Self-excited dust acoustic wave turbulence in dusty plasmas

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Wave turbulence is a ubiquitous phenomenon which describes a non-equilibrium highly excited state composed of numerous non-linear interacting waves. It can be observed in many systems such as the gravity and capillary waves on fluid surfaces [1] and the drift waves in plasma [2]. Comparing to the hydrodynamic turbulence, the understanding of wave turbulence is rare, especially for the acoustic type wave. The free energy cascading and the consequent broad energy distribution are the characteristics of wave turbulence. If the system follows the self-similar dynamical selection rule, the energy will follow the power law distribution in the power spectrum with certain power law exponent.

The dust acoustic wave (DAW) is one of the fundamental collective excitation in the dusty plasma composed of electrons, positive ions, negative charged dust particles, and neutral atoms. It is a low frequency dust density wave with the longitudinal dust oscillation under the interplay of the dust inertia, the screened electric field, and the background pressures of hot electrons and ions. DAW can be self-excited and grow in laboratory discharges through the free energy source such as ion streaming and the unfrozen charges on the dust particle [3]. The 1D DAW turbulence with distinct peaks in the power spectrum has been reported [4]. To our knowledge, there are no experimental observations or the theories for DAW turbulence with the continuous power.

In this work, we experimentally demonstrate the first observation of the DAW turbulence with a broad power spectrum following power law scaling, in a low pressure dusty plasma system by decreasing neutral pressure. The strong compression in the wave crest and the lower bond of dust density in the wave trough leads to an asymmetry histogram of the wave height n. The structure function analysis demonstrates the turbulence exhibits multifractal dynamics.

The experiment is conducted in a cylindrical rf dusty plasma system as described elsewhere [5]. The system can be tuned from the self-excited regular wave to the irregular state reducing background pressure which suppresses dissipation [3]. A CCD at 500 Hz frame rate is used to capture the side view images of the illuminated dust particles for ten seconds. The normalized dust density $n(t) = I_d(t)/\langle I_d \rangle_t$ can be obtained by measuring the scattered laser light intensity I_d from a local point, where $\langle I_d \rangle_t$ is the time average of I_d.

The temporal dust density fluctuations and the power spectra $S(f)$ of run I (180 mTorr, 2.8

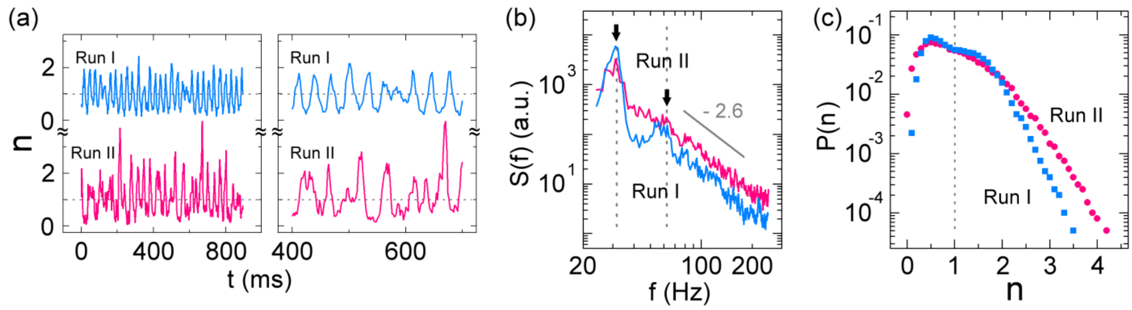

Figure 1: (a) The temporal evolutions of the normalized dust density n for runs I and II, under different time scales, respectively. (b) The power spectra for the two runs. The number by the gray line corresponds to the scaling exponent. (c) The PDFs of wave heights n for runs I and II.

W rf power) and run II (160 mTorr and 2.8 W rf power) are shown in Fig. 1(a) and 1(b), respectively. For run I, $n(t)$ oscillates with small amplitude fluctuations. The broad peaks of the main frequency and the harmonic centered at about 31 and 62 Hz, respectively, manifest the non-linear interactions between waves and the energy cascading associated with the generation of other modes. In the high frequency regime, $S(f)$ obeys the power law scaling $S(f) \propto f^{-2.6}$. It is a direct evidence of the DAW turbulence. When the strength of the wave-wave interaction increases as the background dissipation decreases by decreasing pressure, the amplitude and frequency fluctuations become more violent with the extreme wave crests caused by the stronger compression and the short time scale bursts [see run II in Fig. 1(a)]. The crossover of the power spectra for the two runs and the extending power law relation regime to the low frequency side from run I to run II indicate that energy is transferred from the self-excited fundamental mode to the low and the high frequency regimes.

The semi-logarithmic plots of the histograms $P(n)$ of the normalized dust density for the two runs are shown in Fig. 1(c). For both two runs, $P(n)$ is asymmetric with respective to the average, $n = 1$. In the trough regime ($n < 1$), the fast descending left arm and the lower bound of n are caused by the absence of dust particles ($n = 0$) during the rarefaction. On the other hand, in the crest regime ($n > 1$), the strong compression leads to the stretched right arm with higher n. When pressure decreases, the M-shape distribution is smoothed out and the level of the asymmetry increases with the more stretched right tail in $P(n)$. The asymmetric $P(n)$ is a consequence of the lower bound of the density ($n = 0$) in the wave trough under the strong depletion caused by rarefaction.

