Review

Binary neutron star and short gamma-ray burst simulations in light of GW170817

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Abstract: In the dawn of the multi-messenger era including gravitational waves, which was marked by the first ever coincident detection of gravitational waves and electromagnetic radiation it is important to lay back and think about established knowledge. Numerical simulations of binary neutron star mergers and simulations of short GRB jets have to combine efforts in order to understand such complicated and phenomenologically rich explosions. We review the status of numerical relativity simulations with respect to any jet or magnetized outflow produced after merger. We compare what is known from such simulations, with what is used and obtained from short GRB jet simulations propagating through the BNS ejecta. We point out facts that are established and can be considered known, and things that need to be further revised and/or clarified.

Keywords: keyword 1; keyword 2; keyword 3 (list three to ten pertinent keywords specific to the article, yet reasonably common within the subject discipline.)

0. Introduction

The detection of GW170817 marked the dawn of the multi-messenger gravitational-wave era [1,2]. The subsequent observation of a short gamma-ray burst (GRB) almost ~ 1.7 seconds after merger [3,4], showed that a least a subset of short GRBs is produced by binary neutron star (BNS) mergers. Hours after merger a precise localization could be established through optical observations of GW170817 [5,6], identifying the host as galaxy NGC 4993, which is at a distance of 40 megaparsecs. Further detection in UV/optical/Infrared established perennially the connection of BNS mergers with a kilonova (macronova) [6–20].

A coincident detection of GW and a short GRB from a BNS merger was long ago conjectured that short-duration GRBs come from BNS mergers [21–23]. These unprecedented observations open new windows and insights for the in depth study of such objects and such events. The observation opened the possibility of constraining the maximum mass of neutron stars and the equation of state (EOS) [24–37].

It was long proposed that a BNS merger would give rise to emission powered by the radioactive decay of r-process nuclei [38,39]. Several groups concluded that this was the case for the optical/NIR emission that followed GW170817 [11,14,18,40–47]. This observation triggered further modeling for the actual components that give rise to this emission and how these components were produced.

The prompt gamma-ray emission was reported in [3,4]. It was the most faint (short or long) GRB ever detected [3]. The first X-ray afterglow observations came nine days after merger [19,48,49]. The first radio counterparts came later, sixteen days after merger [50,51]. Every information that would come from the afterglow observations would be invaluable to reveal the nature of the outflow and its structure. A relativistic outflow from a BNS merger was indeed observed [51,52]. Was that the most peculiar short GRB ever detected [14,53]? The continuous rising of the afterglow the first 100 days suggested that a simple top-hat1 jet model seen off-axis is not adequate for explanation[51,54–58]. However, at a 100 days after merger the data could not exclude other jet structure or cocoon models. Energy injection was evident at that time [59]. Then, a turnover in the light curve

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1 A top-hat jet is one with constant Lorentz factor and emissivity within the jet that goes sharply to zero outside of jet opening angle. It is the simplest model to explain GRBs have been widely used to explain GRB properties.
appeared close to 200 days [60–62]. This emission is well understood and comes from the interaction of the outflow as it smashes into the inter-stellar medium producing a shock which accelerates electrons that radiate synchrotron radiation and can give a great insight in the whole structure of the initial outflow.

In order to digest all these new insightful observations, and the yet to come in the next years we have to combine all pieces available. What has been achieved from BNS numerical relativity simulations has to be part of any adequate modeling of short GRB outflows. These are: the ejected matter and the production of neutrino driven winds, the enormous magnetic field evolved in the merger process, and its amplification during merger, the actual possibility of launching a relativistic outflow after merger are the starting points given by numerical relativity. Is it a stable magnetar or the collapse to a black hole (BH) torus system that powers an outflow? In what follows we try to present results from numerical relativity BNS simulations relevant for short GRBs. Afterwards, we turn our attention to efforts in short GRB jet simulations propagating through the BNS ejecta.

This is a rather focused review on what we know from numerical relativity concerning short GRBs and how this knowledge is applied to short GRB simulations. It will not at all follow the path of excellent reviews that exist in the subject of BNS mergers. For the interested reader we cite several detailed reviews of subjects relevant to the detection of a BNS merger, a short GRB and a kilonova. Detailed reviews of all the aspects of numerical relativity and its applications to BNS mergers [63,64], a focused review on BH - neutron star binaries [65], a review discussing the connection between BNS mergers and short GRBs in numerical relativity results [66], observational aspects of short GRBs and connection to BNS mergers [67,68], regarding BNS merger and electromagnetic counterparts from kilonova [69–72], a review on rotating stars in relativity with applications on the post merger phase [73], reviews for short GRBs [74,75] and detailed reviews on all aspects of GRBs [76–78]. In section 1 we review the relevant knowledge from BNS simulations. We mainly follow results from magnetohydrodynamic (MHD) simulations in BNS studies. At the end of section 1 we show the different paths that a BNS may follow after merger with respect to the achieved magnetic energy growth during merger. This translates to the total mass of the binary. In section 2 we follow the studies that focus on the interaction of a BNS relativistic outflow passing through the matter that has been ejected during merger. In section 3 we conclude.

1. BNS numerical simulations

Sixteen systems of double neutron stars have been observed in our galaxy. The observational data for the total mass of double neutron stars from our galaxy show a narrow distribution in the range $2.58 - 2.88 \, M_\odot$ [79]. A double neutron star system will inspiral and emit gravitational waves that result in the orbital decay, shrinking their separation. When they come close enough, tidal forces result in deformation of the two neutron stars. Only numerical relativity can adequately describe the inspiral process from then on.

When the two neutron stars contact each other a merger product is formed. If this is massive enough that cannot support itself from gravitational collapse, a BH is formed in the first millisecond after merger surrounded by a negligible disk. If the configuration is less massive, it does not collapse straight away. The merger product is differentially rotating and thus it can support more mass than the limit for a uniformly rotating star. At this stage the merger product is called a hypermassive neutron star (HMNS) [80]. Gravitational-wave emission and magnetic field instabilities can remove angular momentum and make the HMNS unstable triggering its collapse and leaving a BH with a surrounding disk. The loss of thermal pressure due to neutrino cooling could also trigger the collapse of the HMNS [81,82], however see [83]. However, if the total mass of the object is smaller than the mass that can be supported when allowing for maximal uniform rotation – the supramassive limit – it can also lose differential rotation and not collapse. This would result to a uniformly rotating super massive neutron star (SMNS) surrounded by a disk. The SMNS will continue to loose angular momentum through magnetic spin down and also accrete mass from the surrounding disk. Its lifetime varies from a second to millions of seconds, in the latter case it can be considered as a stable configuration.

A robust picture regarding the ejected matter during and after merger has been drawn from numerical simulations. These include dynamical ejecta during merger and secular ejecta that follow, like neutrino driven winds and magnetic winds [84–104]. Other important properties of the merger product such as the spin and the rotation profile have been studied [105–107]. We continue focusing on the properties of the magnetic field, its
amplification during merger and all the variety of observational outcomes that depend on the collapse time of the merger product and are dictated by the magnetic field.

