Simulations of black hole-neutron star binaries: Influence of the Equation of State

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Motivations

- What are the physical properties of the high-density matter at the core of a neutron star?
  - Different equations of state (EOS) model matter above nuclear density.
    - Variations in their predictions regarding the allowed mass range of neutron stars, the mass-radius relationship,...
  - Can mostly be studied through the behavior of compact astronomical objects.
- Simulations can help in predicting:
  - Impact of the EOS on gravitational waveforms: what will we learn from future detections of BH-NS mergers?
  - Differences in post-merger remnants : accretion disks, and prospects as progenitors of short-hard gamma-ray bursts (SGRB).

Nuclear Equations of State

- Degenerate neutron gas above nuclear density is described by a one-parameter EOS
- Composition and structure of the core of the star is unknown. Existing models include:
  - $ne^- p$ degenerate gas
  - Hyperons
  - Strange quark matter
  - Mesons
- Scarce experimental constraints → difficult to rule out any option.
- Gravitational wave signal from binary neutron stars and BHNS binaries could provide useful additional information.

Numerical results

- Binary neutron stars
  - Existing simulations study the influence of magnetic fields, the NS masses and the EOS.
  - Read et al.: Parametrized EOS used to estimate the accuracy required in gravitational wave measurements to obtain new constraints.
  - Baiotti et al.: Neglecting the thermal part of the EOS affects the evolution of the system (Time before collapse of hypermassive remnant to a BH).
  - Kiuchi et al. : Use EOS based on nuclear theory at $T = 0$ (Akmal-Pandhalipande-Ravenhall), add a thermal term.
- Black hole-neutron stars binaries
  - All simulations : polytropes with $\Gamma = 2$.
  - Stars of different compactness with a nonspinning BH (Shibata et al.):

EOS in SpEC

- First method: EOS divided in a cold part and a thermal part.
- Cold part: polytrope.

$$P_{\rm cold} = \kappa \rho^{\Gamma}$$

$$\epsilon_{\rm cold} = \frac{P_{\rm cold}}{\rho(\Gamma - 1)}$$

- Thermal part:

$$\begin{aligned} \epsilon &= \epsilon_{\rm cold} + \epsilon_{\rm th} \\ P &= P_{\rm cold} + (\Gamma_{\rm th} - 1)\rho\epsilon_{\rm th} \end{aligned}$$

- SpEC can also evolve fluids with more diverse EOS of the form

$$\begin{aligned} \epsilon &= \epsilon(\rho, T, Y_e) \\ P &= P(\rho, T, Y_e) \end{aligned}$$

- Improvements: EOS from nuclear theory, incorporate more microphysics,...

Initial Data: Parameter Space

- Equation of state: for polytropes, only the constant Γ and the compactness $C = \frac{M_{NS}}{R_{NS}}$ (or κ) are freely specifiable.
- BH spin (cf previous talk)
- BH mass, NS mass.
  - When using a polytropic fluid, only the mass ratio is actually relevant.
  - Here: $\frac{M_{BH}}{M_{NS}} = 3$ for all cases.
- Initial separation and velocities
  - Quasi-equilibrium formalism: initial velocities obtained by requiring quasi circular orbits.
  - Initial data remains slightly eccentric
    - Iterative procedure using the first few orbits of the evolution makes it possible to reduce the eccentricity.
  - $d = 10M_{BH}$

Initial Data: Method

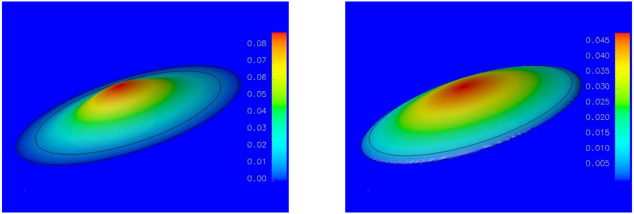
- Extended Conformal Thin Sandwich:

  $$ds^2 = -\alpha^2 dt^2 + \phi^4 \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$$

