of the polar angle θ. Such structure is partly imprinted initially from the engine and partly a consequence of the interaction with the surroundings. Since the afterglow light curves have a strong dependence on the shape of the emerging jet (Ryan et al. 2020) we investigate to what extent an eventual initial shape can be preserved when the jet propagates through a realistic post-merger wind.

2. Simulations setup

All the simulations here presented are full 3D and are run with AMUN (`https://gitlab.com/gkowal/amun-code`), a Eulerian, shock-capturing, special-relativistic (magneto-)hydrodynamics code with adaptive mesh refinement. The reader can refer to Nativi et al. (2021) and Nativi et al. (2022) for the details of the numerical methods adopted in each simulation. In all the runs the computational domain is shaped as a rectangular Cartesian box covering only the region above the equatorial plane. The mergher remnant is in the origin and surrounded by the wind from Perego et al. (2014).

Jets are injected as an unmagnetized conical inflow from the lower boundary of the domain. This is a common procedure in the literature for all the studies focusing on jet propagation, see e.g. Mizuta & Aloy (2009). The hydrodynamic variables of the flow ($\rho_{\mathrm{j}}, v^{\mathrm{i}}_{\mathrm{j}}, p\mathrm{j}$) can be uniquely determined starting from five global parameters: radius of the nozzle r_0, initial jet opening angle $\theta_{\mathrm{j},0}$, Lorentz factor Γ_0, specific enthalpy h_0 and total luminosity L_{j}. All simulations assume ρ_{j} and $v^{\mathrm{i}}_{\mathrm{j}}$ independent on the polar angle in the injected flow, and when the model requires an inner structure the angular dependence is attached to the specific enthalpy $h = h(\theta)$. The models here discussed differ by the total jet luminosity, allowing to compare the effects of low- and high-luminosity jets. In Nativi et al. (2022) the models differ also in their initial structure, comparing the results for an initial top-hat with a Gaussian profile.

3. Results

All the models show a hydrodynamic evolution broadly consistent with the expectations from the literature. After being launched all jets inflate a cocoon and experience several recollimation shocks before breaking out from the wind. After the breakout the

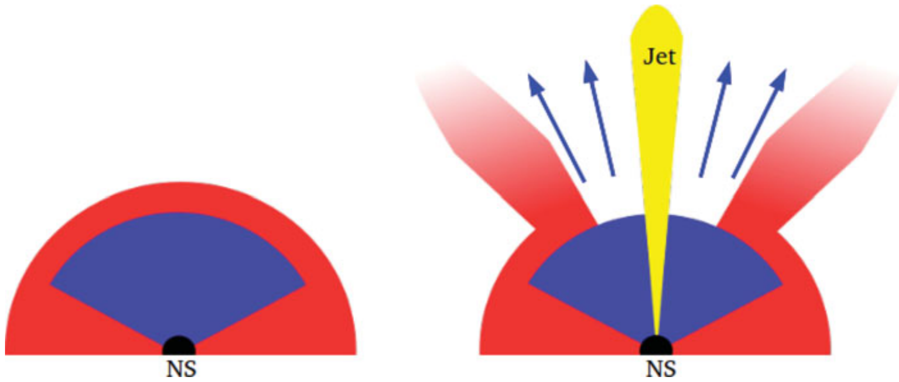

Figure 1. This sketch shows the consequences of a jet drilling through the neutrino-driven wind from Perego et al. (2014).

jets keep propagating through the surroundings by converting their internal energy into kinetic, until a configuration of roughly ballistic expansion is reached.

3.1. *How jets impact the macronova*

The ejecta obtained in Perego et al. (2014) posses a neutron-rich skin ($Y_e \approx 0.1$) that engulfs the whole system and consists in $\approx 10^{-5}$ $M_\odot$ of material retaining the initial composition. During the evolution such skin is characterized by high opacity and act as a "curtain" that can potentially block the thermal emission from the neutron poor material ($Y_e \geq 0.25$) reprocessed by weak interactions.

The successful breakout of a jet can actually push a fraction of that neutron-rich material away from the axis, reducing the opacity and resulting in a earlier brightening of the macronova. This effect is sketched in Fig. 1. The size of the hole drilled on the curtain is proportional to L_j. Subsequent radiative transfer calculations show how the presence of a jet does not affect the light curves for an observer close to the equatorial plane, but if the system is observed close to the axis the macronova can get up to ≈ 1.5 mag more luminous in the bluer bands for the first day after the merger. This number is the extreme case for a jet with $L_j \approx 10^{51}$ erg s^{-1}.

