Simulations by University of Wisconsin researchers explore turbulence at the cosmic scale

The physics of space can be stupefying. The Universe teems with swirling, swelling, exploding stars and galaxies of imponderable size hurtling apart at millions of miles per hour.

To the list of things we think we know about the cosmos — the coalescence of gases to form astronomical bodies, the guiding architecture of black holes, the great fusion reactors inside stars — scientists have recently added a new feature: the Universe’s magnetic personality.

Plasma, or ionized gas, is the most common form of matter in the universe. Stars are simply balls of plasma held together by gravity, and even the space between the stars is filled with plasma, albeit sparsely. Astrophysicists have long believed that this plasma is magnetized. Likewise, they’ve understood that the cosmos is turbulent, filled with non-linear flows and eddies that generate motion and heat.

What they have recently discovered is that for many astrophysical systems, magnetic turbulent energy is comparable to, or at some scales exceeds, kinetic energy, making it one of the most powerful forces shaping the system’s dynamics. In fact, certain astronomical observations, like the behavior of accreting disks and the signature of radio waves from the interstellar medium, only make sense after accounting for magnetic turbulence.

“Astrophysical motions are usually turbulent because in astrophysical space you have very large scales,” explained Stanislav Boldyrev, professor of physics at the University of Wisconsin-Madison. “In that turbulence, plasma will generate flows that eventually will become strongly magnetized. This means that magnetic fields are important dynamically in such flows.”

Unlike regular hydrodynamic turbulence, which can be observed in the natural world and tested in laboratories or wind tunnels, those who study magnetohydrodynamics, or MHD, have little tangible evidence to go on.

“Since we can’t generate large magnetized turbulent flows in our laboratories, we have to rely on really good numerical simulations,” said Boldyrev.

Such simulations require superior algorithms and powerful high-performance computers. Over the last several years, Boldyrev and his colleague, Jean Carlos Perez (University of Wisconsin), developed the theory and methodology required to represent the magnetic turbulence of plasma. Using the Ranger supercomputer at the Texas Advanced Computing Center, they simulated the dynamics believed to be characteristic of most plasma flows with higher resolution than ever before, revealing its fine-scale dynamics.

The Answer is Blowing in the Wind

There is one local source of MHD turbulence that researchers use as a basis for ideas and inspiration. “Solar wind may be the only laboratory where we can directly measure magnetic turbulence,” said Boldyrev.

From measurements of solar wind, scientists learned that the forces of magnetic turbulence are strongly imbalanced, with more waves radiating away from the sun than towards it.

“There’s no accepted theory that says how solar wind should behave and what its energy spectrum should be,” he said. “So the question is how to understand this unbalanced turbulence?”

Boldyrev and Perez’s simulations on Ranger in 2009-10 recreated this imbalanced turbulence and found that the amplitudes and the corresponding rates of energy cascades are significantly affected by the imbalance. The findings were reported in Physical Review Letters in Nov. 2009 and in The Astrophysical Journal in Jan. 2010.

Boldyrev’s research also aims to test a fundamental hypothesis about magnetic turbulence generally. Turbulence is characterized by dynamic, non-linear flows across all length scales. At the largest scale, there is a forcing mechanism that starts the system in motion. At the smallest scale, there are dissipating forces that spend the system’s energy as heat. In the intermediate scales, Boldyrev believes the behavior of turbulence is fairly uniform and easier to characterize.
“It doesn’t matter how you stir the plasma at large scales or how you dissipate the motion at small scales. In the intermediate regime of scales, this turbulence will exhibit universal behavior,” said Boldyrev.

To prove his hypothesis, Boldyrev is creating turbulent, magnetized, virtual worlds of different sizes on Ranger, to correlate the behavior and energy of the turbulence at different scales. He expects the spectrum of turbulent energy fluctuations to be universal.

Simulating these complex dynamics is no easy matter. In addition to the billions of grid points contained in each simulation, MHD algorithms must account for the wave-like behavior of magnetism, which requires more time-steps. Moreover, Boldyrev and Perez's code treats plasma flows in three-dimensions to allow for the bending and shuffling of magnetic field lines, which again increases the complexity of the computations.

None of these simulations would have been possible even five years ago, said Boldyrev. “The impact of these massively parallel computations has been tremendous. It’s hard to do anything analytically without guidance from experiments or numerical simulations.”

**Dynamics of Cosmic Dynamism**

Through his simulations on Ranger, Boldyrev and his collaborators have shown that magnetism cannot be ignored when drafting the history of the Universe. In reality, magnetic turbulence may be the key to explaining some basic astrophysical phenomenon.

“There is a fundamental question in astronomy regarding star formation: How do dense clumps of interstellar gas form stars, and how many stars of a given mass are going to be formed from these clumps?” said Boldyrev. “Recently, scientists have realized that magnetic turbulence may be responsible for the creation of those initial seeds where stars are later born.”

Even the spaces between stars are highly magnetized and turbulent, asserts Boldyrev. For this reason, signals of distant pulsars picked up by radio antennas display scintillation, or twinkling, that scientists now recognize as evidence of the fluctuations produced by a turbulent and magnetized interstellar medium.

“Understanding magnetized plasma turbulence is crucial for explaining very important astrophysical observations,” he said.

Back on earth, one of science’s most dogged questions — how we can generate fusion energy as stars do — may be aided by Boldyrev’s research as well. Both the National Science Foundation (NSF) and Department of Energy (DOE) have recognized the promise of Boldyrev’s work, granting him and his collaborators, Jean Carlos Perez, and Fausto Cattaneo and Joanne Mason (U. Chicago), computing time on TeraGrid and DOE systems through the INCITE award.

These agencies believe that fundamental knowledge derived from Boldyrev’s simulations may drive the next phase of plasma theory and experimentation, including improvements to confinement in fusion reactions.

“If we can study turbulence’s universal behavior, we can understand turbulence in the interstellar medium or turbulence in the intergalactic medium or maybe even turbulence in fusion devices,” said Boldyrev. “It doesn’t matter how we stir turbulence or how we dissipate it; in the range of scale in-between, turbulence is universal.”

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