Nonlocal energy transfer mechanism in three-dimensional quantum turbulence

Elliot Bes*[1], Guillaume Balarac[1], and Juan Ignacio Polanco[1]

[1]Laboratoire des Écoulements Géophysiques et Industriels [Grenoble] – Centre National de la Recherche Scientifique, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes, Institut Polytechnique de Grenoble - Grenoble Institute of Technology – France

Résumé

Near absolute zero, helium-4 enters a superfluid state known as He-II characterised by a near vanishing viscosity. In this limit, because of quantum mechanical constraints, all rotational fluid motion is concentrated on quantum vortices, atomically-thin vortex lines whose circulation is quantised. In the presence of external perturbations, He-II can host a disordered state known as quantum turbulence (QT), in which the collective interaction of a dense tangle of quantum vortices leads to an energy cascade across scales. In the inertial scales, above the typical distance between quantum vortices, this turbulent state has been shown to display major similarities with turbulence in classical fluids.

Here we investigate QT in the zero temperature limit using the vortex filament model (VFM), which represents quantum vortices as three-dimensional curves interacting via the Biot-Savart law. This description is appropriate for describing quantum vortex dynamics in He-II turbulence, where the quantum range of scales, separating the vortex core size to the turbulent scales, spans 5 to 6 orders of magnitude in typical experiments. Using simple theoretical arguments, we predict a novel mechanism directly transferring energy from inertial to quantum scales, thus bypassing the scale-local energy cascade associated to the classical turbulence picture. This nonlocal energy transfer is amplified by the extent of the quantum range, and rests on the preferential alignment between quantum vortices and large-scale straining motions. Such alignment is in fact ubiquitous in classical turbulence where it is responsible for the vortex stretching phenomenon.

Our predictions are then confirmed using steady-state VFM simulations at unprecedented vortex densities and based on a novel large-scale energy injection method. Moreover, our numerical simulations show that, as a result of this mechanism, the kinetic energy spectrum in zero-temperature turbulent He-II strongly departs from the classical Kolmogorov prediction at inertial scales, as the local energy cascade is continuously depleted by nonlocal energy transfers. These results bring new questions on turbulence mechanisms in finite-temperature He-II, where quantum vortices coexist and interact with a viscous normal fluid leading to a two-fluid energy cascade.

*Intervenant