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Jupiter wind as a unifying bridge: a testable paradigm in the Tianwen-4 era

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Key Points:

- Knowledge of a planet wind can draw on different parts of planetary science to provide new insights into planetary systems.
- Three knowledge gaps are discussed and the potential methods to address these gaps are proposed.
- The forthcoming Tianwen-4 mission has a good chance of overcoming these gaps and further investigating Jupiter wind.

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Abstract: Jupiter's rotating magnetic field, together with its satellites and rings, generate a composite flow that we term the Jupiter wind in this paper: a multi-source mixture of particles originating from Io's volcanism, Jupiter's other moons, its rings, and its atmosphere, subsequently reprocessed by ionization, acceleration, corotation, and outward and tailward transport. Inspired by the unifying role of the solar wind in heliophysics, we argue that a Jupiter wind perspective can similarly integrate disparate domains of Jovian science—interior structure, Io's volcanic activity and neutral cloud, plasma dynamics, radiation belts, and distant magnetotail evolution—into a coupled evolutionary framework. We highlight three systematically interconnected knowledge gaps that form a coherent investigative chain: (1) What are the electromagnetic processes inside Io, influencing the fundamental source characteristics of Jupiter wind? (2) What quantitative role do neutral particles play in processes such as supplying the inner radiation belt, representing the intermediate processing stage of Jupiter wind evolution? (3) How do magnetic field and charged particles evolve across the distant (~100 R_J to > 9000 R_J) magnetotail, concerning the ultimate fate and control mechanisms of Jupiter wind? The forthcoming Tianwen-4 mission—potentially synergistic with JUICE and Europa Clipper, if their operations overlap—offers a unique opportunity to deliver instruments to investigate magnetic field and charged and neutral particles, enabling testable predictions regarding the source and evolution of Jupiter wind. Framing Jupiter wind within a generalized "planet wind" paradigm may ultimately clarify how internal driving competes with solar forcing to shape planetary systems across the solar system and beyond.

Keywords: planetary science; planet wind; Jupiter wind; Tianwen-4; Jovian system investigation

1. Introduction

1.1 Planet Wind: A Missing Paradigm in Planetary Science

The proposal of the solar wind (Parker, 1958a, b, c), building on inferences from comet tail dynamics (Biermann, 1951, 1952, 1957), unified previously disparate domains—solar atmosphere, interplanetary structure, magnetospheric and ionospheric processes—into a physical circulation paradigm that transformed space physics from phenomenological observations into a predictive framework (e.g. space weather predictions). An analogous integrative synthesis has not yet fully emerged across planetary science, even though the couplings are evident and fundamental. The evolution of a planet itself directly impacts the evolution of its atmosphere (e.g. Wei Y et al., 2014; Zhong J et al., 2014) and then affects the space environment beyond the atmosphere. In turn, space environment influences the escape of atmospheric particles (e.g. Wei Y et al., 2012) and the evolution of atmosphere also feeds back into the planet's evolution through mechanisms such as carbon cycle and water cycle. These interconnected processes suggest that planetary systems operate as integrated circulation networks, yet we lack a unifying conceptual framework to describe and predict their behavior.

Based on these relations, the recent introduction of the "planet wind" hypothesis (Wei Y, 2024) seeks to formalize this coupling into a testable paradigm. Planet wind is composed of particles escaping, sputtering, or erupting from a planetary system—the planet's surface, atmosphere and/or satellites and rings. These particles evolve in magnetosphere (or induced magnetosphere) and eventually either enter interplanetary space or return to the planetary system, involving various branches of planetary science.

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The concept "planet wind" therefore offers a pathway to integrate these domains into a unified whole, such as the solar wind concept transforming our understanding of star-planet interactions. However, for this paradigm to achieve the transformative impact of the solar wind framework, it must move beyond conceptual appeal and be shown capable of generating specific, testable predictions that can discriminate between competing physical mechanisms.

1.2 Jupiter Wind: A Systematically Coupled Multi-Stage Process

Jupiter may present the most compelling case study for developing and testing a planet wind paradigm. Because Jupiter is a large planet with a rich satellite system, the Jupiter wind serves as a representative case of a satellite planet wind system (Wei Y, 2024), where the primary mass loading originates not from the planet itself but from its volcanically active moons. The strongest planet wind inside the solar system, Jupiter wind, is generated from the largest planet in the solar system, Jupiter, with the strongest planetary magnetic moment in the solar system and the most active geological activity within the solar system, Io's surface and internal processes. Therefore, Jupiter wind can stand for an extreme and perhaps the typical case of the planet winds in the solar system. Jupiter wind can be conceptualized as systematic progression through two interconnected stages: source and evolution.

