Simulating Pulsar Magnetospheres Using Magnetohydrodynamics

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ABSTRACT: Pulsars are rotating neutron stars with periodic bursts of radio emission. These enigmatic objects allow us to peer into matter and electromagnetic fields at their most extreme. In this project, we seek to study the evolution of a pulsar's magnetosphere. We use PLUTO, an astrophysical fluid dynamics code, to perform magnetohydrodynamics (MHD) simulations. As a first step, we reproduce the works of other authors simulating a stable hydrodynamical disk. We then aim to study the evolution of accretion disk morphologies around neutron stars with the introduction of magnetic fields. Our work focuses on accretion characteristics, such as quasi-periodic oscillations, which are not yet well-understood, but thought to be a result of unstable equatorial flows known as "tongues."

Background Information

Pulsars

- End of a supermassive (10–25 M☉) star's life
  - Gravitational force overwhelms core
  - Collapses and goes supernova
  - Protons and electrons merge into neutrons
    - Remnant known as neutron star
- Pulsars
  - Rapidly spinning neutron stars
    - Conservation of angular momentum
  - Relativistic jet present
    - Magnetic axis not aligned with rotation axis
      - Gives characteristic photometric signature - "pulse"

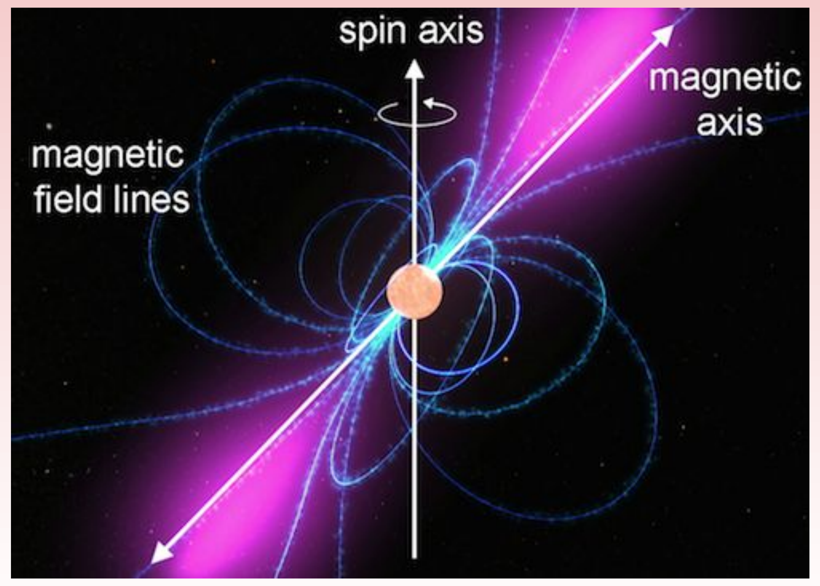


Fig I: Artist rendition of pulsar with labeled axes.

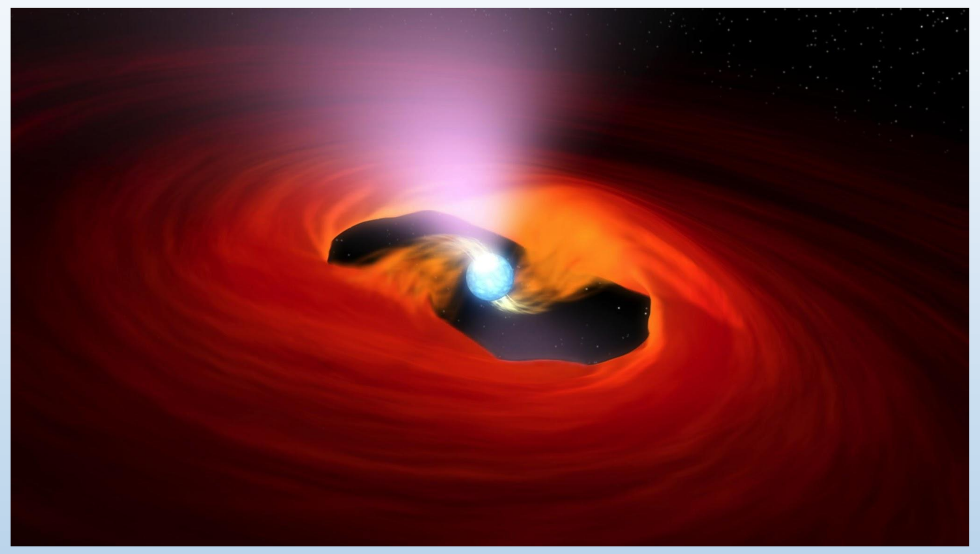


Fig II: Artist rendition of accretion disk.

