Compact binary mergers: an astrophysical perspective

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This paper reviews the current understanding of double neutron star and neutron star black hole binaries. It addresses mainly (nuclear) astrophysics aspects of compact binary mergers and thus complements recent reviews that have emphasized the numerical relativity viewpoint. In particular, the paper discusses different channels to release neutron-rich matter into the host galaxy, connections between compact binary mergers and short Gamma-ray bursts and accompanying electromagnetic signals.

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1. Introduction

In this paper I review the current understanding of the mergers of double neutron stars (DNS) and neutron star black hole systems (NSBH). I will collectively refer to them as "compact binary" mergers, and thus exclude systems with white dwarf components. Only binary systems that merge under the influence of gravitational wave emission will be discussed. Dynamical collisions as they occur in dense regions such as the cores of globular clusters will not be discussed here. Two excellent reviews have recently appeared [44, 37] which put their emphasis on numerical relativity, I want to round up the picture by focusing on the (nuclear) astrophysics aspects of compact binary mergers.

To date 10 binary systems are known where at least the mass function and the periastron advance are consistent with both stars being neutron stars [97]. Five of these systems have small enough orbital separations so that the constant leakage of orbital angular momentum due to gravitational wave emission will cause a coalescence within a Hubble time. Incompletely understood physical mechanisms, poorly known parameters and hard to quantify selection effects make it difficult to estimate the rates at which such events occur. Rates derived from the observed systems roughly agree with those from population synthesis models, about 40 to 700 Myr^{-1} in a Milky Way equivalent galaxy [71, 15], but with an uncertainty of about an order of magnitude in each direction. Even less secure is the rate for NSBH systems, to date none has been observed and population synthesis studies have predicted values from an order of magnitude more [18] to about two orders of magnitude less [15] than the DNS merger rate.

It is difficult to overrate the importance of this type of binary system:

- The first discovered system, PSR 1913+16, has delivered –via the measured decay of the binary orbit– the first unambiguous evidence for the existence of gravitational waves, in excellent agreement with the predictions of General Relativity [162].

- The measurement of at least two Post-Keplerian parameters allows the measurements of *individual* neutron star masses. For example, the masses of PSR 1913+16 are $m_1 = 1.4414$ $M_\odot$ and $m_2 = 1.3867$ $M_\odot \pm 0.0002$ $M_\odot$ [166]. Accurately known masses provide stringent tests for the hadronic physics inside a neutron star [80]. This regime of high densities, but low temperatures is hardly accessible to any laboratory experiment, but it can be probed via accurately known neutron star masses.

- The large "compactness" of neutron stars, $\zeta \equiv GM_{ns}/R_{ns}c^2 \approx 0.2$ (for comparison: the compactness of the Sun is $\sim 10^{-6}$), and their high orbital velocities, $v \sim 10^{-3}c$ (c being the speed of light) make DNS excellent laboratories for strong gravity. They allow for accurate tests that have the potential to distinguish General Relativity from other theories of gravity [76].

- The last stages of the inspiral of a DNS system are a prime candidate for the first *direct* detection by the ground-based gravitational wave detectors [158, 1, 64] that have now finished their first complete science runs. Population synthesis models [15] have predicted detection rates for the Advanced LIGO project near 10 for DNS and around one event per year for NSBH systems. The detection efficiency could be further enhanced by the simultaneous detection of accompanying signals in other channels.

- The astrophysical production site of the r-process is still an unsolved problem. For many years supernovae, in particular the neutrino-driven winds from a new-born neutron star, were

considered very promising sites to forge r-process material, but recent studies find it difficult to reproduce the observed abundance patterns with parameters that are considered plausible for core-collapse supernovae [5, 126]. The main competitor are the neutron-rich ejecta that seem unavoidable in a compact binary merger [82, 79, 137, 144, 107, 101].

- Since the very beginning, compact binary mergers have been considered a prime candidate for the central engine of Gamma-ray bursts (GRBs) [20, 111, 62, 41, 112, 106] and they have survived being confronted with a wealth of observational results. Although the case is far from being settled, they still are the major candidate for the central engine of short GRBs [117, 105, 89, 59].

2. What are the challenges?

Compact binary mergers are prime examples of multi-physics and multi-scale problems. With compactness values ζ of ~ 0.2 for neutron stars and 0.5 at the event horizon of a Schwarzschild black hole, relativistic gravity has obviously a major impact on the dynamics of close, compact binary systems. During the final inspiral stages and the merger the space-time geometry changes on time scales that become comparable to the compact object dynamical time scales of order 1 ms. Their equation of state determines how the neutron stars react on such space-time changes. Tidal heating has no major impact on the bulk matter evolution [78] since thermal energies are tiny in comparison to the relevant Fermi energies. In the merger remnant, however, temperatures can reach ~ 10 MeV and, dependent on the local density, this may not be negligible at all. The neutron stars start out macroscopically from hydrostatic and, microscopically, from cold β-equilibrium. The disruption decompresses a good fraction of the star across the phase transition to inhomogeneous nuclear matter where free nucleons and possibly nuclei and nuclear clusters coexist. Some of the debris is ejected, but most of it forms an accretion torus around the central object. Nuclear reactions during this and subsequent stages can have a number of observable consequences, see Sect. 4.1.2, 4.1.3 and 4.3.

