

Phase Structure of Density Perturbations Modulates Interchange Convection in Jupiter's Inner Magnetosphere*

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Abstract

Outward transport of cold iogenic plasma in Jupiter's inner magnetosphere is governed by the interchange instability, which is highly sensitive to the spatial structure of the Io plasma torus. Using the Rice Convection Model-Jupiter, we investigate how phase shifts in density perturbations, whether imposed initially or induced by background velocity shear, affect interchange convection. A series of runs explore the respective effects of imposed phase shifts and background velocity shear on both a prescribed Io torus and an active Io source. We find that while these factors do not alter the overall evolution of convection, they strongly modulate its morphology and dynamics. Phase shifts exert their strongest influence during the early stage, where larger shifts more effectively suppress interchange instability, modulate morphological evolution, and regulate plasma flow. This influence markedly diminishes by the quasi-steady stage. Background velocity shear suppresses instability via two intertwined mechanisms, inducing phase shifts (dominant early) and reducing local angular velocity (more prominent later), which are often difficult to separate.

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1 Introduction

Mass and energy transport in Jupiter's inner magnetosphere (e.g., $L < \sim 20R_J$, $1R_J = 71492\text{km}$) is primarily governed by the planet's rapid rotation (spin period: $\sim 10\text{h}$) and the dominant internal plasma source originating from its Galilean moon, Io^{[1][2]}. Io's volcanic activity sustains a dense SO_2 -rich atmosphere, from which neutral particles are continuously supplied to the magnetosphere, forming a neutral torus centered near Io's orbit ($L \approx 5.9 R_J$)^[3]. Subsequent ionization of these neutrals, via electron impact or charge exchange, generates the Io plasma torus, which spans radial distances from $L < \sim 4.7 R_J$ to beyond $L \approx 8 R_J$ ^[4]. The Io plasma torus exhibits significant spatial and temporal variability due to complex physical processes, including ion pickup, centrifugal confinement to the equatorial plane, radial transport and collisional physical chemistry interactions. Both remote sensing and in-situ measurements have revealed pronounced longitudinal asymmetries in the torus^[4].

Outward transport of Iogenic plasma in Jupiter's inner magnetosphere is driven by the centrifugally driven interchange instability^[5], which simultaneously produces outward motion of cold iogenic plasma and inward injection of hot plasma^{[6][7][8][9][10][11]}. Theoretical analyses, based on idealized magnetic field geometries and simplified Io plasma torus models, demonstrate that the linear growth rate of this instability depends on the radial plasma density gradient, ionospheric Pedersen conductance, local magnetic field strength, and the presence of energetic particles^{[5][12][13][14][15]}. Rice Convection Model (RCM)-based simulations corroborate these findings and identify additional controlling factors: spatially inhomogeneous Hall conductance, Io plasma source rate^[16], characteristics of energetic particle injections^[9], and magnetic field configuration^[17].

In addition to the aforementioned controlling factors, the spatial structure of the Io plasma torus also plays a pivotal role. However, prior studies have predominantly considered only the radial density profile and total plasma source rate, largely owing to underlying simplifying assumptions^{[5][16]}, thereby neglecting the role of the torus's azimuthal structures. Pontius et al.^[18] first proposed that differential corotation (i.e., shear in the rotational velocity) induces an azimuthal phase shift between radially neighboring density perturbations, disrupting their coherency and consequently stabilizing the interchange instability. This mechanism, together with the influence of energetic particles, was invoked to account for the sharp radial decline in plasma density across $L \approx 7\text{--}8 R_J$ (the so-called plasma ramp) observed by Voyager 1^{[18][19]}. Supporting this, initial-value RCM simulations by Pontius et al.^[18] showed that velocity shear progressively tilts outward-moving, elongated fingers sideways, and inhibits their nonlinear development. Hiraki et al.^[20] utilized a reduced two-dimensional (2D) magnetohydrodynamic (MHD) model to demonstrate the role of velocity shear in shaping interchange-distorted structures in the Io torus. Nevertheless, these

simulations have been confined to initial-value approaches without an active plasma source rather than self-consistent, time-evolving full simulations^{[18][21]}, leaving the cumulative impact of velocity shear on plasma convection over the whole magnetosphere evolution unresolved. Furthermore, azimuthal phase offsets between radially adjacent density perturbations may arise not only from velocity shear but also from intrinsic azimuthal inhomogeneities in the initial Io torus distribution; however, the impact of the latter remains poorly constrained.

Building upon these unresolved issues, this study investigates how the phase structure of density perturbations influences interchange convection in Jupiter's inner magnetosphere, using fully time-dependent simulations implemented with the RCM-Jupiter model^{[9][16][17]}.

The paper is organized as follows: Section 2 outlines the model settings; Sections 3 and 4 present the primary simulation results and their discussion; and Section 5 summarizes the key findings and conclusions.

2 Model Description

The RCM-Jupiter code, a 2D multifluid model, has been successfully used to investigate interchange convection in Jupiter's inner magnetosphere, a process governed by the concurrent outward transport of cold iogenic plasma and injections of energetic particles^{[9][16][17]}. The model simulates bounce-averaged plasma drifts in a prescribed magnetic field geometry, with each fluid species characterized by two parameters: the flux tube content $\eta = \int ndz/B$, representing the number of particles per unit magnetic flux (where n is the plasma number density and B the local magnetic field strength), and the energy invariant $\lambda = E \cdot V^{2/3}$, where E denotes the particle kinetic energy and V the flux tube volume^[22]. Comprehensive details on the RCM-Jupiter framework, including its underlying calculation logic, governing equations, energetic plasma and ionospheric conductance model, are provided in Wang et al.^{[9][16]}. Herein, we only present the main aspects relevant to this study.

2.1 Io plasma torus

The Io plasma torus consists of an active Io source term ($\dot{\eta} = \partial\eta/\partial t$) and an initial torus configuration (η_0), both explicitly incorporated into the RCM-Jupiter model. The model is used to examine how phase structures, defined as azimuthal phase shifts between radially adjacent density perturbations ($\delta\eta_0$), modulate interchange convection in Jupiter's inner magnetosphere. Such structures may arise either in the Io source or in the initial torus. To disentangle their respective effects, the initial density distribution and the Io plasma source must be specified independently.

2.1.1 The Initial Density Distribution η_0

Given that this study isolates the effect of the phase-shifted density perturbations on interchange instability, it does not seek to reproduce a realistic Io plasma torus. Accordingly, the torus density is idealized as a monotonically decreasing profile, and only a single ion species (i.e., cold oxygen ions with zero temperature) is included.

Figure 1 shows the initial equatorial plasma density distribution in the Io torus. We prescribe a radially confined annular torus region in the equatorial plane, extending from Io's orbital radius ($L=5.9R_J$) to $L=8.0R_J$. The initial plasma density η_0 consists of an azimuthally symmetric background η_{00} (Figure 1d) and a perturbation $\delta\eta_0$ (Figure 1e), such that $\eta_0(L, \varphi) = \eta_{00}(L) + \delta\eta_0(L, \varphi)$. Here, L denotes the radial distance from Jupiter and φ the azimuthal angle (i.e., the longitude in Jupiter's corotating frame) in the equatorial plane. The fluxtube content is given analytically as follows.

$$\eta_{00}(L) = \eta_{0,\max} \cdot \begin{cases} \left(\frac{L}{5.9}\right)^{-22}, & 5.9 < L \leq 8.0 \\ 0, & \text{elsewhere} \end{cases} \quad [1]$$

$$\delta\eta_0(L, \varphi) = 0.01 \cdot \eta_{00}(L) \cdot \cos[20(\varphi + \Delta\varphi)] \quad [2]$$

where $\Delta\varphi(L) = -(L - 8.0) / 2.1 \cdot \varphi_{0,\max}$, and $\varphi_{0,\max}$ represents the maximum phase shift in the Io torus, varied across simulation runs (see Section 2.3). $\eta_{0,\max}$ is fixed at $10^{23} T^{-1} m^{-2}$ inferred from Galileo measurements^[23].

Similar to Pontius et al.^[13], Equation 1 describes the background plasma density η_{00} as exhibiting a power-law decay with radial distance L . This profile is generally consistent with observations in the Io torus (Section 4.1) and conducive to interchange instability. The perturbation $\delta\eta_0$ is formulated as a cosine function of longitude φ , preserving azimuthal symmetry while incorporating a radially varying phase shift $\Delta\varphi$ (Figure 1b, 1c and 1e). Figure 1c illustrates how this radial dependence of $\Delta\varphi$ systematically shifts the longitudinal positions of the perturbation peaks with L . The amplitude of $\delta\eta_0$ is limited to 1% of the background density to minimize its impact on the convection system through total density variations. The azimuthal wavenumber is fixed at 20 (Equation 2), an arbitrary chosen value. Although the wavenumber modulates growth rates and finger structure via azimuthal density perturbations^[21], our primary conclusions rely on relative changes and are therefore insensitive to its specific value.

