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TRANSPORT AND MIXING OF r-PROCESS ELEMENTS IN NEUTRON STAR BINARY MERGER BLAST WAVES

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ABSTRACT

The r-process nuclei are robustly synthesized in the material ejected during neutron star binary mergers (NSBMs). If NSBMs are indeed solely responsible for the solar system r-process abundances, a galaxy like our own would be required to host a few NSBMs per million years, with each event ejecting, on average, about $5 \times 10^{-2} M_\odot$ of r-process material. Because the ejecta velocities in the tidal tail are significantly larger than those in ordinary supernovae, NSBMs deposit a comparable amount of energy into the ISM. In contrast to extensive efforts studying spherical models for supernova remnant evolution, calculations quantifying the impact of NSBM ejecta in the ISM have been lacking. To better understand their evolution, we perform a suite of three-dimensional hydrodynamic simulations of isolated NSBM ejecta expanding in environments with conditions adopted from Milky-Way-like galaxy simulations. Although the remnant morphology is highly complex at early times, the subsequent radiative evolution is remarkably similar to that of a standard supernova. This implies that sub-resolution supernova feedback models can be used in galaxy-scale simulations that are unable to resolve the key evolutionary phases of NSBMs. Among other quantities, we examine the radius, mass, and kinetic energy content of the remnant at shell formation. We find that the shell formation epoch is attained when the swept-up mass is about $10^3 (\rho_0 h / 1 \text{ cm}^{-3})^{-2/7} M_\odot$; at this point, the mass fraction of r-process material is enhanced up to two orders of magnitude in relation to a solar metallicity ISM.

Key words: galaxies: ISM – hydrodynamics – ISM: supernova remnants – nuclear reactions, nucleosynthesis, abundances – shock waves – stars: neutron

1. INTRODUCTION

The specific physical conditions and nuclear physics pathways required for the r-process were originally identified in the pioneering work by Burbidge et al. (1957). However, the particular astrophysical site remains open to more than one interpretation (Sneden et al. 2008). Early work on the subject identified both type II supernovae (SNe II) (Takahashi et al. 1994; Woosley et al. 1994) and neutron star binary mergers (NSBMs; Lattimer et al. 1977; Freiburghaus et al. 1999) as likely candidate events to hold the r-process. NSBMs are much rarer (~10 Myr$^{-1}$; e.g., Shen et al. 2015) than SNe II (~10$^{-2}$ yr$^{-1}$; e.g., Argast et al. 2004) and take place far from their birth places, reaching distances of up to a few megaparsecs from their host halo (e.g., Kelley et al. 2010). The two mechanisms synthesize different quantities of r-process material, about $10^{-3}$ and $10^{-2} M_\odot$ for each SN II and NSBM, respectively (e.g., Cowan & Thielemann 2004). These differences should give rise to clear signatures in the enrichment pattern of r-process elements in galaxies and may ultimately help constrain the dominant production mechanism (Shen et al. 2015).

With many difficulties getting the necessary conditions to produce the r-process in SN II winds (Takahashi et al. 1994; Qian & Woosley 1996), the NSBM model has recently been extensively studied and shown to be a viable alternative. The r-process nuclei have been found to be robustly synthesized (Metzger et al. 2010; Roberts et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013; Grossman et al. 2014; Goriely et al. 2015; Mendoza-Temis et al. 2015; Ramirez-Ruiz et al. 2015) and the predicted galactic enrichment history of NSBMs is consistent with the abundance patterns observed in halo stars (Tsujimoto & Shigeyama 2014; Shen et al. 2015; van de Voort et al. 2015; Vangioni et al. 2016). This suggests that the injection of r-process material by NSBMs has been operating in a fairly robust manner over long periods of time in galactic history, while the resultant chemical abundance dispersions in r-process elements, such as Eu, suggests an early, chemically unmixed, and inhomogeneous early Milky Way galaxy. At later times, these localized inhomogeneities would fade out as more events happen and r-process products are given more time to be transported and mixed throughout the galaxy.