In the merger remnant, the neutron to proton ratio evolution is regulated by the competition between electron and positron captures on the one side, and neutrino and anti-neutrino absorptions on the other. At the prevalent densities, photons are completely trapped and neutrinos are the only viable cooling agents. Being released at tremendous luminosities, neutrinos can also be re-absorbed and have the potential to drive strong thermal winds which, in turn, may have a major impact on both nucleosynthesis, Sec. 4.1, and the ability of compact binary mergers to possibly produce Gamma-ray bursts, Sec.4.2.

Neutron stars are naturally endowed with strong magnetic fields and a compact binary merger offers a plethora of possibilities to amplify them. They may be decisive for the fundamental mechanism to produce a GRB in the first place, but they may also determine –via transport of angular momentum– when the central object produced in a DNS merger collapses into a black hole or how accretion disks evolve further under the transport mediated via the magneto-rotational instability (MRI) [10]. A numerical simulation of a compact binary merger is further complicated by several additional challenges. For example, the speed of sound, c_s, inside a neutron star can easily reach tens of percent of the speed of light. For explicit schemes this severely restricts numerical time steps via the Courant-Friedrichs-Lewy stability condition [118], $\Delta t < 10^{-5}(\Delta x/1\text{km})\,(0.3c/c_s)$. This

can become a major stumbling block for phenomena that substantially exceed the dynamical time scales of the central object. Another complication (that this field shares with other astrophysical fluid simulations) are sub-resolution length scales on which physical instabilities such as Kelvin-Helmholtz or the MRI are seeded. In nature they would feed back and leave a noticeable imprint on the large-scale dynamics. Ideally, such cases should be, but rarely are, treated via "subgrid-models". Further challenges can arise from numerical non-conservation of nature's conservation laws. For example, the orbital dynamics in a binary system is very sensitive to the transfer of angular momentum, both via tides and transferred mass. In unfortunate circumstances, purely numerical effects like an artificial loss of angular momentum could swamp true physical effects of the same magnitude, say due to the emission of gravitational waves. Another subtlety, mainly for grid-based codes, is that "vacuum" is difficult to treat as such and it is generally mimicked by some low-density atmosphere. Although the corresponding background densities are usually many orders of magnitude lower than the peak (neutron star) densities, they can still easily exceed the densities inside a white dwarf and may thus have a major impact on questions that are related to low density regions, such as the dynamical ejection of matter or emerging winds. Such effects may also in part be responsible for the current relativistic NSBH calculations not yet converging with respect to resulting disk masses, see below.

3. Current approaches

The last decade has seem a tremendous leap forward on essentially all fronts of the compact binary merger problem. After the first approaches with Newtonian gravity and polytropic equations of state (EOS) [109, 124, 168, 87, 86, 84] a bifurcation took place with one line of research focusing on the strong gravity aspects while neglecting non-gravity physics and another line addressing exactly the latter, but in an essentially Newtonian framework. Both lines obtained substantial progress in the last decade, now the efforts focus on catching up with so far neglected physics aspects.

First steps beyond purely Newtonian gravity are the application of pseudo-relativistic potentials [113] to NSBH systems [86, 127] and the development of post-Newtonian (0+1+2.5 PN) hydrodynamics codes [7, 47]. The latter approaches were somewhat hampered by the limitations of the 1PN approach in a neutron star context, since higher order PN corrections are not necessarily small. The conformal flatness approximation (CFA) [69, 167, 108, 46] represents a further step towards solving the full GR equations. It assumes that the spatial part of the metric, g_{ij}, is, and remains, conformally flat: $g_{ij} = \Psi^4 \delta_{ij}$, where Ψ is the conformal factor. To evolve the space-time dynamically, one needs to solve five coupled, non-linear partial differential equations with non-compact source terms. The CFA is substantially faster than full GR (but substantially slower than Newtonian gravity) and therefore, for the same available computing resources, allows to invest more time in hydrodynamic resolution or other physics ingredients of the problem. CFA is exact for spherical symmetry and at least accurate to 1PN order in the general case. For spinning neutron stars, it has been shown to be accurate to a few percent [31], for general situations the accuracy is not well known and difficult to determine. While overall being a very useful approach, the CFA is restricted by the assumption of a waveless space-time which, at least in principle, leads to formal inconsistencies if gravitational wave backreaction terms are applied to drive the binary towards inspiral and merger.