The first stage, the source of Jupiter wind, is thought to be dominated by particles from Io (Bagenal and Sullivan, 1981), while Jupiter itself, its rings, and its other satellites also contribute (e.g. Roth et al., 2014), creating a complex multi-source system. Io, as the innermost Galilean satellite, is affected by strong tidal effects and has the most dynamic geological activity in the solar system. Io's volcanic eruptions bring plenty of particles into the space environment, which are the main constituent of Jupiter wind. Besides, Jupiter wind has other sources. Europa contributes water vapor (Roth et al., 2014). The surface content of satellites and rings can escape or be sputtered (e.g. Carberry Mogan et al., 2023). Upward beams were observed in Jupiter's polar cap (Mauk et al., 2020). These are also parts of the source of Jupiter wind. Therefore, the source of Jupiter wind involves different areas including Io and Europa's inner processes, Jupiter's polar dynamics, and interactions between its magnetosphere and its satellites and rings.

The second stage, the evolution of Jupiter wind, can be classified roughly into three processes: ionization of neutral particles, dynamics of charged particles within Jupiter's magnetosphere, and competition with solar wind. The first process, ionization, is the main source of charged particles in Jupiter's magnetosphere, different from terrestrial case where the charged particles mainly come from both the Earth and the solar wind. The second and third processes are complex and interact with each other, forming Jupiter's magnetosphere.

The magnetosphere can be roughly divided into 5 layers, showing the evolution of Jupiter wind. The innermost is inside 10 R_J, containing radiation belts and Io plasma torus. The second is 10 to 20 R_J, where the particles corotate rigidly with Jupiter's magnetic field and are radially heated. The third is 20 to about 35 R_J, where the corotation delays and radial heating seems to disappear. The fourth is about 35 R_J to magnetopause, where the corotation breaks down and the global dawn–dusk asymmetry can be significantly identified (e.g. Khurana and Schwarzl, 2005). The last is beyond magnetopause, where is thought to be controlled by the solar wind but the Jupiter-control signature can still be identified (e.g. Gu et al., 2023). The characteristics of particles at different radial distances are shown in Figure 1.

The complexity of Jovian system can be compared with the complexity of the solar system, as the existence of four Galilean satellites (can be compared with four terrestrial planets), Ganymede's intrinsic magnetic field (like the intrinsic magnetic field of the Earth), plenty of small satellites, rings and distant magnetotail (extends to at least 9000 R_J). The differences between the Jovian system and the solar system are also obvious, such as rotation period length (Jupiter is about 10 hours while the Sun is about 25 days) and the temporal variation of magnetic field (the magnetic field of the Sun reverses in 11 years period while this kind of fast periodic magnetic reversal hasn't been identified in

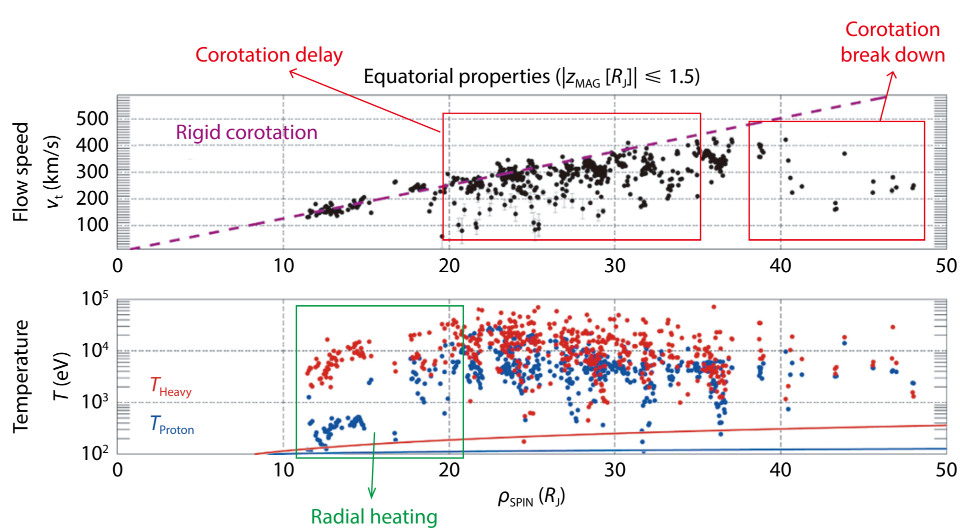

Figure 1. The characteristics of particles at different radial distances identified by Juno data, modified from (Kim et al., 2020).

