

Supplementary Materials for

A slot region in the magnetosphere of Jupiter

Authors:

Minyi Long^{1,2}, Elias Roussos^{2*}, Binbin Ni^{1,3*}, Qianli Ma^{4,5*}, Peter Kollmann⁶, Ruoxian Zhou⁷, George Clark⁶, Norbert Krupp², Xing Cao¹, Peng Lu¹, Yixin Hao², Shaobei Wang¹

Affiliations:

¹School of Earth and Space Science and Technology, Wuhan University, Wuhan, China.

²Max Planck Institute for Solar System Research, Göttingen, Germany.

³CAS Center for Excellence in Comparative Planetology, Hefei, China.

⁴Center for Space Physics, Boston University, Boston, MA, USA.

⁵Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA.

⁶Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

⁷Department of Physics, University of Texas at Dallas, Dallas, TX, USA.

* Correspondence to: roussos@mps.mpg.de; bbni@whu.edu.cn; qianlima@atmos.ucla.edu

This file includes:

Supplementary Text

Supplementary Figs. 1–5

Supplementary Table 1

This Supplementary Information accompanies the manuscript titled “A slot region in the magnetosphere of Jupiter”. It provides additional analysis and figures supporting the main findings, including spatial correlation analysis, wave–particle interaction modeling, and refined coordinate descriptions.

Supplementary Text

Supplementary Fig. 1, we show the orbital configuration of Juno and Europa during the

28 observation interval shown in Figure 1. During this orbit, whistler-mode waves were observed from
29 20:00 to 22:30 UT, at magnetic latitudes ranging from $\sim 20^\circ$ to $\sim 50^\circ$, with particularly intense
30 amplitudes between 20:30 and 22:00 UT. Notably, Juno crossed the same magnetic field line at 21:37
31 UT that Europa had crossed earlier at 20:00 UT. This temporal and spatial proximity suggests that the
32 observed wave enhancements are likely linked to localized coupling processes between Europa and
33 Jupiter's magnetosphere, rather than indicating a broad, global effect. This point better aligns with our
34 overall conclusion that while Europa can locally modify the surrounding plasma environment and
35 wave activity, the global asymmetry patterns observed in Jupiter's magnetosphere appear largely
36 unaffected by the moon's immediate influence.

37 As shown in Supplementary Fig. 2, the averaged wave amplitudes exhibit a sharp increase around
38 Europa's orbit (M-shell = 8 - 10), corresponding to a decrease in omni-directional electron fluxes in
39 the same region. The wave amplitudes are stronger on the dawnside compared to the duskside,
40 consistent with the more pronounced depletion of electron fluxes in the dawn sector. The observed
41 dawn-dusk asymmetries in both electron fluxes and whistler-mode waves are likely influenced by the
42 large-scale dawn-dusk electric field¹⁻⁵. This electric field drives inward transport of electrons to lower
43 M-shells on the dayside and outward transport on the nightside. Electrons accelerated by inward
44 transport on the dayside drift in Jupiter's rotational direction, leading to increased electron fluxes in
45 the dusk sector and a corresponding decrease in the dawn sector. Meanwhile, the combination of the
46 large-scale dawn-dusk electric field with the globally asymmetric distribution of whistler-mode wave
47 amplitudes can further facilitate the observed profile of the dawn-dusk asymmetry in electron fluxes,
48 which however requires four-dimensional (4-D) Fokker-Planck diffusion simulations for further
49 exploration. Additionally, the averaged wave amplitudes near Io's orbit display a pronounced peak on
50 the duskside, though observations in the dawn sector remain insufficient. A radially narrow decrease
51 in energetic electrons, within a broader decrease, is observed along Io's orbit on the wake side of Io,
52 which is consistent with the occurrence of whistler-mode waves⁶. While our primary focus is on the
53 electron slot near Europa, we suggest that variations of energetic electron fluxes near Io's orbit likely
54 follow similar mechanisms.

