Magnetic Energy Transfer in Kerr Black Holes

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Abstract

In this study, we examine the strongly magnetized toroidal magnetic accretion disk, where the pressure exerted by the structured toroidal magnetic field supersedes other pressures. The significance of this research lies in its objective to scrutinize the strength of the magnetic field surrounding a black hole undergoing toroidal accretion, as a function of spin. This subject matter holds substantial importance in Astrophysics, as varying the magnetic field and the spin of a black hole can provide insights into mass-ejecta observations and enhance our understanding of black the radiative efficiency of mass-to-energy conversion which is beyond the scope of this project.

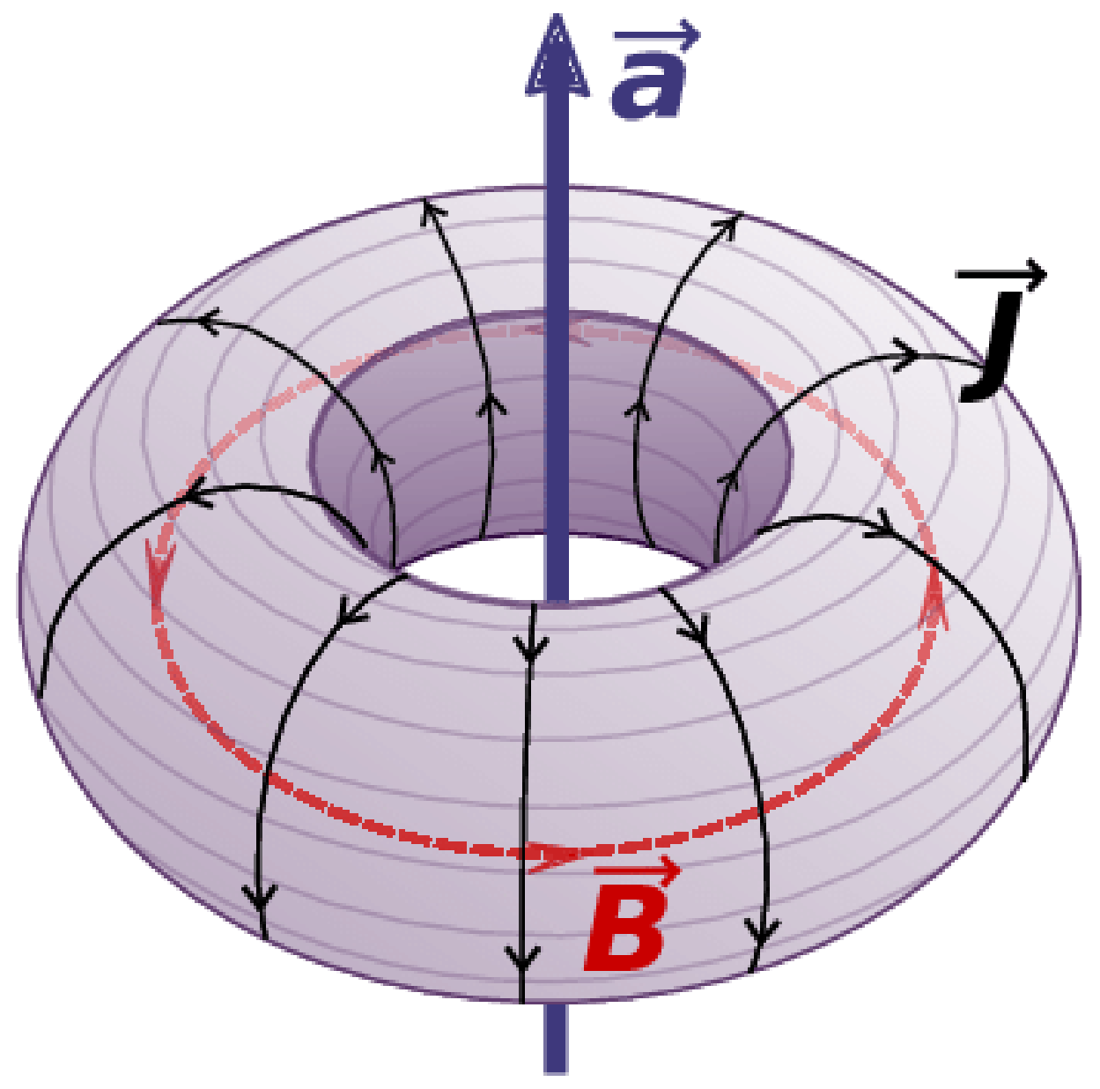


Figure 1. Toroidal Diagram

By using Athena ++, we gathered data of a high resolution simulation of the Toroidal General Relativistic Accretion Disk.

