The dynamic ejecta of compact object mergers and eccentric collisions

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ABSTRACT

Compact object mergers eject neutron-rich matter in a number of ways: by the dynamical ejection mediated by gravitational torques, as neutrino-driven winds and probably also a good fraction of the resulting accretion disc finally becomes unbound by a combination of viscous and nuclear processes. If compact binary mergers produce indeed gamma-ray bursts there should also be an interaction region where an ultra-relativistic outflow interacts with the neutrino-driven wind and produces moderately relativistic ejecta. Each type of ejecta has different physical properties and therefore plays a different role for nucleosynthesis and for the electromagnetic transients that go along with compact object encounters. Here we focus on the dynamic ejecta and present results for over 30 hydrodynamical simulations of both gravitational wave-driven mergers and parabolic encounters as they may occur in globular clusters. We find that mergers eject \( \sim 1\% \) of a solar mass of extremely neutron-rich material. The exact amount as well as the ejection velocity depends on the involved masses with asymmetric systems ejecting more material at higher velocities. This material undergoes a robust r-process and both ejecta amount and abundance pattern are consistent with neutron star mergers being a major source of the “heavy” \((A > 130)\) r-process isotopes. Parabolic collisions, especially those between neutron stars and black holes, eject substantially larger amounts of mass and therefore cannot occur frequently without overproducing galactic r-process matter. We also discuss the electromagnetic transients that are powered by radioactive decays within the ejecta (“Macronovae”), and the radio flares that emerge when the ejecta dissipate their large kinetic energies in the ambient medium.

Key words: neutron stars, black holes, hydrodynamics, nucleosynthesis, transients, gravitational waves

1 INTRODUCTION

Even before the discovery of the first neutron star binary PSR 1913+16 (Hulse & Taylor 1975) efforts were undertaken to estimate how much mass a compact binary merger would eject into space. In a semi-analytic model Lattimer & Schramm (1974) estimated that in a neutron star (ns) black hole (bh) collision \( \sim 5\% \) of the neutron star could become unbound. By estimating the rates of such encounters they already noted that the accumulated amount of ejecta would be roughly comparable to the galactic r-process inventory. It was only more recently, that the potential of the ejected material to produce electromagnetic (EM) transients has been appreciated (Li & Paczyński 1998; Kulkarni 2005; Rosswog 2005; Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Metzger & Berger 2012; Kelley et al. 2012). EM transients from compact binary mergers are nowadays thought to be instrumental for maximizing the science returns from the advanced gravitational wave (GW) detector networks. In fact, EM transients may actually provide compelling evidence for the first direct GW detection and they may deliver information about the nature of the GW source and its astronomical environment.

The matter required to produce such transients from compact binary mergers can be ejected in a number of ways, see Fig. 1. First, there are dynamic ejecta that are launched immediately at first contact by the interplay between hydrodynamics and gravity. This type of ejecta is the main focus here. In addition, the merger remnant emits neutrinos at rates of a few times \( 10^{53} \) erg/s (Ruffert & Janka 2001; Rosswog & Liebendörfer 2003; Sekiguchi et al. 2011) and this neutrino emission has been shown to drive strong baryonic winds (Dessart et al. 2009). In fact, for as long as the central, hypermassive neutron star has not collapsed into a black hole, this baryonic wind may actually represent a serious danger for the emergence of the ultra-relativistic...
outflow that is required to produce a gamma-ray burst (GRB). If compact binary mergers indeed power short GRBs this neutrino-driven wind should interact near the rotation axis with the ultra-relativistic outflow ("jet") producing the GRB. This interaction is expected to accelerate matter to semi-relativistic speeds. In addition, at late stages of the disc evolution, viscous heating and/or recombination of free nucleons into light nuclei/alpha particles ejects most of what is left from the original accretion disc (Beloborodov 2008; Metzger et al. 2009; Lee et al. 2009). The ejecta of each of these channels have different properties, therefore their role in nucleosynthesis and for the production of EM transients needs to be investigated separately for each channel. Recently, dynamical collisions/high-eccentricity mergers between two compact objects have received a fair amount of attention (O’Leary et al. 2009; Lee et al. 2010; Rosswog et al. 2012; East et al. 2012; Kocsis & Levin 2012). They could, for example, be promising GRB central engines and produce repeated bursts of GWs, but recent work Rosswog et al. (2012) concluded that they can only occur at a moderate fraction of the nsns merger rate, otherwise they would cause an overproduction of galactic r-process material. Here we discuss the properties of the dynamic ejecta for a large number of simulations of both mergers and dynamical collisions. For both types of encounters we consider nsns and nsbh systems, the properties of these simulations are summarized in Tab. 1.