Jupiter). The Jupiter wind therefore invites comparison and contrast with solar wind. For example, the radial heating exists in both solar corona (e.g. Samanta et al., 2019) and Jupiter's inner magnetosphere (e.g. Saur, 2004), indicating the similarity between Jupiter wind and solar wind, but the control from Jupiter's magnetic field to the plasma in Jupiter's magnetosphere is much larger than that exerted by the solar magnetic field on the heliospheric plasma, indicating the difference between Jupiter wind and solar wind. The similarities and differences between Jupiter wind and solar wind offer opportunities to test the universal principles of "wind". The concept of solar wind has helped unify different domains of heliophysics, so the concept of Jupiter wind may also help connect different parts of Jovian science.

1.3 Investigating Jupiter Wind: Tianwen-4 Era

Jupiter wind has been investigated for decades, from the first flyby of Pioneer 10 in 1973 (Hall, 1974) to the recent mission Juno (Bolton et al., 2017). With improving data, more and more detailed physical characteristics of Jupiter wind have been indicated (e.g. Gu WD et al., 2024; Xu Y et al., 2024, Yao ZH et al., 2024). Simultaneous observations by spacecraft and telescope also give new evidence (e.g. Yao ZH et al., 2021; 2022). Meanwhile, high-resolution simulations keep giving revelations (e.g. Zhang BZ et al., 2021, 2024). In the coming decades, three missions, JUICE, Europa Clipper and Tianwen-4, will explore the Jovian system systematically, showing that the Jovian system is a focus of exploration.

Tianwen-4 will investigate Jovian system as the 5th spacecraft to orbit Jupiter, after JUICE and Europa Clipper. The main objects of JUICE and Europa Clipper are claimed as Ganymede and Europa, respectively. The main object of Tianwen-4 may be Callisto, while other regions of Jovian system can also be investigated before the spacecraft enters the Callisto orbit. Therefore, these missions will continuously afford systematic investigations of Jovian system. We call the coming decades "Tianwen-4 era" for three reasons:

(1) Tianwen-4 will potentially enter Jovian system when JUICE and Europa Clipper have completed their main missions. In that time these two spacecraft will be orbiting Ganymede and Europa, respectively, or have ended their missions. Hence, Tianwen-4 can investigate Jovian system based on the experience of previous four missions and focus on the regions and scientific problems that lack exploration and research, bringing a brand-new understanding of Jovian system.

(2) If JUICE and Europa Clipper still operate when Tianwen-4 enters the Jupiter orbit, the emerging multi-mission era will create a timely opportunity. The spatial and temporal coordination of these three missions creates opportunities for multi-point observations that may address fundamental questions about Jupiter wind's source and evolution. For example, simultaneous observations of magnetic field and particle properties at different regions could directly measure how periodicities and control mechanisms evolve in the magnetosphere.

(3) Tianwen-4 mission is the first Jupiter system investigation mission of China. Chinese scientific researchers will have unprecedented opportunities to propose, predict and verify scientific problems and perspectives about Jupiter science through Tianwen-4 mission. Tianwen-4 era will be an era for Chinese scientific researchers to investigate Chinese scientific perspectives utilizing Chinese mission, which will undoubtedly make contributions on the planetary science.

The present work therefore discusses three knowledge gaps by comparing Jupiter wind and solar wind. These gaps are selected for their potential accessibility to upcoming observations. The discussion aims to stimulate future research on Jupiter wind and planet wind.