Background

The magnetic field in the accretion disk of a black hole is generated by angular velocity gradients and turbulence around the black hole. Under high magnetic fields, this creates a black hole's jets and leads to the decreasing of the innermost stable radius of the disk.

Fishbone-Moncrief accretion model is the solution to Euler's relativistic equations of the process of a celestial body accreting matter toroidally from its surrounding space through its gravitational attraction. Through this accumulation of matter, the compact object forms a torus shaped structure.

Relevant Equations

- **Magnetic Energy:** This energy is related to the kinetic energy. Over time, the magnetic energy will decrease as the kinetic energy increases.
  The magnetic energy (E) can be calculated using the formula:

  $$E \approx \mu V \tag{1}$$

  where:
  - E represents the magnetic energy,
  - μ (mu) is the magnetic energy density
  - V is the cell volume.
- **Kinetic Energy:** The energy stored in the motion of the particles, expressed in our code as an average kinetic energy density J/m^3
  It is in form:

  $$KE \approx \kappa_B T + \frac{1}{2}\mu v_\theta^2 \tag{2}$$
- **Fishbone-Moncrief Azimuthal Flow:** The mass density of flow of particles around the azimuthal axis.

$$l(r) = \pm\left(\frac{M}{r^3}\right)\left[\frac{r^4 + r^2a^2 - 2Mra^2 \mp a(Mr)^{1/2}(r^2 - a^2)}{r^2 - 3Mr \pm 2a(Mr)^{1/2}}\right] \tag{3}$$

where:

- a is the spin,
- m is the mass of the object
- r is the radius.

Methodology

The simulation is based on the Fishbone-Moncrief accretion disk model that has stationary, axisymmetric, and isentropic fluid flowing about the rotational axis within an axisymmetric gravitational field that remains unchanged over time.

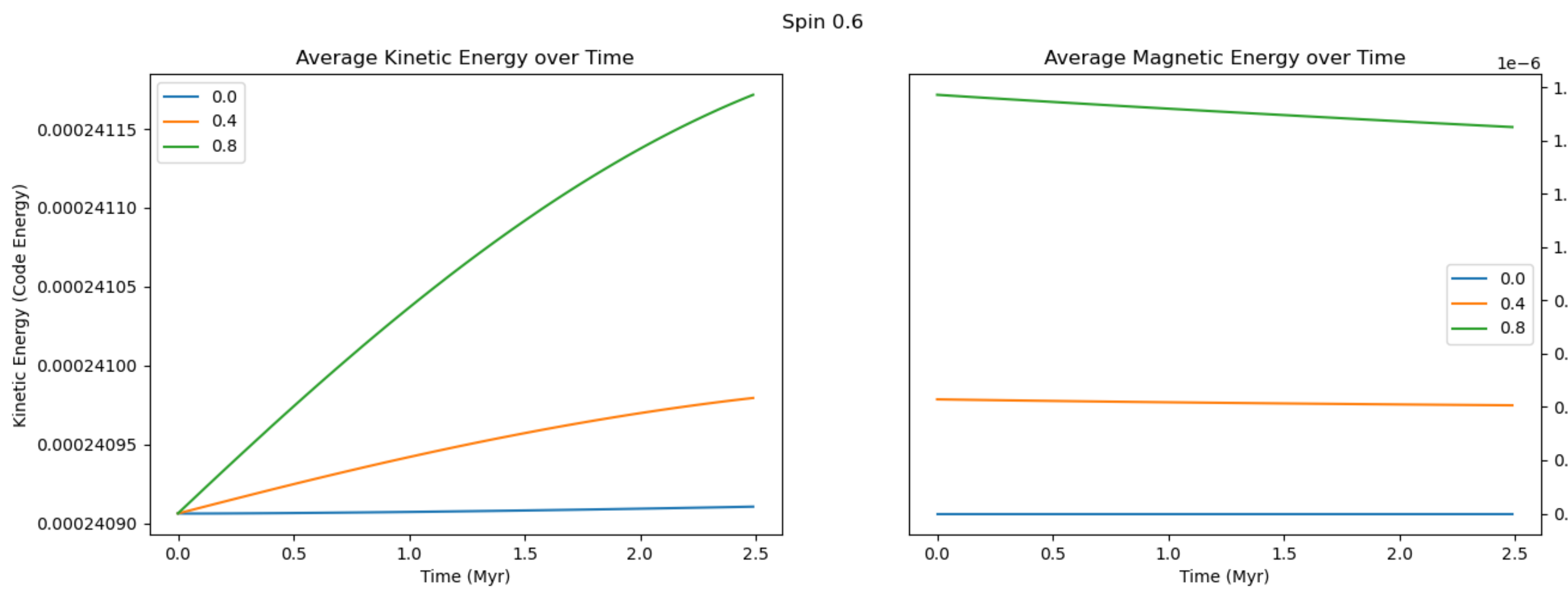
Athena ++ was used to simulate a GRMHD-driven, toroidal accretion disk under the fishbone-mongcrief model, and Jupyter Notebooks and the yt-project python package were used to analyse and plot the data.