2 RESULTS

2.1 Simulations

The presented simulations are performed with a 3D Smoothed Particle Hydrodynamics (SPH) code, implementation details can be found in the literature (Rosswog et al. 2000; Rosswog 2005; Rosswog & Price 2007), for recent reviews of the SPH method consult, for example, Rosswog (2009) or Springel (2010). The neutron star matter is modeled with the Shen et al. equation of state (EOS; Shen et al. (1998a,b)). We apply an opacity-dependent, multi-flavor leakage scheme (Rosswog & Liebendörfer 2003) to account for the change of the electron fraction and the cooling by neutrino emission. Black holes are here simply treated as Newtonian point masses with absorbing boundaries at the Schwarzschild radius. For the case of parabolic encounters we parametrize the impact strength by the ratio $\beta \equiv (R_1 + R_2)/R_{\text{per}}$, where $R_i$ is the neutron star/Schwarzschild radius and $R_{\text{per}}$ is the separation at pericentre passage. The performed simulations and ejecta properties are summarized in Tab. 1.

We also show two examples to illustrate the hydrodynamic evolution. Fig. 2 shows volume renderings of the temperature for a neutron star merger case (run 12), an example of a (substantially more violent) collision between two neutron stars ($\beta = 2$; run 27) is shown in Fig. 3 (the upper half of matter has been "chopped off" to allow for a view inside the remnant; the temperature scales are capped to enhance visibility).
2.2 Dynamic mass loss

Double neutron star mergers have been known for some time to dynamically eject interesting amounts of neutron-rich material (Rosswog et al. 1999). We consider binary neutron star mergers as the most likely type of encounter and run 13 (1.3 and 1.4 M⊙, no initial spins) as our reference case. Parabolic collisions are interesting, but likely rare encounters whose overall occurrence rate is restricted by their large ejecta masses, see below. Our reference nsns merger case dynamically ejects $1.4 \times 10^{-2}$ M⊙, unequal mass cases eject more matter at larger velocities than equal mass cases of the same total mass, see Tab. 1. For mass ratios $q = m_2/m_1 < 1$ the ejected mass is fit well by

$$m_{ej}(m_1,m_2) = (m_1 + m_2) \left( A - B\eta - \frac{C}{1 + \eta^3/\sigma^3} \right),$$

(1)

where $A = 0.0125$, $B = 0.015$, $C = 0.0083$ and $\sigma = 0.0056$ (Korobkin et al. 2012). Here $\eta = 1 - 4m_1m_2/(m_1 + m_2)^2$ is the dimensionless mass asymmetry parameter. Collisions of two neutron stars eject comparable, but slightly larger amounts than double neutron star mergers, typically a few percent\(^1\). We find that collisions between neutron stars and

\(^1\) Our run 27 has the highest numerical resolution with more than $8 \times 10^9$ SPH particles and is the most expensive of all our simulations, therefore it was only run up to t = 9 ms. We consider

\[ \text{Figure 2. Merger of a 1.3 and a 1.4 M⊙ neutron star binary with initial tidal locking. Shown are volume renderings of the temperature at } t = 5.04, 6.30, 7.56 \text{ and } 8.82 \text{ ms after simulation start.} \]
stellar mass black holes, which, due to their larger capture radius, should dominate over nsns collisions by a factor of $\sim 5$ (Lee et al. 2010), eject significantly larger amounts of matter, typically $\sim 0.15$ $M_\odot$. Unless equation of state or relativistic gravity effects dramatically modify these results, the overall rate of compact object collisions should therefore be seriously constrained, otherwise r-process elements would be substantially overproduced.

