Chapter 11
Electromagnetic Emission and Nucleosynthesis from Neutron Star Binary Mergers

Bruno Giacomazzo, Marius Eichler, and Almudena Arcones

Abstract In this chapter we provide a description of the current state of the art in the field of electromagnetic emission and nucleosynthesis from neutron star binaries. We will discuss binaries composed by two neutron stars or by a neutron star and a black hole. While we took the effort to represent what we believe are some of the most important results in this field, we strongly recommend the interested reader to check also the references cited in the mentioned publications for a more in detail view of each topic. As the reader will see from the following sections, this field has gained considerable attention in the latest years with an increasing number of publications on the topic. For each argument we will also discuss what we believe are the current limitations that will need to be addressed in the future.

11.1 Introduction

In the last years there has been a significant increase of theoretical and computational studies of electromagnetic (EM) emission from mergers of two neutron stars or of a neutron star and a black hole. While in the past one of the main motivations was the study of the connection between these systems and short gamma-ray bursts , nowadays there is a strong interest in understanding EM counterparts of gravitational wave (GW) signals. This increased interest, combined with new and

B. Giacomazzo (✉)
Physics Department, University of Trento, Trento, Italy

INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Trento, Italy
e-mail: bruno.giacomazzo@unitn.it

M. Eichler
Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany

A. Arcones
Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

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more accurate numerical codes, has led to a better understanding of all the possible EM emission generated by these mergers, ranging from radio up to gamma rays. These systems are also expected to emit neutrinos during and after merger, but due to their large distances, a neutrino detection is not expected in the next years, even with next-generation detectors such as Hyper-Kamiokande (Sekiguchi et al. 2011).

A major breakthrough in this field happened on August 17th 2017 with the first detection of a GW signal from a binary neutron star (BNS) coalescence (Abbott et al. 2017b). The GW detection was followed by a large number of electromagnetic counterparts observed by ground- and space based telescopes (Abbott et al. 2017c; Cowperthwaite et al. 2017; Drout et al. 2017; Smartt et al. 2017; Tanvir et al. 2017). Those confirm that (at least some type of) short gamma-ray bursts (SGRBs) are indeed associated with binary neutron star mergers (Abbott et al. 2017a) and provided evidence that such systems are also a source of the heaviest elements in the universe produced via the rapid neutron capture process (r-process) in matter ejected by the system (Abbott et al. 2017c; Metzger 2017; Rosswog et al. 2017). Unfortunately the current sensitivity of the Virgo and LIGO detectors was not sufficient to detect a post-merger GW signal (Abbott et al. 2017d) and therefore it is not clear if a black hole (BH) or a neutron star (NS) were the result of the merger. Nevertheless, preliminary constraints for the equation of state (EOS) of NS matter were derived from tidal effects during the inspiral (Abbott et al. 2017b).

In this chapter we will provide an overview of our current understanding of EM emission and nucleosynthesis from neutron star binary mergers. We will describe the most important theoretical and computational results in this field and possible future directions.

11.2 Review of Past Work

11.2.1 Overview of Electromagnetic Counterparts

In the merger of a binary neutron star (BNS) system or of a neutron star (NS) with a black hole (BH) there are mainly two possible end results: the formation of a BH surrounded by an accretion disk or of a long-lived NS (only in BNS mergers). Both scenarios belong to the category of compact binary mergers (CBMs).

In particular, and as we will discuss later, the first scenario is the one that has been strongly correlated with the central engine of short gamma-ray bursts (SGRBs). But while SGRBs represent the strongest possible EM emission, there are other signals that such mergers may emit, ranging from radio to X-rays. Some of these have also the property of not being collimated, but more isotropic, and hence easier to detect. This also depends on whether a BH or a long-lived NS is formed after the merger. Observations of NSs with masses of up to $\sim 2M_{\odot}$ (Demorest et al. 2010; Antoniadis et al. 2013) indicate that a significant fraction of BNS mergers may indeed lead to the formation of a so-called supramassive NS (SMNS), i.e., of an NS with a mass below the maximum mass for a uniformly rotating NS (Piro et al. 2017). This, combined with possible strong magnetic field amplifications, leads to the interesting possibility of forming magnetars after some BNS mergers (Giacomazzo and Perna 2013).

In the scenario where the end result is a spinning BH surrounded by an accretion disk (let us call it the "standard" scenario) and which is also the only possible outcome for the merger of an NS with a BH, all the possible EM emission investigated, at least theoretically, up to now are summarized in Fig. 11.1.

Figure 11.1 shows both the possible emission of a relativistic jet and the ejection of matter. The jet can be responsible for a short gamma-ray burst and its afterglow (from X-rays to radio).

The ejected matter is instead a promising site for the r-process (see Sect. 11.2.2) that can produce very neutron-rich heavy elements. Their decay to stability powers an EM transient, a signal that is known under the name "Kilonova" or "Macronova" (see Sect. 11.2.12) and that was detected after GW170817 (Abbott et al. 2017c; Pian et al. 2017) as well as in connection with other SGRBs (Tanvir et al. 2013; Yang

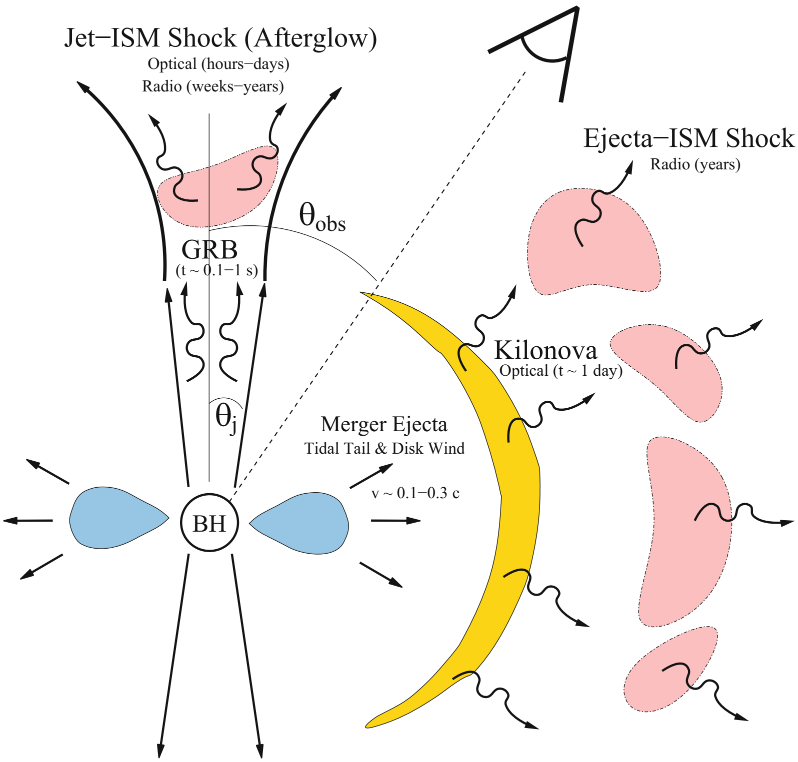

Fig. 11.1 Summary of potential EM emission from BNS and NS-BH mergers. Figure 1 in Metzger and Berger (2012)

et al. 2015; Jin et al. 2015, 2016). The EM signal is affected by the temperature and composition of the ejected matter which is strongly dependent also on whether the matter is ejected via tidal disruption, typical for NS-BH systems, or via shocks at merger, which is the dominant ejection process for NS-NS mergers. Therefore the detection of such a signal may be connected with the properties of the binary system.

On a longer timescale, the ejected matter may also shock with the interstellar medium giving rise to radio emission (Rosswog et al. 2014; Grossman et al. 2014).

We will now proceed on describing in more details some of the main processes taking place in NS-NS and NS-BH mergers.

11.2.2 Nucleosynthesis in Compact Binary Mergers

The electromagnetic afterglow of a compact binary merger (CBM) is thought to originate from the radioactive decay of neutron-rich heavy nuclei that are produced in the r-process . It is therefore essential to address the current status of nucleosynthesis research in these events, which is closely linked with the search for the cosmic r-process site(s). While regular core-collapse supernovae (CCSNe) were an early favourite and are still contenders to be a (maybe secondary) source of low- to intermediate-mass r-process isotopes up to Ag or higher, CBMs of two neutron stars (NS-NS) or a neutron star and a black hole (NS-BH) are now the most promising astrophysical scenario to host the r-process. It was always undisputed that the decompressing matter during a NS-NS or NS-BH merger would be extremely neutron-rich, but before the emergence of computer simulations it was all but impossible to estimate how much, if any, matter would become gravitationally unbound in such a scenario. Lattimer and Schramm (1974) were the first to propose that r-process material could be ejected from a NS-BH merger. Hydrodynamical simulations later confirmed this finding (Davies et al. 1994; Rosswog et al. 1999), followed by the first nucleosynthesis calculations based on trajectories obtained from these simulations (Freiburghaus et al. 1999). Since then, research in this field has mainly focused on two branches: (a) improving the physical treatment of e.g., neutrino interactions, general relativity, etc. in hydrodynamic models, and (b) understanding the nuclear properties (such as masses, excitation levels, decay rates) of the neutron-rich isotopes involved in the r-process path. The former is important for constraining the electron fraction and expansion timescales of the ejecta, while the latter is required in order to reduce uncertainties in the final abundances of r-process calculations and to compare the results with the r-process abundances in the solar system or metal-poor stars.