An accurate treatment of the evolution of the ejecta in NSBMs is thus crucial not only for models of electromagnetic transients (Nakar & Piran 2011; Metzger & Berger 2012; Kelley et al. 2013; Rosswog et al. 2014) following coalescence but also for models of r-process enrichment in galaxies. In contrast to the extensive efforts developing models for supernova remnant (SNR) evolution, (Cox & Smith 1974; McKee & Ostriker 1977; Blondin et al. 1998; Joung & Mac Low 2006; Kim & Ostriker 2015; Martizzi et al. 2015) studies quantifying the impact of NSBM remnants in a cosmological context have not been carried out. The efficacy of transport and mixing of the r-process in NSBM remnants has not been properly quantified mainly due to the highly inhomogeneous initial conditions and the excessive radiative losses expected during the shock propagation.
In this paper, we present the results of a series of controlled three-dimensional hydrodynamic simulations of NSBM remnants. To calculate the ejected mass and initial structure of the tidal tails, we make use of three-dimensional smoothed particle hydrodynamics (SPH) simulations (Roberts et al. 2011) of NSBMs (Section 2.1). The resultant homologous structure of the tidal tail is then mapped into an adaptive-mesh refinement (AMR) simulation with optically thin radiative cooling (Section 2.2). Our goal is to understand the evolution of single NSBM remnants, which is quantified in Section 3, and how it might depend on the properties of the surrounding medium, which are derived using a cosmological simulation of the formation of the Milky Way (Section 2.3). Our simulations of isolated NSBMs are used to construct sub-resolution prescriptions for galaxy-scale simulations with inadequate resolution to properly define the the cooling radius of NSBM blast waves. Discussion of the results as well as detail comparisons with studies from spherical models are presented in Section 4.

2. METHODS

2.1. Initial Conditions

Tidal tails are a common feature formed during mergers and collisions between compact objects. These are typically a few thousand kilometers in size by the end of the merger event in the case of neutron star disruptions by black holes and NSBMs (Lee & Ramirez-Ruiz 2007; Faber & Rasio 2012). Some small fraction of the material ($10^{-3}$–$10^{-2} M_\odot$) in the tails is actually unbound and will escape to the surrounding medium. The exact mass and structure (density and velocity distribution) of the ejected material depends on the mass ratio and details of the equation of state (EOS; e.g., Roberts et al. 2011). Due to its Lagrangian nature SPH is well suited to accurately capture, within the limitations of the post-Newtonian framework, the tail formation process, which involves only a tiny fraction of the mass of the system.

To calculate the density and velocity structure of the unbound tidal tails, we use a similar method to the one described by Roberts et al. (2011). We use three-dimensional SPH simulations (Lee & Ramirez-Ruiz 2007; Lee et al. 2010) to follow the merger of two neutron stars during which the geometry, densities, and timescales change rapidly (Rasio & Shapiro 1994; Lee 2000; Rosswog et al. 2003). As a representative example, we study the dynamics of the $M_t = 0.05 M_\odot$ material ejected during an NSBM with mass ratio $q = M_2/M_1 = 0.88$ (Roberts et al. 2011). The mass resolution is $\sim 10^{-5} M_\odot$. The ejected mass is similar in all the cases considered in Roberts et al. (2011; see their Figure and Table 1). A clear progression is observed from equal mass tails formed in the $q = 1.0$ case to almost no secondary tail produced in the $q = 0.88$ case studied here. For simplicity, we consider the $q = 0.88$ case to better track the evolution of the mass ejected, which in this case is restricted to one structure. A hybrid EOS, similar to that implemented by Shibata et al. (2005), is used, which combines the cold Friedman–Panhar-ipande–Skyrme nuclear EOS with an ideal gas component. This treatment of the low-density EOS seems to prevent hydrodynamic instabilities in the ejecta (Lee & Ramirez-Ruiz 2007), but does not significantly change the ejected mass. Once the initial dynamical interaction is realized, the fluid elements in the unbound tails are verging on ballistic trajectories, moving primarily under the influence of the central mass potential. The hydrodynamical calculations are stopped only after the expansion of the unbound material becomes homologous.

2.2. Hydrodynamical Evolution of NSBM Remnants

Here we follow the expansion of the tidal tail produced by an NSBM with $q = 0.88$ in three dimensions with the parallel, adaptive-mesh, hydrodynamical code FLASH (Fryxell et al. 2000). We evolve the ideal fluid in three-dimensional cartesian coordinates. The flux between grid cells is solved using the piecewise parabolic method, which incorporates second-order directional operator splitting. A metallicity-dependent cooling function, which is constructed using the ion-by-ion cooling efficiencies for low-density gas derived by Gnat & Ferland (2012) for gas temperatures between $10^4$ and $10^6$ K. As it is generally adopted, we do not include metal fine structure transitions or molecular line cooling and so the cooling function is effectively truncated below $T \approx 10^4$ K.

