Magnetic disks in space

A new generation of simulations and experiments aim to pinpoint the origins of instability in accretion disks

Accretion disks—structures formed by material falling toward and then orbiting around a gravitational source—are a key part of the process by which newly born stars and black holes accumulate mass and grow (Figure 22). The gravitational energy released by accretion is believed to power many of the energetic phenomena observed in the universe, such as the jets streaming from galactic nuclei (Figure 23).

Accretion disks form because most of the matter being attracted toward the gravitational well has some angular momentum, which results in the matter orbiting the proto-star or black hole rather than falling right in. And that creates a problem for theorists, according to Fausto Cattaneo, a researcher at Argonne National

Laboratory and the Center for Magnetic Self-Organization at the University of Chicago.

"If the angular momentum is conserved," Cattaneo said, "the material will happily orbit the central object and never fall in. In order for material to fall, it must lose its angular momentum."

In the early days of accretion disk theory, the loss of angular momentum was not considered a problem, because two obvious explanations were easily available: collisional processes like friction or viscosity, and shear-driven turbulence.

If two particles in the disk collide, they will exchange angular momentum, and the faster-rotating one will slow down and fall into a lower orbit. If the collision rate is high enough, there will be a spiral of matter flowing down into the central gravitational well. This hypothesis makes sense until you do the math. "In most astrophysical situations, collisional processes are many orders of magnitude too small to account for the observed energy release rates," Cattaneo explained. Accretion disks are simply too big to be destabilized by such processes.

Turbulence is a more promising hypothesis, because turbulent eddies

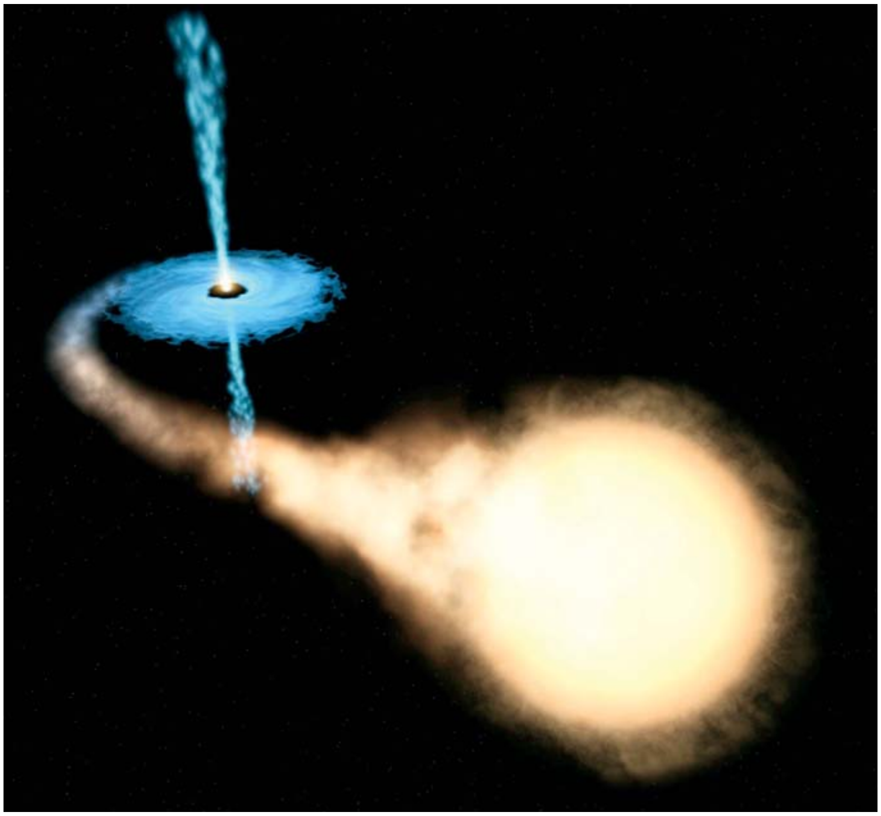

FIGURE 1. An artist's impression of a black hole with a closely orbiting companion star. In-falling matter forms an accretion disk, which feeds matter into the black hole. Hot gas rushes from the vicinity of the black hole, creating jets perpendicular to the disk. (Image courtesy of NASA.)