55 The traditional M-shell, as used in many previous studies, represents only the instantaneous traced

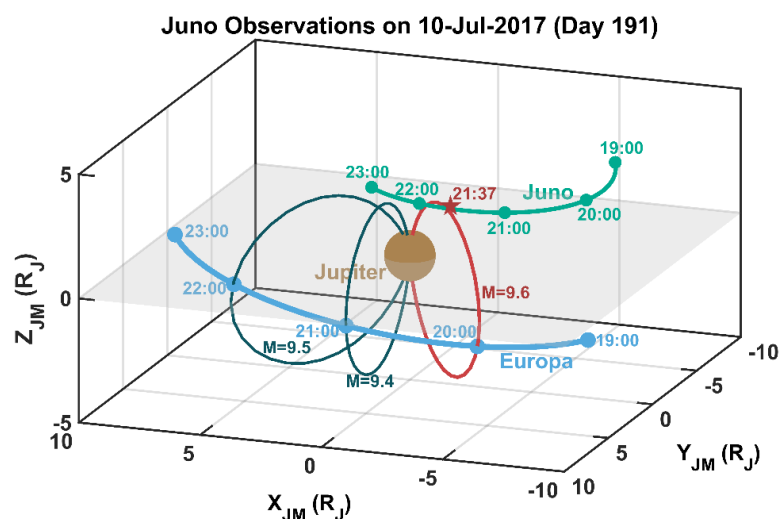
magnetic equator distance of Juno (or a moon) but is not a true invariant of drift motion. Using the M-shell to compare observations at different longitudes or local times may introduce systematic errors, as the same M-shell at different longitudes around Jupiter may not correspond to the same drift shell. Hence, in our investigation of local time asymmetries, we propose a new, simplified, and practical definition of the M-shell, based on the approximation that particle drifts occur at a nearly constant equatorial magnetic field strength. Specifically, the equivalent M-shell (M_{eq}) is defined as $(B_s/B_{eq})^{1/3}$, by assuming a surface magnetic field (B_s) of 4.28×10^5 nT.

We use the M_{eq} to investigate the whistler-mode wave and electron flux distributions in Supplementary Fig. 3. Overall, the statistical results are similar to those in Figs. 1. The intensification of wave amplitudes corresponds to a decrease in electron fluxes. However, the spatial coverage of wave amplitude enhancements extends to a broader range of M_{eq} , and the averaged wave amplitudes are more intense. This suggests that the effect of wave scattering may be stronger when considering the wave intensity on the M_{eq} grid.

Furthermore, we show in Supplementary Fig. 4 the spatial correlation between whistler-mode waves and energetic electron distributions in the (M_{eq} , MLAT)-space. There is a strong negative correlation between the averaged wave amplitudes and the latitudinally averaged f_N . The corresponding correlation coefficients (CC) are -0.92, -0.85, and -0.62 for each energy channel within $M_{eq} = 7.25 - 13.75$, with very low p-values (3.7×10^{-6} , 1.2×10^{-4} , and 1.7×10^{-2}). When using the parameter M_{eq} to analyze the spatial correlation, while the peak amplitudes and normalized electron fluxes shift in the coordinate position, the correlations remain consistent with the results shown in Fig. 2. These analyses indicate that the systematic differences introduced by use of M_{eq} are likely small for the investigation in this study. Given that the Juno community commonly uses the M-shell (M) as the mapping reference, we prefer to use M-shell rather than M_{eq} so that our results can be suitably mapped for comparisons with other published studies using Juno data. It is noted that M_{eq} can be considered as an improved mapping approximation for future researches.