Whether the system exhibits multifractal dynamics can be tested by the analysis of the struc-

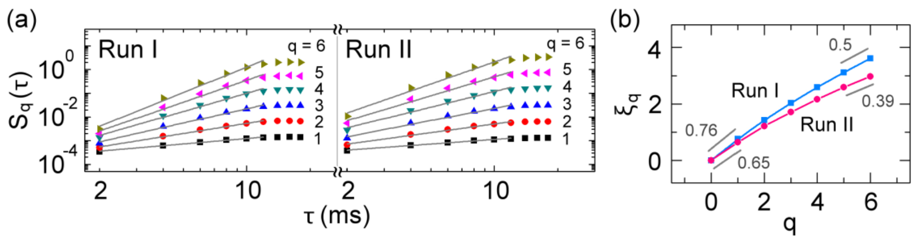

Figure 2: (a) Structure function $S_q(\tau)$ of the wave height increments δn_τ versus τ, under different q. Solid lines are the best power-law fits, $S_q(\tau) \propto \tau^{\xi_q}$. The data are shifted by a multiplicative factor. (b) The plots of the exponent ξ_q, obtained from the slopes of the gray lines in (a), versus q for both runs. The numbers correspond to the slopes of gray solid lines at the two ends of the curves. The stronger downward bending of the curve of run II manifests the stronger multifractality of the more turbulent state.

tural function,

$$S_q(\tau) = \langle|\delta n_\tau|^q\rangle = \langle|n(t+\tau) - n(t)|^q\rangle, \tag{1}$$

where $\langle ... \rangle$ is the time average and δn_τ is the dust density increment [2]. The moment q is used to determined the dominant δn_τ during the averaged process. Over the self-similar regime of $n(t)$, the power law relation $S_q(\tau) \propto \tau^{\xi_q}$ are found. ξ_q is called the scaling exponent of the structure function. It describes how the dominant δn_τ varies as τ varies. In order to understand ξ_q-q relation, other scaling behaviors $\delta n_\tau \sim \tau^\alpha$ and $P(\delta n_\tau) \sim \tau^{f(\alpha)}$ are introduced, where $P(\delta n_\tau)$ is the probability distribution function of δn_τ. Therefore,

$$S_q(\tau) = \int P(\delta n_\tau)|\delta n_\tau|^q d\delta n_\tau \tag{2}$$

is contributed from different δn_τ^*, the dominant δn_τ at different q, which is determined by

$$\frac{d}{d\alpha}(f(\alpha) + \alpha q) = 0. \tag{3}$$

It leads to the scaling relation $S_q(\tau) \sim \tau^{\xi_q}$ with $\xi_q = f(\alpha) + \alpha q$. α_q corresponding to the *Lipschitz − Hölder* exponent of δn_d^* at q is used to characterize the singularity. It can be obtained through

$$d\xi_q/dq = \frac{df(\alpha)}{d\alpha}\frac{d\alpha}{dq} + q\frac{d\alpha}{dq} + \alpha = \alpha. \tag{4}$$

At the low (high) q, $S_q(\tau)$ probes the scaling rule of the small (large) δn_τ. Wave turbulence is considered as monofractal (multifractal) if the ξ_q-q relation is linear (non-linear). The multifractality can be attributed to the irregular transfer or dissipation of the forwardly cascaded energy in turbulence [2].

Fig. 2(a) shows the structure function $S_q(\tau)$ versus τ at different q. Fig. 2(b) shows the scaling exponent ξ_q measured from the power law fitting from τ = 2 to 12 ms at different q in Fig. 2(a). For both two runs, the nonlinear ξ_q-q curves indicate the multi-fractal scaling behaviors of the local dust density. The downward bending and the decreasing α_q along q (from 0.76 to 0.5 for run I and from 0.65 to 0.39 fro run II) implies the stronger singularity for the higher δn^*_τ. For the more turbulent run II, the stronger compression causes the stronger singularity which can be directly observed as the strong intermittent bursts in the evolution of n [see Fig. 1(a)].

In conclusion, we experimentally demonstrate the observation of the self-excited dust acoustic wave turbulence with multifractal dynamics in the low pressure dusty plasma. The major findings are listed below. A) $n(t)$ has a broad power spectrum following $S(f) \sim f^{-2.6}$, with energy cascaded from the self-excited low frequency mode to the high frequency end through nonlinear interaction. B) The strong dust compression and the lower bound of n due to dust rarefaction leads to asymmetric $P(n)$. C) The nonlinear ξ_q-q relation obtained from $S_q(\tau)$ analysis reveals the multifractal behavior. D) Decreasing background pressure decreases neutral dissipation and leads to the more turbulent state with larger amplitude fluctuation, broader power law distribution in the power spectrum, the higher asymmetric level of $P(n)$, and the stronger downward bending of the ξ_q-q curve associated with the more frequent intermittent bursts in $n(t)$.

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