2. Three Interconnected Critical Knowledge Gaps

2.1 What Are the Electromagnetic Processes in Io's Interior?

Io is the innermost Galilean satellite. As Jupiter is the largest planet in the solar system and has four big satellites called Galilean satellites, the Jovian system can be compared with the solar system. In the solar system, Mercury and Earth (the first and third terrestrial planets) have intrinsic magnetic fields, while Venus and Mars (the second and fourth terrestrial planets) don't have. In the Jovian system, Europa and Callisto (the second and fourth Galilean satellites) don't have intrinsic magnetic field, while Ganymede (the third Galilean satellite) has (Kivelson et al., 1996; Khurana et al., 1998). Therefore, whether Io has an intrinsic magnetic field is an interesting question concerning the similarities and differences between the Jovian system and the solar system. On the other hand, the strong tidal effect leads to the most active geological activity in the solar system, and the material erupted from Io's volcanoes is thought to be the main source of Jupiter wind (Thomas et al., 2004; Saur et al., 2004). As the presence or absence of an intrinsic magnetic field is a question concerning the internal processes of Io, it's a question about the source of Jupiter wind. However, approaching Io will ruin the spacecraft due to the harsh environment, and the complex and changeable electromagnetic environment around Io make it hard to figure out the electromagnetic processes within Io (e.g. Jia XZ et al., 2010).

Current knowledge of the electromagnetic environment around Io mainly comes from the multiple flybys of Galileo mission in different regions around Io containing its equatorial plane and two polar regions. The closest of these flybys was at an altitude of 200 km (Jia XZ et al., 2010). These flybys lead to a conclusion by comparing the electromagnetic environment in different regions around Io that, the electromagnetic environment around Io is mainly controlled by the interactions between Io and the magnetosphere, such as the periodically changing induced magnetic field from a global magma ocean inside Io (Khurana et al., 2011), while the existence of a strong intrinsic magnetic field can be excluded (Jia XZ et al., 2010). The absence of a strong intrinsic magnetic field may be attributed to lack of core cooling which makes the interior of Io to be a quasi-stationary state (Spohn, 1997; Schubert et al., 2004). However, it's still unknown whether Io has a weak intrinsic magnetic field. So it still can't be confirmed whether Io has a dynamo, which concerns the inner processes of Io and the source of Jupiter wind.

If one wants to figure out whether Io has a weak intrinsic magnetic field, a more precise measurement is needed. Detecting the magnetic field in lower altitude has stronger possibility to detect the potential intrinsic magnetic field, but the induced magnetic field will be stronger as well. Therefore, the first step is supposed to figure out the induced magnetic field and exclude it from the data. In this process, the understanding of Io's internal electromagnetic dynamics will be clearer and more comprehensive. The more specific and detailed measurements of the magnetic field around Io will provide new insights about the induced magnetic field. If the induced magnetic field can be excluded from the data, the presence or absence of a dynamo may be confirmed, or a new upper limit of the intrinsic magnetic field can be obtained.

2.2 What Role Do Neutral Particles Play in Some Unclear Processes Like Supplying the Inner Radiation Belt?

One of the main differences between Jupiter wind and solar wind is that most particles supplied by Io are initially released as neutral particles, unlike the charged particles coming from the Sun. Part of the neutral particles from Io are ionized through complex processes, which are thought to be the main source of charged particles in Jupiter's magnetosphere (e.g. Thomas et al., 2004; Saur et al., 2004). Magnetospheric physics primarily focuses on charged particles and often disregards neutral particles, and the same trend applies to detection efforts. However, it's impossible that all the neutral particles from Io are ionized. In contrast, the neutral particles can diffuse to at least hundreds of Jovian radii (Thomas et al., 2004), as shown in Figure 2. These neutral particles are also an important part of Jupiter wind and certainly affect the evolution of Jupiter wind in ways that may not yet have been fully explored.

For example, neutral particles may participate in supplying the inner radiation belt. The inner radiation belt was discovered by Juno (Kollmann et al., 2017; Roussos et al., 2022), as shown in Figure 3. Because particles in Jupiter's magnetosphere are

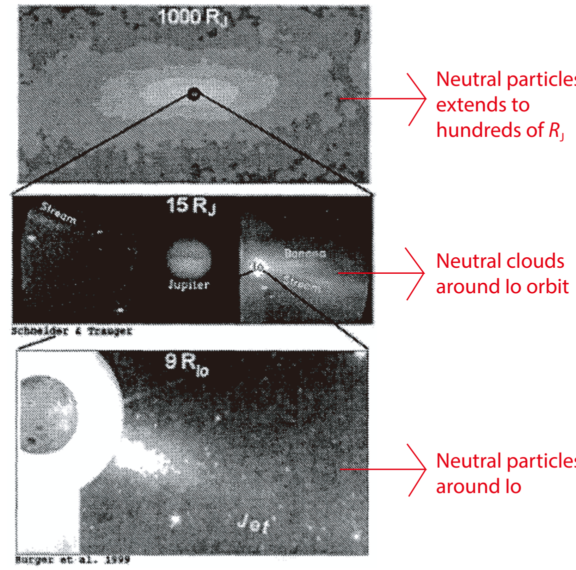

Figure 2. Images of the neutral sodium clouds on three different scales, modified from (Thomas et al., 2004).