**Magnetic Field Amplification** The importance of the Kelvin-Helmholtz instability in BNS mergers was pointed out by Rasio & Shapiro [109]. As the stellar surfaces come into contact, a vortex sheet (shear layer) is developed which is Kelvin-Helmholtz (KH) unstable. The first simulation reporting on the KH instability for BNS was [110]. It was reported in [111] that the KH instability could amplify the magnetic field beyond the magnetar level. They reported a lower value of $2 \times 10^{15}$ G. However, they mentioned that numerical difficulties do not allow to reach the realistic values of amplification, which could be far above this limit. To address the full problem in numerical relativity is not so easy, the reason is that high-resolution simulations are necessary, since the KH instability growth rate is proportional to the wave number of the mode, the shortest wavelengths grow the most rapidly. Studies of BNS mergers tried to clarify the picture and indeed showed some amplification, yet the saturation level was not pinpointed [112–118]. Another approach is local simulations that can imitate the conditions of shear layers and study in detail the different phases of such procedure. The growth phase, where the KH vortex is formed, the amplification phase where the magnetic field is wound up by the evolving KH vortex and the last phase where the magnetic field has locally reached equipartition that results in the KH vortex to lose its energy. In figure 1 such configuration is depicted after the end of the amplification phase. The blueish regions in the lower panel of figure 1 indicate strongly magnetized regions that occur after amplification. Local simulations do not have such stringent resolution limitations as the global ones [108,119].

A high resolution study by Kiuchi [121] showed that for an initial maximum magnetic field of $10^{13}$ G, the maximum magnetic field during merger and in the first $4 - 5$ ms can reach $10^{17}$ G. They showed that the saturation magnetic energy is above $\gtrsim 4 \times 10^{50}$ erg, which is $\gtrsim 0.1\%$ of the bulk kinetic energy. Going to even higher resolution and running for longer time, the upper bound for the amplified magnetic energy has not been reached yet. Higher values of the amplified magnetic energy live in denser regions [120]. This may indicate that the higher values of the magnetic field are either trapped in the dense core, or that they need a diffusion timescale to diffuse out from the core and reorder [122]. These results have built stable foundations that magnetic field amplification is an integral part of the BNS merger and happen in the first millisecond after merger as seen in figure 2. Another point to make here is that this is true only if the binary does not experience a prompt collapse,
Figure 2. The evolution of the magnetic-field energy as a function of time from [120]. The growth of the magnetic field is evident in the first five milliseconds. However, the strong dependence to resolution indicates that the upper limit of amplification is not yet known. Solid and dashed curves indicate the poloidal and toroidal magnetic field components, respectively. (Reprinted with permission from [120]. © (2018) by the American Physical Society.)

Observational signatures during magnetic field amplification Are there direct observational signatures of the field amplification? The magnetic energy increases in extreme values. It has been proposed that if only a fraction of this energy dissipates by reconnection it yields an EM counterpart at the time of merger. This could be observable to a distance of 200 Mpc [125]. This radiation can only escape if produced in an optically thin surface layer. However, the higher values for amplification were reported in the dense core of the merger remnant [120]. The evolution of this turbulent magnetic field is not yet fully understood, it may take a much larger amount of time than the merger timescale to diffuse from the dense core [122]. If the merger remnant lives for at least a second, then the Hall effect becomes important, and would depict the structure of the magnetic field at late times [122].

BH torus from BNS in MHD Strong magnetic fields are present during and after the merger of a BNS. The next meaningful ingredient is the outcome and lifetime of the merger remnant. Due to numerical limitations, existing studies cover the collapse of the merger remnant to a BH only if it happens before \( \sim 100 \text{ms} \) after merger. It was long ago proposed that BNS mergers could launch a short GRB. This connection was made clear by the recent observations [51,52]. However, it is still something that should be achieved by global simulations. The first attempts in a magnetohydrodynamic (MHD) concept in full GR, did not show any signs of a jet production following merger and the collapse of the merger remnant [112,113]. In subsequent studies a magnetic jet structure, as called by the authors, was reported, this is a low density funnel with ordered poloidal magnetic field above the BH [127]. This is indeed the first step in order to imagine the production of a relativistic magnetized jet. Another important aspect, is that an ordered poloidal magnetic field is needed in order to account for energy extraction from the BH in a Blandford-Znajek way [128]. However, even if the magnetic field is not poloidal there could be other outcomes for an outflow. Another simulation by a different group did not find such a structure, instead
Figure 3. The magnetic field structure for a model from [126]. It is depicted at 35.1ms after merger. Two isosurfaces of density are shown in yellow \((10^8 \text{g/cm}^3)\) and cyan \((10^{10} \text{g/cm}^3)\). The field lines are colored indicating magnetic field strength. The toroidal field inside the torus is easily seen, together with a poloidal funnel above the BH. This model collapsed to a BH at \(t_{BH} \sim 8.7\text{ms}\) after merger. Due to resolution the KH instability is not entirely accounted for in these simulations. (Reprinted with permission from [126]. © (2016) by the American Physical Society.)

the picture drawn from their simulations indicated in an expanding toroidal field [118], which is also capable of producing a kind of a jet with a different mechanism [129].

It was further showed and confirmed in a resistive MHD framework that, at least for merger remnants that collapse in the first \(\sim 10\text{ms}\), the BH-torus system produces a low density funnel above the BH [116]. This is usually reported as a low density region above the newly formed BH. But, how low is low? In order to launch an outflow, it is at least needed that the magnetic pressure from the jet can push and accelerate this material in the polar region. The studies in [116,127] used an ideal fluid equation of state (EOS), whereas in [118] a piece-wise polytrope, as was pointed by [66,130] the jet structure depends on the EOS. Also other studies have reported the production of a magnetic structure even using a different EOS [126,131], including also a neutrino treatment [117]. In figure 3 such a configuration with a BH-torus system is depicted. In this specific model the merger product collapsed to a BH at \(t_{BH} \sim 8.7\text{ms}\). The snapshot is taken at \(t \sim 35.1\text{ms}\) after merger. In the low density funnel above the BH the magnetic structure is clearly seen.

Lately, a production of an incipient jet (as called by the authors) was reported, which attained a Poynting luminosity of \(\sim 10^{51}\text{erg/s}\) and a maximum Lorentz factor of \(\Gamma = 1.25\) [130]. Towards the end of the simulation they reported a magnetically dominated funnel above the BH, which can be seen in the lower panel of figure 4. The snapshot is taken at \(t \sim 67.7\text{ms}\), whereas the merger product collapsed to a BH at \(t_{BH} \sim 18\text{ms}\) after merger. It is clear that at late times the low density funnel above the BH is decreasing even more in density. That allows a magnetically dominated region to evolve. Using the magnetization of the outflow, they estimated the half opening angle of the jet funnel to be \(\sim 20^\circ - 30^\circ\) [130].