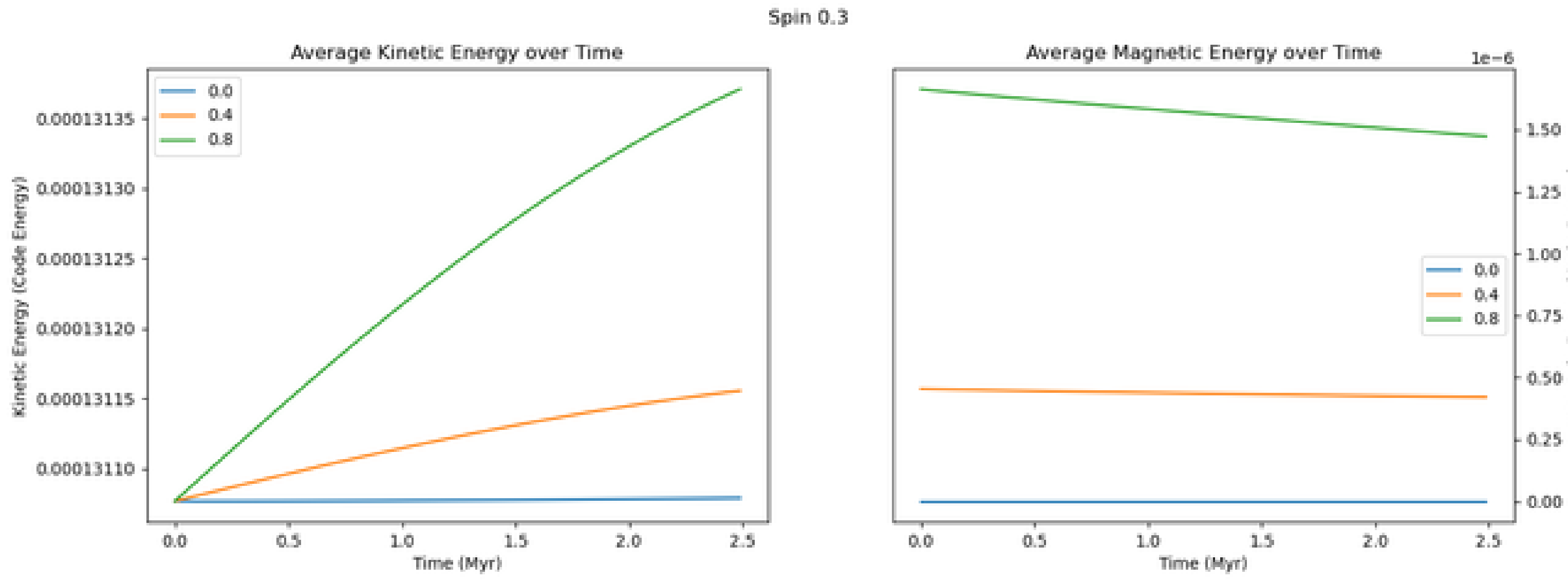
In these simulations, a torus of uniform angular momentum, which is unstable to the magneto-rotational instability (MRI), is surrounded by empty space and is seeded with a magnetic field.

