Formation Process of a Solitary Vortex in a Zonal Flow – Drift-Wave Dynamics

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A solitary vortex organization process in drift-wave type fluctuations interacting with the zonal flow was identified experimentally in a linear magnetized plasma. An azimuthal probe array was used to evaluate temporal changes in the amplitude and phase in the density fluctuations. Excitation/damping of the solitary vortex is synchronized with zonal perturbation, and the waveform of drift-wave type fluctuation and its harmonics also changes synchronously. The solitary vortex is formed primarily through the phase modulation of the fundamental drift-wave type fluctuation and its harmonics.

Keywords: magnetized plasma, zonal flow, drift wave, solitary wave, solitary vortex

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Zonal flow, a secondary organized structure, is usually detected as a jet air stream on earth [1], ocean currents [2], Tachocline in the sun [3], Jupiter's striped atmosphere [4] and plasma [5–7]. For many practical applications, such as predicting the climate in long-term planetary atmospheres and creating a control system of magnetically-confined nuclear fusion, it is crucial to clarify the physics of interactions between turbulence and zonal flow. In such scenarios of coexisting turbulence and zonal flow, a solitary vortex, which lives longer than the usual wave period of turbulence, is often formed. The great red spot in the Jovian atmosphere and cyclones and typhoons in the earth's atmosphere [8] are well-known examples. Moreover, the generation of solitary vortex impacts the energy balance among turbulence and structures [9]. Therefore, showing that the role of the solitary vortex is crucial.

Recent investigations on plasma turbulence have noted the coexistence of a solitary vortex structure in addition to zonal flows and drift-wave type fluctuations [10–12]. The solitary vortex is a perturbation with circumnavigating motion, localized radially and azimuthally, and survives longer than the characteristics wave period of the drift-wave type fluctuations [10]. These studies' drift-wave type fluctuations are characteristic of nonlinear solitary waves [12]. These studies have demonstrated that the solitary vortex enhances the zonal flow as well as the nonlinear solitary wave and thus plays an important role in the plasma transport [10]. However, the way in these structures are organized is still unclear.

In this study, the formation process of the solitary vortex in a zonal flow–nonlinear solitary wave system was identified experimentally. A spatio-temporal analysis was conducted for the solitary vortex and the nonlinear solitary wave synchronized with zonal perturbations. It was clear how the nonlinear solitary wave's amplitude/phase changes relate to the solitary vortex's excitation and damping.

Turbulence excitation experiments were conducted in a linear magnetized plasma (LMD-U) [13, 14]. A cylindrical argon plasma with a diameter of 0.1 m and an axial length of 3.74 m was produced using a radio frequency (RF) wave and radially restricted using the magnetic field. The operational circumstances were 3 kW RF power, 900 G magnetic field and 5 mTorr argon gas pressure with no external source of momentum. The charac-

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teristic plasma parameters are ~$6 \times 10^{18}\,\mathrm{m^{-3}}$ of central plasma density and ~2.5 eV electron temperature. The primary diagnostic tool is an azimuthal array with 64 probes located at radius $r = 4$ cm, where the density gradient is maximum. The Langmuir probe determine the ion saturation current (I_{is}), which is presumed to be proportional to the electron density.