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The first fully general relativistic merger calculations were performed by Shibata and collaborators [156, 155, 154]. Today, two GR formulations are commonly used, the so-called BSSN-formulation [152, 11] and the generalized harmonic formalism [52, 57, 24, 119, 95]. In both cases, certain first order derivatives are promoted to the status of independent functions and this allows for the numerically stable evolution of dynamical space-times. To date, many numerically stable evolutions of compact binary systems have been carried out in full GR, e.g. [9, 157, 8, 39]. In hybrid approaches with a fixed Kerr space-time and Newtonian self-gravity [123] black hole spin effects on the NSBH merger dynamics were studied. These effects have recently also been addressed in full GR [49].

But as outlined above, compact binary mergers are not only a dynamical strong gravity problem. They are, for example, heavily influenced by the nuclear EOS. Its stiffness varies substantially over the density range that is relevant for compact binary mergers. The effective adiabatic exponents range from beyond 3 near nuclear densities to close to 4/3 for decompressed nuclear matter (for an illustration see, e.g. Fig. 5 in [134]) and this leaves a pronounced imprint on the matter evolution (compare, for example, Figs. 1 and 2 in [137]). Temperature and composition dependent nuclear equations of state, mainly those of Lattimer and Swesty [83] and Shen et al. [148, 149], have been heavily used in a variety of studies [142, 143, 137, 134, 120, 107, 38]. Some studies have also explored the impact of strange matter on the merger outcome [85, 12, 13].

For grid-based hydrodynamics, opacity-dependent neutrino leakage schemes in compact binary merger simulations have been pioneered by [142]. In [136] a leakage scheme was suggested that does not make use of average neutrino energies, but instead determines the neutrino emission by integrating over a neutrino energy distribution. This scheme was applied in SPH merger simulations [139, 120] and has recently been generalized for the use in general relativistic calculations [146]. While these leakage schemes have turned out to be encouragingly accurate in describing the ν-cooling of matter [36], they do not account for heating effects from neutrinos that were emitted at a different location. Therefore, they do not allow to study phenomena such as neutrino-driven winds. The latter have been explored recently with more elaborate neutrino transport methods [36]. Effects from the equation of state and neutrino cooling on remnant disks have also been intensively studied [88, 92, 93].

The past few years have further seen the exploration of the magnetic field evolution in compact binary mergers, both in the Newtonian [120, 138] and the general-relativistic case [150, 2, 96, 61].

4. The emerging patchwork picture

As outlined above, the merger phenomenon is physically far too complex for any of today's models to address all interesting aspects accurately at the same time. We are thus left with a "patchwork picture": for each question we have to pick the best available approach in the hope that the imperfect aspects do not substantially alter the conclusions.

4.1 Mass loss and nucleosynthesis

The enrichment of the Galaxy with neutron-rich material during a compact binary merger is not only possible, but, on the contrary, rather difficult to avoid. Apart from the matter that is ejected dynamically by gravitational torques, there is an additional contribution due to neutrino-driven winds and last, but not least, neutron-rich matter that becomes dispersed into space in the

course of the viscous evolution of a neutron star debris disk. While the initial starting point is the same, cold neutron star matter in β-equilibrium, the three channels differ in the amounts of released matter, in their entropies, expansion time scales and electron fractions. Therefore they likely produce a different nucleosynthetic signature.

4.1.1 Dynamic ejection

In their study of neutron star black hole binaries Lattimer and Schramm [81] had found that the "Roche limit", where the neutron star's self-gravity has to surrender to the tidal forces exerted by the black hole, lies outside the event horizon. They estimated that a fraction of about ~ 0.05 of the neutron star could become unbound, and realized that, folded with the estimated neutron star black hole merger rate, the amount of ejected material would be comparable to the estimated r-process inventory of the Galaxy. They concluded that the most important observational consequence of a neutron star black hole encounter may be nucleosynthesis [82] and further speculated that also double neutron stars may enrich the Galaxy with neutron-rich material. This latter topic has been discussed in more detail together with the production mechanism of GRBs in [41].

Early Newtonian hydrodynamic simulations [137] that made use of a nuclear equation of state [83] found dynamically ejected masses between 4×10^{-3} and 4×10^{-2} M$_\odot$, depending on the initial neutron star spins. They also noted a strong sensitivity to the stiffness of the nuclear EOS [135] with too soft an EOS leading to no resolvable mass loss. Recent simulations [107] that make use of the conformal flatness approximation and explore several nuclear equations of state find an ejecta range from $\sim 10^{-3}$ up to a few times 10^{-2} M$_\odot$, with the arguably most common case (1.38 and 1.42 M$_\odot$ with negligible neutron star spins) ejecting about 3×10^{-3} M$_\odot$. More asymmetric systems show the tendency to eject larger amounts of material, therefore, in nature double neutron star mergers should produce a distribution of dynamical ejecta, essentially set by the binary mass distribution. With the estimated rates [71], the dynamical ejection alone could enrich the Galaxy by an amount of matter that is comparable to its estimated r-process inventory, $\sim 10^5$ M$_\odot$.

4.1.2 Neutrino-driven winds from merger remnants

Similar to the proto-neutron star case [40], the huge neutrino luminosities from the remnant of a compact object merger ablate a substantial amount of baryons from its surface. It had been realized early on that such a neutrino-driven wind holds much promise as a possible nucleosynthesis site [41, 143, 139], but also that it could pose a serious threat to the emergence of the ultra-relativistic outflow that is required to power a GRB.