Recent simulations have shown that in addition to the *dynamic ejecta* which become unbound either by tidal forces or shocks during the merger phase, other mass loss channels are possible. A neutrino-driven baryonic wind component similar to the one in CCSNe (Perego et al. 2014; Just et al. 2015; Martin et al. 2015) has been found in the aftermath of CBM simulations, while material from the remnant torus that can form around the dense central object during the merger phase can later become unbound due to viscous dissipation and the release of recombination energy (Fernández and Metzger 2013; Just et al. 2015; Wu et al. 2016). The nucleosynthesis in these additional ejecta mechanisms has only been studied in the past few years, and it will be addressed further below in this chapter.

11.2.3 The r-Process

In order to explain the origin of stable nuclei heavier than iron, including some long-lived actinides (^{232}Th, ^{235,236,238}U, and ^{244}Pu), Burbidge et al. (1957) and Cameron (1957) proposed the *rapid neutron capture process* (r-process). As the name suggests, it operates on the basis of very fast neutron captures in comparison to β-decays, and runs close to the neutron-drip line. Wherever the path crosses isotopes with a closed neutron shell, both the neutron capture cross sections and β-decay rates become significantly smaller, leading to an accumulation of material in these nuclei, and the path moves closer to stability (see Fig. 11.2). After the supply of free neutrons has ceased, the extremely neutron-rich isotopes undergo a series of β-decays to stability. The mass numbers where the r-process path crossed the magic neutron numbers can be identified in the final abundance pattern by characteristic peaks, as is shown in Fig. 11.2.

The r-process can operate only if certain conditions are met. Neutron capture rates are dependent on the neutron density n_n, which means that material from the surface or the vicinity of neutron stars provides a good environment. Furthermore, the duration of the r-process and the maximum mass number of the final products is characterized by the ratio between the neutron abundance and the summed up abundances of all seed nuclei (usually iron group nuclei), Y_n/Y_{seed}. This ratio is a measure of the amount of neutrons every seed nucleus can capture before neutrons become depleted and the r-process stops. We can estimate the final average mass number $\langle A\rangle_f$ using

$$\langle A\rangle_f = \langle A\rangle_i + \left(\frac{Y_n}{Y_{seed}}\right)_i , \tag{11.1}$$

where i denotes the initial values. As mentioned above, iron group nuclei are typical seed nuclei, giving a typical value for $\langle A\rangle_i = 60$. Under these assumptions, a neutron-to-seed ratio of $Y_n/Y_{seed} = 184$ would be needed in order to reliably produce the heaviest long-lived actinide ^{244}Pu. Y_n/Y_{seed} is determined by several factors. A high Y_n can be achieved wherever the electron fraction Y_e is low (since charge neutrality is always assumed for astrophysical plasmas), making ejecta from the vicinity of neutron stars a natural environment favourable for the r-process. On the other hand, Y_n/Y_{seed} can reach large enough values if the abundances of seed nuclei are kept low. High entropies can counter the build-up of seed nuclei, with energetic photons dissociating them into nucleons and α-particles. Moreover,

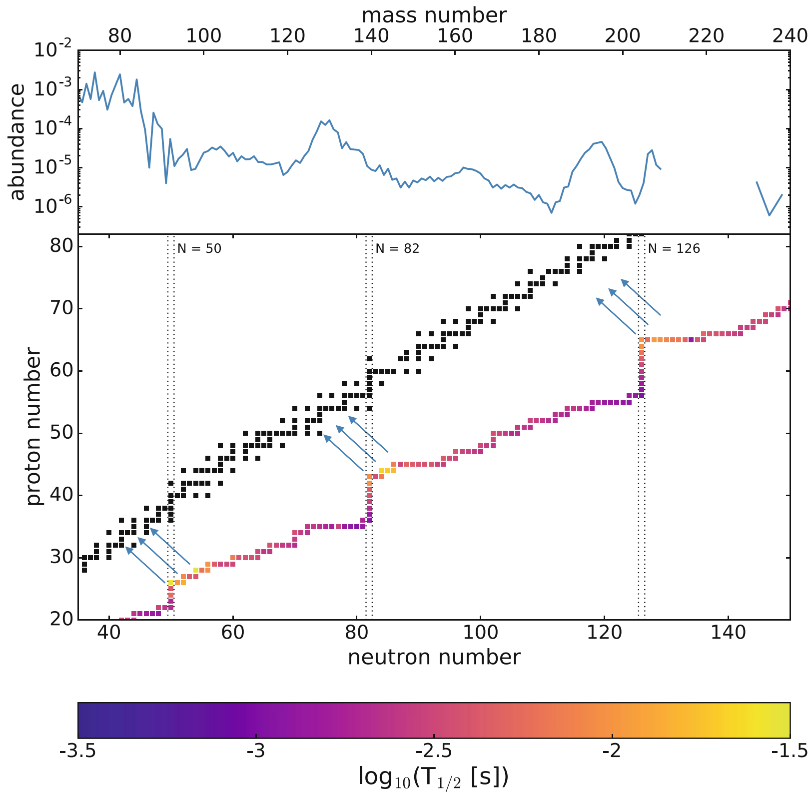

Fig. 11.2 Top panel: Solar r-process abundances as a function of nuclear mass number A. The values are taken from Sneden et al. (2008). Bottom panel: Typical r-process path in the nuclear chart and the corresponding β-decay half-lives according to Möller et al. (2003). Stable isotopes are marked in black and the magic neutron numbers are indicated by vertical dotted lines. The overlay of the two panels demonstrates how regions of large $T_{1/2}$ at the magic neutron numbers are responsible for the r-process abundance peaks after decay to stability

short dynamical timescales (i.e., fast expansions) also guarantee that the density decreases quickly past the point where seed nuclei can be efficiently produced from α-particles, leading to an α-rich freeze-out from charged-particle reactions. Qian and Woosley (1996), Otsuki et al. (2000), and Thompson et al. (2001) have explored the combinations of entropies, dynamical timescales, neutrino luminosities, and neutron star masses that result in the production of r-process nuclei of the second and the third peak, respectively. However, in hydrodynamic simulations of neutron star mergers, Y_e in the ejecta is so low that also the heaviest stable and long-lived nuclei are produced, independent of the other factors discussed here (Freiburghaus et al. 1999).

If the neutron-to-seed ratio is considerably larger than 180, very heavy and large nuclei are produced. While the attractive nuclear force has a limited range and acts mainly between two neighbouring nucleons, the repulsive Coulomb force of the protons has a larger range and its influence grows with increasing proton number, until it is strong enough to disrupt the nucleus and fission occurs. The freshly produced fragments continue capturing neutrons as long as the neutron density is high enough, and can eventually undergo fission themselves in a phenomenon that is called *fission cycling* (Beun et al. 2008). Assuming that each fission cycle divides $\langle A \rangle$ by two, we have to modify Eq. (11.1) as follows:

$$\langle A \rangle_f = \frac{\langle A \rangle_i + (Y_n/Y_{seed})_i}{2^{N_{cyc}}}, \tag{11.2}$$

where N_{cyc} is the number of fission cycles. The products of each fission process depend on the nuclear properties of the parent nucleus as well as of the possible fragments. Furthermore, the fission rate is extremely sensitive to the height of the potential barrier that needs to be overcome (or tunnelled through). This makes the prediction of fission rates and the distribution of fission fragments a very challenging field of research (see e.g. Giuliani et al. 2017).

