Generating Initial Data for Binary Neutron Stars using Lorene

Josh Faber, Tanmayee Gupte, Grace Fiacco (RIT)
Trung Ha (UofR)

Initial Data Generation

The conformal Thin-sandwich formalism, combined with an assumption of a helical Killing vector, is the dominant approach used by initial data codes

- Field solutions reduce to elliptic equations -- this is the “easy part”
- Matter fields are described by an enthalpy equation, and the NS surface by an isenthalpic contour
- The NS surface introduces non-smooth behavior -- spectral methods solvers need to apply a domain boundary there to avoid Gibbs phenomenon errors
- The velocity field can be derived using a potential-based approach that depends on the spin -- the most well-studied cases are irrotational or corotating

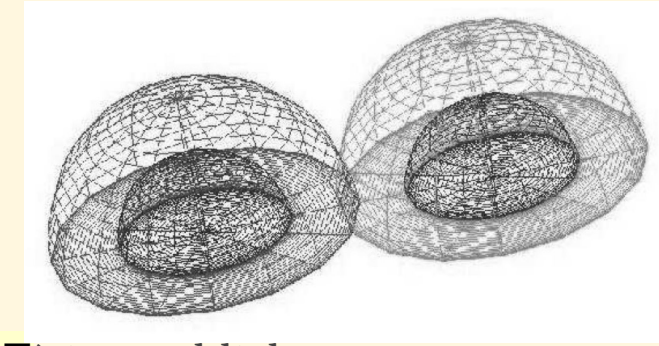
Initial Data Formalism Challenges

There are at least two current problems with widely used implementations of initial data formalisms, and one that is not such a challenge

- There are some formalisms to describe arbitrary spins (e.g. Baumgarte et al. 2009), but these have NOT been widely implemented. Depending on the magnitude of the non-irrotational spin, perturbative methods might be acceptable?
- Magnetic fields have not been widely implemented in initial data formalisms, but this shouldn't be impossible if a rule can be derived for Tmunu as a function of local parameters for a specified configuration

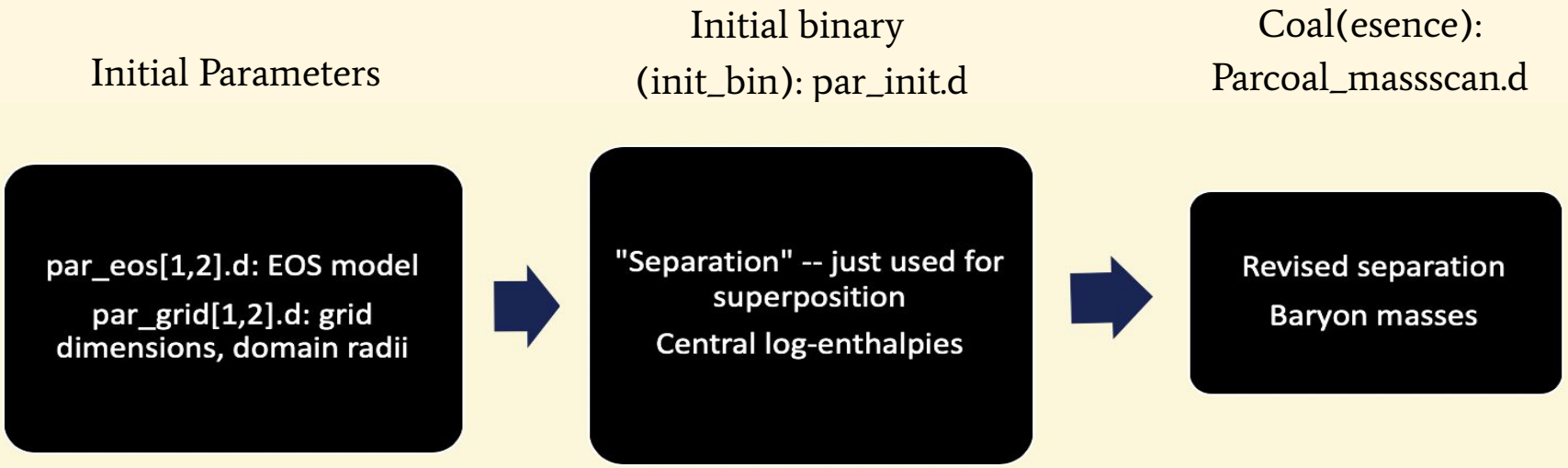
EOS models for just about any pressure as a function of density can basically be implemented without much complication.