Figure 1 shows the cooling function for an optically thin thermal plasma with solar abundances assuming collisional equilibrium (blue curve). The full radiative spectra of the r-process material at the relevant densities and temperatures is not well known as complete atomic line lists for these heavy species are not available (Kasen et al. 2013; Tanaka et al. 2014; Lippuner & Roberts 2015). We therefore simply assume that the energy integral of the full radiative spectra of r-process material is similar to that of Fe. The computed cooling curves with enhanced Fe abundances are plotted in Figure 1. However, this assumption is of no consequence at all because radiative losses begin to influence the NSBM remnant evolution only when the metal content is almost exclusively dominated by the swept-up gas (see Section 3 for specifics). As such, the resulting evolution is quantitatively similar to that computed using solar abundances, but note that we have implemented metal enhanced cooling rates here for completeness.

2.3. Properties of the Ambient Medium

The evolution of an NSBM remnant depends on the character of the ambient medium. In Figure 2, we show the expected properties of the gas in and around the NSBM injection sites, derived using the cosmological zoom-in simulation Eris, which at a redshift of $z = 0$ is a close analog of the Milky Way (Guedes et al. 2011). The merger rate is inferred by convolving the star formation history with a standard delay-time distribution of mergers modeled by $P(t) \propto t^{-n}$ for $t > t_c$ and zero probability otherwise, where $t_c \sim 100$ Myr and $n = 1$ (Shen et al. 2015). The resulting NSBM history in the simulation is shown in Figure 1 of Shen et al. (2015). The spatial distribution of NSBM mergers is then assumed to roughly follow the stellar distribution. Using these two key model ingredients, the number and location of NSBMs can be estimated, which in turn can be used to infer the density, temperature, and metallicity of the surrounding ambient gas (Figure 2). Motivated by this, we run three different types of simulations:

1. isolated NSBM in a homogeneous ISM with $n_H = 1$ cm$^{-3}$, $T = 10^4$ K and $Z = Z_\odot$;
2. isolated NSBM in a homogeneous, dense ISM with $n_H = 100$ cm$^{-3}$, $T = 10^4$ K and $Z = Z_\odot$; and
3. isolated NSBM in a homogeneous, rarefied ISM with $n_H = 10^{-4}$ cm$^{-3}$, $T = 10^6$ K and $Z = Z_\odot$. 

2
The parameters of the different simulations are outlined in Table 1. For comparison, standard blast wave simulations initiated by injecting the same total energy in a spherical region are computed in order to determine how the evolution of an NSBM is initially altered by its non-uniform original structure. In all cases, we consider computational boxes filled with ISMs initially in pressure equilibrium and adopt a refinement scheme based on pressure and density gradients, which is refining around the expanding shock.

3. HYDRODYNAMICAL EVOLUTION OF NSBM REMNANTS

The evolution of an isolated NSBM remnant expanding into a uniform medium can be broadly characterized by the well-known evolutionary stages of an SNR:

1. the free expansion phase, during which the mass of the tidal ejecta is larger than the mass of the swept-up ISM;
2. the energy conserving phase, during which radiative losses are not important;
3. the cooling-modified pressure-driven snowplow phase, during which shell formation occurs; and
4. the final momentum-conserving expansion phase.

However, differences in ejected mass and initial structure modifies the evolution of an NSBM remnant relative to that of an SNR, as illustrated in Figure 3 for our fiducial run (labeled ISM in Table 1). The various panels show the evolution long after the free expansion phase and during the energy conserving phase. The kinetic energy of the NSBM $q = 0.88$ tidal tail is $3.58 \times 10^{51}$ erg. The ensuing strong blast wave converts much of this energy into thermal energy, which leads to the observed cooling processes.

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As the NSBM remnant ages, the thermal energy is lost due to radiative cooling, the shock slows down, and shell formation is established. The bottom panel in Figure 4 shows the propagation of the NSBM remnant in a dense uniform medium at time $t = 72.238$ kyr soon after the onset of the remnant’s cooling-modified snowplow phase.

