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Key Points:

- We systematically investigate the hourly periodic variations in Jupiter's magnetosheath by analyzing magnetic field data
- Periodicities from 2 to 10 hr are widely identified, where results of periodic analysis change from time to time
- Similar hourly periodicities were identified in both dawn and dusk sides

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Hourly Periodic Variations of Ultralow-Frequency (ULF) Waves in Jupiter's Magnetosheath

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Abstract Periodic variations are widely identified in the Jovian system, varying from 10 s of seconds to several days or even longer. These processes are strongly influenced by solar wind conditions, planetary rotation and Io's volcanic activity. Ultralow-frequency (ULF) waves at 10 s of minutes, which are the typical time scale of field-line resonance, are considered as a crucial process in driving the Jovian energy circulation. The longer time-scale periodicities are likely associated with global mass circulation. In this study, we focus on multihour variations of the ULF wave energy, which are difficult to identify within the magnetosphere due to the rapid planetary rotation modulation. Using the magnetic field observations from Juno and Galileo in Jupiter's magnetosheath, we found multiple significant multihour periodicities, widely distributed from 2 to 10 hr, peaked at different values from case to case. The most common periodicities were between 3 and 5 hr, existing in both the dawn and dusk sides. These common periodicities are likely associated with the energy transport from the inside to the magnetosheath.

Plain Language Summary Periodicities, as detected in aurora, particles, waves, etc., widely exist in the Jovian system. The periodic variations are key signatures to assess theoretical hypotheses, and the coherence between the periodicities in different types of observations can be a crucial constraint to reveal physical causality. Jupiter's magnetic axis is about 10 degrees offset from the rotation axis, resulting in a periodic vibration of the magnetosphere. A spacecraft traveling in Jupiter's magnetospheric space would persistently detect rapid variations of the magnetic field every several hours, and the variation feature depends on the relative location to the magnetic equator and the dynamic magnetospheric processes. Therefore, the investigation of hourly variation of the Jovian magnetosphere is highly challenging due to the strong mixture of spatial and temporal effects. To overcome this difficulty, we analyze magnetic field and plasma wave data in Jupiter's magnetosheath, where the planetary rotation induced spatial variations no longer exist. Many multihour periodicities are identified, which are believed to be consequences of compressions from the rotating magnetospheric plasma to the magnetopause.

1. Introduction

Solar wind interactions with Jupiter's global magnetic field form a magnetosphere with structures similar to the terrestrial magnetosphere, including a compressed dayside structure and a highly extended nightside tail. Similar magnetospheric configurations naturally result in fundamental similarities in their magnetospheric dynamics (Artemyev et al., 2020; Ge et al., 2007, 2010; Russell et al., 1998). The terrestrial magnetosphere and giant planet magnetospheres may share many commonalities in energy releases, such as magnetic reconnection (Arridge et al., 2016), Alfvenic waves (Keiling et al., 2003; Pan et al., 2020; Sulaiman et al., 2020), and auroral acceleration (Bonfond et al., 2021; Mauk et al., 2017).

On the other hand, the energy circulation in Jupiter's magnetosphere is very different from that in the Earth due to the strong planetary magnetic field, weak solar wind dynamic pressure, rapid planetary rotation, and internal plasma sources produced by Io's volcanic activities (Bagenal, 2007). The global circulation of plasma and energy

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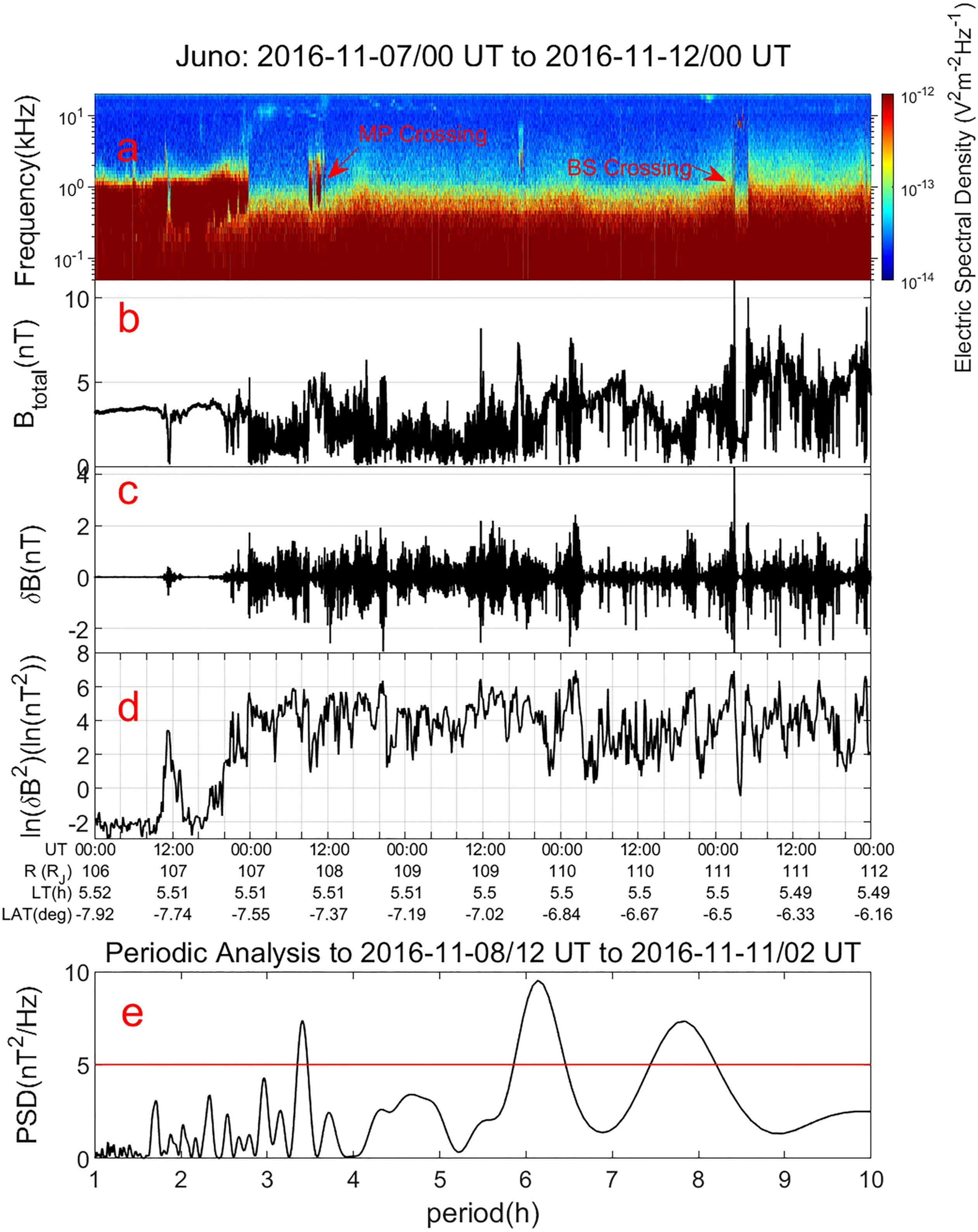

Figure 1. The results of the Juno case study from Nov. 8 to 11 in 2016. Panel (a) shows the plasma wave spectrogram. Panel (b, c) are the magnetic strength and the bandpass-filtered results using a 1–10 min window. Panel (d) shows the proxy of wave energy in panel (c), and panel (e) gives the result of periodic analysis of the proxy of wave energy shown in Panel (d). The red line in panel (e) shows the confidence level at 0.95.