**EM luminosity** But why so much discussion about magnetic field and its activity on the production of jets. Other mechanisms have been proposed, such as neutrino annihilation [21,132]. However recent studies in which neutrinos are also treated to study a BNS merger and the evolution of accretion to a BH, it was found that due to a very baryon-loaded environment such a mechanism alone does not suffice [46,133]. In the other hand the electromagnetic energy extraction from a BH (known as the Blandorf-Znajek mechanism) has been widely studied (numerically [134,135], semi-analytically [136] and analytically [137]) and mostly understood
Figure 4. Snapshots of the rest-mass density of a model from [130]. Magnetic field lines are depicted as white lines and arrows indicate plasma velocities. In this model the merger remnant collapses to a BH at $t_{BH} \sim 1215M = 18$ms after merger. The upper panel is at a slightly later time after collapse, whereas the lower panel is at $t \sim 67.7$ms. We have to point out that while the density contours are selected far from the magnetic jet structure, the funnel is filled with low density matter which supports the collimation of the magnetic structure. The length scale of the plots is $M = 4.43$km. (Reprinted from [130]. © AAS. Reproduced with permission.)

and accepted. It needs only two ingredients, a rotating BH and an ordered poloidal magnetic field to extract this rotational energy.

$$L_{BZ} \sim \frac{1}{6\pi^2c} \Psi_m^2 \Omega_{BH}^2 \sim B_p^2 R_{BH}^2 \left( \frac{\alpha}{M_{BH}} \right)^2$$

$$\sim 10^{51} \left( \frac{B_p}{2 \times 10^{15} \text{G}} \right)^2 \left( \frac{M_{BH}}{2.8M_\odot} \right)^2 \left( \frac{\alpha}{0.8M_{BH}} \right)^2$$

(1)

where $\Psi_m$ is the magnetic flux accumulated on the BH horizon, $\Omega_{BH}$ the angular velocity of the BH, $B_p$ the poloidal magnetic field on the BH horizon, $\alpha$ the spin parameter of the BH and $M_{BH}$ the mass of the BH [138].

In a BNS merger you have both, when the merger remnant collapses, a BH is formed and in all cases reported it attains a spin of $\sim 0.8$, and magnetic field is a known ingredient of a neutron star and as we have already discussed it is further amplified during merger. In a baryon polluted environment like the one that exists around the remnant after merger, there are also other things to worry about. The ram pressure from the material of the polar regions, or even fall-back material in this region may not allow this outflow to form and evolve. Maybe this is the reason, together with a low magnetic field, that in some studies with limited amount of evolution time no outflow was formed [126]. If this is the case, then it is expected that some hundreds of milliseconds later, the overall pressure of the funnel could decrease significantly to allow for a magnetically dominated outflow to emerge.

**Duration of a BH torus** Following the above discussion it is evident to ask how long this configuration will last. This is indicated by the mass of the surrounding disk plus the mass accretion rate. We briefly discuss the duration connected with mass of the torus. It is usually assumed that the duration of the short GRB ($< 2$s) is due to accretion timescale of the surrounding torus. Studies have shown that the mass of the torus can be as large as $M_T \sim 0.001 - 0.2M_\odot$ [104,112,126,139–142]. Through numerical simulations, a simple phenomenological expression can be derived that reproduces the mass from the surrounding torus [87,140]. A general result is that unequal mass binaries have a more massive torus around the BH formed. Whereas, equal mass binaries acquire less massive torus. Of course, in the case of a prompt collapse the surrounding torus is negligible, but this is something we discuss after the accretion timescale comment. Furthermore, in the case of a late collapse the surrounding disk is expected to be negligible [143,144].
Figure 5. Density profiles on the equatorial plane at different time slices $t \sim 0, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, \text{ and } 2.4$ s. The torus gradually expands with time and the torus density decreases. This is due to the viscous angular momentum transport. Even at one second after merger the SMNS lives in a low density torus, compared to its nuclear densities. (Reprinted from [104]. © AAS. Reproduced with permission.)

The duration of any event coming from the BH torus depends on the lifetime of the torus, and the torus will live on an accretion timescale. A rough estimate for the viscous accretion timescale can be given as:

$$t_{\text{accr}} \simeq 1 \left( \frac{R_T}{50 \text{ km}} \right)^2 \left( \frac{H_T}{25 \text{ km}} \right)^{-1} \left( \frac{\alpha}{0.01} \right)^{-1} \left( \frac{c_s}{0.1c} \right)^{-1} \text{s}$$

(2)

where $R_T$ and $H_T$ are the radius and the typical vertical scale height of the torus, $c_s$ the speed of sound and the $\alpha$ parameter [145]. As such, if the BNS merger produces a BH torus system the accretion timescale sets the duration of the outflow, if any is produced. However, we should point here that it is also relevant to discuss the duration of a gamma-ray pulse produced by a relativistic outflow in a different way. The photosphere is defined as the radius that the outflow first becomes transparent and the first photons are emitted. If an outflow has attained a Lorentz factor $\Gamma$, then photons emitted at any point on the jet are beamed within a $1/\Gamma$ cone, as seen in the lab frame. Thus, assuming that the outflow has a conical shape with opening angle $\theta_j$, initially when $\Gamma > 1/\theta_j$, an observer can see only radiation from a small fraction of the jet. The duration of the pulse can be interpreted as photons coming from this cone that the observer is able to see, the $1/\Gamma$ cone. For a mildly relativistic outflow with $\Gamma > 1/\theta_f$, the relevant timescale of the pulse is

$$dt \sim 1 - 2 \left( \frac{r_{\text{em}}}{10^{12} \text{cm}} \right) \left( \frac{\Gamma}{6 - 10} \right)^{-2} \text{s}$$

(3)

where $r_{\text{em}}$ is the emission radius [76]. The point here is that even if the accretion timescale is smaller and a relativistic outflow is produced, then the duration can be provided also by other robust physical arguments. For an ultra relativistic outflow the duration of the pulse is very small and then the accretion timescale can enter as a justification of the duration of the event.

The discussion so far was mainly for a merger remnant that collapses to a BH after 10 ms or more. The effect of the collapse of the merger remnant when it occurs in the first milliseconds is different. The general thinking in the community leads to no expectations for an EM counterpart, if the BNS merger undertakes a prompt collapse to a BH. This is based on results of simulations that showed some robust features of this evolution track, for the case of an equal mass binary. These features are, limited amount of mass is dynamically ejected and no expectation for a kilonova whatsoever. Another feature is the limited amount of time between merger and collapse which does not allow for a significant magnetic field amplification, as a result the magnetic energy will not reach such high values. However, a detailed high resolution study of a prompt collapse does not exist.

Lastly, the limited amount of mass left around the BH can not sustain any magnetic structure for an amount of time more than few milliseconds. This means that whatever is formed after merger will be lost on this.
timescale. However, the magnetic field that stays outside the BH will dissipate away on this timescale. Most of the matter will be lost behind the BH horizon, but the magnetic field lines will snap violently. This will produce a magnetic shock that will dissipate a significant fraction of the magnetic energy by accelerating electrons and produce a massive burst, similar to a blitzar [146]. This can produce an EM counterpart on such a timescale. Prompt collapse events produce less massive accretion disks than those arising from delayed collapse. Studies have shown that the result of a prompt collapse is a spinning BH and a accretion disk with a negligible mass of $M_T \sim 0.0001 - 0.001M_\odot$ [112,139,140,147–149]. Of course negligible mass for the surrounding torus in the delayed collapse scenario can also be due to the EOS [87,140].

