Mass Ejecta and Magnetic Winding in a Highly Magnetized, Hypermassive Neutron Star

Mentee: Carlin Will
Mentor: Patrick Cheong
Network for Neutrinos, Nuclear Astrophysics, and Symmetries

N3AS PHYSICS FRONTIER CENTER

NSF Physics Frontier Award number 2020275

Abstract

We model 3 permutations of a highly magnetized, hypermassive neutron star with varying initial angular speeds: C3, C4, and C5 (increasing). We compare the mass ejecta and effects of magnetic winding between each of the models. We find that higher initial angular speeds eject more mass, but there is a more complicated relationship with angular speed and magnetic field strength, which we must further investigate.

Introduction

A hypermassive neutron star is an unstable fusion of two neutron stars. The object may expel mass via jets or other forms of ejecta. The star will then evolve into either a black hole or a black hole with an accretion disk, depending on the behavior of its mass expulsion. By studying how a hypermassive neutron star loses mass, we can anticipate observables like kilonovae (a transient event which may emit gamma ray bursts and electromagnetic radiation), and whether its byproduct is a black hole with or without an accretion disk.

Our simulations consider a highly magnetized internal environment which can cause a magnetic winding effect (entanglement with other magnetic field lines). Magnetic winding transports angular momentum, affecting the behavior of ejected mass and the ultimate fate of the star.

Methods

We use gmunu, a magnetohydrodynamical code written in fortran, to simulate a hypermassive neutron star for 1 second. We model 3 speeds, labeled C3, C4, and C5 in order from slowest to fastest. We extract the square of the toroidal magnetic energy to approximate the behavior of the magnetic field.

Then, we plot the angular velocity profile (radially outward) at 4 different times.

To visualize the 2D slices of density and Toroidal magnetic field in and around the star, we use the yt package.

Current Progress

Below, I have plotted a 2D density slice of the C5 (fastest spinning) star. Then, I plot the radial profile of its angular velocity at 4 different times.

Figure 1: Below are 2D slices of the density (left) and Toroidal B-frield squared (right).

