Cyclone dynamics in an ideal environment: the motion and stability of Jupiter’s circumpolar cyclones

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Abstract

The Juno mission observed that both poles of Jupiter have polar cyclones (PCs) that are surrounded by a ring of circumpolar cyclones (CPCs). The north pole holds eight CPCs and the south pole possesses five, with both circumpolar rings positioned along latitude ~84° N/S. Here we explain the location, stability and number of the Jovian CPCs by establishing the primary forces that act on them, which develop because of vorticity gradients in the background of a cyclone. In the meridional direction, the background vorticity varies owing to the planetary sphericity and the presence of the polar cyclone. In the zonal direction, the vorticity varies by the presence of adjacent cyclones in the ring. Our analysis successfully predicts the latitude and number of circumpolar cyclones for both poles, according to the size and spin of the respective polar cyclone. Moreover, the analysis successfully predicts that Jupiter can hold circumpolar cyclones, whereas Saturn currently cannot. The match between the theory and observations implies that vortices in the polar regions of the giant planets are largely governed by barotropic dynamics, and that the movement of other vortices at high latitudes is also driven by interaction with the background vorticity.

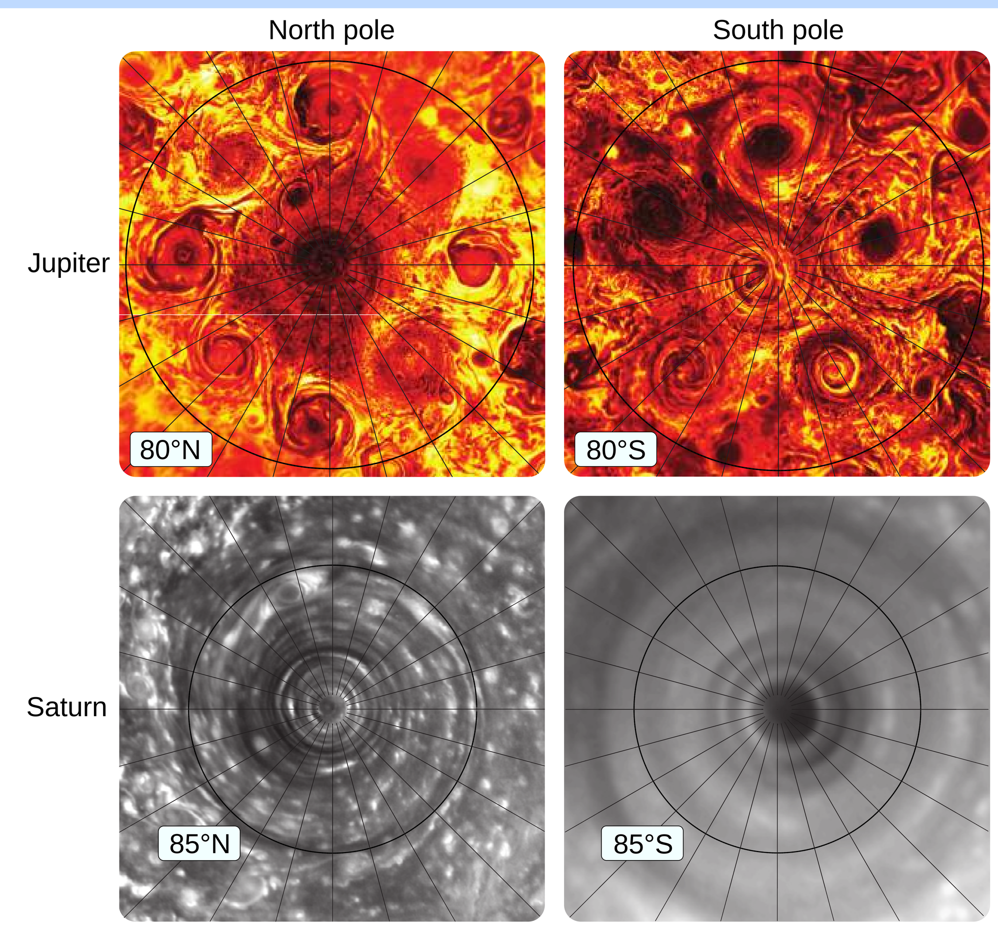

Fig. 1 | Polar cyclones (PCs) and circumpolar cyclones (CPCs) of Jupiter and Saturn. Jupiter images: Infrared (Juno JIRAM, adapted). Saturn images: Visible (Cassini ISS, adapted). Longitude lines are 15° apart, with 0° System III longitude at the right for Jupiter. Latitude circles: 80° N/S (Jupiter), 85° N/S (Saturn).