2.3 Impact on heavy element nucleosynthesis

Approximately half of the elements heavier than iron are formed by rapid (in comparison to $\beta$-decays) neutron capture reactions or “r-process” for short. The r-process production sites, however, are still matters of debate. The r-process elements observed in metal-poor stars (Snedden et al. 2008; Honda et al. 2006). It may actually be the case that a superposition of a number of different sources. The other one is rarer and produces whenever it occurs the heaviest r-process elements (beyond Ba, $Z = 56$) in nearly exactly solar proportions. So far, there is no generally accepted explanation for the robustness of this unique heavy r-process component. Traditionally supernovae were considered the most likely source of r-process elements, but a number of recent investigations has cast doubts over this view (e.g. Arcones et al. 2007; Roberts et al. 2010; Fischer et al. 2010; Freiburghaus et al. 1999). The main contenders of supernovae in terms of r-process nucleosynthesis are compact binary mergers of either two neutron stars or a neutron star and a stellar-mass black hole (Lattimer & Schramm 1974, 1976; Eichler et al. 1989; Freiburghaus et al. 1999). The matter that is ejected by double neutron star mergers shows a narrow distribution of electron fractions around $Y_e \approx 0.03$. Collisions produce a slightly broader but still very neutron-rich distribution, see Fig. 11 in Rosswog et al. (2012). The latter occurs due to the larger temperatures in collisions which allow positron captures to increase $Y_e$. We have explored the nucleosynthesis within these ejecta (Korobkin et al. 2012) and found a very robust r-process nucleosynthesis which produces all the elements from the second to the third r-process peak in close-to-solar ratios. The extreme neutron richness makes the r-process path meander along the neutron drip line and, as a result, the final abundance patterns are predominantly determined by nuclear properties rather than by those of the merging astrophysical system. Consequently, all cases produce essentially identical abundance patterns, see Fig. 4c in Korobkin et al. (2012); Substantial deviations from this pattern only occur for trajectories that have initial $Y_e$-values above $\sim 0.17$ (see Fig. 8 in Korobkin et al. 2012). Such material, however, is too rare to have a noticeable impact on the resulting abundance pattern.

2.4 Constraints on occurrence rates

To gauge the possible relevance of nsns mergers for the enrichment of the Cosmos with heavy elements, we take the ejecta masses found in the simulations and make the (very strong) assumption that the considered mergers are the only source of r-process elements. The occurrence rates that are required under these assumptions to reproduce the galactic r-process enrichment rate of $\sim 10^{-6}$ $M_\odot$ yr$^{-1}$ (Qian 2000) are plotted in Fig. 4. The quantity $\eta$ is the dimensionless mass asymmetry parameter $\eta$ that was also used in Eq. (1). These required rates are compared to the 95% confidence interval for the estimated nsns merger rate that is based on the observed binary neutron star population (Kalogera et al. 2004). Thus, within the existing uncertainties, double neutron star mergers eject enough material to deliver a major contribution to the Galactic r-process record. Collisions, on the other hand, eject substantially larger amounts. nsbh collisions are expected to occur five times more frequently than nsns collisions Lee et al. (2010), therefore an average collision ejects $\sim (5 \times 0.15 + 0.06)/6 \sim 0.135$ $M_\odot$ per event, about an order of magnitude more than the typical merger case. We can obtain a robust upper limit on the collision rate if we make the extreme assumption that collisions are the only producers of r-process and that no other event contributes. Under this extreme assumption their occurrence rate would be about 10% of the nsns merger rate. The rate realized in nature may actually be well below this value.