Next, a description of the spatio-temporal evolution of the turbulence detected using the probe array follows. Figure 1 (a) indicates the azimuthal-temporal variation of I_{is}, and Fig. 1 (b) is for $\theta = 0$. The triangular wave (a nonlinear solitary wave) propagates articulately in the electron diamagnetic direction. The fundamental drift-wave type mode ($m = 1$, $\omega_{DW} = 1.2$ kHz) and its higher harmonics, which have nearly identical phase velocities, make up the nonlinear solitary wave [12]. In this study, the m is the azimuthal mode number, which is related to the wave number (k_θ) as $m = 2\pi r k_\theta$ and ω_{DW} shows the frequency of the fundamental mode. The waveform of the nonlinear solitary wave propagates in a slowly changing form, synchronized with the period of the zonal flow (~0.4 kHz), and is accompanied by the solitary vortex [10, 11]. The spatio-temporal evolution of I_{is} in a plasma frame is presented in Fig. 1 (c), where the linear phase shift of the azimuthal angle θ is subtracted to clarify the changes of the nonlinear solitary wave. The nonlinear solitary wave ($\theta' = 0$ - 0.7 rad/2π) and satellite ($\theta' = 0.7$ - 1 rad/2π) are differentiated. Azimuthal profiles of I_{is} at $t = 234.5$ and $t = 236.3$ ms are shown in Fig. 1 (d), which correspond to the cases with and without the satellite, respectively. The slope of the azimuthal profile in the nonlinear solitary wave at $\theta' = 0.3$ - 0.7 rad/2π is also observed to change due to the formation of the satellite. The satellite is made up of two-phase velocity structures: the density bump connected to the solitary vortex under study has a lower velocity of $2.6 \times 10^3\pi$ rad/s, while the splash has a greater velocity of $4 \times 10^3\pi$ rad/s and a shorter lifetime [11, 12]. This excitation/damping is also synchronized with zonal fluctuation. Note that the two-dimensional cross-sectional image for the nonlinear solitary wave and the solitary vortex was evaluated in [10, 11]. Figure 1 (e) shows a cross-sectional image with the excited solitary vortex (dotted ellipse), where the filled contours denote the fluctuation component of I_{is} and the contour lines denote the potential fluctuation reconstructed using a radially movable Langmuir probe and the azimuthal probe array (see [11] for more details). The brown colored circle indicates the radial location of the azimuthal probe array ($r = 4$ cm).

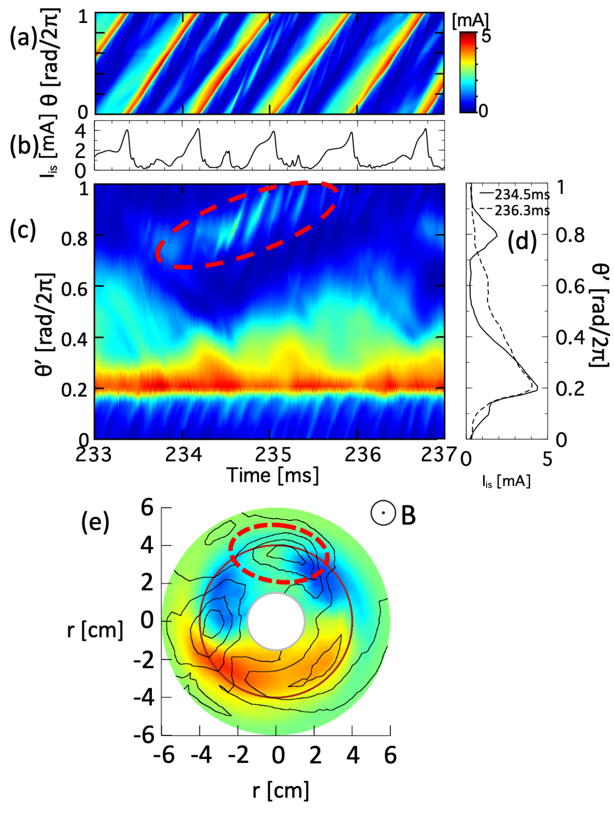

Fig. 1 (a) Spatio-temporal evolution of ion saturation current [$I_{is}(\theta, t)$] by azimuthal probe array at $r = 4$ cm. The positive azimuthal direction indicates the electron diamagnetic direction. (b) Temporal evolution of $I_{is}(0, t)$. (c) Spatio-temporal evolution of $I_{is}(\theta, t)$ with plasma frame on (a). The dotted ellipse indicates the excitation of the solitary vortex and the splash. (d) Azimuthal profiles of $I_{is}(\theta, t = 234.5\,\mathrm{ms})$ (solid line) and $I_{is}(\theta, t = 236.3\,\mathrm{ms})$ (dashed line). (e) Cross-sectional structure of I_{is} fluctuation (filled contours) and potential fluctuation (contour lines) [10, 11]. The dotted ellipse indicates the excitation of the solitary vortex. The brown colored circle indicates $r = 4$ cm.