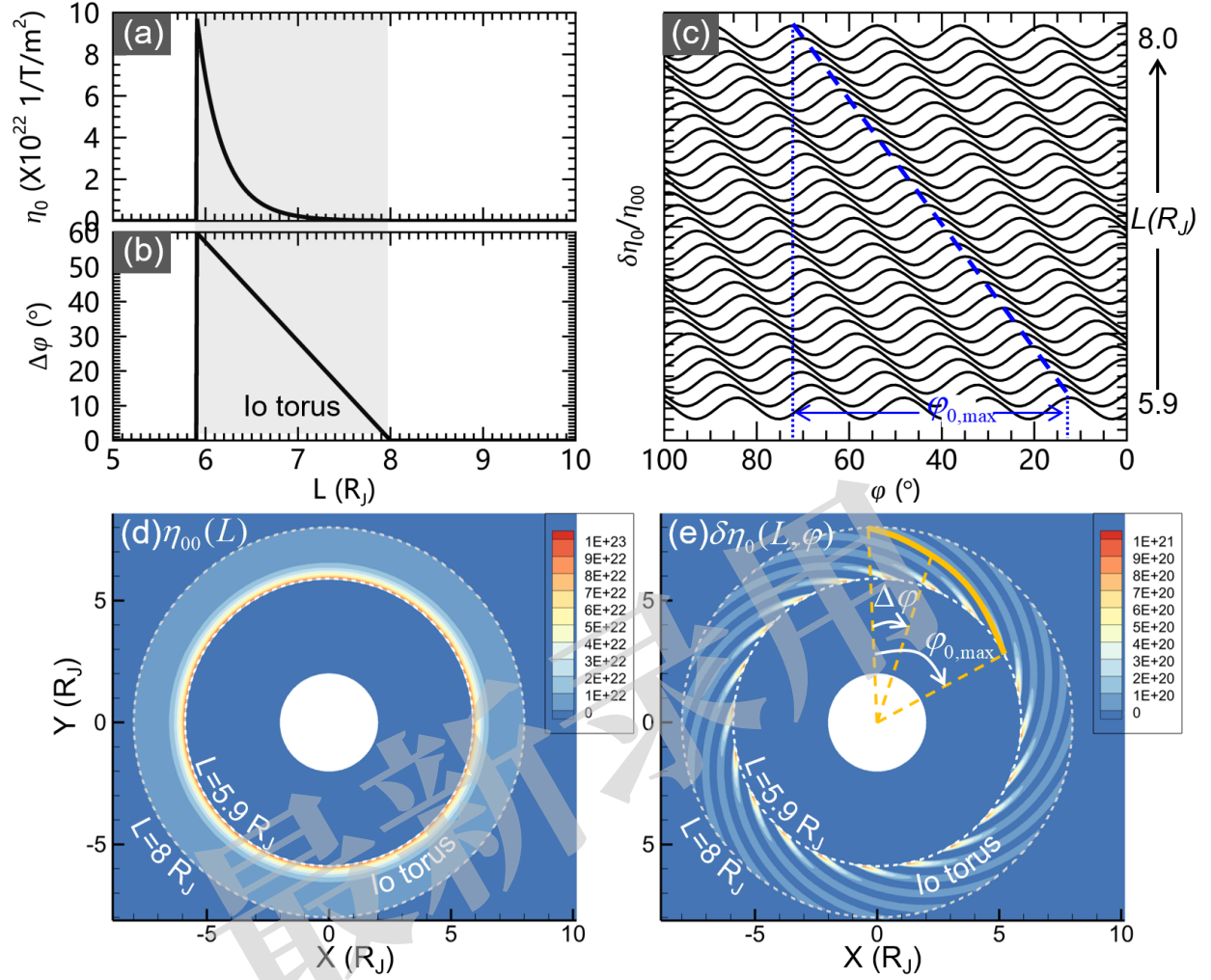


Figure 1. Initial equatorial plasma density distribution in the Io torus. (a) Radial profile of the background plasma density. (b) Radially varying phase shift $\Delta\phi$, reaching a maximum of $\phi_{0,max}=60^\circ$. The grey shading indicates the Io torus region. (c) Normalized density perturbation $\delta\eta_0/\eta_{00}$ as a function of longitude ϕ and radial distance L . Profiles at fixed L are vertically offset for visual clarity. (d) Background density η_{00} in the equatorial plane. (e) Corresponding perturbation $\delta\eta_0$ in the equatorial plane. White dashed circles mark the inner and outer radial boundaries of the Io torus.

2.1.2 The Io Plasma Source $\dot{\eta}$

Similar to the initial density distribution, the Io plasma source rate exhibits azimuthal symmetry with a radially varying phase shift. The source rate $\dot{\eta}$, defined as the ionization rate per unit magnetic flux ($T^{-1}m^{-2}s^{-1}$), is decomposed as $\dot{\eta}(L, \phi) = \dot{\eta}_0(L) + \delta\dot{\eta}(L, \phi)$.

where the background component $\dot{\eta}_0$ is given by

$$\dot{\eta}_0(L) = \dot{\eta}_{max} \begin{cases} (\frac{L}{5.9})^{-22}, & 5.9 < L \leq 8.0 \\ 0, & \text{elsewhere} \end{cases} \quad [3]$$

and the perturbation $\delta\dot{\eta}$ is

$$\delta\dot{\eta}(L, \varphi) = 0.01 \cdot \dot{\eta}_0(L) \cdot \cos[20(\varphi + \Delta\varphi)] \quad [4]$$

with the phase shift $\Delta\varphi$ identical to that of the initial density distribution (Section 2.1.1). The perturbation amplitude $\dot{\eta}_{max}$ is set to match a total source rate of 1.5 ton/s (Section 2.3), which corresponds to the upper bound observed empirically^[24]. Consequently, the resulting source rate distribution closely mirrors the morphology of the initial density distribution (Figure 1).

2.2 Velocity Shear

As outlined in Section 1, phase shifts in density perturbations can also arise from azimuthal velocity shear in the Io torus. Following Pontius et al.^[18], the background azimuthal velocity Δv_φ in Jupiter's corotating frame is adopted as:

$$\Delta v_\varphi = \begin{cases} 0, & L < L_0 \\ -\frac{\sqrt{2e} \cdot v_{max}}{\Delta L} \exp[-(\frac{L-L_0}{\Delta L})^2] \cdot (L-L_0), & L \geq L_0 \end{cases} \quad [5]$$

where $\Delta L = 1.3R_J$ is the width of the velocity trough, $L_0 = 5.0R_J$ its inner boundary, and $e \approx 2.71828$ the mathematical constant. Three values of v_{max} are examined: 0, 4 and 8 km/s (Section 2.3). It should be noted that in a realistic magnetosphere, the background velocity shear profile can be dynamic and complex. Here, it is simplified and idealized; the origin of this shear lies beyond the scope of this study.

Figure 2a shows that the velocity shear induces a retrograde deviation from rigid corotation ranging from $L = 5 R_J$ to beyond $8 R_J$, fully covering the Io torus. The associated electric field, $\mathbf{E} = -\Delta \mathbf{v}_\varphi \times \mathbf{B}$, points radially inward. Figures 2b-2d present the radial profiles of Δv_φ , the radial electric field component E_r and the plasma density η . The azimuthal velocity peaks at $L \approx 5.9R_J$ near Io's orbit, whereas the electric field maximum occurs slightly inward due to the radially declining magnetic field strength. As a result, the magnitudes of both the velocity and the associated electric field decrease monotonically across the torus and asymptotically vanish toward its outer edge. For $v_{max} = 4$ and 8 km/s, the resulting angular velocities are approximately 0.054 and $0.108\Omega_J$, respectively, where Ω_J is Jupiter's rotational angular velocity.

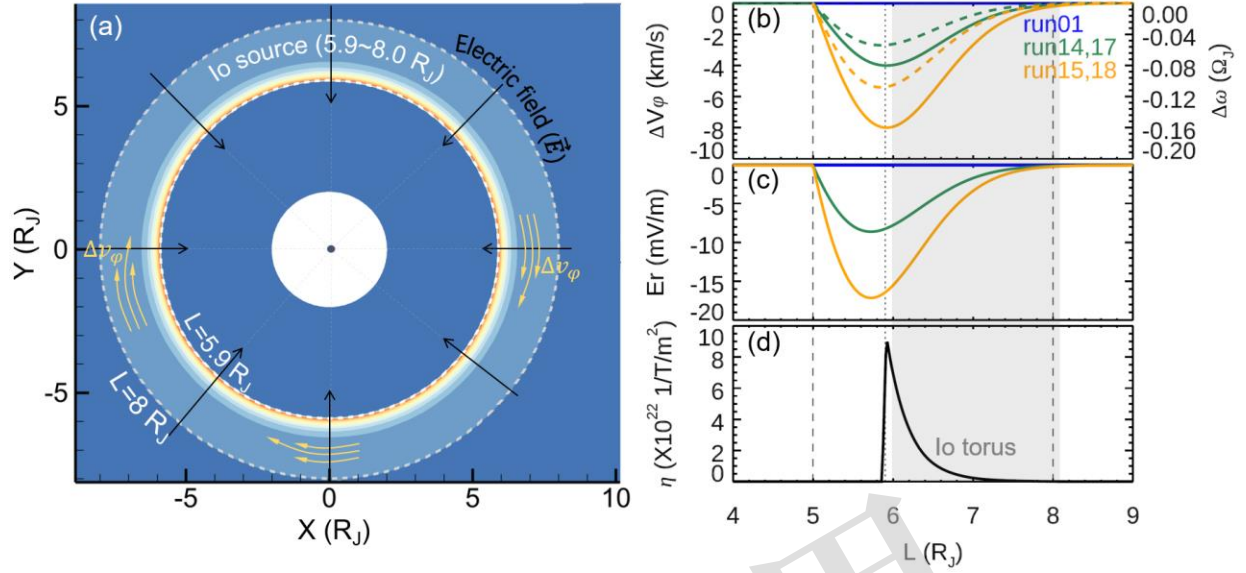


Figure 2. Schematic of velocity shear in Jupiter's inner magnetosphere. (a) Imposed background azimuthal velocity (yellow arrows) and the resulting radially inward electric field (black arrows). Contours indicate the plasma density distribution of the Io torus, bounded by two white dashed circles indicating its nominal boundaries. Panels (b)-(d) display radial profiles versus L : (b) azimuthal velocity Δv_ϕ (solid) and angular velocity (dashed), (c) corresponding radial electric field for different simulation runs (Section 2.3), and (d) plasma density. The Io torus region is shaded in grey.