In a simplified approach, we neglect all reactions that are not (n, γ), (γ, n) reactions, or β^--decays, resulting in a set of differential equations involving all of the above reactions that either produce or destroy isotope i:

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_j N^i_{j,n} \rho N_A \langle \sigma v \rangle_{j(n,\gamma)} Y_j Y_n, \tag{11.3}$$

where ρ is the density in units of g cm^{-3}, N_A is Avogadro's constant, $\langle \sigma v \rangle_{j(n,\gamma)}$ is the velocity integrated cross section of the reaction $j(n, \gamma)$, and the coefficients N^i_j and $N^i_{j,n}$ can take the values ± 1, determining if nucleus i is produced or destroyed. The first term on the right hand side contains β-decays and (γ, n) reactions, with the decay constant λ_j which relates to the half-live via

$$\lambda_j = \frac{\ln(2)}{\tau_{1/2}}. \tag{11.4}$$

The second term contains only two reactions in our example: the (n, γ) reaction producing nucleus i and the neutron capture on nucleus i itself. While the neutron capture rates mainly depend on the neutron density $n_n = \rho N_A Y_n$, the (γ, n) rates are affected by the temperature. Depending on the hydrodynamic trajectory, the (n, γ) reactions can therefore be in equilibrium with their reverse reactions (γ, n) for the majority of the duration of the r-process (this *hot r-process* scenario was first discussed by Seeger et al. 1965). The (n, γ)-(γ, n) equilibrium is established in every isotopic chain (isotopes with the same proton number Z) independently, and the abundance maximum in each chain is determined by the neutron separation energy S_n of the nuclei involved. The neutron separation energy of a nucleus (Z, A) is defined as the energy that is required to strip one neutron off of this nucleus, or, in other words, the negative Q-value of the (Z, A) (γ, n) reaction. As a trend, S_n

decreases with increasing neutron number $N = A - Z$, until it becomes 0 at the neutron-drip line, which means that no energy can be gained from further neutron captures.

Consider a neutron capture on a nucleus (Z, A) with a known reaction rate. We can find the rate of the reverse reaction $(Z, A+1)$ (γ, n) from a concept called *detailed balance*. The equilibrium abundance ratio between the nuclei (Z, A) and $(Z, A+1)$ is equal to the ratio of the (γ, n) and (n, γ) reaction rates:

$$\frac{Y(Z, A+1)}{Y(Z, A)} = n_n \frac{G(Z, A+1)}{2G(Z, A)} \left[\frac{A+1}{A}\right]^{3/2} \left[\frac{2\pi\hbar^2}{m_u kT}\right]^{3/2} \exp(S_n(A+1)/kT), \tag{11.5}$$

with the partition functions G that describe the thermally populated excited states, and the nuclear-mass unit m_u. This relation is valid for all nuclei in a given isotopic chain. For known n_n and T, the neutron separation energy at maximum abundance can be found by approximating $Y(A+1)/Y(Z, A) \approx 1$, identifying the most abundant isotopes in each isotopic chain. Note that this does not require the knowledge of the individual neutron capture cross sections, but only the nuclear masses which determine S_n. Adding the β-decay rates of these most abundant nuclei we can construct a simplified model for the r-process, the so-called *waiting point approximation*.

Reaction rates depend on the nuclear properties, such as masses or the energy levels of the excited states. Since the r-process path moves through very exotic neutron-rich region of the nuclear chart, these properties are not known experimentally for all nuclei involved. Thus, theoretical models are being developed which are fitted to the known nuclear data of less exotic isotopes and then extrapolated to all nuclei up to the neutron-drip line. Nowadays mass models belong to one of two categories: macroscopic-microscopic models which contain phenomenological terms to describe the overall behaviour of the nucleons and including microscopic corrections, such as shell effects or non-spherical ground-state configurations (e.g., Möller et al. 1995, 2012) and fully microscopic models. These are based on effective nucleon-nucleon interactions (e.g., Aboussir et al. 1995, Goriely et al. 2016, and references therein). Although there are many mass models of both categories which reproduce the experimental nuclear data very well, the mass predictions for very neutron-rich nuclei differ significantly, which has an impact on the reaction rates used in the nuclear network. Calculated r-process abundances are therefore heavily dependent on the mass model employed. For recent studies on the impact of nuclear masses on the calculated r-process abundances see, e.g., Arcones and Martínez-Pinedo (2011), Kratz et al. (2012), Martin et al. (2016), Mendoza-Temis et al. (2015), Mumpower et al. (2015), and Wanajo et al. (2005).

11.2.4 Observational Evidence for r-Process in CBMs

The r-process requires specific conditions to operate, such as large neutron densities, short dynamical timescales, etc. (see Sect. 11.2.3). These requirements point towards explosive environments containing decompressing deleptonized (e.g., neutron-star) material. Both CCSNe and CBMs can in principle meet the requirements. However, recent research suggests that regular CCSNe are ruled out as a source for the heaviest r-process nuclei. With the detection of GW170817, neutron star mergers have now been confirmed as an operating site of the r-process (Cowperthwaite et al. 2017; Drout et al. 2017; Kasen et al. 2017; Kasliwal et al. 2017; Kilpatrick et al. 2017; Rosswog et al. 2017; Smartt et al. 2017; Tanvir et al. 2017), as the light curve powered by the radioactive decays of heavy, neutron-rich nuclei has been observed (see Sect. 11.2.12). The ejected mass for this event is estimated to be at least $1.5 \times 10^{-2}\ M_{\odot}$, but may be larger if not all the energy released from radioactive decays ends up in the observed emission (Rosswog et al. 2017). In addition to the direct observation of a kilonova (Abbott et al. 2017c), a multitude of indirect observational evidence exists that points towards CBMs as a major r-process production site. The atmospheres of different extremely metal-poor (old) stars show the same abundance pattern for the heavy r-elements as the solar system abundances (e.g., Sneden et al. 2008), with very little scatter among them. This suggests that the r-process component producing the heaviest elements is robust and insensitive to small changes in the density or temperature evolution during the decompression of the ejecta. The robustness of the abundance pattern is a characteristic of the r-process in CBMs (Korobkin et al. 2012) because the environment is so neutron-rich that the reaction path runs along the neutron-drip line.

Regular CCSNe have a well-determined event rate in our galaxy, and in order to account for the accumulated r-process material in the present-day solar system a relatively low r-process ejecta mass per event is required (around $10^{-5}\ M_{\odot}$ of r-process material or even less). CBMs, on the other hand, are expected to occur at a much lower frequency, but ejecting around $10^{-3}\ M_{\odot}$ of r-process material. This degeneracy of high-rate/low-mass and low-rate/high-mass events can be broken by recent discoveries. For instance, the strong enhancement of r-elements in a group of stars belonging to the dwarf galaxy Reticulum II compared to other dwarf galaxies strongly supports a rare r-process event (Ji et al. 2016). From these data Beniamini et al. (2016) estimate an r-process event rate between 2.5×10^{-4} and 1.4×10^{-3} times lower than the event rate of regular CCSNe, and an ejected r-process mass between $6 \times 10^{-3}\ M_{\odot}$ and $4 \times 10^{-2}\ M_{\odot}$ per event, consistent with GW170817 and the values obtained in models of neutron star mergers. We can even find evidence in terrestrial deep sea sediments that exhibit the nuclear traces of the ejecta of nearby explosive events that rained down on earth millions of years ago. Studying long-lived radioactive isotopes in these sediments does not only reveal the history of explosive events in our solar neighbourhood, but helps us disentangle the different nucleosynthesis processes at the same time. ^{60}Fe has a half-life of $T_{1/2} \approx 2.6$ Myr and it is produced in CCSNe. A sediment layer between 1.7 and 3.2 Myr old was found to contain increased amounts of ^{60}Fe, indicating that around that time the earth was polluted by the ejecta of a nearby CCSN (Wallner et al. 2016). Assuming that this CCSN also produced and ejected some r-process material, one should also find heavier long-lived r-process nuclei. However, the same ocean sediment samples contain significantly less ^{244}Pu ($T_{1/2} \approx 81$ Myr) than expected from a continuous enrichment from CCSN ejecta (Wallner et al. 2015). On the other hand, the measured abundances are compatible with the expected (lower) frequency and (higher) ejecta masses of CBMs (Hotokezaka et al. 2015).

Another hint comes from the observed frequency of SGRBs. The only observed kilonovae so far have been associated to GRB 170817A (Abbott et al. 2017a), SGRB 130603B (Tanvir et al. 2013), SGRB 060614 (Yang et al. 2015; Jin et al. 2015), and SGRB 050709 (Jin et al. 2016), and the observed frequency of SGRBs supports the required frequency of CBMs as the main r-process source.

It is noteworthy that all the pieces of observational evidence presented above are independent from each other, however the constraints presented by these observations to the r-process event rate all agree, pointing to a rate around 5×10^{-4} lower than the rate of CCSNe. The resulting ejected mass of r-process material needed to explain the origin of the r-process element abundances in the solar system (10^{-3}–10^{-2} $M_\odot$) agrees very well with the ejecta mass in CBM models. Upcoming gravitational wave detections from CBMs will provide further constraints to this current picture.