Azimuthal changes in amplitude and phase synchronized with zonal perturbation were evaluated to clarify the relationship between the solitary vortex and the nonlinear solitary wave. The amplitude and phase change can be decomposed as $I_{is}(\theta, t) = \sum_m A(m, t) \exp(i\phi(m, t)) \exp(im\theta)$. The amplitude variation, $A(m, t)$, directly impacts the wave variation. The phase, $\phi(m, t)$, is expressed as follows;

$$\phi(m, t) = m\omega_{DW}t + \int \frac{m}{r} v_{ZF} dt + \psi(m, t), \tag{1}$$

where, $m\omega_{DW}t$ is the linear phase shift due to nonlinear solitary wave, v_{ZF} is the zonal flow velocity, $m/r \cdot v_{ZF}$ is the linear frequency shift due to the zonal flow and $\psi(m, t)$ is the higher-order nonlinear component, which is effective in distorting the waveform of the nonlinear solitary wave. Conditional averaging with the template method [15] was applied to the spatio-temporal I_{is} in the plasma frame to observe how the wave varies. The result is presented in Fig. 2 (a). The time t_0 at a local peak of density bump on the solitary vortex was used as the reference waveform because the solitary vortex excitation/damping is synchronized with the zonal perturbation. The delay time for the i-th period, τ, is defined as $\tau = t - t_0(i)$. The wave distortion by the phase change can be assessed by subtracting

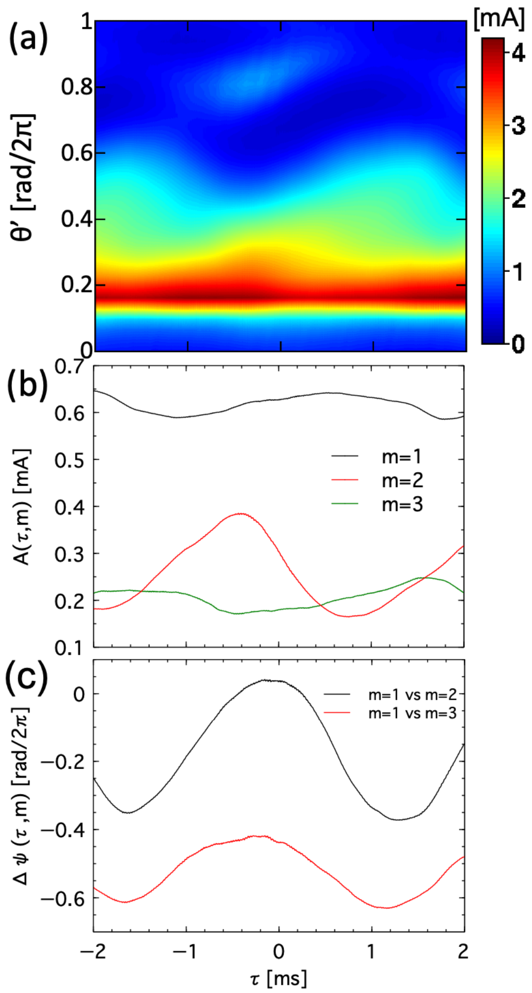

Fig. 2 (a) Spatio-temporal evolution of the nonlinear solitary wave and the the density bump of the solitary vortex, which is conditionally averaged using the template method with plasma frame. (b) Temporal evolution of amplitudes of azimuthal mode numbers $m = 1$ - 3 around $\tau = 0$ ms, $A(m, \tau)$. (c) Eq. (2) defines the temporal evolution of $\Delta\psi(m, \tau)$.