2.3 Model Settings for All Runs

As outlined in Section 1, phase shifts in plasma density perturbations may originate from two mechanisms: (i) an imposed initial phase offset in the density distribution, or (ii) velocity shear, where differential rotation causes the phase shift to accumulate over time. These phase structures may be embedded either in the Io mass source or in the initial torus configuration (Section 2.1).

To disentangle the contributions of initial configuration, source structure, and velocity shear, we consider two distinct scenarios: (i) the evolution of prescribed phase structures in the absence of an active Io source, modelled by driving the system to a plasma-depleted state, and (ii) the evolution of sustained phase structures under a continuous Io mass loading, modelled by evolving the system from an initially empty magnetosphere to a quasi-steady state, consistent with the approach of Wang et al.^[16]

These scenarios are systematically explored through four groups of simulations (see Table 1):

- (1) Prescribed Io torus with an initial phase shift, no Io source, and no velocity shear (runs 1-7);
- (2) Initially empty magnetosphere with a phase-shifted Io source but no velocity shear (runs 8-13);

(3) Prescribed Io torus with no initial phase shift, no Io source, but with velocity shear (runs 14-16);

(4) Initially empty magnetosphere with an unshifted Io source and velocity shear (runs 17-19).

As summarized in Table 1, Group 1 quantifies how amplitudes of an initial phase shift in the plasma density distribution affect interchange convection. Group 2 investigates the effect of a persistent phase shift in the Io source across all evolutionary stages, especially the quasi-steady state. Group 3 assesses the influence of velocity shear on a prescribed Io torus, while Group 4 examines how a persistent velocity shear within the Io source modulates plasma convection. Groups 1 and 3 correspond to the first scenario (initial torus, no Io source), whereas Groups 2 and 4 correspond to the second scenario (no initial torus, active Io source).

Notably, the velocity shear profiles in runs 14-15 (or runs 17-18) locally reduce the angular velocity by up to 0.054 and $0.108\Omega_J$, respectively (see Figure 2b). Thus, the resulting convection is affected not only by velocity shear but also by the accompanying reduction in local angular velocity. To isolate the effect of velocity shear from that of reduced angular velocity, control runs 16 and 19 are performed with a uniform planetary rotation rate of $0.9\Omega_J$ (i.e., a $0.1\Omega_J$ subcorotation in Jupiter's corotating frame) and no velocity shear. A full description of these simulations is provided in Section 3.

Table 1. Model Settings for Simulation Runs of This Study

runs	Initial Io torus	Total Io source rate ($\dot{m}$, ton/s)	Max of Initial phase shift ($\varphi_{0,max}$, °)	Velocity shear (v_{max} , km/s)	Instability Onset (h)
1	Yes	0	0	0	4.3
2			10		4.4
3			20		4.7
4			30		5.0
5			60		5.4
6			120		5.7
7			180		5.9
8	No	1.5	0	0	22.3
9			10		22.7
10			20		23.8
11			30		24.0
12			60		24.2
13			120		25.0

14	Yes	0	0	4	4.4
15				8	4.7
16				0 ($0.9\Omega_J$)	5.3
17	No	1.5	0	4	25.5
18				8	28.5
19				0 ($0.9\Omega_J$)	24.8

3 Simulation Results

In this Section, we present simulation results from the four run groups listed in Table 1. We first examine how imposed phase shifts applied to either the initial plasma torus or the Io source affect plasma convection, followed by an analysis of velocity shear effects. All results are presented in Jupiter’s corotating frame.

3.1 Effects of Imposed Phase Shifts on Plasma Convection

3.1.1 Phase-Shifted Initial Plasma Torus (No Io Source)

Figures 3-5 show results from Group 1 (runs 1-7), which were initialized with varying imposed phase shifts in the Io plasma torus and no Io source. Although all runs evolve similarly, reshaping and transporting the initial torus outward via interchange instability to produce a largely plasma-depleted magnetosphere, distinct differences emerge across runs.

Figure 3 shows the normalized density perturbation ($\delta\eta_0/\eta_{00}$) for runs 1, 3 and 5, illustrating the evolution of magnetospheric convection over $T=0-7h$. At $T=0h$, the initial perturbation is set as uniformly spaced azimuthal sectors of alternating high-density ($\delta\eta_0>0$, yellow) and low-density ($\delta\eta_0<0$, purple) regions, forming a striped pattern whose azimuthal phase varies radially, thereby reflecting the imposed phase shift $\varphi_{0,max}$ across the Io torus (see Equation 4). During the early phase ($T=1-2h$), interchange convection drives the formation of radially extended structures in the inner magnetosphere, redistributing plasma and reshaping the torus. A clear radial displacement emerges: at the torus’s inner edge ($L\approx 5.9R_J$), high-density structures shift outward, while adjacent low-density sectors move inward. At this stage, runs with different imposed phase shifts $\varphi_{0,max}$ exhibit significant differences in the morphology and spacing of these evolving structures (see $T=1h$ in Figure 3). By $T=2h$, the initial stripes have evolved into radially elongated density structures with minimal azimuthal bending. Runs with smaller $\varphi_{0,max}$ show more developed and radially extended structures than those with larger $\varphi_{0,max}$. Beyond $T=5h$, these structures narrow and stretch into highly elongated, outward-propagating bent fingers, often displaying “Y”-shaped morphologies. However, in run 5 ($\varphi_{0,max}=60^\circ$), each high-density stripe breaks into two distinct elongated fingers, in contrast to the single-finger morphology observed in runs 1 and 3. More

generally, runs with $\varphi_{0,max} \leq 20^\circ$ (runs 1-3) consistently produce single-finger structures, whereas those with $\varphi_{0,max} \geq 30^\circ$ (runs 4-7, not shown) develop double-finger configurations. This bifurcation arises because the width of the initial azimuthal density stripes in the Io torus increases with $\varphi_{0,max}$. Wider stripes exhibit azimuthally varying radial density gradients, establishing two preferred longitudes within each high-density sector where local conditions favor the fastest growth of interchange instability.

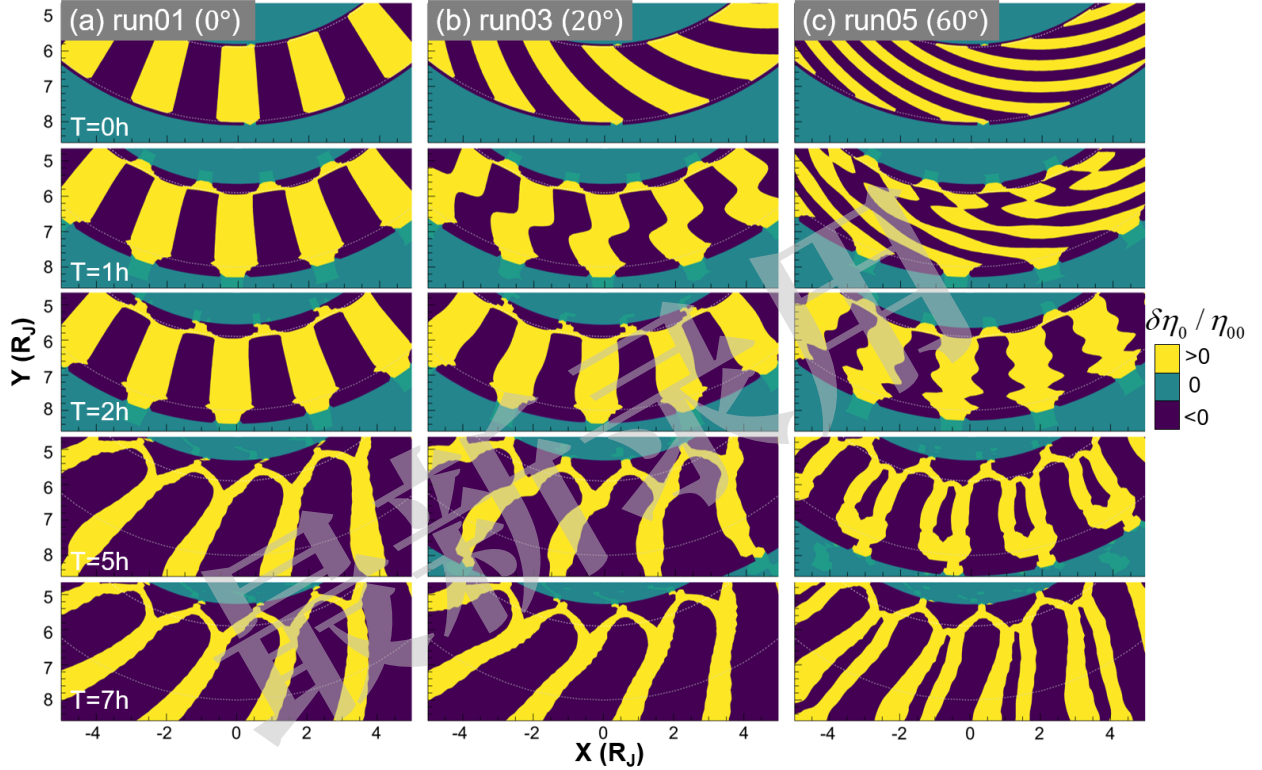


Figure 3. Normalized density perturbations $\delta\eta_0/\eta_{00}$ in the equatorial plane at selected times for (a) run 1, (b) run 3 and (c) run 5. White dashed curves denote the initial radial extent of the Io torus ($5.9 < L \leq 8.0 R_J$).