**Prompt Collapse** The prompt collapse has also an impact on the magnetic field evolution, since the HMNS lifetime is limited also the magnetic field amplification is limited [29]. However, the exact level of such limitation is not known. The mass threshold at which the HMNS prompt collapses to a BH strongly depends on the EOS [140,148,150–152]. It is clear that a soft EOS, meaning that matter can be compressed in a more effective way, is more compact and the threshold mass to collapse to a BH is smaller. The other way around, a stiff EOS does not allow for such compression and a star is less compact, thus allowed to have a larger threshold mass [140]. A BNS with a total mass of $M_{\text{tot}} \sim 2.8M_\odot$ can in principle promptly collapse to a BH, whereas for a slightly less mass it can lead to a delayed collapse some milliseconds after merger [148]. Reducing even further the total mass to be less than $\lesssim 2.7M_\odot$, a stable configuration can be achieved. Interestingly, from the known double neutron star systems observed in our galaxy the total mass is around $\sim 2.7M_\odot$ [153]. This means that we could expect all outcomes, meaning prompt, delayed collapse or a stable configuration.

It was reported that following a prompt collapse to a BH no kind of jet can be formed [154]. The system does not have the time to develop a jet structure. However it posses a magnetic field, for which we do not know exactly the level of amplification. So, when the negligible torus is eventually accreted, all this magnetic energy will dissipate away. As we discussed before, prompt collapse leads also to a very small torus. The torus lifetime can be as small as $t_T \sim 5\left(\frac{M_T}{0.001M_\odot}\right)\left(\frac{M}{0.2M_\odot}\right)^{-1} \text{ms}$ [154]. We may estimate the energy stored in the near by magnetosphere to be

$$E_{\text{EM}} \simeq 10^{40} b_{12}^2 r_{10}^3 \text{ erg}.$$  \hspace{1cm} (4)

assuming no amplification took place. It has a millisecond duration and an energy close to the requirement for a fast radio burst (FRB, [155,156]). Overall, this could be similar to the model proposed for FRBs where a supramassive neutron star collapses to a BH [146,157]. Thus, a prompt collapse is lacking of many interesting features coming from the delayed collapse, but could give answers to other mysterious EM signals.

**SMNS spin down** A stable neutron star configuration can also be the end of a BNS merger. If the total mass of the binary is below a certain limit, then even significant accretion of the surrounding matter cannot trigger its collapse. This may have distinct observational features and could explain X-ray plateaus in the
afterglow of short GRBs [158]. It has been suggested that a long-lived magnetar as a BNS merger product can power such emission by its spin down dipolar radiation [159–163]. Such simulations showed that a stable neutron star with a surrounding disk can be a BNS merger product and the luminosity from such configuration is significant [164,165]. However, the first gamma-rays from the short GRB could not be explained. To overcome this drawback, different scenarios have been proposed. The production of the gamma-rays is attributed to the collapse of this long-lived object to a BH which happens after the production of of the X-ray radiation, the observational features of such model together with the prompt gamma-rays of a short GRB comes from diffusion arguments [166,167].

In most studies mentioned the long-lived merger product is presumably loosing angular momentum due to magnetic spin down and the production of dipolar radiation where energy is lost in a rate

\[ \dot{E}_{\text{mag}} = \frac{\mu^2 \Omega^4}{c^3} (1 + \sin^2 \chi), \]  

where \( \mu = B r_{NS}^2 \) is the magnetic dipole moment, \( B \) the dipole magnetic field, \( r_{NS} \) the neutron star radius, \( \Omega \) the angular velocity and \( \chi \) the inclination angle between the magnetic and the rotation axis [169,170]. However, if a stable object is produced, it entirely lives in the environment of a surrounding torus starting exactly at the surface of the star [164]. This means that this neutron star is impossible to acquire a dipolar magnetic field, since the magnetic loops cannot close through the torus but they have rather opened up during merger or they will open up due to differential rotation [94]. Also if any closed field lines are left, they are influenced by neutrino heating [171–173], however this effect will be lost in \( 1 \sim 2 \) seconds. The last, but most significant argument is that field lines which thread the disk will open up, due to the differential rotation of the two footpoints of the magnetic field line, one anchored on the SMNS and one footpoint threading the disk, similar to the BH case [174–176]. Even if most of the mass of the disk is accreted or expelled, the remaining negligible mass will not allow the field lines to close. Thus, the structure of the magnetosphere of the merger remnant can be approximately a split-monopole configuration [26]. A neutron star with a split-monopole configuration spins down with a different dependence on rotation, similar to a BH spin down where all field lines are open [177,178]. The spin down follows an exponential decrease

\[ \dot{E}_{\text{mag}} = -\frac{2}{3\pi c} B^2 r_{NS}^4 \Omega^2 \exp^{-t/\tau_B} \]  

where \( \tau_B = 67 \,(B/10^{15} \, G)^{-2} \,(r_{NS}/12 \, km)^{-2} \, s \). Essentially, the spin down of such configuration goes faster than the dipolar one, since all the field lines are open and contribute to the spin down process.

**SMNS and the surrounding disk** Next we want to discuss about the evolution of the surrounding disk of the remnant and the outcome of the collapse of the remnant after one second from merger. Due to transfer of
angular momentum the disk expands over time and due to accretion onto the compact remnant, its mass decreases over time \[104\]. As in (2) the viscous accretion timescale estimated for the torus:

\[
t_{\text{accr}} \simeq 1 \text{s} \left( \frac{R_T}{50 \text{ km}} \right)^2 \left( \frac{H_T}{25 \text{ km}} \right)^{-1} \times \left( \frac{\alpha}{0.01} \right)^{-1} \left( \frac{c_s}{0.1c} \right)^{-1},
\]  
(7)

where \(H_T\) is the typical vertical scale height of the torus and \(R_T\) is its radius. Then, the mass accretion rate onto the SMNS yields

\[
M_{\text{SMNS}} \simeq \frac{M_T}{t_{\text{accr}}} \sim 0.2 \odot \text{s}^{-1} \left( \frac{\alpha}{0.01} \right) \left( \frac{M_T}{0.2 \odot} \right) \times \left( \frac{R_T}{50 \text{ km}} \right)^{-2} \left( \frac{H_T}{25 \text{ km}} \right),
\]  
(8)

where \(M_T\) is the mass of the torus. The mass of the torus decreases in time and the torus expands, thus, this accretion rate is not stationary. This effect is seen in figure 5, where the density profile is shown in the equatorial plane at different time slices. As time goes by, the torus expands and the torus density decreases significantly. The radius of the torus may reach \(140 \text{ km}\) in \(1\) s. The sum of the mass accreted can be estimated to be \(\sim 0.12 \odot\) in \(1\) s \[104\].

If the SMNS is close to its maximum mass limit, this significant mass accretion in one second may trigger its collapse. Furthermore, the expansion of the torus is also significant during this time. The density of the torus in the vicinity of the SMNS could designate the outcome of the collapse to an induced magnetic explosion. The estimation for the density of the torus at \(1\) s yields:

\[
\rho_T \simeq \frac{M_T}{2H_T \pi R_T^2} \sim 9.2 \times 10^9 \text{g/cm}^3 \left( \frac{M_T}{0.08 \odot} \right) \times \left( \frac{R_T}{140 \text{ km}} \right)^{-2} \left( \frac{H_T}{70 \text{ km}} \right)^{-1},
\]  
(9)

quantities are for the expanded torus at \(1\) s after merger. The density in the poloidal plane is shown in figure 6 at time \(t \sim 1.6\) s after merger. The density drops around \(5 - 6\) orders of magnitude in the first \(1300 - 1500\) km. The possibility that no debris disk is formed at all, has also been discussed \[143,144\].