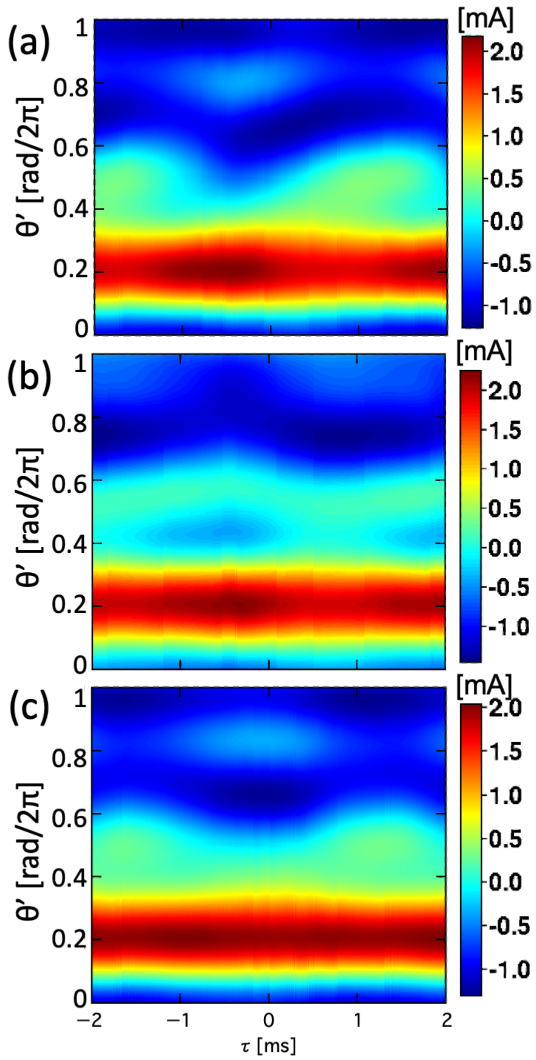

Fig. 3 (a) Reconstructed $I_{is}(\theta', \tau)$ considering the changes of both $A(m, \tau)$ and $\Delta\psi(m, \tau)$ with $m = 1$ - 3. (b) Reconstructed $I_{is}(\theta', \tau)$ considering the changes of $A(m, \tau)$ only. (c) Reconstructed $I_{is}(\theta', \tau)$ variations in $\Delta\psi(m, \tau)$ only.

the phase of $\phi(m = 1, \tau)$ as [16],

$$\Delta\psi(m, \tau) = \phi(m, \tau) - m\phi(1, \tau) = \psi(m, \tau) - m\psi(1, \tau). \quad (2)$$

Figures 2 (b) and (c) show the amplitude change [$A(m, \tau)$] for $m = 1$ - 3 and the comparative phase change [$\Delta\psi(m, \tau)$] for $m = 2$ - 3 synchronized with the zonal perturbation. $A(m, \tau)$ and $\Delta\psi(m, \tau)$ change synchronously with the zonal flow. $A(m, \tau)$ varies particularly for $m = 2$, while $\Delta\psi(m, \tau)$ varies significantly for both $m = 2$ and $m = 3$ relative to $m = 1$. These indicate that the zonal flow nonlinearly modulates the waveform.

The nonlinear solitary wave and the solitary vortex are formed principally in the lower azimuthal modes. Figure 3 (a) indicates the reconstructed spatio-temporal structure considering $m = 1$ - 3 for $A(m, \tau)$ and $\Delta\psi(m, \tau)$. The figure shows excitation/damping of the solitary vortex, similar to Fig. 2 (a), including variation in the slope of the nonlinear solitary wave.

The waveform was reconstructed by isolating either $A(m, \tau)$ or $\Delta\psi(m, \tau)$ to clarify the dominant mechanism of solitary vortex generation. Figure 3 (b) or (c) indicates the reconstructed waveform when considering the time variation in one of $A(m, \tau)$ or $\Delta\psi(m, \tau)$. The solitary vortex excitation/damping is recovered for $\theta' = 0.7$ - 1 rad/2π in Fig 3 (c); however, not in Fig. 3 (b). Furthermore, the variation in the slope of the nonlinear solitary wave ($\theta' = 0.3$ - 0.7 rad/2π) is also obtained in Fig. 3 (c) but not in Fig. 3 (b). Therefore, the nonlinear phase change of the nonlinear solitary wave due to the zonal flow was the central factor in the formation of the solitary vortex. This observation would be attributed to the regulation of the fundamental mode of the nonlinear solitary wave by the zonal flow, which in turn impacts the amplitude and phase relationship between the fundamental and harmonics.

In conclusion, the solitary vortex formation process is observed in nonlinear solitary wave–zonal flow system in a linear magnetized plasma. The amplitude and phase of the waves synchronized with zonal fluctuation (~ 0.4 kHz) were evaluated using an azimuthal probe array. The solitary vortex is primarily organized using the phase changes of the fundamental drift-wave type mode ($m = 1$, $\omega_{DW} = 1.2$ kHz) and its higher harmonics in the nonlinear solitary wave. Therefore, it must develop a theory of solitary vortex formation that considers the phase regulation effects caused by zonal flow.

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[1] F.J. Beron-Vera, M.G. Brown, M.J. Olascoaga, I.I. Rypina, H. Koçak and I.A. Udovydchenkov, Zonal jets as transport barriers in planetary atmospheres, J. Atmos. Sci. **65** (10), 3316 (2008).