In addition to modulating the evolutionary morphology shown in Figure 3, the imposed phase shear $\varphi_{0,max}$ in the initial Io torus strongly affects plasma velocity and mass flux. Figure 4 shows the temporal evolution of the longitude-averaged radial velocity V_r , angular velocity ω and mass flux sampled at $L=8 R_J$, the immediate outer boundary of the Io torus. These quantities start near zero, peak at $T \approx 4.6h$, and then decay toward baseline levels, reflecting a transition to a depleted state. As shown in Figure 4c, runs with smaller $\varphi_{0,max}$ begin evolving earlier, as indicated by the initial rise in mass flux (see instability onset times in Table 1). The inflow V_r becomes comparable to the outflow for $\varphi_{0,max} \geq 30^\circ$. The peak V_r for the outflow increases with $\varphi_{0,max}$ for $\varphi_{0,max} \leq 20^\circ$ (runs 1-3), then drops abruptly to a lower plateau, before rising again for $\varphi_{0,max} \geq 30^\circ$ (runs

4-7 in Figure 4a). A similarly non-monotonic trend appears in the peak $|\omega|$. This behavior correlates with the structural bifurcation of interchange fingers described above: narrow initial stripes produce a single-finger structures, while wider stripes split into two (see $T=7h$ in Figure 3). Run 4 represents a transitional state, displaying three local maxima in its mass flux profile, likely due to partial finger splitting.

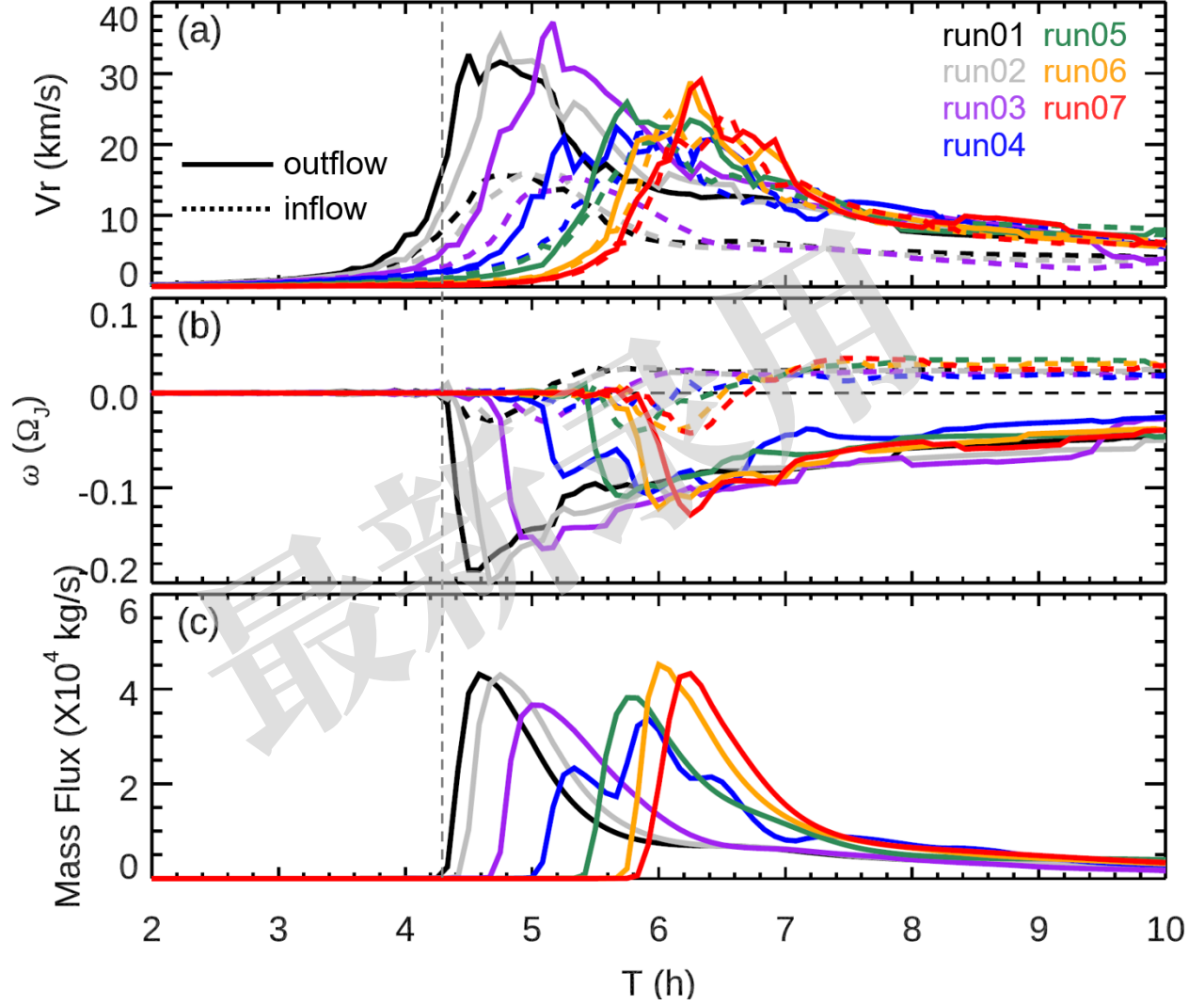


Figure 4. Temporal evolution of plasma convection across runs 1-7. (a) Longitude-averaged radial velocity V_r at $L=8R_J$ for the outflow (solid) and inflow (dashed). (b) Longitude-averaged angular velocity ω . (c) Outflow mass flux. The vertical dashed line marks the onset of mass flux increase in run 1.

While the preceding analysis addresses the global temporal evolution of the magnetosphere, we now focus on an individual interchange finger. Figure 5 shows key parameters at the leading edge (“fingertip”) for runs 1 and 5-7. The finger originates in the Io torus and propagates radially

outward with a subcorotational flow (clockwise azimuthal motion; Figures 5c and 5d). Both V_r and $|\omega|$ generally increase with L (or time), reaching $V_r \approx 80 \text{ km/s}$ and $|\omega| \approx 0.4\Omega_J$ by $T=9\text{h}$, when the fingertip extends beyond $L=15R_J$. Runs with larger $\varphi_{0,max}$ begin evolving later, propagate outward with generally lower V_r , and exhibit generally weaker subcorotation ($|\omega|$). These results suggest that larger $\varphi_{0,max}$ generally leads to stronger suppression of the interchange instability.

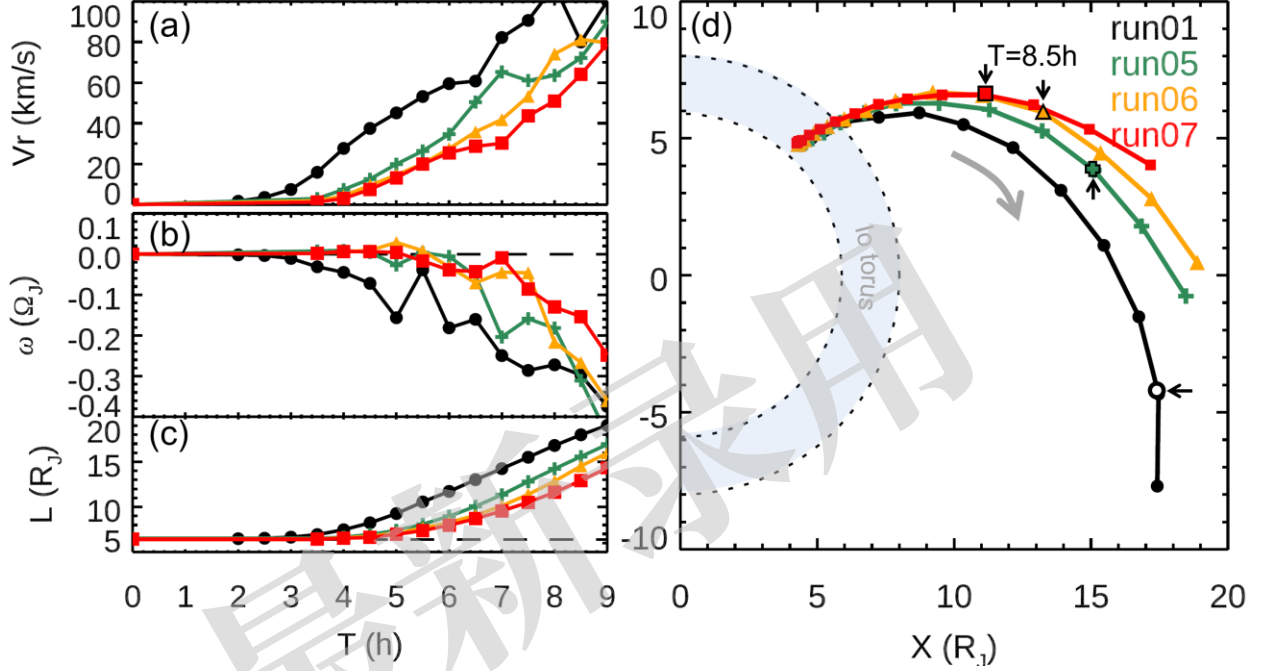


Figure 5. Temporal evolution of an individual finger for runs 1 and 5-7. (a) Radial velocity V_r , (b) angular velocity ω , and (c) radial distance of the fingertip from Jupiter versus time. (d) Fingertip trajectories in the equatorial plane. Black boxes with arrows mark the same initial fingertip at $T=8.5\text{h}$ across runs. The grey shading bounded by dashed circles denotes the Io torus.