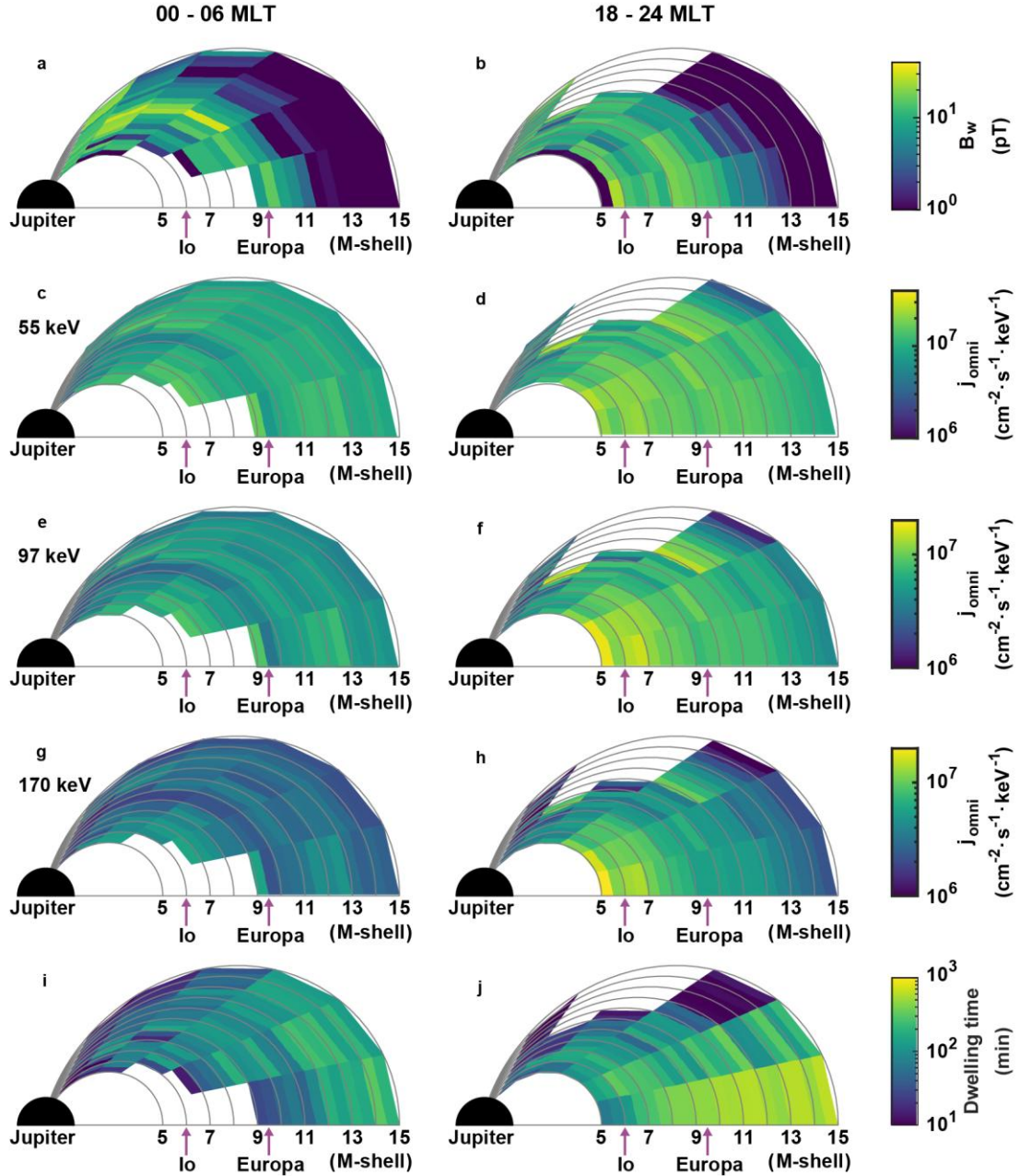
We show the resultant bounce-averaged diffusion rates in Supplementary Fig. 5 by using the wave normal angle model shown in Supplementary Table 1. The bounce-averaged pitch angle diffusion rates are 1 - 2 orders of magnitude larger than the mixed and momentum diffusion rates. LFWs can pitch