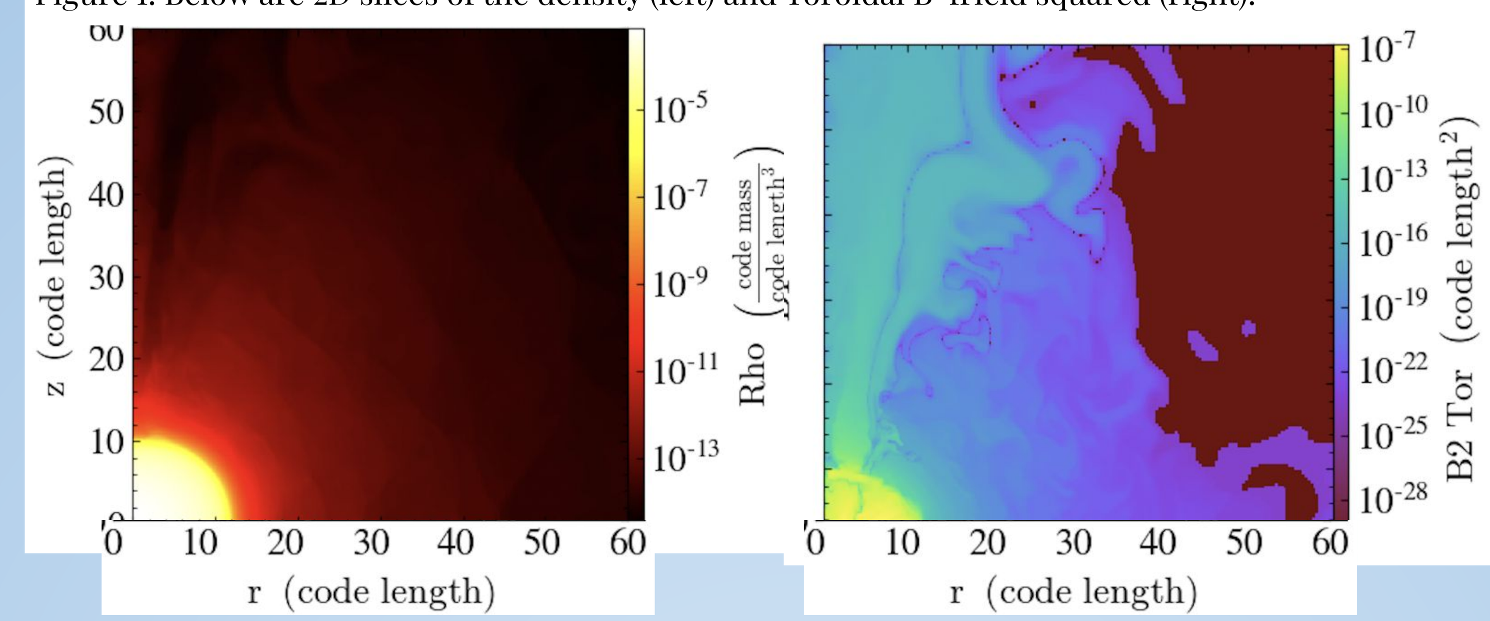
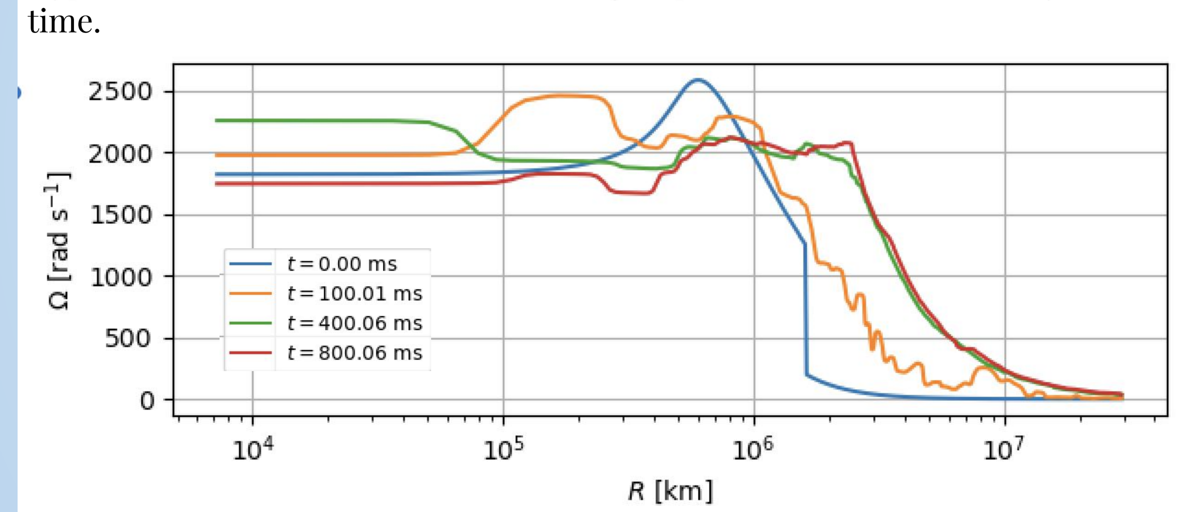


Figure 2: This is the radial profile of the angular velocity plot for the C5 Hypermassive neutron star. The motion gets pushed out farther radially over time.



In plot 3, I plot the mass ejected from the star over time in each C3, C4, and C5. Finally, plot 4 shows the magnetic field strength over time of each C3, C4, and C5, estimated by square rooting the average toroidal magnetic energy.