3.1.2 Steady Io source with Phase Shift

Figures 6 and 7 illustrate the characteristic evolution of plasma convection driven by an active Io source, initialized from an empty magnetosphere. Consistent with Wang et al.^{[9][16]}, this evolution undergoes three stages: accumulation (Stage 1), developing (Stage 2) and quasi-steady stage (Stage 3). Figure 6 shows that runs 8-13 (Group 2, see Table 1) follow a consistent pattern across all three stages, although the influence of phase shifts remains evident.

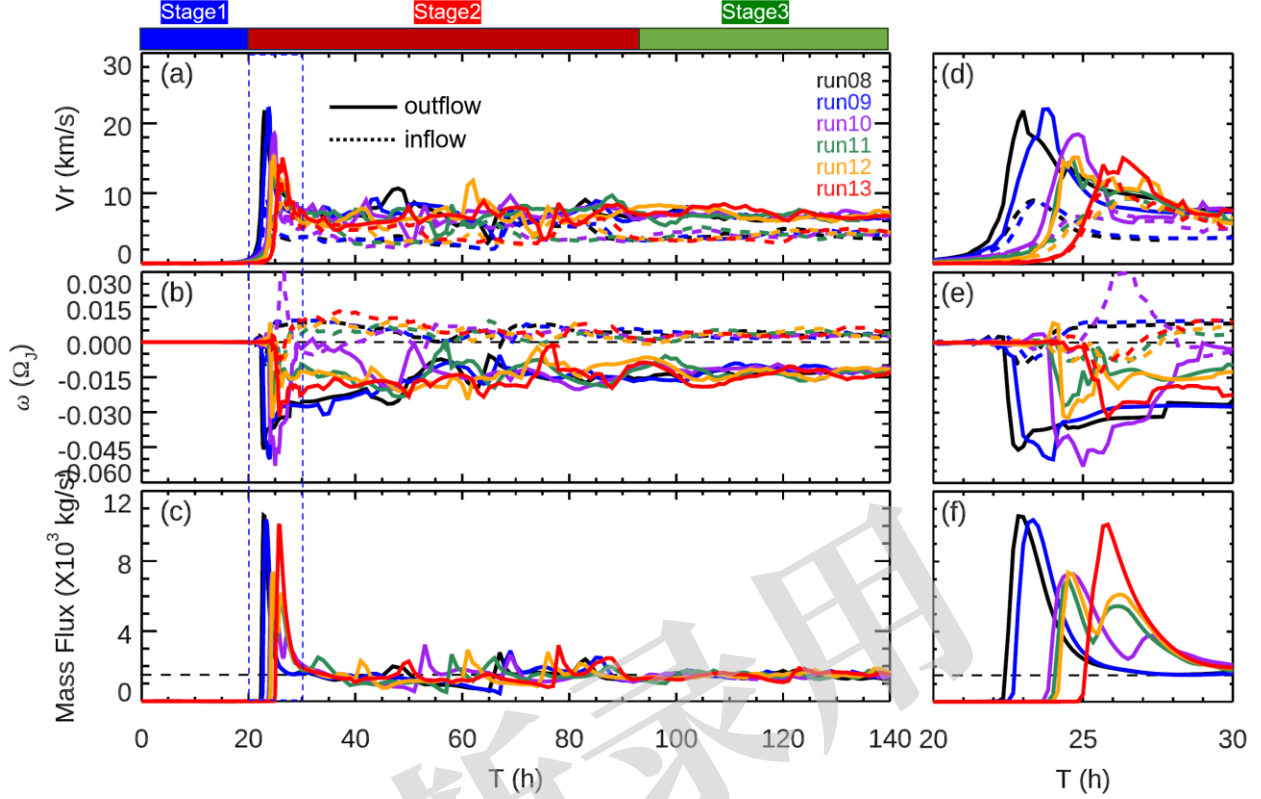


Figure 6. Temporal evolution of plasma convection from runs 8-13. (a, d) Longitude-averaged radial velocity V_r at $L=8R_J$ for the outflow (solid) and inflow (dashed). (b, e) Longitude-averaged angular velocity ω . (c, f) Outflow mass flux. Vertical dashed blue lines in left-column panels denote the time interval enlarged in the adjacent right-column panels.

Specifically, during State 1 ($T < \sim 20$ h), iogenic O^+ progressively accumulates under the prescribed Io source defined in Section 2.1.2. This source is azimuthally symmetric, with a production rate that decreases exponentially with L ; however, its perturbation incorporates a radially varying phase shift (see Equations 3 and 4). The freshly produced plasma corotates rigidly with Jupiter ($\omega=0$) and has zero V_r . At $T \approx 20$ h, the interchange instability initiates, marking the onset of Stage 2 and accompanied by rapid increases in V_r , $|\omega|$ and mass flux. By the end of Stage 1 (i.e., $T=20$ h), the magnetospheric evolution matches that of Group 1 runs with the same $\varphi_{0,max}$ (see Figure 3): the plasma accumulates over time, forming a striped pattern characterized by radial phase shear. As the instability develops, these structures align radially and evolve into elongated bent fingers that transport plasma outward. As in Group 1 runs of Section 3.1.1, runs with larger $\varphi_{0,max}$ in the Io source begin evolving later. In contrast to runs 1-7, the peak V_r first generally decreases with $\varphi_{0,max}$ for $\varphi_{0,max} \leq 20^\circ$ (runs 8-10), and then saturates at $\varphi_{0,max} \geq 30^\circ$ (runs 11-13; see Figure 6a). The $|\omega|$ and mass flux profiles also exhibit distinct characteristics across these two phase-shift ranges, reflecting the bifurcation detailed in Section 3.1.1. The plasma convection

reaches a quasi-steady state (Stage 3) after sufficient temporal evolution, with V_r , ω and the mass flux stabilized and insensitive to $\varphi_{0,max}$ of the Io source. This is further confirmed in Figure 7: longitude-averaged V_r and ω versus L , averaged over $T=120-140$ h (orange shading in Figure 7c), are nearly identical across runs 8-13 despite differing $\varphi_{0,max}$. The density morphology is also consistent across these runs (not shown here).

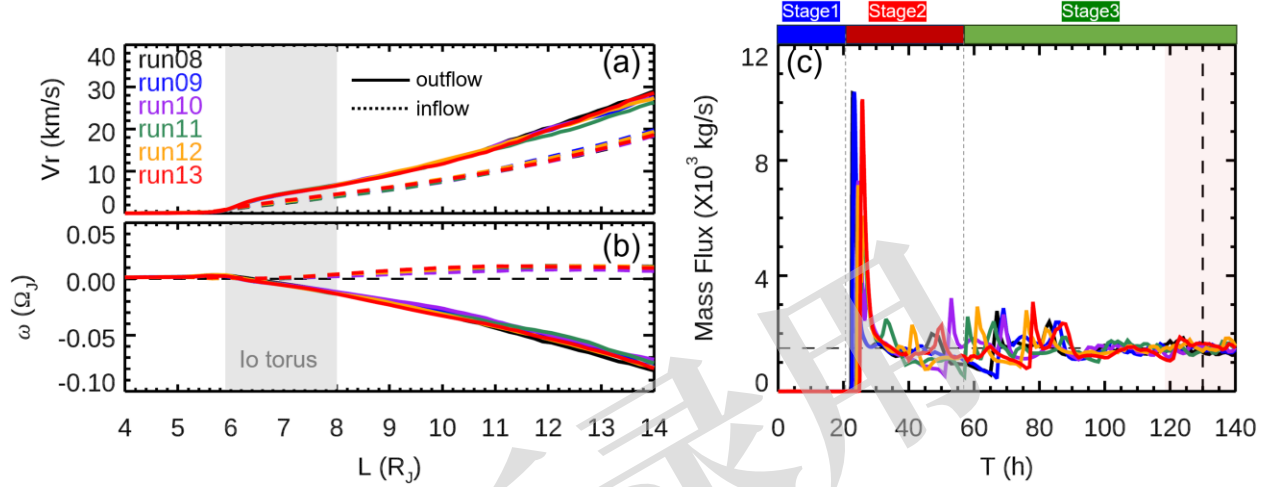


Figure 7. Evolution of plasma convection from runs 8-13. (a) Longitude-averaged radial velocity V_r versus L averaged over $T=120-140$ h for the outflow (solid) and inflow (dashed). (b) Longitude-averaged angular velocity ω . The grey shading denotes the Io torus. (c) Outflow mass flux at $L=8R_J$ versus time. The orange shading indicates the averaging interval $T=120-140$ h, with the central black dashed line denoting its midpoint.

