nature portfolio

Peer Review File

The Origins of Patchy Aurora at Jupiter

Corresponding Author: Dr Alec Daly

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
See Attached

(Remarks on code availability)
The results presented in this paper are fully reproducible, and the accompanying codebase is a robust, well-documented resource designed to support and accelerate further research within the community.

Reviewer #2

(Remarks to the Author)
The Origins of Jupiter's Patchy Aurora

A. Daly et al.

This paper present auroral imaging of low latitude "patchy auroras" and in situ measurements of the source regions for these emissions. The paper concludes that various wave-particle interactions in the magnetosphere are responsible for pitch angle-diffusing trapped plasma into the loss cone to produce auroral emissions. This challenges previous suggestions that plasma injects from the outer magnetosphere to the inner magnetosphere are solely responsible for these emissions, though the authors admit that the two phenomena could be linked. The authors go on to suggest that the shape and size of the patchy emissions could be a way of remote-sensing those regions in the magnetosphere where these wave-particle interactions are occurring.

The paper is well-written, it presents a nice set of observations, its arguments are relatively compelling, and it does advance our understanding of auroral processes at Jupiter. Based on these considerations, I recommend it for publication.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)
Report about: The origins of Jupiter's patchy aurora

This manuscript describes the mechanism responsible for Jupiter's patchy aurora, aiming to identify their potential drivers and origins. The authors present a case study based on the observations from the Juno satellite at low altitude and equatorial crossings. According to the authors' conclusions, the patchy aurora is associated with electron precipitation due to pitch-angle scattering driven by wave-particle interactions. This result is a new contribution to previous works that related Jupiter's aurora to particle injections. The methodology used by the authors is suitable to support the conclusions, and they presented some high-standard discussions and arguments to validate their conclusions; however, it is required that the authors improve some points that need to be clarified as described below.

Major
Line 49: The authors need to clarify the sequence of events that results in the patchy aurora. Particle injection is usually associated with acceleration, whereas pitch angle scattering is often related to precipitation. The sentence is misleading. In addition, it is not clear if the wave-particle interaction contributes to the injection or to the pitch angle scattering.
Lines 53-58: the authors argue that the interchange instability plays a critical role in mass and plasma transport in Jupiter's magnetosphere; however, there is no description of such instability. Once this mechanism is relevant to discuss the presented results, the authors must add its description and how it is observed at Jupiter's magnetosphere.
Line 71: The authors mentioned the use of Hubble Space Telescope observation, but the description of the instruments is not presented before Results. The authors need to add a paragraph describing the measurements and the instruments.
Lines 103-104: The particle precipitation signature is very clear, so it is necessary to explain in detail what the facts are for the statement that the observed precipitation is due to wave-particle interactions at lower latitudes.
Line 106: The wave-particle interaction mediated by whistler waves has a resonant nature; thus, a wide energy range of precipitating particles is related to broad whistler emission spectra or different magnetic field magnitudes. The authors must include a discussion about this result.
Lines 151-159: The authors identify the whistler waves based on the frequency of emission only; there aren't any discussions about the polarity of the waves, though it is pertinent to cite past references related to Juno wave measurements that are based on the same arguments, e.g.:
Kurth, W. S., Imai, M., Hospodarsky, G. B., Gurnett, D. A., Tetrick, S. S., Ye, S. Y., ... & Levin, S. M. (2017). First observations near Jupiter by the Juno Waves investigation. Planetary radio emissions VIII, 1-12.
Kurth, W. S., Mauk, B. H., Elliott, S. S., Gurnett, D. A., Hospodarsky, G. B., Santolik, O., ... & Levin, S. M. (2018). Whistler mode waves associated with broadband auroral electron precipitation at Jupiter. Geophysical Research Letters, 45(18), 9372-9379.
Elliott, S. S., Gurnett, D. A., Yoon, P. H., Kurth, W. S., Mauk, B. H., Ebert, R. W., ... & Sulaiman, A. H. (2020). The generation of upward-propagating whistler mode waves by electron beams in the Jovian polar regions. Journal of Geophysical Research: Space Physics, 125(6), e2020JA027868.
Lines 252–269: In this paragraph, the authors discuss the main contribution of the paper. The explanation looks very interesting and plausible; however, some points need to be clarified:
253-256: the author cites the first mechanism responsible for producing auroral patches as being discussed in previous works. They related this mechanism to the ECH wave generation but apparently it is not related to the auroral precipitation. The authors need to explain here the reason for such a conclusion.
259-260: Here we have the explanation for the second mechanism. What are the "similar processes" that do not require the wave growth? Clarify.
261-262: The author started the paragraph using "Instead," and it is not clear if the proposed idea is in contrast with the wave growth driven by plasma injections or is in contrast with the second scenario. In addition, they propose that the plasma (whistler?) waves were generated without injection, but they did not present other wave source mechanisms at this point. So, it is important to clarify the arguments.
Figure 7: In this figure is represented the generation of whistler waves due to particle injections. However, in the manuscript, particle injection is attributed only to the ECH generation, while chorus waves are not. It is not clear what the relevance of this figure is for the discussions presented in the manuscript, since the diagram does not represent the other processes described throughout lines 261-262.
Lines 262-264: Clarify what the energy of the electrons presenting a pancake PAD is supposed to be—chorus wave source in this case. It is needed to clarify which is the electron population related to the injections that support the wave growth and the electron population with pancake PAD that is mentioned as a possible source of chorus waves.
Minor
Line 51: there is a preposition lost in the sentence.
Line 59-60: Rephrase this sentence: the wave-particle interaction is the cause of pitch angle scattering. Specify the waves considered here.
Line 78: I couldn't find the figure showing the in situ particle and wave measurements from 00:40:00 to 11:50 UT. The authors need to indicate which one is the figure.
Line 147-148: Include a reference about the pitch angle distributions and the generation and amplification of whistler plasma waves.

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
See attached

(Remarks on code availability)
Code is reproduceable and can used further such types of studies.

Reviewer #3

(Remarks to the Author)
The revised manuscript demonstrates significant improvement, and the authors have satisfactorily addressed all reviewer comments. I recommend the paper for publication in Nature Communications.

(Remarks on code availability)

Reviewer #1

The results presented in this paper are fully reproducible, and the accompanying codebase is a robust, well-documented resource designed to support and accelerate further research within the community.

Summary: The authors use data from NASA's Juno spacecraft to study the cause of Jupiter's patchy aurora. They analyze measurements from several instruments, including JEDI, JADE, Waves, MAG, and UVS. These tools help them study particles, plasma waves, magnetic fields, and ultraviolet auroral images. Overall, this is a worthwhile study, shows that Jupiter's patchy auroras are mainly caused by electron precipitation triggered by plasma waves, not just by magnetospheric injections. Injections help the waves grow, but the waves themselves are key to creating the auroras. This helps us better understand how Jupiter's magnetosphere connects to its Ionosphere/atmosphere and may apply to other planets too. This manuscript serves as an update to previous results; with new information about the JUNO observations and numerical calculations described beforehand. This is a valuable and well-structured study. It gives new information about Jupiter's auroras and supports ongoing research in planetary auroral processes.

Main Findings:

- The patchy auroras are caused by electron precipitation into Jupiter's ionosphere.
- Interestingly, diffuse auroral emissions on Jupiter sometimes form patchy shapes, which have been observed in both the northern and southern hemispheres by the Hubble Space Telescope and the Juno spacecraft.
- This precipitation is triggered by interactions between particles and plasma waves, especially ECH and whistler-mode waves.
- Particle injections help these waves grow and make the precipitation stronger.
- The study gives new insights that build on earlier work with more detailed data and calculations.

Strengths:

- The study uses a wide range of data from multiple instruments.
- It explains how wave-particle interactions lead to auroral emissions.
- The findings help improve our understanding of how Jupiter's magnetosphere and ionosphere are connected. The following are minor comments of the manuscript.

The authors would like to thank the reviewer for the thorough evaluation and useful suggestions, which helped improve the quality of this paper. In the following sections, we have provided a point-by-point response to the reviewer's comments and have incorporated the necessary revisions into the manuscript, which are highlighted through blue text.