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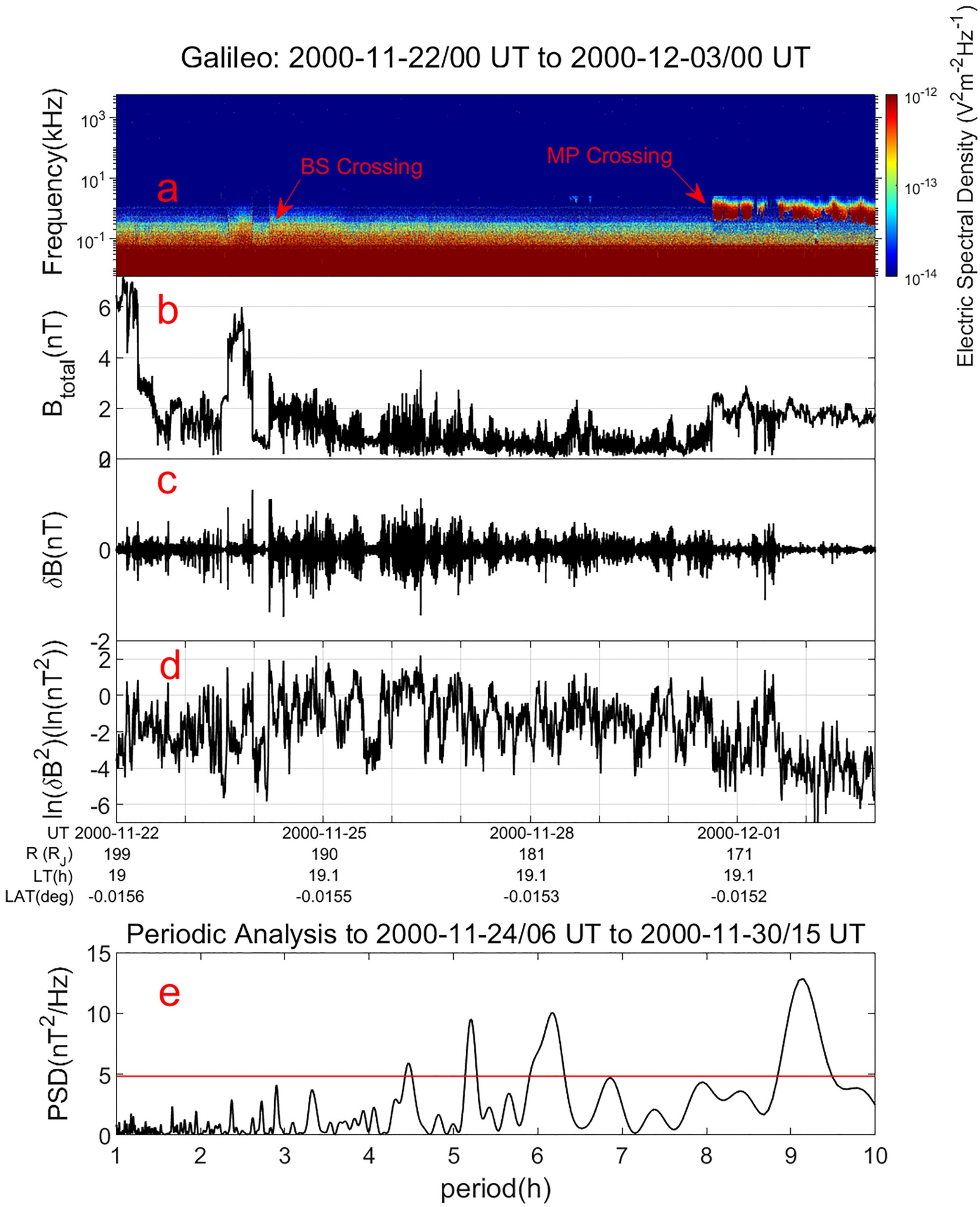

Figure 2. The result of the Galileo case study from November 24 to 30, 2000. The format is the same as Figure 1.

Table 1
Time Duration of Selected Events

Order number of Juno events	Time duration (yyyy-mm-dd-hh to yyyy-mm-dd-hh)	Order number of Galileo events	Time duration (yyyy-mm-dd-hh to yyyy-mm-dd-hh)
t1	2016-11-08-12 to 2016-11-11-02	t1	2000-05-29-15 to 2000-05-30-17
t2	2016-11-12-00 to 2016-11-13-01	t2	2000-06-03-18 to 2000-06-05-19
t3	2016-11-21-23 to 2016-11-23-16	t3	2000-06-10-07 to 2000-06-11-15
t4	2017-01-24-18 to 2017-01-25-19	t4	2000-11-24-06 to 2000-11-30-15
t5	2017-02-19-06 to 2017-02-21-01	t5	2000-12-04-22 to 2000-12-06-09
t6	2017-04-08-15 to 2017-04-09-11	t6	2000-12-11-10 to 2000-12-12-10
t7	2017-05-05-14 to 2017-05-07-01	t7	2001-01-10-21 to 2001-01-12-06
t8	2017-06-16-08 to 2017-06-17-14	t8	2001-01-19-13 to 2001-01-20-14
t9	2017-06-18-09 to 2017-06-19-05	t9	2001-01-21-04 to 2001-01-23-02
t10	2017-10-01-06 to 2017-10-02-18	t10	2002-01-05-07 to 2002-01-06-20
		t11	2002-10-31-20 to 2002-11-01-17

in the terrestrial magnetosphere is well summarized by Dungey (1961), while the circulation of giant planets is a combination of the Dungey cycle and the internally driven Vasyliunas cycle (Vasyliunas, 1983).