2.5 Electromagnetic transients

The electromagnetic transients that go along with a compact binary merger have recently attracted much interest (Li & Paczyński 1998; Kulkarni 2005; Rosswog 2005; Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Metzger & Berger 2012; Kelley et al. 2012). Such transients can provide information on the distance, on the type of and the position with respect to the host galaxy, on its metallicity and on the ambient matter densities. In other words EM transients help to place a compact binary coalescence into an astrophysical context. After having been operational intermittently during the last decade the LIGO and VIRGO detectors are currently being upgraded (Abbott et al. 2009; Sengupta et al. 2010). By about 2016 they should reach their new design sensitivities which are 10-15 times higher than those of the initial instruments, so that the accessible volume increases by more than three orders of magnitude. This will push the detection horizons for nsns mergers out to a few hundred Mpc and to nearly a Gpc for nsbh mergers (Abadie et al. 2010). The first detections are expected to be near threshold and accompanying EM signals could substantially boost the confidence in a candidate event and thus effectively increase the instrument sensitivities (Kochanek & Piran 1993; Hughes & Holz 2003; Dalal et al. 2006; Arun et al. 2009). Rather than relying on accidental coincident EM and GW detections one could increase the detection rate by either following a GW candidate event by target-of-opportunity searches for EM transients or by scanning through archival data based on EM triggers (e.g. Kochanek & Piran (1993); Mohanty (2005); Mandel & O’Shaughnessy (2010); Nakar...
Figure 3. Collision of a 1.3 and a 1.4 M⊙ neutron star with an impact strength of $\beta = 2$. Shown are volume renderings of the temperature (at $t = 1.49, 3.83, 6.27$ and $8.32$ ms after simulation start), only matter below the orbital plane is shown.

2.5.1 GRBs

The most luminous expected EM transients are short Gamma-ray bursts (sGRBs; Paczynski (1986); Eichler et al. (1989); Narayan et al. (1992); Piran (2004); Nakar (2007); Lee & Ramirez-Ruiz (2007). The physical mechanisms behind launching such a burst are still far from being settled, it seems, however, that the ultra-relativistic outflows that produce the bursts are collimated into half-opening angles of $\sim 5^\circ$ (Fong et al. 2012), consistent with theoretical expectations (Rosswog & Ramirez-Ruiz 2003; Aloy et al. 2005). As discussed previously, the emerging neutrino-driven winds pose a serious threat to the emergence of an ultra-relativistic outflow and therefore not every nsns merger may actually be able to produce a sGRB. In other words, the detected sGRB rate may possibly be only a small fraction of the true nsns merger rate, $R_{sGRB} = f_s f_p R_{nsns}$, where $f_s$ is the beaming fraction and $f_p$ the fraction of nsns mergers that is not choked by baryonic pollution (e.g. through neutrino-driven winds). Cases where a GW signal is detected but no GRB might then be used as trigger on those EM transients that are less beamed such as...
Table 1. Overview over the performed simulations, the superscript + indicates that the primary is a black hole. Unless otherwise noted, neutron stars have zero initial spin.

### Binary mergers

| Run | \(m_1\) [M\(_\odot\)] | \(m_2\) [M\(_\odot\)] | \(N_{\text{SPH}}\) \([10^6]\) | \(t_{\text{end}}\) [ms] | \(m_{\text{ej}}\) \([10^{-2}\text{M}_\odot]\) | \(\langle v \rangle\) [c] | comment |
|-----|----------------|----------------|----------------|----------------|----------------|-------------|---------|
| 1   | 1.0            | 1.0            | 1.0            | 15.3           | 0.76           | 0.10        |         |
| 2   | 1.2            | 1.0            | 1.0            | 15.3           | 2.5            | 0.11        |         |
| 3   | 1.4            | 1.0            | 1.0            | 16.5           | 2.9            | 0.13        |         |
| 4   | 1.6            | 1.0            | 1.0            | 31.3           | 3.1            | 0.13        |         |
| 5   | 1.8            | 1.0            | 1.0            | 30.4           | >1.6           | 0.13        | second, still orbiting |
| 6   | 2.0            | 1.0            | 0.6            | 18.8           | >2.4           | 0.16        | second, still orbiting |
| 7   | 1.2            | 1.2            | 1.0            | 15.4           | 1.7            | 0.11        |         |
| 8   | 1.4            | 1.2            | 1.0            | 13.9           | 2.1            | 0.12        |         |
| 9   | 1.6            | 1.2            | 1.0            | 14.8           | 3.3            | 0.13        |         |
| 10  | 1.8            | 1.2            | 1.0            | 21.4           | 3.4            | 0.14        |         |
| 11  | 2.0            | 1.2            | 0.6            | 15.1           | >3.0           | 0.14        | second, still orbiting |
| 12  | 1.3            | 1.4            | 2.7            | 20.3           | 5.0            | 0.15        | nsns, corot. |
| 13  | 1.3            | 1.4            | 2.7            | 20.3           | 1.4            | 0.12        |         |
| 14  | 1.4            | 1.4            | 1.0            | 13.4           | 1.3            | 0.10        |         |
| 15  | 1.6            | 1.4            | 1.0            | 12.2           | 2.4            | 0.12        |         |
| 16  | 1.8            | 1.4            | 1.0            | 13.1           | 3.8            | 0.14        |         |
| 17  | 2.0            | 1.4            | 0.6            | 15.0           | 3.9            | 0.15        |         |
| 18  | 1.6            | 1.6            | 1.0            | 13.2           | 2.0            | 0.11        |         |
| 19  | 1.8            | 1.6            | 1.0            | 13.0           | 1.7            | 0.12        |         |
| 20  | 2.0            | 1.6            | 0.6            | 12.4           | 3.8            | 0.14        |         |
| 21  | 1.8            | 1.8            | 1.0            | 14.0           | 1.5            | 0.12        |         |
| 22  | 2.0            | 1.8            | 0.6            | 11.0           | 2.0            | 0.13        |         |
| 23  | 2.0            | 2.0            | 0.2            | 21.4           | 1.2            | 0.11        |         |
| 24  | 5.0 +          | 1.4            | 0.2            | 138.7          | 2.4            | 0.15        | nsbh |
| 25  | 10.0 +         | 1.4            | 0.2            | 139.0          | 4.9            | 0.18        | nsbh   |