The top panel of Figure 5 shows the evolution of the forward shock radius $R$ with time $t$ for the NSBM remnant case shown in Figure 3. For comparison, the evolution of a spherical blast wave with the same initial mass and energy is also shown together with the analytical Sedov–Taylor solution. For spherical simulations, $R$ is identified by measuring spherically averaged profiles, while for the NSBM simulations we approximate $R$ as the radius of the sphere enclosing 90% of the total energy (no significant difference in the measured radio was obtained from slightly different percentages). The radial temperature $T$ and metal mass fraction $\chi_{\text{metal}}$ profiles are then calculated by measuring the spherically averaged values of such quantities at $R$.

The initial configuration of the ejected tidal tail material is highly inhomogeneous, as can be seen in Figure 3, with shock expansion velocities being larger along the original orbital plane of the NS binary. As a result, the rate of ambient material swept up by the blast wave is reduced relative to the spherical case until lateral expansion becomes important. The Sedov–Taylor solution is an attractor and the NSBM remnant evolution slowly adjusts to match this spherical, energy

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6 Similar to the case of remnants arising from jet-driven supernova explosions (Ramirez-Ruiz & MacFadyen 2010; González-Casanova et al. 2014) or from the unbound debris of stars disrupted by massive black holes (Kasen & Ramirez-Ruiz 2010; Guillochon et al. 2015).

### Table 1

| Tidal Tail | NSBM with $q = 0.88$ |
|------------|---------------------|
| $M_i$      | $5.8 \times 10^{-3} M_\odot$ |
| $E_k$      | $3.58 \times 10^{51}$ erg |

| ISM |
|----|
| $n_H$ | $1 \text{ cm}^{-3}$ |
| $T$  | $10^4 \text{ K}$ |
| $Z$  | $Z_c$ |
| Box size | 100 pc |
| Cell size | $3.02 \times 10^{17}$ cm |

|^|---|
|Rarefied | |
| $n_H$ | $10^{-4} \text{ cm}^{-3}$ |
| $T$  | $10^6 \text{ K}$ |
| $Z$  | $Z_c$ |
| Box Size | 3 kpc |
| Cell Size | $3.01 \times 10^{14}$ cm |

|^|---|
|Dense | |
| $n_H$ | $10^2 \text{ cm}^{-3}$ |
| $T$  | $10^4 \text{ K}$ |
| $Z$  | $Z_c$ |
| Box Size | 40 pc |
| Cell Size | $1.20 \times 10^{17}$ cm |

**Note.** Cell size value refers to the minimum cell size at the lowest resolution reached by the simulation (see the Appendix).
conserving solution. As shown in Figure 5, the NSBM remnant becomes radiative before matching the Sedov–Taylor solution, which increases the local cooling time and leads to a decrease

Figure 4. NSBM remnants expanding into different density environments. Top: evolution at time 8.401 kyr in the uniform ISM case depicted in Figure 3 (labeled ISM in Table 1). Density surfaces (green) are plotted for 12 levels from \( \log(\rho) = -25.5 \) to \(-23.1 \) g cm\(^{-3}\). \( \chi_{\text{metal}} \) contours (red) are plotted with 16 levels from \( \log(\chi_{\text{metal}}) = -6 \) to 0. The size of the box shown is 20 pc. The total computational size is 100 pc with 512 \( \times \) 512 cells on the coarsest grid and 11 levels of refinement corresponding to a maximum resolution of \( 3.760 \times 10^{16} \) cm. Bottom: evolution at time 72.238 kyr in a uniform dense medium (labeled Dense in Table 1). Density surfaces (green) are plotted for 14 levels from \( \log(\rho) = -26 \) to \(-20.7 \) g cm\(^{-3}\). \( \chi_{\text{metal}} \) contours (red) are plotted with 16 levels from \( \log(\chi_{\text{metal}}) = -5 \) to 0. The size of the box shown is 36 pc. The total computational size is 40 pc with 512 \( \times \) 512 cells on the coarsest grid and 11 initial levels of refinement corresponding to a maximum resolution of \( 1.504 \times 10^{16} \) cm.