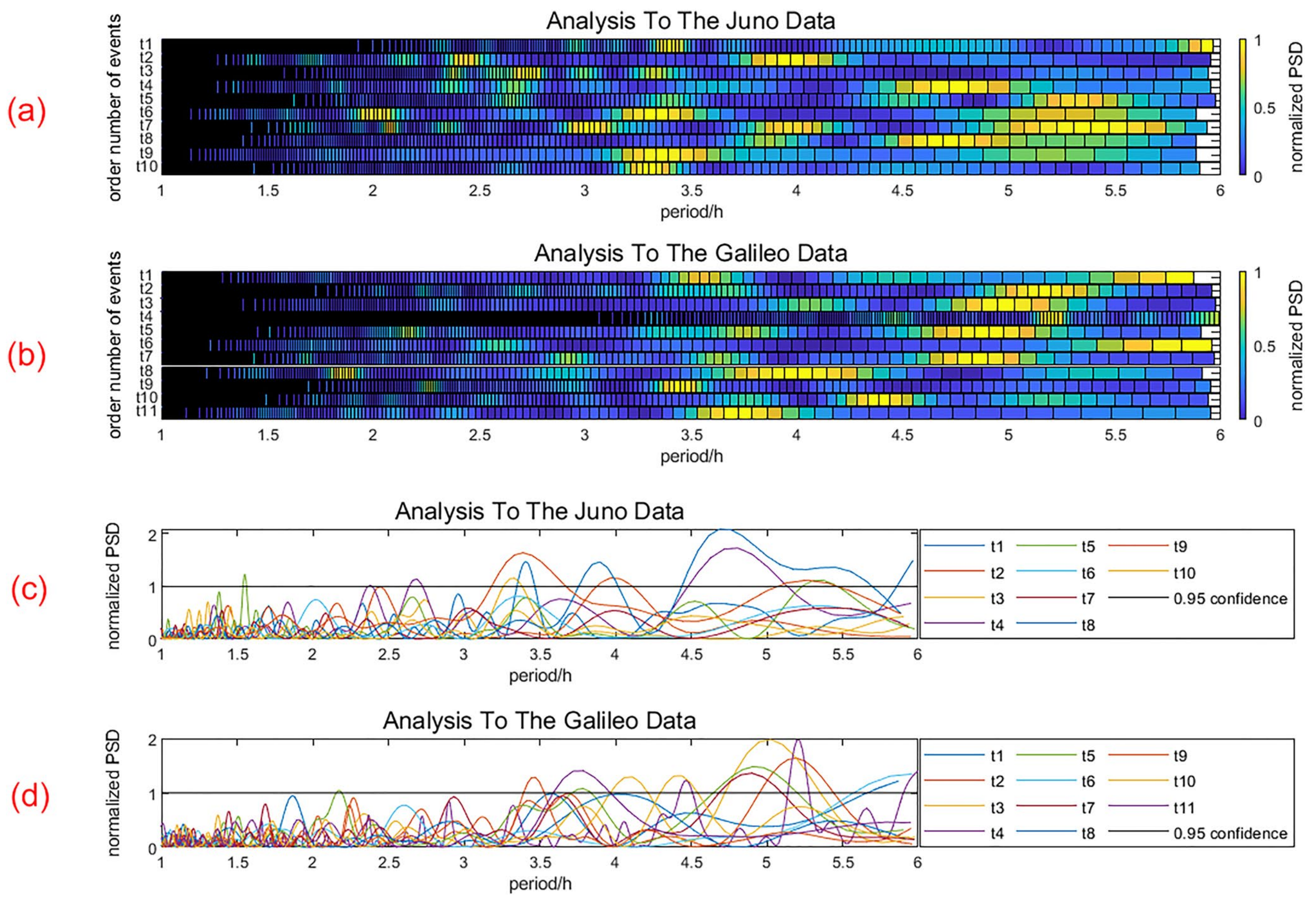

Figure 3. The periodicities of magnetic field perturbations during all Jupiter's magnetosheath crossings by Juno and Galileo using Lomb-Scargle analysis. Two kinds of images are used to show the results: (a, b) are pseudo-color images for Juno and Galileo datasets, respectively. (c, d) Line images showing the same results as (a, b). Colors in (a, b) represent the ratios to the confidence of 0.95 for each event. The black horizontal line in (c, d) shows a confidence of 0.95.

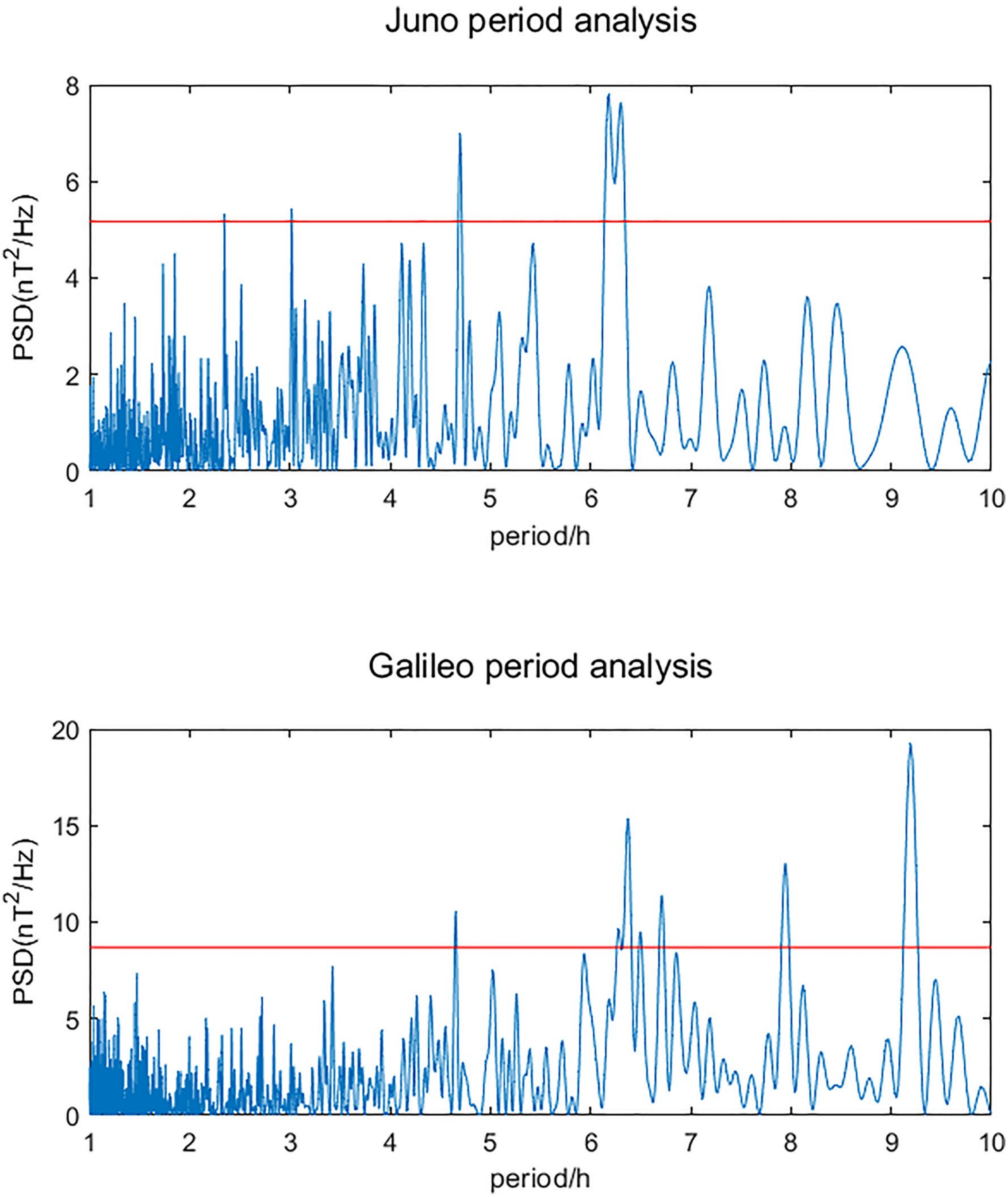

Figure 4. Periodicity analysis of combined magnetic field data from different periods in the magnetosheath for Juno or Galileo datasets. Each magnetic field data is normalized to the averaged wave energy of every event. Blue lines are results of periodicity analysis and red lines indicate the confidence level of 0.95.

Periodicities in detected or derived parameters are ideal opportunities to reveal the physical processes of a planetary system and beyond (e.g., laboratory system, astrophysical environments), as different processes often have different time scales. In investigations of the Jovian system, periodicities are found in many physical parameters and with the time scale varying in a large range, including 2–3 min periods in Jupiter's UV aurorae (Bonfond et al., 2016), 10 s min periods in Jupiter's X-ray aurorae (Dunn et al., 2017), several days periods of energy loading/unloading (Yao et al., 2019) and 1.5–7 days periods of Jupiter substorms (Kronberg et al., 2009). These periodicities correspond to fundamentally different magnetospheric and ionospheric processes, some of which are known, while others remain unknown.

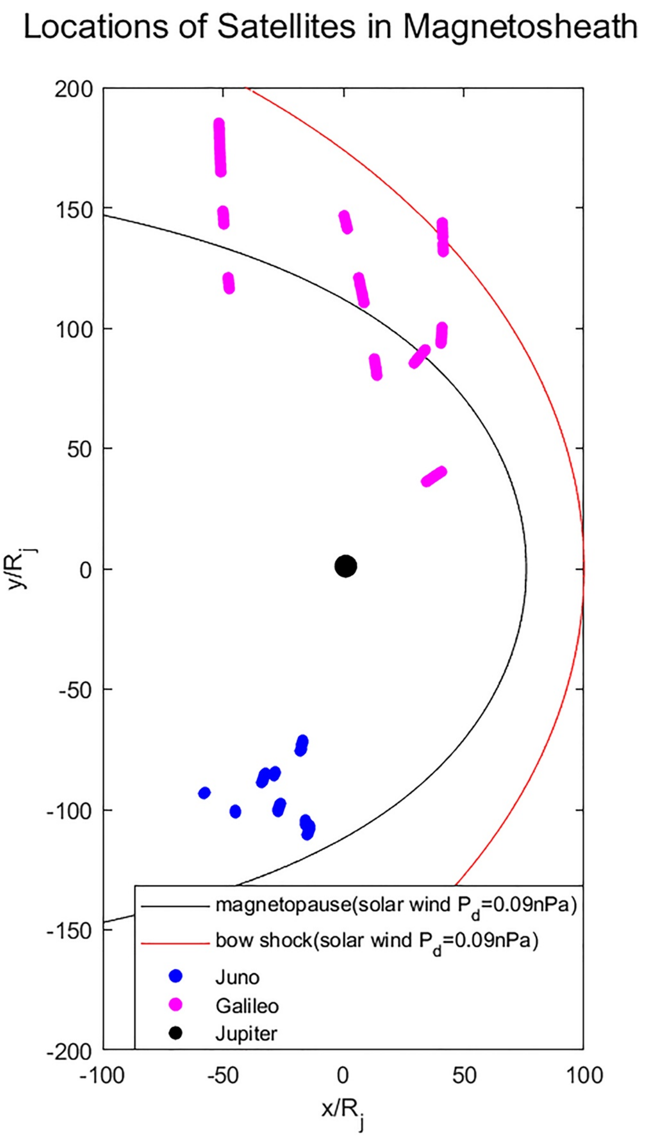

Figure 5. The locations of satellites during the 21 chosen events in which the satellite (Juno or Galileo) is in Jupiter's magnetosheath.

