Magnetic Fields (Magnetohydrodynamics) in Binary Black Hole Systems

Fox Hamann, Kaleb Crouch, Jess Thiara, Yuri Macaspac, Abdullah Alshaffi, Taeho Ryu
University of Colorado Boulder – Fund of Scientific Inquiry

Introduction

Magnetohydrodynamics (MHD) is the study of the dynamics of electrically conducting fluids. In astrophysics, MHD is often used to study plasmas such as solar winds. For our purposes, we have used MHD to model the magnetic fields of orbiting black holes, using the accretion disks as the electrically conducting fluid in the system. However, binary black holes introduces additional complexity, making the evolution of magnetic fields of plasma in those given environments more challenging to model compared to a single black hole. By exploring these dynamics, our research aims to clarify how accreting plasma and magnetic fields behave within binary black hole systems and contribute to a deeper understanding of these environments.

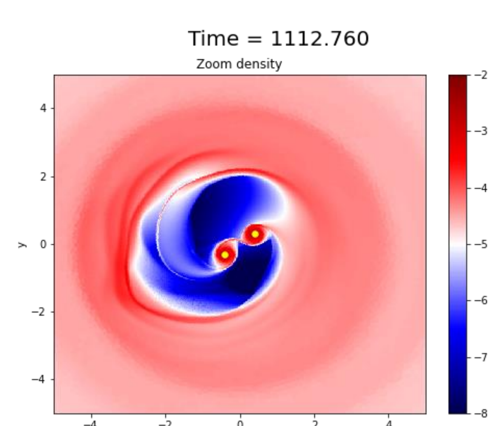


Fig 1.1

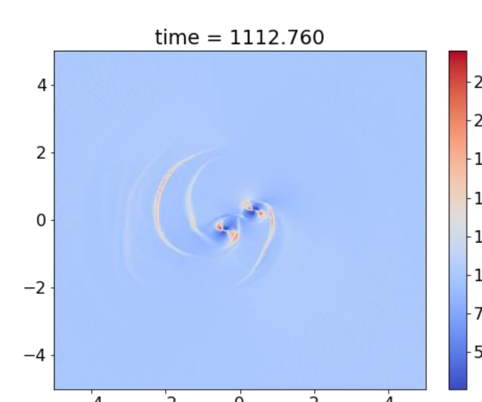


Fig 2.1

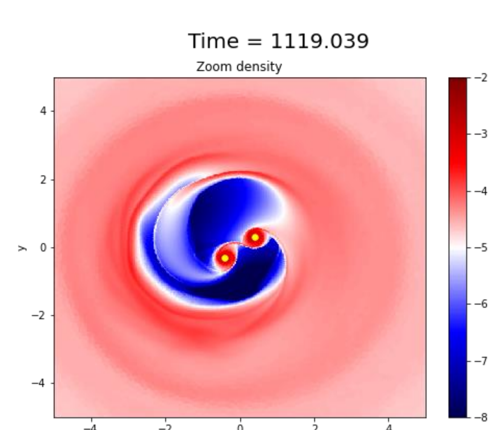


Fig 1.2

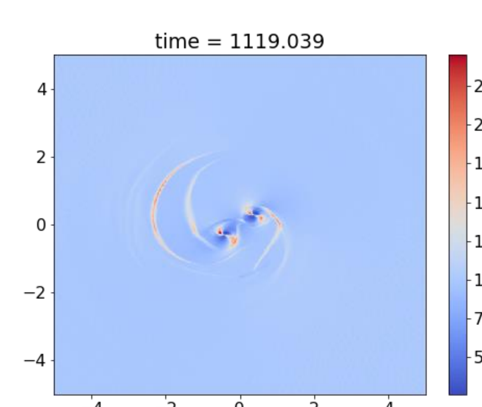


Fig 2.2

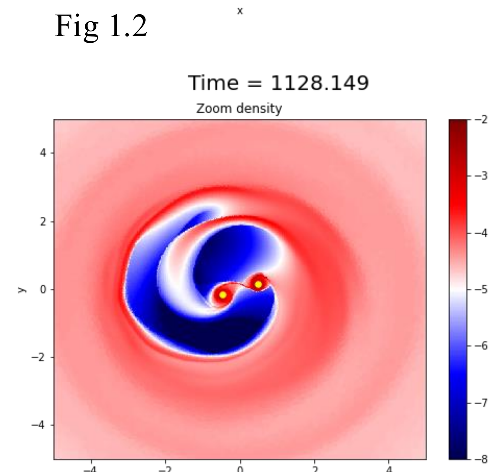


Fig 1.3

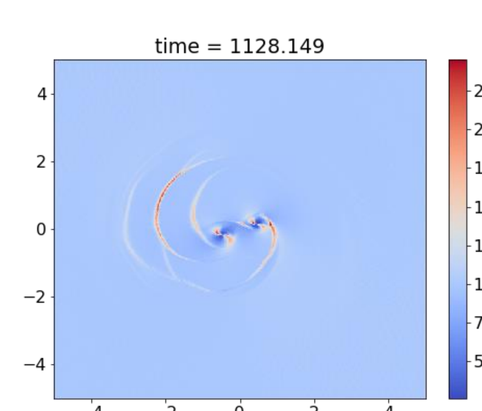
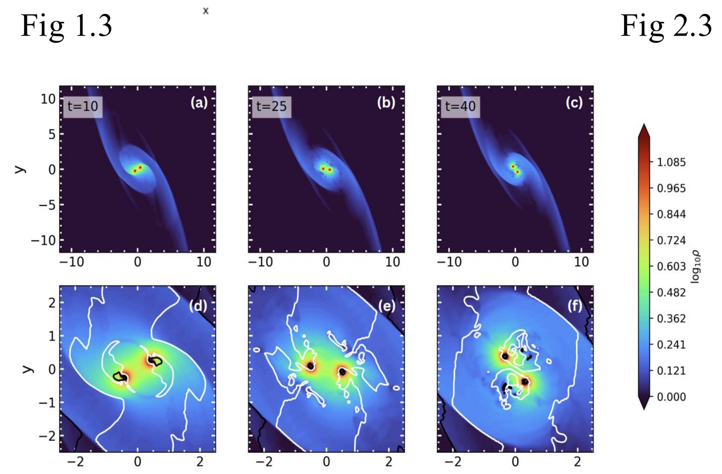


