Numerical Simulations of Binary Neutron Star Mergers

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Neutron Star Merger Evolution

From Bartos, Brady, & Márka 2013 of the emitted GW is indicated GW is indicated for the different stages. NS–NS inspirals are observable for a

Multimessenger Emissions

Phases of a neutron star (NS) merger as a function of time, showing the associated observational signatures From Fernández & Metzger 2016

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Gravitational Waves

Tidal Effects (I) 20

Tidal Effects (II) $TialalEffAeth$ (II)

From Del Pozzo+ 2013

Postmerger Peak Frequency Eur. Phys. J. A (2016) 52: 56 Page 5 of 22

- Post-merger signal has a characteristic peak frequency strated and sensitivity constraints of the construction of the sensitivity of the theorem is a sensitivity of the theorem is a sensitivity of the mass of the 1.6 *M* for discreption of the 1.6 μ masses for 2.4 *M*⊘, constructed for 2.7 *M*⊘, construction for 2.7 *M*⊘, construction for 2.7 *M*⊘, construction for 2.7 *M*
- Empirical correlations: fpeak vs. EOS properties Einstein Telescope [45] (black). 3.0 *M*⊙) and a mass ratio of unity. The solid lines are leasts. \sf{EOS} properties. The different binary mass \sf{EOS}
- Small statistical uncertainty: radii to within few hundred meters Sinan Station at foottainty fraun to within fow framarou motors

Postmerger: Universal Relations

complamentary measure of the tidal parameter Complementary measure of the tidal parameters

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Akami+ 2014: Rezzolla & Takami a*RaITH* **LOTT**, **ROLLOR & TaRaITH** See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bose+ 2017 1 + *n*1*^T* ² + *n*2(*^T*

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Extreme-Density Physics

- Neutron stars in binaries have masses clustered around ~1.35 Mo
- What happens if we change the EOS at high density?
- Different collapse time of remnant?
- What about f_{peak} ?
- What can we say about the EOS with GWs?

Einstein Toolkit / WhiskyTHC

Gravity: BSSN, Z4c;

GRHD: high-order FD; FV

Nuclear EOS

Neutrino radiation: leakage, ray-by-ray moment-based transport

THC = Templated Hydrodynamics Code

To be released soon!

$1.4~{\rm M_\odot}$ vs 1.4 ${\rm M_\odot}$

 $t = 0.00$ ms

Hyperons No Hyperons

1.3 M⊙ vs 1.3 M[⊙]

 $t = 0.00$ ms

Hyperons No Hyperons

Binding Energy

High-density EOS encoded in the binding energy

Gravitational Waves

- Frequency evolution: a black-hole formation signature
- EOS softening always imprinted as amplitude modulation

Detectability

What About Magnetic Fields?

Magneto-Turbulence Effects

- MHD instabilities are known operate at a scale of few meters or less
- Resolution in global simulations is orders of magnitude too low
- Previous approach: neglect these effects or use unrealistically large Bfields & idealized configurations
- Our approach: explicit subgrid-scale modeling with large-eddy simulations

See also: Shibata & Kiuchi 2017

Large-Eddy Simulations (LES)

From: T. Itami; <http://www.cradle-cfd.com/tec/column04>

Large scale flow is resolved, small scale flow is modeled

Relativistic LES

Special relativistic Euler equations

$$
S_i = \rho h W^2 v_i \qquad \qquad \partial_t S_i + \partial_j (S_i v^j + p) = 0
$$

Only large scales are resolved in a simulation

$$
\partial_t \overline{S_i} + \partial_j(\overline{S_i v^j + p}) = 0
$$

Small scales are modeled

$$
\overline{S_i v^j} = \overline{S}_i \overline{v}^j + \tau_i^j \qquad \qquad \partial_t \overline{S}_i + \partial_j (\overline{S}_i \overline{v}^j + \overline{p}) = -\partial_j \tau_i^j
$$

Turbulent-Viscosity Models

Rely on numerical viscosity; Implicit LES approach

$$
\tau_{ij}=0
$$

Turbulence modeled as an effective viscosity: Smagorinsky (1963)

$$
\tau_{ij} = -2\nu_T \overline{\rho h W^2} \left[\frac{1}{2} (\partial_i \overline{v}_j + \partial_j \overline{v}_i) - \frac{1}{3} \partial_k \overline{v}^k \delta_{ij} \right]
$$

 v_T turbulent viscosity

- Relativistic LES not relativistic viscous hydrodynamics
- Lorentz invariance is broken and only recovered as a limit*
- \cdot v_T is not an intrinsic fluid quantity