The understanding of periodic variations based on in situ observations is strongly limited at the time scale of several hours. Jupiter completes its rotation in just below 10 hr. Therefore, the observations from remote sensing instruments are strongly modulated by the changing field of view during planetary rotation (Dunn et al., 2017; Tao et al., 2021; Yao et al., 2021), and the in situ measurements in the magnetosphere are strongly modulated by the plasma disc oscillation due to the magnetic dipole tilt of about 10° (Khurana, 1992). If a spacecraft is located near the equator, it would periodically switch from one hemisphere to the other in a period of multihour time scale. Thus, the magnetic field and particle fluxes would show rapid variations every few hours. Since the magnitude of magnetic variation due to the plasma disc oscillation is greater than most physical perturbations, the calculation of other multihour variations is highly challenging.

To overcome this difficulty, here we focus on magnetic observations in the magnetosheath to avoid the high mixture of spatial and temporal effects in the magnetosphere. Since the magnetopause is repeatedly compressed by rotating plasma due to the Vasyliunas cycle, the compressional effects would likely cause significant perturbations in the magnetosheath, allowing us to indirectly diagnose magnetospheric periodicities. The spatial effect due to the relative location between the satellite and Jupiter's magnetodisc does not imply any physical process. The magnetodisc oscillation and planetary rotation could impose compressional effects on the magnetosheath. The measured perturbation in the magnetosheath is no longer a spatial effect although the magnetodisc oscillation may provide a part of the cause for the perturbations in the sheath. The magnetic field and plasma wave data from Juno and Galileo were used in this study to identify the satellite's duration in the magnetosheath, and ULF waves were filtered from the magnetic field data. Then, periodic analysis of ULF wave energy is performed. Data and the methodology are shown in Section 2, followed by the main results in Section 3. A discussion on possible mechanisms of the discovered periodicities is provided in Section 4.

2. Data and Methodology

The magnetic field data from the Juno Magnetic Field investigation (MAG) (Connerney, 2022) and Galileo's Magnetometer (Kivelson, 2022), and wave data from the Juno Waves instrument (Waves) (Kurth & Piker, 2022) and the Galileo Plasma Wave Science instrument (PWS) (Gurnett et al., 1997) are analyzed. The magnetic field and wave data are used to identify periods when the spacecraft entered Jupiter's magnetosheath, and ULF waves are filtered from the magnetic field data to perform periodic analysis.

Juno-MAG includes two independent magnetometer sensor suites. Each suite includes a Fluxgate Magnetometer (FGM) and two imaging sensors (Connerney et al., 2017). For most of the observations presented, the temporal resolution of the Juno magnetic field data is approximately 1 s. Galileo's Magnetometer is an FGM including two sensor assemblies (Kivelson et al., 1992). For most of the observations presented, the temporal resolution of the used magnetic field data is approximately 24 s.

The Juno Waves instrument includes an electric dipole antenna and a magnetic search coil (Kurth et al., 2017). Data from the low frequency receiver (LFR) is used, which consists of plasma waves in the frequency range of 50 Hz to 20 kHz. The temporal resolution is approximately one second. The Galileo PWS instrument includes an electric dipole antenna and two search coil magnetic antennas (Gurnett et al., 1992). The data of waves in the frequency range of 5.62 Hz–5.65 MHz is used. The temporal resolution is approximately 37 s.

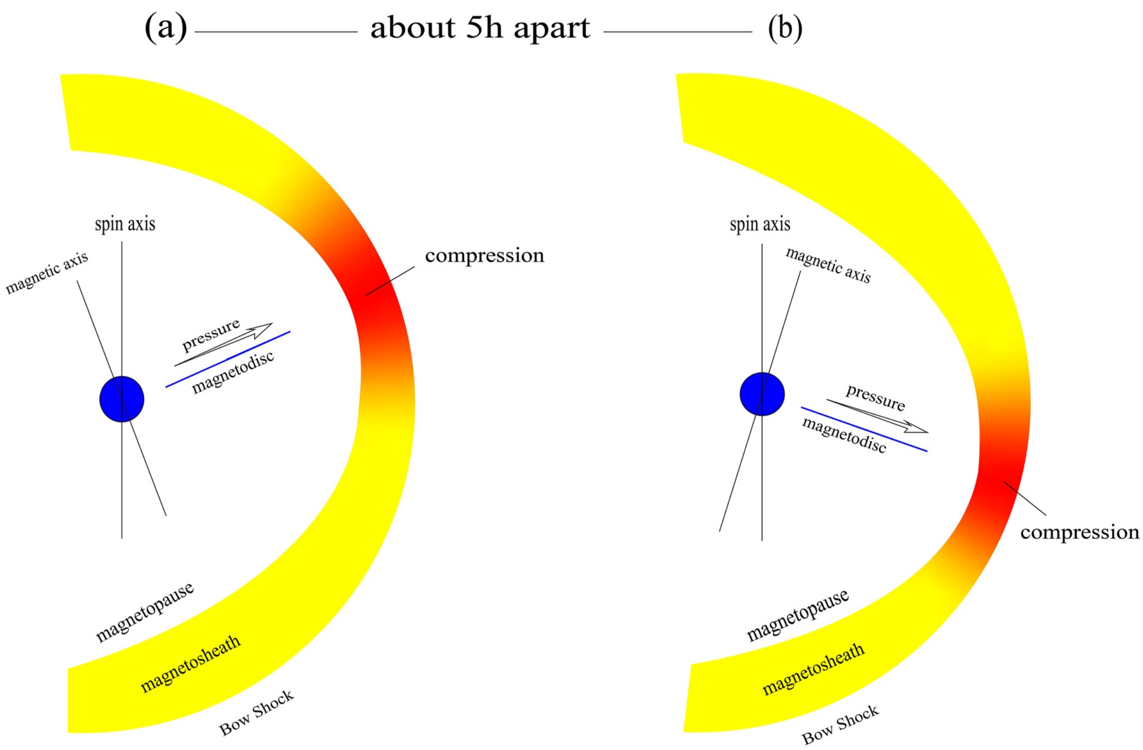

Figure 6. A schematic diagram to show how the disc oscillation cause ~5 hr periodic perturbations to the magnetosheath.

Magnetic field and plasma waves are used to examine the magnetopause and bow shock crossings and thus to determine the durations in Jupiter's magnetosheath. Distinct radio wave structures are expected when a satellite crosses the magnetopause or bow shock. A bow shock crossing is identified by a broadband, intense signal in plasma wave data and the change in the magnetic field's magnitude (the magnetic field in the solar wind is significantly weaker than in magnetosheath), and a magnetopause crossing is identified through the appearance or disappearance of trapped continuum radiations near the frequency of 1,000 Hz, as there is trapped nonthermal continuum radiation filling Jupiter's outer magnetosphere (Gurnett et al., 1979, 1980; Scarf et al., 1979) that disappears in the magnetosheath due to high plasma density (Hospordarsky et al., 2017).