Minor Comments:

1. Some sentences in the manuscript are long and complex [e.g.,(Lines 51-53: "Particle injections……..toward the planets"), (Lines 83-86: "This flyby occurred ……….ranging from 54.7° to -58.7°"), (Lines 91-93: "In some cases ……space density" give a region briefly).

Thank you for the comment. The sentences described have been shortened accordingly, with the revised sentences listed below:

Lines 50-52: "Particle injections are azimuthally localized regions of plasma that move radially inward and represent a key particle transport process at Jupiter [16,19,23,24]."

Lines 93-96: "This flyby occurred three minutes before the UVS observations (see Fig. 1). At that time, the spacecraft was located between M-shells 7.7 and 12 in the dawn sector near 6 magnetic local time (MLT), at high magnetic latitudes ranging from -54.7° to -58.7°."

Line 100: To avoid confusion, we have removed this sentence, as it is not essential.

2. Add a brief explanation of the numerical methods/including assumptions or limitations, (e.g., Li et al., 2020; Daly et al., 2023; Ma et al., 2024; Tripathi et al., 2024).

Thank you for the suggestion.

Tripathi et al., 2024: In this paper, to calculate the pitch angle diffusion coefficients of electrons driven by ECH waves at Jupiter, they used a temporal growth rate profile from Tripathi & Singal (2005) to represent the ECH wave spectral intensity and assumed that the wave amplitude is 1 mV/m. Note that only the first harmonic band is considered in their calculation, and the waves are assumed to be confined within 0.55° of magnetic latitude. We have included the details of our assumptions used in the model (e.g., total electron density, wave spectra, wave amplitude, wave normal distribution) in the "Methods" section on lines 335–377.

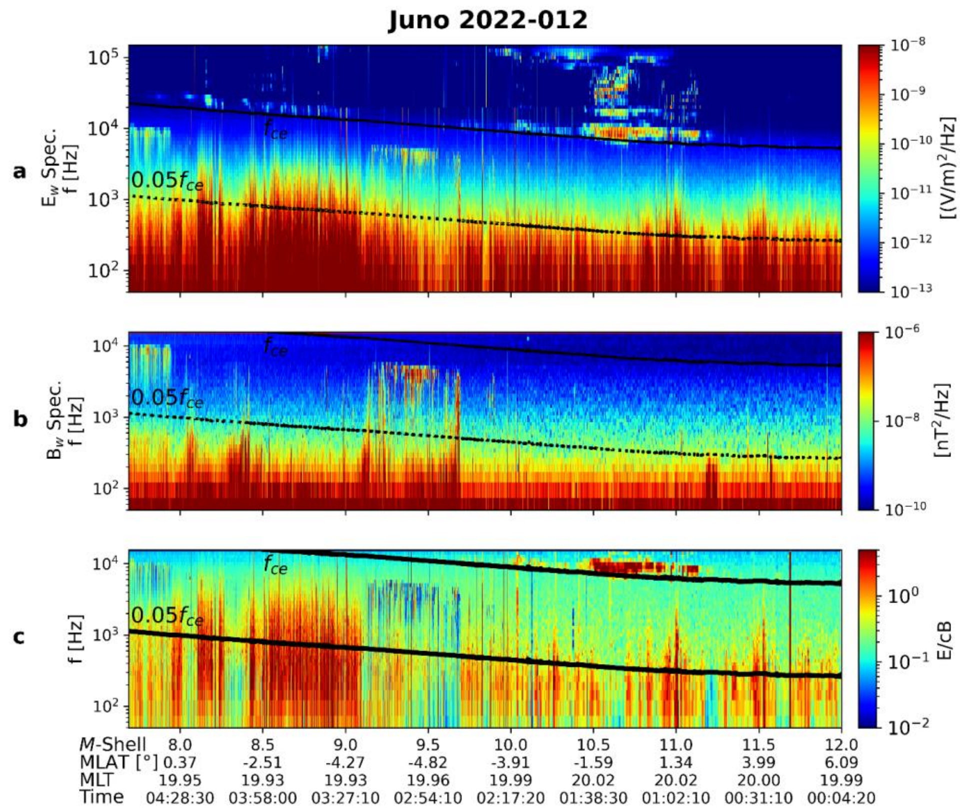
Tripathi, A. K., & Singal, R. P. (2005). Electrostatic electron cyclotron harmonic instability due to energetic electrons in Jupiter's magnetosphere. Journal of Geophysical Research, 110(A12), A12205. https://doi.org/10.1029/2005JA011113

Li et al., 2020; Daly et al., 2023; Ma et al., 2024: We would like to clarify that these three papers mainly focus on analyzing plasma wave properties and distributions using the Juno data without using numerical methods. Whistler-mode waves are identified by their occurrence in the frequency range between f_{cp} and f_{ce}, where strong electromagnetic signatures are present, as indicated by the wave electric to magnetic field ratio (E/cB). These were further distinguished as whistler-mode chorus and hiss depending on the frequency, with whistler-mode chorus between ~0.05 f_{ce} and f_{ce} and whistler-mode hiss between f_{cp} and ~0.05 f_{ce}. As the whistler-mode waves during the equatorial observations show a low E/cB (~0.01), they agree with the expected features for parallel-propagating, right-hand polarized whistler-mode waves. To show this, the E/cB ratio across this event has been included below, as well as its figure caption and description:

"1. Equatorial observations of plasma waves on 12 January 2022

Supplementary Fig. 1. shows the wave electric spectrogram, wave magnetic spectrogram, and E/cB ratio for equatorial observations on 12 January 2022. Here, E/cB represents the ratio of wave electric to magnetic power (where c is the speed of light) from 50 Hz to 20 kHz. For electromagnetic whistler-mode waves propagating parallel to the magnetic field with right-hand polarization, E/cB is expected to be less than 1. The identification of whistler-mode waves by

E/cB is also in agreement with the frequency range of the observed waves, falling between 0.05 f_{ce} and f_{ce} for whistler-mode chorus waves, and below 0.05 f_{ce} for whistler-mode hiss waves."



Supplementary Fig. 1. Equatorial observations of plasma waves on 12 January 2022. a Wave electric spectrogram from 50 Hz to 150 kHz, with solid and dotted black lines representing f_{ce} and $0.05f_{ce}$, respectively; **b** Wave magnetic spectrogram from 50 Hz to 20 kHz; **c** Ratio of wave electric to magnetic power (E/cB, where c is the speed of light) from 50 Hz to 20 kHz as a function of M-shell.

We have also included the following description in the manuscript on lines 167-178:

"Intense whistler-mode chorus waves, typically spanning frequencies between 0.05 and 1 f_{ce}, are detected between M-shells of 5.5 and 13 within ±20° magnetic latitude. In contrast, whistler-mode hiss waves, which occur at lower frequencies (mostly below 0.05 f_{ce})[67], are observed across a broader region[66-68] spanning M-shells of 5.5 to 15 and extending to magnetic latitudes up to ±50°. The Waves instrument provides single-axis measurements of electric and magnetic fields, limiting a complete characterization of wave properties. Furthermore, burst-mode data are unavailable during the equatorial observations, preventing the determination of the wave polarization[69,70]. As a result, whistler-mode waves are identified using their characteristic frequency range and their ratio of wave electric to magnetic power (*E*/*cB*) (see Supplementary Fig. 1), where *c* is the speed of light. Values of *E*/*cB* < 1 are consistent with expectations for parallel-propagating, right-hand polarized whistler-mode waves[66]**.**"

Relevant references:

66) Li, W. *et al.* Global distribution of whistler mode waves in Jovian inner magnetosphere. *Geophys. Res. Lett.* **47**, e2020GL088198 (2020).

67) Ma, Q. *et al.* Survey of whistler-mode wave amplitudes and frequency spectra in Jupiter's magnetosphere. *Geophys. Res. Lett.* **51**, e2024GL111882 (2024).

68) Menietti, J. D. *et al.* Analysis of whistler-mode and Z-mode emission in the Juno primary mission. *J. Geophys. Res. Space Phys.* **126**, e2021JA029885 (2021).

69) Elliott, S. S. *et al.* The generation of upward‐propagating whistler mode waves by electron beams in the Jovian polar regions. *J. Geophys. Res. Space Phys.*, 125(6), e2020JA027868 (2020).