Fig 2.3



Joshi, Raj Kishor, Aryan Bhake, Biswajit Banerjee, et al. "Binary Black Holes in Magnetized AGN Disks." *Astronomy & Astrophysics* 703 (November 2025): A304. https://doi.org/10.1051/0004-6361/202555874.

Joshi et al., "Binary Black Holes in Magnetized AGN Disks."

Methodology

1D Shock Tube Test

- Obtain hydrodynamic and magnetic field data for this problem
- Separately evolve a magnetic field with the Lax-Friedrichs method.
- Compare evolved magnetic field to the actual magnetic field of the shock tube simulation

3D Binary System Data

- Obtain hydrodynamic quantities of a 3D circumbinary simulation
- Evolve magnetic field using the same method used in the shock tube simulation.
- Choose a hydrodynamic quantity
- Observe the effect of chosen hydrodynamic quantity on the behavior of the magnetic field.

$$\frac{\partial B}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B})$$

The Induction Equation relates the change, with respect to time, of the magnetic field with the velocity of an electrically conducting fluid.

$$B_i^{n+1} = \frac{1}{2}(B_{i+1}^n + B_{i-1}^n) - \frac{\Delta t}{2\Delta x}\left(f(B_{i-1}^n) - f(B_{i+1}^n)\right)$$

The Lax-Friedrichs method averages the position of neighboring quantities and updating it by finding the differences of their flux.

