FEEDING BLACK HOLES: TILT WITH A TWIST

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EXECUTIVE SUMMARY

For the past 40 years, the scientific community has been wondering what happens to a black hole feeding on the disk of gas that is tilted relative to the black hole midplane. The analytic prediction of Bardeen and Petterson in 1975, [1] that such a disk aligns to conform to the black hole midplane, has not been seen previously in numerical simulations that took into account the crucial effects of general relativity, magnetic fields, and turbulent motions in the disk. Using the power of Blue Waters' GPUs, our team for the first time demonstrated that such disks indeed align with the black hole midplane and, surprisingly, break up into individual segments with important astrophysical implications.

RESEARCH CHALLENGE

Tilted accretion is common in astrophysical systems. In fact, we expect that nearly all black hole accretion disks are tilted at some level relative to the black hole rotational equator. This is because the gas that approaches the black hole from large distances has no idea which way the black hole is spinning. However, studies of such tilted accretion disks are extremely challenging, especially in the crucial regime of luminous, radiatively efficient accretion that powers bright quasars. Such accretion disks are razor-thin and difficult to resolve numerically, requiring high resolutions and adaptive grids to follow the body of the disk as it moves through the computational grid. In a seminal paper, Bardeen and Petterson [1] predicted that purely general relativistic effects of black hole spin would cause the inner regions of such disks to align with the black hole equatorial plane. However, this model used a simplified model of the disk. In nature, the accretion disks are magnetized and turbulent, yet no general relativistic simulation of such a tilted magnetized turbulent disk has shown the long-sought alignment.

METHODS & CODES

Using our new code H-AMR [2] (pronounced "hammer"), which includes adaptive mesh refinement, local adaptive timestepping, and efficiently runs on GPUs, we were able to overcome these challenges. H-AMR performs 10 times faster on a GPU than on similar vintage 16-core CPU. H-AMR is parallelized via MPI with domain decomposition and scales well to thousands of GPUs, achieving weak scaling efficiency of 85 per cent on 4,096 GPUs on the Blue Waters supercomputer. The performance of the code allowed us to study tilted discs at higher resolutions and over longer durations than was previously possible.

RESULTS & IMPACT

More than 40 years after it was first proposed by Bardeen and Petterson, we have finally demonstrated the existence of the Bardeen–Petterson alignment of geometrically thin disks. In fact, at larger tilt angles, the outer misaligned part of the disk breaks off from the inner aligned part.

WHY BLUE WATERS

Blue Waters access has been instrumental to our ability to obtain these groundbreaking results, which require not only enormous amounts of computing power, but also fast interconnect to make use of hundreds of XK nodes. Further, Mark Van Moer helped us enormously with 3D visualization.

PUBLICATIONS & DATA SETS

Liska, M., et al., General relativistic simulations of moderately misaligned thin accretion flows. *Monthly Notices of the Royal Astronomical Society*, in preparation (2018).

Liska, M., et al, Formation of precessing jets by tilted black hole discs in 3D general relativistic MHD simulations. *Monthly Notices of the Royal Astronomical Society Letters*, 474 (2017), DOI:10.1093/mnrasl/slx174.

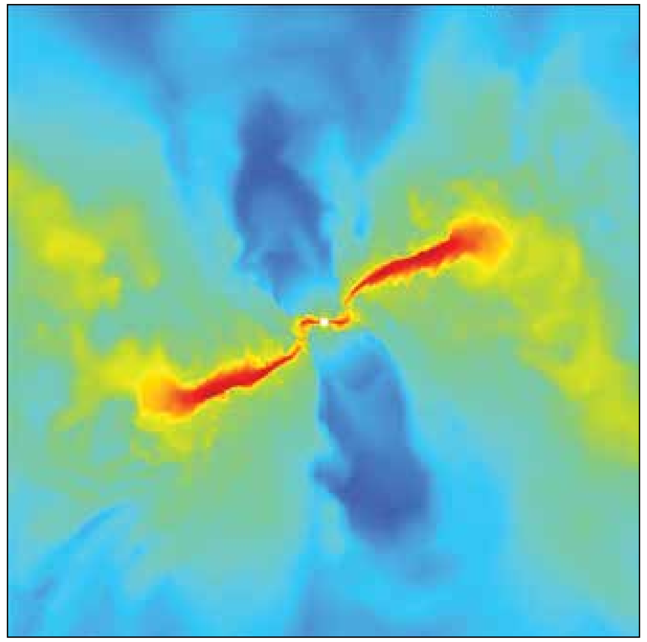

Figure 1: The inner part of a disk of half-thickness h/r = 0.03 tilted by 45 degrees aligns with the black hole midplane and breaks off from the outer misaligned part of the disk. This is the first demonstration of the Bardeen–Petterson effect in a general relativistic magnetohydrodynamic (GRMHD) numerical simulation.

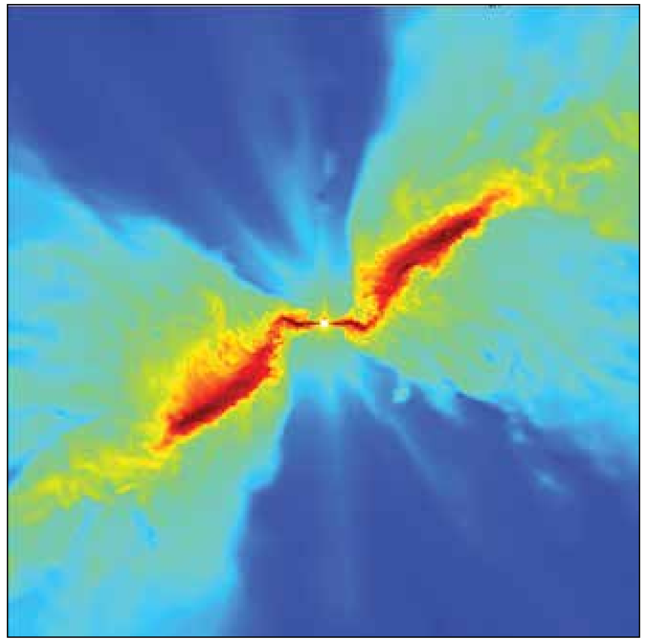

Figure 2: If h/r decreases from 0.03 to 0.015, the size of the aligned part increases from 5 to 10 gravitational radii., indicating that the alignment effect becomes stronger for thinner disks. This is the simulation of the thinnest black hole accretion disk in general relativistic magnetohydrodynamic (GRMHD) numerical simulations.