70) Kurth, W. S. *et al.* Whistler mode waves associated with broadband auroral electron precipitation at Jupiter. *Geophys. Res. Lett.*, 45(18), 9372-9379 (2018).

3. Figures (4e) and (4f) identify the electrostatic and electromagnetic waves observed, revealing their intense amplitudes. In this context, I would like to know whether the ECH waves exhibit multiple harmonics — for example, second to fourth harmonics — in a weak pattern.

The ECH waves observed during equatorial observations exhibit strong enhancements in the first to third harmonics, as shown in the spectrogram below. The ECH waves are cutoff above the third harmonic by the upper hybrid frequency, shown here as the red line 'f_{uh} – JADE', where the lower bound of the upper hybrid frequency is estimated from the electron density measured by JADE electrons and in situ magnetic field strength. It is possible that the upper hybrid frequency is greater than the estimated value from JADE, with the modeled f_{uh} plotted with the magenta line, calculated from the modeled density from Dougherty et al. (2017). If this is the case, then the ECH wave frequency would extend to even greater harmonics of f_{ce}, as the modeled f_{uh} is near 10 f_{ce} at 01:30:00 UT.

We have added the following sentence to clarify its harmonic feature.

"Fig. 4e shows that ECH wave intensity peaks between M-shells 10.4–11.2 and exhibits multiple harmonics, with strong power in the first three harmonics."

Dougherty, L. P., Bodisch, K. M. & Bagenal, F. Survey of Voyager plasma science ions at Jupiter: 2. Heavy ions. *J. Geophys. Res. Space Phys.* **122**, 8257–8276 (2017).

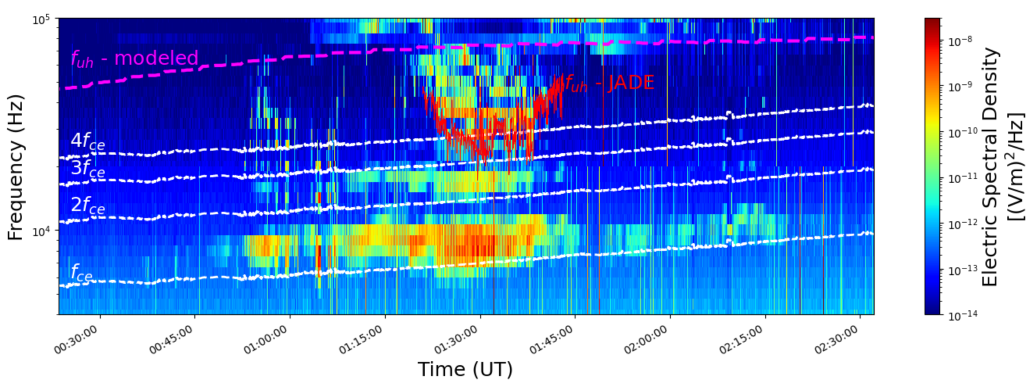


Figure R1. Electric wave spectrogram during ECH observations. The in-situ electron cyclotron frequency (f_{ce}) and its first 4 harmonics are shown as dashed white lines. The red line indicates the upper hybrid frequency estimated by the electron density from JADE, while the magenta dashed line represents the modeled upper hybrid frequency based on Dougherty et al. (2017).

4. Line 160: The statement "which occur at lower frequencies (mostly below 0.05 fce)"……. requires a citation to support it.

Line 169 has been modified to "In contrast, whistler-mode hiss waves, which occur at lower frequencies (mostly below 0.05 f_{ce})[67]"…… , citing

Ma, Q. *et al.* Survey of whistler-mode wave amplitudes and frequency spectra in Jupiter's magnetosphere. *Geophys. Res. Lett.* **51**, e2024GL111882 (2024).

5. Line 225: The statement "In addition, the accuracy of magnetic field mapping may contribute to the slight shifts observed in the M-shell" is too brief. More elaboration is required regarding how the magnetic field mapping was performed and how this could influence the observed shifts in the M-shell.

Thank you for comment. In this study, the JRM33 internal field model and CON2020 current sheet model (Connerney et al., 2020, 2022) are used to map the spacecraft location to a specific M-shell. This mapping requires tracing the model field line to the magnetic equator to determine the equatorial crossing radius or M-shell. Therefore, uncertainties in the magnetic field model account for corresponding uncertainties in the derived M-shell values. The figure below (Figure R2) compares the in situ magnetic field strength measured by the magnetometer with the magnetic field strength predicted by the JRM33+CON2020 model along the same trajectory. The two values agree closely, but small deviations (~ a few nT) still exist. These slight differences in magnetic field strength lead to small offsets in the derived M-shell and its mapped ionospheric footprint. These discrepancies have been noted in prior work, such as Moirano et al. (2024), which found offsets of up to ~600 km between the observed and modeled footprints of the Jovian moons in the southern hemisphere. This uncertainty may contribute to slight M-shell shifts and therefore small latitudinal shifts observed in our analysis.

To improve the clarity of the manuscript, Lines 242-245 have been modified to "In addition, the accuracy of magnetic field mapping may contribute to the slight shifts observed in the M-shell. Small discrepancies between the observed and modeled field strength shift the mapped equatorial radius from Jupiter, resulting in slight offsets in M-shell and the conjugate footprint path[75]."

47) Connerney, J. E. P. *et al.* A new model of Jupiter's magnetic field at the completion of Juno's Prime Mission. *J. Geophys. Res. Planets* **127**, e2021JE007055 (2022).

48) Connerney, J. E. P., Timmins, S., Herceg, M. & Joergensen, J. L. A Jovian magnetodisc model for the Juno era. *J. Geophys. Res. Space Phys.* **125**, e2020JA028138 (2020).

75) Moirano, A. *et al.* The infrared auroral footprint tracks of Io, Europa and Ganymede at Jupiter observed by Juno-JIRAM. *J. Geophys. Res. Planets*, 129, e2023JE008130 (2024).

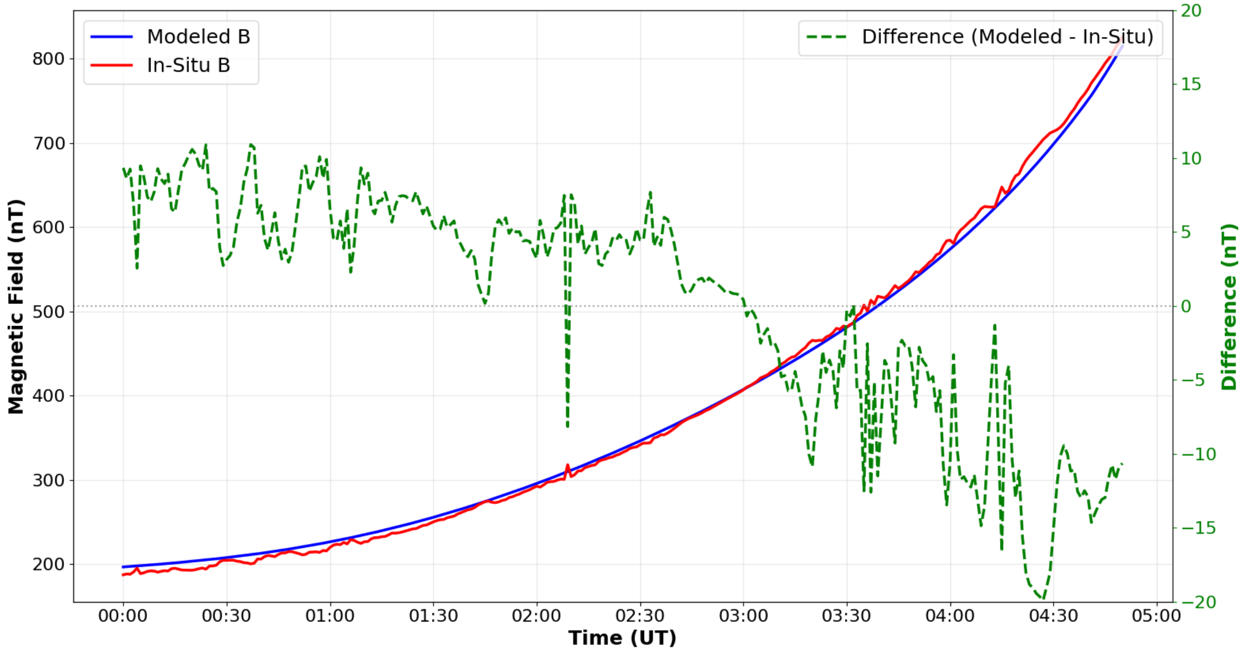


Figure R2. Comparison between the modeled and observed magnetic field intensity. The modeled magnetic field intensity, based on the JRM33 + CON2020 model, is shown by the blue line, while the in situ observed magnetic field intensity is shown by the red line. The green line represents the difference between the modeled and observed magnetic field intensity, with its scale indicated on the right-hand axis.