84 angle scatter energetic electrons with energies greater than 100 keV through cyclotron resonance, and
 85 scatter electrons with energies around 10 keV to 1 MeV at large equatorial pitch angles ($80^\circ - 90^\circ$) via
 86 Landau resonance. HFWs can resonate efficiently with electrons of $\alpha_{eq} < 80^\circ$ in the energy range from
 87 10 keV to 100's keV. The combined effects of the two frequency bands suggest that whistler-mode
 88 waves act as the primary driver of electron loss in Jupiter's radiation belt near Europa's orbit.



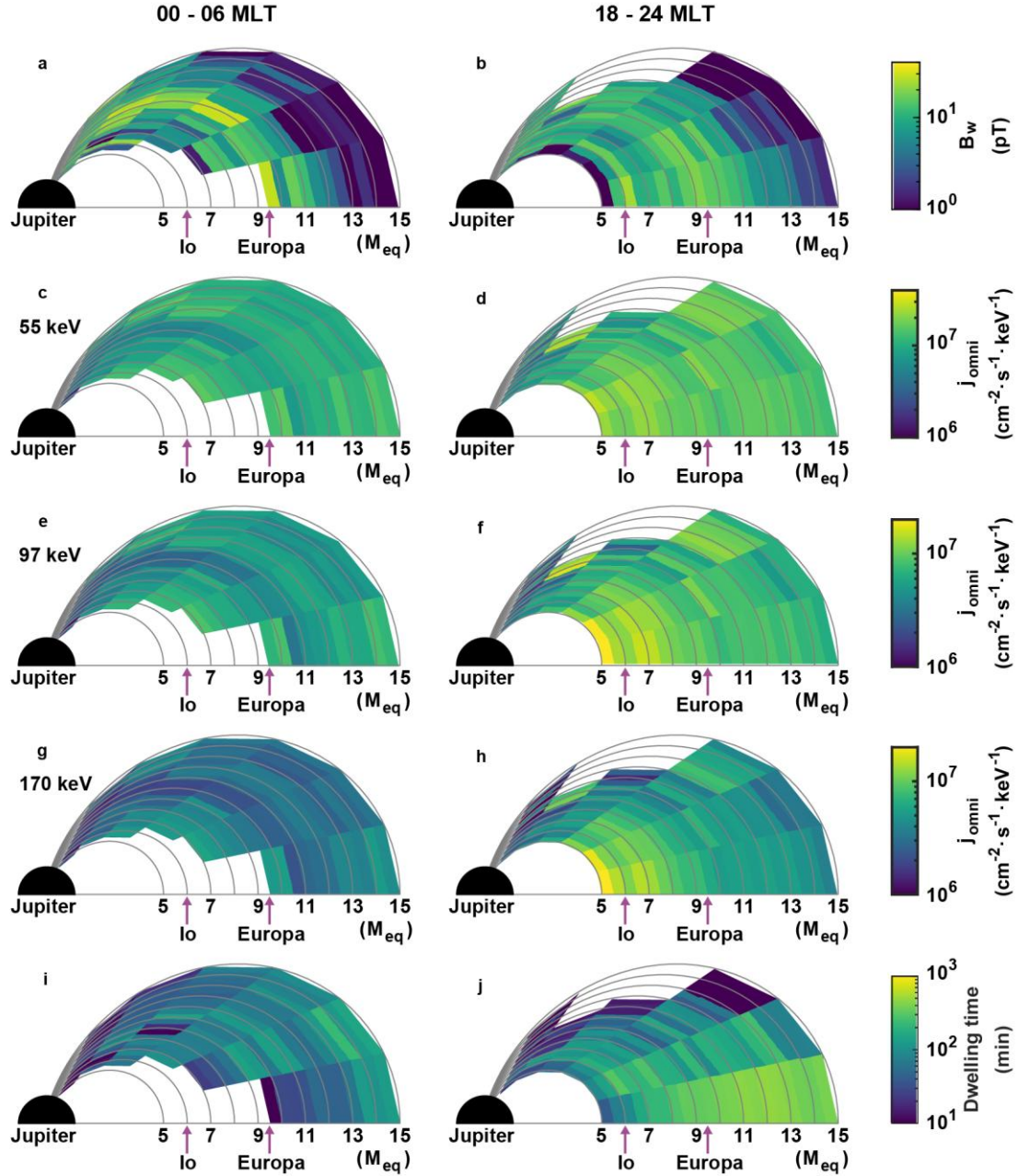
89
 90 **Supplementary Figure 1** | Three-dimensional trajectories of the Juno spacecraft and the Europa moon
 91 in Jupiter-centered magnetic (JM) coordinates during the interval of 10 July 2017 (Day 191). The
 92 sphere denotes Jupiter, and the field line illustrates a representative magnetic field line connected to
 93 Europa's orbit. Time labels along the trajectories mark universal time (UT) in hours, and M means M-
 94 shell (the distance from the magnetic equator to Jupiter's center, normalized by Jupiter's radius). The
 95 five-pointed star symbol indicates a key moment when Juno crossed a magnetic field line (UT=21:37)
 96 swept by Europa's orbital motion, occurring approximately 1.5 hours after Europa's closest magnetic
 97 (UT=20:00) mapping to Juno's position. Source data are provided as a Source Data file.