After identifying magnetosheath durations, magnetic field data is filtered in frequency between 1 and 10 min to obtain ULF waves ($\delta \boldsymbol{B}$). We calculate an averaged wave energy ($\delta \boldsymbol{B}^2$) per 10 min and use Lomb-Scargle Periodogram to analyze the periodicity. The periodicities that exceed a confidence level of 0.95 are studied.

3. Results

Repeated visits to the dawn magnetosheath are provided by the initial orbits of the Juno spacecraft during apojoves, while the Galileo spacecraft explored the Jovian magnetosheath at a range of local times. Jupiter's magnetopause and bow shock are highly dynamic, and thus the location changes significantly in several hours or tens of hours. To allow a reliable analysis of periodicities at several hours, we identify magnetosheath times through wave and magnetic field data, and only select durations longer than 20 hr for the statistical studies. Moreover, we selected the longest duration in the magnetosheath from Juno and Galileo for two case studies respectively. The case studies are described in Section 3.1, and the statistical studies are introduced in Section 3.2.

3.1. Case Studies With Observations From Juno and Galileo

The longest duration in the magnetosheath from a single orbit in Juno's data set is from 12:00 UT, November 8th to 02:00 UT, November 11th in 2016. For Galileo, the longest duration was from 06:00 UT, November 24th to 15:00 UT, November 30th in 2000. The overview observations of the two cases are presented in Figure 1 (Juno)

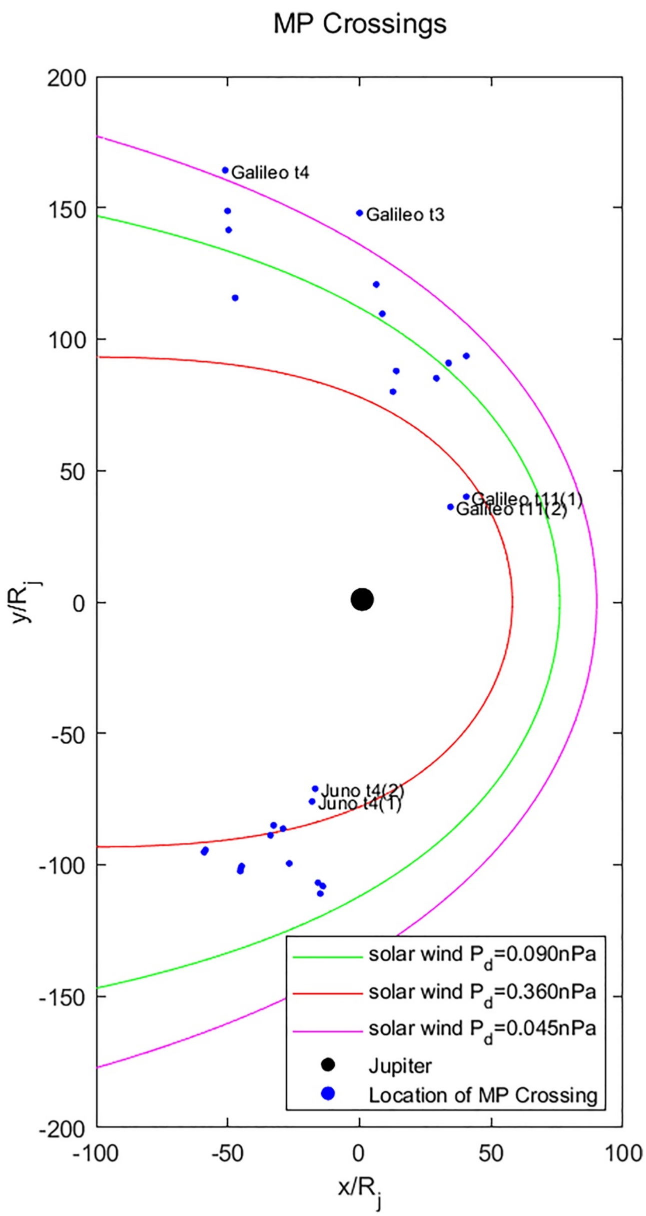

Figure 7. Locations of MP crossings compared to the MP model under several typical solar wind dynamic pressures (0.045 (magenta line), 0.09 (green line) and 0.36 nPa (red line)) from Joy et al. (2002). We think the dynamic pressure of 0.09 nPa is the normal state. The selected events are marked.

and Figure 2 (Galileo) in the same format. From the top to the bottom, the plots are the plasma wave spectrogram of the electric field (a), total magnetic field strength (b), ULF waves filtered from the total magnetic field strength in frequencies between 1 and 10 min (c), and the proxy of wave energy calculated from ULF waves in panel c per 10 min (d). Panel (e) shows the results of periodic analysis using Lomb-Scargle Periodograms. The red line indicates the confidence level of 0.95.

Using the appearance and disappearance features of nonthermal continuum radiation, we can assess satellite's crossings of the magnetopause (Hospodarsky et al., 2017). As seen in Figure 1, there are waves at a frequency near 1,000 Hz (i.e., nonthermal continuum radiation) before 0 UTC and between 9 UTC and 11 UTC on 8 November 2016. And there is a broadband, instance signal in wave data and a sudden decrease in magnetic field data near 3 UTC on 11 November 2016, which indicate a bow shock crossing. To avoid additional complexity due to the mixture of magnetosphere, magnetosheath, and solar wind environments, here, we do not include the data before the magnetopause crossing and the data after the bow shock crossing to ensure that the environment analyzed was purely magnetosheath. Similarly, the Galileo data as shown in Figure 2 also includes a bow shock crossing near 5 UTC on 24 November 2000 and a magnetopause crossing near 16 UTC on 30 November 2000. We also exclude the data in the solar wind and the data in the magnetosphere.

As clearly demonstrated by Figures 1e and 2e, ULF waves in Juno data have significant periodicities of about 3.5, 6 and 8 hr, and the Galileo results have significant periodicities of about 5.2, 6 and 9 hr. The periodicities near 5 hr (or 6 hr) and 9 hr (or 8 hr) are perhaps associated with planetary rotation modulation. We speculate that these periodicities in the magnetosheath may come from the influence of Jupiter's magnetosphere. ULF waves serve as a crucial media of energy transport, implying that the internal process can transport energy to the magnetosheath in the Jovian system.

3.2. Statistical Studies

Besides case studies, we have also performed statistical investigations of the periodicities in Jupiter's magnetosheath using the Juno and Galileo datasets. We identify magnetosheath times and choose the durations longer than 20 hr for the statistical studies. As shown in Table 1, 21 events were selected, including 10 from the Juno data set and 11 from the Galileo data set. For each event, we perform Lomb-Scargle analysis individually to obtain periodicities. The main results are shown in Figure 3. Panels (a, Juno) and (b, Galileo) show the normalized PSD (power spectral density) for each event using pseudo-color images. The normalized PSD is the ratio of PSD to the confidence level of 0.95 for each event. Panels (c, Juno) and (d, Galileo) are line plots of the periodicities for each event. The confidence level of 0.95 is shown by the horizontal lines in Panels (c) and (d). Since the durations of some events are not much longer than 20 hr, we only show the periodicities from 1 to 6h in this study.