7. Line 250: The results suggest that plasma waves are the direct drivers of isolated patchy aurora at low altitudes. Were these results consistent with or supported by previous observations? If so, provide relevant references or comparisons to earlier studies.

Thank you for the comment and suggestion. While isolated patchy aurora has been reported in previous studies at Jupiter, plasma waves have not, to the best of our knowledge, been directly identified as their primary driver. Earlier work generally attributed patchy structures to particle injections, under the assumption that injection-associated anisotropies would generate plasma waves and produce pitch-angle scattering. However, no observational study has demonstrated plasma waves directly driving isolated auroral patches at Jupiter. The present results therefore provide the first observational evidence of wave-driven patchy aurora and further show that in this event whistler-mode waves are anti-correlated with the injections, contrary to the former expectation that injections should drive wave growth.

It is also important to note that the plasma waves responsible for pitch-angle scattering in the low-altitude observations are expected to be confined to low magnetic latitudes. Whistler-mode and ECH waves observed by Juno are strongest near the magnetic equator and typically are not observed at low altitudes, as shown in Figures 2 and 3. The auroral patches detected at low altitudes do not require wave activity at the same latitudes. Rather, the electrons are scattered into the loss cone at lower latitudes, move along the field line, and precipitate into the atmosphere. We include the following sentence in the manuscript to clarify this point (Lines 260-263):

"Although no plasma waves were detected locally during the low-altitude pass, electrons are scattered into the loss cone by interacting with whistler-mode and ECH waves at lower magnetic latitudes where these waves preferentially occur[65-67]."

8. Lines 328-332: The statement "The measured electron…………are highly oblique" provides a useful description of the modeling approach. However, it is noted that the cyclotron resonance dominates electron scattering in the energy range of 30 eV to 1 MeV, and that this fitted distribution is used to calculate the wave growth rate. In earlier studies, it has been shown that anisotropic electron distributions are often modeled as a superposition of a Maxwellian distribution for cold electrons and a Kappa distribution for energetic electrons, particularly in the context of analysis of pitch angle scattering leading to diffuse aurora by both ECH and whistler-mode wave. I suggest the authors clarify why a six-component bi-Maxwellian model was chosen in this case, and whether the use of Kappa distributions for energetic electrons was considered or could influence the results (For example, References 31, 35, 55, 65, 67, and 71 have already addressed this in previous studies).

Thank you for the suggestion. The six-component bi-Maxwellian model is used as an input to the WHAMP code and provides a good fit to the observed electron distributions during intervals of ECH wave activity, as shown in the figure below. We agree that a Kappa distribution may describe the observed phase space density in a simpler form. However, it is easier to use multiple component Maxwellian distributions in the WHAMP code instead of revising the code to adopt a Kappa distribution as input. As demonstrated in Figure R3, the fitted distribution reproduces both the energy and pitch angle structure of the phase space density. Because the observed distributions are well captured by this multi-component bi-Maxwellian model, the use of a Kappa distribution was not considered in this case and is not expected to significantly influence the modeled results.

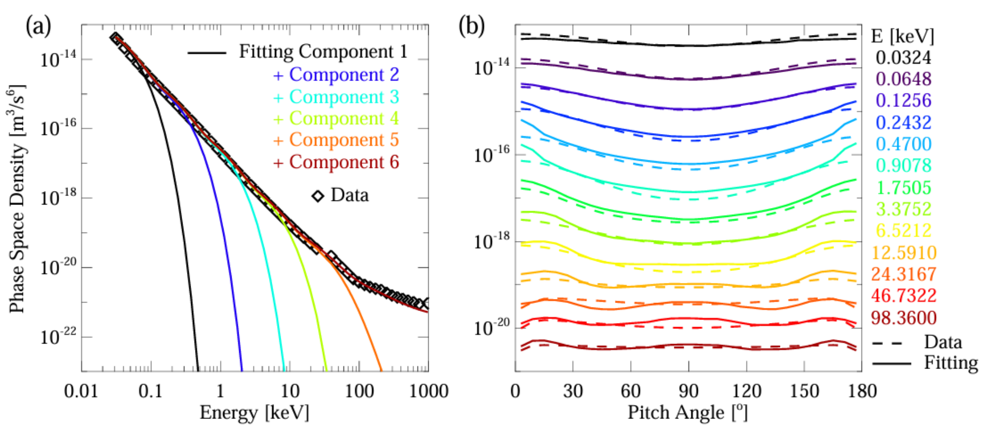


Figure R3. Comparison between the observed and modeled electron distributions. **a** Energy spectra of electron phase space density for the modeled six components of bi-Maxwellian distribution (solid lines) and the observation (empty diamonds). **b** Modeled (solid line) and observed (dashed line) electron pitch angle distribution color coded for various energies.

9. Figure 3(e) shows the comparison of auroral brightness and precipitating electron flux as a function of M-shell during a low-altitude pass. It is noted that the precipitating electron flux is enhanced compared to the auroral brightness at M-shell values less than 10, whereas the pattern

reverses at values greater than approximately M = 10. My concern is: which type of waves could be responsible for this pattern?

Thank you for the question. The waves responsible for the precipitation pattern near M~10 are likely whistler-mode waves, indicated by the high color ratio (Fig. 3b,f) and the prevalence of high-energy electrons found within the southern loss cone in Fig. 2g. Whistler-mode waves resonate with electrons in the energy range from tens to several hundred keV, consistent with the characteristic energies, reflected in the UVS color ratio at these M-shells.

At larger M-shells (>10), both the precipitation and color-ratio patterns remain consistent with whistler-mode scattering. Between M-shells 8 and 10, the precipitating electron flux curve remains persistently elevated relative to the auroral brightness curve, which may be attributable to residual radiation belt contamination that is more prevalent at lower M-shells. Although efforts were made to mitigate this contamination, it may persist, as indicated by the mild peak near ~200 keV between M-shells 8 and 10 in Fig. 2g.

We further clarify the likelihood of whistler-mode waves being responsible for this pattern in lines 303-310:

"Under this assumption, the auroral patch observed in the low-altitude measurements (Fig. 3a, b) may be associated with whistler-mode waves originating from lower magnetic latitudes. These waves were not detected during the low-altitude flyby, as observations were limited to high latitudes (< -50°), beyond the typical range where whistler-mode chorus and hiss waves are observed[66,67]. Because the resonance condition for whistler-mode waves depends on magnetic field strength and pitch angle along the field line, these waves can scatter electrons across a broad energy range, consistent with the tens to hundreds of keV precipitating electron population observed by JEDI."

Conclusion

"I wholeheartedly accept and recommend this manuscript for publication in Nature Communications."

The authors would like to thank the reviewer again for the positive comment and helpful comments!

Reviewer #2 (Remarks to the Author):

The Origins of Jupiter's Patchy Aurora

A. Daly et al.

This paper present auroral imaging of low latitude "patchy auroras" and in situ measurements of the source regions for these emissions. The paper concludes that various wave-particle interactions in the magnetosphere are responsible for pitch angle-diffusing trapped plasma into the loss cone to produce auroral emissions. This challenges previous suggestions that plasma injects from the outer magnetosphere to the inner magnetosphere are solely responsible for these emissions, though the authors admit that the two phenomena could be linked. The authors go on to suggest that the shape and size of the patchy emissions could be a way of remote-sensing those regions in the magnetosphere where these wave-particle interactions are occurring.