Figure 5. Evolution of the forward shock \( R \) with time \( t \) for the NSBM remnant case depicted in Figure 3 (labeled as Tail). The evolution of a spherical blast wave with identical energy and mass content, labeled as Sedov, is plotted for comparison. The analytical Sedov–Taylor solution \( R(t) \) is shown as a gray line. The vertical line corresponds to the time of the snapshot shown in the top panel of Figure 4. Also shown are the temperature \( T \) and metal mass fraction \( \chi_{\text{metal}} \) with \( R \). The NSBM remnant propagates faster owing to the reduced rate of ambient mass sweeping, which is subsequently increased as the remnant becomes progressively more spherical. As a result, shell formation is delayed relative to the spherical case.
in radiative losses when compared to the spherical case. Similar behavior is also seen in simulations of an NSBM remnant expanding into a dense ambient medium (Figure 6) and into a rarefied, hot external environment (Figure 7). The key parameters of the late evolution of the NSBM remnant are the kinetic energy of the tidal tail, $E_{k,tail}$, and the density of the ambient medium. As long as the evolution is adiabatic, the
Table 2

| Simulation | \( R_s/\text{pc} \) | \( M_s/M_\odot \) | \( E_{\text{kin,rad}}/E_{\text{kin,order}} \) | \( \langle \chi_{\text{rem}} \rangle \) | \( \langle \chi_{\text{metal}} \rangle \) |
|------------|----------------|-----------------|-----------------|-----------------|-----------------|
| ISM        | 22.23          | 1.29 \times 10^3 | 1.04            | 209.73          | 4.93 \times 10^{-5} |
| Rarefied   | 1.13 \times 10^3 | 19.98 \times 10^3 | 1.04            | 12.34           | 2.90 \times 10^{-5} |
| Dense      | 2.83           | 425.58          | 1.06            | 615.77          | 1.45 \times 10^{-4} |

The radius of the blast wave at shell formation is

\[
R_s \approx 14 \left( \frac{E_{\text{tot}}}{10^{51} \text{erg}} \right)^{2/7} \left( \frac{n_\text{H}}{1 \text{ cm}^{-3}} \right)^{-3/7} \left( \frac{Z}{Z_\odot} \right)^{-1/7} \text{pc.} \tag{1}
\]

Here we evaluate the radius \( R_s \), swept-up mass \( M_s \), and kinetic energy \( E_{\text{kin}} \) of the NSBM remnant at shell formation. The results for all simulations are given in Table 2. The radius, total remnant mass, and outward radial momentum at shell formation are similar to those obtained using spherical simulations and as such are close to the analytic estimates. Despite the initial differences in ejecta mass and geometry, our conclusions regarding shell formation and momentum injection in NSBM remnants are quite similar to those obtained for SNRs. The reader is referred to the Appendix for a discussion on the importance of resolution and for details on our convergence study.

At the time of shell formation, the mass fraction \( \chi_{\text{metal}} \) arising from metals ejected during the NSBM remnant is about 5 \times 10^{-5}. We thus only expect metal cooling from \( r \)-process material to influence the dynamics of NSBM remnants if they expand into an ambient medium with \( Z \lesssim 10^{-3} Z_\odot \), under the assumption that the metal cooling function of \( r \)-process material is similar to that of Fe (Section 2.2). The \( r \)-process enrichment of the gas depends on how efficiently the metals are mixed with the ambient material swept up by the blast wave. At the time of shell formation, we find the mass fraction of \( r \)-process material in the NSBM remnant to be drastically enhanced in relation to a solar metallicity ISM (\( n_\text{H} \approx 1 \text{ cm}^{-3} \)) to about 10^2 (\( Z/Z_\odot \)).

4. DISCUSSION AND CONCLUSIONS

The importance of SNR evolution for detailed models of the ISM but also for models of galaxy evolution and chemical enrichment has been appreciated for decades. In recent years, it has become increasingly clear that an accurate treatment of NSBM remnant evolution is crucial not just for detailed models of electromagnetic transients (Nakar & Piran 2011; Metzger & Berger 2012; Kelley et al. 2013; Rosswog et al. 2014) but also for models of heavy element enrichment (Tsujiimoto & Shigeyama 2014; Shen et al. 2015; van de Voort et al. 2015). NSBMs are thought to play a predominant role in creating (Metzger et al. 2010; Roberts et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013; Grossman et al. 2014; Goriely et al. 2015; Ramirez-Ruiz et al. 2015; Vangioni et al. 2016) and dispersing \( r \)-process elements, yet modern cosmological simulations are still not able to resolve the evolution of SNRs. Motivated by this, we have employ a grid of three-dimensional hydrodynamic simulations of isolated NSBM remnants expanding in environments with thermodynamical properties similar to those found in cosmological simulations (Section 2.3).