A compact binary merger results [143, 137, 144, 134] in a central remnant consisting of either a black hole or, if the initial ADM mass of the binary was smaller than a threshold mass of 1.35 times the maximum mass of a cold, non-rotating neutron star [153], it could produce a meta-stable, neutron star-like central object. The recent determination of the neutron star mass in J1614-2230 with $M_{ns} = 1.97 \pm 0.04$ M$_\odot$ [34] places this threshold mass to at least 2.66 M$_\odot$ and therefore many, maybe most (depending on the binary mass distribution), merging DNS could pass through a phase with a metastable central object. This central object is surrounded by a disk of ~ 0.1 M$_\odot$, the detailed value depending on spin, mass ratio and nuclear EOS, composed of mainly free nucleons at a temperature of a few MeV. Some fraction of material (0.02 - 0.08 M$_\odot$) [128] is sent into nearly unbound orbits that will fall back at a later time and a smaller mass fraction, see Sec. 4.1.1, that is
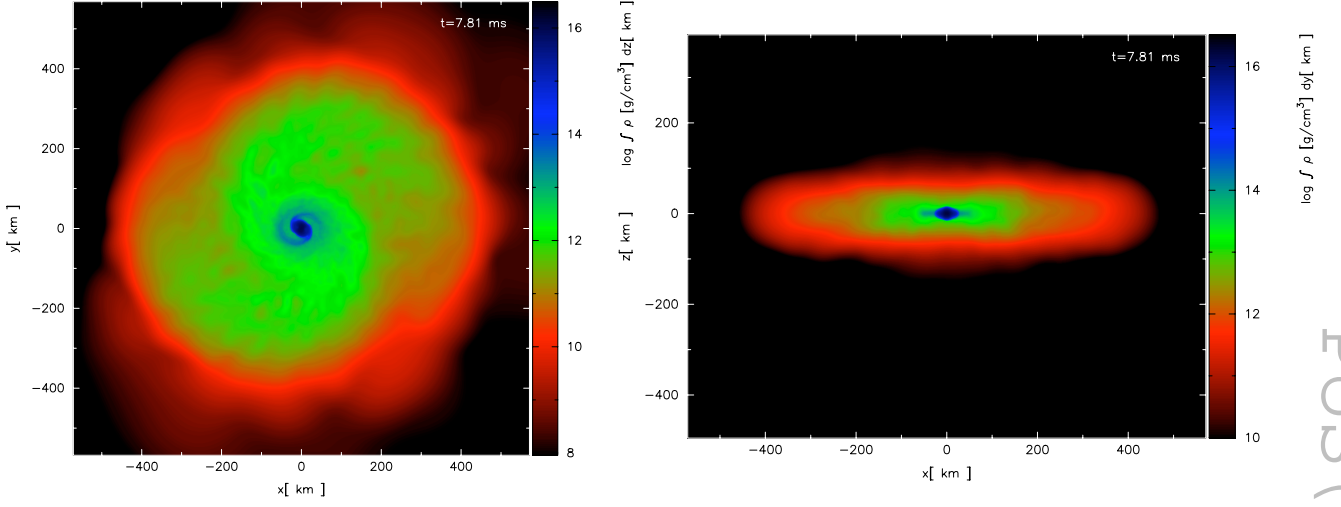
Figure 1: Mass distribution resulting from an irrotational double neutron star system with with 1.4 $M_\odot$ per star. Shown is the column density distribution in XY- (left) and XZ-plane (right) at about 5 ms after merger (7.81 ms after simulation start).

dynamically ejected.

Nucleons in the inner parts of the disk at a distance r from the center are gravitationally bound with an energy of $E_{grav} \approx -35$ MeV $(M_{co}/2.5\ M_\odot)\ (100\ km/r)$, to the central object of mass M_{co}, i.e. $|E_{grav}|$ in the remnant is comparable to the typical neutrino energies [143, 136]. Therefore, chances are good that neutrinos can lift nucleons out of the remnant gravitational potential and drive a wind. Such winds have been investigated as possible nucleosynthesis sites [161, 74] in parametric studies, but a quantitative investigation of their evolution and geometry has only become feasible recently [36]. In the latter work the authors started from the 3D remnant structures as calculated in [120, 138] and further evolved them with a 2D neutrino-hydrodynamics code [25]. As a byproduct, they scrutinized existing neutrino leakages schemes [143, 136] against more sophisticated transport methods and found them reassuringly accurate. The main result of the study was that charge-current neutrino reactions thermally drive a bipolar wind with a mass loss rate of $\langle \dot{M} \rangle \approx 10^{-3}\ M_\odot s^{-1}$. In each merger neutrino-driven winds blow $\sim 10^{-4}\ M_\odot$ of material with $Y_e \approx 0.1 - 0.2$ into the host galaxy (assuming a central object lifetime of ~ 100 ms). Magneto-rotational effects were not accounted for in this study, but are likely to substantially increase this mass loss [103]. The above ν-wind study assumed that the central neutron star remains stable during the time scale of the simulation. Since a substantial part of the mass loss stems from the surface regions of the central object (see Fig. 10 in [36]), an early collapse to a black hole could seriously influence the amount of mass loss by shutting off the central object contribution. This could be favorable for GRBs in allowing ultra-relativistic outflow to develop along the binary rotation axis. How the wind evolves after the formation of a black hole still remains to be explored in future studies.

