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Key Points:

- Contemporaneous observations reveal a direct correlation between ULF wave and auroral activities at Jupiter
- The correlation exists for the wave periodicity in range of 1–60 min
- The Poynting flux associated with ULF waves could be sufficient to power the observed aurora

Supporting Information:

- Supporting Information S1

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Ultralow-Frequency Waves in Driving Jovian Aurorae Revealed by Observations From HST and Juno

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Abstract Large-scale electrical currents and Alfvénic waves are the two main drivers responsible for producing planetary aurorae. The relative contribution of each process is a central question in terrestrial auroral science, and poorly understood for other planets due to the relatively rare opportunity of in-situ spacecraft measurements. Here, we present observations of Jupiter's aurorae from the Hubble Space Telescope (HST) contemporaneous with Juno magnetometer measurements in the magnetosphere. For three successive days, we found that the magnetospheric ultralow-frequency (ULF) wave activity (with periods of 1–60 min) was correlated with auroral power. This was especially true for the Alfvénic modes. We further performed a statistical analysis based on HST visits during Juno's third and seventh orbit, which revealed a systematic correlation between ULF wave and auroral activity. Our results imply that Alfvénic wave power could be an important source in driving Jupiter's aurorae, as theoretically predicted.

Plain Language Summary Jupiter has the most powerful aurora in our solar system, reflecting the intense energy dissipation in the largest planetary magnetosphere. It is still an open question on how auroral particles are accelerated at a planet. At Earth, there are two prestigious mechanisms for auroral acceleration, which are wave-particle interaction and electrical potential drop. Recent Juno observations have been shown direct evidence on both wave-particle interaction and electrical potential drop in the auroral region. However, the importance of wave-particle interaction on Jovian aurora still remains unclear. In this study, we reveal a systematic correlation between aurora and magnetospheric waves using the large campaign of Hubble Space Telescope during the NASA Juno mission. The results can significantly improve our understanding on wave-particle interaction in driving Jovian aurora.

1. Introduction

Jupiter has the most powerful aurorae in our solar system. Unlike the terrestrial magnetosphere, which is mainly driven by the solar wind, Jupiter's magnetospheric dynamics are governed by a complex combination of internal processes (such as mass-loading from Io's volcanoes and energy imparted by Jupiter's rapid rotation) and solar wind perturbations. The resulting Jovian ultraviolet aurora is often grouped into three components: equatorward emissions (such as Io's auroral footprint (Bonfond et al., 2013)), the main aurora, and the polar aurora emissions (Grodent, 2015). While the aurora is often separated into these three distinct components, they do not always behave independently of one another (Grodent et al., 2018). For instance, recent work shows that dawn storms on the main aurora are systematically connected with the spectacular auroral injections found in the equatorward emissions (Yao et al., 2020a).

In general, the main auroral emission provides one-third of the total emitted UV power (Grodent et al., 2018) integrated over the whole polar region. The width of the main auroral emission varies from 100 to 500 km, and it is generally broader on the duskside (Grodent, 2015). The most popular theory for the production of the main aurora is that it is generated by a corotation breakdown magnetosphere-ionosphere current system, which could be sensitive to solar wind compressions (Hill, 1979). Modeling predictions suggest an anticorrelation between solar wind dynamic pressure and dayside main auroral emission (Cowley & Bunce, 2001; Southwood & Kivelson, 2001). Such theoretical predictions were reproduced by a three-dimisional global