3.2 Effects of Velocity Shear on Plasma Convection

3.2.1 Initial Plasma Torus with Velocity Shear (No Io Source)

Figures 8 and 9 present results from Group 3 (runs 1 and 14-16, see Table 1), which show overall evolution consistent with Section 3.1.1. Despite nearly identical temporal evolution across varying velocity shear strengths, stronger shear delays the onset of interchange instability (compare runs 1, 14 and 15 in Figure 8). The instability initiates at around $T=4.2$ h, by which time the maximum phase shifts, driven by the respective velocity shears defined in Figure 2b, reach 0° , 8° and 16° for runs 1, 14 and 15, respectively. This delay is consistent with the conclusion in Section 3.1.2 that initially imposed phase shifts in the Io torus suppress interchange instability. By $T=5.0$ h, the maximum phase offset remains below 20° , placing these runs within the first bifurcation branch ($\varphi_{0,max} \leq 20^\circ$ in Section 3.1.1). Accordingly, peak V_r of the outflow increases with stronger velocity shears. As will be shown in Section 3.2.2, if the instability onset is significantly delayed and the accumulated phase shift exceeds 30° , the magnetospheric evolution lie on the second branch ($\varphi_{0,max} \geq 30^\circ$).

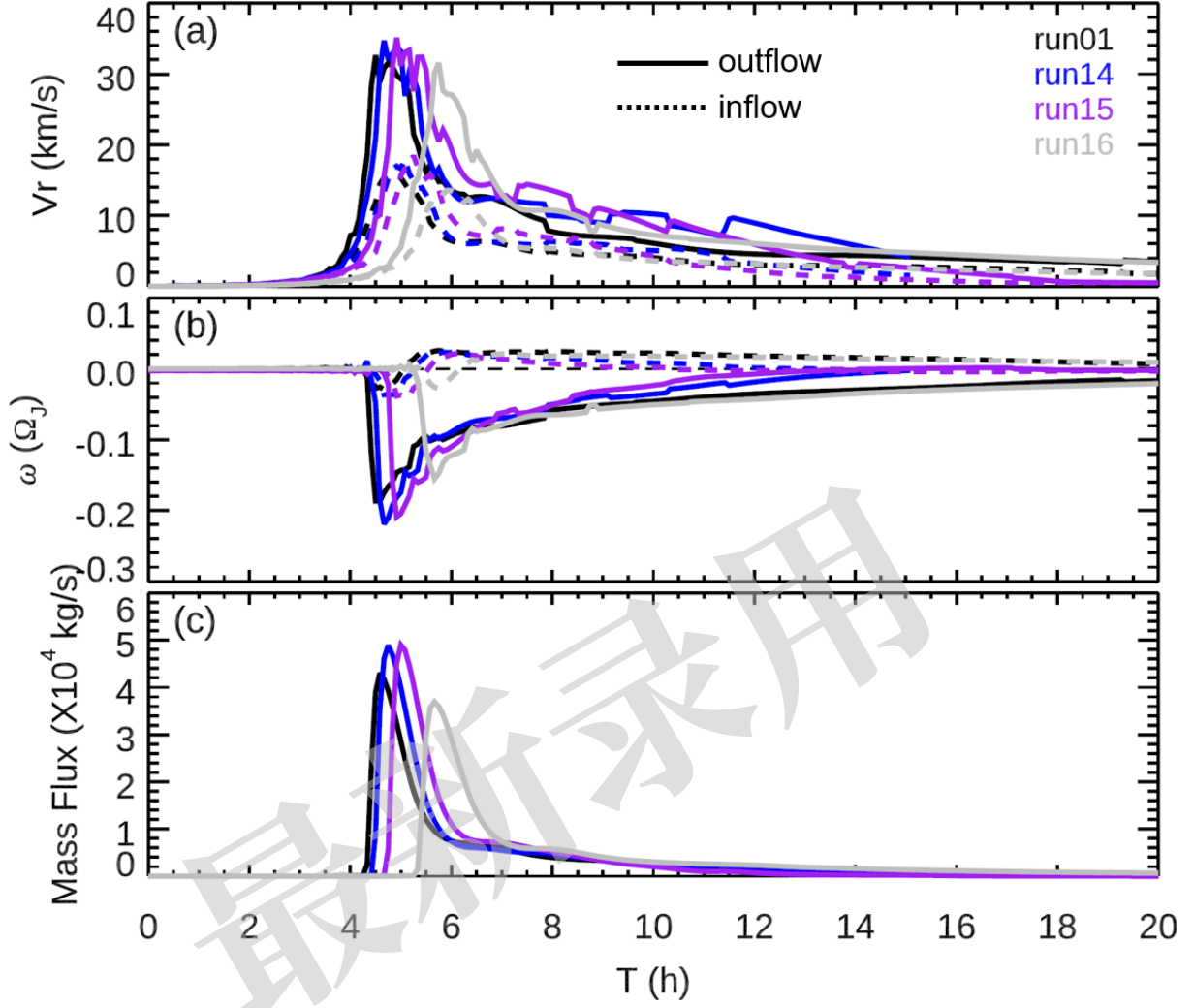


Figure 8. Same format as Figure 4, but for runs 1 and 14-16 with different velocity shear strengths.

Figure 9 shows V_r and $|\omega|$ as functions of L , sampled at times of peak mass flux. Despite delays in instability onset under stronger velocity shears, the V_r profiles remain nearly unchanged across equivalent L . The effect of velocity shear is most evident in the ω profile. As shown in Figure 9b, the imposed background shear produces a significant reduction in ω relative to the baseline run 1, especially in regions between $L=5R_J$ and $L=8R_J$. This shear-induced subcorotation peaks near $L=5.9R_J$ (compare runs 14-15 with run 1), coinciding with the location of maximum velocity shear specified in Figure 2b. At $L \approx 8R_J$, where $|\omega|$ peaks, the effect of the imposed shear is relatively weaker.

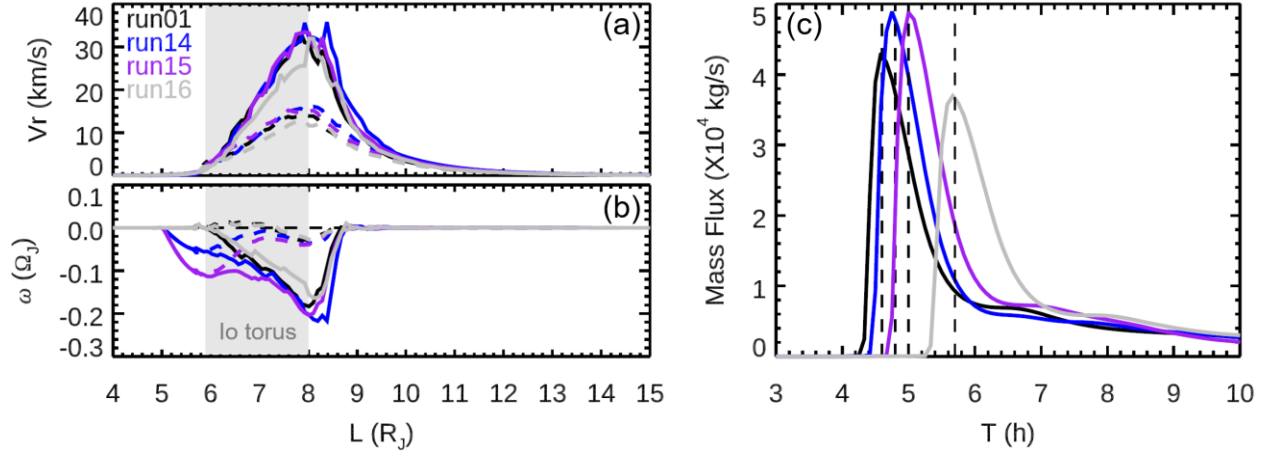


Figure 9. Same format as Figure 7, but for runs 1 and 14-16. Velocity profiles in panels (a) and (b) are sampled at the times marked by vertical dashed lines in panel (c), corresponding to peak mass flux values.

As noted in Section 2.3, the velocity shear in runs 14 and 15 not only induces phase shifts in plasma density but also locally reduces the angular velocity by up to 0.054 and $0.108\Omega_j$, respectively. To isolate the impact of this angular velocity reduction, run 16 adopts a uniform subcorotation of $0.1\Omega_j$ with no imposed velocity shear. Figures 8 and 9 show that this slower rotation yields lower peak values of V_r , $|\omega|$ and mass flux, along with a delayed instability onset relative to run 1. Therefore, both reduced rotation and an induced phase shift suppress interchange convection, making their individual contributions difficult to disentangle. However, in certain cases, the effect of one factor is clearly discernible. For example, runs 14 and 15, despite their locally reduced angular velocities, produce higher peak values of V_r , $|\omega|$ and mass flux than run 1, highlighting the role of induced phase shifts. The influence of the reduced angular velocity is evident in the ω profile, particularly near the Io torus region.

3.2.2 Steady Io Source with Velocity Shear

Figure 10 shows the temporal evolution of plasma convection driven by an active Io source under imposed velocity shears. The evolution of runs 8 and 17-19 proceeds through three stages and closely resembles that of runs 8-13 discussed in Section 3.1.2. Phase shifts across the Io source region accumulate over time due to differential rotation along L (see Figure 2). Interchange instability initiates after $T=20$ h, by which time the maximum phase shifts reach 0° , 39° and 78° for runs 8, 17, and 18, respectively. Consequently, runs 17 and 18 fall within the second bifurcation branch ($\varphi_{0,max} \geq 30^\circ$, Section 3.1.1), exhibiting double-finger structures early in their development. This is reflected in the multiple local peaks in the mass flux profile (Figure 10f) during the early developing stage, in contrast to the single-peak structure of the baseline run 8.

