Mixed Black Hole - Neutron Star Simulations with Whisky

Roland Haas (Georgia Tech)
Center for Relativistic Astrophysics

Collaborators: Tanja Bode, Jim Healy, Pablo Laguna, Deirdre Shoemaker

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Initial Data

York-Lichnerowicz initial data

- transverse-traceless, conformally flat decomposition of the three-metric
- time-symmetric initial data requires only a solution for the conformal factor ψ

$$\partial^i \partial_i \psi + \frac{1}{8}\psi^5 K_{ij} K^{ij} = -2\pi\psi^{-3}\tilde{E} \qquad \tilde{E} = \psi^8 n^\alpha n^\beta T_{\alpha\beta}$$

- non time-symmetric initial data adds three coupled equations for the extrinsic curvature [York, Baumgarte & Shapiro]

$$\partial^j \partial_j W^i + \frac{1}{3}\partial^i \left(\partial_j W^j\right) = 8\pi\tilde{\jmath}^i \qquad \tilde{\jmath}^a = -\psi^{10}\gamma^{ab} n^c T_{bc}$$

Initial Data

TwoPunctures

- spectral accuracy for vacuum initial data
- used by many groups today to generate initial data for vacuum simulations
- modular design which can be extended relatively easily

TwoPunctures + Matter

- spectral accuracy is lost due to non-analytical source term on the right-hand side
- difficult to put black hole inside of non-vacuum region
- no iteration on the matter configuration

MayaKranc + Carpet + Whisky

- high resolution, general relativistic, shock capturing
- Valencia formulation of hydrodynamics
- reconstruction – recovery type of evolution
- atmosphere treatment somewhat ad-hoc
- mesh refinement is vertex centered, quantities are cell centered
- BSSN moving puncture recipe for gravity

each of the last three can cause problems during the evolution, which usually manifest as NaNs in the the hydro variables

Whisky Basics

Valencia formulation of hydrodynamics (Ibanez et. al.)

- First order flux-conservative formulation.

$$\frac{\partial D}{\partial t} + \frac{\partial}{\partial x^i}\left[D\left(\alpha v^i - \beta^i\right)\right] = s$$

- Conservative: $D = \sqrt{\gamma} W \rho$, primitive: ρ, v^j.
- Low density "atmosphere" in the vacuum region.

Stumbling stones

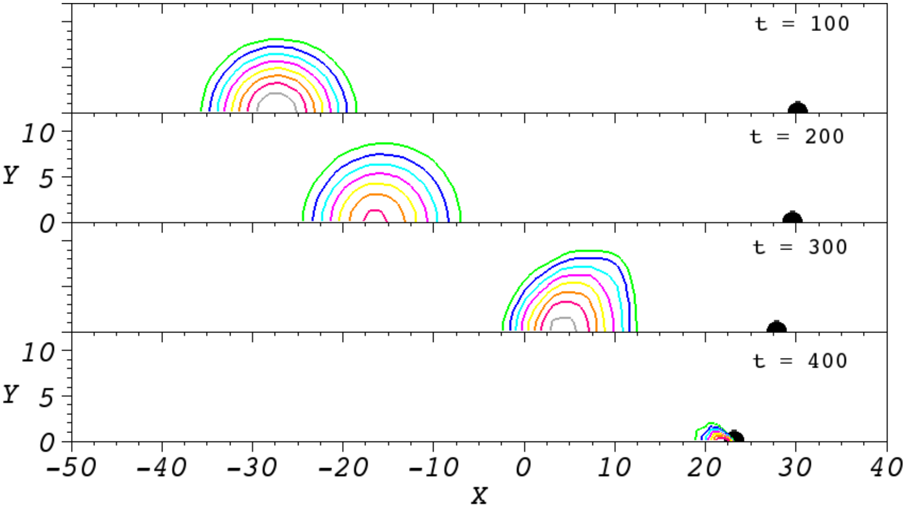
- reconstruction operates on the primitive variables, assuming a smooth metric
- prolongation after regridding can lead to unphysical primitive variables
- prolongation in atmosphere treatment can lead to unphysical variables
- finite volume integration assumes smooth background metric

Test case: head on collision

- black hole and neutron star start from rest
- black hole considerably more compact than its companion
- initial data provided by TwoPunctures + TOVSolverC
- octant symmetry increases speed
- generally slow dynamics
- purely polytropic EOS used during the evolution
- static grid setup

was first calculated by Löffler et. al. in 2007

Head on collision: density contours



Head on collision: observations

- unmodified Whisky produces NaNs near the black hole singularity
- use trick of Faber et. al. [arXiv:0708.2436] inside the apparent horizon
  - limit τ from below to ensure positive enthalpy

$$h = (1 + \epsilon + P/\rho) \tag{1}$$

  - limit $|S^2|$ to ensure that

$$|v^2| < c^2 \tag{2}$$

- after each MoL substep, sweep grid for $\tau < 0$ or $D < 0$ and flag as invalid (set atmosphere bitmask)
- with Faber trick evolution succeeds to merger and ringdown

Black Hole – Neutron Star Binaries

- black hole and neutron star orbit each other
- black hole and neutron star have about the same extent
- polytype EOS used for initial data, Γ-law ideal gas EOS used during evolution
- high velocities present in the matter system $|v| \geq 0.9c$
- moving meshes

BHNS: observations

- pure polytype evolution succeeds to merger and ringdown
- using the Ideal Gas EOS fails
- failures concentrated in region around puncture, mesh refinement, inter processor and symmetry boundaries
- there is a certain minimum resolution needed for runs to succeed
- need to limit the speeds during reconstruction

Future

- find parameters required to evolve an ideal gas in the presence of a puncture singularity
- clean up recipe and make results public
- possibly modify reconstruction to take constraints into account
- physically motivated initial data, thin-sandwich formalism