Illuminating Black Holes through Turbulent Heating

Predictions indicate that it should be possible to directly identify how turbulence heats a given black hole's plasma from the spectrum of that plasma's radiation.

By **Gregory Howes**

Black holes are some of the most enigmatic objects in the Universe, harboring intense magnetic fields and colossal gravitational forces that even light cannot escape. A black hole becomes visible to astronomers when its encircling plasma falls inward, causing this ionized gas to heat up and emit radiation. The nature of this emitted radiation depends strongly on the way that energy is generated in the plasma, but those heating mechanisms remain unidentified. Now, Joonas Nättilä and Andrei Beloborodov of Columbia University identify through simulations that plasma heated by the dissipation of so-called "Alfvénic" turbulence should radiate via a different process than that heated by other routes, giving it different spectral properties [**1**]. This finding implies that it should be possible to distinguish observationally the mechanisms that govern this heating, a critical step in developing a more complete understanding of black hole physics.

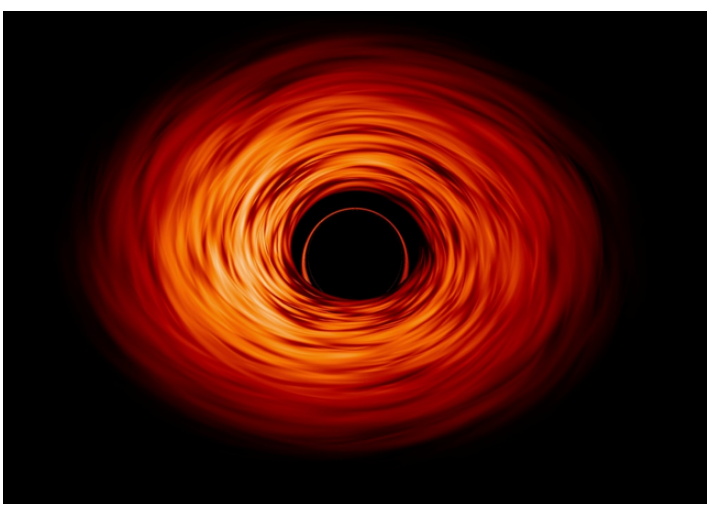

Figure 1: A simulation showing the turbulent plasma around a black hole.
Credit: NASA's Goddard Space Flight Center/J. Schnittman

Astrophysicists have a general idea of how the plasma around a black hole taps energy from a black hole's gravitational potential. The mechanism is as follows: A magnetic-field-driven disturbance, called a magnetorotational instability (MRI), causes plasma close to the black hole—and thus faster moving—to fall inward, while plasma further away—and thus slower—moves outward. That motion is unstable, generating fluctuations in both the magnetic field and the flow of the plasma [**2**]. These fluctuations interact and generate turbulence, which cascades energy in the plasma from large to small scales, where the turbulence dissipates into heat. The heated plasma then emits this energy as radiation. Although the generation of plasma turbulence by the MRI is well understood, still unsolved is how MRI-driven turbulence is dissipated in the hot and diffuse conditions of the plasma around the black hole.

To gain insight, astrophysicists have turned to numerical simulations. But even modern supercomputers lack the power to capture simultaneously the large-scale driving of turbulence by the MRI and the small-scale dissipation of turbulence into heat. To explore the dissipation mechanisms, previous work has focused on modeling only the small scales. These simulations start with a so-called relativistic pair plasma, in which the plasma is dominated by electron-positron pairs. To emulate the intermediate scales of the MRI-driven turbulent cascade, these models introduce an artificial "stirring" mechanism in the form of violent magnetic-field deformations.

Turbulence driven in this manner is found to dissipate via magnetic reconnection, which accelerates the plasma particles to energies well above the thermal energy, resulting in a nonthermal tail for the velocity distribution [**3**, **4**].

But while the MRI taps the differential rotation of the plasma to drive unstable wave modes, it is unlikely to yield the violent magnetic-field deformations used to drive turbulence in previous simulations. Recognizing this issue, Nättilä and Beloborodov take a different route to modeling the intermediate scales of MRI-driven turbulence, driving turbulence through the nonlinear interaction of Alfvén waves. Alfvén waves are natural modes of oscillation of a plasma that travel along magnetic field lines and are analogous to the waves that are generated when a stretched rubber band is plucked. When Alfvén waves traveling in opposite directions pass through each other, they distort each other, transferring their energy to new Alfvén waves with smaller wavelengths. This cascade of energy from large to small scales is terminated when some physical mechanism damps the fluctuations, converting the wave energy into plasma heat. The central role of Alfvén-wave interactions in generating turbulence in plasmas was first recognized in the 1960s, and these interactions have since been termed the fundamental building block of astrophysical plasma turbulence [**5**–**7**].

In their simulations, Nättilä and Beloborodov simulate Alfvén-wave-driven turbulence in a relativistic pair plasma, varying the amplitude of the initial Alfvén waves. For magnetically dominated pair plasmas around a black hole, MRI-driven turbulence will likely consist of interactions among Alfvén waves with amplitudes smaller than the magnitude of the background magnetic field. For such cases, the duo found that the dissipation of Alfvénic turbulence yielded a nearly thermal velocity distribution of the accelerated particles, which is dramatically different from the nonthermal tail seen in previous simulations. Furthermore, the heated particles were found to be accelerated primarily parallel to the magnetic field.

Delving into how the Alfvénic turbulence dissipates in their simulations, Nättilä and Beloborodov found that it occurs through a well-known collisionless plasma process called Landau damping, in which the plasma's electrons and positrons "surf" along the magnetic field, extracting energy from the electric field of the Alfvén waves as they move. Particles undergoing Landau damping are accelerated in the direction parallel to the magnetic field, which is consistent with the duo's simulation results but is a markedly different outcome than the dissipation of turbulence via magnetic reconnection found in previous works, where the particle-energy gain is not limited to parallel acceleration. The duo's finding of primarily parallel acceleration agrees with recent analyses of spacecraft measurements of nonrelativistic turbulence in near-Earth space that indicate that Landau damping plays a significant role in energizing plasma particles at the expense of the turbulent energy [**8**, **9**].

So, what do these findings mean for the visual appearance of black holes? Relativistically hot, magnetized plasmas with particles that have large velocities perpendicular to the magnetic field tend to emit copious amounts of synchrotron radiation—emission generated by the centripetal acceleration of the particles' spiral motion about the magnetic field. If the dissipation of Alfvénic turbulence instead dominantly accelerates the plasma particles parallel to the magnetic field, such synchrotron emission would be suppressed. Nättilä and Beloborodov suggest that inverse Compton (IC) scattering—where low-energy photons are scattered to high energies by ultrarelativistic electrons—would then be expected to be the dominant radiative process. Assuming the IC photons can escape the black hole environment without being scattered, the black hole would have a synchrotron-deficient spectrum, a distinct signature of plasma heating through Alfvénic turbulence. Thus, this landmark finding of Nättilä and Beloborodov provides a potential path to directly identify how turbulence heats the plasma—heretofore an unaccomplished feat. It will also force astrophysicists to reexamine the turbulence-driving mechanisms that they incorporate into future simulations of astrophysical plasmas.

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