thought to mainly come from Io's volcanic eruptions and the corotating charged particles will flow away from Jupiter, the source of the plenty of charged particles in the inner radiation belt is mysterious, as the inner radiation belt is inside Io plasma torus. Besides, as plenty of sulfur ions have been observed in the inner radiation belt (Kollmann et al., 2017), Io is still an important source of the particles in the inner radiation belt. The charged particles in the inner radiation belt can originate from the ionization of local neutral particles and the movement of charged particles outside Io's orbit. The local neutral particles can come from Jupiter's satellites and rings and the movement of neutral particles from Io, as the neutral particles from Io do not necessarily corotate with

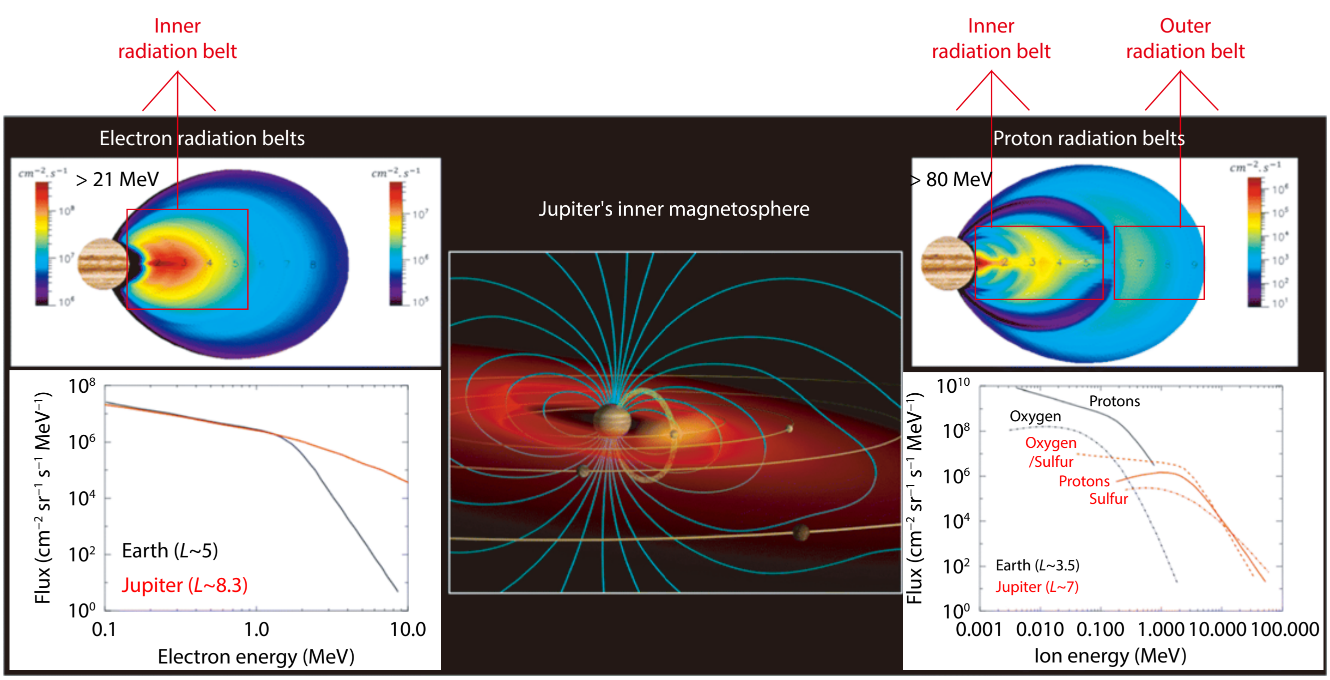

Figure 3. Some information about Jupiter's radiation belts, modified from (Roussos et al., 2022).

Jupiter and could potentially fall into Jupiter or revolve in an orbit inside Io's orbit. These neutral particles may be hit by cosmic rays and generate energetic charged particles (Kollmann et al., 2017). They may also be picked up (generating charged particles) and then be accelerated through mechanisms like wave–particle interactions (e.g. Southwood and Kivelson, 1982). Therefore, the detection of the motions and distributions of charged and neutral particles can help figure out the origins of the inner radiation belt.