* Eyink & Drivas 2017

Mixing Length Theory

Turbulent viscosity can be written in terms of characteristic speed and length

 $\nu_T = \ell_{\rm mix} c_s$

 ℓ_{mix} is the correlation scale (typical eddy size) of the turbulence. Two ways to estimate:

1. for MRI driven turbulence we assume

$$
\ell_{\rm mix} \sim \lambda_{\rm MRI} \sim 3\,{\rm m}\; \left(\frac{\Omega}{4\;{\rm rad}\;{\rm ms}^{-1}} \right)^{-1} \left(\frac{B}{10^{14}\;{\rm G}} \right)
$$

2. equivalent choice [see Shibata & Kiuchi 2017] is

$$
\ell_{\rm mix} \sim H_p \sim c_s / \Omega_s \sim 10 \,\text{km} \qquad \ell_{\rm mix} = \alpha \, c_s / \Omega
$$

observations^{*} and simulations⁺ show: $\alpha \gtrsim 0.1$

* King+ 2007 + Shi+ 2016

Mixing Length

- MRI studies focus on steady-state thin-disk flows
- HMNS evolution is non-steady (and not a thin disk),
- MRI must do something within few rotational periods to be relevant for GWs
- Current simulations of HMNS available support $\ell_{\rm mix} \sim \lambda_{\rm MRI}$
- Caveat: these simulations are too short! More work needed!

Angular Momentum Transport

Delayed collapse?!?

Rotational Profile 6 8 10 12 \smile $\bf C$ i*xy* [rad ms $\overline{}$] $\ell_{\rm mix} =$

l

0 2 4 6 8 10 12 14 16 *r* [km] 4 $t - t_{\rm mrg} \simeq 10 \text{ ms}$

See also Shibata & Taniguchi 2006; Kastaun+ 2015, 2016; Hanauske+ 2016 **DR** 2017

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DR 2017

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Effect on the Waveforms

- f_{peak} is robust
- GW amplitude more sensitive
- MHD models needed

Effect on neutrino luminosity

- Inverted hierarchy compared to CCSNe: $L_{\nu_e} \lesssim L_{\bar{\nu}_e}$
- The remnant is re-leptonizing
- Turbulent dissipation some impact on luminosity: r-process?

The Origin of the Elements

How are heavy elements formed?

R-process Sites

• Magnetorotational supernovae

- Core-collapse supernovae
	- Neutron star mergers
		- Nuclear explosions

This results is asymmetric on large shock more stated shock more was produced using yt (Turk et al. 2011). This figure was produced using yt (Turk et al. 2011). This figure was produced using yt (Turk et al. 2011). This fi

All four models exhibit very similar average neutrino energies, the expected hierarchy of neutrino energies, h✏⌫*^e* i *<* h✏⌫¯*^e* i *<* h✏⌫*µ/*⌧ i, and spectral hardening as a function of time. The large average energies of the ⌫*µ/*⌧ , relative to the aver-

This is unlikely to have a large effect on heating in the gain region, since *µ* and ⌧ neutrinos do not effectively deposit their heavy flavored neutrinos near the electron neutrino sphere can modestly increase the average energies of electron flavored neutrinos (Müller et al. 2012b), but the absence of inelastic scattering is unlikely to make a qualitative difference to the outcome of our simulations. Tamborra et al. (2014) have also investigated 3D models of CCSNe using the s27 progenitor. Our ⌫*^e* and ⌫¯*^e* luminosities and average energies are within 10% of those found by Tamborra et al. (2014), but our simulations show a different hierarchy of luminosities than theirs, with *L*⌫*^e < L*⌫¯*^e* . Our ⌫*µ/*⌧ luminosities are also about 25% lower than those reported in Tamborra et al. (2014).