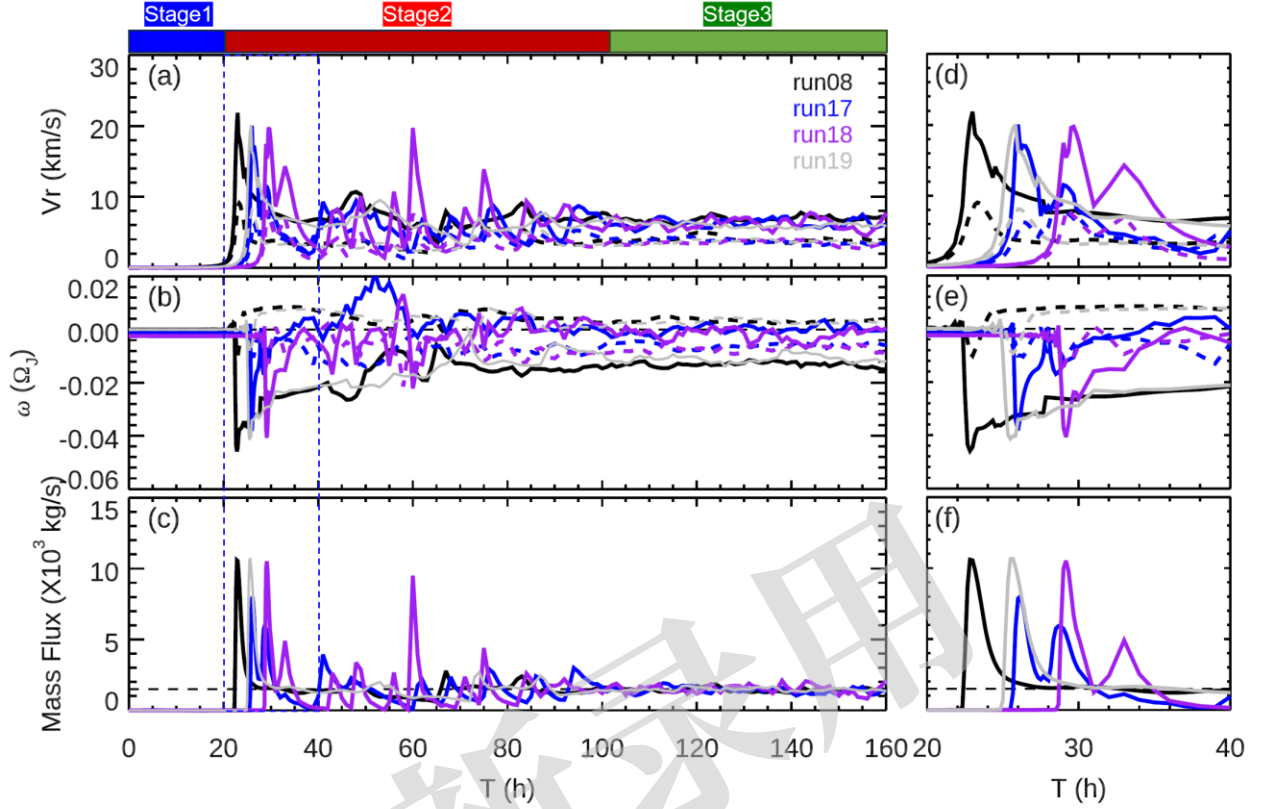


Figure 10. Same format as Figure 6, but for runs 8 and 17-19.

A comparison of runs 8, 17 and 18 reveals that at $L=8R_J$, ω exhibits only minor deviations during Stage 1, as expected from the weak velocity shear imposed at that location in Figure 2b. In early Stage 2, stronger shears delay the onset of interchange instability. By Stage 3, although the instantaneous V_r exhibits large fluctuations and frequent crossings among runs (Figure 10a), its time-averaged value decreases with increasing velocity shear strength (Figure 11a). In contrast, ω differs significantly between run 8 (no shear) and runs 17-18 (with shear): in run 8, outflow (inflow) ω stabilizes near $-0.015\Omega_J$ ($+0.004\Omega_J$), whereas in runs 17-18, it settles around $-0.005\Omega_J$ ($-0.012\Omega_J$). This discrepancy is not due to the structural bifurcation in runs 17-18, as neither V_r nor ω is affected by the phase shifts during Stage 3 (Section 3.1.2). Instead, it likely stems from the outward transport of more strongly subcorotating plasma from $L < 8R_J$, where the velocity shear is pronounced.

Figures 11 show radial profiles of V_r and $|\omega|$ during Stage 3. Within $L < 8R_J$, ω of both inflow and outflow closely matches the imposed velocity shear (see Figure 2b). Beyond the Io source region ($L > 8R_J$), both V_r and $|\omega|$ decrease slightly with increasing shear strength, attributable to the suppression of interchange instability by the velocity shear.

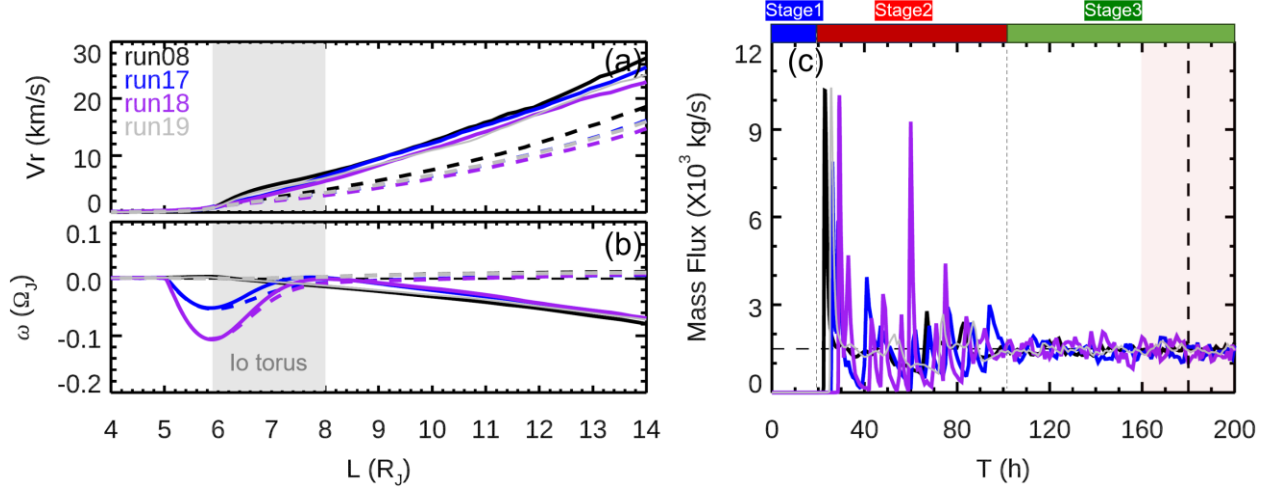


Figure 11. Same format as Figure 7, but for runs 8 and 17-19.

Similar to the approach in Section 3.2.1, run 19 isolates the effect of angular velocity reduction by imposing a uniform subcorotation of $0.1 \Omega_j$ with no velocity shear. Compared to run 8, run 19 exhibits a slower V_r and delayed instability onset, confirming that globally reduced rotation suppresses convection. However, despite its larger subcorotation ($0.1 \Omega_j$) relative to the peak local reduction in run 17 ($\sim 0.054 \Omega_j$), run 19's instability onset occurs even earlier than that of run 17 (Figure 10). This suggests that during the early Stage 2, velocity shear primarily influences the instability through induced phase shifts rather than local angular velocity reductions. By Stage 3, however, the effect of the local angular velocity reduction becomes prominent: V_r in run 19 falls below that in run 18 (which features a peak local reduction of $\sim 0.108 \Omega_j$) at locations such as $L=11R_j$ (Figure 11a). As a result, velocity shear modulates plasma convection through both phase shifts and local angular velocity reduction, with the latter gaining relevance in later stages (e.g., Stage 3).

4 Discussion

4.1 Comparison with Observations

Consistent with previous RCM-Jupiter simulations using an idealized, unshifted Io source^{[9][16][17]}, the present model systematically underestimates plasma number density N , radial outflow velocity V_r , and angular velocity ω relative to Galileo measurements^[24], although it captures the correct overall radial trends. This discrepancy may arise from simplifications in the Io torus/source, energetic particles and ionospheric conductances, and the exclusion of kinetic physics beyond the RCM's fluid framework^[16].

Figure 12 quantifies deviations in N across runs driven by an active Io source with either imposed phase shifts or background velocity shears. To facilitate comparison of spatial gradients despite

the systematic magnitude offset between model and data, the observation-based empirical profile is scaled to 3% of its original amplitude. During the early developing stage, imposed phase shifts substantially enhance the radial density gradient (dN/dL), aligning closely with observations ($T=20\text{-}30\text{h}$ in Figures 12a and 12c). Background velocity shear steepens the gradient primarily within $L < 8R_J$, with negligible impact farther out ($T=20\text{-}40\text{h}$ in Figures 12b and 12d). By the quasi-steady state, however, all profiles flatten significantly, resulting in a generally much weaker decay than observed, especially beyond $L=8R_J$. Increasing the imposed phase shift further fails to strengthen the gradient, indicating that Io source phase shifts cannot effectively suppress radial transport at this stage ($T=120\text{-}140\text{h}$ in Figure 12a). In contrast, background velocity shear slightly steepens the gradient in the Io source region ($T=120\text{-}140\text{h}$ in Figure 12d), likely due to local angular velocity reduction (see Section 3.2.2).