Figure 3 shows that periodicities exist between 3 and 4 hr and around 5 hr in every orbit of both satellites, although periodicities between 3 and 4 hr may not be so significant. Similar periodicities are also shown in the two selected case studies. Such periodicities are probably associated with the plasma disc flapping as a modulation of planetary rotation. The periodicities near 5 hr suggest that the magnetodisc flapping could transfer energy to the magnetosheath and thus generates the detectable ULF wave signals as reported here, in addition to causing artificial signals in periodic analysis within the magnetosphere, which make it difficult to research the periodicities. The energy transport from the inner magnetosphere to the magnetosheath is probably a fundamental

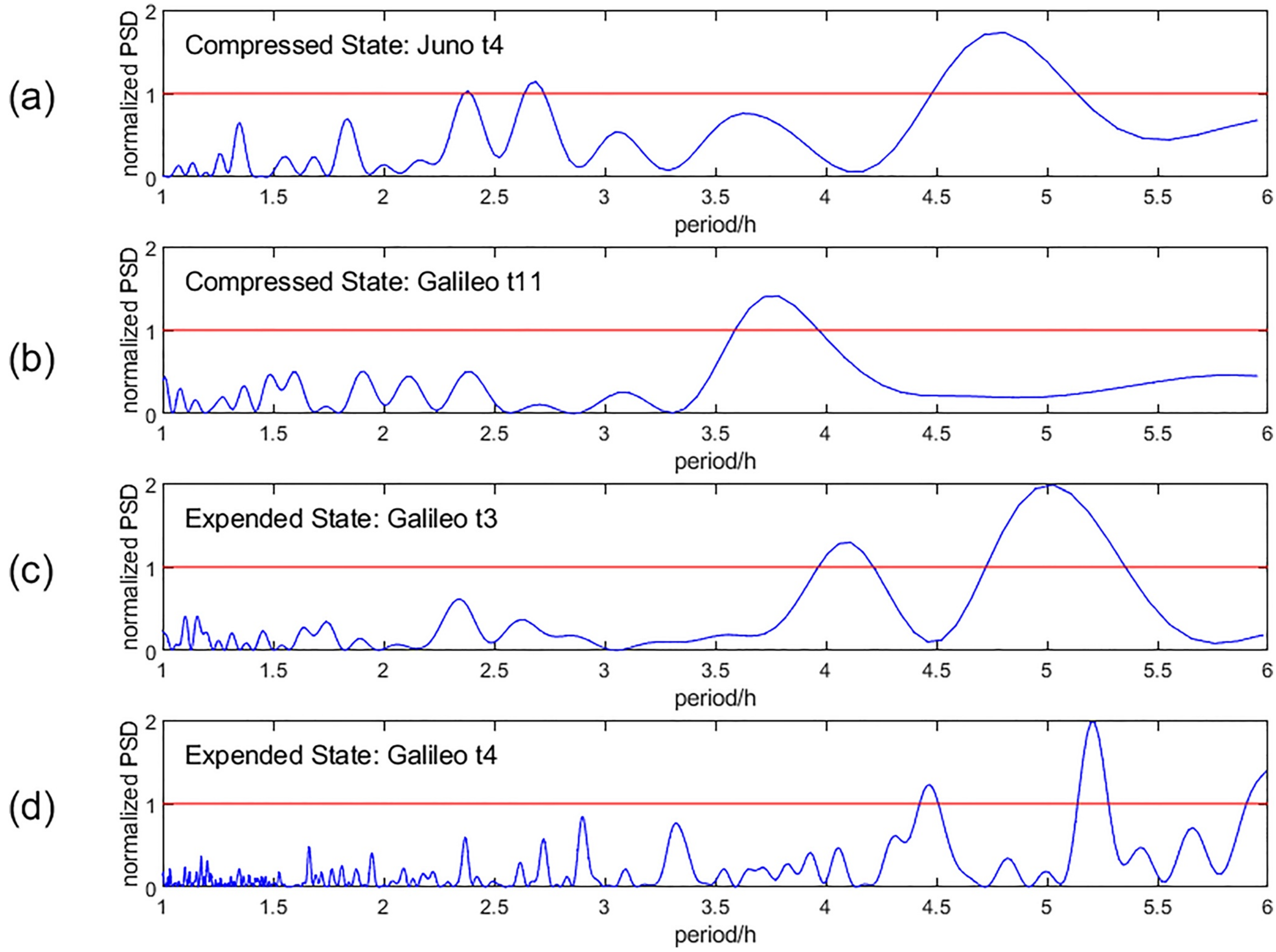

Figure 8. Comparison of the periodic analysis to Galileo t3, t4, t11, and Juno t4. We think Galileo t3 and t4 are in the expended state, and Galileo t11 and Juno t4 are in the compressed state.

process which remains poorly understood. The flapping disc is expected to encounter the equatorial region of the magnetopause every half a planetary rotation period, that is, ~5 hr. Since the flapping is strongly coupled with the rotation of the magnetosphere, it is possible that the rotation could induce various shifts on the peak, which probably explains that the frequency peaks are not exactly half a planetary rotation period. Further investigations (e.g., numerical simulation or case studies) are required to further confirm the hypothesis.

To extend our analysis to longer periodicities (6–10 hr), a longer time series of data is needed. We combine all magnetic field data from one satellite in the magnetosheath from selected events. Since the variations of magnetic field strength could vary a lot from event to event, we normalize the filtered magnetic field data. We use the ratio of wave energy to the averaged wave energy for each event as the normalized data and combine the data together for periodicity analysis. The results are shown in Figure 4, and the red lines are the confidence level of 0.95.

As we can see, there are significant periodicities near 4.7 and 6.2 hr in both results, while the periodicities near 8 and 9 hr are only significant in the Galileo data set. Periodicities near 4.7 and 9 hr are near 5 and 10 hr, possibly resulting from the influence of Jupiter's magnetosphere as we have previously mentioned. There were two peaks near 2 and 3 hr, which are possibly the harmonics of the 6.2hr peak. We shall also notice that the ~9 hr period was only significant in the Galileo data set, which is perhaps related to a dawn-dusk asymmetry as the two satellite samples were from very different local times, as shown in Figure 5. However, it is important to note that by combining the magnetosheath data from different intervals, we may have included some unknown artificial signals in periodogram analysis. This asymmetry doesnt exist in the case studies.

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4. Discussion

In this study, we analyze multihour periodic variations of ULF wave power using Juno and Galileo observations in Jupiter's magnetosheath. To assure the validation of periodicity analysis, the events were selected only when the spacecraft was continually in the magnetosheath for more than 20 hr. Under such requirements, 21 events are analyzed to obtain a global picture. The locations of satellites during the 21 events are shown in Figure 5. From case to case, the periodicities are scattered. However, across the datasets, we often find periodicities between 3 and 4 hr, and periodicities near 5 hr. Periodicities near 9 hr are often found in long time analysis. The variability of periodicities may represent different magnetospheric states caused by mass loading and/or solar wind conditions.

Extensive literature has been focused on the periodic variations in Jupiter's magnetosphere. However, hitherto, fluctuations on multihour timescales have been difficult to explore because the ∼5-hr motion of the plasma sheet means that a quasi-stationary single spacecraft mission will sample different magnetospheric regions across this timescale. Consequently, multihour periodic variations are rarely investigated. However, once the spacecraft is in the magnetosheath, such problems of data sampling are no longer applicable.

Jupiter's magnetosphere constantly rotates, producing a dynamic magnetopause boundary layer, which could potentially pass magnetospheric signatures to the magnetosheath. While the disc oscillation may cause perturbations to the magnetosheath (as shown in Figure 6), the perturbations are physical and could lead to energy dissipation rather than a spatial variation related to the regions sampled by the spacecraft. As clearly shown in the datasets, ∼5 hr perturbations are widely observed, which is probably associated with the rotation modulation. Periodicities between 3 and 4 hr, and periodicities near 9 hr may be caused by supercorotation in the outer magnetosphere. The hypothesis could potentially be examined by global numerical simulations of the Jovian system (Zhang et al., 2021).

The multihour periodicities of ULF wave power represent a type of modulation of energy release. At Earth, repetitive energy release, such as through periodic substorms, is believed to be driven by the solar wind (Huang & Cai, 2009). Besides the external driver caused by the solar wind (Dungey, 1961), internal processes are also believed to drive periodic substorms on Earth (Brambles et al., 2011). In comparison with the Earth, the Jovian magnetosphere is mainly controlled by loading of internal mass and associated processes (e.g., Yao et al., 2019). For example, the relation between quasi-periodic reconfiguration and the solar wind has not been found in observation (Kronberg et al., 2009). Internal processes, such as planetary rotation and Io's volcanic activity, are crucial in driving magnetospheric dynamics (Delamere, 2016). It is unclear whether or not these internal processes could be strong enough to influence Jupiter's magnetosheath. This work suggests that they are. The significant and common periodicities near 5 hr (common in all analysis) and 9 hr (common in long time analysis) indicate that the magnetospheric plasma circulation could modulate energy processes in the magnetosheath. Perhaps the interaction could result in energy transfer from the magnetosphere to the magnetosheath, which requires further examination with multiinstrument measurements.