11.2.5 Nucleosynthesis in Dynamic Ejecta

While the first hydrodynamic simulations of CBMs have been performed with the intention to determine the mass of the ejecta (Davies et al. 1994), recent models aim to pin down the conditions for r-process nucleosynthesis. This includes the expansion timescales and the Y_e distribution of the ejecta, which are affected by the mass asymmetry of the merging objects, the equation of state (EOS), the treatment of gravity, the neutrino treatment, and the simulation method (grid, SPH). Both the EOS and the gravity prescription determine the radii of the neutron stars, setting the conditions for the actual merger phase. With smaller radii, the neutron stars are more compact and the collision is more energetic. This means that more matter from the center of the collision (the interaction region) is flung out and ejected, with very high initial temperatures. If the collision is less energetic, the component which becomes gravitationally unbound from tidal forces dominates. The matter from the tidal component is cooler than the interaction component. While other mass loss channels related to CBMs exist (see Sect. 11.2.6), the dynamic ejecta have the lowest Y_e and constitute the most promising source for heavy r-process elements. Typical velocities for the dynamic ejecta are around 0.1 c. It is therefore generally expected that the effect of neutrino irradiation is small and the Y_e stays low during the first second of the expansion.

Goriely et al. (2011) and Korobkin et al. (2012) both found narrow Y_e distributions of the dynamic ejecta centered around 0.015 (0.03) for a series of NS-NS and NS-BH mergers with different mass asymmetries. The latter further showed that the low Y_e values guarantee a robust r-process abundance pattern across the different models even for differing temperature and density evolutions, since the reaction flow proceeds along the neutron-drip line, in a (n, γ)-(γ, n) equilibrium (see also Eichler et al. 2015). In addition, the extremely neutron-rich conditions lead to several fission cycles, which further enhance the robustness in the abundance pattern beyond the second peak, while lighter elements are not produced in significant amounts. The insensitiveness of the abundances with respect to the temperature and density evolution means that the final abundance pattern is almost purely determined by the nuclear physics employed in the nuclear reaction network, providing an ideal testing ground for nuclear physics. Several studies have investigated the impact of nuclear mass models, β-decay rates, fission barriers, fission fragment distribution models, nuclear heating, and neutrino interactions (Panov et al. 2008; Surman et al. 2008; Panov et al. 2013; Bauswein et al. 2013; Goriely et al. 2013; Rosswog et al. 2014; Mumpower et al. 2015; Goriely et al. 2015; Mendoza-Temis et al. 2015; Eichler et al. 2015; Mumpower et al. 2017; Roberts et al. 2017).

As neutron capture rates and β-decay rates directly depend on the nuclear masses, so do the final abundances. This was shown in detail in Mendoza-Temis et al. (2015), where four independent mass models (FRDM (Möller et al. 1995), WS3 (Liu et al. 2011), DZ31 (Duflo and Zuker 1995), and HFB-21 (Goriely et al. 2010)) were employed to calculate the r-process abundances on the same hydrodynamic model of a neutron star merger. They found that mass models with small neutron separation energies around the $N = 130$ isotone exhibit a shift of the third abundance peak (compared to the solar abundances) due to a hold-up in the reaction flow in these nuclei. In addition, it was shown in Eichler et al. (2015) that the shift is amplified by late captures of neutrons which are emitted from fission reactions after the freeze-out from the (n, γ)-(γ, n) equilibrium (see also Caballero et al. 2014), while β-delayed neutrons also contribute. The strength of the effect depends on the timing of the last fission cycle with respect to the freeze-out from (n, γ)-(γ, n) equilibrium. The β-decay rates along the reaction path determine the waiting points where material is accumulated as well as the duration of the r-process. Therefore, they also have a say in the position of the third peak in the final abundances. Recent experimental (Domingo-Pardo et al. 2013; Kurtukian-Nieto et al. 2014) and theoretical (Suzuki et al. 2012; Zhi et al. 2013; Panov et al. 2015; Marketin et al. 2016) β-decay rate determinations find faster rates for the heaviest neutron-rich nuclei, decreasing the shift effect after freeze-out. Caballero-Folch et al. (2016) find that for nuclei beyond $N = 126$, however, the often used theoretical β-rates of Möller et al. (2003) give good predictions. Different fission fragment distribution models (FFDMs) were also tested within the framework of Eichler et al. (2015), revealing that the region around the second abundance peak is shaped by the fission fragments produced in the last fission cycle (see also Goriely 2015).

Late-time effects also affect the small peak around the rare-earth region (Surman and Engel 2001; Mumpower et al. 2012). An enlightening illustration of how nuclear masses shape the final rare-earth abundances is given in Mumpower et al. (2017). Their approach is fundamentally different, as they vary nuclear masses in Monte-Carlo calculations and from these determine new β-decay and neutron capture rates. The comparison of the obtained abundance pattern with the solar abundances in the region of the rare-earth peak allows to draw conclusions about the unknown masses of the nuclei far from stability in this mass range.

Depending on the setup of the hydrodynamical model, the Y_e distribution of the dynamic ejecta can be broader, which also allows for the production of first peak material in the dynamic ejecta (Wanajo et al. 2014; Sekiguchi et al. 2015, 2016; Radice et al. 2016), possibly at the price of the robustness discussed above. In order to settle this question, the neutrino treatment, in particular, has to be improved. As it is computationally very expensive, approximations are still used in simulations.

11.2.6 Disk Formation and Ejected Matter

In order to be able to asses the EM emission summarized in Fig. 11.1 and perform accurate nucleosynthesis calculations, it is crucial to make simulations as accurate as possible in order to compute the amount of mass that is ejected from these systems and its properties, such as temperature distribution and electron fraction. It is also important to compute the properties of the disks that may be formed after merger. Numerical simulations have in particular shown that, in the case of NS-NS mergers, larger disks with masses of up to $\sim 0.3M_\odot$ are produced in mergers that form hypermassive neutron stars (i.e., NSs with masses larger than the maximum mass for an uniformly rotating NS and that collapse to a BH in less than $\sim$ 1s after merger), while systems that produce a prompt collapse to BH are left with much smaller disks, with masses smaller than $\sim 10^{-2}M_\odot$ (Rezzolla et al. 2010; Giacomazzo et al. 2013). The mass of the disk can also be affected by the mass ratio of the system, with lower mass ratios producing larger disks. In the case of NS-BH merger, where mass ratios as low as $1/7$ can be expected, the BH spin plays an essential role in the disk formation, where disks as massive as $\sim 0.1M_\odot$ may be formed if the BH was rapidly rotating with a spin of ~ 0.9 (Foucart 2012).

On timescales of $\sim$ 100 ms a part of the disk becomes gravitationally unbound due to viscous dissipation and nuclear recombination. The fraction of the disk mass ejected this way depends sensitively on the survival time of the hypermassive NS (HMNS) before it collapses into a black hole, but according to simulations, around 20–25 % of the disk material can be ejected this way, making it an important factor for the overall ejecta. The timescales are much longer than for the dynamic ejecta, and the disk material, which eventually is ejected, can have a much larger Y_e due to neutrino interactions. Just et al. (2015) and Wu et al. (2016) show that in this component nuclei up to the third r-process peak (A=195) can be produced, and that it is a reliable source for second peak (A=130) material.

Similar to the neutrino-driven wind in core-collapse supernovae, a neutrino-driven wind component has been found in CBMs, where neutrinos can transfer enough energy to nuclei in the disk resulting in a baryonic wind. This mass loss channel mainly ejects matter in a direction usually perpendicular to the orbital plane, adding an angular dependence to light curve models. This mass loss channel relies on the absorption of neutrinos, which means that Y_e in the initially very neutron-rich material increases. Martin et al. (2015) find a Y_e distribution between 0.2 and 0.4, and a total ejecta mass of almost $10^{-2}\ M_{\odot}$, comparable to the mass of the dynamic ejecta. The mass of the neutrino-driven wind depends on the total mass of the accretion disk. Due to the higher electron fractions, this channel is not thought to host a full r-process, but a weak r-process which produces first r-process peak nuclei.

In order to obtain the full picture, all the three mass loss channels need to be considered, adding complexity to the determination of the nuclear composition in the ejecta of a CBM. Figure 11.3 presents an overview on the different channels and their dynamical timescales.