Beta-drift

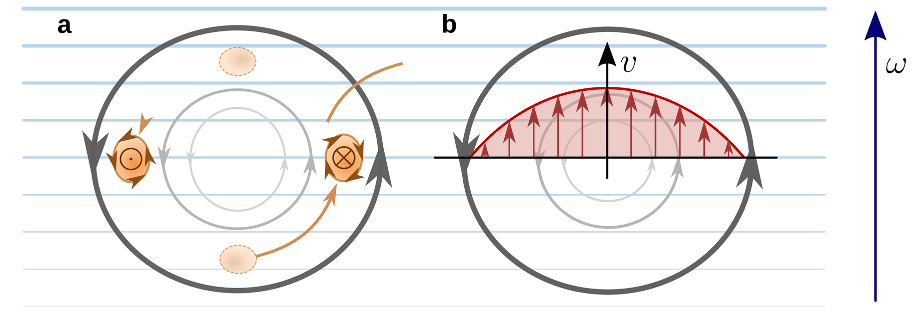

Fig. 2| Generalized β-drift schematic. Grey contours: vortex streamlines. Blue contours: background vorticity (ω), increasing with thickness. (a) Lagrangian motion creates a vorticity dipole via PV conservation. (b) Vortex velocity profile induced by the dipole’s shear.

