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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 (tilt) 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 owing to the assumption of a phenomenological viscosity to describe the internal dissipation necessary for alignment. The team's 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 probes 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.

RESEARCH CHALLENGE

Accretion disks occur in a wide variety of astrophysical systems. Whenever the disk's angular momentum is oblique to the angular momentum of the central object(s), a torque causes rings within the disk to precess, twisting and warping it. Because the torque weakens rapidly with increasing radius, it has been thought that some unspecified "friction" brings the inner portions of such disks into alignment with the equator of the central object. Despite considerable theoretical effort, researchers are still unable to predict the alignment radius for a disk. 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].

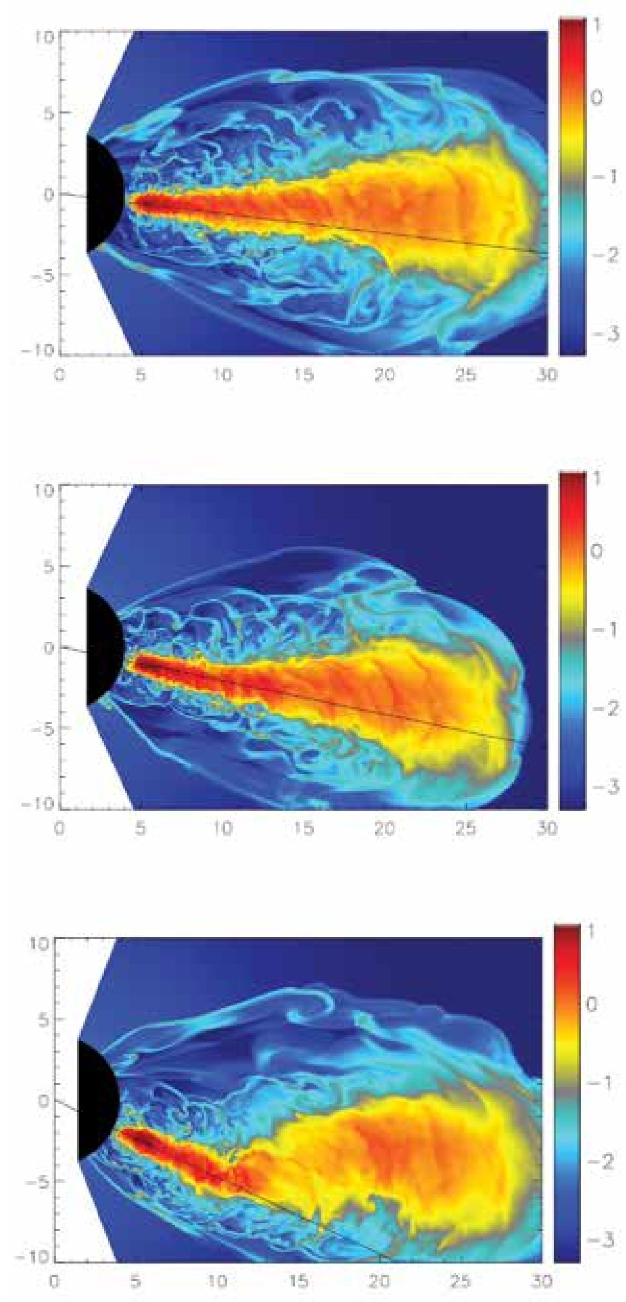

Figure 1: Logarithmic density contour for disk tilt angles of 6° (top), 12° (middle), and 24° (bottom) after 20 orbits of applied torque. The inner disk regions have aligned with the black hole equatorial plane (overlaid line), and the transition from alignment to outer obliquity occurs at approximately the same radius.

Simulating MHD turbulence in a tilted disk is demanding. To evolve MHD turbulence, a simulation must have a timestep that is very short compared to an orbital time, whereas the precession timescale of orientation transition is many orbital periods long. This project's numerical simulations 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 predictive model for the location alignment front in disks subjected to alignment torques.

METHODS & CODES

The research team used 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 and including only a lowest-order post-Newtonian term to represent the relativistic Lense–Thirring torque. This idealized model allowed the team to focus on the important physical processes governing alignment; these can be studied in isolation and in detail. They examined the influence of black hole tilt on the alignment process, evolving three models where the tilt angle is changed without altering anything else. This approach stands in contrast to those efforts that simulate model disks in the full general-relativistic context.

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 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 project team investigated the effects of black hole tilt angle on accretion disk alignment, modeling three initial black hole tilts of 6°, 12°, and 24° using both magnetohydrodynamic and (inviscid) hydrodynamic evolutions. By considering a single sound speed and a simple underlying disk model, the researchers isolated the effect of tilt amplitude, which is found to have a limited influence on alignment. The imposed tilt angle simply sets the "unit," and the resulting dynamics are determined by ratios in terms of that unit. The radial shape of the transition region between the aligned inner disk and unaligned outer disk, as well as the location of the head of the alignment front, are very nearly identical once the black hole tilt (see Fig. 1) is scaled out. Tilt does have some secondary effects. The steady state warp within the alignment front increases at a slightly faster rate with tilt than simple proportionality. Another effect is a small decrease in the initial alignment front velocity with increasing tilt.

Purely hydrodynamic disks behave similarly, but because the amplitude of the disk warp is a function of the tilt angle for a given disk thickness, h/r, higher tilt angles have larger relative warp values. From this it follows that bending waves produced in the disk are increasingly nonlinear, and hence more dissipative. Bending waves propagating through the disk without hindrance promote solid-body precession which, in turn, can end alignment at an earlier time compared to an MHD disk where the turbulence inhibits wave propagation [6]. In this work, the hydrodynamic models saw a rapid diminution of precession phase gradient in the outer disk, which brought alignment to a halt and reversed the motion of the alignment front.

Some simulations of tilted disks have either seen evidence for a possible separation of the inner and outer disk [7], or clear disk breaking, whether the central object is a binary or a spinning black hole (*e.g.*, [8]). In this project's simulations, even when the initial misalignment is 24°, which, for the sound speed studied, is four vertical scale heights at the disk fiducial radius, the surface density remains a smooth function of radius; *i.e.*, the team found no examples in which the disk inner-aligned and outer-misaligned regions separated, or "broke."

WHY BLUE WATERS

The research team has used Blue Waters to compute new thin disk simulations subject to Lense–Thirring torque with unprecedented resolution to explore the mechanisms behind, and scaling properties of, disk alignment. The unique high-performance capabilities of Blue Waters enabled key maximum-resolution simulations.

PUBLICATIONS & DATA SETS

J. F. Hawley and J. H. Krolik, "Sound speed dependence of alignment in accretion disks subjected to Lense–Thirring torques," *Astrophys. J.*, vol. 866, no. 1, 2018, doi: 10.3847/1548-4357/aadf90.

J. F. Hawley and J. H. Krolik, "Tilt dependence of alignment in accretion disks subjected to Lense–Thirring torques," *Astrophys. J.*, vol. 878, 2019, doi: 10.3847/1538-4357/ab1f6e.