The study of matter ejected in these systems has also provided new interesting results with general relativistic simulations showing that, in the case of NS-NS mergers, the shocks developed during merger have a mayor role in ejecting matter with respect to tidal disruption and that hence more compact NSs produce larger ejecta, in contradiction with previous Newtonian results that were underestimating

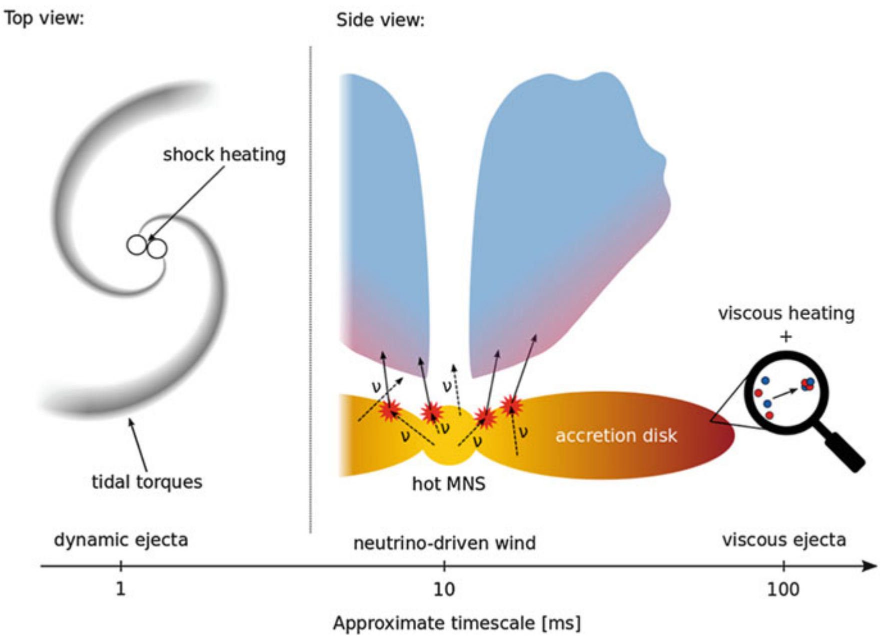

Fig. 11.3 Mass loss channels in a CBM, shown face-on (left) and edge-on (right). Typical timescales for the outflows are indicated at the bottom. Figure courtesy of D. Martin

the energy released in shocks. Tidal disruption is still instead the main mechanism for ejecting matter in NS-BH mergers, but also in this case the NS compactness, as well as the BH spin and mass ratio, play a fundamental role with less compact NS ejecting more matter, when keeping the mass ratio and BH spin fixed (Foucart 2012).

11.2.7 Short Gamma-Ray Bursts

One of the strongest EM signals expected from the merger of two NSs or of an NS and a BH are short gamma-ray bursts. Even before the simultaneous detection of GW170817 and GRB 170817A (Abbott et al. 2017a), there were already several indirect evidences that linked such systems to the central engine of SGRBs (Berger 2014). The main idea is that NS-BH and NS-NS mergers will produce a spinning BH surrounded by an accretion disk. Such a system could then launch a relativistic jet which, as in the case of long GRBs, will produce gamma-ray emission, e.g., via internal shocks.

The simultaneous detection of GW170817 and GRB 170817A proved that at least some type of SGRBs are indeed caused by BNS mergers. The detection was quite a surprise since it was thought to be quite unlikely. The most optimistic rate was estimated to be of up to $\sim$2 simultaneous detections every year for the advanced LIGO and Virgo detectors at design sensitivities (Clark et al. 2015). This was due to the probably collimated nature of SGRBs, which are observed with median jet opening angles of 16 ± 10 degrees, but such measurements are very scarce being based on the few detected jet breaks (Fong et al. 2015). Moreover GRB 170817A was quite a peculiar SGRB with a delayed X-ray afterglow (Troja et al. 2017) that is thought to be due to the jet being observed off axis (Lazzati et al. 2017) or to a chocked jet (e.g., the cocoon model (Mooley et al. 2018)).

Numerical and theoretical studies are therefore still one of the best ways to try to assess the connection between SGRB properties and CBM. In the last few years there have been a number of efforts, as also described in more detail in the following sections, in order to try to explain current observations. As of today the main mechanism to produce the observed gamma-ray emission and at the same time explain short time-scale variability in the lightcurves is for the central engine to produce a strongly relativistic jet, with Lorentz factor of order $\sim$100 or larger. Such jets need also to be collimated and have a sufficiently long (short) lifetime to fit the burst duration. Moreover, any theoretical model needs also to be able to explain the afterglow emission, including extended emission in the gamma rays and X-ray plateaus. All of this is clearly challenging and in the following sections we will describe our current understanding, thanks also to numerical simulations of CBMs.

11.2.8 *Jet Formation*

While it has been known for a while that accretion disks around spinning BHs can produce relativistic jets via neutrino–antineutrino annihilation (Birkl et al. 2007) or via magnetic fields (Blandford and Znajek 1977; Komissarov and Barkov 2009), only very recently simulations of NS-NS and NS-BH mergers have started to show the formation of such jets, even if with quite low Lorentz factors (lower than ~ 2). In particular magnetic fields can give rise to relativistic jets via the Blandford-Znajek (BZ) mechanism (Blandford and Znajek 1977). In the BZ mechanism, which describes a spinning BH immersed in a magnetically dominated plasma, magnetic fields can extract energy from the BH and produce a relativistic outflow.

The first simulation showing that NS-NS mergers may produce relativistic jets was the so called "Missing Link" paper (Rezzolla et al. 2011) where the authors showed for the first time that a collimated and mainly poloidal magnetic field was produced at the end of a simulation of an equal-mass system. While the formation of a collimated poloidal magnetic field structure is a necessary condition for the production of a relativistic jet (De Villiers et al. 2005; McKinney 2006), that simulation was not able to actually show the formation of a jet. The main reason is that in order to activate the Blandford-Znajek mechanism (Blandford and Znajek 1977), a magnetically dominated region needs to be formed in the BH ergosphere (Komissarov and Barkov 2009). Very recently simulations of NS-NS and NS-BH mergers performed with much higher magnetic fields (i.e., $\sim 10^{16}$ G at the NS center) were instead able to see the formation of a mildly relativistic jet (Paschalidis et al. 2015; Ruiz et al. 2016), even if only for one specific model with a simple ideal-fluid EOS. Figure 11.4 shows the end result of those simulations with the formation of an outflow along a magnetically dominated funnel. More recently, following what was done in Rezzolla et al. (2011) and Kiuchi et al. (2014), a different group performed simulations of different NS-NS systems with different EOSs, mass ratios, and magnetic field orientations (Kawamura et al. 2016). Even if in this case no jet was produced because of the much lower initial magnetic field value (i.e., $\sim 10^{12}$ G), all the simulations showed the formation of a collimated and

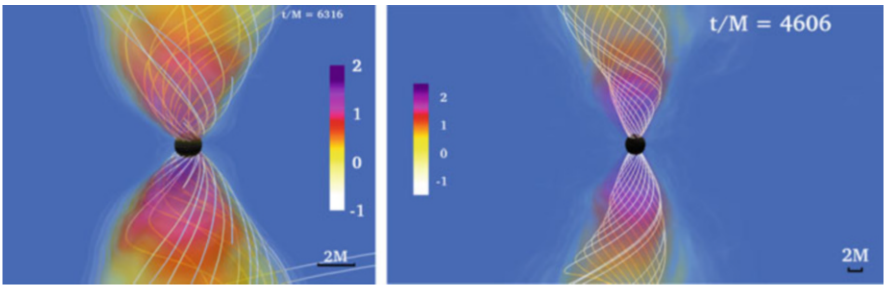

Fig. 11.4 Ratio of magnetic energy density over rest-mass energy density at the end of a NS-BH merger (Paschalidis et al. 2015) and NS-NS merger (Ruiz et al. 2016) respectively

mainly poloidal magnetic field configuration at the end of the simulations. Therefore it seems that, at least in the case of NS-NS mergers, the results produced in Ruiz et al. (2016) should be general.

11.2.9 The Problem of Magnetic Field Amplification

Magnetic fields can play a crucial role in launching relativistic jets and in giving rise to SGRBs and other EM emission. It is therefore important to better understand their evolution in NS-NS and NS-BH mergers. While their evolution can be mainly neglected during the inspiral phase (Giacomazzo et al. 2009), hydrodynamic and magnetohydrodynamic instabilities and turbulence may strongly affect the magnetic field structure and strength during and after merger. There are two instabilities that play an important role in the magnetic field evolution: Kelvin-Helmholtz (KH) and the Magneto-Rotational Instability (MRI).

The KH instability develops when a shear layer is formed in the velocity field during the merger of two neutron stars. A series of vortices can be formed in this case and they can twist magnetic field lines. So, even when starting with a purely poloidal magnetic field configuration, the KH instability may lead to the production of a strong toroidal component and amplify the total magnetic field. How strong that amplification can be is still matter of debate. Preliminary Newtonian simulations (Price and Rosswog 2006) showed that the magnetic field can be amplified by several orders of magnitude up to at least $\sim 10^{15}$G. Such simulations seem to be supported by local simulations of turbulent fluid both in Newtonian (Obergaulinger et al. 2010) and Special Relativistic MHD (Zrake and MacFadyen 2013). In these local high-resolution simulations magnetic fields are shown to be amplified until the magnetic energy reaches equipartition with the kinetic energy of the turbulent flow. This means possible magnetic field amplifications up to values of $\sim 10^{16-17}$G.