The paper is well-written, it presents a nice set of observations, its arguments are relatively compelling, and it does advance our understanding of auroral processes at Jupiter. Based on these considerations, I recommend it for publication.

The authors would like to thank the reviewer for the positive comment!

Reviewer #3 (Remarks to the Author):

This manuscript describes the mechanism responsible for Jupiter's patchy aurora, aiming to identify their potential drivers and origins. The authors present a case study, based on the observations from Juno satellite at low altitude and equatorial crossings. According to the authors conclusions, the patchy aurora is associated with electron precipitation due to pitch-angle scattering driven by wave-particle interactions. This result is a new contribution to previous works that related Jupiter's aurora to particle injections. The methodology used by the authors is suitable to support the conclusions and they presented some high standard discussions and arguments to validate their conclusions; however it is required that the authors improve some points that need to be clarified as described below.

The authors would like to thank the reviewer for the careful review of our manuscript and for the constructive comments and suggestions below. In the following sections, we have provided a point-by-point response to the reviewer's comments and have incorporated the necessary revisions into the manuscript, which are highlighted through blue text.

Major

Line 49: The authors need to clarify the sequence of events that results in the patchy aurora. Particle injection is usually associated with acceleration whereas pitch angle scattering is often related to precipitation. The sentence is misleading. In addition, it is not clear if the wave-particle interaction contributes to the injection or to the pitch angle scattering.

Thank you for noting this ambiguity. Our intended meaning was that injections can create the plasma conditions suitable for wave growth, and that the waves (not injections) drive the pitch-angle scattering responsible for precipitation.

To clarify this point, we revised the text from lines 50-66 to introduce the origins of injections, and then lines 67-72 to clarify the sequence of events leading to patchy aurora, which is included below:

Lines 67-71: "Injections modify particle velocity distributions, potentially producing unstable populations that provide the free energy necessary for plasma wave generation[34,35]. The waves generated in association with injections pitch-angle scatter and precipitate electrons through resonant wave-particle interactions[36-41]. Some of the observed waves that have been generated through injection processes at Jupiter include electron cyclotron harmonic (ECH) waves and whistler-mode waves[33,42]."

Line 53-58: the authors argue that the interchange instability plays a critical role in mass and plasma transport in Jupiter's magnetosphere, however there is no description of such instability. Once this mechanism is relevant to discuss the presented results; the authors must add its description and how it is observed at Jupiter's magnetosphere.

Thank you for the suggestion. Interchange motions are unstable in an environment where an outward decrease in flux tube plasma content ($N = \int n \cdot dl/B$) dominates over the stabilizing outward increase in flux tube entropy ($H = \int p^{1/\gamma} dl/B$). Here, n represents plasma number density, dl is the elemental length along the magnetic field line, p is the thermal pressure, and B is the magnetic field strength. This instability occurs in rapidly rotating magnetospheres with strong internal plasma sources, such as Jupiter, and is analogous to a Rayleigh-Taylor instability, where a dense fluid resting above a relatively lighter fluid is subject to gravity, causing it to mix with the underlying layer and produce a temporarily unstable system. At Jupiter, mass loading from Io and rapid rotation act to impart an outward centrifugal force, substituting gravity.

We have modified lines 58-66 to the following:

"Another mechanism capable of producing injections is the interchange instability, a fundamental process that plays a key role in mass and plasma transport in Jupiter's magnetosphere. This instability occurs when an outward decrease in flux tube content exceeds the stabilizing increase in flux tube entropy[30]. In this regime, centrifugal force plays a role analogous to gravity in the Rayleigh–Taylor instability, driving flux tubes of cold, dense plasma from the inner magnetosphere to interchange with more distant flux tubes of hot, tenuous plasma[29-32]. Interchange injections are characterized by rapid enhancements in magnetic field strength, as well as changes in particle flux and associated plasma waves on timescales of seconds to minutes[33]."

Line 71: The authors mentioned the use of Hubble Space telescope observation, but the description of the instruments is not presented before Results. The authors need to add a paragraph describing the measurements and the instruments.

We would like to clarify that Hubble Space Telescope (HST) observations are not used in this study. HST is mentioned in the Introduction and Discussion as a brief reference to previous works that identified patchy auroral structures using HST imaging. All observations within this study are obtained exclusively from instruments onboard Juno. Specifically, we used the Ultraviolet Spectrograph (UVS)[15] to measure auroral emission properties. The related descriptions on the Juno instruments are included on lines 74–79.

Line 103 -104: The particle precipitation signature is very clear, so it is necessary to explain in detail what are the facts to the statement that the observed precipitation is due to wave-particle interactions at lower latitudes.

Thank you for this suggestion. The precipitation signature in Fig. 2g spans a broad energy range (10s–100s of keV), which is characteristic of pitch-angle scattering by whistler-mode waves rather than by local processes at low-altitude. During the low-altitude pass, Juno was positioned at high magnetic latitudes (-55° to -59°), where the propagation of whistler-mode waves is typically inhibited. Statistically, whistler-mode wave power extends up to 50° (Ma et al., 2024). Because of this, the absence of local wave activity at low altitude is consistent with a scenario in which electrons are scattered into the loss cone at lower magnetic latitudes, precipitate along the field line, and are subsequently detected by the JEDI instrument during the low-altitude flyby. However, the corresponding observation of plasma waves that potentially account for this electron precipitation and the patchy aurora (shown in Fig. 3) is unavailable.

To clarify this, we have added the following sentences to lines 260-263:

"Although no plasma waves were detected locally during the low-altitude pass, it is possible that electrons are scattered into the loss cone by interacting with whistler-mode and/or ECH waves at lower magnetic latitudes where these waves preferentially occur[65-67]."

Ma, Q. *et al.* Survey of whistler-mode wave amplitudes and frequency spectra in Jupiter's magnetosphere. *Geophys. Res. Lett.* **51**, e2024GL111882 (2024).

Line 106: The wave-particle interaction mediated by whistler waves has a resonant nature, thus a wide energy range of particles precipitating is related to broad whistler emission spectra or different magnetic field magnitude, the authors must include a discussion about this result.

Thank you for the comment. We have added additional clarification in the Discussion section to explain that the broad range of precipitating energies observed at low altitude is consistent with whistler-mode wave scattering. Currently, lines 303–307 state: "Under this assumption, the auroral patch observed in the low-altitude measurements (Fig. 3a, b) may be associated with whistler-mode waves originating from lower magnetic latitudes. These waves were not detected during the low-altitude flyby, as observations were limited to high latitudes (< -50°), beyond the typical range where whistler-mode chorus and hiss waves are observed[66,67]".

This has now been further supported by including discussion of the precipitating population of high energy electrons that are within a suitable range to resonate with whistler-mode waves (see lines 307–310):

"Because the resonance condition for whistler-mode waves depends on magnetic field strength and pitch angle along the field line, these waves can scatter electrons across a broad energy range, consistent with the tens to hundreds of keV precipitating electron population observed by JEDI."

Lines 151-159: The authors identify the whistler waves based on the frequency of emission only, there aren't any discussions about polarity of the waves, though it is pertinent to cite past references related to Juno waves measurements that are based in the same arguments, e.g.:

Kurth, W. S., Imai, M., Hospodarsky, G. B., Gurnett, D. A., Tetrick, S. S., Ye, S. Y., ... & Levin, S. M. (2017). First observations near Jupiter by the Juno Waves investigation. Planetary radio emissions VIII, 1-12.