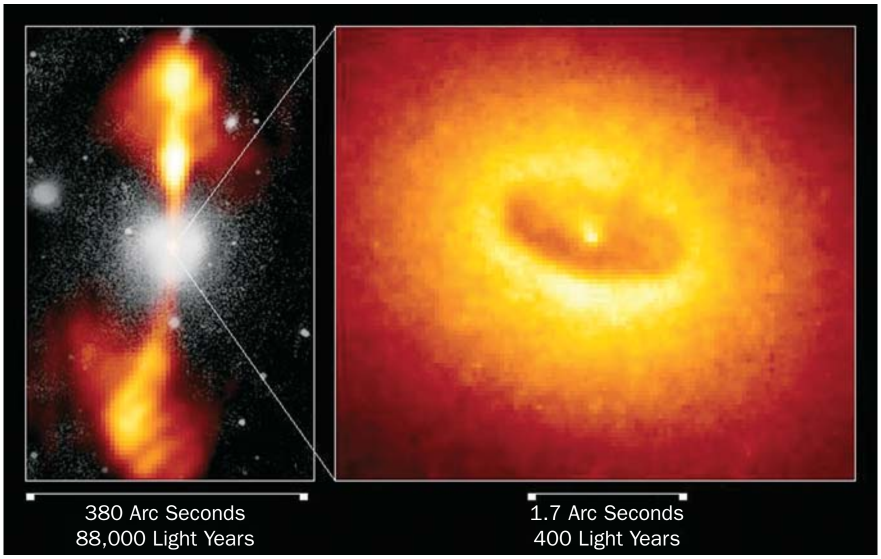

FIGURE 2. The giant elliptical galaxy NGC 4261, one of the 12 brightest galaxies in the Virgo cluster. (Left) Composite ground-based optical and radio view of the galaxy. Photographed in visible light (white), the galaxy appears as a fuzzy disk of hundreds of billions of stars. A radio image (orange) shows a pair of opposed jets emanating from the nucleus. (Right) Hubble Space Telescope image of the core of NGC 4261: The disk is tipped enough to provide a clear view of the bright hub, which presumably harbors a black hole. The dark, dusty disk represents a cold outer region which leads to an ultra-hot accretion disk within a few hundred million miles from the black hole. (Image courtesy of NASA.)

provide a much more efficient mechanism for transporting angular momentum. And models of accretion disks that assume a reasonable amount of turbulence have produced credible accretion rates. “The challenge has been to provide an underlying physical mechanism to generate the turbulence in the first place,” Cattaneo said. Shear-driven instabilities, arising from the varying rotational speeds within the disk, were another attractive possibility that had to be ruled out. “The problem is that the rotation profiles—the average angular velocity as a function of radius—of typical accretion disks are close to following Kepler’s laws of planetary motion, and so they are very stable to infinitesimal perturbations.”

“Two decades of accretion disk research failed to provide a single local instability mechanism that could operate in disks and lead to the desired state of turbulence,” Cattaneo continued. “This lamentable state of affairs improved significantly in the early 1990s when it was realized that the stability properties of near-Keplerian disks could be dramatically affected by magnetic fields. Disks that were hydrodynamically stable could become hydromagnetically unstable, and remarkably, all it took was a weak magnetic field. Since most astrophysical accretion disks are ionized and hence good electrical conductors, this *magneto-rotational instability,* as it came to be called, could provide the desired mechanism for turbulence production.”

The physical origin of magneto-rotational instability can be illustrated by a simple analogy: Imagine two spacecraft orbiting near each other at slightly different altitudes. If the orbits are nearly circular, the inner spacecraft will have higher angular velocity than the outer one. Now assume that a light elastic cord joins the two spacecraft, providing a weak tension. The effect of the tension on the inner spacecraft is to slow it down, i.e., to reduce its angular velocity, and therefore to move it into a lower orbit. In contrast, the effect of the tension on the outer spacecraft is to accelerate it, i.e., to increase its angular velocity, thereby moving it to a higher orbit. With one spacecraft going lower and the other going higher, it is hard to predict what will happen when they stretch their cord to its full length—will they start bouncing wildly, or will the cord break and propel them further apart?—but clearly, the system will become unstable.

A magnetic field in an electrically conducting disk can produce magnetic tension effects that are analogous to the elastic tension in the spacecraft example. By connecting portions of the disk that are rotating at different speeds, the magnetic field turns angular velocity into a source of instability. And because the central gravitational field does not play a direct role in magneto-rotational instability, laboratory experiments have been developed that can test many aspects of this mechanism on a small scale. In these experiments, the space between two coaxial rotating cylinders is filled with an electrically conducting fluid, typically liquid sodium or gallium. The rotation rates of the inner and outer cylinders are chosen so that the rotation profile is hydrodynamically stable. Then a weak external magnetic field is applied so that the origins and development of magneto-rotational instability can be studied.

“Although the physical input provided by these experiments is invaluable,” Cattaneo said, “they suffer from two limitations: First, in a flow of liquid metal, it’s impossible to see, and difficult even to detect, what is happening.” The second limitation concerns the Reynolds number, a mathematical expression that measures the strength of advective effects relative to diffusion. “In any laboratory setup, the magnetic Reynolds number of liquid metals is a few tens, and with extreme efforts it can be raised slightly to exceed one hundred,” he said. “This should be contrasted with the typical astrophysical situation in which the magnetic Reynolds number is huge—millions to billions.”