**Jet or magnetic explosion** Observational signatures of magnetic fields Previously, we discussed about the production of a low density funnel that appears after the collapse of the merger remnant to a BH. All results

| Possibilities for the merger remnant | Prompt collapse | Delayed collapse | "further" collapse | no collapse |
|-------------------------------------|-----------------|-----------------|-------------------|------------|
| collapse to BH, \(t_{BH}\)          |                 |                 |                   |            |
| B-amplification                     |                 |                 |                   |            |
| Magnetic energy, \(E_B\) ejecta     |                 |                 |                   |            |
| BH surrounding disk                 |                 |                 |                   |            |
| disk lifetime                       |                 |                 |                   |            |
| EM outcome                          |                 |                 |                   |            |
| Estimated energy                    |                 |                 |                   |            |

| Possibilities for the merger remnant | Prompt collapse | Delayed collapse | "further" collapse | no collapse |
|-------------------------------------|-----------------|-----------------|-------------------|------------|
| collapse to BH, \(t_{BH}\)          |                 |                 |                   |            |
| B-amplification                     |                 |                 |                   |            |
| Magnetic energy, \(E_B\) ejecta     |                 |                 |                   |            |
| BH surrounding disk                 |                 |                 |                   |            |
| disk lifetime                       |                 |                 |                   |            |
| EM outcome                          |                 |                 |                   |            |
| Estimated energy                    |                 |                 |                   |            |

Table 1. Outcome of the collapse of the merger remnant, the different columns indicate the different possible outcomes for the merger remnant. The different outcomes depend on the collapse time to a BH. Different rows are: the collapse time to a BH \(t_{BH}\), if magnetic field amplification occurs or not, the amount of the magnetic energy \(E_B\), if there is ejected matter, the amount of mass surrounding the BH when it is formed, the lifetime of this disk around the BH, the EM outcome will be produced either by the collapse or by the absence of the collapse and the estimated energy that is released during the collapse or the absence of collapse.
from simulations so far, describe such evolution in the case that the collapse occurred in the first milliseconds after merger. Here, we describe the conditions and the outcome of the collapse to a BH, if this happens after 1s from merger. The foremost point, is the condition for the establishment of a magnetic jet. A stable magnetic jet configuration needs the torus pressure to balance the magnetic pressure from the jet itself. Due to magnetic field amplification discussed earlier, we assume that the mean magnetic field of the SMNS is $B \approx 10^{16} \text{ G}$. This yields:

$$B_{\text{SMNS}}^2 / 8\pi \approx 4 \times 10^{30} \text{ dyn/cm}^2 \left( \frac{B_{\text{SMNS}}}{10^{16} \text{ G}} \right)^2 \gg 9.2 \times 10^{29} \text{ dyn/cm}^2 \left( \frac{\rho_T}{9.2 \times 10^9 \text{ g/cm}^3} \right) \approx \rho_T c^2.$$  \hspace{1cm} (10)

At later times that the torus has expanded even more, the establishment of a magnetic jet becomes more problematic, due to the imbalance between the magnetic pressure and the disk ram pressure. We may use also the accretion rate at 1s as reported in [104], which is $\sim 0.02 M_\odot s^{-1}$. This yields:

$$B_{\text{SMNS}}^2 / 8\pi \gg 2.6 \times 10^{28} \text{ dyn/cm}^2 \sim \dot{M} c / 4\pi r_{\text{BH}}^2.$$

Figure 7 summarizes the above discussion. The main point is that, if the collapse is triggered around or after $\sim 1$ s after merger, the magnetic energy of the SMNS is released and induce a powerful explosion of $E_{\text{exp}} \sim 10^{51} \text{ erg}$, contrary to a magnetic jet expected [168].

We may summarize our own understanding of the outcome of the collapse of the merger remnant, which strongly depends on the time that the collapse is triggered. Of course, the triggering of the collapse depends on the EOS and the total mass of the binary, however here we will not go to that depth and only characterize the outcome with respect to the collapse time. The possible outcomes are summarized in Table 1. The four columns represented four different types for the outcome of a BNS merger. The different rows show characteristics that are essential to the observable outcome of a BNS merger.

The prompt collapse that is characterized by the collapse of the merger product in the first $1-2 \text{ ms}$ (first column of Table 1) does not have an effective magnetic field amplification phase and also no significant ejecta, but due to the negligible disk that surrounds the newly formed BH, the lifetime of this disk is on the order of few milliseconds. As a result, all its magnetic energy will dissipate in that timescale. The energetics of such an explosion (depicted in Eq. (4)) and its timescale points to an event similar to FRBs. In all cases that the remnant lives longer than the first milliseconds, it is certain that magnetic field is amplified to high values. The case where the merger product (a HMNS at this stage) collapses in a few milliseconds to tens of milliseconds, is the most discussed case. This is expected to produce a canonical magnetic jet that interacts with the merger ejecta. If the collapse is delayed for a second (or more) then the low density of the torus may be insufficient to act as a boundary for a magnetic jet and a magnetic explosion is triggered.

At the end of this section we list some interesting and critical points known from numerical simulations of BNS mergers and provide some comparison with points known from short GRBs.

**Critical points**

- If the merger product does not collapse in the first millisecond, then the magnetic energy is amplified to values higher than $10^{50} \text{ erg}$ [120].
- the saturation level of magnetic field amplification is not yet known [120].
- amplified magnetic field is turbulent, it needs time (more than a second) to rearrange in a coherent large scale structure [122].
- after the collapse to a BH in 10ms, a magnetic jet structure is produced [126,127,130].
- ordered poloidal magnetic field above $10^{15} \text{ G}$ is needed for a BZ luminosity of $\sim 10^{51} \text{ erg/s}$ [128].
- the production of an ultra relativistic outflow has never been reported in BNS simulations [116–118,126, 127,130].
- the magnetic jet funnel reported in BNS simulations has an opening angle of $\gtrsim 20^\circ - 30^\circ$, and a maximum Lorentz factor reported $\Gamma = 1.25$ [130].
• if the collapse of the SMNS to a BH occurs late enough, the mass of the surrounding disk is negligible [143,144].

All these critical points should be taken into account for the understanding for any magnetized outflow (relativistic or non-relativistic) that emerges from the merger remnant or the collapse of the merger remnant to a BH. In order to help comparisons with observations, we should also mention here that there are short GRBs observed with a lower limit on the opening angle $\gtrsim 15^\circ$ and some observed short GRBs that have jets with opening angles of $7^\circ - 8^\circ$, [68]. However, the opening angle given from numerical relativity simulations at the base of the jet may (most probably) change through the interaction with the BSN ejecta, this is discussed in the next section.

2. Short GRB Jet simulations

It is understood that if the merger does not follow a quick prompt collapse then significant mass is ejected following the BNS merger. Mass can be ejected dynamically, by winds driven from the newly formed hypermassive neutron star (HMNS) and from the debris disk that forms around it [84–104]. As a result, any outflow that emerges from the merger remnant or the collapse of the merger remnant has to pass through this dynamical ejecta.

