Order from chaos: Australian vortex studies are first proof of 70-year-old theory of turbulence in fluids

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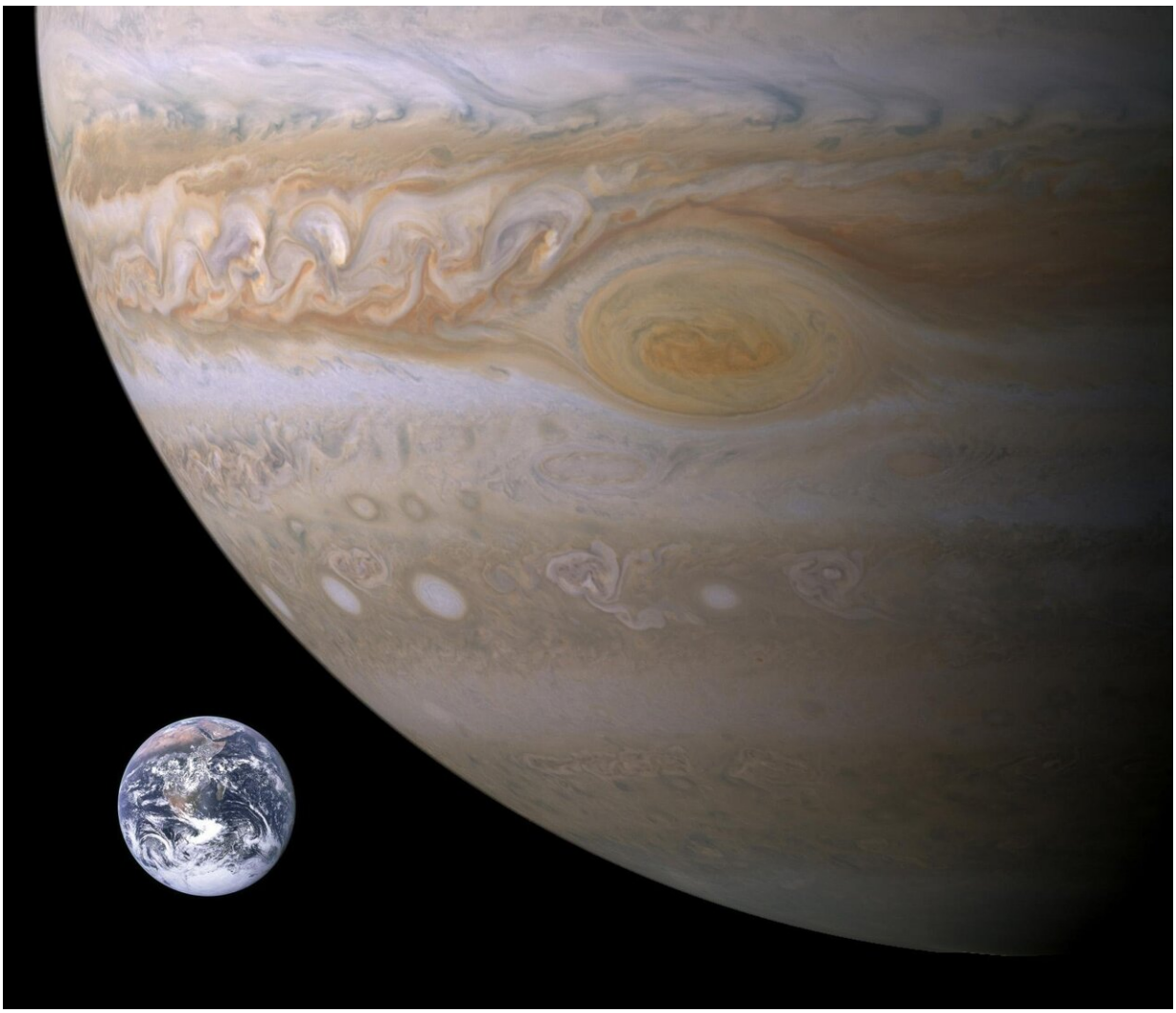


Jupiter's Great Red Spot. Credit: NASA

Two Australian studies published this week offer the first proof of a 70-year-old theory of turbulence.

"The studies confirm a seminal theory of the formation of large-scale vortices from turbulence in 2-D fluid flow, where the large vortices emerge from an apparent chaos of smaller vortices," says author Prof Matt Davis, FLEET's lead on the University of Queensland paper.

Fluids restricted to flow in two-dimensions can be observed in systems ranging from electrons in semiconductors, to the surface of soap bubbles, to atmospheric phenomena such as cyclones.

"One of the commonly observed features in such 2-D flow is the formation of large-scale swirling motion of the fluid from the initially chaotic swirling motion typical of turbulent flow, such as Jupiter's famous Great Red Spot," says the Monash study's lead author, Shaun Johnstone.

Turbulence, with its seemingly random and chaotic motion of the fluid, is a notoriously difficult problem, for which there is no general theoretical description. (In fact, the Clay Mathematics Institute offers a million dollar prize to anyone that come up with a theory of turbulence.)