98



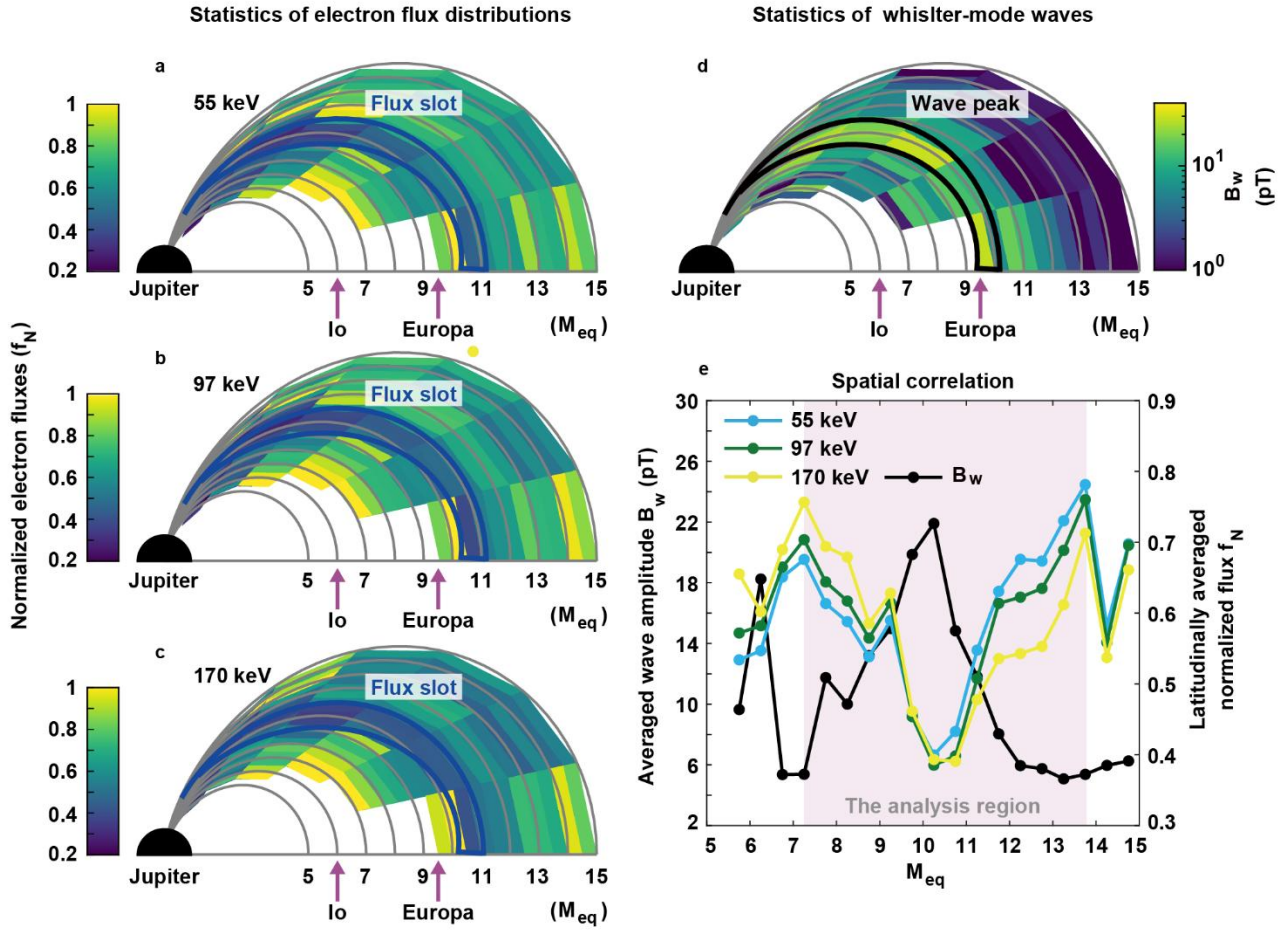
99

100 **Supplementary Figure 2** | Statistics of whistler-mode waves and corresponding energetic electron
 101 fluxes as functions of M-shell (the distance from the magnetic equator to Jupiter's center, normalized
 102 by Jupiter's radius) and MLAT (magnetic latitude) in the magnetic meridian plane for different MLT
 103 (magnetic local time) sectors in Jupiter's magnetosphere. **a-b**, average wave amplitude distributions
 104 on the dawnside (00-06 MLT) and on the duskside (18-24 MLT). **c-h**, omni-directional electron flux
 105 distributions for three indicated energy channels (55, 97, 170 keV) on the dawnside and on the duskside.
 106 **i-j**, the corresponding spacecraft dwelling time. The magnetic latitude resolution is 10° , and the M-
 107 shell resolution is 0.5. Source data are provided as a Source Data file.