2.3 What Are the Electromagnetic Processes Along the Distant Magnetotail?

With Io's active geological activity continually injecting particles into Jupiter wind, Jupiter wind becomes the strongest planet wind in the solar system, stretching Jupiter's distant magnetotail to at least 9000 Jovian radii (R_J) as observed by Voyager-2 (Kurth et al., 1982; Lepping et al., 1983; Sittler et al., 1987). The New Horizons spacecraft detected charged particles along the distant magnetotail (McComas et al., 2007), while the magnetic field along the distant magnetotail within 9000 R_J remains unknown.

When comparing Jupiter wind and solar wind, a similarity is the distant propagation, as Jupiter has the longest magnetotail in the solar system. If the distant magnetotail has electromagnetic processes different from the processes in the solar wind, the difference offers a new avenue for exploring the difference between Jupiter wind and solar wind. Inversely, if the electromagnetic processes along the distant magnetotail and along the solar wind are similar, the independence of Jupiter's distant magnetotail would become complex. The similarity can come from the similarity between Jupiter wind and solar wind, while it can also come from the influence from solar wind to the distant magnetotail. Hence, the electromagnetic processes along Jupiter's distant magnetotail concern the controlling factors of distant magnetotail.

While the charged particles with characteristics of charged particles in Jupiter's magnetosphere have been identified along the distant magnetotail (McComas et al., 2007), as shown in Figure 4, the