MHD simulation (Sarkango et al., 2019). However, considering the asymmetry of a compressional magnetosphere, Chané et al. (2017) suggest a positive correlation between the brightness of main oval and solar wind ram pressure. Based on contemporaneous measurements from the Cassini and Juno spacecraft and the HST, the main aurora is observed to enhance during solar wind compressions (Nichols et al., 2007; Yao et al., 2020b). Previous investigations also reveal that solar wind compressions could enhance the auroral emissions for other wavebands, such as X-ray (Dunn et al., 2016), infrared (Sinclair et al., 2019), and radio (Gurnett et al., 2002; Hess et al., 2012, 2014). A recent observational study further showed that the intensity of Jovian main auroral emission correlates with the enhancement of magnetic field azimuthal and radial components (Nichols et al., 2020). In contrast with the theory that corotation breakdown is responsible for Jupiter's main auroral, there are several recent studies offering alternative plausible explanations. Bonfond et al. (2020b) reviewed six pieces of evidence that challenge the traditional theory in driving Jupiter's main aurora. A study using simultaneous measurements from Juno and the Hubble Space Telescope (HST), as well as Hisaki, suggests the Jovian main aurora could be driven by magnetospheric unloading processes (Yao et al., 2019), independent of the corotation breakdown enhancement theory.

In comparison with the main aurora, the generation of the polar auroral emissions is less commonly discussed. Moreover, it is poorly understood whether or not the polar auroral emission is connected to open or closed field lines. Polar auroral flares can be extremely dynamic, with their intensity increasing by orders of magnitude within 10 s (Waite et al., 2001). Recently, Zhang et al. (2021) reveal that the magnetic field lines connecting the polar regions are helical and closed between the northern and southern ionospheres.

While the polar emissions map to processes in the outer magnetosphere, the equatorward injection signatures are thought to be driven by plasma processes in the inner magnetosphere, which may be less influenced by solar wind conditions because of the planet's fast rotation and abundant plasma from Io (Khurana et al., 2004; Kimura et al., 2015; Krupp et al., 2004; Vasyliunas, 1983). Auroral injections are a transient phenomena, normally lasting for 5–10 h, although sometimes longer (Bonfond et al., 2012; Dumont et al., 2018; Haggerty et al., 2019). The energetic particle injections associated with these auroral emissions are thought to be triggered by middle magnetosphere processes such as corotating magnetic dipolarizations and dawn storms (Bonfond et al., 2021; Yao et al., 2020a, 2020b). The links between transient aurora and particle injections in the inner magnetosphere and during Juno perijove passes are, respectively, shown by Mauk et al. (2002) and Haggerty et al. (2019).

Ultralow-frequency (ULF) waves (~1mHz–1Hz) are magnetohydrodynamic pulsations in Earth's magnetosphere that play an important role in magnetospheric dynamics. These waves have also been reported at Jupiter, but for a lower frequency than at Earth (at period of tens of minutes) due to the huge Jovian magnetosphere (Khurana & Kivelson, 1989; Manners et al., 2018). Alfvén waves are one type of ULF waves, which carry field-aligned currents responsible for energy transportation. At Earth, using a wealth of measurements both in space and from the ground, it is known that both current loops and Alfvénic power are important in driving the auroral dynamics. Observational and simulation studies both show that these electromagnetic waves lead to energy deposition in the ionosphere, powering auroral acceleration processes (Chaston et al., 2005; Keiling et al., 2003, 2019; Lotko et al., 1998; Newell et al., 2009). At Jupiter, the large-scale, corotation enforcement currents have been widely discussed for producing Jovian aurora, particularly the main aurora. Theoretical studies have also proposed that the Alfvénic power may account for Jupiter's aurora (Saur et al., 2018). To date, observational studies have confirmed the existence of intense Alfvénic power connected to the auroral region (Saur et al., 2003), and also Io's auroral footprint tail (Gershman et al., 2019). However, we are unaware of any observational studies that have shown a direct correlation between measured wave power and Jupiter's auroral intensity. Using simultaneous observations from HST and the Juno spacecraft, we investigate the role of Alfvénic waves (1–60 min) in driving Jovian aurorae. Our results show direct evidence of correlations between Jovian aurorae and Alfvénic power, providing strong implications for the development of theory on Jupiter's auroral drivers.