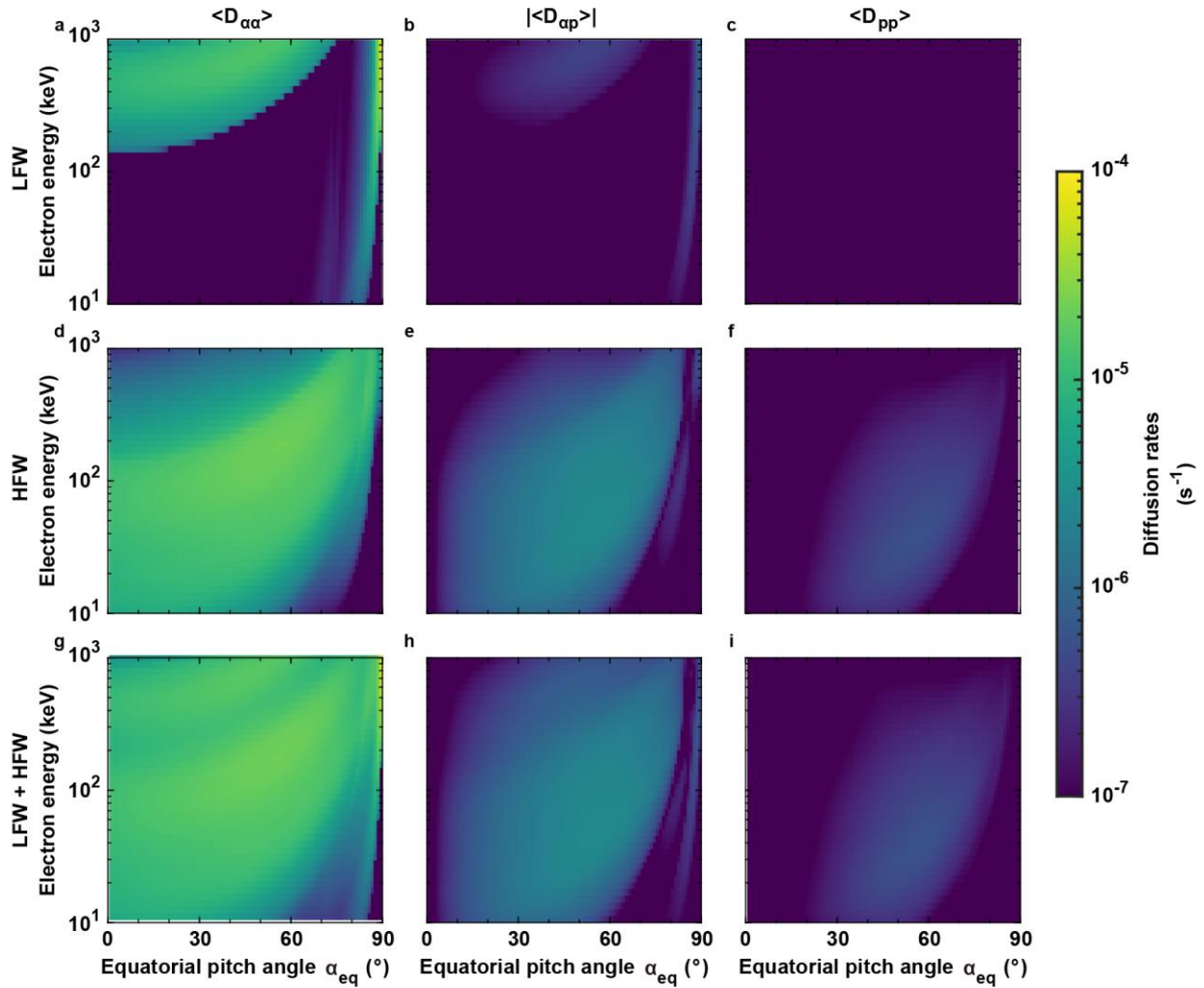


108

109 **Supplementary Figure 3** | Statistics of whistler-mode waves and corresponding energetic electron
 110 fluxes as functions of M_{eq} (the cube root of the local-to-equatorial magnetic field strength ratio along
 111 the same field line) and MLAT (magnetic latitude) in the magnetic meridian plane for different MLT
 112 (magnetic local time) sectors in Jupiter's magnetosphere. **a-b**, average wave amplitude distributions
 113 on the dawnside (00-06 MLT) and on the duskside (18-24 MLT). **c-h**, omni-directional electron flux
 114 distributions for three indicated energy channels (55, 97, 170 keV) on the dawnside and on the duskside.
 115 **i-j**, the corresponding spacecraft dwelling time. The magnetic latitude resolution is 10° , and the M-
 116 shell resolution is 0.5. Source data are provided as a Source Data file.