3.2. *How the ejecta impact the jet*

The interaction between a jet and its surroundings results in the development of hydrodynamic instabilities and turbulence at their interface. The consequent mixing plays a key role in altering the Lorentz factor distribution within the jet. Despite the relatively modest amount of mass in the chosen environment ($\approx 10^{-3}$ $M_\odot$) the interaction plays the major role in shaping the final jet. Both the initial and final profiles for energy and Lorentz factor are shown in Fig. 2. The emerging structures for jets of same luminosity appear very similar, showing that eventual initial profiles have only a minor impact. Nevertheless some small scale differences are still present in jets injected with different initial structure and in a fit with the same real dataset these small scale features can still have an impact on the best-fit parameters, actually affecting the inferred properties of the system.

4. Conclusions

Here we show how the jet-ejecta interaction has a relevant impact on the final outcome, and it should always be taken into account when interpreting observations. If

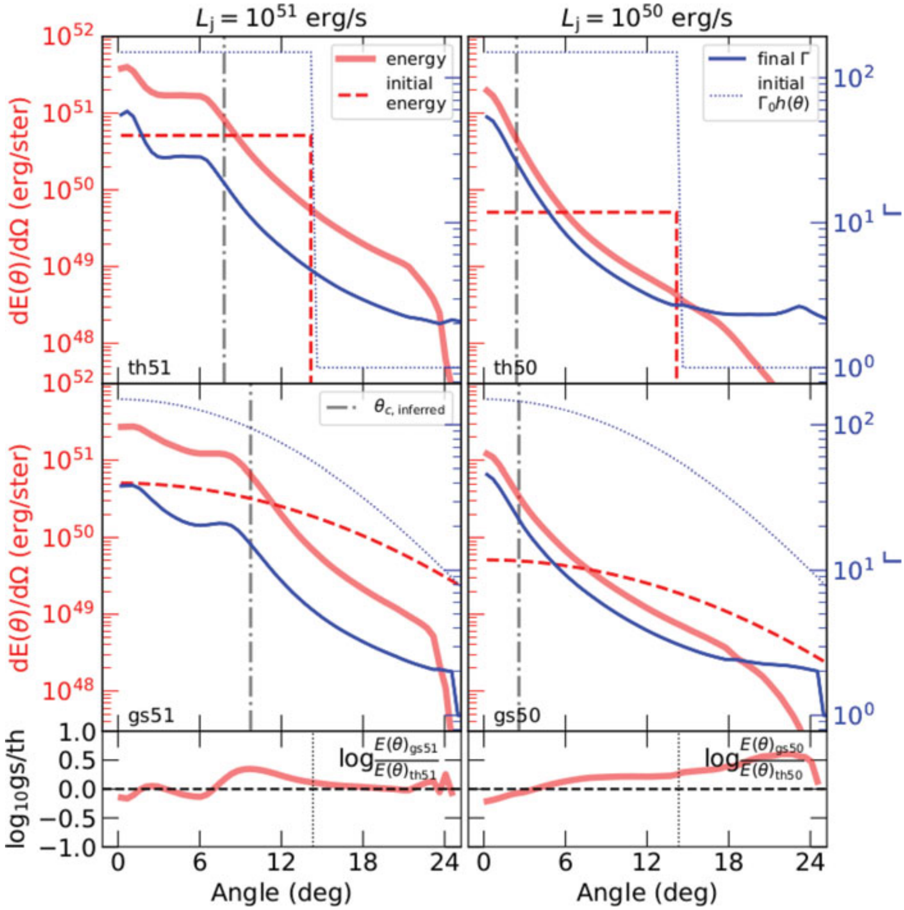

Figure 2. Angular profiles of the Lorentz factor (blue) and energy per solid angle (red) at the injection (dashed) and when the jets emerge from the environment (solid lines) for the models presented in Nativi et al. (2022). Jets with the same luminosity emerge with very similar profiles, even if they have been injected with different initial structure.

the macronova appears brighter as a consequence of jet breakout, the properties of the ejecta inferred using simplified models will be affected. Moreover, mass ejection such as neutrino-driven winds appear to have an impact in shaping the emerging jet, with consequences on the information we get from the afterglow. For these reasons a better understanding of the post-merger environment and its interplay with the jet will be required in the future to have a proper interpretation of the overall observations.

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