### Parabolic collisions

| Run | \(m_1\) [M\(_\odot\)] | \(m_2\) [M\(_\odot\)] | \(N_{\text{SPH}}\) \([10^6]\) | \(t_{\text{end}}\) [ms] | \(m_{\text{ej}}\) \([10^{-2}\text{M}_\odot]\) | \(\langle v \rangle\) [c] | comment |
|-----|----------------|----------------|----------------|----------------|----------------|-------------|---------|
| 26  | 1.4            | 1.3            | 2.7            | 21.2           | 6.0            | 0.13        | nsns, \(\beta = 1\) |
| 27  | 1.4            | 1.3            | 8.0            | 9.0            | 0.9            | 0.22        | nsns, \(\beta = 2\) |
| 28  | 1.4            | 1.3            | 2.7            | 13.2           | 3.0            | 0.28        | nsns, \(\beta = 5\) |
| 29  | 3.0 +          | 1.3            | 1.3            | 127.5          | 14.2           | 0.19        | nsbh, \(\beta = 1\) |
| 30  | 5.0 +          | 1.3            | 1.3            | 143.6          | 17.2           | 0.24        | nsbh, \(\beta = 1\) |
| 31  | 10.0 +         | 1.3            | 1.3            | 540.3          | 13.4           | 0.24        | nsbh, \(\beta = 1\) |

"orphan afterglows" or macronovae, see below.

#### 2.5.2 Macronovae

"Macronovae" are radioactively powered transients that emerge from the decaying ejecta of compact object mergers Li & Paczyński (1998). In contrast to GRBs, they should be "isotropic" in the sense that they are visible from all sides, although the ejecta distribution suggests a viewing angle dependence, see Figs. 1 and 2 in Piran et al. 2012. Macronovae share some similarities with supernovae, in particular, without late-time energy injection from radioactive decays they would be hardly detectable at all. The ejecta composition of a macronova is unique and very different from any type of supernova. While the latter produce elements up to the iron group near \(Z = 26\), the dynamic ejecta of neutron star mergers consist entirely of r-process elements up to the third peak near \(Z \approx 90\), see above, and should thus leave a distinctive imprint on the observable electromagnetic display.

Given the expected complexity of the involved physics, the models that exist to date are still rather basic. They rely on estimates for the ejected mass and its velocity distribution (or alternatively \(dm/dv\)), which can be straightforwardly extracted from hydrodynamics simulations. Via nuclear network calculations along hydrodynamic trajectories
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Figure 4. Relevance for cosmic r-process inventory. Shown is the event rate that is, based on the simulation results, required to reproduce the galactic r-process enrichment rate, $\dot{M}_{r,\text{gal}}$, for a given mass asymmetry parameter $\eta$. For each value of $\eta$ the required rate (square) is calculated as $\dot{M}_{r,\text{gal}}/m_{\text{ej, sim}}$, where $m_{\text{ej, sim}}$ is the ejecta mass found in the simulations. For comparison, the expected 95% confidence interval for the nsns merger rate as derived from observations (Kalogera et al. 2004) is shown. Within the existing uncertainties, the ejecta masses are consistent with nsns mergers being major production sites of r-process material.