Unfortunately in order to reproduce the results of such local simulations in a global simulation of NS-NS mergers one would need to run with much higher resolutions than those that can be currently afforded. A recent attempt was done by Kiuchi and collaborators who performed simulations with resolution of up to 17.5 meters (Kiuchi et al. 2015), $\sim$ 1 order of magnitude higher that the typical resolution used in NS-NS mergers ($\sim$ 200 meters). Their simulations show an amplification in the magnetic energy of up to $\sim$ 6 orders of magnitude and with magnetic fields growing from $\sim 10^{13}$ G to $\sim 10^{16}$ G. They also showed that the saturation of the magnetic energy should be at least $\sim 0.1\%$ of the bulk kinetic energy. Such simulations were possible thanks to the use of the K supercomputer in Japan, but their computational cost was so high that the group was not able to study what happens to the magnetic field after this initial amplification (the simulations were terminated soon after merger).

Other groups have recently proposed different subgrid models to mimic such large amplification without the need to use such expensive resolutions (Giacomazzo et al. 2015; Palenzuela et al. 2015).

While the KH instability and its related magnetic field amplification can be present only in NS-NS merges, MRI (Balbus and Hawley 1991) can affect the evolution of magnetic fields both in NS-NS and NS-BH mergers. In the former the magnetic field may be amplified both in the differentially rotating post-merger remnant and in the disk, while in the latter only in the disk.

11.2.10 Magnetar Formation

In case a long-lived NS is formed after a NS-NS merger, large magnetic fields may be able to give rise to a magnetar (Giacomazzo and Perna 2013). The production of a long-lived magnetar may be used to explain some EM observations, such as the X-ray plateaus observed in some SGRBs (Rowlinson et al. 2013). The main idea is that the angular momentum of the magnetar is extracted via magnetic fields and powers a long-duration EM emission. Unfortunately, while GRMHD simulations of NS-NS mergers have improved significantly the level of details with which such mergers are studied, they are still too expensive to be able to follow the magnetar for the long time scales ($\sim$ hours) required to match with current EM observations. Simple models have been proposed to overcome this issue and provide estimates for the EM emission that can be produced by post-merger NS remnants (Siegel and Ciolfi 2016a,b). In particular such models can provide an estimate of the X-ray emission and link it to the one observed in some SGRBs.

We stress though that the formation of a magnetar requires not only a large amplification of magnetic fields inside the NS remnant, but also the formation of a powerful poloidal magnetic field outside the NS remnant. It is not clear at the moment how the large magnetic field that is expected to be produced inside the remnant can emerge outside and form the typical poloidal configuration expected in magnetars.

11.2.11 The Time-Reversal Scenario

The "standard" scenario of SGRBs, depicted in Fig. 11.1, is based on the idea that the jet powering the SGRB is emitted from a BH surrounded by an accretion disk and that the afterglow is emitted by the interaction of the jet with the surrounding interstellar medium. An alternative model, the magnetar one, predicts instead that the SGRB is produced by the large magnetic energy contained in the magnetar formed soon after merger. The latter model excludes NS-BH as the source of SGRBs and it has the problem of explaining how highly relativistic jets may be emitted due to the baryon pollution problem. Numerical simulations show indeed that, when a NS is formed after the merger, it is surrounded by a dense baryonic region with densities of $\sim 10^{10}$ g cm^{-3} (Ciolfi et al. 2017). Such densities seem to be too high

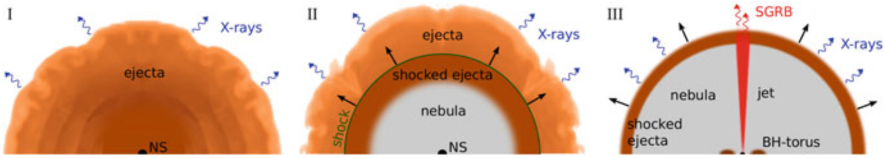

Fig. 11.5 The "time-reversal" scenario different evolution phases: (I) The differentially rotating supramassive NS ejects a baryon-loaded and highly isotropic wind; (II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta; (III) The NS collapses to a BH, a relativistic jet drills through the nebula and the ejecta shell and produces the prompt SGRB, while spin-down emission diffuses outwards on a much longer timescale. Figure and caption are taken from Ciolfi and Siegel (2015)

to allow the production of relativistic jets with Lorentz factors as high as those measured in SGRB jets (i.e., ∼100–1000).

The former model instead has difficulties explaining the X-ray plateaus that seem to indicate that energy is injected into the system on time scales much larger than the typical survival time for an accretion disk (typically less than 1 s).

Therefore alternative models have been developed in order to try to solve both issues. In particular the two models presented in Rezzolla and Kumar (2015), Ciolfi and Siegel (2015) and called respectively "two-winds" and "time-reversal" scenario are both based on the idea that a long-lived magnetar is formed after merger. In Fig. 11.5 we present the main stages of the evolution of the system as described in the "time-reversal" scenario (Ciolfi and Siegel 2015).

Both models require a long-lived NS to be formed after merger. Therefore both models exclude NS-BH mergers as the source of SGRB (while they are not excluded by the "standard" scenario). The idea is that a baryon-rich wind is generated by the highly-magnetized remnant followed by the production of a faster but baryon-poor wind. The interaction between the two gives rise to an X-ray emission. Once the NS collapses to a BH and a BH-disk system is formed a relativistic jet may be finally launched and give rise to the SGRB. The wind will still produce the X-ray emission and therefore, what we observe as a plateau in the afterglow is actually an emission that originated from an earlier stage of the evolution with respect to the jet (from this the name "time-reversal" (Ciolfi and Siegel 2015)).

The problem with these models is that they require a disk to be formed after the collapse to BH of the long-lived NS. Simulations of uniformly rotating NS collapsing to BH do not show indeed the formation of disks (Baiotti et al. 2005, 2007). Other groups have expressed also doubts that such disks may be formed on the base also of simpler analytic models (Margalit et al. 2015). We note though that such models were based on the idea that the NS collapsing to a BH was not already surrounded by an accretion disk. If such disk was present at the moment of collapse it would not be destabilized by the collapse and hence form a BH-disk system (Giacomazzo and Perna 2012). Moreover magnetic fields may also be able to redistribute angular momentum in the rapidly rotating remnant and help the formation of a disk (Duez et al. 2006), even if this effect will be more relevant initially when the external regions of the star are still differentially rotating. Unfortunately such long timescales cannot be simulated and it is therefore difficult at the moment to state if a disk will be present or not and this is a strong constraint for both these scenarios.

11.2.12 Kilonovae/Macronovae

The r-process produces heavy and very neutron-rich nuclei which eventually decay radioactively to stability by means of β-, α-decays, and fission. Li and Paczyński (1998) were the first to suggest that these series of decays can lead to an electromagnetic transient, similar to the decay of ^{56}Ni in core-collapse SNe or Type Ia SNe. This was followed by light curve predictions based on real r-process compositions performed by Metzger et al. (2010), who assumed opacities in the ejecta similar to that in CCSN ejecta. Only later it was found that the ejecta in a CBM stay optically thick for a long time, even though they expand quickly and comprise only a small mass. This is due to the production of large amounts of lanthanides, which have a high line transition density and therefore a particularly high opacity (Kasen et al. 2013; Tanaka and Hotokezaka 2013). As a consequence, the emitted photons are absorbed and the ejecta are thermalized before radiation can break out eventually when the densities have sufficiently decreased. If only heavy r-process elements ($A > 130$) are synthesised, the high opacities cause the light curve to peak at a timescale of about 1 week instead of 1 day, at a lower luminosity and at a wavelength in the near-infrared region, as opposed to optical or ultra-violet. A good approximation for the time of peak luminosity is given e.g., in Metzger (2016):

$$t_{peak} \approx 1.6\,\mathrm{d} \left(\frac{M}{10^{-2}\,M_\odot} \right)^{1/2} \left(\frac{v}{0.1\,\mathrm{c}} \right)^{1/2} \left(\frac{\kappa}{1\,\mathrm{cm}^2\,\mathrm{g}^{-1}} \right)^{1/2}, \tag{11.6}$$

where M is the mass, v is the velocity, and κ is the opacity of the ejecta.

Lanthanide production is not guaranteed throughout the ejecta. In less neutron-rich conditions ($Y_e > 0.3$) the composition is almost lanthanide-free, with a direct consequence on the opacity. Electromagnetic emission from this lanthanide-free component would become visible already after about 1 day, and the spectrum would be at smaller wavelengths compared to the lanthanide-rich ejecta. Moreover, some simulations suggest that a small fraction of the ejecta is subject to extremely fast decompression, such that free neutrons are not captured but decay directly, producing a blue precursor to the kilonova that peaks on a timescale of a few hours (Metzger et al. 2015). A distinction can therefore be made into a red and a blue kilonova component, depending on the amount of lanthanides. Since the very neutron-rich dynamic ejecta provide large opacities along the equatorial plane (their emission is lanthanide-rich, therefore red), the blue component would only be visible if the event is viewed with a certain angle to the plane. The kilonova signal may therefore also depend on the viewing angle under which the event is observed.