To continue further in the discussion of the interaction between the BNS ejecta and a (maybe mildly) relativistic outflow that emerges after merger, we need to define characteristic names widely used in the literature. We follow the terminology, as nicely given by Nakar & Piran [179]:

It is important to define the angle that the observer is looking to the emission produced from the outflow, with respect to the motion of the outflow itself. Assume that an emitting region moves relativistically with a Lorentz factor $\Gamma$, then the emission is called:

**On-axis emission:** if the angle $\theta$ between the line-of-sight and the velocity of the emitting material satisfy $\theta \lesssim 1/\Gamma$. This emission is Lorentz boosted for relativistically moving material.

**Off-axis emission:** if the angle $\theta$ between the line-of-sight and the velocity of the emitting material satisfy $\theta \gtrsim 1/\Gamma$. In the case for a relativistically moving emitting material, then this appears fainter than being on-axis. It is clear that emission, which originally is observed off-axis, will become on-axis when the emitting material decelerates significantly and expands sideways. Originally, on-axis emission, stays always on-axis. We should also point that the observer angle is usually defined as the angle between the jet axis (the symmetry axis) and the line-of-sight. For BNS mergers it is generally supposed that the jet axis coincides with angular momentum axis of the BNS system. Next, we define characteristic names concerning the intrinsic properties and structure of the emitting material.

**Structured relativistic jet:** as the name indicates, this is a relativistic jet along the symmetry axis that acquires a certain structure. This structure can be angular and/or radial. A simple example can be a "top-hat" jet, a blast wave where the energy and radial velocity are uniform inside a cone (Blandford-McKee [181]). Another example, usually inferred for short GRBs, is a successful jet with a cocoon, where the cocoon term is defined below. In general, a jet can be composed by a fast core at small polar angles surrounded by a slower, underluminous sheath. The presence of a spine-sheath structure can be independent from that of a cocoon.

**Cocoon:** If a jet propagates within a dense medium, then the jet transfers energy and shocks this material. There is also a reverse shock that goes down to the jet itself. The resulting configuration is called a cocoon. In the case of BNS mergers the dense medium is the ejected material (dynamical and secular ejecta). So, if a jet is produced after merger, then also a cocoon is. There is a differentiating factor of whether the jet was successful or not.

**Choked jet with cocoon:** The jet that produced a cocoon from the interaction with a dense medium did not have enough energy to break out of the medium and it is choked. The jet transfers all its energy to the medium and the shocked material may acquire a certain angular structure. The reverse shock may produce also a radial structure inside the cocoon in the region of the choked jet. In the case of a BNS mergers, a choked jet would mean that no usual short GRB was produced. However, a mildly relativistic outflow may be produced.

**Successful jet with cocoon:** The jet that produced a cocoon from the interaction with a dense medium had enough energy to break out of the medium. An ultra relativistic outflow passed through the medium and
eventually decelerates through the interaction with the inter-stellar medium (ISM). The jet transferred some of its energy to the medium and a cocoon was produced. In the case of a BNS merger, a successful jet would mean that a usual short GRB was produced, pointing along the jet (BNS) axis. However, a mildly relativistic outflow may also be produced. In this case two components can be identified, an ultra relativistic core which is surrounded by a mildly relativistic cocoon.

Assuming the possibility discussed in the previous section, that a jet is never formed, we could rephrase the last case to a successful explosion with a cocoon. Meaning, that no jet was formed but rather an instantaneous explosion occurred which followed the delayed (over a second) collapse of the remnant [168]. In such case the core is not ultra relativistic, but just a bit faster than the surrounding cocoon itself.

It is important to note that there exist previous studies that have discussed the formation of cocoons in a slightly different context. Namely, for long GRBs where the jet has to propagate through the stellar envelopes and not the BNS ejecta. The main differences should be in the density profile and how it falls off. Cocoons in long GRBs have been discussed by [182]. The mixing of the cocoon components has been discussed in [183–187].

In what follows we review studies that have developed a robust picture regarding the outcome of a BNS merger with respect to the prompt emission which is a short GRB and the afterglow emission which can give a physical insight on the outflow that produced it. The common understanding for the prompt emission is that it is powered by some internal dissipation mechanism within the jet. The common interpretation of the late afterglow is the interaction of the produced outflow with the ISM, during which the outflow sweeps up matter from the ISM and that results on the eventual deceleration of the outflow.

**Jet through the BNS ejecta** In that respect, [180] took into account the density profile of a BNS numerical relativity simulation [92], in order to study the propagation of a hydrodynamical jet through such ejecta and develop a picture of whether the jet could break out from them or not. Such studies built a consensus that even if the outflow emerging from the BNS has a wide opening angle, it will be subsequently collimated as it tries to pass through the ejecta[180,188,189]. These works described a density distribution that the jet should pass through, this density distribution of matter has been ejected primarily during merger. Any outflow produced in the base of the merger configuration has to pass through these ejecta and may change its shape through collimation or lose some energy by the interaction with the ejecta. This way, some energy deposits to the ejecta producing a cocoon structure.

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**Figure 8.** Two snapshots from a model of [180]. The top panel is at the time where the jet breaks out and the lower panel at the end of the simulation. The jet was injected at 50 ms after merger with an opening angle of 15°. The average opening angle of the jet after break out is 12.6°. (Reprinted from [180]. © AAS. Reproduced with permission.)
Figure 9. The left panel shows luminosity versus time, where $t_w$ is the lifetime of the neutrino wind and the time that the jet begins to expand. The colored lines indicate a model from [188], that has a wind injection rate of $\dot{M}_w \sim 10^{-3} M_\odot s^{-1}$ with a velocity of $0.3c$, each line indicates a different termination time $t_w \sim 0.01, 0.1, 1$ s. For such a heavy wind, the luminosity of the jet has to be above $10^{51}$ ergs$^{-1}$ and operate for at least the same time as the wind. (Reprinted from [188]. © AAS. Reproduced with permission.)

In the work of [180], the jet opening angle was placed to be $15^\circ - 45^\circ$, with an injected luminosity of $L \sim 10^{50}$ erg/s. As they pointed out, their results were similar to equivalent simulations in the context of the collapsar model [187,190]. The opening angle at the base of the jet is determined through the interaction of the jet and the surrounding disk. An important consequence of this study is to to find that irrespective to the initial opening angle, all jets succeed in breaking out and form what we would call a structured jet with a cocoon. Only for the model with an initial opening angle of $45^\circ$ this is not true and a choked jet with cocoon is formed. Due to the large cross section of the jet, it cannot go sideways into the cocoon and expands quasi-spherically.

In figure 8 a model from [180] is shown. The ejected mass is $10^{-3} M_\odot$ and the initial jet is injected with an opening angle of $15^\circ$. The density profile of the produced structure is shown for two snapshots, one at the time that the jet breaks out from the ejecta and the other at the end of the simulation. The average opening angle of the jet after break out, which has changed due to the interaction with the surrounding ejecta is $\theta_{jet} \sim 12.6^\circ$. Interestingly except the break out of the jet, a cocoon is formed and is clearly shown in the above mentioned figure 8. However, there does not exist in this study a detailed description of this component. The density profile for the ejecta used in this study has a steep profile $\rho \propto r^{-3.5}$ with a spherical shape.

