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Spontaneous excitation of multiscale acoustic vortices in dust acoustic wave turbulence

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With increasing driving, the transition from order to turbulence, associated with the spontaneous emergence of multiscale coherence structures, ubiquitously occurs in various nonlinear extended media ranging from hydrodynamic flow to nonlinear waves. For example, in hydrodynamic turbulent flow, multiscale interacting vortices surrounding filament-like singular cores, are basic multiscale coherent structures. Strong correlations, such as entanglement and clustering of vortices were found [1]. Nevertheless, in nonlinear wave turbulence, past studies mainly focused on the energy cascades and scaling of the continuous power spectra. Whether multiscale coherent excitations also exist and their spatiotemporal behaviors remain elusive, especially for three-dimensional (3D) acoustic-type wave turbulence.

Before the transition to the strong wave turbulence, increasing driving first leads to the transition from single-scale ordered waves to the single-scale weakly disordered waves with the emergence of spatiotemporal modulations of amplitudes and phases. The modulation instability causes the broadening of the sharp peaks in the power spectrum, and generation of rogue wave events at envelope peaks [2,3], or topological defects at the envelope troughs where amplitudes are null and phases are undefined [4].

In acoustic and optical waves, such defects are called acoustic vortices (AVs) [4] and optical vortices (OVs) [5], respectively, which are waves with helical wavefronts winding around low-amplitude filament-like cores. The spontaneous pair generation and pair annihilation of AVs with opposite topological charges, through rupture and reconnection of sequential wave crests, were experimentally observed in single-scale weakly disordered dust acoustic waves (DAWs) [4]. It shows that those AVs are the basic coherent excitations characterizing the waveform dynamics of single-scale weakly disordered acoustic-type waves, similar to the vortex excitations in hydrodynamic flows.

Dust acoustic wave, a longitudinal wave composed of oscillating negatively charged micrometer-sized dust particles in plasma, is a fundamental nonlinear acoustic-type density wave. It can be self-excited through the interplay of dust inertia, screened Coulomb interactions, and ion streaming in a dusty plasma [2,3,4,6,7]. Due to its proper spatiotemporal scales, the ability of monitoring large-area dust density evolution through direct optical imaging makes it a good platform for exploring the spatiotemporal waveform dynamics in the 2+1D space-time space. By decreasing the system pressure, which increases the effective driving, the transition from plane wave state, through the weakly discorded state, to wave turbulence state is observed [6].

However, for wave turbulence with a continuous spectrum, the absence of spectral gaps disables spatiotemporally decomposing it into multiscale modes through Fourier band-pass filtering. It makes the finding of multiscale coherent excitations in wave turbulence even more challenging.

In our work [7], using a novel method, multidimensional Hilbert-Huang transform, we decompose the turbulent waveform into multiscale modes and demonstrate that DAW turbulence can be viewed as a zoo of interacting multiscale AVs. It is found, in different-scale modes, AVs with opposite helicities are spontaneously pair-generated and pair-annihilated to conserve the total topological charges (helicities), similar to that in the single-scale weakly disordered DAW. In addition to intermode AV interaction, the intramode AV entanglement and wavefront synchronization are key dynamical processes in acoustic wave turbulence, similar to the interaction between multiscale vortices observed in hydrodynamic turbulence.

Our study sheds light on understanding the basic multiscale coherent excitation of 3D density wave turbulence in plasma and gaseous media. It should inspire future works on finding coherent excitations in other nonlinear waves such as optical waves.

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