4.1.3 Disk disintegration

Also the remnant disk of a compact binary merger can release neutron-rich matter into the galaxy,

either via viscous heating in an advective, thick disk [101] or via the energy release from the recombination of nucleons into nuclei [30].

The geometry of a post-merger configuration (2 x 1.4 $M_\odot$, no initial stellar spins) is shown in Fig. 1. At this stage, the disk is not yet in an equilibrium state, where radial velocities are entirely determined by the viscous transport of angular momentum. In our (Newtonian) simulations the disk extends after a few milliseconds out to ~ 500 km (somewhat dependent on EOS, the initial stellar spins and the mass ratio) and possesses temperatures of ~ 3 MeV at the inner edge. GR effects tend to decrease disk mass and size and to increase the temperatures. The decompression occurs too rapidly for the weak interactions to instantly reach β-equilibrium and therefore the initial disk possesses the (advected) Y_e values from the original neutron star, typically close to 0.05. After the initial transient stage, the disk evolution is driven by the viscous coupling between annuli of neighboring radii which transports angular momentum outwards and allows matter to be accreted onto the central object. At the same time, the disc spreads on a viscous time scale $\tau_{\rm visc} \approx \frac{1}{\alpha\Omega}(r/H)^2$. Here α is the Shakura-Sunyaev viscosity parameterization [147], Ω the angular frequency and H the disk scale height. If a central, hypermassive neutron star is present, matter piles up rapidly around it and forms a hot bulge with neutrino optical depths τ_ν of a few [136]. For non-spinning black holes, the densities and optical depths are lower, but they can reach the previous values for spin parameters a in excess of 0.9 [30]. Apart from possibly very close to the center, the inner disk regions are efficiently neutrino-cooled and therefore geometrically thin, $H/r \sim 0.2$. As the disk spreads further and becomes cooler, neutrinos are no longer able to efficiently discharge the viscously released heat and the disk becomes geometrically thick and advective [16, 102]. Such advective disks are only marginally bound and expected to loose a substantial fraction of their mass in a disk wind [19]. 1D models [102] indicate that the disk masses evolve according to $M_{\rm d} \propto t^{-1/3}$ and that about 70% of the initial disk mass has been accreted by the time the disk becomes advective. Thus, about 0.03 $M_\odot$ ($M_{\rm d,0}/0.1 M_\odot$) of debris material become unbound in a DNS merger. Fairly independent of the detailed viscous spreading, the released material is moderately neutron rich, $\sim 0.1 < Y_e < 0.5$ with a peak at $Y_e \approx 0.3$ and possesses entropies between 3 and 20 $k_{\rm B}$ per baryon [102].

This mass loss is most likely further enhanced by burning processes [89, 16, 90]. Outside of $R_{\rm He} = 450$ km ($M_{\rm co}/2.5$ $M_\odot$) the formation of alpha particles from free nucleons releases enough nuclear energy to gravitationally unbind the disk. Thus a substantial part, if not most, of the late-time disk mass becomes dispersed into space. Such a burning-driven wind has also been suspected [90] to suppress the mass supply to the central engine which could explain the shutting off of post-burst GRB activity that has been observed in some GRBs [59].

4.1.4 R-process enrichment of the Galaxy

As outlined above, a neutron star coalescence unbinds neutron-rich material in at least three different ways:

   i) dynamic ejecta, $m_{\rm ej} \approx 3 \times 10^{-3}$ $M_\odot$ [107], with entropies of $s \sim 4$ $k_{\rm B}$ baryon^{-1}[137] and $0.01 < Y_e < 0.5$ with most of the mass possessing $Y_e \approx 0.05$ [127],

   ii) neutrino-driven winds release additional $\sim 10^{-4}$ $M_\odot$ with $s \sim 40$ $k_{\rm B}$ baryon^{-1} [36] and a resulting electron fraction set by the neutrino properties, $Y_e^f \simeq [1 + L_{\bar{\nu}_e}\langle\varepsilon_{\bar{\nu}_e}\rangle/L_{\nu_e}\langle\varepsilon_{\nu_e}\rangle]^{-1}$ [122] and

iii) viscously/nuclearly disintegrated accretion disks deliver another $\sim 3 \times 10^{-2}\,\mathrm{M_\odot}$ with Y_e from 0.1 to 0.5 with a peak around 0.3 and entropies from 3 - 20 k_B baryon^{-1} [102].