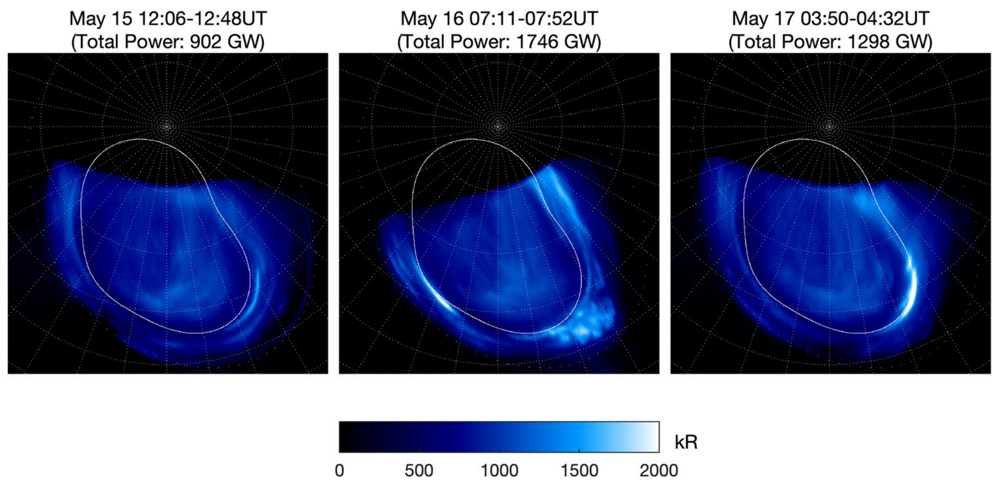

Figure 1. North pole projections of Jupiter's aurora from HST UV observations on May 15–May 17, 2017. Each image was averaged over ~41 min. HST, Hubble Space Telescope.

2. Observations

All auroral observations used in this study are from the HST program GO-14634. The observations were conducted by the Space Telescope Imaging Spectrograph (STIS) UV camera on HST. This program was mostly dedicated to Juno orbits 3–7, which provides a good opportunity for contemporaneous comparisons between Jupiter's aurora and the Jovian magnetosphere. Our statistical study of Jupiter's aurorae is based on the Grodent et al. (2018) auroral list, comprising 118 auroral visits.

Figure 1 shows HST polar projections of auroral images for three successive days from May 15, 2017. Each auroral image was averaged over a 41 min window. The auroral power of the total visible area for the three auroral images are 902 GW, 1,746 GW, and 1,298 GW, respectively (see details in Grodent et al. (2018)). The aurora on May 16 was the most intense of the three observations, suggesting an active magnetosphere at this time. The aurora on May 15 was much weaker than the other days, indicating a relatively quiet magnetosphere.

During this period, Juno moved toward Jupiter from ~50 R_J to ~30 R_J in a local time region of ~4.5 h. Figure 2 shows the magnetic field measurements from Juno and the auroral power for the total visible area for HST for three successive days from May 15, 2017. Figures 2a–2c show magnetic field B_R, B_θ, and B_Φ components in Jupiter-De-Spun-Sun (JSS) coordinates measured by the Magnetic Field Investigation instrument (Connerney et al., 2017). This study uses 1-s time resolution magnetic field data. The sawtooth oscillations shown in B_R and B_Φ components (Figures 2a and 2b) suggest current sheet flapping associated with planetary rotation. When B_R and B_Φ decrease, the normal component B_θ increases, indicating a magnetodisc crossing. Moreover, we note that the magnetic field fluctuates at a short time scale (at periods of minutes to hours) when Juno is close to the magnetodisc. Quasiperiodic tens of minute magnetic field perturbations representative of standing Alfvén waves have been reported at Jupiter as a range of eigenperiods (Khurana & Kivelson, 1989; Manners & Masters, 2019; Manners et al., 2018). Therefore, we transfer the magnetic field data to field-aligned coordinates, and filter the perpendicular components B_r and B_ϕ for periods between 1 and 60 min (Figures 2d and 2e), to compare with auroral variations.