Accretion Disk

- Disk of rotating diffuse matter
- Accretion Stability
  - Stable
    - Funnels
      - Follows along magnetosphere
      - Deposits material to magnetic poles
  - Unstable
    - Tongues
      - Pierces magnetosphere
      - Deposits material along equator

Computational Method

PLUTO Code

- Solves conservation laws
- Simulates fluid dynamics in astrophysical systems
- MHD module utilized
  - Considers
    - Mass density
    - Pressure
    - Velocities
    - Magnetic Fields
- Assumes Ionized conducting plasma

Simulation

- Two regions:
  - Sphere
    - Strong dipolar magnetic field
    - Rapidly rotating
    - Dense
  - Disk
    - Rotating
    - Diffuse
    - Viscous

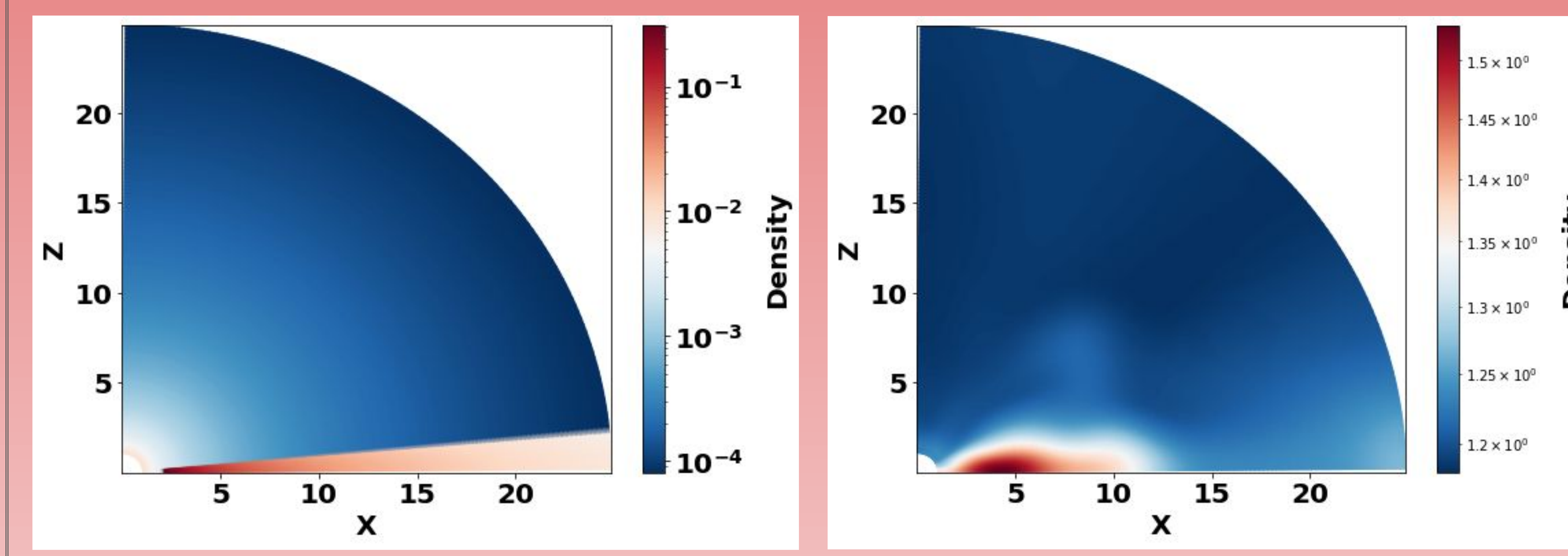


Fig III: Initial distribution of disk (left) vs after thirty rotations (right).

Hydrodynamic Case

- Produces stable accretion after long runtime
  - tstop ≈ 10,000 rotation periods
- Successfully replicates a Keplerian profile

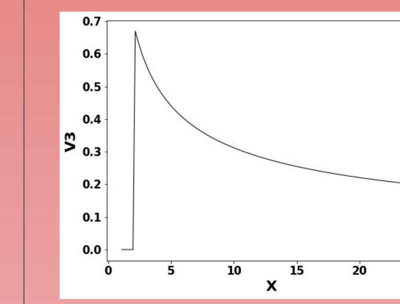
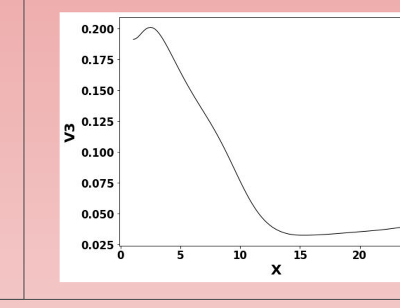


Fig IV: Vphi profile initially vs after thirty rotations (below).