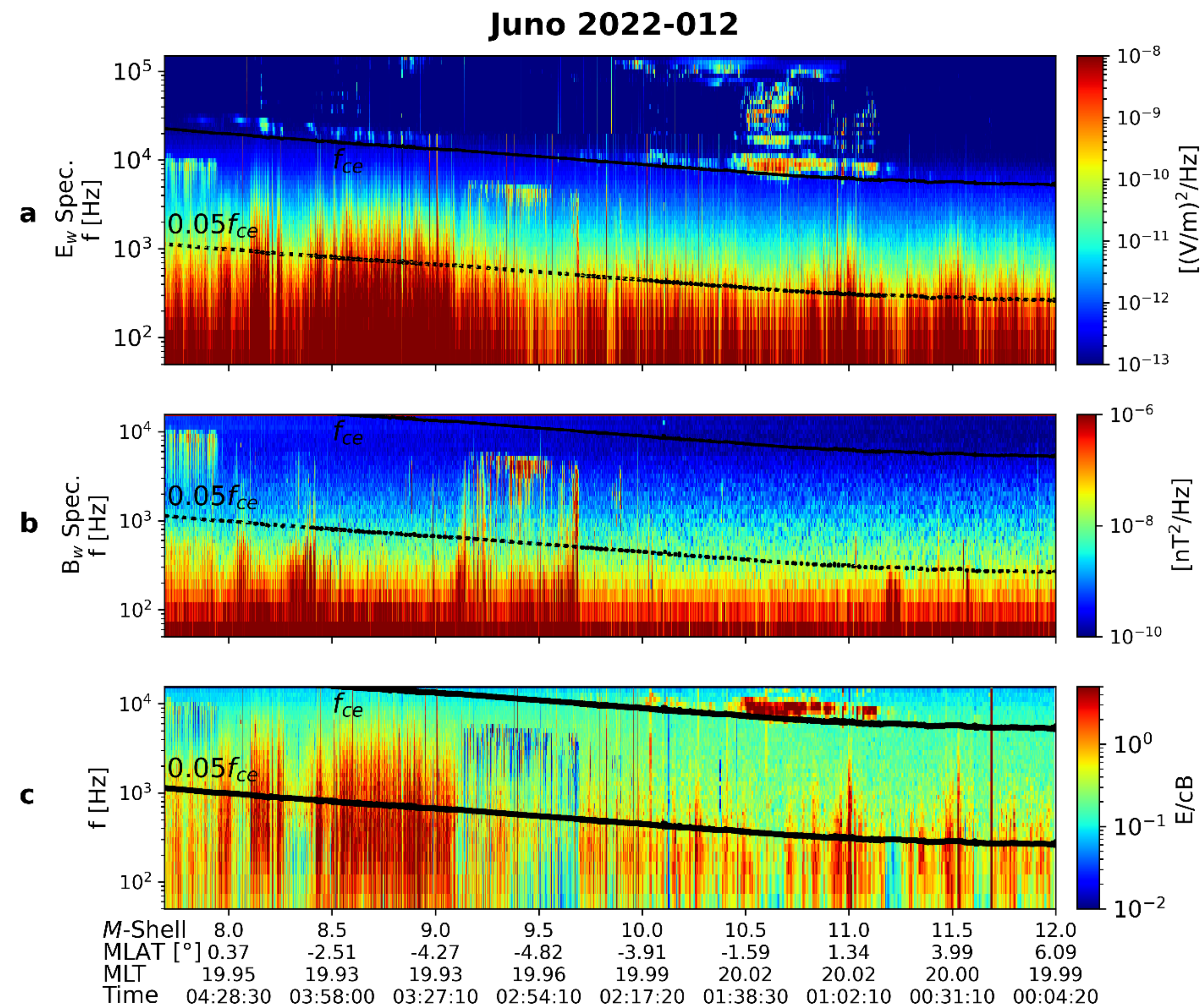
Kurth, W. S., Mauk, B. H., Elliott, S. S., Gurnett, D. A., Hospodarsky, G. B., Santolik, O., ... & Levin, S. M. (2018). Whistler mode waves associated with broadband auroral electron precipitation at Jupiter. Geophysical Research Letters, 45(18), 9372-9379.

Elliott, S. S., Gurnett, D. A., Yoon, P. H., Kurth, W. S., Mauk, B. H., Ebert, R. W., ... & Sulaiman, A. H. (2020). The generation of upward‐propagating whistler mode waves by electron beams in the Jovian polar regions. Journal of Geophysical Research: Space Physics, 125(6), e2020JA027868.

We would like to thank the reviewer for the suggestion as well as the references provided. It is true that our identification of whistler-mode waves relies primarily on the frequency range of the emissions in the electric and magnetic field spectra, as survey-mode data do not provide vector information needed for polarization analysis, and burst mode data were unavailable for the relevant whistler-mode waves observed in this study. Because of this, the identification of whistler-mode waves is assumed through the range of frequencies between f_{cp} and f_{ce} that show strong electromagnetic signatures, which can be observed through the electric to magnetic field ratio (E/cB). These were further distinguished as whistler-mode chorus and hiss depending on the frequency, with whistler-mode chorus between ~0.05 f_{ce} and f_{ce} and whistler-mode hiss between f_{cp} and ~0.05 f_{ce}. As the whistler-mode waves during the equatorial observations exhibit a low E/cB (~0.01), they match the expected features for a parallel-propagating, right-hand polarized whistler-mode waves. To show this, the E/cB ratio across this event has been included below, as well as its figure caption and description:

"1. Equatorial observations of plasma waves on 12 January 2022

Supplementary Fig. 1. shows the wave electric power spectrogram, wave magnetic power spectrogram, and E/cB ratio for equatorial observations on 12 January 2022. Here, *E/cB* represents the ratio of wave electric to magnetic power (where *c* is the speed of light) from 50 Hz to 20 kHz. For electromagnetic whistler-mode waves propagating parallel to the magnetic field with right-hand polarization, *E/cB* is expected to be less than 1. The identification of whistler-mode waves by *E/cB* is also in agreement with the frequency range of the observed waves, falling between 0.05 f_{ce} and f_{ce} for whistler-mode chorus waves, and below 0.05 f_{ce} for whistler-mode hiss waves."



Supplementary Fig. 1. Equatorial observations of plasma waves on 12 January 2022. a Wave electric power spectrogram from 50 Hz to 150 kHz, with solid and dotted black lines representing f_{ce} and $0.05f_{ce}$, respectively; **b** Wave magnetic power spectrogram from 50 Hz to 20 kHz; **c** Ratio of wave electric to magnetic power (E/cB, where c is the speed of light) from 50 Hz to 20 kHz as a function of M-shell.

We have also included the following description in the manuscript on lines 167-178:

"Intense whistler-mode chorus waves, typically spanning frequencies between 0.05 and 1 f_{ce}, are detected between M-shells of 5.5 and 13 within ±20° magnetic latitude. In contrast, whistler-mode hiss waves, which occur at lower frequencies (mostly below 0.05 f_{ce})[67], are observed across a broader region[66-68] spanning M-shells of 5.5 to 15 and extending to magnetic latitudes up to ±50°. The Waves instrument provides single-axis measurements of electric and magnetic fields, limiting a complete characterization of wave properties. Furthermore, burst-mode data are unavailable during the equatorial observations, preventing the determination of the wave polarization[69,70]. As a result, whistler-mode waves are identified using their characteristic frequency range and their ratio of wave electric to magnetic power (E/cB) (see Supplementary Fig. 1), where c is the speed of light. Values of $E/cB < 1$ are consistent with expectations for parallel-propagating, right-hand polarized whistler-mode waves[66]."

Relevant references:

66) Li, W. *et al.* Global distribution of whistler mode waves in Jovian inner magnetosphere. *Geophys. Res. Lett.* **47**, e2020GL088198 (2020).

67) Ma, Q. *et al.* Survey of whistler-mode wave amplitudes and frequency spectra in Jupiter's magnetosphere. *Geophys. Res. Lett.* **51**, e2024GL111882 (2024).

68) Menietti, J. D. *et al.* Analysis of whistler-mode and Z-mode emission in the Juno primary mission. *J. Geophys. Res. Space Phys.* **126**, e2021JA029885 (2021).

69) Elliott, S. S. *et al.* The generation of upward - propagating whistler mode waves by electron beams in the Jovian polar regions. *J. Geophys. Res. Space Phys.*, 125(6), e2020JA027868 (2020).

70) Kurth, W. S. *et al.* Whistler mode waves associated with broadband auroral electron precipitation at Jupiter. *Geophys. Res. Lett.*, 45(18), 9372-9379 (2018).

Lines 252 – 269: In this paragraph, the authors discuss the main contribution of the paper, the explanation looks very interesting and plausible, however some points need to be clarified:

253-256: the author cites the first mechanism responsible to produce auroral patches as being discussed in previous works. They related this mechanism to the ECH waves generation but apparently is not related to the auroral precipitation. The authors need to explain here the reason for such conclusion.