In [188] they studied what is the influence of the neutrino driven wind to the expansion and propagation of the formed jet. They considered the post-merger production of neutrino fluxes that contribute to a wind density profile. They quantified this wind as:

$$\dot{M}_w \sim 5 \times 10^{-4} \left( \frac{L_\nu}{10^{52} \text{ergs}^{-1}} \right) M_\odot s^{-1},$$

[86,191,192], which results in limiting the Lorentz factor of the jet:

$$\Gamma_\nu \sim 10 \left( \frac{L_{\text{jet}}}{10^{52} \text{ergs}^{-1}} \right) \left( \frac{\dot{M}_w}{5 \times 10^{-4} M_\odot s^{-1}} \right),$$

Their wind profile depends on how long the neutrino driven wind was active. At the time that the wind stops, a jet is injected. In figure 9 (left panel) they show a parameter study on whether the jet can break out or not from such a wind. The axes are the luminosity of the jet versus time, where $t_w$ depicts the time that the neutrino wind stops, supposedly when the merger remnant collapses to a BH. Matter is injected in the wind as $\dot{M}_w \sim 10^{-3} M_\odot s^{-1}$ with a velocity of $u \sim 0.3c$. The colored lines indicate a different termination time for the neutrino wind, where $t_w$ is the time that the neutrino wind stops. As a comparison the $T_{90}$ distribution (the duration distribution of short GRB from [74,194]) is over plotted to show that when the neutrino wind operates
Figure 10. A model from [193] where the shape of the BNS ejecta is assumed to be oblate. In the upper and lower row two different times are depicted \(ct/R_0 = 15, 25\), where \(R_0 = 850\) km is the initial radius of the mass cloud. The initial opening angle of both models is \(60^\circ\). The left panel of each plot shows the density and the right panel of each plot shows the Lorentz factor. The outer surface of the expanding mass ejecta is depicted with a dashed cyan curve. The model depicted in this figure with the oblate shape cloud clearly produces a narrow relativistic outflow. In both cases the ratio between the energy of the engine to the rest mass energy of the ejecta is \(E_{\text{engine}}/M_0c^2 = 0.024\), where \(M_0 = 10^{-4}M_\odot\) is the mass of the cloud ejecta. (Reprinted from [193]. © AAS. Reproduced with permission.)

for more than \(t_w > 0.1\) s then jet duration times that exceed the observed ones, are needed. Interestingly all jets with luminosity less than \(10^{51}\) ergs\(^{-1}\) are choked and never break out from the neutrino wind. This can be regarded as the limiting value for a production of a structured jet with a cocoon or a choked jet with a cocoon.

However, this result strongly depends on the amount of mass that is ejected through this process. Thus the next thing to compare is jet luminosity with respect to the mass injection from the neutrino wind. The result is shown in figure 9 (right panel). The mass injection rate is plotted versus the jet luminosity and depict different regions in the parameter space. If the luminosity is low (on the left part of the figure) then the velocity of the head of the jet is not exceeding the velocity of the wind and consequently never breaks out resulting in a choked jet with a cocoon. Even for smaller luminosity, if the mass injection is less than \(10^{-5} - 10^{-4}M_\odot s^{-1}\) then a successful jet can be formed. It is also known that in order to produce a successful jet, the jet injection time has to exceed the break out time through any medium. They further comment on the production of a cocoon as the jet advances through the ejecta and deposits some of its energy to form such a cocoon [182].

**Spherical versus oblate BNS ejecta** In the above mentioned studies the shape of the density profile that is mimicking the BNS ejecta was spherical. So all results have to be interpreted as arising within a spherical expanding mass cloud. However, there is a possibility that this is not true [195]. Recent simulations of BNS mergers show indeed that the merger ejecta and/or the post merger driven winds are not at all spherical [97–99,101,102,104]. In [193] they consider the interaction of the jet with an oblate mass cloud mimicking the BNS ejecta, opposed to a spherical one. The earlier idea that the ejecta can provide the collimation of the jet [196] is stronger in the case where the BNS ejecta have an elongated shape. They inject a luminosity of

\[
L = eM_{\text{cloud}}c^2/\tau
\]  

(13)

where \(M_{\text{cloud}}\) is the mass of the cloud, \(e\) is the ratio of the energy deposited in the mass cloud and \(\tau\) is the engine duration. Engines that act through an oblate cloud can collimate even wider initial angles. When the overall injected energy from the injected luminosity (13) is low, then the kinetic energy of the dynamical ejecta can be higher and this does not allow for collimation. In the other limit where the injected energy is large, then the mass of the ejecta cannot sufficiently provide any collimation to the outflow. In the latter case the outflow keeps the
initial opening angle. For an initial opening angle of $29^\circ$, a mass cloud of $10^{-4} M_\odot$ and oblate shape, a jet with luminosity of $10^{48-49}$ is collimated significantly with a resulting opening angle of $5^\circ - 8^\circ$ when breaking out from the cloud.

In figure 10 a model is shown from [193]. In this model the mass cloud that mimics the BNS ejecta has an oblate shape. It is clearly seen that the interaction through the oblate mass cloud produces a narrow outflow with high Lorentz factor. We should also note here the possibility that jet formation may be accounted also to the production of a magentar after the BNS merger [198,199].

The next step was to use more realistic profiles taken from [94,200], in order to continue a more detailed study for the interaction of the jet with the neutrino driven and a magnetically driven wind as studied in [189]. They concluded that a jet with luminosity comparable to the observed ones from short GRBs can break out from such winds with the requirement of having an initial opening angle of less than $20^\circ$. They further used the observed duration of short GRBs to set limits on the lifetime of the production of winds from a HMNS, which is determined by the time that the jet needs to break out.

**Observables from off-axis emission** All of such simulations act as a first step towards understanding the jet and cocoon observables that follow a BNS merger. The next step was to see how these components would show up when observed off-axis. Furthermore, late radio counterparts from BNS mergers were long been proposed and expected [201]. Wide angle signatures from jet and cocoon interactions were presented through semi-analytical calculations in [202]. They calculated the on-axis and off-axis emission of a short GRB. They included the prompt and afterglow emission from a relativistic jet, as well as the prompt and afterglow emission from the cocoon formed through the interaction of the jet and the surrounding ejected material. The energy of the cocoon was found to amount approximately 10% of the energy of the burst itself. However, the cocoon energy strongly depends on the structure and size of the ejected material.

In the case of long GRBs the propagation of the jet through a baryon loaded region (such as the interior of a massive star) has been studied and shown a clear and robust observational picture. Nakar & Piran [203] made a comprehensive (mostly analytical) study on the observable signatures of GRB cocoons. Their main focus was on the collapsar model for long GRBs, which envisions the propagation of a jet inside a massive star. While, their focus was cocoons emerging from long GRBs, short GRB cocoons should have an analogous signature (maybe weaker) as they indicated. All the formulas and equations reported in this study can give a quick in-depth description of the characteristics of a cocoon and its emission. The analytical modeling by [204], calibrated by
Figure 12. the appearance of a jet model after break out from the BNS ejecta. A model from [205]. In the figure jet luminosity $\Lambda(\theta)$ (in arbitrary units) and Lorentz factor as a function of the observer’s angle. Quantities are extracted at three different radii. It is evident that even in angles greater than 20°, the luminosity is reduced but still significant. (Reprinted from [205]. © Oxford University Press. Reproduced with permission.)