Due to the relatively short time interval for each auroral visit (~41 min) and the planetary rotation modulated transient wave power, it is unlikely there will be perfectly simultaneous observations between auroral power and wave activity in magnetodisc. Hence, we use the wave intensity of $\delta B_\perp$ over 10-h time interval, centered on the HST observation time (shaded by red area shown in Figure 2f), to represent the wave amplitude corresponding to each auroral visit. Each 10-h time window contains one complete oscillation of the plasma sheet over the spacecraft. As shown in Figure 2f, the wave power variation is consistent with the auroral power. The period window was empirically selected, since we know that the field line resonance (FLR)

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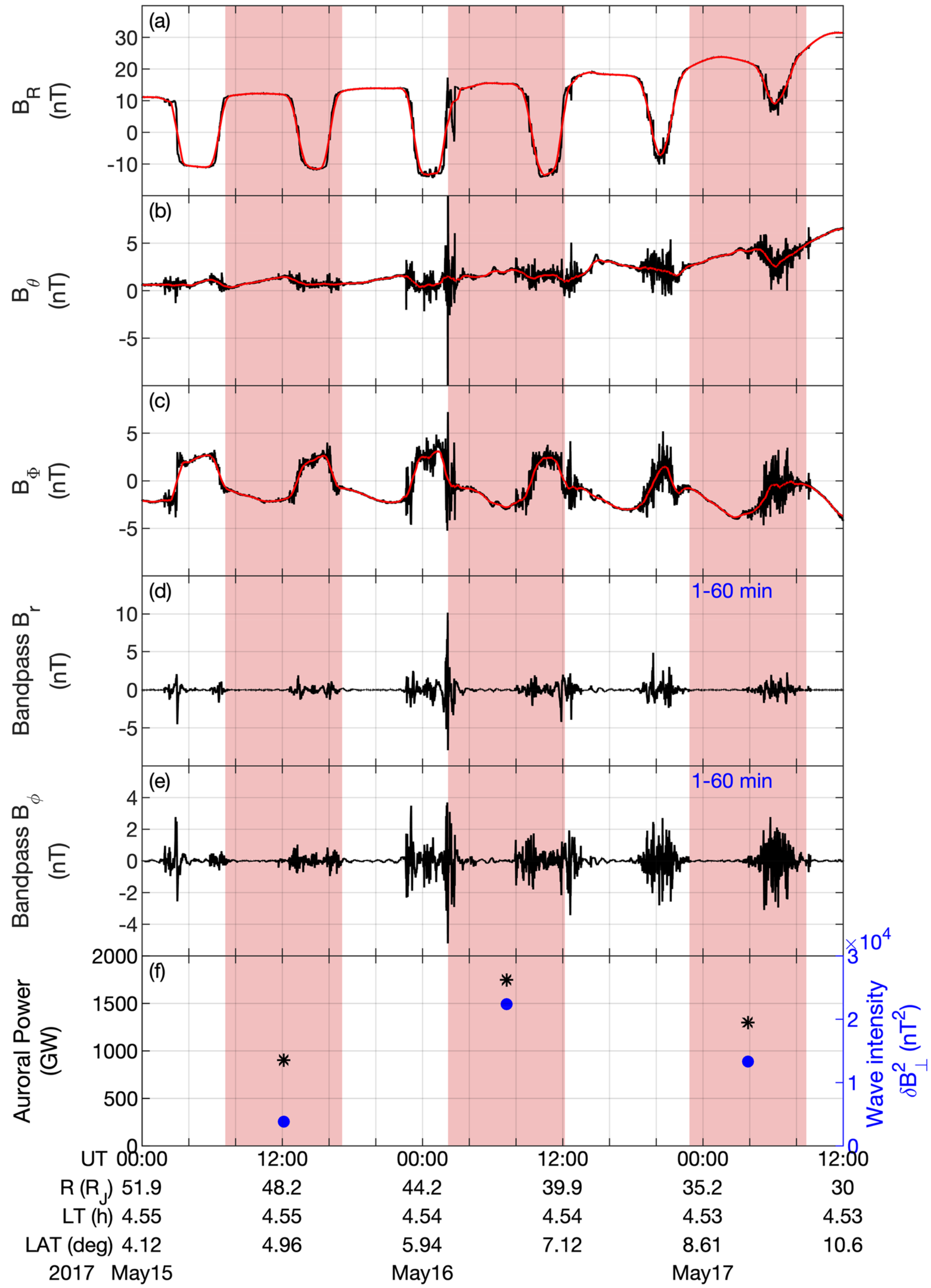