$$F_\theta \equiv \frac{\partial \xi_{PC}}{\partial r} + \beta$$

Meridional stability of circumpolar cyclones

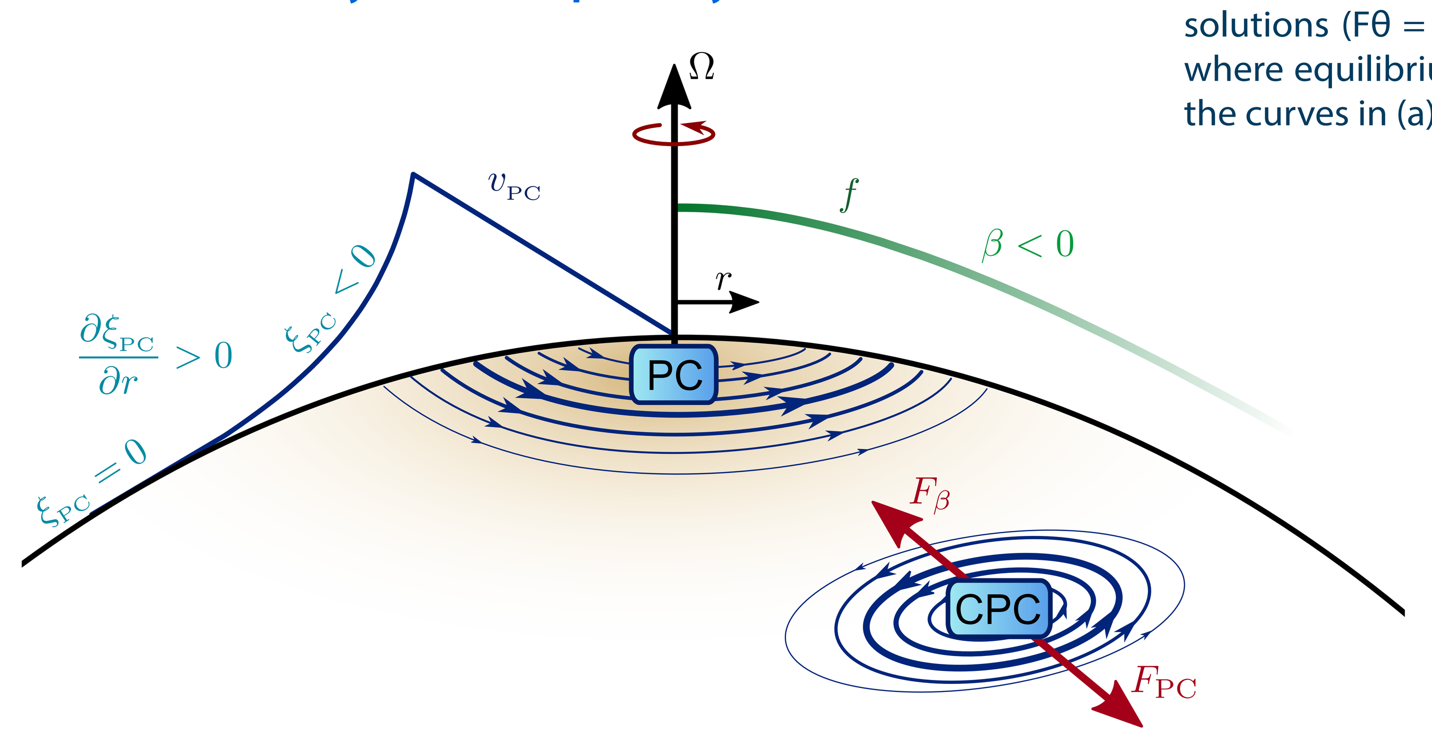

Fig. 3| Balance maintaining a CPC around a PC. Green curve: planetary vorticity (f). Blue curve: tangential velocity profile around the PC. ξPC: relative vorticity from the PC. Red arrows: vorticity gradient forces induced by the PC and planetary sphericity. arrows are vorticity gradient forces on the CPC, induced by the PC and by planetary sphericity.

Meridional stability of circumpolar cyclones

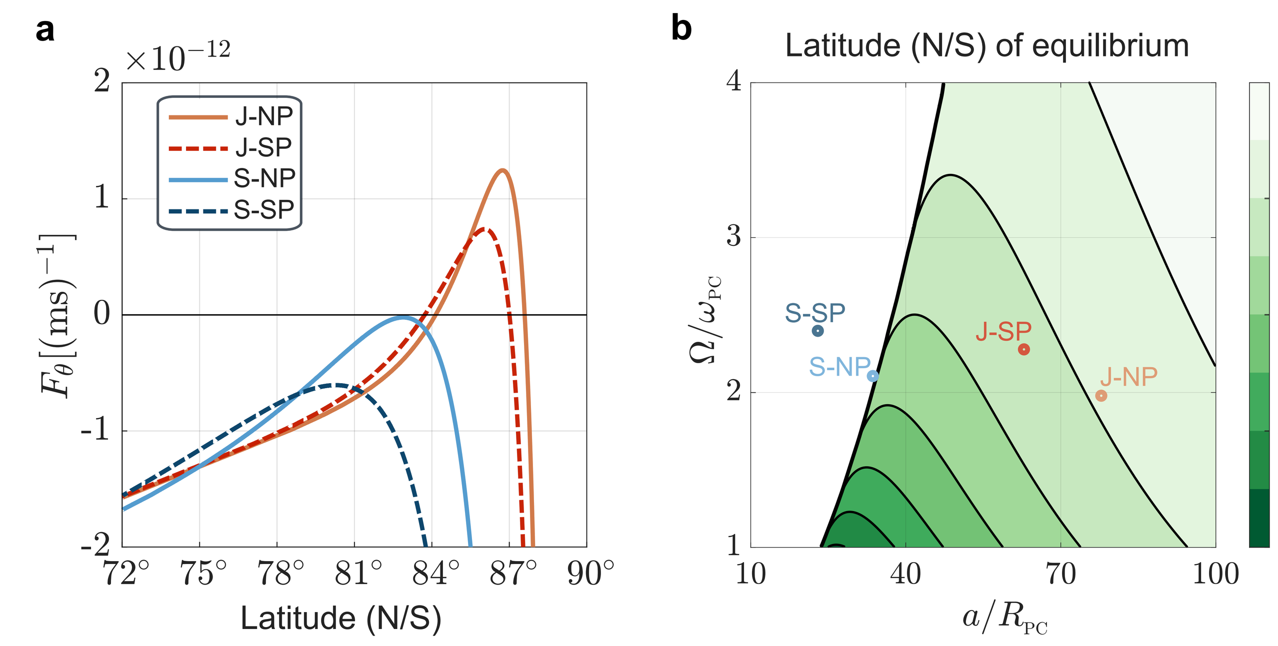

Fig. 4| Latitudes of equilibrium in the gas giants (a) Curves of Fθ as a function of latitude. Red curves: Jupiter's north (solid, J-NP) and south (dashed, J-SP) poles. Blue curves: Saturn's north (solid, S-NP) and south (dashed, S-SP) poles. Equilibrium points (Fθ = 0) exist only for Jupiter, with stable balance achieved farther from the pole. (b) Latitude (N/S) of equilibrium as a function of the ratios a/RPC and Ω/ωPC. Only stable solutions (Fθ = 0) are shown. The white area on the left represents regions where equilibrium is not possible. Points represent values corresponding to the curves in (a). Both of Saturn's poles lie in the no-solution region.

Gavriel, N, & Kaspi, Y. (2021). The number and location of Jupiter’s circumpolar cyclones explained by vorticity dynamics. Nature Geoscience, 14(8), 559–563.