Fortunately, this is a case in which numerical simulations can elucidate and reach even further than the experiments. In an INCITE-funded project titled “Magneto-Rotational Instability and Turbulent Angular Momentum Transport,” Cattaneo and his colleagues Paul Fischer and Aleksandr Obabko have created three-dimensional numerical simulations that reproduce the geometry of the laboratory experiments conducted by Hantao Ji of the Princeton Plasma Physics Laboratory and Jeremy Goodman of Princeton University. But unlike the experiments, the simulations have magnetic Reynolds numbers exceeding 50,000—not quite as high as in actual accretion disks, but a valuable extension of the liquid metal results. The purpose of these simulations is to clarify the mechanisms of angular momentum transport in magnetized, rotationally constrained turbulence, and to apply them to the problem of astrophysical accretion flows.

“If you can do the research both computationally and experimentally, you are much better off than just using one approach,” Cattaneo said. “Seeing is knowing, and in numerical simulations, you can visualize anything, so it is much easier to identify the beginnings of the instability and the structures that transport angular momentum.”

In these simulations, as in most experiments to date, the magnetic field that catalyzes the magneto-rotational instability is aligned with the rotation axis. Visualizations show that in this case, the coherent structures that transport the angular momentum outward are toroidal vortex rings emanating from the inner cylinder (Figure 24). Knowing what the structures look like and how they behave advances the theoretical understanding of this instability and also makes possible the future creation of phenomenological models to describe this phenomenon. These models could then be plugged into simulations that can run on workstations instead of supercomputers, or that can use parameters closer to those found in real astrophysical accretion disks.

Although Cattaneo and his colleagues will be spending the next year analyzing all the data from their simulations, some intriguing possibilities are already emerging. “If you turn the cylinders on their side,” he said, “the transport of angular momentum looks similar to the transport of heat in a convecting fluid, like a pot of water on a hotplate. We’re going to examine this in more detail to see whether some of the ideas of convection theory can be applied to fluid flow in accretion disks.”

The close collaboration between the theorists in Chicago and the experimentalists in Princeton facilitates the exchange of results from both approaches. “We used the experimental results to validate our computational approach,” Cattaneo said. “And our simulations are giving the experimental researchers a better idea of what to look for and where to look for it. They are already using our results to improve the design of their experiments.”

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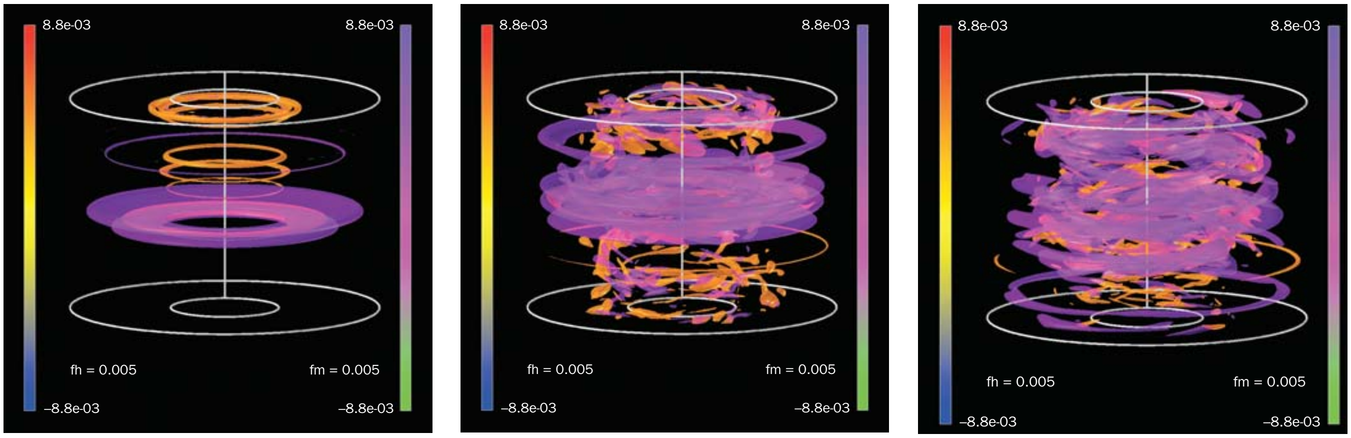

FIGURE 3. Visualization of the time evolution of the outward transport of angular momentum in a magnetic fluid bounded by rotating cylinders. The two colors correspond to the transport by hydrodynamic (orange) and hydromagnetic (purple) fluctuations. (Simulations by F. Cattaneo, P. Fischer, and A. Obabko, with visualization assistance from Cristina Siegerist of the Berkeley Lab/NERSC Visualization Group. The animation can be viewed at http://flash.uchicago.edu/~cattaneo/Animations/fh-fm_1024x768_1.mpg.)