Figure 2. Magnetic field measurements by the Juno Magnetic Field Investigation instrument and HST northern aurora observations from May 15, 2017 to May 17, 2017. (a–c) Magnetic field components in Jupiter-De-Spun-Sun (JSS) coordinate system; (d–e) δB_r, the δB_ϕ components in field-aligned coordinate (FAC), filtered between 1 and 60 min; (f) total auroral power from HST (black stars) and wave intensity of $\delta B_\perp$ (blue dots). The shaded areas mark 10-h time intervals around each auroral observation (±5 hours). HST.

period at Jupiter is ∼1–60 min. The rapid planetary rotation would oscillate the plasma disk at any given location (e.g., the location of a spacecraft in the magnetosphere), therefore the spacecraft captures magnetic signatures with a strong mixture of spatial and temporal variations. It is extremely challenging to separate the spatial and temporal variations in magnetic data. We here introduce a new tool named empirical mode decomposition (EMD), which could decompose signals without presuming sine and cosine components

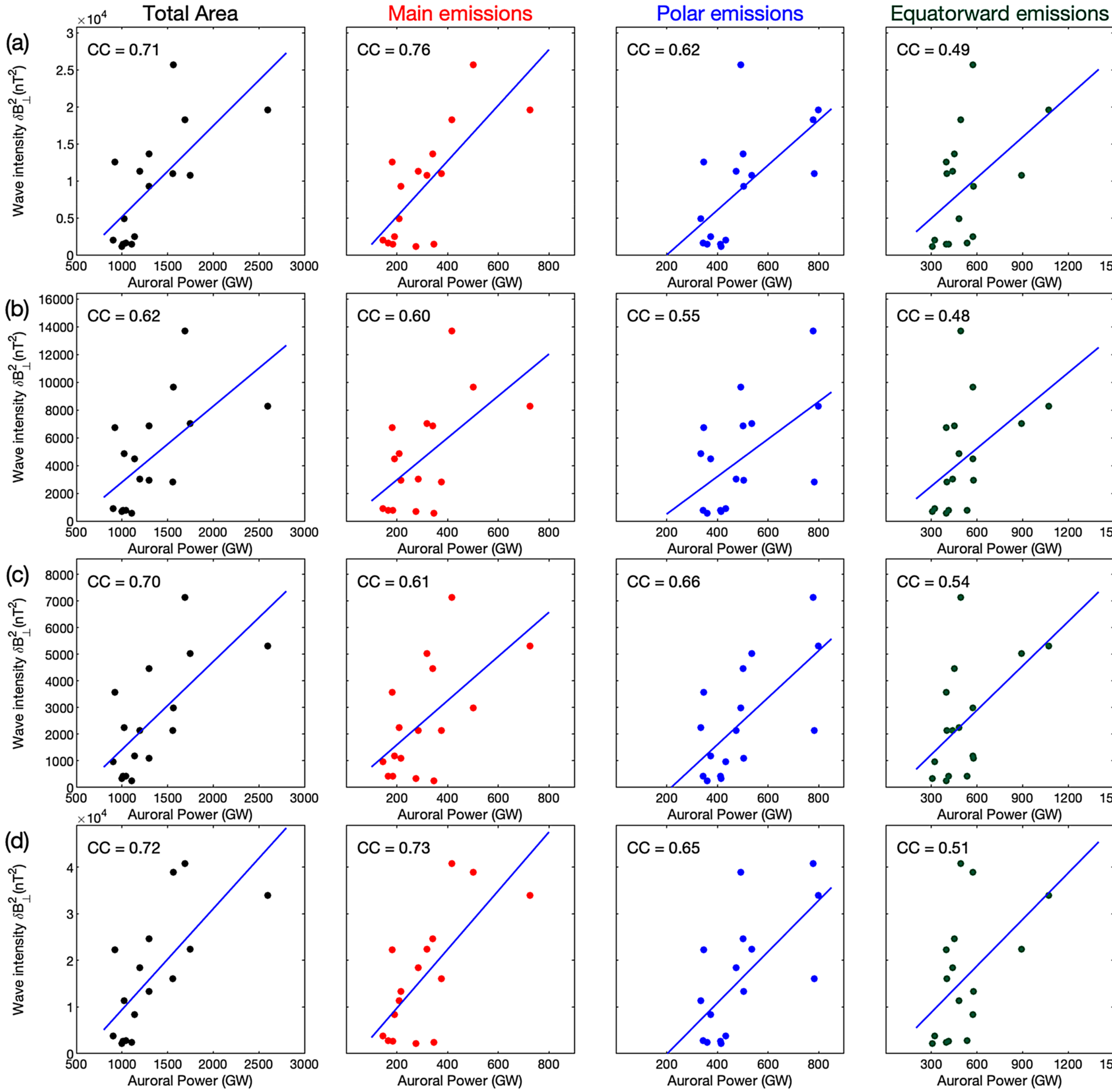

Figure 3. Scatter diagram of 16 auroral events observed by HST. The abscissa of each point is the auroral power for total area (black), main aurora (red), polar aurora (blue), and equatorward aurora (dark green), respectively. The ordinate is the wave intensity, integrated bandpass filtered $B_\perp$ component for the 10-h time interval centered on the auroral observation, for (a) 1–20 min, (b) 20–40 min, (c) 40–60 min, and (d)1–60 min.

(Rilling & Flandrin, 2009; Stallone et al., 2020). EMD is a method that can decompose a signal into several empirical modes, which is useful to resolve nonlinear signals. Here, we just test the application of EMD to Jupiter's ULF wave activity based on Juno measurements (see supporting information). This showed similar results to the bandpass study and none of conclusions of the paper is affected by the extra test of a new tool.

To examine whether or not the wave power and auroral power are systematically connected, we surveyed all HST observations from November 2016 to July 2017, and show the correlation between auroral power and wave intensity of $\delta B_\perp$ in Figure 3. The auroral morphology in the northern hemisphere is significantly different to that in southern hemisphere. Considering that more auroral events are observed in the northern hemisphere by HST, we only selected aurora emitted in the northern hemisphere for a statistical analysis.