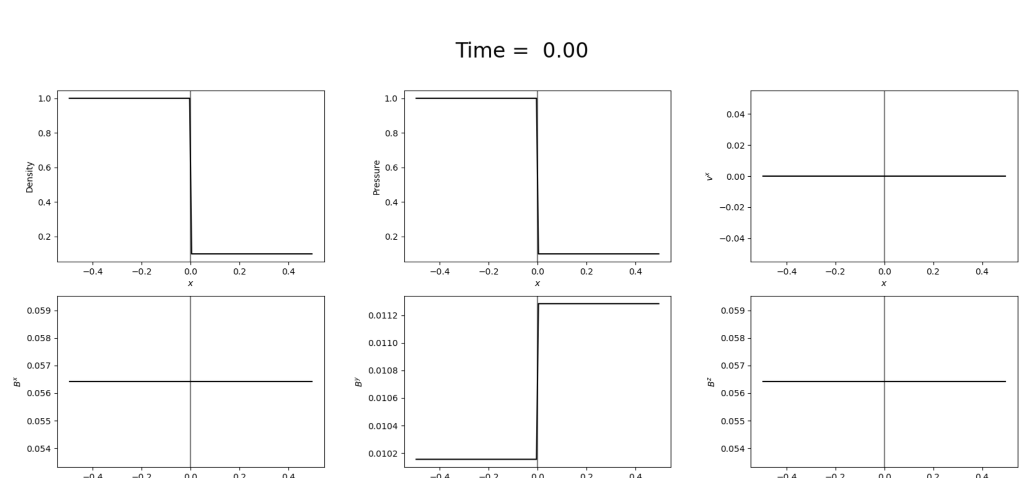


Fig 3.1

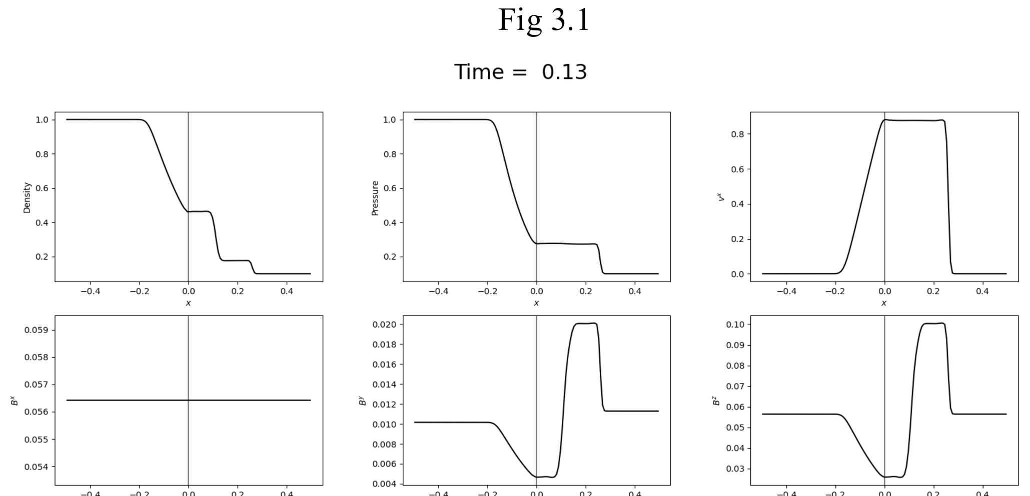


Fig 3.2

Results

Results for the 1D Shock Tube Test are shown in Fig. 3.1-3.2 at the initial time 0.00 and a later time 0.13. We used this test to confirm that the code for evolving magnetic fields would be accurate.

Results for the evolved magnetic field of the black holes are shown in Fig. 2.1-2.3, measured in units of gauss. In this data, we see that there is a kind of tidal wake occurring in the same regions where tidal wake occurs in the density graphs given in Fig. 1.1-1.3.

Our approximation becomes incorrect when the pressure from the magnetic field exceeds the pressure from the shear velocity of the disk; data is taken in a time interval before this occurs.

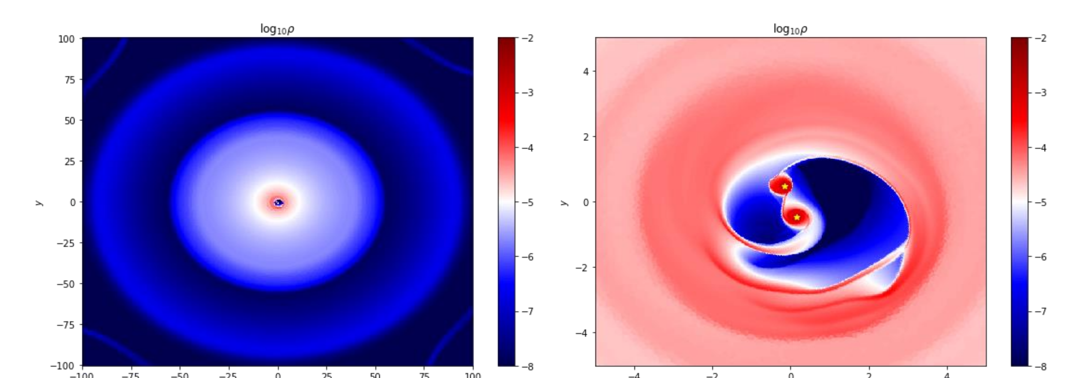


Fig 4.1 – Density zoomed out (left) and zoomed in (right)