[2] N.A. Maximenko, B. Bang and H. Sasaki, Observational evidence of alternating zonal jets in the world ocean, Geophys. Res. Lett. **32** (12), L12607 (2005).

[3] D.W. Hughes, R. Rosner and N.O. Weiss, *The Solar Tachocline* (Cambridge University Press, 2007).

[4] A.R. Vasavada and A.P. Showman, Jovian atmospheric dynamics: An update after Galileo and Cassini, Rep. Prog. Phys. **68**, 1935 (2005).

[5] P.H. Diamond, S.-I. Itoh, K. Itoh and T.S. Hahm, Zonal flows in plasma–a review, Plasma Phys. Control. Fusion **47**, R35 (2005).

[6] A. Fujisawa, K. Itoh, H. Iguchi, K. Matsuoka, S. Okamura, A. Shimizu, T. Minami, Y. Yoshimura, K. Nagaoka, C. Takahashi *et al.*, Identification of zonal flows in a toroidal plasma, Phys. Rev. Lett. **93** (16), 165002 (2004).

[7] M. Nakata, M. Nunami, H. Sugama and T. Watanabe, Isotope effects on trapped-electron-mode driven turbulence and zonal flows in helical and tokamak plasmas, Phys. Rev. Lett. **118** (16), 165002 (2017).

[8] G.K. Vallis, *Atmospheric and oceanic fluid dynamics* (Cambridge University Press, 2017).

[9] J. Tollefson, M.H. Wong, I. de Pater, A.A. Simon, G.S. Orton, J. Rogers, S.K. Atreya, R.G. Cosentino, W. Januszewski, R. Morales-Juberías *et al.*, Changes in jupiter's zonal wind profile preceding and during the juno mission, Icarus **296**, 163 (2017).

[10] H. Arakawa, S. Inagaki, M. Sasaki, Y. Kosuga, T. Kobayashi, N. Kasuya, Y. Nagashima, T. Yamada, M. Lesur, A. Fujisawa *et al.*, Eddy, drift wave and zonal flow dynamics in a linear magnetized plasma, Sci. Rep. **6**, 33371 (2016).

[11] H. Arakawa, M. Sasaki, S. Inagaki, Y. Kosuga, T. Kobayashi, N. Kasuya, T. Yamada, Y. Nagashima, F. Kin, A. Fujisawa, K. Itoh and S.-I. Itoh, Roles of solitary eddy and splash in drift wave-zonal flow system in a linear magnetized plasma, Phys. Plasmas **26** (5), 052305 (2019).

[12] H. Arakawa, T. Kobayashi, S. Inagaki, N. Kasuya, S. Oldenbürger, Y. Nagashima, T. Yamada, M. Yagi, A. Fujisawa, K. Itoh *et al.*, Dynamic interaction between a solitary drift wave structure and zonal flows in a linear cylindrical device, Plasma Phys. Control. Fusion **53** (11), 115009 (2011).

[13] T. Yamada, S.-I. Itoh, T. Maruta, N. Kasuya, Y. Nagashima, S. Shinohara, K. Terasaka, M. Yagi, S. Inagaki, Y. Kawai *et al.*, Anatomy of plasma turbulence, Nature Phys. **4** (9), 721 (2008).

[14] H. Arakawa, S. Inagaki, Y. Nagashima, T. Yamada, K. Kamataki, T. Kobayashi, S. Sugita, M. Yagi, N. Kasuya, A. Fujisawa, S.-I. Itoh and K. Itoh, Bifurcation of the plasma turbulence on LMD-U, Plasma Phys. Control. Fusion **52** (10), 105009 (2010).

[15] S. Inagaki, Y. Miwa, T. Kobayashi, T. Yamada, Y. Nagashima, T. Mitsuzono, H. Fujino, M. Sasaki, N. Kasuya, M. Lesur, Y. Kosuga, A. Fujisawa, S.-I. Itoh and K. Itoh, Identification of quasi-periodic nonlinear waveforms in turbulent plasmas, Plasma Fusion Res. **9**, 1201016 (2014).

[16] M. Sasaki, N. Kasuya, T. Kobayashi, H. Arakawa, K. Itoh, K. Fukunaga, T. Yamada, M. Yagi and S.-I. Itoh, Formation mechanism of steep wave front in magnetized plasmas, Phys. Plasmas **22**, 032315 (2015).