one can extract the nuclear energy injection rate, $\dot{\epsilon}$, which shows little sensitivity to the exact details (Metzger et al. 2010; Korobkin et al. 2012). The latter authors find that

$$\dot{\epsilon}(t) = 2 \times 10^{18} \text{erg/s} \left(\frac{1}{2} - \frac{1}{\pi} \arctan \frac{t - 1.3s}{0.11s}\right)^{1.3} \times \left(\frac{\epsilon_{\text{th}}}{0.5}\right)$$

provides a good fit to the results of the network calculations. Here $\epsilon_{\text{th}}$ is the fraction of energy that is injected as thermal radiation. The last ingredient of existing models is an average value for the opacity $\kappa$. The opacity value is crucial since it determines the diffusion time which, in turn, sets the time of peak emission. In existing models this value has been taken as $0.1 \text{ cm}^2/\text{g}$ which is characteristic of the line expansion opacity from iron group elements (e.g. Kasen & Woosley (2007)).

With these assumptions one finds that a macronova resulting from a $2 \times 1.4 \text{ M}_\odot$ nsns merger peaks after $\approx 0.4$ days with $L_{\text{peak}} \approx 5 \times 10^{41} \text{ erg/s}$ (Piran et al. 2012). Nearly all other nsns and nsbh cases, both mergers and collisions, deliver larger ejecta masses and velocities and therefore produce larger luminosities (up to $\sim 10^{42} \text{ erg/s}$) at slightly later times ($t_{\text{peak}} < 1 \text{ day}$) see Fig. 13 in Piran et al. (2012) for the merger and Fig. 15 in Rosswog et al. (2012) for the collision cases. Other groups (Metzger et al. 2010; Goriely et al. 2011; Roberts et al. 2011) find similar results for nsns merger cases.

It was recently pointed out (Kasen 2012) that the opacities of the freshly synthesized r-process material are very poorly known. Most likely, they will be dominated by millions of Doppler-broadened lines from the lanthanide group ($Z = 57 - 71$). Little atomic data is available to date for these elements, but initial calculations of Kasen and collaborators suggest that the opacities might be about two orders of magnitude larger than those of iron group elements. As a result, the larger diffusion times are expected to lead to lightcurves that peak only after several days rather than just a few hours. The effective temperatures will be substantially degraded so that the bulk of radiation may actually escape in IR rather than optical/UV (optical is suppressed by line blanketing). The important topic of macronova transients certainly deserves more efforts in the future.

2.5.3 Radio transients

It is important to realize that compact object merger ejecta can contain a kinetic energy that is comparable to a supernova. For example, the ejecta of a typical nsns merger ($1.3 \text{ & } 1.4 \text{ M}_\odot$) contain $2 \times 10^{50} \text{ erg}$. The more extreme, but probably rare collision cases can even contain up to $10^{52} \text{ erg}$ of kinetic energy (Rosswog et al. 2012). The deceleration of this sub-/mildly relativistic material drives a strong shock into the ambient medium. Shocks with similar properties have been observed in late stages of GRB afterglows and in the early phases of some supernovae. In both circumstances they produce bright radio emission. The ejecta of compact object encounters are sprayed with a distribution...
of velocities into the surroundings, for typical nsns mergers the average velocity is close to 0.1c. Asymmetric mergers \((q \neq 1)\) deliver average velocities up to 0.18c, but how often these higher-velocity cases occur depends on their not so well-known mass distribution. Collisions yield substantially larger average velocities (up to 0.28c, see Tab. 1) with a high velocity tail reaching close to the speed of light. The highest of these velocities, however, need to be interpreted with care since the simulations are essentially Newtonian. Nevertheless, it is a robust result that dynamical collisions produce substantially larger ejecta velocities, therefore their radio signals are brighter and peak earlier. It needs to be reiterated, though, that collisions must be rare in comparison to nsns mergers.