To investigate the influence from the solar wind, we may compare the periodicities of events during compressed and expanded magnetospheric states. Since the determination of solar wind conditions is highly challenging without a monitor from upstream solar wind, we only chose several events when the magnetopause was under extremely compressed or expanded conditions. Figure 7 shows the locations of magnetopause crossings for all events. For a convenient comparison, the modeled magnetopause following Joy et al. (2002) under several typical solar wind dynamic pressures (0.045, 0.09, and 0.36 nPa) is also provided in Figure 7. As we can see, the MP crossings in Galileo t3 and t4 are significant outside the magnetopause model under the solar wind dynamic pressure of 0.045 nPa, which is significantly weaker than the normal state (0.09 nPa). Thus, the two events can be considered as expended situations. The magnetopause crossings in Galileo t11 and Juno t4 are inside of the modeled magnetopause under the solar wind dynamic pressure at 0.36 nPa, so that they are compressed events. The periodic analysis of Galileo t3, t4, t11, and Juno t4 are shown in Figure 8. Although it seems the two events during compressed situation are at slightly shorter periods, the difference is very minor. The periods at ∼4 and ∼5 hr are significant for both compressed and expanded situations. These results suggest that the solar wind has little influence on the periodicities. We speculate that these hourly periods in the magnetosheath are likely mainly controlled by the magnetospheric plasma circulations. As the ULF wave plays an important role in the energy circulations in the Jovian system, the results in this study therefore highlight the influence from the inside process of Jupiter's magnetosphere to the magnetosheath.

5. Conclusion

In this study, multihour periodicities are systematically investigated for the first time, using magnetosheath measurements from the Juno and Galileo spacecraft. The results show multihour variations in both dawn and dusk local times, which is suggested to be a consequence of magnetospheric plasma circulation and disc oscillation. Although the solar wind compressions can drive significant energy dissipation as visualized by auroral images (Nichols et al., 2007, 2017; Yao et al., 2022), our results show that the compressions may have little influence on the hourly periodicities. But the exact generator of multihour variations still needs to be confirmed. Numerical simulations would be an ideal complementary investigation to reveal the mysterious hourly variation revealed in this study. The periodicities near 5 and 9 hr are likely the influence of Jupiter rotation. How the planetary oscillation exactly modulates the interaction between the magnetosheath and rotating magnetospheric plasma circulation may be next work. The processes associated with the magnetopause boundary layer are crucial to answer this question. The main results are summarized as follows:

1. Jupiter's magnetosheath has many hourly periodic variations, which are likely a consequence of magnetospheric plasma circulation. Periodicities from 2 to 10 hr are widely identified, but the periods can change from time to time.
2. We found little difference in the periods during solar wind compression or quiet situations, which perhaps suggested that the hourly periods are mostly controlled by internal processes.
3. The hourly ULF waves are identified throughout the orbits of Juno and Galileo spacecraft, indicating that the Jovian system can systematically generate hourly perturbations. The mechanism is still unclear, and numerical simulations are likely ideal tools to answer this question.

Data Availability Statement

All Juno and Galileo data presented here are publicly available from NASA's Planetary Data System. The Juno-MAG data set is from NASA Planetary Data (Connerney, 2022) and the Juno-Wave data set is from NASA Planetary Data System (Kurth & Piker, 2022). Galileo-MAG data set is from NASA Planetary Data System (Kivelson et al., 2022) and Galileo-Wave data set is from NASA Planetary Data System (Gurnett et al., 1997). The matlab scripts used to produce Figures 1–5, 7, and 8 are available at Gu et al. (2023). Figure 6 is produced by Adobe Illustrator.

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References

Arridge, C. S., Eastwood, J. P., Jackman, C. M., Poh, G.-K., Slavin, J. A., Thomsen, M. F., et al. (2016). Cassini *in situ* observations of long-duration magnetic reconnection in Saturn's magnetotail. *Nature Physics*, *12*(3), 268–271. https://doi.org/10.1038/nphys3565

Artemyev, A. V., Clark, G., Mauk, B., Vogt, M. F., & Zhang, X.-J. (2020). Juno Observations of heavy ion energization during transient dipolarizations in Jupiter magnetotail. *Journal of Geophysical Research: Space Physics*, *125*(5), e2020JA027933. https://doi.org/10.1029/2020ja027933

Bagenal, F. (2007). The magnetosphere of Jupiter: Coupling the equator to the poles. *Journal of Atmospheric and Solar-Terrestrial Physics*, *69*(3), 387–402. https://doi.org/10.1016/j.jastp.2006.08.012

Bonfond, B., Grodent, D., Badman, S. V., Gérard, J.-C., & Radioti, A. (2016). Dynamics of the flares in the active polar region of Jupiter. *Geophysical Research Letters*, *43*(23), 11963–11970. https://doi.org/10.1002/2016GL071757

Bonfond, B., Yao, Z. H., Gladstone, G. R., Grodent, D., Gérard, J.-C., Matar, J., et al. (2021). Are dawn storms Jupiter's auroral substorms? *AGU Advances*, *2*(1), e2020AV000275. https://doi.org/10.1029/2020AV000275

Brambles, O., Lotko, W., Zhang, B., Wiltberger, M., Lyon, J., & Strangeway, R. (2011). Magnetosphere sawtooth oscillations induced by ionospheric outflow. *Science*, *332*(6034), 1183–1186. https://doi.org/10.1126/science.1202869

Connerney, J. (2022). Juno magnetometer Jupiter archive JNO-J-3-FGM-CAL-V1.0 [Dataset]. NASA Planetary Data System. https://doi.org/10.17189/1519711

Connerney, J. E. P., Benn, M., Bjarno, J. B., Denver, T., Espley, J., Jorgensen, J. L., et al. (2017). The Juno magnetic field investigation. *Space Science Reviews*, *213*(1–4), 39–138. https://doi.org/10.1007/s11214-017-0334-z

Delamere (2016). A review of the low-frequency waves in the giant magnetospheres. In *Low-frequency waves in space plasmas* (pp. 365–378). The AGU Publications Committee. https://doi.org/10.1002/9781119055006.ch21

Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. *Physical Review Letters*, *6*(2), 47–48. https://doi.org/10.1103/PhysRevLett.6.47

Dunn, W. R., Branduardi-Raymont, G., Ray, L. C., Jackman, C. M., Kraft, R. P., Elsner, R. F., et al. (2017). The independent pulsations of Jupiter's northern and southern X-ray auroras. *Nature Astronomy*, *1*(11), 758–764. https://doi.org/10.1038/s41550-017-0262-6

Ge, Y., Jian, L., & Russell, C. (2007). Growth phase of Jovian substorms. *Geophysical Research Letters*, *34*(23), L23106. https://doi.org/10.1029/2007gl031987

Ge, Y., Russell, C., & Khurana, K. (2010). Reconnection sites in Jupiter's magnetotail and relation to Jovian auroras. *Planetary and Space Science*, *58*(11), 1455–1469. https://doi.org/10.1016/j.pss.2010.06.013

Gu, W. D., Guo, R. L., Yao, Z. H., & Xu, Y. (2023). Weidong-Gu/2022JE007625R: Matlab scripts used in paper (v2.0). *Zenodo*. https://doi.org/10.5281/zenodo.7544226

Gurnett, D. A., Kurth, W. S., & Granroth, L. J. (1997). Galileo orbiter Jupiter: GO-J-PWS-2-REDR-RTS-SA-FULL-V1.0 [Dataset]. NASA Planetary Data System. https://doi.org/10.17189/1519682