Thank you for the comment. The first mechanism describes how particle injections generate unstable electron distributions that lead to plasma wave growth. In this event, we find that although injections transport energetic electrons inward, the flux of electrons does not match the pattern of the observed auroral brightness. Therefore, the injections themselves do not explain the precipitation. Instead, wave-particle interactions are required to scatter additional electrons into the loss cone. To clarify this point in the manuscript, we added the sentence "The injecting electron fluxes are not directly correlated with the observed auroral brightness" to line 265.

Our intention was that the first mechanism applies directly to the ECH-related auroral precipitation observed in this event. In Figs. 5-6, the ECH waves associated with injections produce enhanced pitch angle diffusion for ~100 eV to a few keV electrons, and the resulting modeled precipitation reproduces the ECH-related auroral patch marked in Fig.6. To make this connection more explicit, we have revised the text as (Lines 281–284):

"This injection-driven mechanism is manifested through the observed ECH waves, which are correlated with the electron injections (Fig. 4a, b) and are associated with electron precipitation aligned with an auroral patch (green dashed circle in Fig. 6a)."

259-260: here we have the explanation for the second mechanism, what are the "similar process" that does not require the wave growth? Clarify.

Thank you for pointing out this ambiguity. By "similar process," we intended to convey that the scattering mechanism is the same in both cases – once plasma waves are present, they pitch-angle scatter electrons into the loss cone and generate auroral emission. The difference in the second mechanism is in the origin of the waves, as they are not required to be generated by injections. Instead, waves such as whistler-mode chorus waves in the equatorial observations can be generated directly by local electron anisotropies (pancake-like distribution in this scenario), as shown in Fig. 4c,d. To clarify this distinction, we added the sentence:

"The second scenario follows the same scattering process but does not require wave growth driven by plasma injections. Instead, we propose that plasma waves may be generated without injections and can pitch-angle scatter electrons into Jupiter's atmosphere, generating auroral patches."

261-262: the author started the paragraph using "Instead" and it is not clear if the proposed idea is in contrast with the wave growth driven by plasma injections or is in contrast with the second scenario. In addition, they propose that the plasma (whistler?) waves were generated without injection, but they did not present other wave source mechanism at this point. So, it is important to clarify the arguments.

Thank you for the helpful comment. In this paragraph, "instead" refers to "instead of wave growth driven by plasma injections." This is clarified by including "we propose that plasma waves may be generated without injections" in the same sentence.

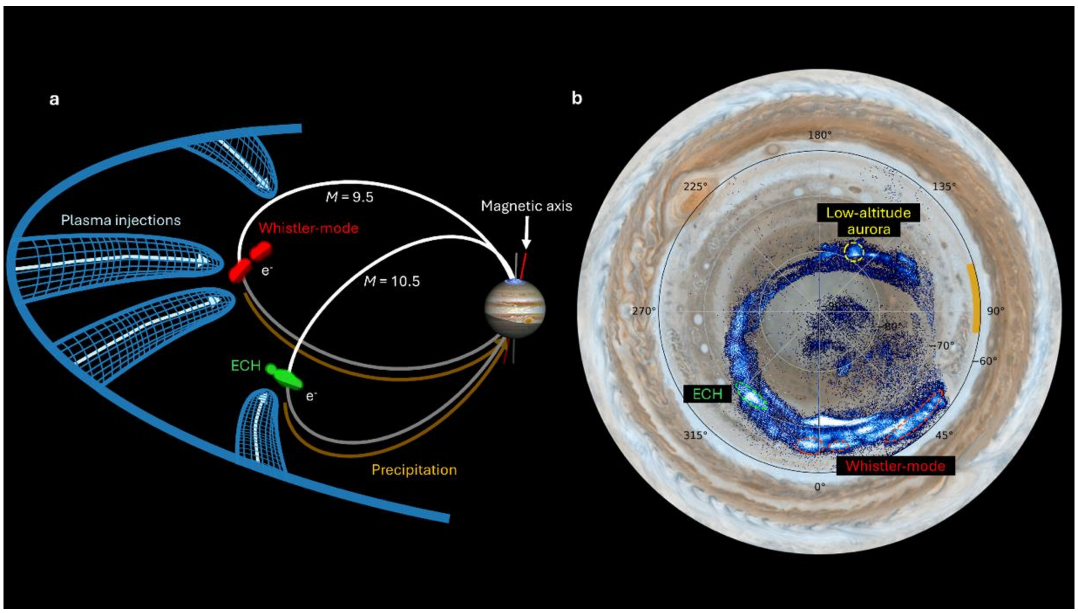
Regarding the wave source mechanism, our intention was not to investigate or speculate a new process. Whistler-mode chorus waves can be generated independently of injections through anisotropic electron distributions. In this event, the equatorial observations show strong pancake distributions (Fig. 4c,d), which provide the free energy for chorus wave growth. So, in the second scenario, the scattering process remains the same as in the injection-driven mechanism, but the wave generation arises from anisotropic pitch-angle distributions rather than from injection-triggered instability.

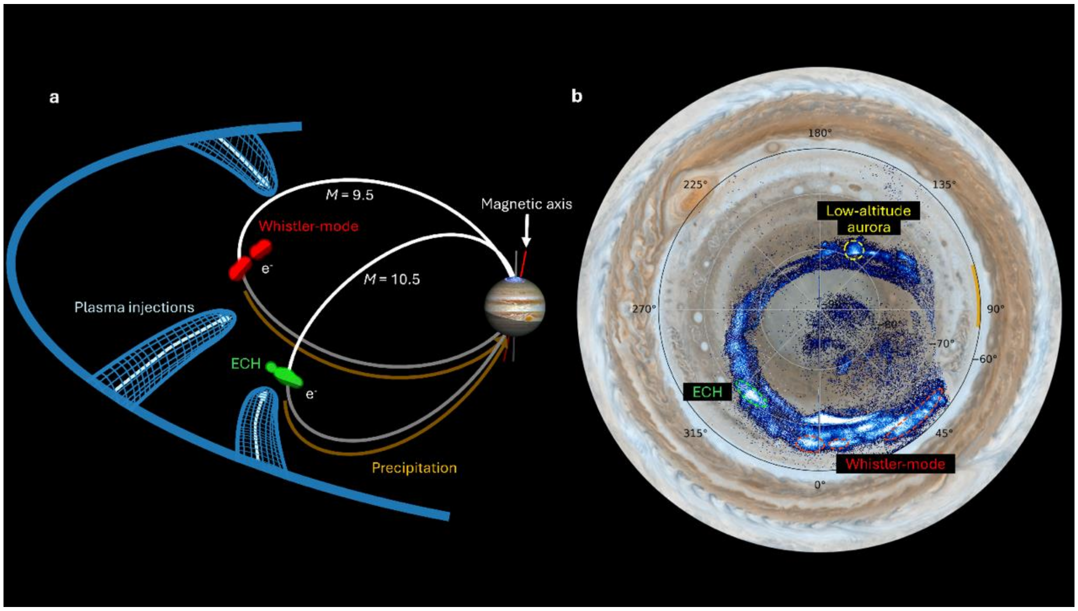
To make this clearer, we revised lines 285-289 to the following:

"Instead, we propose that plasma waves may be generated without injections and can pitch-angle scatter electrons into Jupiter's atmosphere, generating auroral patches. This is evident from the observed whistler-mode chorus waves during non-injection intervals, which correlate strongly with electrons exhibiting pancake distributions from ~1 keV to several hundred keV–conditions favorable for wave generation (Fig. 4c, d).

Figure 7: In this figure is represented the generation of whistler waves due to particle injections. However, in the manuscript, particle injection is attributed only to the ECH generation, while chorus waves are not. It is not clear the relevance of this figure for the discussions presented in the manuscript, since the diagram does not represent the other processes described throughout lines 261-262.

Thank you for pointing this out. To remain fully consistent in the manuscript and to display the scenario observed here, Fig. 7 has been updated so that the injections are no longer shown as directed toward the whistler-mode waves. The original version is provided below, followed by the revised figure.