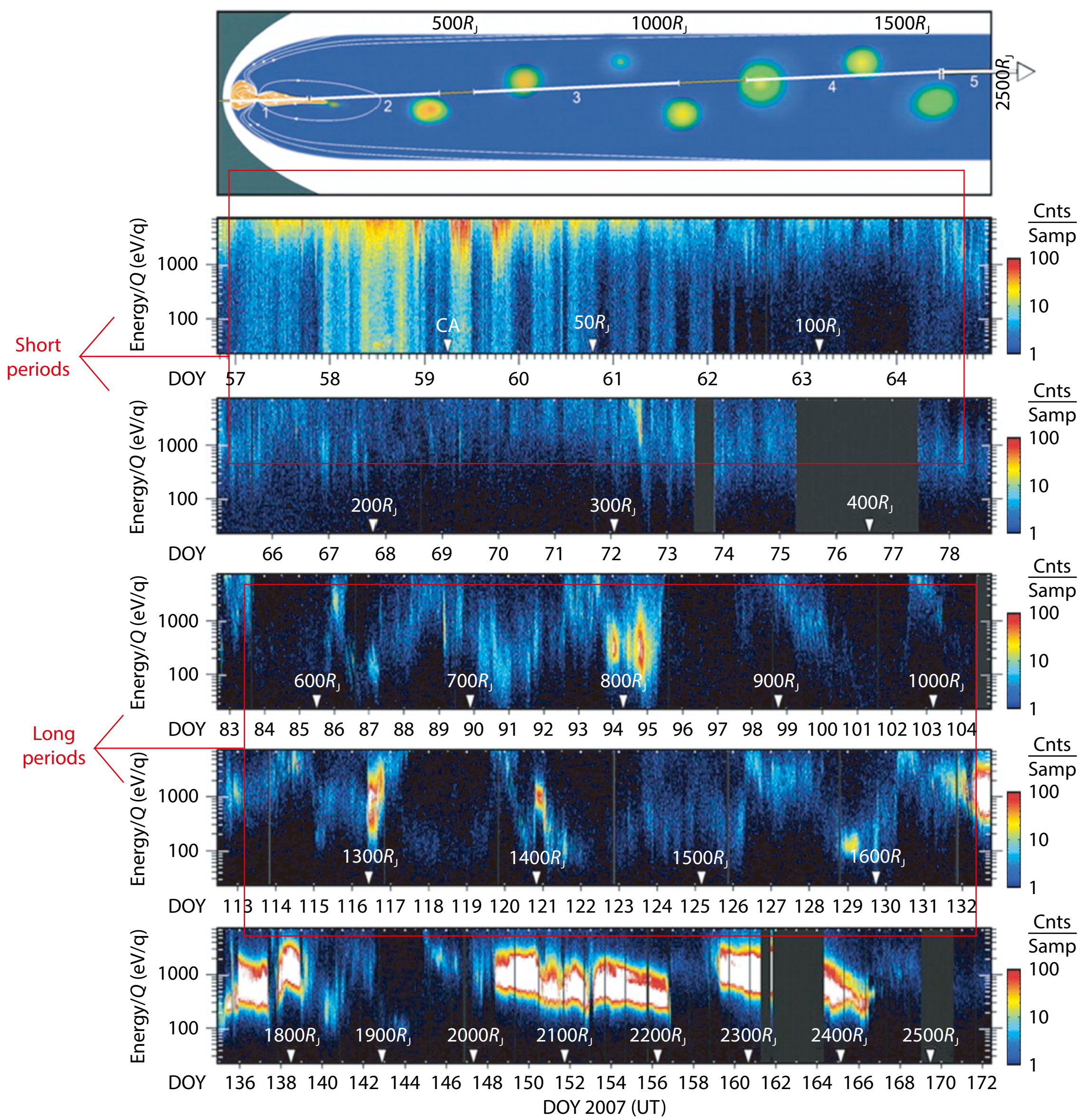

Figure 4. Charged particles observations along Jupiter's distant magnetotail, modified from (McComas et al., 2007).

influence from solar wind can't be excluded. In fact, the magnetic field of Jupiter's distant magnetotail in about 9000 R_J observed by Voyager-2 shows both the influence from solar wind (e.g. 25 days periodicities) and differences from the solar wind in terms of magnetic direction and pressure (Lepping et al., 1983), as shown in Figure 5. These intermittent observations suggest that Jupiter's distant magnetotail is controlled by both solar wind and Jupiter system, indicating the competition between Jupiter system and solar wind, while the specific controlling mechanisms and weights of Jupiter system and solar wind remain unknown, showing the demand for more observation along the distant magnetotail.

Besides, the magnetic field is supposed to evolve with distance along the distant magnetotail as the charged particles frozen with magnetic field were observed to evolve with distance (McComas et al., 2007), as shown in Figure 4. In addition, the magnetic field and charged particles in Jupiter's near magnetotail are thought to be controlled by the Jovian system, and the influence from solar wind is less significant (e.g. Vasyliunas, 1983; Kronberg et al., 2009), which is different from Voyager-2's observation at about 9000 R_J (Lepping et al., 1983) as discussed above, showing the existence of evolution with distance as well. Based on these observations, the magnetic field and charged particles along the distant magnetotail are supposed to evolve together and the controlling factors may change gradually.

3. Testable Predictions

3.1 Multiple Detections of the Magnetic Field Near the Surface of Io Potentially Indicating the Inner Processes of Io

As Galileo had reached 200 km above Io, a nearer detection may be needed to confirm whether Io has a weak intrinsic magnetic field. Besides, as Galileo has flown by different regions around Io providing a global insight into the electromagnetic environment around Io (Jia XZ et al., 2010), new methods should be employed to obtain the information that Galileo hasn't found.

One potential method is investigating the magnetic field around Io systematically to obtain a magnetic field model around Io, analogous to the construction of Jupiter's magnetic field model from Juno observations (Connerney et al., 2022) (shown in Figure 6). If the model can show the magnetic field generated by Io's dynamo, distinguished from Jupiter's magnetic field and Io's induced magnetic field, the existence of Io's intrinsic magnetic field can be confirmed. However, as the space environment around Io is harsh, the spacecraft may be damaged if flying around Io.

Another method is to fly by Io multiple times just like Galileo. In fact, the confirmation of Ganymede's intrinsic magnetic field (Kivelson et al., 1996) and Callisto's induced magnetic field (Khurana et al., 1998) is based on multiple flybys of Galileo. When Galileo flew by the satellite at different times, the background magnetic field is different. When Galileo observed an unchanged dipole moment, the intrinsic magnetic field of Ganymede was discovered (Kivelson et al., 1996), as shown in Figure 7. When Galileo observed a magnetic field changing with background magnetic field, the induced magnetic field of Callisto was confirmed (Khurana et al., 1998), as shown in Figure 8. On the other hand, to obtain the information that Galileo hasn't obtained, the method of flying by should be different. A potential new method is to fly by the same region multiple times in different local times to avoid the spatial variations of the environment around Io and show only the variations with the background

