ELUCIDATING THE ALIGNMENT MECHANISM FOR BLACK HOLE ACCRETION DISKS SUBJECTED TO LENSE–THIRRING TORQUES

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EXECUTIVE SUMMARY

The research team uses Blue Waters to study astrophysical accretion onto a spinning black hole in which there is a misalignment between the orbital axis of the incoming gas and the black hole rotation axis. Astrophysicists have long expected that an initially misaligned orbiting accretion disk would align with the black hole's spin axis at some location near the hole. A detailed understanding of this alignment process has, however, been limited due to the assumption of a phenomenological viscosity to describe the internal dissipation necessary for alignment. Our simulations capture the physical internal stress due to magnetohydrodynamic turbulence with no reliance on phenomenological viscosity; such simulations are only possible with the high grid resolution made feasible by Blue Waters. The investigation will probe how a time-steady transition might be achieved between an inner disk region aligned with the equatorial plane of the central mass's spin and an outer region orbiting in a different plane.

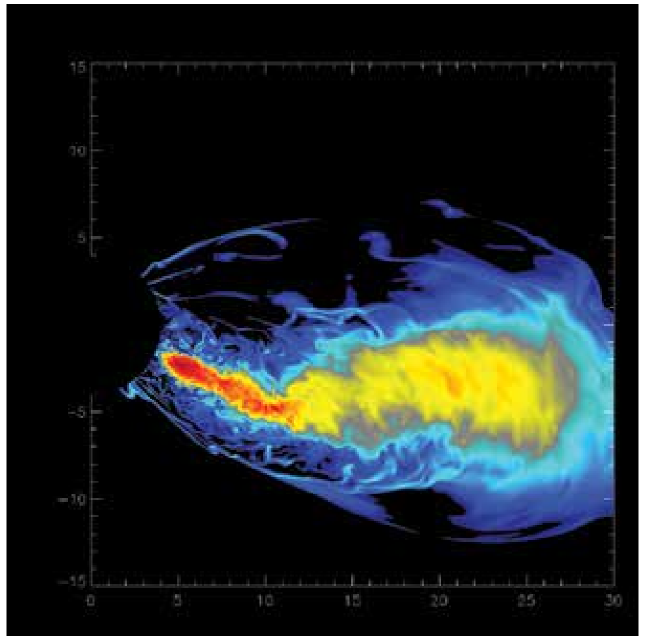

Figure 1: A contour plot of log density after 20 orbits of evolution subject to the external torque. Overlaid is a line showing the equatorial plane for the spin axis of 24° showing how the inner disk has aligned with the black hole.

RESEARCH CHALLENGE

Accretion disks occur in a wide variety of astrophysical contexts, from planet formation to black holes, both in binary systems and in the cores of active galaxies. Whenever the disk's angular momentum is oblique to the angular momentum of the central object(s), as should often be the case, a torque causes rings within the disk to precess, twisting and warping it. Because the torque weakens rapidly with increasing radius, it has long been thought that some unspecified "friction" brings the inner portions of such disks into alignment with the equator of the central object while the outer parts remain in their original orientation. Identifying and quantifying that friction has been difficult.

Despite considerable theoretical effort, it is not known how to predict the radius at which a given astrophysical disk would become aligned with the equatorial axis of the black hole. Nearly all previous work on this topic has assumed that such a disk's internal stresses can be described by a parameterized isotropic viscosity. However, there is a well-established physical mechanism for internal stresses in accretion disks—correlated magnetohydrodynamic (MHD) turbulence, driven by the magnetorotational instability [1,2].

Treating MHD turbulence in a tilted disk requires very demanding numerical simulations. The central difficulty is that if a numerical simulation is to follow the MHD turbulence, it must have a timestep very short in comparison to an orbital timescale, whereas the precession timescale where the orientation transition may occur is almost certainly many orbital periods long. This project is to carry out such numerical simulations to investigate how twisted disks align when their mechanics are described only in terms of real forces, including MHD turbulence. The aim is to develop a model that will predict the location of the stationary alignment front in disks subjected to Lense–Thirring (relativistic) torques.

METHODS & CODES

This work uses a simplified disk model first studied in [3], consisting of an isothermal disk orbiting a point-mass in Newtonian gravity with a Keplerian angular velocity distribution. It includes only a lowest-order post-Newtonian term to represent the relativistic Lense–Thirring torque. This idealized model allows us to focus on the important physical processes governing alignment; these can be studied in isolation and in detail. In this project we examine the influence of sound speed and black hole tilt. We evolve a series of models where the dependence of sound speed and tilt are studied in the sense of measuring a partial derivative: We change those terms without altering anything else. The use of an isothermal equation of state further isolates the effect of sound speed by ignoring the spatial and temporal changes expected in a more complex model.

The simulations were done with a Fortran 95 version of *Zeus*, an operator-split code that solves the equations of compressible MHD by time-explicit finite-differencing [4] using the CT (constrained transport) algorithm [5] to preserve the divergence-free property of the magnetic field. *Zeus* uses domain decomposition and MPI for parallelization.

RESULTS & IMPACT

The simulation results confirm that the influence of the sound speed can be encapsulated in a simple "lumped-parameter" model first proposed by [6]. In this model, alignment fronts propagate outward from the inner disk at a speed proportional to the local test-particle precession frequency. Meanwhile, transonic radial motions transport angular momentum both inward and outward at a rate that may be described roughly in terms of an orientation diffusion model with diffusion coefficient proportional to c_s^2/Ω for sound speed c_s and orbital frequency Ω. The competition between the two leads to, in isothermal disks, a stationary position for the alignment front at a radius proportional to $c_s^{-4/5}$. For alignment to happen at all, the disk must either be turbulent due to the magnetorotational instability in MHD, or, in HD, it must be cool enough for the bending waves driven by disk warp to be nonlinear at their launch point. The alignment process is largely independent of black hole tilt angles, at least for the range of angles studied here.

WHY BLUE WATERS

We have used Blue Waters to compute new thin disk simulations subject to Lense–Thirring torque with unprecedented resolution to improve the representation of MHD turbulence in the disk, and to make use of a larger black hole tilt angle to increase the torque effect and further explore the mechanisms behind, and scaling properties of, alignment. The unique high-performance capabilities of Blue Waters enabled key linchpin maximum-resolution simulations that support a wider effort involving a suite of less demanding simulations carried out on other systems.