Magnetohydrodynamic Case

- Introduce a dipolar magnetic field to the star
  - System becomes highly unstable
  - Vary the magnitude of the strength of this field
    - Disk center of mass appears to radially displace further more rapidly as field strength increases
      - Makes sense since the field strength approaching zero should converge to the purely hydrodynamic case
    - Tongues observed in all cases
  - Magnetic field lines observed breaking and reconnecting

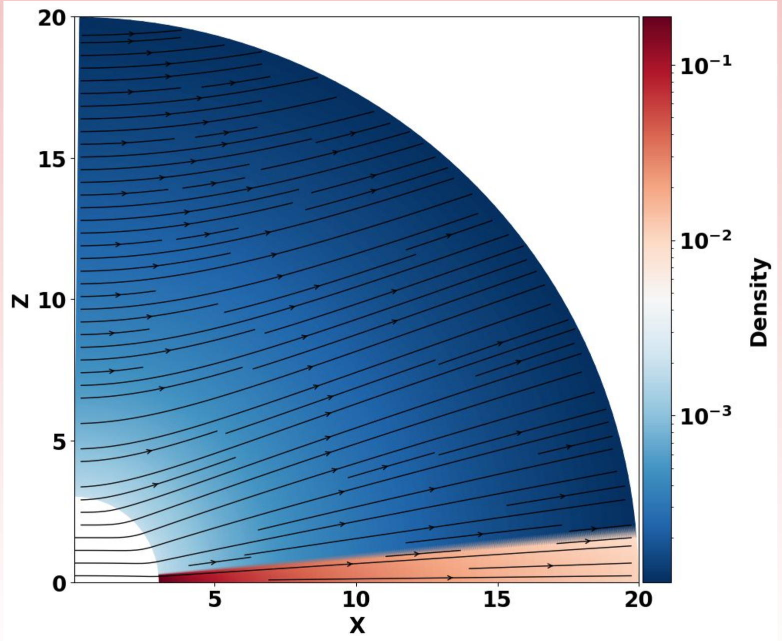


Fig V: Initial distribution of disk.

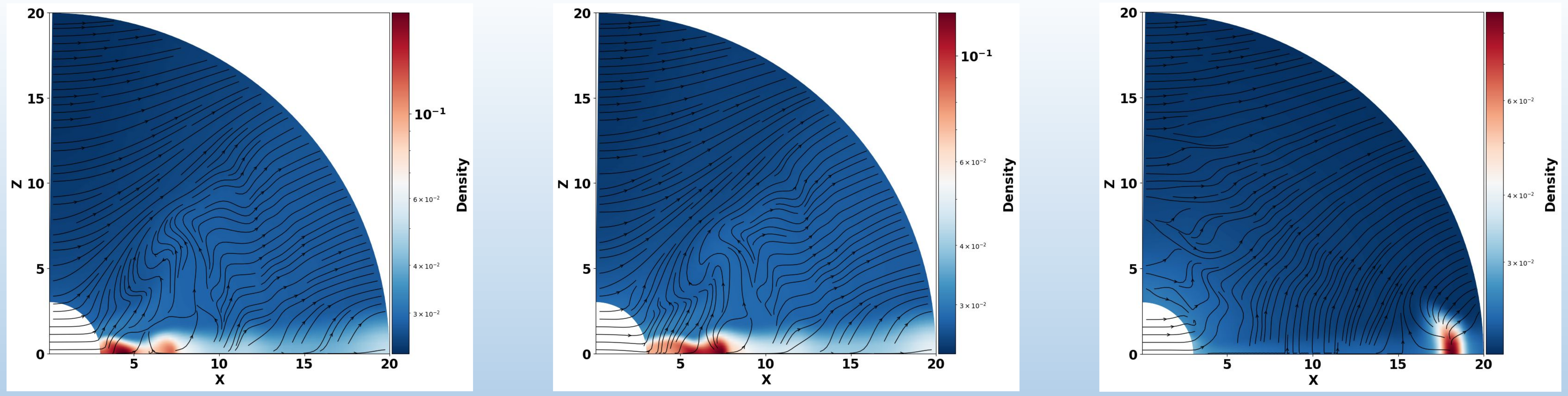


Fig VI: Distribution after three hundred rotations at field strengths B=0.01 (left), 0.1 (center), and 1.0 (right).

Results & Future Work

- Accomplishments
  - Hydrodynamic
    - We have successfully produced a stable accretion disk, inspiring confidence in the accuracy of the code.
    - We have successfully incorporated viscosity into the disk.
  - Magnetohydrodynamic
    - We have included an evolving dipolar magnetic field of the star.
      - The morphology of the disk depends strongly on the field strength.
- Things to Come
  - We wish to add a roughly monopolar magnetic field to the disk.
    - We may observe the interplay of the fields.
  - There may exist a method to convert our data to light curves in order to observe quasi-periodic oscillations.

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