In a uniform medium, the shell formation epoch, which occurs when an SNR becomes radiative, is usually well characterized by the time the mass of swept-up material attains \( M_s \approx 10^3 (n_\text{H}/1 \text{cm}^{-3})^{-2/7} M_\odot \). Previous studies of SNRs expanding in a homogeneous ambient medium (Cioffi et al. 1988; Thornton et al. 1998) approximate the cooling radius as

\[
R_s \approx 14 \left( \frac{E_{\text{tot}}}{10^{51} \text{erg}} \right)^{2/7} \left( \frac{n_\text{H}}{1 \text{ cm}^{-3}} \right)^{-3/7} \left( \frac{Z}{Z_\odot} \right)^{-1/7} \text{pc.} \tag{1}
\]

Here we evaluate the radius \( R_s \), swept-up mass \( M_s \), and kinetic energy \( E_{\text{kin}} \) of the NSBM remnant at shell formation. The results for all simulations are given in Table 2. The radius, total remnant mass, and outward radial momentum at shell formation are similar to those obtained using spherical simulations and as such are close to the analytic estimates. Despite the initial differences in ejecta mass and geometry, our conclusions regarding shell formation and momentum injection in NSBM remnants are quite similar to those obtain for SNRs. The reader is referred to the Appendix for a discussion on the importance of resolution and for details on our convergence study.

At the time of shell formation, the mass fraction \( \chi_{\text{metal}} \) arising from metals ejected during the NSBM remnant is about 5 \times 10^{-5}. We thus only expect metal cooling from \( r \)-process material to influence the dynamics of NSBM remnants if they expand into an ambient medium with \( Z \lesssim 10^{-3} Z_\odot \), under the assumption that the metal cooling function of \( r \)-process material is similar to that of Fe (Section 2.2). The \( r \)-process enrichment of the gas depends on how efficiently the metals are mixed with the ambient material swept up by the blast wave. At the time of shell formation, we find the mass fraction of \( r \)-process material in the NSBM remnant to be drastically enhanced in relation to a solar metallicity ISM (\( n_\text{H} \approx 1 \text{ cm}^{-3} \)) to about 10^2 (\( Z/Z_\odot \)).

1. First, a free expansion phase is observed, during which the mass of the ejecta is larger than the mass of the swept-up gas. This evolutionary phase is significantly shorter than that of a typical SNR due mainly to the low-mass content of the ejecta (\( 5.8 \times 10^{-2} M_\odot \)) and, to a lesser degree, the initial complex geometry.

2. Second, an energy conserving phase takes place, during which radiative losses are negligible (Figure 3). During this phase the rate of mass swept up by the blast wave is reduced when compared to a standard SNR but is then subsequently increased as the NSBM remnant becomes progressively more spherical. However, radiative losses begin to influence the NSBM remnant evolution before it is accurately described by a standard spherical solution (Figure 5). In addition, the overall evolution takes slightly longer, with the cooling time reaching its critical value only when the shock has travelled a distance that is a few times larger than in the spherical case. This is observed in all simulations listed in Table 1.

3. Third, a pressure-driven snowplow phase sets in, during which radiative losses begin to influence the evolution of the NSBM remnant and shell formation is found to set in at a time when the swept-up mass attains a value of \( M_s \approx 10^3 (n_\text{H}/1 \text{cm}^{-3})^{-2/7} M_\odot \), as is commonly found in SNRs (Table 2). The radius, total swept-up mass, kinetic energy, and outward radial momentum at shell formation for NSBM remnants, we conclude, are close to the standard estimates given for SNRs (Cox & Smith 1974; McKee & Ostriker 1977; Blondin et al. 1998; Joung & Mac Low 2006).