With assumptions similar to those successfully applied in GRB afterglows, i.e. constant internal energy fractions behind the shock in electrons, \(\epsilon_e = 0.1\), and in magnetic field, \(\epsilon_B = 0.1\), and electrons being accelerated into a power law distribution with index \(p = 2.5\), one can estimate the resulting radio emission (for a detailed description see Piran et al. (2012)). At 1.4 GHz the radio signal that emerges from a typical nsns merger at the detection horizon of advanced LIGO (300 Mpc) remains on a level of \(\sim 50\mu Jy\) for several years, provided that it occurs in an environment similar to the one of the observed Galactic nsns systems where the density is of order \(1 \text{ cm}^{-3}\). Asymmetric \(q \neq 1\) mergers and in particular collisions with their larger ejecta velocities and masses produce brighter and longer lasting radio flares (Piran et al. 2012; Roswog et al. 2012). The ambient matter density is a major uncertainty for the detectability, though. Neutron star binary systems that receive a kick at birth could easily travel out of the galactic plane and merge where densities are substantially lower (Fryer et al. 1999; Bloom et al. 1999; Rosswog et al. 2003; Belczynski et al. 2006; Fong et al. 2010). The transients from the dynamic ejecta of such cases would be very hard to detect. Due to their velocities of \(\sim 0.1c\), the transients resulting from the dynamic ejecta peak after about one year. If present, mildly relativistic outflows would dominate the radio emission at earlier times. The physics to account for such outflows is not included in the presented simulations, such mildly relativistic outflows are, however, likely to occur. As sketched in Fig. 1, they are expected at the interface between the ultra-relativistic outflows that trigger the sGRB and the neutrino-driven winds. It is a numerical challenge, though, to calculate their velocity structure/Lorentz factor distribution in a reliable way. The dynamics in the interaction region will be dominated by fluid instabilities such as Kelvin-Helmholtz where the shortest perturbations grow fastest. These perturbations are usually set by the finite numerical resolution length. Nevertheless, since this type of outflow may dominate the early radio emission it deserves further studies in the future.

### 3 DISCUSSION

We have briefly summarized the ways in which a compact binary encounter ejects neutron-rich matter into its surroundings. Our focus was on the dynamic ejecta, launched by hydrodynamic effects and gravitational torques, and on their implications for nucleosynthesis and EM transients going along with a compact binary encounter. nsns mergers eject close to one percent of a solar mass with an extremely low electron fraction, \(Y_e \approx 0.03\). The exact amount of ejecta and their velocities depend on both the total mass and the mass ratio of the binary system. Our reference system, the merger of a \(1.3\) and \(1.4 M_{\odot}\) binary system, ejects \(1.4 \times 10^{-2} M_{\odot}\) at an average velocity of 0.12c. Robust r-process within the ejecta produces elements in close-to-solar proportions from the second to the third r-process peak. This abundance pattern is extremely robust and essentially the same for all investigated cases, see Korobkin et al. (2012). The ejected amounts are consistent with nsns mergers being a major source of heavy r-process. A question that needs further investigation, though, is whether/under which conditions this is consistent with galactic chemical evolution. Earlier work (Argast et al. 2004) concluded that neutron star mergers could not be the major source of r-process, but all existing studies found that the conditions in merger ejecta are very favorable for r-process isotopes to be forged in close-to-solar proportions (Freiburghaus et al. 1999; Goriely et al. 2011; Roberts et al. 2011; Korobkin et al. 2012) and this discrepancy remains to be understood. Dynamical collisions as they are expected to occur, for example, in the cores of globular clusters, eject substantially larger amounts of matter and the overproduction of r-process material by collisions can only be avoided if they are rare in comparison to nsns mergers (less, possibly much less, than 10\%). We have also discussed the implications for macronovae, radioactively powered, fast EM transients and for the radio flares that are produced when the ejecta share their kinetic energy with the ambient medium. The presented amounts of ejecta and their velocities are numerically converged and very robust. They may depend, however, on the employed physics. In particular, they may be affected by general relativistic and possibly nuclear equation of state effects. We suspect that such effects may change the ejecta masses at maximum by a factor of a few, therefore, the conclusions with respect to the role of mergers as r-process production sites should be robust. The sensitivity to GR and nuclear equation of state effects will be explored in future studies.

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Movies from our hydrodynamic simulations and ejecta trajectories can be downloaded from: http://compact-merger.astro.su.se/

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