The oscillatory motion of Jupiter’s circumpolar cyclones

Abstract

The polar cyclone at Jupiter's south pole and the 5 cyclones surrounding it oscillate in position and interact. These cyclones, observed since 2016 by NASA's Juno mission, present a unique opportunity to study vortex dynamics and interactions on long time scales. The cyclones' position data, acquired by Juno's JIRAM, is analyzed, showing dominant oscillations with ~12-month periods and amplitudes of ~400 km. Here, the mechanism driving these oscillations is revealed by considering vorticity-gradient forces generated by mutual interactions between the cyclones and the latitudinal variation in planetary vorticity. Data-driven estimation of these forces exhibits a high correlation with the measured acceleration of the cyclones. To further test this mechanism, a model is constructed, simulating how cyclones subject to these forces exhibit similar oscillatory motion.

Gavriel, N, & Kaspi, Y. (2022) The oscillatory motion of Jupiter’s polar cyclones results from vorticity dynamics. Geophysical Research letters, 49(15):e2022GL098708.

Mechanism of of the cyclone’s motion

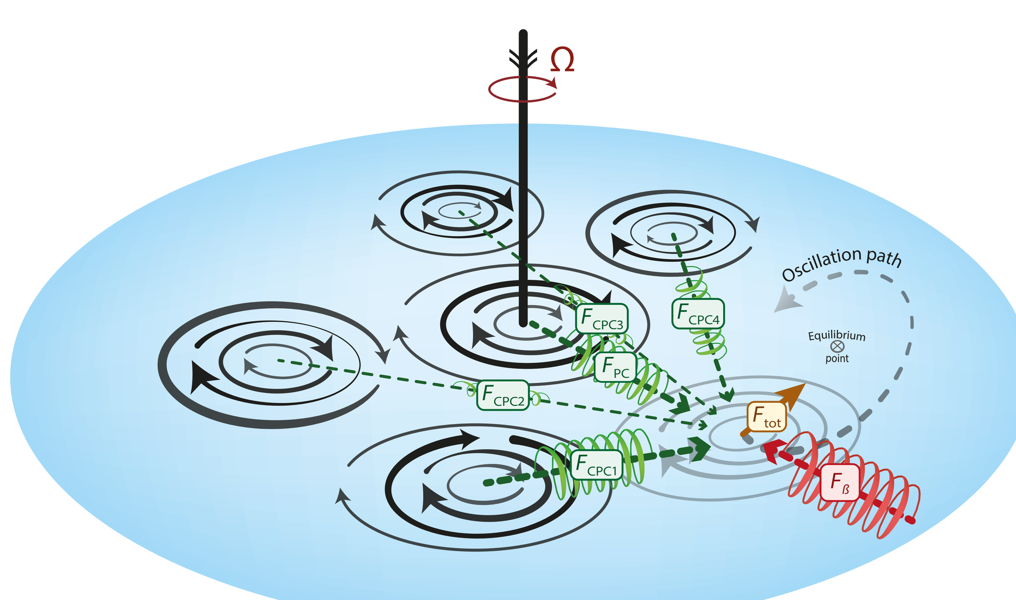

Fig. 6| Dynamics driving the motion of south polar cyclones. The central thick black line represents the planetary rotation axis pointing to the pole. Green arrows and springs illustrate rejection forces on a circumpolar cyclone (CPC) caused by vorticity-gradient forces from individual cyclones. Force magnitudes (FCPCi from CPC i, and FPC from the polar cyclone) are qualitatively indicated by arrow sizes and decrease with cyclone distance. Farther cyclones, such as CPC2 and CPC3, exert weaker forces on the CPC. The red Fβ arrow depicts polar attraction due to beta-drift, with the blue shading representing its potential magnitude, vanishing at the pole (white) and increasing away from it (darker blue). The brown arrow (Ftot) represents the total net force on the cyclone, pointing to the equilibrium point where the net force is zero. The gray dashed arrow illustrates the cyclone’s oscillatory path around the equilibrium point, with inertia causing the net force to remain perpendicular to the path. While the forces are not perfectly analogous to linear springs, this simplification is used for illustrative purposes.

Fig. 7| Comparison of net force and cyclone acceleration. Time series showing acceleration and force for each cyclone in one direction. Rows correspond to individual cyclones, with the left column representing meridional direction and the right column zonal direction. The abscissa indicates observation time, and the ordinate (m/s²) shows the amplitude of the curves. Dashed blue curves: cyclone acceleration, derived from the second derivative of observed positions. Solid brown curves: net force, combining mutual cyclone repulsion and Fβ. The alignment of blue and brown curves reflects the proposed force balance. Pearson correlation coefficient (ρ) between the curves is displayed above each panel.