4. Finally, during the momentum-conserving phase, the evolution of an NSBM remnant is remarkably similar to that of an SNR. This implies that sub-resolution supernova feedback models (e.g., Kim & Ostriker 2015; Martizzi et al. 2015) can be accurately used in galaxy-scale simulations that are unable to resolve the early evolutionary stages of an NSBM remnant.
While our simulations of NSBM remnants have confirmed the similarities and highlighted the differences of the well-known evolutionary stages of SNRs, one of the key distinct processes affecting their structure is the contribution of \( r \)-process material to the cooling of the swept-up material. Because complete atomic line lists for these heavy species are not available (Kasen et al. 2013), we have simply assumed that the energy integral of the full radiative spectra of \( r \)-process material is similar to that of Fe. Under these conditions, we find that metal cooling from \( r \)-process material is not expected to influence the dynamics of NSBM remnants expanding into an ambient medium with \( Z \gtrsim 10^{-3}Z_\odot \). The resulting NSBM remnant evolution in these environments should solely be determined by the metal cooling of the swept-up material. However, the mass fraction of \( r \)-process material at shell formation within the remnant is expected to be severely enhanced to about \( 2.5 \times 10^4 (Z/10^{-2}Z_\odot) \), assuming a solar abundance ratio and \( \eta_{\text{H}} \approx 1 \text{ cm}^{-3} \). In contrast, with a total \( r \)-process mass per supernova of \( M_p \approx 7.4 \times 10^{-5}M_\odot \) (Shen et al. 2015), we expect a local enhancement of only about \( 31.9 (Z/10^{-2}Z_\odot) \) when a Type II SNR attains shell formation in similar external conditions.

Of particular relevance in this case is the heavy element composition of galactic halo stars with the metallicity regime \( 10^{-3}Z_\odot \lesssim Z \lesssim 10^{-2}Z_\odot \), which has been found to have pure \( r \)-process products with a distribution that is characteristic of solar system matter but with a large star-to-star scatter in their \( r \)-process concentrations (Sneden et al. 2008). In some stars with \( Z \approx 10^{-2}Z_\odot \), the \( r \)-process enrichment can be as large as \( 10^2 \), assuming a solar abundance ratio. The presence of \( r \)-process material in these stars with a distribution that is characteristic of solar abundance ratios illustrates that \( r \)-process enrichment has operated in a fairly robust manner, while their abundance dispersions further suggest that \( r \)-process production sites must be rare and locally very enhanced, as expected from NSBM enrichment (e.g., Shen et al. 2015). These localized inhomogeneities would then be smoothed out as more NSBMs take place and \( r \)-process material is given more time to be transported and mixed together in the Milky Way. Metal feedback from NSBM remnants is thus essential to understand the formation of \( r \)-process enhanced stars in galaxies. Despite the initial differences, our conclusions regarding the efficacy of the transport and mixing of \( r \)-process material by NSBM remnants in a cosmological context should be similar to that expected from single SNRs.

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APPENDIX

RESOLUTION CONVERGENCE

Here we describe the results of our resolution study. Simulations are initialized with a static AMR and with a maximum level of refinement of 10 within a sphere enclosing all of the tail material. In all cases, we reduce the refinement by two levels after the size of the tidal remnant reaches 1/20 of the size of the computational box. The grid mesh refinement is then based on the value of the density. To test how our results are sensitive to the refinement criteria and resolution, we run two more simulations using the initial fiducial model parameters but subtracting three and one level(s) of refinement, respectively. We compare the different simulations in Figure 8 with final resolutions of 6.02, 3.01, and \( 1.504 \times 10^7 \text{ cm} \), respectively. Figure 8 shows the evolution of the shock radius and temperature for the three different simulations. We note that in all cases, the grid is sufficiently fine, the resolution element with respect to the cooling radius \( R_c \) is 1/115, 1/230, and 1/460, respectively. The progress through the radiative stages can thus be properly followed and the standard resolution requirement of \( R_c/10 \) is easily met (see, e.g., Kim & Ostriker 2015; Martizzi et al. 2015, and references therein). We note that in the fiducial simulation \( R_c \) is accurate to about 1% when compared to the higher resolution run. In all of our simulations, the resolution elements are \( R_c < 1/100 \).
REFERENCES