Supplementary Figure 4 | Spatial correlation of energetic electron fluxes and whistler-mode wave amplitudes (B_w) in the neighboring environment of Europa. MLAT denotes magnetic latitude, MLT means magnetic local time, and the M_{eq} represents the cube root of the local-to-equatorial magnetic field strength ratio along the same field line. **a-c**, the normalized electron fluxes in the magnetic meridian plane ($\Delta|MLAT| = 10^\circ$) for the three specified energy channels (55, 97, 170 keV) within the equivalent M -shell range of 5 – 15 ($\Delta M_{eq} = 0.5$) in the dawn sector (MLT = 00 – 06). The normalized flux (f_N) is the ratio between the omni-directional electron fluxes (j_{omni}) and the maximum j_{omni} within each magnetic latitude bin within $5 < M_{eq} < 15$. **d**, the averaged whistler-mode wave amplitudes in the magnetic meridian plane on the dawnside. Flux slot indicates the region of reduced electron fluxes, while wave peak highlights the region with enhanced wave amplitudes. **e**, spatial correlation between latitudinally averaged normalized electron fluxes for the three energy channels and averaged wave amplitudes, calculated within the shaded region of $M_{eq} = 7.25 - 13.75$ (shaded region). Due to limited data coverage within M -shell < 9 within $|MLAT| < 10^\circ$, the latitudinally averaged normalized electron fluxes and wave amplitudes are calculated within $|MLAT| = 10^\circ - 60^\circ$. Source data are provided as a Source Data file.



Supplementary Figure 5 | 2-D plots of bounce-averaged diffusion rates induced by whistler-mode waves at Jovian M-shell = 9.5 (M-shell is the distance from the magnetic equator to Jupiter's center, normalized by Jupiter's radius), as a function of electron kinetic energy and equatorial pitch angle. From left to right, the panels show bounce-averaged pitch angle diffusion rates ($\langle D_{\alpha\alpha} \rangle$), cross diffusion rates ($\langle D_{\alpha p} \rangle$), and momentum diffusion rates ($\langle D_{pp} \rangle$). From top to bottom, the panels display the diffusion rates due to LFWs (low frequency whistler-mode waves), HFWs (high frequency whistler-mode waves), and their combined scattering coefficients. Source data are provided as a Source Data file.

143 **Supplementary Table 1** | Wave normal angle models used for calculating diffusion rates induced by
 144 whistler-mode waves. MLAT is magnetic latitude, the LFWs are low frequency whistler-mode waves,
 145 the HFWs are high frequency whistler-mode waves. ψ_m denotes the maximum wave normal angle, and
 146 $\delta\psi$ represents the angular width. ψ_{lc} and ψ_{uc} indicate the lower and upper limits of the wave normal
 147 angle range, respectively. Source data are provided as a Source Data file.

Waves	MLAT (°)	ψ_m (°)	$\delta\psi$ (°)	ψ_{lc} (°)	ψ_{uc} (°)
LFWs	0-5	0	15	0	25
	5-10	20	15	0	40
	10-15	40	20	0	55
	15-20	50	30	15	70
	20-25	60	40	30	75
	25-30	70	50	50	80
	30-35	80	60	65	85
	35-40	80	70	75	85
	40-60	80	80	80	85
HFWs	0-20	0	10	0	30

148 **References**

149 1. Krupp, N. et al. Local time asymmetry of energetic ion anisotropies in the Jovian magnetosphere.
 150 Planet. Space. Sci. **49**, 283–289 (2001).
 151 2. Roussos, E. et al. Drift-resonant, relativistic electron acceleration at the outer planets: Insights from
 152 the response of Saturn’s radiation belts to magnetospheric storms. Icarus **305**, 160–173 (2018).
 153 3. Hao, Y. et al. The formation of Saturn’s and Jupiter’s electron radiation belts by magnetospheric
 154 electric fields. Astrophys. J. **905**, L10 (2020).
 155 4. Wang, J. et al. Dawn-dusk asymmetry of plasma flow in Jupiter’s middle magnetosphere observed
 156 by Juno. Geophys. Res. Lett. **51**, e2024GL110209 (2024).
 157 5. Yuan, C. et al. Galileo observation of electron spectra dawn-dusk asymmetry in the middle Jovian
 158 magnetosphere: Evidence for convection electric field. Geophys. Res. Lett. **51**, e2023GL105503
 159 (2024).
 160 6. Paranicas, C. et al. Io’s effect on energetic charged particles as seen in Juno data. *Geophys. Res.*
 161 *Lett.* **46**, 13615–13620 (2019).