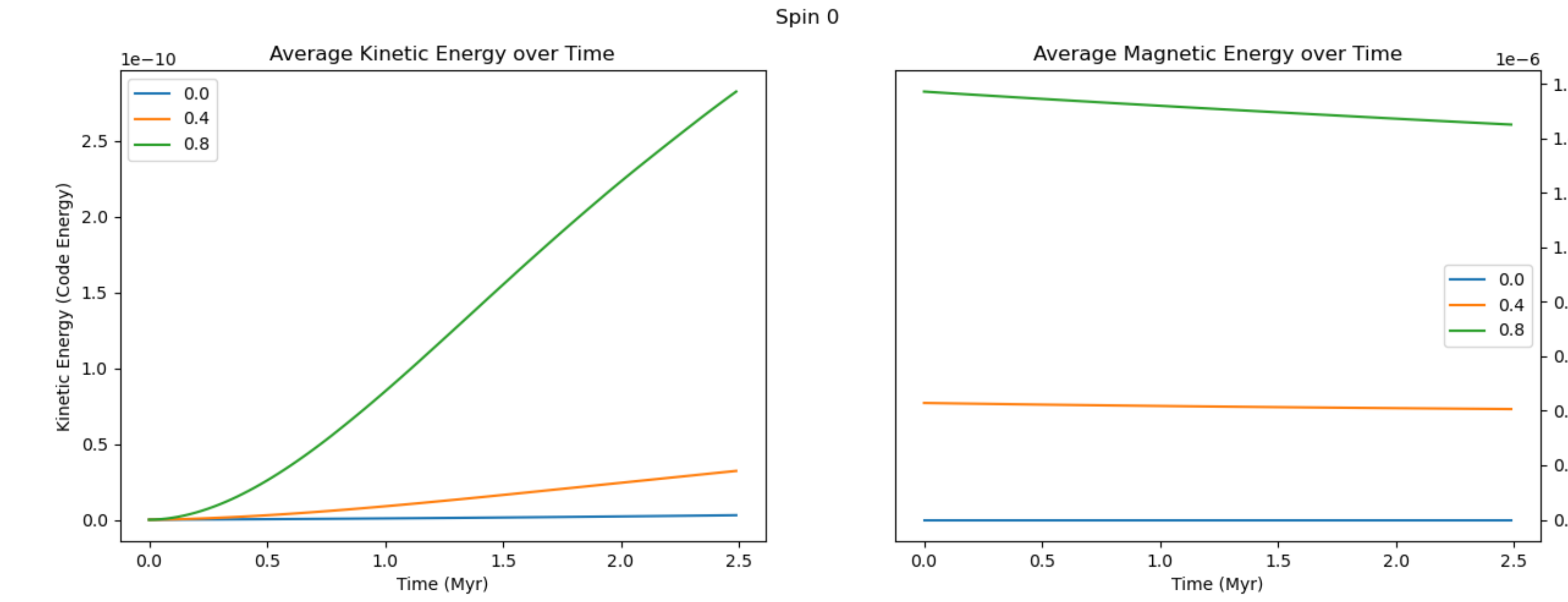
We varied the spin of the black hole to analyze the strength of the magnetic field around the black hole in different spin regimes. We also directly adjusted the magnetic potential field strength to compare results between the organically derived and artificial changes in magnetism.

1. Parameters we modified: Spin: (0,0.3,6), and Magnetic Potential: (0,0.4,0.8)
2. Conserved Values: Simulation time = 10.0 (code time), output time interval = 0.1 (code time), output format = '.hdf5', all other parameters default from 'athinput.fm_torus'
3. Axes we investigated: Time, kinetic energy, magnetic field strength, temperature, radius