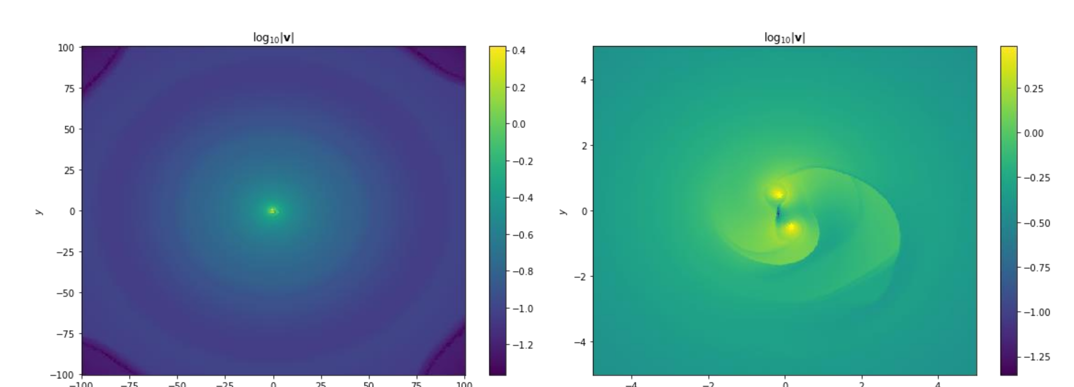


Fig 4.2 – Velocity zoomed out (left) and zoomed in (right)

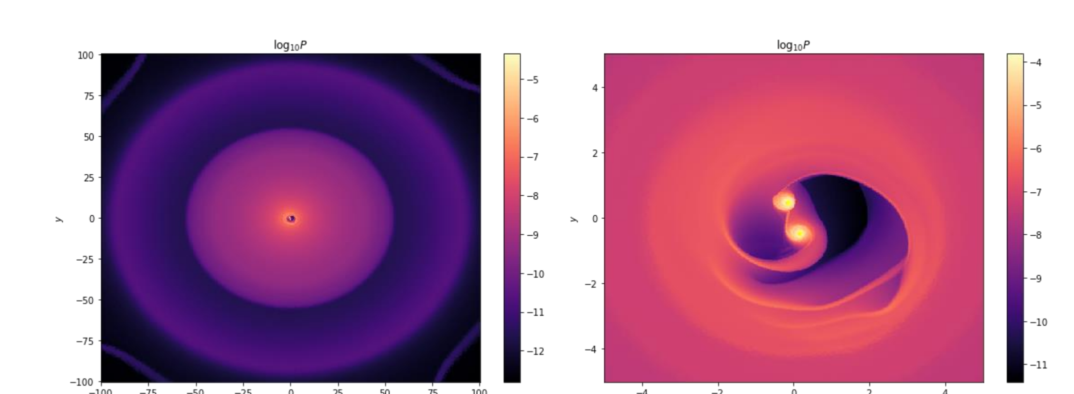


Fig 4.3 – Pressure zoomed out (left) and zoomed in (right)

Conclusion

From the approximation and the resulting model of the magnetic field, we can find overlaps between different types of data relating to the orbiting black holes. We have already discussed the relation of the pressure and the magnetic field in the results section by looking at where tidal wakes are occurring. Although it will also be important to look at similarities between the magnetic field and the velocity or pressure of the black hole, whose graphs are also given. Moving into the future, research on MHD of black holes can be studied more closely through similar methods. In this study, we used an idealized system of black holes that orbit continuously and never collide. A more realistic study may look at non-idealized systems, considering the gravitational forces at play and the unusual orbits or even the collision of black holes. For future studies, it is also important to account for parts of this research that have caused errors. Firstly, we must keep in mind that the data we have evolved for the magnetic field is only an approximation. The model also provides a magnetic field, which is theoretically too strong; this was done in this specific study so that the results in the graph would be visible. Otherwise, the magnetic field is not typically supposed to exceed ~18 gauss.

Acknowledgements

We would like to extend special thanks to several individuals and contributors to our project. Firstly, graduate students Maggie Huber and Jack Farrell for running the PHYS1400 course, allowing us to pursue undergraduate research in the first place. Next, we thank Professor Taeho Ryu. Dr. Ryu provided our group with data on density, pressure, and velocity fields of a stable black hole orbiting system and took an interest in following along and receiving updates about our progress. And our final thanks go to Abdullah Alshaffi, our graduate student mentor, who helped with much of the heavy lifting where it needed to be done and really made this project possible.