The first nucleosynthesis calculations [51] based on the hydrodynamic ejecta trajectories from neutron star mergers [137] yielded (for an initial $Y_e \sim 0.1$) an excellent agreement with the observed observed r-process distribution beyond Ba. Subsequent, inhomogeneous chemical evolution studies [4], however, disfavored neutron star mergers as *dominant* r-process sources. This judgment was based on low occurrence rates which produced an r-process enrichment and a scatter in [r-process/Fe] ratios considered inconsistent with observations at low metalicities. In the meantime the best estimates for merger rates have increased by about an order of magnitude [71] and it has been realized, both from population synthesis, e.g. [14], and the observations of a short GRB at a redshift of z= 0.923 [63], so just shortly after the time when most stars were being assembled in galaxies, that an interesting fraction of DNS systems could possibly merge very early in the cosmic history.

Given the above numbers for released material and merger rates, a natural concern is whether r-process like material could be overproduced with respect to the Galactic observations. It first needs to be said that for most of the above mass loss mechanisms no thorough nucleosynthesis calculations exist yet and conclusions concerning their nucleosynthesis mainly rely on estimates on the final Y_e. With respect to a possible overproduction, Metzger et al. [101] suspected that this could point to low initial disk masses. These could come about, for example, by DNS mass ratios being very narrowly clustered around unity, since such systems produce the least massive disks and the smallest amount of dynamic ejecta. For black hole neutron star systems, Newtonian and pseudo-relativistic simulations [140, 127], came to the conclusion that for much of the parameter space the formation of massive disks is not possible anyway since the tidal disruption of the neutron star occurs close to or even inside of the last stable orbit. This conclusion may need modification once fully conclusive GR calculations exist, but so far they do not yet seem to agree on the size of possible disk masses [42, 43, 151]. Given that it is likely only a small fraction of the NSBH parameter space that is able to produce sizeable accretion disks (the exception may be systems with low bh masses and large bh spins), combined with the possibly low event rates, NSBH systems may only play a minor role in the chemical enrichment of galaxies. Another possibility that would avoid a conflict with the stellar enrichment history of the universe, is that much of the ejecta do not end up inside of their host galaxies, but, being ejected at large velocities predominantly, but not exclusively, in the outskirts of galaxies [53], would escape to intergalactic space.

4.2 GRBs

The potential of compact binary mergers, either in the form of DNS [20, 111, 62, 41] or NSBH systems [112, 106], as central engines of GRBs has been realized more two decades ago. Today they are still arguably the most likely central engine for the short-hard variety of Gamma-ray bursts (sGRBs), long-soft bursts (lGRBs) seem to be robustly linked to the death of very massive stars. There is by now strong evidence that we are seeing the manifestations of (at least) two different types of central engines, although the classification scheme into long (> 2s) and short (< 2 s) is by no means incontestable: some bursts belong formally in one class, but possess properties usually attributed to the other [54, 55, 163].

An observational breakthrough for sGRBs came with the first detection of afterglows in summer

2005 by the SWIFT mission [60, 23], and like in the case of type Ia supernovae, host galaxies provided decisive hints on the nature of the progenitors. Already the first few detections showed that sGRBs can occur in elliptical galaxies without star formation and therefore supported the idea that sGRBs are, in contrast to lGRBs, not directly related to the deaths of massive stars, but instead can be triggered (at least in some cases) by an old stellar population. As of now, there are indications of sGRBs occurring in at least three types of galaxies: i) low redshift ($z < 0.5$), high-mass ($L \sim L^*$), early-type galaxies and galaxy clusters, ii) low redshift, sub-L^*, late-type galaxies and iii) faint, star-forming galaxies at $z > 1$, not too different from the hosts of lGRBs [59]. Overall, sGRBs seem to occur in galaxies that possess higher metalicities than those of lGRBs [17]. Recent HST observations show that sGRBs have a median projected offset of about 5 kpc from the center of their host galaxies [48]. Again, this would be consistent with an DNS origin, where at least in a substantial fraction of cases, the binary having been "kicked" in the last supernova explosion, can travel substantial distances before merging. Moreover, no supernova explosion seems to go along with sGRBs [29, 50, 67, 23], although in exceptional cases, the kick could accelerate the inspiral and cause a high-energy transient, possibly a short gamma-ray burst, typically within a few days of the supernova [165]. SWIFT has now detected more than 50 sGRBs, their redshifts lie between 0.2 and 2, with a mean of 0.4, while $0.009 < z < 8$ for long bursts with a mean of 2.3 [58]. Typically short bursts show an isotropic energy of $\sim 10^{51}$ erg, about two orders of magnitude lower than for lGRBs. With the estimated (but uncertain) jet opening half-angles of $\theta_j \sim 15°$ for short and $\sim 5°$ for long bursts [26, 65] this translates into true energies of $\sim 10^{49} - 10^{50}$ ergs for short and $\sim 10^{50} - 10^{51}$ ergs for long bursts [58].