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We confined the distances from the Juno spacecraft to Jupiter between 80 R_J and 30 R_J, and excluded the events when Juno was in the magnetosheath, during some extreme solar wind compression conditions. Since Jupiter's dipole tilt is ∼10°, we selected events when Juno was at latitudes between −10° and 10°, to ensure that the Juno spacecraft measured the magnetodisc current sheet during a 10-h time interval for each auroral visit. For some events, the wave amplitude could vary considerably during the two successive crossings of the magnetodisc, implying a rapid changing magnetosphere. Therefore, the 10-h averaged wave activity may not well represent the magnetosphere status when the HST observation was obtained. To remove this uncertainty, we calculated a ratio α between wave intensities for $\delta B_\perp$ during the 5-h before the HST auroral visit and during the 5-h after the auroral visit (the α is calculated as the larger value divided by the smaller one). In order to exclude the events during which the magnetosphere changed rapidly, we only considered the events for which $\alpha \leq 3$. The number 3 is an empirical choice, and resulted in the 16 events shown for the statistical analysis. The α value was chosen to provide a good balance between a reasonable number of events and the rejection of events characterized by a dramatic change of the magnetospheric conditions.

As shown in Figure 3, the abscissa of each point is the auroral power averaged over ∼41 min for total area (black), main emissions (red), polar emissions (blue), and equatorward emissions (dark green), respectively. The ordinate is the wave intensity of $\delta B_\perp$ over 10-h time interval for each auroral visit. The resultant linear profile of the scatter diagram suggests a good correlation between auroral power and $\delta B_\perp$ wave intensity for different bands, especially for the main emissions, which indicate that Alfvénic wave power could be an important source in driving Jupiter's main aurora.

