Viewpoint

Turbulent Plasma in the Lab

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Published December 17, 2012

Confirmation that interacting magnetic plasma waves can generate "daughter" waves of a higher frequency supports the current picture of how turbulence leads to heat in astrophysical plasma.

Subject Areas: **Fluid Dynamics, Plasma Physics**

A Viewpoint on:
Toward Astrophysical Turbulence in the Laboratory
G. G. Howes, D. J. Drake, K. D. Nielson, T. A. Carter, C. A. Kletzing, and F. Skiff
Phys. Rev. Lett. **109**, 255001 (2012) – Published December 17, 2012

The Universe is full of turbulent fluid, most of which was ionized by the ultraviolet radiation emitted by the first stars and galaxies in the early Universe. Before this reionization, the Universe was nearly homogeneous, but gravitational instabilities turned the cosmic fluid into a weblike structure made of clusters, filaments, and voids [1]. Gas continues to accrete supersonically onto these structures, thus producing high Mach number shocks that generate vortices, and with them, turbulence. The resulting rotational ionized plasma carries electric currents and magnetic fields, and turbulence in these cosmic conducting fluids is thought to play a significant role in shaping the evolution of the Universe over a vast range of length scales.

Although it is at a very different length scale, studying plasma in the lab can teach us about the physics of its astrophysical counterpart. Now, writing in *Physical Review Letters*, Gregory Howes, at the University of Iowa, and collaborators have achieved a breakthrough in the observation that a nonlinear interaction between two magnetic waves, known as Alfvén waves, can generate "daughter" waves with a shorter wavelength. The nonlinear interaction is believed to be the primary mechanism by which turbulent motion in astrophysical plasmas is transferred to increasingly smaller length scales [2], and the new experiments provide an opportunity to study the conditions under which it occurs.

Turbulence is a fundamental factor at many length scales, from galaxies and clusters of galaxies, to the solar corona, down to our own magnetosphere around the Earth. The dynamics of turbulence dictates that there is a flow of energy carried by the baryonic fluid (i.e., the plasma that constitutes almost all the visible Universe) and that it is transported from a larger scale to a smaller one. This flow of energy continues until eventually it is dissipated into heat by kinetic effects or atomic collisions. How this "cascade" process actually takes place in a conducting plasma remains an open question. Particularly challenging is the fact that, as distinct from ordinary hydrodynamic turbulence typical of terrestrial fluids, the cosmic plasma is threaded by a magnetic field, thus adding a substantial number of complications in identifying the origin of cascade [3].

It has been more than half a century since the importance of the effect of magnetic field on turbulence was realized [4, 5], but still, our understanding of magnetized plasma turbulence remains far from complete. Numerical simulations have advanced our knowledge significantly, but they are not without their limitations. Including all the relevant physics over the necessarily large separation of length scales is intractable even with the largest computing facilities currently available. Solving the reduced set of equations for incompressible magnetohydrodynamics (MHD) is commonplace, but even here, there is disagreement between interpretations. Astrophysical observations and *in situ* spacecraft measurements can give guidance, but they lack the necessary resolution to resolve the kinetic scales of interest.

It is in this context that laboratory experiments provide an invaluable tool to help us understand how turbulence works. The magnetohydrodynamic equations that describe plasmas are invariant when scaled from cosmic sizes (kilometers and greater) to meters (the rough size of experimental plasma chambers), but only under certain conditions: the ratios of heat convection to conduction (the Peclet number), inertial forces to viscosity (the Reynolds number), and inertial forces to magnetic diffusivity (the magnetic Reynolds number) must all be large compared to unity. Essentially, these requirements mean that viscosity, resistivity, and thermal conduction can be neglected over a large range of spatial and temporal scales. If these conditions are satisfied, it is possible to scale experiments to length and time scales relevant to space or astrophysical plasmas [6]. The similarity between laboratory and astrophysical systems has been exploited in laser-plasma experiments to investigate colli-