Numerical results from [187], can be used to estimate the cocoon parameters through the jet break out time and the characteristics of the ejected matter.

Simulations of short GRB cocoons can provide more details on the production of the cocoon itself together with realistic characteristics for its shape and initial Lorentz factor which are key elements for a realistic description of any observables coming from it [197,206]. The numerical setup from Lazzati et al. [197] is an injected jet with luminosity of $L_j = 10^{50}\text{ergs}^{-1}$, an initial opening angle of $\theta_j = 16^\circ$ and the duration of this engine was defined to be $t_{\text{engine}} = 1s$.

Through the isotropic equivalent energy three different components can be identified. The core of the outflow, which is the initially injected jet modified through the interaction with the ejecta and is the brightest part confined in $\theta_j \sim 15^\circ$. The surrounding material of the jet that forms a hot bubble is the energized cocoon which occupies a region between $15^\circ - 45^\circ$. The third component is a fairly isotropic wide angle structure that stops at an angle of $65^\circ$. From the initial energy of $10^{50}\text{erg}$ that was injected, $5.5 \times 10^{49}\text{erg}$ stay in the confined jet, $3.8 \times 10^{48}\text{erg}$ are given to the surrounding cocoon and $7 \times 10^{47}\text{erg}$ are found in the shocked ambient medium. The rest of the energy is stored in slow moving material ($\Gamma < 1.1$). Figure 11 shows the results from [197], in the left panel the isotropic equivalent energy where the three components can be identified, in the right panel the peak photon energy is plotted as seen from different angles. The cocoon emission was studied in detail also by [206]. Their main focus was the appearance of a kilonova following the radioactive heating of the merger ejecta.

Jet with core and sheath In a similar spirit [205] simulated the off-axis emission from a short GRB jet including magnetic field. They argued that for a realistic jet model, one whose Lorentz factor and luminosity vary smoothly with angle, detection can be achieved for broader range of viewing angles. In figure 12 the luminosity and Lorentz factor is shown from their model. It is clear that even in angles larger than $20^\circ$ the luminosity from the jet is significant. As the jet breaks out from the cocoon, the prompt emission is released [199,207]. In figure ?? the time that the shock breaks out is illustrated, from a simulation of [207]. As the shock propagates through the expanding BNS ejecta it accumulates mass on top of the jet head. The wide parts of the jet are not collimated, they propagate conically inside the mass cloud. If the engine operates long enough, the shock breaks out and it is not choked inside the ejecta giving all its energy to them. The break out of this shock in the magnetised case was studied by [199].

Magnetic explosion It was argued in the last part of section 1 that if the collapse of the compact remnant comes late (after a second), then the small amount of mass left at the torus cannot give a sufficient boundary for a magnetic jet to be launched. As such all the magnetic energy dissipates away producing an explosion. In figure 13 such an explosion is depicted at the time that the outflow has entered a low density region. The main characteristics of a cocoon are still entering this picture. A main difference is that there does not exist an easily
Figure 13. A late magnetic explosion triggered by the collapse of the compact remnant is shown, a model similar to the one from [168]. The amount of magnetic energy released is on the order of \(5 \times 10^{51}\) erg. The left panel shows the density and the right panel the Lorentz factor. The snapshot is taken at the time that the shock enters the low density region and expands sideways. It is interesting to note that there is no clear relativistic core with a small opening angle, there are parts of the outflow in bigger angles that go slightly faster.

distinguishable relativistic core with a small opening angle. Faster moving material can be found in bigger angles as can be seen in figure 13. This is a model from [? ].

Afterglow In late observations, following a BNS merger event, it is important to understand the signatures from different components and the differences in observations from different models. As the outflow, that was produced from the BNS merger, hits the ISM, a shock is produced were particles are energized and emit synchrotron radiation. The outflow continues to sweep up matter and begin to decelerate. This is the standard picture for the source of a GRB afterglow. In case of short GRBs from BNS mergers this has been discussed significantly before the detection of GW170817 [201,208,209]. Afterglow model predictions from numerical simulations have been studied in the context of long GRBs (e.g. [210]), also as seen off-axis [211].

After the coincident detection of GW170817 together with GRB170817A and the following afterglow observations there is an enormous effort to analyze the data and fit them with realistic models in order to clarify what are the actual components that powered such emission. It would be unrealistic to review such ongoing effort. We restrict ourselves to a brief overview of observations and the corresponding modeling of them.

The prompt gamma-ray emission was reported in [3,4]. The first detection of X-rays from the event came nine days later [48,49], whereas the first radio observations sixteen days after merger [50]. The first interpretation acknowledged that we are observing something quite different than other short GRBs [14,53].

The ongoing effort for understanding the EM counterparts of GW170817 include: afterglow modeling through hydrodynamic simulations of a jet propagating through the merger ejecta [212–214], radio imaging that could show the exact morphology of the outflow and polarization measurements that could help to distinguish different outflow structures [215–218]. Ideas that the merger event did not include a jet have been proposed [219–221] or models that follow the canonical picture with a short GRB jet [222,223]. Observation of GW170817 can give a deep understanding of short GRB modeling [179,224]. It has been also proposed that the afterglow may come from the interaction of the fast tail of the BNS ejecta with the ISM [225]. Also indicative may be what will be the appearance of the counter jet [226].

Before finishing this section, we would like to gather some important points that should be kept in mind for the study of a relativistic outflow passing through the BNS ejecta.

Critical points

- The amount of dynamically ejected matter strongly depend on the total mass of the binary and the mass ratio [84–104].
• The BNS ejecta are not spherical, but they rather have a unique structure for every different EOS used [102].
• The time that the engine begins to produce an outflow is extremely important, since this will depict how much mass has been ejected by neutrino and magnetic winds [94,189,200].

3. Conclusions

In the years to come more detections of BNS mergers are expected from ground-based interferometers. It is important to analyze in detail observations of GW170817 and all its EM counterparts, starting with GRB170817A. It is equally important to reproduce realistic physics through numerical simulations in order to match and explain observations. This brief review can act as a quick introduction to BNS numerical relativity simulations for people interested in short GRB outflows through BNS ejecta. Or as a brief introduction to short GRB jet simulations and setups used for people from BNS merger simulations. Overall, we want to point out the importance of combining knowledge from both paths in order for a consistent picture to be drawn at the end.

In section 1 we went through studies from numerical relativity for magnetized BNS mergers. We highlight important aspects of this physical process as given in the literature. Points, such as the magnetic field amplification, the difficulty of launching a relativistic jet and certainly the mass ejection during merger and all possible winds produced after merger can become clear through detailed studies. At the end of the section we state several important points (importance is a subjective criterion).

Next step is to take these ingredients from BNS simulations and study any outflow emerging after merger. A relativistic outflow has been observed from a BNS merger [51,52]. Thus, we need to understand how it was launched and what is the initial structure of this outflow. Furthermore, how it will evolve through its interaction with the BNS ejecta. In section 2 we briefly go through previous works on these aspects. This is a rapidly evolving sub-field, especially after the detection. Now, any model and idea can be simulated and be exposed to the data that followed GW170817. However, we should keep in mind that a BNS can have a different evolution even with a slightly difference in mass. At the end, modeling and studying outflows of such events should be inspired by GW170817.

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