Data







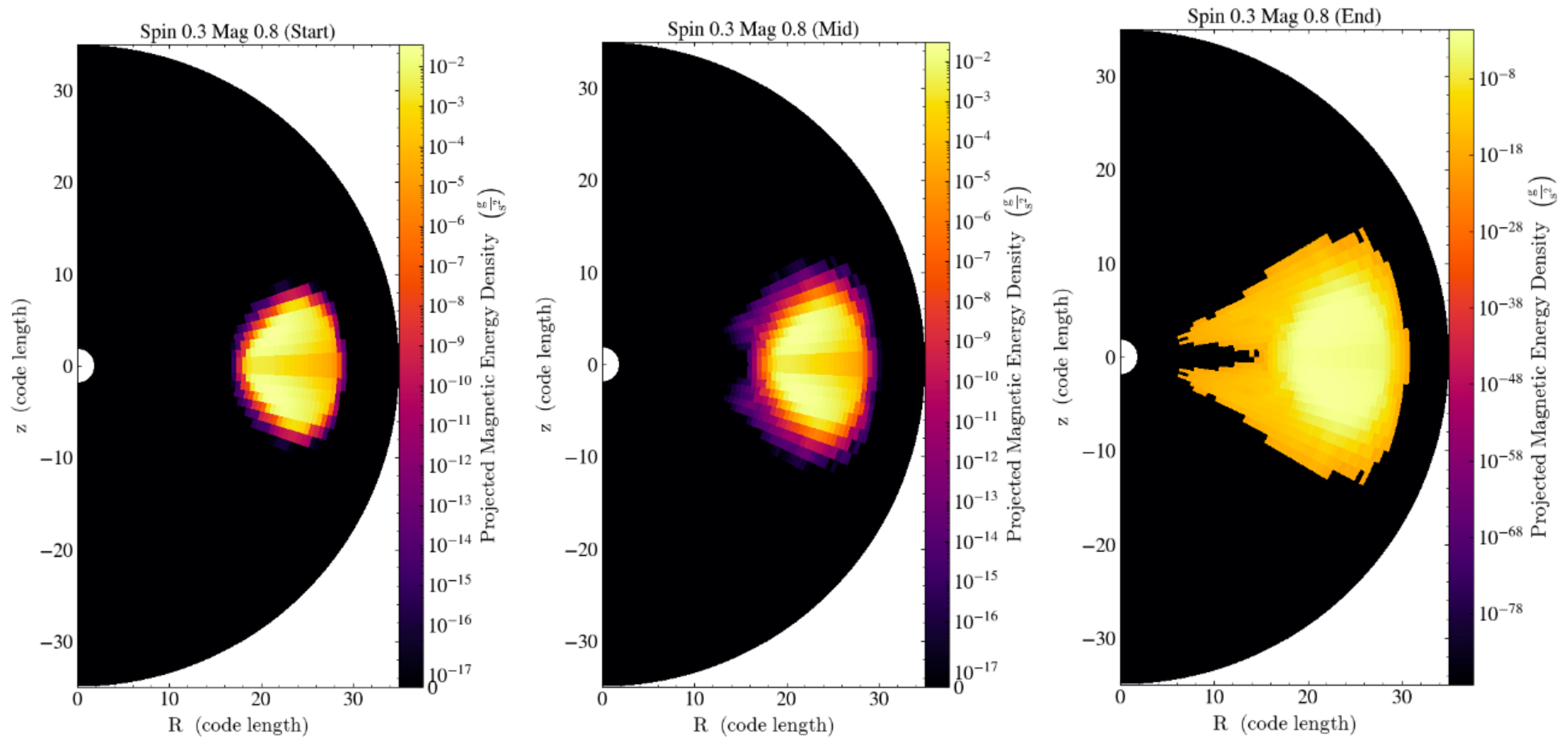


Figure 2. A plot of the magnetic field for a realistically spinning, strongly magnetized accretion disk over time. The colormaps are normalized to the maximum value in each data set

Analysis

The data plots express average energies over time for different magnetic field strengths. The left plot shows an increase in kinetic energy, while the right plot shows a decrease in magnetic energy. The three lines in each plot indicate that energy is both present and transferred in larger amount when there is higher magnetism.

Additionally, higher spin appears to indicate a larger decrease in magnetic energy over time, which is matched by significantly higher increases in kinetic energy. This indicates that the energy stored in the magnetic field is being converted into average kinetic energy

Lastly, the slice plots show a net decrease and density of magnetic energy over time, which correlates with the transfer of magnetic energy into kinetic energy.

Conclusion

In the Fishbone and Moncrief model surrounding a Kerr black hole, a significant portion of the elevated magnetic energy is transformed, into rotational kinetic energy, over time. This suggests that matter with a high degree of magnetization contributes to the transport of angular momentum, potentially resulting in an increased amount of mass ejection and enhanced efficiency. The influence of magnetism on the gas dynamics in the vicinity of Kerr Black Holes is substantial.

Additionally, Magnetorotational Instability, MRI, plays a vital role in the forming the dynamics of accretion disks as the magnetic fields and rotations create fluid instability and heightened angular momentum. This contributes to the transfer of magnetic energy to rotational kinetic energy .

Future studies could consider conducting simulations over extended timescales to determine whether the transfer of magnetic energy reaches an asymptotic value and if the system eventually achieves a steady-state solution. This would provide further insights into the dynamics of such complex systems.

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