Apart from the amount of lanthanides, the nuclear composition produced in the precedent r-process also sets the conditions for the nuclear heating rate in the ejecta. Since decay half-lives become longer as the composition approaches stability, the nuclear heating rate is another big factor in the temporal evolution of the kilonova light curve. The details of the heating rate depend on the nuclear composition and its decay history as well as the thermalization efficiency ϵ_{th} with which the decay products thermalize with the ejecta. However, a fitting formula can be found for a large sample decaying to stability. Korobkin et al. (2012) suggest the following fit for the specific heating rate:

$$\dot{\epsilon}(t) = \epsilon_0 \left(\frac{1}{2} - \frac{1}{\pi} \arctan \frac{t - t_0}{\sigma}\right)^{\alpha} \times \left(\frac{\epsilon_{th}}{0.5}\right) \tag{11.7}$$

with $\epsilon_0 = 2 \times 10^{18}$ erg g^{-1} s^{-1}, $t_0 = 1.3$ s, $\sigma = 0.11$ s, and $\alpha = 1.3$. The thermalization efficiency ϵ_{th} itself is time-dependent and varies significantly for different thermalization processes (e.g., photoionization, Compton scattering, Coulomb interactions, etc.), but again the collective behaviour can be approximated by (see Barnes et al. 2016)

$$\epsilon_{th}(t) = 0.36 \left[\exp(-at) + \frac{\ln(1 + 2b\,t^d)}{2b\,t^d}\right], \tag{11.8}$$

where a, b, and d are parameters that depend on the mass and velocity of the matter in the layer of ejecta considered. Values for these parameters are given for a range of ejecta masses and velocities in Table 1 of Barnes et al. (2016).

The detailed dependence of the overall heating rate and the kilonova light curve on the initial electron fraction Y_e, the specific entropy e, and the expansion timescale τ is demonstrated in Lippuner and Roberts (2015). Furthermore, Barnes et al. (2016) and Hotokezaka et al. (2016) have investigated the nuclear heating rates from the individual decay types (α-decay, β-decay, and fission) and find a sensitivity to the initial nuclear composition, which in turn is strongly affected by the nuclear mass model employed for the r-process calculation. The discrepancies mainly originate from the different abundances of actinides ($220 \leq A \leq 250$) which usually undergo α-decay, as well as the large uncertainties in fission rates. The relationship between the nuclear composition before decay and the kilonova heating rates, if understood better, could ultimately lead to new independent constraints on the nuclear mass model for neutron-rich nuclei derived from kilonova light curves.

Such theoretical predictions is supported by recent detections in the afterglow emission of some SGRBs. The first claim for the possible detection of a kilonova was made for GRB 130603B (Tanvir et al. 2013), a SGRB at redshift $z = 0.356$. Unfortunately this claim was supported only by a single data point which showed a stronger emission in the near infrared with respect to what one would expect from an afterglow emission due to a decelerating jet. Nevertheless this was the first observation that could be explained as a kilonova powered by an ejected amount of matter between 10^{-2} and $10^{-1} M_{\odot}$. There were also other detections of kilonovae possibly associated with GRB 060614 (Yang et al. 2015; Jin et al. 2015) and with GRB 050709 (Jin et al. 2016). Now the observation of the kilonova GW170817 confirms the production of heavy r-process and lighter heavy elements in neutron star mergers. The electromagnetic followup of GW170817 shows a initial blue emission associated with lanthanide free ejecta and thus $Y_e > 0.3$ followed by a red/infrared late emission due to heavy r-process elements (e.g. Kilpatrick et al. 2017).

11.2.13 Electromagnetic Precursors

While in the previous part of this chapter we focused on EM emission powered after the merger, also because this is expected to be the most powerful one, there is also the possibility to have EM emission before merger.

Observations of SGRB precursors (Troja et al. 2010) have indeed triggered studies of possible EM emission generated before mergers. There are two main mechanisms that have been studied. The first one is related to the possibility that the NS crust may break because of tidal interaction between the NSs in a NS-NS merger (Tsang et al. 2012). The second one is instead due to the interaction between the NSs magnetosphere in a NS-NS binary (Palenzuela et al. 2013b,a) or between the magnetic field of the NS and a BH in the case of a NS-BH system (Paschalidis et al. 2013; McWilliams and Levin 2011). In both cases the expected luminosity may be quite low with maximum values between $\sim 10^{40}$ and $\sim 10^{43}$ erg/s in the hard X-ray part of the EM spectrum (Palenzuela et al. 2013b; Paschalidis et al. 2013).

No precursor was observed in the case of GW170817 (Abbott et al. 2017c), but such a possible detection would have required X-ray and gamma-ray observations of the site of the BNS before the detection of the GW peak. Therefore an early GW detection of the inspiral signal is required in order to be able to point EM telescopes before merger.

11.3 Present Challenges and Future Prospects

Numerical and theoretical modelling of EM counterparts and nucleosynthesis in CBM have made significant progresses in the last few years, but the number of questions that remain to be addressed is still large. In the following section we provide an overview of the main topics that need to be addressed in the next years.

11.3.1 Electromagnetic Emission

One of the main challenges is to provide accurate estimates of the lightcurves of the EM emission produced by NS-NS and NS-BH mergers. Most of the simulations (if not all of them) provide only preliminary estimates of the EM luminosity, often based simply on the integration of the Poynting flux. Such luminosity, while useful to get an idea of the possible maximum luminosity produced by such events, do not help in fitting current observation (e.g., SGRBs). It is therefore crucial to better address the long-term evolution of matter ejecta and magnetic field interaction.

In the case of matter ejected via tidal disruption during the late phase of inspiral or via shocks at merger, it is fundamental to take into account finite-temperature effects and neutrino emission and absorption. Very few simulations, as of today, have started to include both effects in full general relativity.

In the case of systems producing a BH surrounded by an accretion disk, there is preliminary evidence for the formation of jets, but how these jets depend on the properties of the binary has not been studied yet. Up to now there have been indeed only two papers (by the same group and with the same code) showing the production of a mildly relativistic outflow (Paschalidis et al. 2015; Ruiz et al. 2016). In both cases the initial magnetic field was several orders of magnitude larger than the typical magnetic field expected in merging neutron star binaries. While in the case of NS-NS binaries large magnetic fields may be produced during merger, but only in the region inside the HMNS/SMNS, such large amplification is not expected in NS-BH mergers, but it may only be produced later in the disk (if any). Therefore it is not clear yet if such results will apply also to simulations starting with lower and more realistic magnetic field values. Clearly these simulations will also need to properly resolve the turbulent scales on which the magnetic field is amplified and hence require large computational resources (Kiuchi et al. 2015).

In the case of systems producing a long-lived NS after merger, most of the studies have been focused on a detailed calculation of the GW emission and very few on the possible EM counterparts that such systems may emit (Siegel and Ciolfi 2016a,b). It is not currently possible to follow these systems numerically on the long time scales required to study their long-term EM emission. It will therefore be important to be able to better study the properties of post-merger remnants in order to develop better (analytic) models.

In all cases, it seems evident that a correct description of finite-temperature effects, magnetic field evolution, neutrino emission and reabsorption, and turbulence is crucial to provide more accurate models. Unfortunately all of this will require more robust and powerful computational algorithms and the use of faster supercomputers.

11.3.2 Nucleosynthesis

The young field of nucleosynthesis in CBMs has made considerable progress in the past few years, culminating in the observation of the kilonova related to GW170817. Nevertheless, many open questions remain, connected both to the hydrodynamical simulations and the nuclear physics. Since the r-process operates close to the neutron-drip line in the nuclear chart, no experimental data exist for the extremely neutron-rich isotopes that lie on the typical reaction path. The nuclear mass models that are used for nucleosynthesis calculations all reproduce the known nuclear data very well, but drastically diverge with increasing distance to the valley of stability, as is shown e.g., in Goriely et al. (2007).

Next-generation experimental facilities (e.g., RIKEN in Japan, while FAIR at GSI Darmstadt and FRIB at Michigan State University are currently being built at the time of writing) will push the boundaries of experimentally studied isotopes, in some mass regions almost reaching the typical r-process reaction path. The new data from mass measurements will significantly help to further constrain nuclear mass models.

On the theoretical side, more extensive models based on density functional theory are needed, e.g., fission barrier and fragment distribution calculations (Sadhukhan et al. 2016) or β-decay rates (Marketin et al. 2016). Efforts should be made to incorporate new experimental data and reach consistent treatments of (theoretically derived) nuclear properties. Recently, a lot of progress has been made in modelling the EM afterglow powered by radioactive decay of the r-process products. The link between the nuclear compositions achieved in the r-process calculations with different mass models and reaction rates and the radioactive heating rates should be studied further.