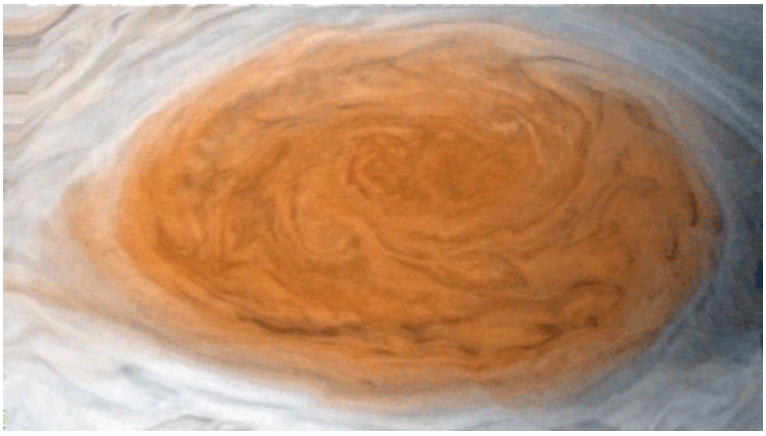
There is, however, a simple theory, proposed in 1949 by the Nobel laureate Lars Onsager, to explain the formation of large-scale vortex motion from initially turbulent 2-D flow.

Despite the appeal of Onsager's physical picture of 2-D turbulence, it can only make quantitative predictions for one special type of fluid: a 'superfluid," which flows without any viscosity or drag, and which can only be realised at extremely low temperatures. This had made a testing

of Onsager's theory difficult, until now.

"The study is broadly relevant to the emerging research field of non-equilibrium physics, and more specifically relevant to study of superfluids and superconductors," says author Prof Kris Helmerson, who works with Johnstone in Monash's School of Physics and Astronomy.

The new research is described in two papers out in *Science* today, with one experimental study led from FLEET's Monash University node, and the other led from an EQUS/FLEET collaboration at the University of Queensland.



Jupiter's Great Red Spot is an example of a 2D vortex. Credit: NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstadt/Justin Cowart

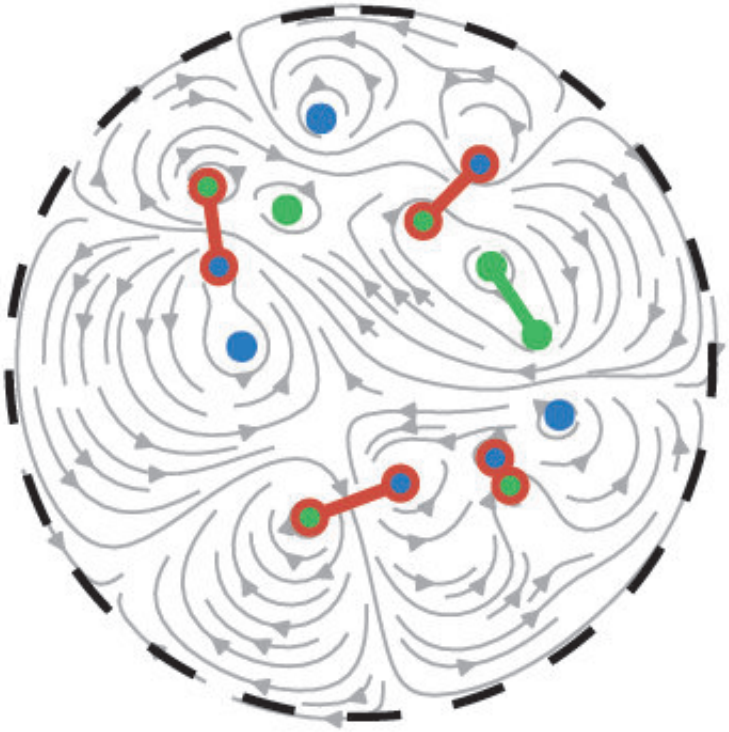
Why vortices & quantum turbulence

Most people are familiar with the concept of a vortex: whether the familiar twisting shape of a tornado, or the simple whirlpool that forms at a bathtub drains away through the plughole.