Gurnett, D. A., Kurth, W. S., & Scarf, F. L. (1979). Plasma-wave observations near Jupiter—Initial results from Voyager-2. *Science*, *206*(4421), 987–991. https://doi.org/10.1126/science.206.4421.987

Gurnett, D. A., Kurth, W. S., & Scarf, F. L. (1980). The structure of the Jovian magnetotail from plasma-wave observations. *Geophysical Research Letters*, *7*(1), 53–56. https://doi.org/10.1029/GL007i001p00053

Gurnett, D. A., Kurth, W. S., Shaw, R. R., Roux, A., Gendrin, R., Kennel, C. F., et al. (1992). The Galileo plasma wave investigation. *Space Science Reviews*, *60*(1–4), 341–355. https://doi.org/10.1007/BF00216861

Hospodarsky, G. B., Kurth, W. S., Bolton, S. J., Allegrini, F., Clark, G. B., Connerney, J. E. P., et al. (2017). Jovian bow shock and magnetopause encounters by the Juno spacecraft. *Geophysical Research Letters*, *44*(10), 4506–4512. https://doi.org/10.1002/2017GL073177

Huang, C.-S., & Cai, X. (2009). Magnetotail total pressure and lobe magnetic field at onsets of sawtooth events and their relation to the solar wind. *Journal of Geophysical Research*, *114*(A4), A04204. https://doi.org/10.1029/2008JA013807

Joy, S. P., Kivelson, M. G., Walker, R. J., Khurana, K. K., Russell, C. T., & Ogino, T. (2002). Probabilistic models of the Jovian magnetopause and bow shock locations. *Journal of Geophysical Research*, *107*(A10), 1309. https://doi.org/10.1029/2001JA009146

Keiling, A., Wygant, J. R., Cattell, C. A., Mozer, F. S., & Russell, C. T. (2003). The Global morphology of wave poynting flux: Powering the aurora. *Science*, *299*(5605), 383–386. https://doi.org/10.1126/science.1080073

Khurana, K. K. (1992). A generalized Hinged-magnetodisc model of Jupiter's nightside current sheet. *Journal of Geophysical Research*, *97*(A5), 6269–6276. https://doi.org/10.1029/92JA00169

Kivelson, M. G., Khurana, K. K., Means, J. D., Russell, C. T., & Snare, R. C. (1992). The Galileo magnetic field investigation. *Space Science Reviews*, *60*(1–4), 357–383. https://doi.org/10.1007/BF00216862

Kivelson, M. G., Khurana, K. K., Russell, C. T., Walker, R. J., Joy, S. P., & Mafi, J. N. (2022). Galileo Jupiter magnetometer magnetospheric survey data collection Galileo-mag-jup-calibrated [Dataset]. NASA Planetary Data System. https://doi.org/10.17189/fq45-wv97

Kronberg, E. A., Woch, J., Krupp, N., & Lagg, A. (2009). A summary of observational records on periodicities above the rotational period in the Jovian magnetosphere. *Annales Geophysicae*, *27*(6), 2565–2573. https://doi.org/10.5194/angeo-27-2565-2009

Kurth, W. S., Hospodarsky, G. B., Kirchner, D. L., Mokrzycki, B. T., Averkamp, T. F., Robison, W. T., et al. (2017). The Juno waves investigation. *Space Science Reviews*, *213*(1–4), 347–392. https://doi.org/10.1007/s11214-017-0396-y

Kurth, W. S., & Piker, C. W. (2022). Juno waves survey standard science products JNO-E/J/SS-WAV-3-CDR-SRVFULL-V2.0 [Dataset]. NASA Planetary Data System. https://doi.org/10.17189/1520498

Mauk, B. H., Haggerty, D. K., Paranicas, C., Clark, G., Kollmann, P., Rymer, A. M., et al. (2017). Discrete and broadband electron acceleration in Jupiter's powerful aurora. *Nature*, *549*(7670), 66–69. https://doi.org/10.1038/nature23648

Nichols, J., Badman, S. V., Bagenal, F., Bolton, S., Bonfond, B., Bunce, E., et al. (2017). Response of Jupiter's auroras to conditions in the interplanetary medium as measured by the Hubble Space Telescope and Juno. *Geophysical Research Letters*, *44*(15), 7643–7652. https://doi.org/10.1002/2017GL073029

Nichols, J., Bunce, E., Clarke, J. T., Cowley, S., Gérard, J. C., Grodent, D., & Pryor, W. R. (2007). Response of Jupiter's UV auroras to interplanetary conditions as observed by the Hubble Space Telescope during the Cassini flyby campaign. *Journal of Geophysical Research*, *112*(A2), A02203. https://doi.org/10.1029/2006JA012005

Pan, D. X., Yao, Z. H., Manners, H., Dunn, W., Bonfond, B., Grodent, D., et al. (2020). Ultralow-frequency waves in driving Jovian aurorae revealed by observations from HST and Juno. *Geophysical Research Letters*, *48*(5), e2020GL091579. https://doi.org/10.1029/2020GL091579

Russell, C., Khurana, K., Huddleston, D., & Kivelson, M. (1998). Localized reconnection in the near Jovian magnetotail. *Science*, *280*(5366), 1061–1064. https://doi.org/10.1126/science.280.5366.1061

Scarf, F. L., Gurnett, D. A., & Kurth, W. S. (1979). Jupiter plasma-wave observations—Initial Voyager-1 overview. *Science*, *204*(4396), 991–995. https://doi.org/10.1126/science.204.4396.991

Sulaiman, A. H., Hospodarsky, G. B., Elliott, S. S., Kurth, W. S., Gurnett, D. A., Imai, M., et al. (2020). Wave-particle interactions associated with Io's auroral footprint: Evidence of Alfvén, ion cyclotron, and whistler modes. *Geophysical Research Letters*, *47*(22), e2020GL088432. https://doi.org/10.1029/2020GL088432

Tao, C., Kimura, T., Kronberg, E. A., Tsuchiya, F., Murakami, G., Yamazaki, A., et al. (2021). Variation of Jupiter's aurora observed by Hisaki/EXCEED: 4. Quasi-periodic variation. *Journal of Geophysical Research: Space Physics*, *126*(2), e2020JA028575. https://doi.org/10.1029/2020ja028575

Vasyliunas, V. M. (1983). Plasma distribution and flow. In A. J. Dessler (Ed.), *Physics of the Jovian magnetosphere* (p. 395453). Cambridge University Press. https://doi.org/10.1017/CBO9780511564574.013

Yao, Z., Bonfond, B., Grodent, D., Chane, E., Dunn, W. R., Kurth, W. S., et al. (2022). On the relation between auroral morphologies and compression conditions of Jupiter's magnetopause: Observations from Juno and the hubble space telescope. *Journal of Geophysical Research*, *127*(10), e2021JA029894. https://doi.org/10.1029/2021ja029894

Yao, Z., Dunn, W. R., Woodfield, E. E., Clark, G., Mauk, B. H., Ebert, R. W., et al. (2021). Revealing the source of Jupiter's x-ray auroral flares. *Science Advances*, *7*(28), eabf0851. https://doi.org/10.1126/sciadv.abf0851

Yao, Z. H., Grodent, D., Kurth, W. S., Clark, G., Mauk, B. H., Kimura, T., et al. (2019). On the relation between Jovian aurorae and the loading/unloading of the magnetic flux: Simultaneous measurements from Juno, Hubble Space Telescope, and Hisaki. *Geophysical Research Letters*, *46*(21), 11632–11641. https://doi.org/10.1029/2019GL084201

Zhang, B., Delamere, P. A., Yao, Z., Bonfond, B., Lin, D., Sorathia, K. A., et al. (2021). How Jupiter's unusual magnetospheric topology structures its aurora. *Science Advances*, *7*(15), eabd1204. https://doi.org/10.1126/sciadv.abd1204