Lorene - How it Works



- Lorene (**L**angage **O**bjet pour la **RE**lativité **N**umériqu**E**) is a publicly available multidomain spectral methods code that can solve elliptic equations and generate quasi-equilibrium binary configururations in GR
- Allows placement of quasi-equilibrium ellipsoidal surface at boundary of neutron star to minimize Gibbs errors -- this is critical to generating good initial data
- The code actually “splits” all fields into a component centered on each star; this minimizes errors from the stellar surfaces (or if the companion is a BH), but does not eliminate them
- LORENE does not handle cusps well near the tidal limit -- spectral methods codes assume smooth functions!

Launching a Run on Lorene



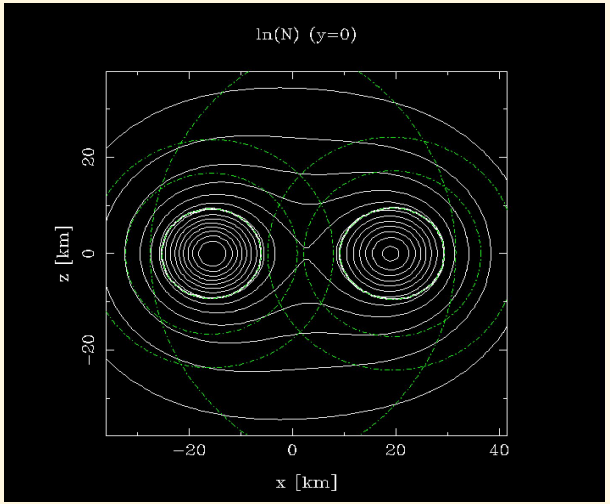
The current 2-step approach DOES assume implicit knowledge of a sequence of isolated NS models for a given EOS, e.g., relationship between central enthalpy and baryon mass

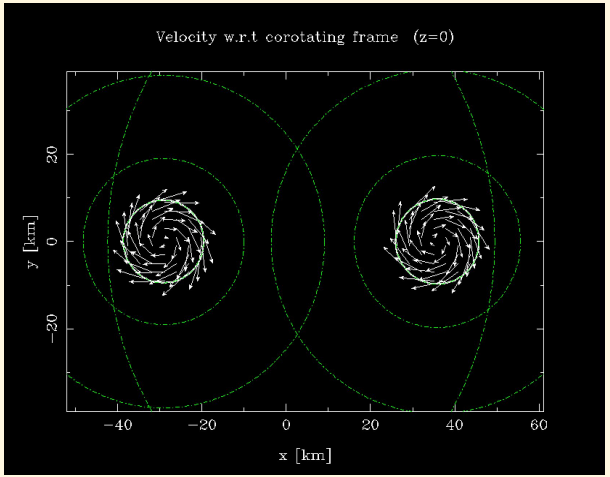
Grid sizes are not arbitrary; there are FFT-like conditions on certain parameters

Lorene Configurations and Uses

Notes

- Green: domain boundaries -- both sets of domains fill all of space, in order to calculate each field in split fashion
    - This means the “other” set of domains sees the NS star surface, and there will be some unavoidable Gibbs phenomenon errors
- White: isocontours of global system -- the “cuspier” the surface, the more one encounters high-frequency noise