Argast, D., Samland, M., Thielemann, F.-K., & Qian, Y.-Z. 2004, A&A, 416, 997
Baumwein, A., Goriely, S., & Janka, H.-T. 2013, ApJ, 773, 78
Blondin, J. M., Wright, E. B., Borkowski, K. J., & Reynolds, S. P. 1998, ApJ, 500, 342
Burbridge, E. M., Burbridge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547
Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, ApJ, 334, 252
Cowan, J. J., & Thielemann, F.-K. 2004, PhT, 57, 47
Cox, D. P., & Smith, B. W. 1974, ApJL, 189, L105
Faber, J. A., & Rasio, F. A. 2012, LRR, 15, 8
Freiburghaus, C., Rosswog, S., & Thielemann, F.-K. 1999, ApJL, 525, L121
Fryxell, B., Olson, K., Ricker, P., et al. 2000, ApJS, 131, 273
Gnat, O., & Ferland, G. J. 2012, ApJS, 199, 20
González-Casanova, D. F., De Colle, F., Ramirez-Ruiz, E., & Lopez, L. A. 2014, ApJL, 781, L26
Goriely, S., Bauswein, A., Just, O., Pfllumbi, E., & Janka, H.-T. 2015, arXiv:1504.04377
Grossman, D., Korobkin, O., Rosswog, S., & Piran, T. 2014, MNRAS, 439, 757
Guedes, J., Callegari, S., Madau, P., & Mayer, L. 2011, ApJ, 742, 76
Guillochon, J., McCourt, M., Chen, X., Johnson, M. D., & Berger, E. 2015, arXiv:1509.08916
Joung, M. K. R., & Mac Low, M.-M. 2006, ApJ, 653, 1266
Kasen, D., Badnell, N. R., & Barnes, J. 2010, ApJ, 774, 25
Kasen, D., & Ramirez-Ruiz, E. 2010, ApJ, 714, 155
Kelley, L. Z., Mandel, I., & Ramirez-Ruiz, E. 2013, PhRvD, 87, 123004
Kelley, L. Z., Ramirez-Ruiz, E., Zemp, M., Diemand, J., & Mandel, I. 2010, ApJL, 725, L91
Kim, C.-G., & Ostrikov, E. C. 2015, ApJ, 802, 99
Korobkin, O., Rosswog, S., Arcones, A., & Winteler, C. 2012, MNRAS, 426, 1940
Lattimer, J. M., Mackie, F., Ravenhall, D. G., & Schramm, D. N. 1977, ApJ, 213, 225
Lee, W. H. 2000, MNRAS, 318, 606
Lee, W. H., & Ramirez-Ruiz, E. 2007, NJPh, 9, 17
Lee, W. H., Ramirez-Ruiz, E., & van de Ven, G. 2010, ApJ, 720, 953
Lippuner, J., & Roberts, L. F. 2015, arXiv:1508.03133
Martizzi, D., Faucher-Giguère, C.-A., & Quataert, E. 2015, MNRAS, 450, 504
McKee, C. F., & Ostriker, J. P. 1977, ApJ, 218, 148
Mendoza-Temis, J. d. J., Wu, M.-R., Langanke, K., et al. 2015, PhRvC, 92, 055805
Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48
Metzger, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Nakar, E., & Piran, T. 2011, Natur, 478, 82
Qian, Y.-Z., & Woosley, S. E. 1996, ApJ, 471, 331
Ramirez-Ruiz, E., & MacFadyen, A. I. 2010, ApJ, 716, 1028
Ramirez-Ruiz, E., Trenti, M., MacLeod, M., et al. 2015, ApJL, 802, L22
Rasio, F. A., & Shapiro, S. L. 1994, ApJ, 432, 242
Roberts, L. F., Kasen, D., Lee, W. H., & Ramirez-Ruiz, E. 2011, ApJL, 736, L21
Rosswog, S., Korobkin, O., Arcones, A., Thielemann, F.-K., & Piran, T. 2014, MNRAS, 439, 744
Rosswog, S., Ramirez-Ruiz, E., & Davies, M. B. 2003, MNRAS, 345, 1077
Shen, S., Cooke, R. J., Ramirez-Ruiz, E., et al. 2015, ApJ, 807, 115
Shibata, M., Taniguchi, K., & Uryu, K. 2005, PhRvD, 71, 084021
Sneden, C., Cowan, J. J., & Gallino, R. 2008, ARA&A, 46, 241
Takahashi, K., Witti, J., & Janka, H.-T. 1994, A&A, 286, 857
Tanaka, M., Hotokezaka, K., Kyutoku, K., et al. 2014, ApJ, 780, 31
Thornton, K., Gaullitz, M., Janka, H.-T., & Steinmetz, M. 1998, ApJ, 500, 95
Tsujimoto, T., & Shigeyama, T. 2014, ApJL, 795, L18
van de Voort, F., Quataert, E., Hopkins, P. F., Kereš, D., & Faucher-Giguère, C.-A. 2015, MNRAS, 447, 140
Vangioni, E., Goriely, S., Daigne, F., François, P., & Belczynski, K. 2016, MNRAS, 455, 17
Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229