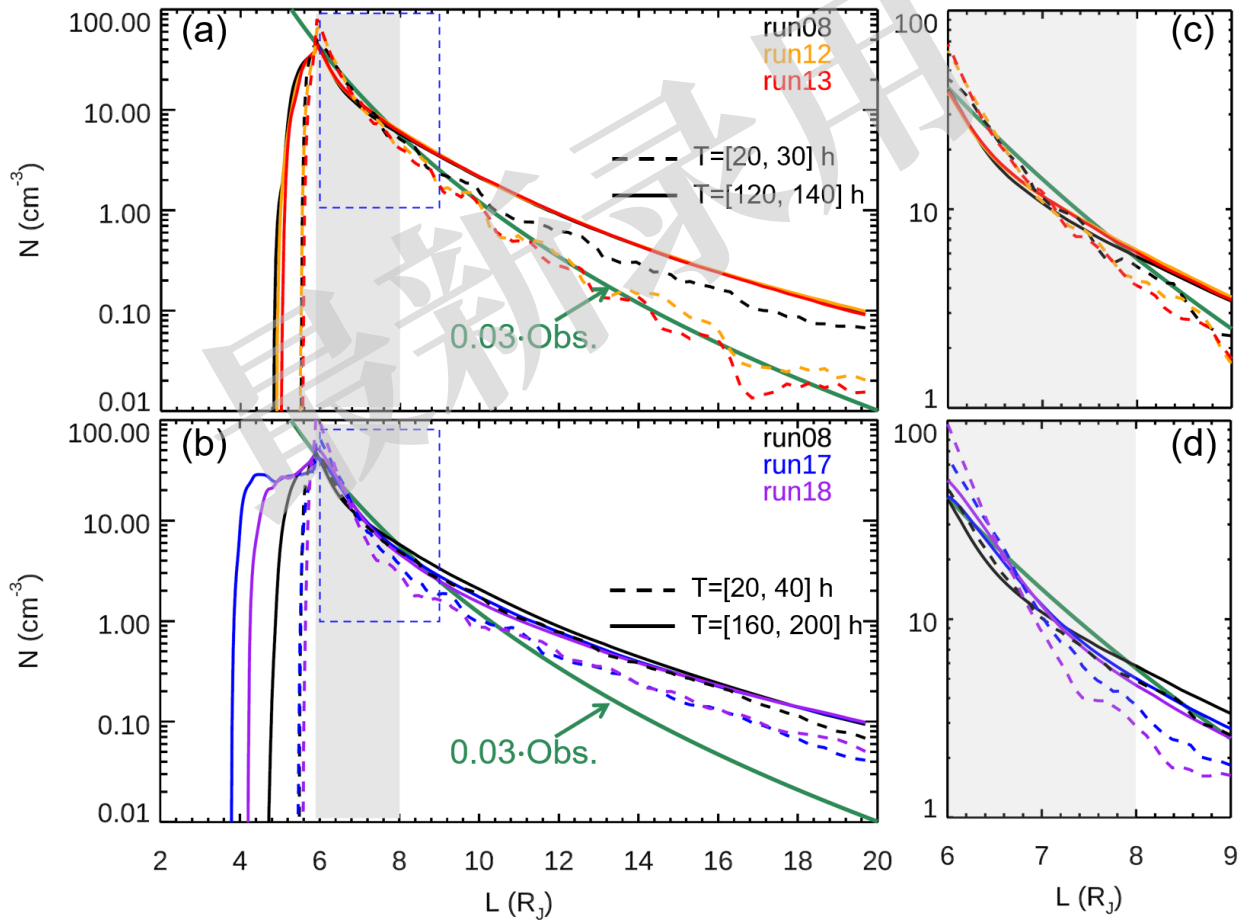


Figure 12. Radial profiles of plasma number density (N) from selected runs, compared against an observation-based empirical model. (a) Runs 8, 12 and 13. (b) Runs 8, 17 and 18. Dashed curves represent the early developing phase; solid curves denote the quasi-steady stage. The Io torus region is shaded in grey. Blue dashed boxes in left-column panels denote the area enlarged in the

adjacent right-column panels. The observation-based empirical profile is scaled to 3% of its original amplitude and labelled as $0.03 \cdot \text{Obs}$.

Collectively, phase shifts in the Io source, whether intrinsic to the source itself (runs 12-13) or induced by background velocity shear, can effectively steepen the density gradient and thereby suppress radial transport during the early developing stage. Phase shifts produce a strong enhancement of gradient, closely matching observations, whereas velocity shear primarily sharpens the gradient within $L < 8R_J$, where the prescribed shear is applied (see Figure 2b). By the quasi-steady state, however, the influence of intrinsic phase shifts markedly diminishes. Background velocity shear still slightly steepens the gradient in the shear region, but its effect is considerably weaker than during the early developing stage.

Steep density gradients observed during the early developing stage, which diminish in the quasi-steady state, may arise from initial plasma transport governed by local interchange instability and the steeply graded Io source distribution (Equation 3). During this phase, interchange instability rapidly expels accumulated plasma into the tenuous outer magnetosphere, forming a steep density profile that subsequently relaxes as the system approaches equilibrium (see Section 4.2 for further discussion).

4.2 Stage-dependent Effects of Phase Shift and Velocity Shear

As demonstrated in Section 3.1.2, the imposed phase shift $\varphi_{0,max}$ at the active Io source most strongly influences V_r , ω and mass flux during the early developing stage (Figures 6 and 7). Subsequently, these parameters stabilize and become less sensitive to $\varphi_{0,max}$. This behavior may be attributed to early-stage convection being governed primarily by local interchange instability modulated by phase-shifted density perturbations. In the quasi-steady stage, however, such perturbations in the Io source are likely smoothed by non-linear evolution (e.g., Figure 3), leaving the system dominated by a balance between the Io plasma source and outer boundary losses. This source-loss equilibrium is particularly evident in the mass flux profile. In contrast, although velocity shear similarly exerts its strongest influence during the early developing stage (Section 3.2.2), it remains significant during the quasi-steady stage by continuously modulating convection within the shear region. Consequently, while mass flux becomes insensitive to velocity shear, V_r and ω remain markedly affected (Figures 10 and 11).

Critically, Jupiter's magnetosphere is highly dynamic and rarely sustains a quasi-steady state. It frequently reverts to transient developing phases, especially in response to abrupt events such as Io volcanic eruptions, which can rapidly reconfigure the phase structure of density perturbations in the Io source/torus and thereby reset the conditions for interchange convection. Therefore, the

phase structure of density perturbations plays a critical role in regulating Jupiter's inner magnetosphere.

4.3 Directions for Future Work

This study investigates how the phase structure of the Io plasma torus influences plasma convection in Jupiter's inner magnetosphere. To isolate this effect, the present model adopts a simplified, axisymmetric torus composed solely of cold ions. Future work should implement a more realistic multi-species plasma torus. Additionally, while the current simulations assume a spin-aligned dipole field, future simulations should incorporate a more realistic magnetic field, which can be derived from a Jovian MHD model^{[25][26]}. Coupling the RCM with an MHD model will enable investigation of solar wind effects on the energy-dependent convection of charged particles in the inner magnetosphere. Lastly, the stabilizing influence of energetic particles, known to suppress the interchange instability^[21], should be included in a future study.

5 Summary and Conclusions

This study employs the RCM-Jupiter model to investigate how the phase structure of density perturbations, whether imposed initially or induced by background velocity shear, modulates interchange convection in Jupiter's inner magnetosphere. Four groups of controlled simulations were performed, systematically varying the magnitude of phase shifts and velocity shears to examine their respective effects on both a prescribed Io torus and an active Io source. The results demonstrate that the phase structure of density perturbations plays a critical role in regulating interchange convection at Jupiter.

The results of this study can be summarized as follows:

1. Imposed phase shifts and background velocity shear do not alter the general evolution of plasma convection. In simulations with an initial Io torus and no Io source, interchange instability initiates at $T \approx 4\text{h}$, with V_r , $|\omega|$ and mass flux peaking within 1-2h and then decaying as the system depletes. By contrast, simulations with an initially empty magnetosphere and an active Io source evolve through three stages: accumulation ($T < \sim 20\text{h}$), developing ($T \approx [20, 100]\text{h}$) and quasi-steady stage ($T > \sim 100\text{h}$).
2. The phase shift $\varphi_{0,max}$ exerts its strongest influence during the early stage: larger $\varphi_{0,max}$ more effectively suppresses interchange instability, modulates morphological evolution, and regulates plasma velocity and mass flux.
3. By the quasi-steady stage, V_r , ω and mass flux stabilize and become nearly insensitive to the phase shift $\varphi_{0,max}$; the density morphology appears consistent across different values of $\varphi_{0,max}$.

4. Background velocity shear strongly modulates interchange convection via two mechanisms, induced phase shifts and local angular velocity reduction, both of which suppress interchange instability and are often difficult to disentangle. Induced phase shifts primarily act during the early evolution (as stated in conclusion 2), while local angular velocity reduction gains prominence at later stages. As a result, by the time a quasi-steady stage is reached, velocity shear continues to significantly affect plasma convection.
5. Phase shifts in the Io source, whether intrinsic or induced by background velocity shear, effectively steepen the radial density gradient during early evolution, making it broadly consistent with observations. However, this effect markedly diminishes by the time a quasi-steady state is reached.

Acknowledgments

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Data Availability Statement

In this study, all simulation data and the program for reading are available at the Science Data Bank^[27].

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