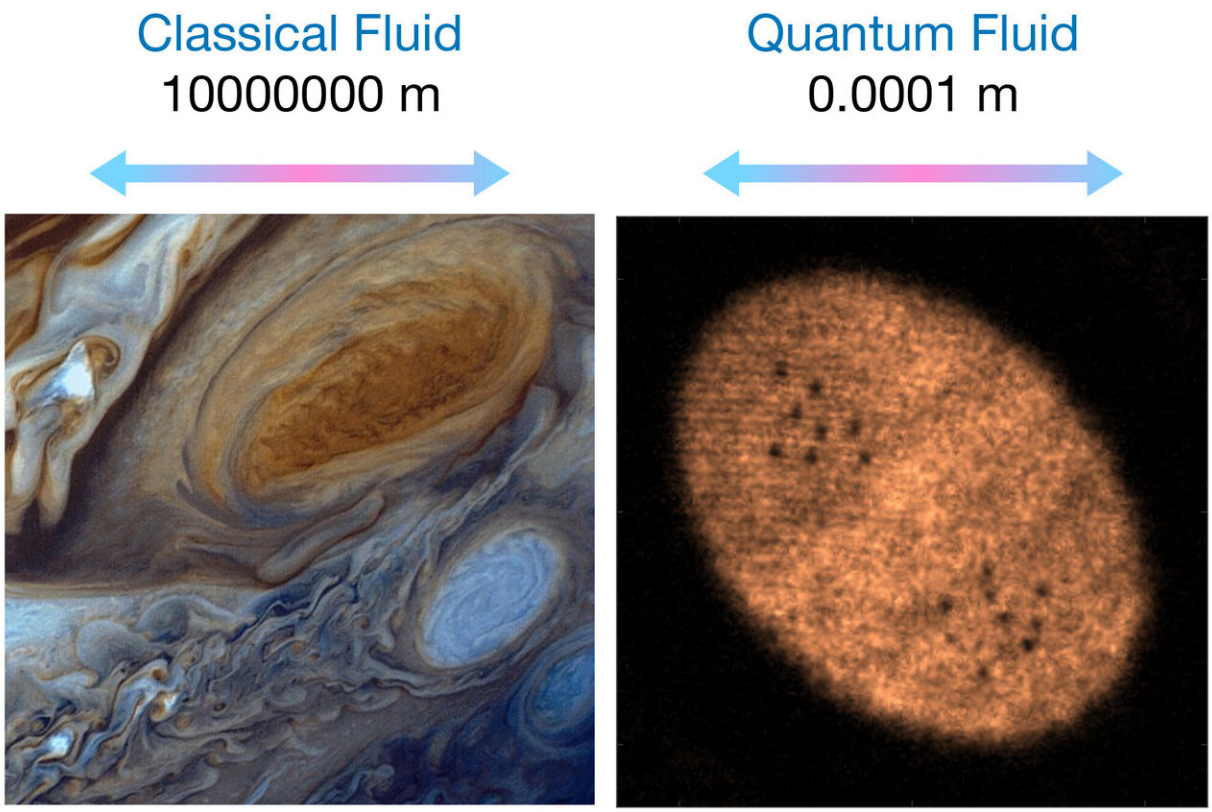
Vortices also occur in 2-D systems where there is no vertical movement, such as at the surface of liquids, or in atmospheric system such as cyclones. In fact, 2-D vortices cover a vast range of systems, from the superfluid movement of neutrons on the surface of neutron stars to the Atlantic Ocean Gulf Stream to the zero-resistance movement of electrons in high-temperature superconductors.

For 70 years, our understanding of such 2-D vortex systems has been governed by Lars Onsager's theory that as more energy is put into the chaotic mix of small vortices in a turbulent 2-D system, over time the vortices rotating in the same direction would cluster to form larger, stable vortices—the system becomes ordered, rather than more chaotic.

In order to make his 1949 theory mathematically tractable, Onsager considered a superfluid, which he stated would have quantised vortices (vortices with quantised angular momentum), a concept further developed by Richard Feynman.



Dipole dominated vortex (Monash study). Credit: School of Physics and Astronomy, Monash University



A turbulence comparison from the very big (a storm on Jupiter) to the incredibly small (quantum turbulence). Credit: The University of Queensland

Onsager's theory described a 2-D turbulent system's energy congregating in high-energy, long-lived, large-scale vortices. This is an unusual equilibrium state where entropy decreases as a function of energy—the opposite of what we would consider 'normal' thermodynamic regimes.

The Monash-led team generated vortex distributions at a range of temperatures and observed their subsequent evolution. States that began with relatively random distributions of vortices were seen to begin to order themselves, as Onsager had described. The University of Queensland study, on the other hand, directly generated two large clusters of vortices, flowing in opposite directions, testing the stability of this highly-ordered configuration.

Both studies experimented using Bose Einstein Condensates (BECs), a quantum state that exists at ultra-low temperatures, and in which quantum effects become visible at a macroscopic scale.

The researchers created turbulence in condensates of rubidium atoms using lasers, and observed the behaviour of the resulting vortices over time.

Both studies offer great promise for future studies of emergent structures in interacting quantum systems driven far from equilibrium.

The two studies: "Evolution of large-scale flow from turbulence in a two-dimensional superfluid" and "Giant vortex clusters in a two-dimensional quantum fluid," were both published in *Science* today.

More information: "Evolution of large-scale flow from turbulence in a two-dimensional superfluid" *Science* (2019). science.sciencemag.org/cgi/doi … 1126/science.aat5793

"Giant vortex clusters in a two-dimensional quantum fluid" *Science* (2019). science.sciencemag.org/cgi/doi … 1126/science.aat5718

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