3. Discussion and Conclusion

Here, we present a case study and a statistical study that both showed a correlation between Jupiter's auroral power and magnetospheric ULF wave power. The results suggest that ULF wave activity is closely connected with Jupiter's auroral emissions. We found that the wave activity was well correlated with the main auroral emission and possibly also with the polar emissions. Here, we suggest two possible pictures for auroral intensifications associated with Alfvénic waves. The first possibility is that the Alfvén waves directly transfer the energy to produce the auroral emission. The second possibility is that the detected Alfvén waves and the aurora are both consequences of a shared process and thus correlated.

For the first possibility, widely distributed Alfvénic waves may simultaneously generate transient aurorae for different areas by transporting Poynting flux from the magnetosphere to the ionosphere. The brightness of aurorae is usually ∼1,000–2,000 kR (as seen from Figure 1), corresponding to 100–200 mW/m^2 precipitating electron fluxes (Gérard & Singh, 1982; Waite et al., 1983). Because of the lack of electric field data, here we adopt the method from (Yao et al., 2017) to estimate the observed wave Poynting flux. By adopting the plasma density of ∼0.05 cm^{-3} at 30 R_J (Bagenal et al., 2016), together with $B \sim 20$ nT, we obtain a typical Alfvénic speed of 1,950 km/s in Jovian magnetosphere. The observed wave amplitude is ∼1 nT. Therefore, we estimate the disturbed electric field to be ∼1.95–19.5 mV/m by assuming the phase speed of the kinetic Alfvénic wave to be 1–10 times the local Alfvénic speed. The resulting Poynting flux was estimated to be 0.0016–0.016 mW/m^2 in Jovian magnetosphere, corresponding to 62–620 mW/m^2 near the auroral acceleration region (the magnetic field strength is $\sim 7.8 \times 10^5$ nT on approach to perijove (Connerney et al., 2017)). This is of the same order as the downward energy flux estimated by JEDI measurements (Gérard et al., 2019; Mauk et al., 2017), sufficient to produce Jovian aurorae. Although, we caution that this is only an estimation that serves to demonstrate that the energy budget from the waves is sufficient, but we do not know how much of the wave energy could be transferred into particles during the precipitation.

Alternatively, the second possibility is that the correlation between ULF waves and auroral activity does not directly suggest causality. It may be possible that the ULF waves and auroral emissions are both consequences of other processes (e.g., injections, magnetic reconnection or depolarization, etc.). Furthermore, contemporaneous intensifications of different auroral components were reported by Grodent et al. (2018). It may therefore be the case that some auroral emissions are directly produced by the Alfvén waves, while others are produced by other processes that share the same driving electromagnetic perturbation, such as a global reconfiguration (Louarn et al., 2000; Woch et al., 1999). A simulation for global Jovian magnetosphere dynamics would be invaluable for a more comprehensive understanding of how the different auroral components connect.

Due to the limited spatial coverage of Juno orbits, the detection of ULF waves is mostly restricted to regions beyond 30 R_J. These ULF waves, as an indicator of magnetospheric perturbations, allow us to analyze the connection between magnetospheric processes and auroral emissions. For each HST observation, Juno could only provide single-point measurements of a specific location in the magnetosphere between 30 and 80 R_J and not the whole region covering the aurora. However, the statistical correlation between ULF waves and different auroral components is probably indicative that the wave activities are enhanced over a large area in the magnetosphere for most cases. Further studies are needed to understand whether and how these ULF waves drive aurora, with reliable physical connections between the magnetosphere and ionosphere.

In summary, we present contemporaneous observations from the HST and Juno spacecraft, to investigate the relationship between Jovian aurorae and ULF waves. Our results suggest a positive correlation between auroral power and ULF wave intensity, as theoretically predicted, indicating that Alfvénic waves are deeply connected to the processes driving Jovian aurorae.

Data Availability Statement

This research is based on observations with the NASA/ESA Hubble Space Telescope (program HST GO-14634), obtained via https://archive.stsci.edu/proposal_search.php?id=14634&mission=hst at the Space Telescope Science Institute (STScI), which is operated by AURA for NASA. All data are publicly available at STScI. The Juno data presented in this paper are available at http://pds-ppi.igpp.ucla.edu/.

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