All these observations are consistent with the basic idea that sGRBs originate (at least predominantly) from compact binary mergers. There are, however, several open issues in the sGRB compact binary connection. First, despite the tremendous progress on the theoretical side during the last decade, see Sec. 3, the related challenges have so far prohibited models to go the full way from the central engine to the production of the detectable emission. For example, the central engine works on scales of $\sim 10^7$ cm, while the "prompt" γ-radiation is thought to be produced by internal shocks at a distance $R_{is} \sim c\Delta t \Gamma^2 \sim 3 \times 10^{14}$ cm $(\Delta t / s) \, (\Gamma / 100)^2$, where Δt is the variability time scale of the central engine and Γ the outflow Lorentz factor. The GRB "afterglow", in contrast, is produced near the deceleration radius, $R_{dec} \sim 3 \times 10^{16}$cm $(E/10^{52} \text{ erg})^{1/3} (100/\Gamma)^{2/3} (1\text{cm}^{-3}/n_{ext})$, where the swept-up matter has substantially slowed down the blast wave [116]. Moreover, the central engine requires physics (strong gravity, high-density matter physics) that is very different from the emission regions (collisionless, relativistic plasma shocks). Up to now, there is not even a model that self-consistently shows the production of the required ultra-relativistic outflow. This is partially due to the difficulty to numerically resolve the relevant scales, for example the growth length scale of the MRI [10] or the density contrasts between the central parts of a merger remnant and its surrounding "near-vacuum" material, and due to the lack of appropriate 3D neutrino-radiation-hydrodynamics codes that include apart from cooling also neutrino heating and annihilation processes.

Maybe the most difficult challenge for the compact binary merger model is the emission long after the burst: SWIFT has observed X-ray flares in both long and short bursts, which in the latter case occur tens or even hundreds of seconds after the burst, corresponding to $\sim 10^5$ dynamical time scales of central compact object. A variety of different physical interpretations has been offered,

including refreshed shocks [114], magnetic regulation of the accretion flow [121], the interaction with a stellar companion [98, 35], the (at least temporary) survival of a highly magnetized central neutron star [139, 32, 56, 129, 141] and the fallback from neutron star debris returning to the central object at late times [45, 128, 89]. After the initial dynamical phase of a merger, the importance of hydrodynamic forces in the nearly unbound fallback material ceases and the material becomes essentially ballistic until it returns towards the central remnant at late times. Since the ballistic phase far from the central remnant dominates the return time scale, the latter can be estimated in an analytical way from the final matter configuration of a numerical simulation. The resulting time scales are encouragingly long (e.g. Fig. 3 in [128]), but the model is too simple to predict, say, the detailed structure of flares. If at fallback the circularization radii are large enough, such material could form another, larger disk with possibly much longer time scales, ~ 100 s [89], and for the right set of parameters can possibly produce signatures similar to the observed ones [28]. While fallback can likely explain some of the flaring activity, it may be overstrained in explaining the most extreme cases such as flares ~ 12 h after the burst observed in GRB050724 [27, 65]. Similarly problematic are those short bursts where the fluence in the "extended emission" exceeds the one of the initial short spike. For example, in GRB 080503 the fluence of the extended emission exceeds the spike fluence by a factor of about 30 [115]. It is at least not obvious how this should be accommodated within the standard merger model, where one expects more mass in an initial accretion disk than in the fallback material. Some of the magnetar-like models would be less strained to explain these extreme events, but in the light of the essentially unsolved baryonic pollution problem discussed in Sec. 4.1.2, it is not obvious how such events would produce the ultra-relativistic outflow for the prompt emission in the first place.

The problem of late time flares containing a lot of energy may be less problematic for dynamical compact object *collisions* instead of gravitational-wave-driven binary mergers. A recent study [91] finds that the collision rates should be substantially larger than previously estimated and comparable to merger rates. Moreover, the authors find that fallback material in the form of tidal tails can contain in some cases more mass than the initial accretion disk. A burst produced by the disk and flares triggered by fallback could in such a scenario possibly explain late-time flares that are more energetic than the initial burst.

These are interesting open issues that need further thought and work. In this context, it may be worth reiterating that one should remain open-minded about the central engines and that different progenitors may (at some rate) contribute to the observed population of sGRBs.