Observations of the cyclone’s motion

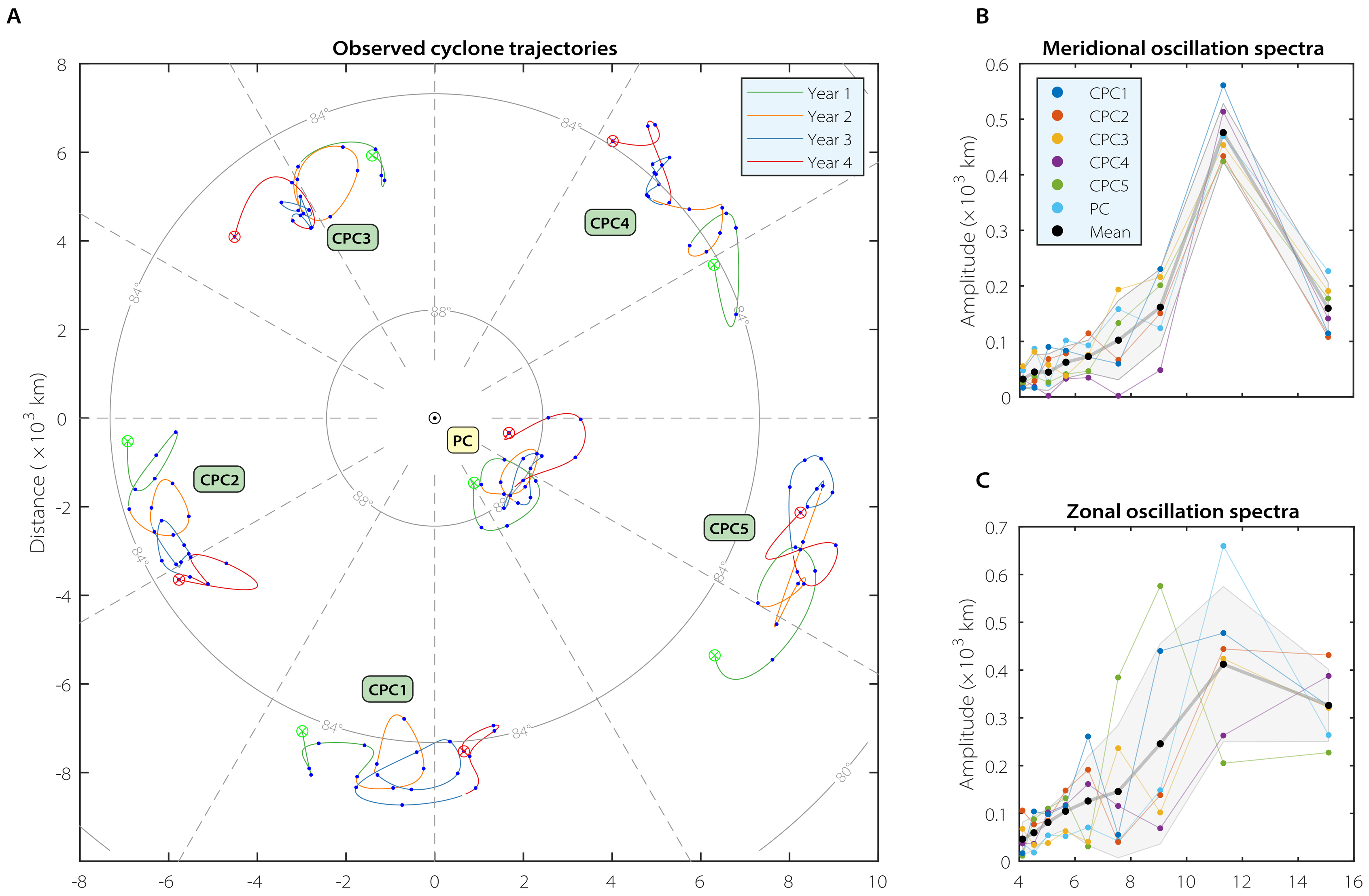

Fig. 5| Cyclone oscillation in Juno’s observations. (a) Trajectories of cyclones at Jupiter's south pole. Green X's mark cyclone locations at PJ4 (Dec. 11, 2016), and red X's mark their positions at PJ30 (final observation). Dots: observed coordinates (Mura et al., 2021); lines: interpolated paths, changing color yearly. Red curves represent the last 9 months. Black dot: pole, gray circles: latitude lines, dashed gray lines: 30° longitude intervals (System III, 0° longitude points upward). (c, d) Frequency spectra of observed meridional and zonal cyclone motion. Colored dots: calculated values; lines: linear interpolations (not real spectra). Black dots: mean spectra across six cyclones; gray shading: standard deviation. Time units are Earth years and months, without physical significance such as orbital periods.