  Constraints → elliptic equations for ϕ, $\alpha\phi$ and β^i.
- Excised BH: boundary conditions impose that the excision surface is an apparent horizon in quasi-equilibrium, and fix the spin of the BH (Cook and Pfeiffer).
- Quasi-equilibrium configurations: $\partial_t \gamma_{ij} = 0$, $\partial_t K = 0$.
- Hydrostatic equilibrium, irrotational configuration of the fluid → elliptic equation for a velocity potential.
- K and $\gamma_{ij} \sim$ Kerr close to the BH, flat space otherwise (Lovelace et al.).
- The elliptic equations are solved using Spells (Pfeiffer et al.) within an iterative solver driving the system to the desired configuration (Foucart et al.).

Initial Data: Evolved Binaries

Binary	Γ_{EOS}	$\frac{R_{NS}}{M_{NS}}$	S_{BH}
$G2C15S0$	2.0	0.15	0.0
$G2C15S5$	2.0	0.15	0.5
$G275C15S5$	2.75	0.15	0.5
$G275C25S5$	2.75	0.25	0.5



Initial configuration for stars with $\Gamma_{EOS} = 2$ (left) and $\Gamma_{EOS} = 2.75$ (right)

Inspiral and Disruption

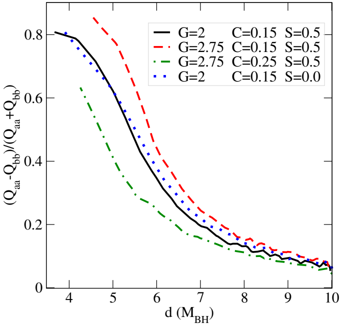
The disruption point is defined by $q = 0.5$, where

$$q = \frac{Q_{aa} - Q_{bb}}{Q_{aa} + Q_{bb}}$$

and the Q_{ij} are the second moments of the density:

$$Q_{ij} = \int \rho x_i x_j dV.$$

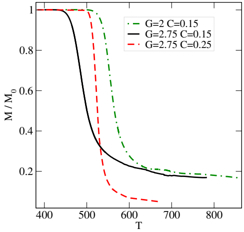
The axes a, b are chosen so that $Q_{ab} = 0$.

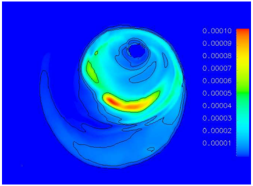


Binary	$\frac{T_{disrupt}}{M_{BH}}$	$\frac{d_{disrupt}}{M_{BH}}$	N_{orbits}
G2C15S0	318	5.4	2.1
G2C15S5	498	5.3	3.2
G275C15S5	420	5.8	2.7
G275C25S5	485	4.7	3.1

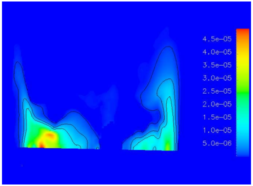
Merger and Disk formation

Binary	$\frac{T_{disrupt}}{M_{BH}}$	$\frac{T_{50\%}}{M_{BH}}$	M_{disk}/M_{NS}	$T_{disk}(MeV)$
$G2C15S5$	498	564	0.15	2
$G275C15S5$	420	497	0.17	2
$G275C25S5$	485	524	0.05	3





Disk formation for the G275C15S5 binary: equatorial plane ($T = 765M$, $R \sim 300km$)



Disk formation for the G275C15S5 binary: transverse plane ($H \sim 100km$)

Summary

- Evolved BH-NS binaries through their late inspiral, disruption, and disk formation phases while varying the BH spin, the star compactness, and the stiffness of the EOS.
- The inspiral rate seems dominated by the effect of the BH spin, with little influence from the actual composition of the star.
- The disruption point varies with the stiffness and the compactness of the star, but doesn't seem to be impacted by the spin of the BH.
- The resulting accretion disk depends mostly on the spin of the BH and the compactness of the star.
- The first two effects will induce different waveforms (rate of change of the wavelength, cut-off frequency), while the third is more relevant to our understanding of SGRB.