4.3 Pre- and post-merger transients

The predicted compact binary merger detection rates for ground-based detector facilities span a broad range [73, 110] and could be as low as just a few events per year, even for the advanced versions of LIGO and VIRGO [159]. Therefore, additional electromagnetic signals accompanying the gravitational wave emission from compact binaries could be crucial to extract as much scientific information as possible from individual detections, e.g. [145, 21]. For example, if position and time could be determined independently, degeneracies in the gravitational wave signal could be removed [68, 6] and the signal-to-noise ratio required for a confident detection could be significantly reduced [75, 33]. Moreover, additional signatures that accompany sGRBs could help to finally unambiguously identify their central engines.
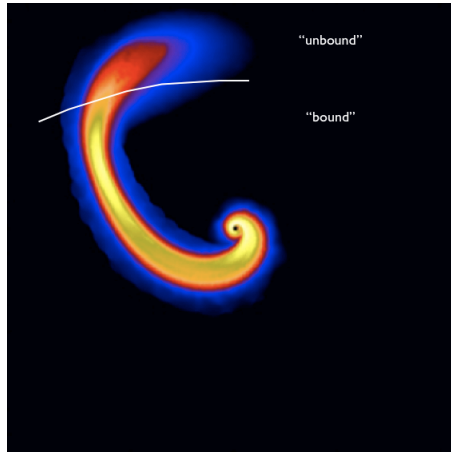
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Figure 2: In the course of a compact binary merger, gravitational torques launch 0.02 - 0.08 $M_{\odot}$ into highly eccentric, but still bound orbits. This material will fall back on a time scale that is much longer than the dynamical time scale of the central remnant. This is illustrated at the example of a neutron star black hole merger [127].

Recently, electromagnetic precursor events have been detected for short GRBs [164]. These could, for example, be the results of the interaction of the neutron star magnetospheres prior to the merger [66]. This mechanism would require at least one neutron star to be highly magnetized, therefore such precursors would not be expected in every merger event.

Electromagnetic emission *after* such a coalescence is expected from the radioactive nuclei that form via decompression of neutron star matter [94, 137, 127, 77, 100]. GRBs seem to produce highly beamed prompt emission, in contrast to the expected isotropic electromagnetic transients that result from radioactive decay in the merger debris. Thus, while the GRB prompt emission can only be detected when it points towards Earth, the subsequent, radioactively powered transients should, provided they are bright enough, be visible from all directions. Under rare circumstances this may lead to "orphan transients" when the GRB prompt emission is directed away from us. With the recent and near-future instruments such as the Palomar Transient Factory (PTFS [70], SkyMapper [72], the VLT Survey Telescope (VST) [99], the Large Synoptic Survey Telescope (LSST) [160] and the Synoptic All Sky Infrared Imaging (SASIR) survey [22], we are now entering an era of large-scale surveys which could revolutionize our understanding of transient events. The detection of a radioactive transient coincident with a short GRB could lead to the unambiguous identification of the central engine and provide constraints on the r-process production site.

5. Summary and future directions

The past decade has seen a tremendous progress in our ability to reliably model the mergers of compact binary systems. On the one side, fully relativistic 3D simulations have become possible and are now performed regularly. On the other side, many physical processes have been explored from (exotic) high-density nuclear physics, over both neutrino cooling and heating to nuclear reactions and magnetic fields.

Technically, the "hydrodynamics plus gravity" part of the models is likely to see a couple of sub-

stantial improvements. Eulerian approaches are today substantially hampered in their ability to accurately follow lower density material, to a large extent due to heavy computational burden, so that it is difficult to afford large computational volumes. Although some refinement techniques are already used [8, 3], the field will most likely profit a lot from the implementation of fully adaptive mesh refinement schemes. Closely related is the treatment of "numerical vacuum" and its impact on low-density regions. The latter include also the accretion disks which are thought be crucial in the transformation of gravitational binding energy into observable radiation. As outlined above, this technical progress will have major implications for both nucleosynthesis and GRB questions. Another natural improvement would be the exploration of higher order methods, though there is a tradeoff between the order of the method and the affordable resolution.

Lagrangian, and in astrophysics this usually means Smoothed Particle Hydrodynamics, methods, are currently somewhat lagging behind in their treatment of dynamical space-time evolution with CFA currently being the most advanced gravity approach [46, 108, 13]. The method has recently made much progress with the most advanced sets of relativistic equations following directly from ideal fluid Lagrangians [104, 130, 131, 132] and hybrid approaches that couple SPH with grid-based space-time solvers seem promising for an interesting class of problems. Moreover, adaptive Lagrangian-Eulerian (ALE) approaches may be worth the development effort.

Also on the non-gravity side remains much to do. Problems where the hard to reach numerical resolution is the major stumbling block need apart from massive parallelism further algorithmic developments and suitable approximation methods. Today, still many simulations are run with polytropic equations of state with fixed adiabatic exponents which are insufficient approximations for the required broad spectrum of physical conditions in a merger. With resolution becoming better, the simulated times becoming longer and low-density phenomena such as winds now becoming feasible, also the presently available physical/nuclear equations of state reach their limits, mainly at low densities and temperatures. Closely related is the question of nucleosynthesis, another crucial facet in the multi-messenger picture of compact binary mergers. Despite its importance it is still in its infancy and many pressing questions are essentially unexplored. For some related technical problems, say the implementation of nuclear reactions into existing hydrodynamics codes, the development effort should be moderate. For others, say for self-consistent 3D calculations of neutrino-driven winds, a serious amount of work is needed to achieve computationally affordable and reasonably accurate results.

In anticipation of the first *direct* gravitational wave detection, one can overall be optimistic that the field will keep its high current momentum, so that hopefully in time for the first gravitational wave detections reliable multi-physics models will be in place.

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