Additionally, Tamborra et al. (2014) found that the lepton flux is asymmetric about the center of mass with a strong

DR+ 2017

Roberts+ 2016

Compact Binary Mergers

- Neutron-rich outflows: the site of the r-process?
- Nucleosynthetic yields
- Radioactively powered transients

Strong and Weak R-process

nuclides with even neutron numbers are favored. Even though there are not many free neutrons available, there is still a significant amount **Same in the seeds of landanizer in the seeding index in the seed of the initial second in the initial second i** lighter and the initial free neutron and increase increasing. However, the initial free neutron abundance in the initial free neutron abundance is not enough to o the compecition is the mest important parameter where the composition is the most important parameter leads to a full r-process in the *s* = 100 *k^B* baryon¹ case. tion and radionative hooting: Nucleosynthetic yields, opacities, and radioactive heating: though *s* = 3*.*2 *k^B* baryon¹ and *s* = 10 *k^B* baryon¹ have essentially the same heating rate, the *s* = 3*.*2 *k^B* baryon¹ case is significantly dimmer because in har amount of landscape it has a binary neutron star merger is expected to have entropies be
In the entropies between to have entropies between 1990s between 1990s between 1990s between 1990s between 199 the composition is the most important parameter

FRANCOIS FOULART ENTIRE ET AL. PHYSICAL REVIEW D 90, 024 H 2016 (2014) STATE ET AL. PHYSICAL REVIEW D 90, 0240 Neutron-Star Black-Hole Merger Outflows

R_{NS}, M_{NS}, M_{BH}, and a_{BH}

• Ejects ~up to 10-1 M[⊙]

• Very neutron rich

• Tidal disruption of NS

• Crucially depends on

neutron star and rapid accretion onto the black hole if we

-up to 10⁻¹ M_e

around the black hole. This is due largely to qualitative

differences in the distrustion of the distrustion process: the neutron star in the neutron star in the neutron

FIG. 5 (color online). Matter distribution during the distribution during the distribution during the distribution of \sim From Foucart+ 2014

Neutron Star Merger Outflows

DR, Galeazzi, Lippuner+ 2016

Secular Ejecta

Figure 8. Isosurfaces of parameterial in the part of parameterial in the set of perfection, green material in the set of From Fernandez+ 2015 **From Metzger+ 2014**

Metzger, Kaplan & Georgievan and Berger 2013; Nissanke, Kaslim & Georgievan and Georgie

From Motzgory 2014 ejecta that powers it. Material extensive dynamics in the equatorial planet of equations in the equatorial planet of \sim

Late-time eiecta can in some cases dominate vields and have an $\frac{1}{\sqrt{2}}$. The large sky error re-definition across the large sky error re-definition across the large sky error reimpact on the EM signal. Need to be included in emission models. \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n Late-time ejecta can in some cases dominate yields and have an

Approximate neutrino transport

1. Different treatment for trapped and free-streaming components

Trapped component: leakage

- Use effective emissivities weighted with the optical depth
- Leaked trapped neutrinos become free-streaming

Free-streaming component: M0

1. Free-streaming neutrinos stream radially out

$$
\vec{J} = n_{\nu}\vec{k} \qquad \qquad \nabla \cdot \vec{J} = R_{\nu}^{\text{eff}} - \kappa_{a}^{\text{eff}}n_{\nu}
$$

2. Assume \vec{t} to be a Killing vector

$$
\vec{p}_{\nu}\cdot\vec{t}=\mathrm{const}
$$

- 3. Use effective grey emissivities and opacities (no scattering)
- 4. Solve equations fully-implicitly on a radial grid "ray-by-ray"

- Mostly grey
- Idealized geometry
- Simple microphysics (no scattering!)
- Computationally inexpensive
- Clear physical interpretation
- No "radiation shocks"
- Velocity dependent terms
- Some spectral effects

 $Time = 0$ ms

 $Time = 7.38869$ ms

Outflows

Record outflows at ~440 km

Impact of Neutrino Radiation

- The tidal tail is also irradiated
- Strong r-process yields are robust;
- but non-equilibrium effects are crucial: need spectral transport

See also: Sekiguchi 2015, 2016, and Foucart+ 2015, 2016 **DR**+ in prep

Impact of Equation of State

- Nuclear EOS affects composition and ejecta mass
- Relative abundances are robust

Uncertainties: Ejecta Mass

EOS: SFHo $M = 1.35 M_{\odot}$

Factor of \sim 3 uncertainty in the ejecta mass!

Uncertainties: Composition

- \overline{a} $r \cdot r \cdot \frac{1}{\sigma}$ than the present estimates of Galactic rate (a few 10−5 yrs) is necessary to ex-• Not yet a consensus on the exact composition
- Quantitative differences for nucleosynthesis, opacities

Conclusions

Conclusions

- Postmerger GWs: probing of extreme-density physics
- MHD turbulence effects: what is ℓ_{mix} ?
- More work needed for fully-quantitative nucleosynthetic yield predictions: MHD turbulence, detailed microphysics