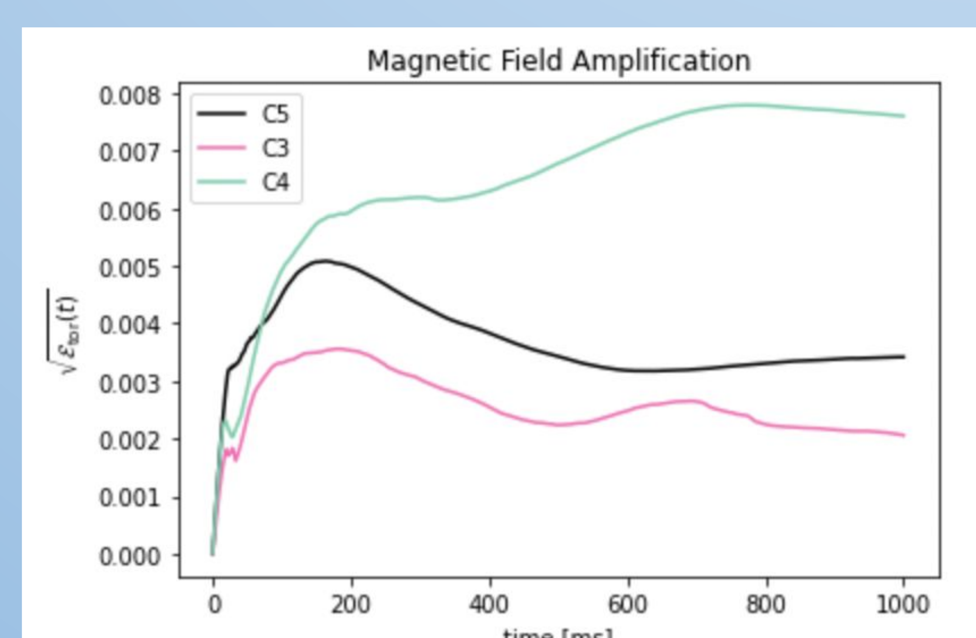


Figure 3: Here, the magnetic field of C3, C4, and C5 evolve over time. While C3 and C5 are similarly bounded, C4 seems to increase twice to a stronger magnetic field. We did not expect this result for C4, and plan to do an investigation into possible numerical issues or a more complicated relationship between kinetic energy and magnetic energy than we hypothesized.

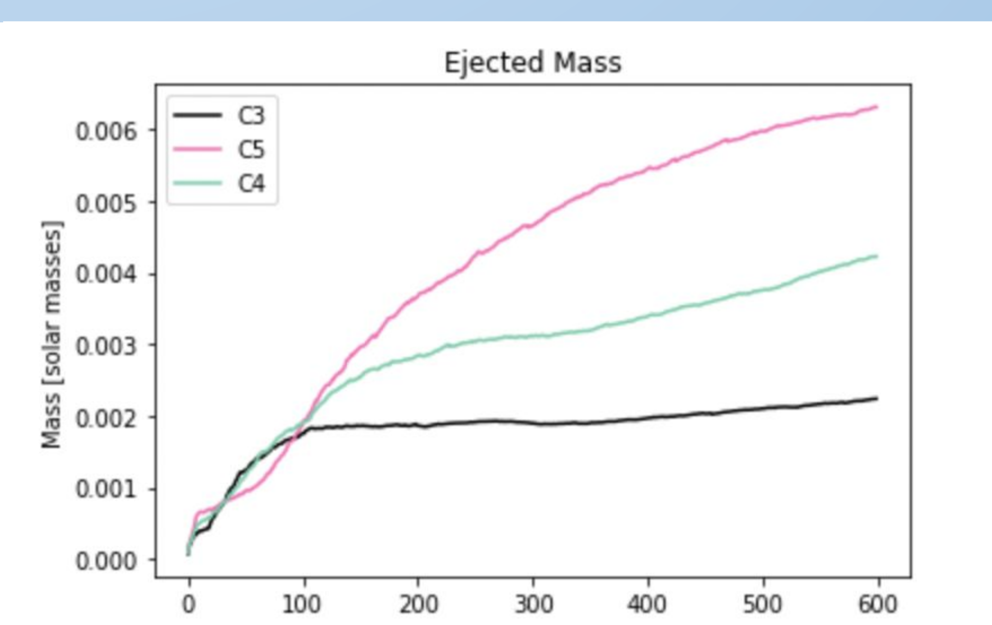


Figure 4: The mass ejected of C3, C4, and C5 are plotted over time. The amount of mass ejected increases with the speed level 3, 4 and 5. This makes sense, because the angular momentum of the star is greater, thus more matter has velocity high enough to escape the gravitational pull of the star.

Conclusion

The angular velocity plot for C5 shows that as time goes on, the matter further away from the star gets faster. We found similar results for C3 and C4.

In our models, the faster-spinning stars eject more mass overall. This is due to the angular momentum on the outside of the star (as implied from angular velocity), which mobilizes matter to escape the gravitational pull of the star.

We found that magnetic field amplification grows between C3 to C5, but C4 has a stronger magnetic field than C5. This is unexpected, and it may be a numerical error in our code. If not, it could imply that the winding affect of transporting angular momentum is not direct, and other factors may constrain or feed the angular momentum (like heat).

Future Plans

In the future, we plan to explore the effects of varying magnetic field strengths upon the star's topology. Then, we will incrementally modify the resistivity of the plasma, which we hypothesize will more accurately constrain matter loss and amplify the magnetic winding. We will investigate how magnetic field amplification and mass ejection compete versus mutually intensify. Finally, we may explore the 3D simulations of our project because they uphold greater physical symmetry.

Acknowledgements

I would like to thank my mentor Patrick Cheong for developing the gmunu code and teaching me detailed background astrophysics for our project. I would also like to thank the N3AS program for funding my research and giving me opportunities to share science in this community.

References

This research was support by NSF Physics Frontier Center Award # **2020275.**