Lines 262-264: Clarify what is the energy of the electrons presenting a pancake PAD supposed to be chorus waves source in this case. It is needed to clarify which is the electron population related to the injections that support the wave growth, and the electron population with pancake PAD that is mentioned as possible source of chorus waves.

Thank you for the suggestion. The population of electrons relevant to whistler-mode wave growth ranges from energies of ~1 keV to tens of keV. During equatorial observations, this population exhibits a pancake pitch angle distribution, resulting in enhanced whistler-mode wave growth. To clarify the energy of electrons presenting this distribution for the source of whistler-mode chorus waves, we have modified lines 287-289 to the following:

"This is evident from the observed whistler-mode chorus waves during non-injection intervals, which correlate strongly with electrons exhibiting pancake distributions from ~1 keV to several hundred keV–conditions favorable for wave generation (Fig. 4c, d)."

Minor

Line 51: there is a preposition lost in the sentence.

Thank you for pointing this out. The sentence has been modified to read: "Particle injections are azimuthally localized regions of plasma that move radially inward and represent a key particle transport process at Jupiter [16,19,23,24]."

Line 59-60: rephrase this sentence: the wave-particle interaction is the cause of pitch angle scattering. Specify what are the waves considered here.

This sentenced has been modified to read: "The waves generated in association with injections pitch-angle scatter and precipitate electrons through resonant wave-particle interactions[36-41]. Some of the observed waves that have been generated through injection processes at Jupiter include electron cyclotron harmonic (ECH) waves and whistler-mode waves[33,42]."

Line 78: I couldn’t find the figure showing the in situ particle and wave measurements from 00:40:00 to 11:50 UT. The authors need to indicate which is the Figure.

The referenced line refers to the trajectory of the spacecraft in Figure 1. The in situ particle and wave measurements are shown from 00:04:00 to 04:50:00 UT in the equatorial observations and from 11:39:00 to 11:50:00 UT for the low-altitude observations. To clarify this, lines 85-91 have been rewritten to:

“The primary auroral observations are mapped by co-adding UVS data recorded from 11:52:50 to 12:25:14 universal time (UT), while the in situ particle and wave measurements span two distinct intervals: a near-equatorial pass from 00:04:00 to 04:50:00 UT and a high-latitude (or low-altitude) pass from 11:39:00 to 11:50:00 UT. During UVS observations, patchy auroral enhancements extending several degrees in both latitude and longitude are observed. Our analysis focuses on these two in situ observations — equatorial and low-altitude — to assess the underlying processes driving these phenomena.”

Line 147-148: Include a reference about the pitch angle distributions and the generation and amplification of whistler plasma waves.

Thank you for the suggestion. The following references have been included into the manuscript on line 158.

Hospodarsky, G. B. *et al.* Plasma wave observations at Earth, Jupiter, and Saturn. In *Dynamics of the Earth's Radiation Belts and Inner Magnetosphere* 249–260 (American Geophysical Union, 2012).

Kennel, C. Low-frequency whistler mode. *Phys. Fluids* **9**, 2190–2202 (1966).

Li, W. *et al.* Evaluation of whistler mode chorus amplification during an injection event observed on CRRES. *J. Geophys. Res. Space Phys.* **113**, A09210 (2008).

Reviewer #1
(Remarks to the Author)

Manuscript Evaluation Report

Title: Origins of Jupiter's Patchy Aurora by A. Daly, W. Li, Q. Ma,…… et al.

Manuscript No: NCOMMS-25-40440

Summary:

The authors use data from NASA's Juno spacecraft to study the cause of Jupiter's patchy aurora. They analyze measurements from several instruments, including JEDI, JADE, Waves, MAG, and UVS. These tools help them study particles, plasma waves, magnetic fields, and ultraviolet auroral images. Overall, this is a worthwhile study, shows that Jupiter's patchy auroras are mainly caused by electron precipitation triggered by plasma waves, not just by magnetospheric injections. Injections help the waves grow, but the waves themselves are key to creating the auroras. This helps us better understand how Jupiter's magnetosphere connects to its Ionosphere/atmosphere and may apply to other planets too. This manuscript serves as an update to previous results; with new information about the JUNO observations and numerical calculations described beforehand. This is a valuable and well-structured study. It gives new information about Jupiter's auroras and supports ongoing research in planetary auroral processes.

Main Findings:

- The patchy auroras are caused by electron precipitation into Jupiter's ionosphere.
- Interestingly, diffuse auroral emissions on Jupiter sometimes form patchy shapes, which have been observed in both the northern and southern hemispheres by the Hubble Space Telescope and the Juno spacecraft.
- This precipitation is triggered by interactions between particles and plasma waves, especially ECH and whistler-mode waves.
- Particle injections help these waves grow and make the precipitation stronger.
- The study gives new insights that build on earlier work with more detailed data and calculations.

Strengths:

- The study uses a wide range of data from multiple instruments.
- It explains how wave-particle interactions lead to auroral emissions.
- The findings help improve our understanding of how Jupiter's magnetosphere and ionosphere are connected.

The following are minor comments of the manuscript.

Minor Comments:

1. Some sentences in the manuscript are long and complex [e.g.,(Lines 51-53: "Particle injections……..toward the planets"), (Lines 83-86: "This flyby occurred ………..ranging from -54.7° to -58.7°"), (Lines 91-93: "In some cases ……space density" give a region briefly).

2. Add a brief explanation of the numerical methods/ including assumptions or limitations, (e.g., Li et al., 2020; Daly et al., 2023;Ma et al., 2024; Tripathi et al., 2024).

3. Figures (4e) and (4f) identify the electrostatic and electromagnetic waves observed, revealing their intense amplitudes. In this context, I would like to know whether the ECH waves exhibit multiple harmonics—for example, second to fourth harmonics—in a weak pattern.

4. Line 160: The statement “which occur at lower frequencies (mostly below 0.05 f_{ce})”……. requires a citation to support it.

5. Line 225: The statement *“*In addition, the accuracy of magnetic field mapping may contribute to the slight shifts observed in the M-shell*”* is too brief. More elaboration is required regarding how the magnetic field mapping was performed and how this could influence the observed shifts in the M-shell.

7. Line 250: The results suggest that plasma waves are the direct drivers of isolated patchy aurora at low altitudes. Were these results consistent with or supported by previous observations? If so, provide relevant references or comparisons to earlier studies.

8. Lines 328-332: The statement “The measured electron…………are highly oblique” provides a useful description of the modeling approach. However, it is noted that the cyclotron resonance dominates electron scattering in the energy range of 30 eV to 1 MeV, and that this fitted distribution is used to calculate the wave growth rate. In earlier studies, it has been shown that anisotropic electron distributions are often modeled as a superposition of a Maxwellian distribution for cold electrons and a Kappa distribution for energetic electrons, particularly in the context of analysis of pitch angle scattering leading to diffuse aurora by both ECH and whistler-mode wave . I suggest the authors clarify why a six- component bi- Maxwellian model was chosen in this case, and whether the use of Kappa distributions for energetic electrons was considered or could influence the results (For example, References 31, 35, 55, 65, 67, and 71 have already addressed this in previous studies).

9. Figure 3(e) shows the comparison of auroral brightness and precipitating electron flux as a function of M-shell during a low-altitude pass. It is noted that the precipitating electron flux is enhanced compared to the auroral brightness at M-shell values less than 10, whereas the pattern reverses at values greater than approximately M = 10. My concern is: which type of waves could be responsible for this pattern?

Conclusion

"I wholeheartedly accept and recommend this manuscript for publication in *Nature Communications*."

Reviewer #1
(Remarks to the Author)

NCOMMS-25-40440A	
Title	The Origins of Jupiter’s Patchy Aurora

A. Daly[1], W. Li[1], Q. Ma[1,2], X.-C. Shen[1], V. Hue[3], G. Clark[4], T. K. Greathouse[5], G. R. Gladstone[5,6], B. H. Mauk[4], W. S. Kurth[7], G. B. Hospodarsky[7], F. Allegrini[5,6], and S. J. Bolton[5]

Decision of the Manuscript:

The paper is well written. The authors have clearly addressed all the questions raised. It provides an advance in our understanding of auroral processes at Jupiter. The work presented in this paper has very significant outcomes. I accept the paper and recommend it for publication.