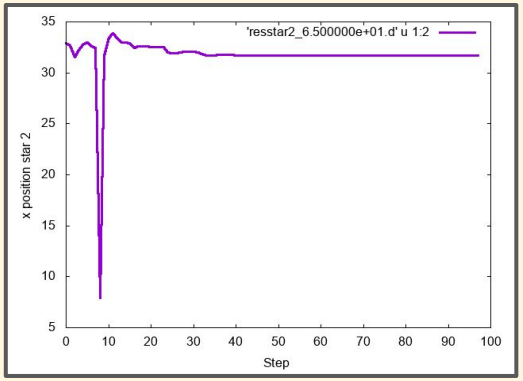


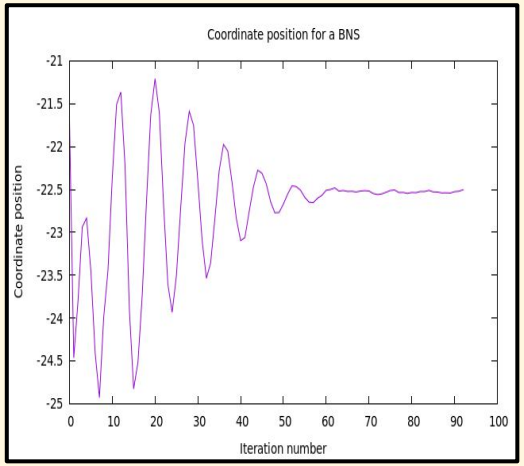
Modifications

- Complicated relaxation scheme (~6 different relaxation parameters for different field components) has multiple failure modes. The safest parameter choices are
  - Lower-mass NS
  - Well-separated configurations, but not TOO separated -- resolution is coarsest in the outermost domains

- The current routine to locate the rotation axis relies on an unstable secant method implementation; numerical fixes for the function whose zero we want to find are necessary

- This has historically been a barrier to generating mass ratios far from unity



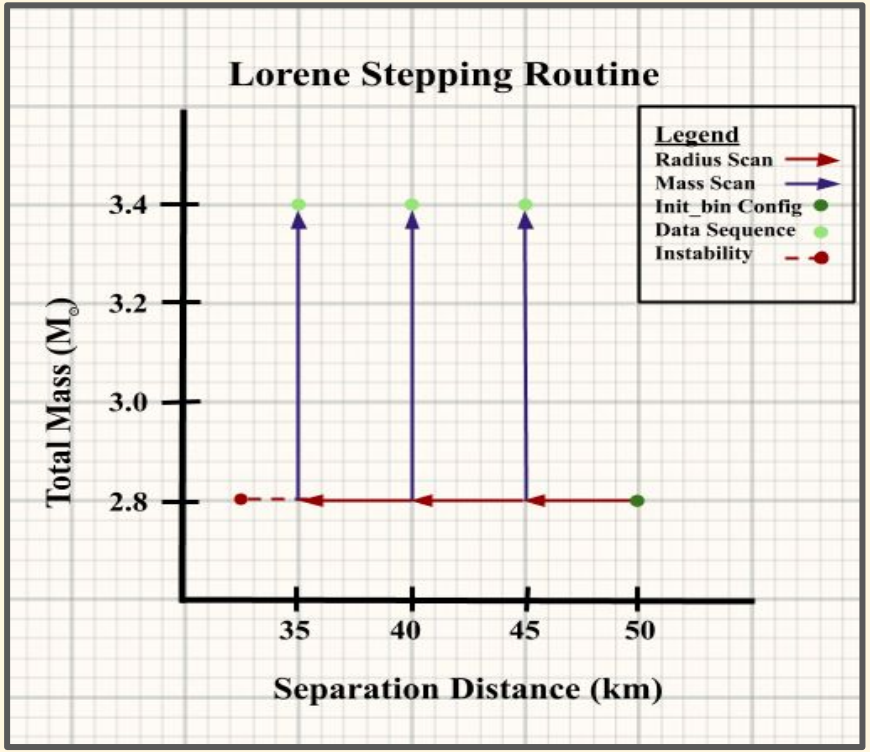


Computing High Mass Binaries - Lorene Stepping Routine

- LORENE's relaxation scheme makes it difficult to relax configurations extremely slowly -- different effects come in at different timesteps, certain quantities are re-computed from scratch, etc. -- and it is best to assume things will end up "underdamped"