DOI: 10.1103/Physics.5.141
URL: http://link.aps.org/doi/10.1103/Physics.5.141

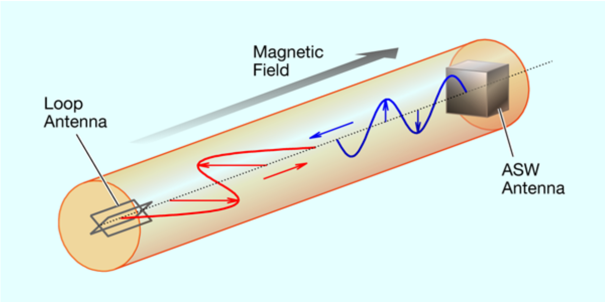

FIG. 1: Schematic of the experiment performed by Howes *et al.*[2]. Counterpropagating Alfvén waves, which travel parallel to an applied magnetic field, are generated from a loop antenna and an arbitrary spatial waveform (ASW) antenna. The nonlinear interaction of the two waves results in a third wave which has frequency and wave number equal to the sum of the frequency and wave number of the parent waves. (Adapted from G. G. Howes *et al.*, [2])

sionless shock formation [7], the generation of magnetic seeds at shocks [8], and to explore self-organization in turbulent plasmas [9].

In their experiment, Howes *et al.* focus on the fundamental interactions that facilitate the MHD energy cascade. Exploiting the unique experimental capabilities at the Large Plasma Device (LAPD), a basic science user facility operated at the University of California, Los Angeles, the team has studied the building blocks of astrophysical plasma turbulence. The LAPD is a pulsed discharge device producing a magnetized plasma column with a very good degree of reproducibility. One important aspect of the LAPD is the possibility of driving Alfvén waves—a kind of hydrodynamic wave in a plasma, whose frequency is below the ion cyclotron frequency [10]. The key element in Howes *et al.*[2] research is the nonlinear interaction among such Alfvén waves [10] (see Fig. 1). These MHD waves propagate along the direction of the magnetic field lines. Like other waves, their oscillations can be described in terms of an oscillation frequency ω (or energy $\hbar\omega$) and wave number k, or equivalently a spatial scale $\ell = \frac{2\pi}{k}$. In astrophysical plasmas, Alfvén waves are believed to be continuously excited by a variety of turbulent processes, and the nonlinear interaction of multiple waves is likely to occur.

Using the pristine plasma environment provided by the LAPD, Howes *et al.* have isolated the interaction of two counterpropagating Alfvén waves that are polarized such that a nonlinear transfer of energy is favorable (see Fig. 1). What they find is that the interacting waves generate a third wave (a daughter wave) with a frequency and wave vector that are the sum of those of the previous two waves, in agreement with theoretical predictions and satisfying conservation of energy and momentum.

These results provide a clear demonstration of the energy transfer to a smaller scale, because the wave number of the daughter wave is larger than the parent waves, thus its associated length scale is shorter. This process happens via the nonlinear interaction of Alfvén waves, and serves as a validation for the physical mechanism that mediates the energy cascade in MHD turbulence. While this exciting discovery was already predicted by incompressible MHD theory, its demonstration for the first time in a laboratory setting gives us an important model system that links turbulence in the lab to larger scale systems.

Howes *et al.*'s work represents a novel approach to astrophysical turbulence studies. As a general comment on the state of the art, laboratory astrophysics has now reached the point where important questions on the property of astrophysical systems can be addressed in experiments complementary to observations and numerical simulations.

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DOI: 10.1103/Physics.5.141
URL: http://link.aps.org/doi/10.1103/Physics.5.141

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Since 2010, Brian Reville has been a research assistant at the University of Oxford Physics Department. He received his B.Sc. (2004) and Ph.D. (2007) from University College Dublin before moving to the Max-Planck-Institut für Kernphysik, Heidelberg, as an Alexander von Humboldt fellow. In 2013 he will join the Centre for Plasma Physics at Queen's University Belfast. His research focus is primarily in the areas of theoretical and laboratory astrophysics.

DOI: 10.1103/Physics.5.141
URL: http://link.aps.org/doi/10.1103/Physics.5.141