Equation (11.5) shows that for a given mass model the only factors that determine which nuclei lie on the r-process path in a hot r-process scenario are the temperature and the neutron density, with the latter directly dependent on the electron fraction Y_e. These are quantities that are evolved in the tracer particles used for nucleosynthesis post-processing, and in turn depend on the framework of the hydrodynamical setup, such as the EoS, the neutrino treatment, etc. The different Y_e and temperature distributions in the ejecta of different simulations therefore add another layer of uncertainties to any calculated r-process results. Further future detections of gravitational waves from binary neutron star mergers will greatly constrain the high-density EOS, since any gravitational wave signal carries the signature of the EOS (Radice et al. 2016; Kuroda et al. 2016; Clark et al. 2016; Chirenti et al. 2017; Richers et al. 2017; Bauswein et al. 2017). The three gravitational wave detectors LIGO-Hanford, LIGO-Livingston, and Virgo are currently being upgraded. Additional GW observatories (KAGRA, and LIGO India) are already being built or in the final planning stages. Future observing runs from these facilities will have a sensitivity high enough to detect several CBMs per year. The direction of any GW signal has to be determined by means of triangulation. Therefore the additional detectors are essential to constrain the coordinates of the GW event and enable follow-up observations of the ensuing kilonova, as it has been demonstrated by the LIGO-Virgo observation of GW170817 (Abbott et al. 2017b).

Parallel to gravitational wave signals, detections of kilonovae are needed to match theoretically derived light curves, which will provide new insights on nuclear aspects such as the dominant decay types and the end point of the r-process. These comparisons will allow for a quality assessment of the currently available predictions of nuclear properties far from stability (see Sect. 11.2.12). Furthermore, observed light curves will also let us draw conclusions about the amount of (dynamically) ejected matter. Observations including detailed study of features (i.e., absorption/emission lines) in kilonova spectra can also rise new insights about the composition of the ejecta in combination with the peak luminosity time and color (e.g., Pian et al. 2017).

11.4 Conclusions

Compact binary mergers are currently one of the most exciting astrophysical scenarios to be studied in the GW and EM spectrum, especially after the simultaneous observations of GW170817 and GRB170817A. That single event provided the first evidence that BNS mergers are among the main r-process site in our universe, but also established a link between them and at least some type of SGRBs. While the actual mechanism to produce the gamma-ray emission is not completely understood, the main idea is that a jet can be launched from the central BH formed after merger, emitting highly energetic gamma-rays, which would on earth be observed as a short GRB. Moreover, the radioactive decays of the fresh r-process products to stability power an electromagnetic transient known as “kilonova” (or “macronova”) that peaks days after the actual merger in the optical or near-infrared wavelengths. In this chapter, the current status of research is presented with respect to nucleosynthesis in the ejecta of CBMs as well as the origins of the different kinds of electromagnetic counterparts that are expected in the aftermath of a merger. In particular, we have discussed the following aspects:

Possible Precursor EM Emission Before the merger takes place, the two neutron stars in a NS-NS merger affect each other by means of both their gravitational and magnetic fields, the former leading to a breaking up of the NS crust. Simulations have shown that these interactions can lead to EM emission before the merger phase. No precursor was observed in the case of GW170817, but such an observation would very probably require a very rapid EM search before the merger GW signal.

Dynamic Ejecta During the merger, matter can become gravitationally unbound mainly by two methods. First, a tidal tail forms behind each NS, ejecting cold, very neutron-rich matter at a high velocity. Second, at the collision interface matter gets heated and accelerated by the collision shock. Both components are expected to harbour a strong r-process, however the second component is considerably hotter than the tidal ejecta and subject to more neutrino interactions which alter the electron fraction. Therefore, the ratio of tidal ejecta to shocked ejecta can have an impact on the nucleosynthesis yields. Major uncertainties in the r-process nucleosynthesis yields are connected to the unknown properties of neutron-rich nuclei and the Y_e distribution of the ejecta. The radioactive decay of the heavy elements produced in the r-process later on powers the kilonova light curve (see below).

Short Gamma-Ray Bursts SGRBs are the result of highly relativistic jets that are launched from the central compact object shortly after the merger. Modern simulations with increased resolution or enhanced magnetic fields only recently have started to find favourable conditions for jet formation in NS-NS and NS-BH mergers, that is, a collimated and poloidal magnetic field configuration at the end of the simulation. The exact mechanism leading to the gamma-ray signal, however, is still uncertain. Different scenarios have been proposed and are summarized in this chapter. Apart from the "standard" scenario, where the relativistic jet is launched from a spinning BH surrounded by an accretion disk (which is the one possibly behind GRB170817A), other models rely on a long-lived NS emitting isotropic winds at different stages before its collapse to a BH and the resulting jet launch ("two-winds" and "time-reversal" scenarios).

The Fate of the Central Remnant In NS-NS mergers the dynamics of the post-merger remnant depends on the maximum stable NS mass ($M_{NS}^{max} \geq 2\ M_{\odot}$; still unknown today) and the initial masses of the two merging objects. If the resulting mass of the central object is larger than the maximum allowed NS mass, the system will collapse into a spinning BH. However, there is a possibility that the initial fast rotation can temporarily stabilize a central object that is only marginally more massive than M_{NS}^{max}, resulting in a hypermassive NS that can survive up to a few 100 ms. If the combined mass in a NS-NS merger is not larger than M_{NS}^{max}, a stable, supramassive NS is formed. In this case, simulations show that strong magnetic field amplifications can lead to the formation of a magnetar. Magnetars add complexity to the EM emission after a merger, as angular momentum can be extracted by the strong magnetic fields, powering a long-duration EM emission. This effect could explain some observed phenomena, e.g., X-ray plateaus in some SGRBs, and account for an additional heating source in the baryonic ejecta. However, more detailed and long-term simulations are needed in the future to pin down the role of this possible central engine.

Disk Formation and Additional Mass Loss The possible formation of a disk in the aftermath of a merger is linked to the fate of the central remnant. Simulations show that a prompt BH formation from a NS-NS merger leaves at most a small disk of around $10^{-2}\ M_{\odot}$, while HMNS or SMNS may be surrounded by much larger disks with up to $0.3\ M_{\odot}$. Fast spinning BHs in a NS-BH merger also allow for considerable disk formation. The existence of a disk opens up additional opportunities for the system to eject matter, which need to be considered for the successful modelling of CBMs. Namely, neutrinos from the central object can interact with the disk material and drive a baryonic wind (similar to the ν-driven wind scenario in CCSNe). According to simulations, material ejected this way amounts to about $10^{-2}\ M_{\odot}$ (although this number depends on the total mass of the accretion disk), comparable to the dynamic ejecta. However, the wind component is considerably less neutron-rich and therefore a good candidate for a weak r-process site which produces elements of the first r-process peak. On longer timescales, a fraction of the disk material becomes gravitationally unbound due to viscous dissipation and nuclear recombination. In this component, the whole range of r-process elements can be produced, as recent studies show.

EM Afterglow of the Ejecta (kilonova) The neutron-rich, heavy nuclei that have been freshly synthesized in the ejecta radioactively decay to stability, releasing energy that thermalizes the surroundings and leads to an EM transient. This phenomenon is known as a "kilonova" or "macronova", such as the one detected after GW170817. Depending on the opacity in the ejecta, the break-out of the EM radiation occurs on a timescale of days to weeks after the merger. The presence of lanthanides greatly increases the opacity and also leads to a red-shift in wavelength. The dependence of the EM signal on the nuclear r-process yields and the spatial configuration of the ejecta is the topic of ongoing research. Ultimately, future observations of kilonovae could provide more constraints on properties of nuclei along the r-process path. Since no significant amount of lanthanides is produced in the wind, the wind opacities are comparable to CCSNe, amounting to an EM emission component that peaks earlier and at smaller wavelengths.

Ejecta Shocks with the Interstellar Medium When the expanding baryonic and non-baryonic (jet) ejecta interact with the interstellar medium, the arising shock produces radio emission. This emission can potentially be observed even years after a CBM.

Synthesized r-Process Elements The ejecta will eventually mix with the interstellar medium and increase the content of heavy elements in new-born stars in the vicinity. Several independent observations of r-elements in metal-poor stars, the ocean crust, as well as the recent discovery of a dwarf galaxy that is strongly enhanced in r-elements point strongly toward a relatively rare r-process site ejecting about $10^{-2}\ M_{\odot}$ of r-process material per event. These indications complement the observation of GW170817, suggesting that CBMs are a major production site for r-process nuclei, if not the only one.

Finally, we discuss future prospects for the research of CBMs in the context of nucleosynthesis and EM radiation signals. Most of the expected developments revolve around the new exciting opportunities arising with the emergence of multi-messenger astronomy. In particular, future follow-up EM observations of other CBM GW signals, including possibly a NS-BH merger, will provide more details about the properties of SGRBs central engines and the production of r-process material.

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