- It is helpful to view a sequence through a "time-evolving" lens, even though nothing is "evolving" as we relax towards quasi-equilibrium; thus, "mass loss" instabilities are a problem during relaxation

- The most stable results begin from low mass configurations, moving inwards to the desired radius, and then slowly increasing the target mass of the binary

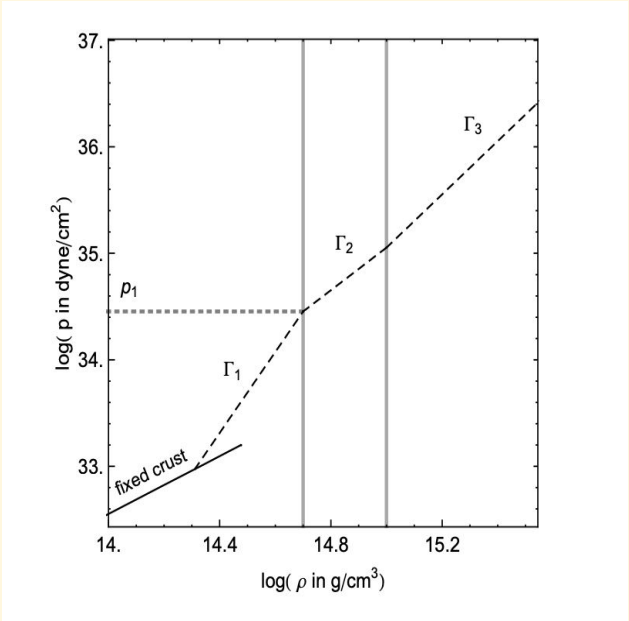


Equations of State

- Polytropic EOS: $P = k\rho^{\gamma}$
- Piecewise polytropic EOS: Using 4 segments of polytropes

$$P = K_i \rho^{\Gamma_i} \ (\text{for } \rho_i \leq \rho < \rho_{i+1}, 0 \leq i \leq 3)$$

- Piecewise polytope is parametrized using adiabatic indices and the pressure at the first dividing density (rho_1 = 10^14.7; rho_2 = 10^15)
- The low density region is typically not resolved.
- High density behavior can be captured using the parameters.



Log of density vs pressure for piecewise polytrope

Initial Data Library

- Covers different piecewise polytropic approximants to physically motivated equations of state
  - Sly, AP3, AP4, WFF1, MPA1, MS1, MS1b
- Covers different mass ratios (with masses 2.0, 1.8, 1.6 and 1.4 $M_\odot$)
  - 1, 1.14, 1.28, 1.428
- Covers different separations starting from 50km and decreasing by 5km till 30km (until stability limit is reached)
- Tabulated EOS: Built-in Lorene module present to calculate tabulated EOS: Sly4, AkmalPR, FPS, etc.
  - Table format: baryon density, total energy density and pressure (in CGS units) -- simpler than the multi-temperature/Y_e format from stellarcollapse.org

Launching a Dynamical Simulation

- You will need:
  - resu_%.d file from the Lorene run
  - Compile Einstein Toolkit using the thorns written by Parma University or West Virginia University
    - http://www.fis.unipr.it/gravity/Research/BNS2016.html and http://astro.phys.wvu.edu/zetienne/ILGRMHD/index.html
    - Both have piecewise polytropic compatibility
- Modify the parameter file to include:
  - resu_%.d file
  - Gamma and rho values specific to EOS of choice
    - https://arxiv.org/pdf/0812.2163.pdf
- AHFinderDirect parameters for finding black holes, as indicated
    - Find_after_individual_time = 500
    - Reset_horizon_after_not_finding = yes

Movies (made with ILLinois GRMHD code)

EOS: Sly, distance between stars= 32.5km

Masses: 1.4 $M_\odot$ each

EOS: Sly, distance between stars= 37.5km,
Masses: 1.4 $M_\odot$ and 1.8 $M_\odot$

Black hole formed at 656.827