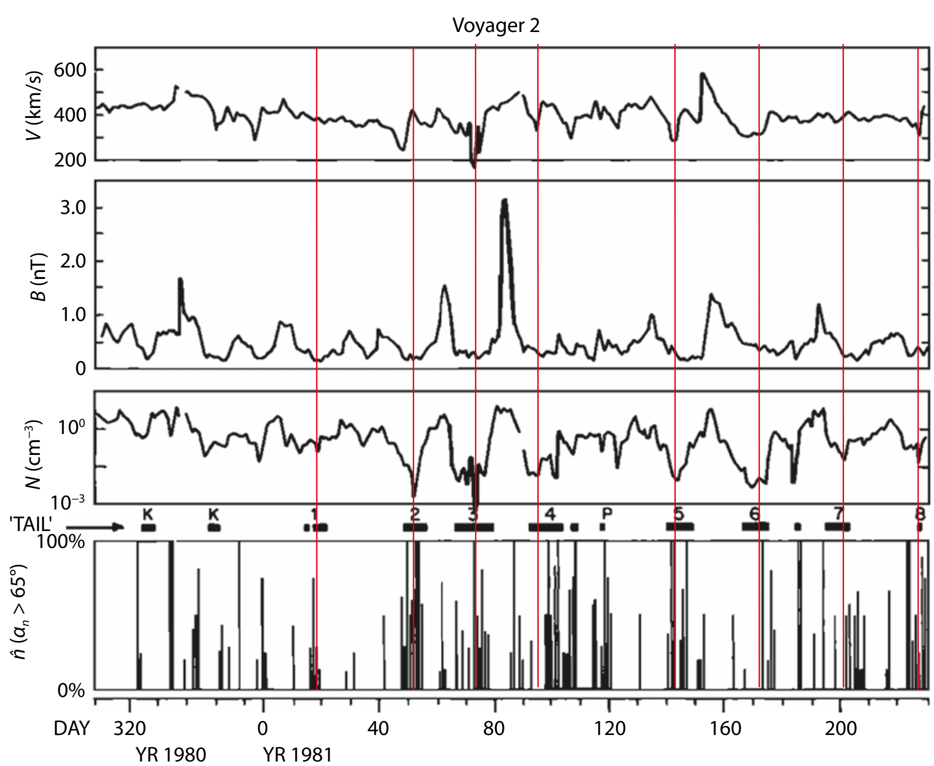

Figure 5. A survey of Voyager 2 data over a 287-day period, modified from (Lepping et al., 1983). α_n is the angle between the Jupiter direction.

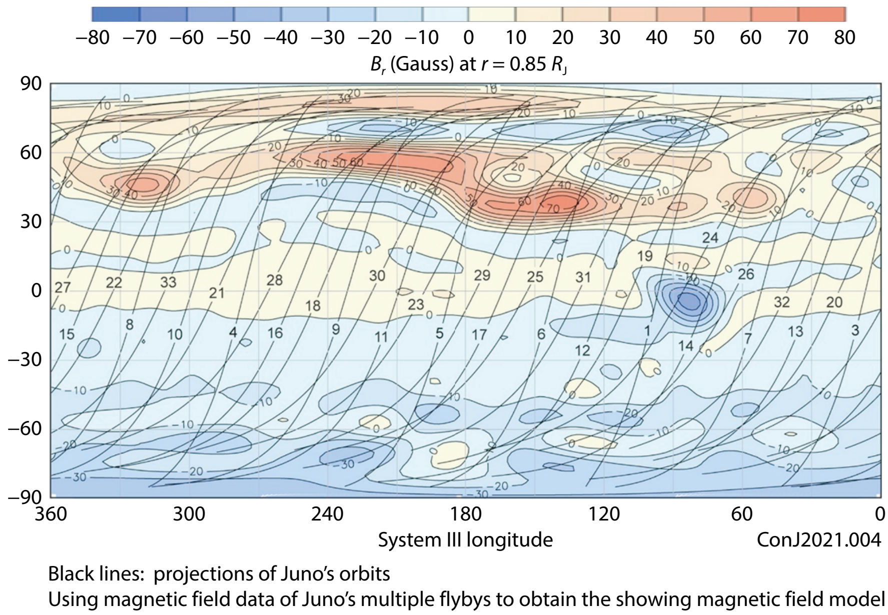

Figure 6. The magnetic field model of Jupiter can be obtained utilizing Juno magnetic field data of multiple orbits, modified from (Connerney et al., 2022).

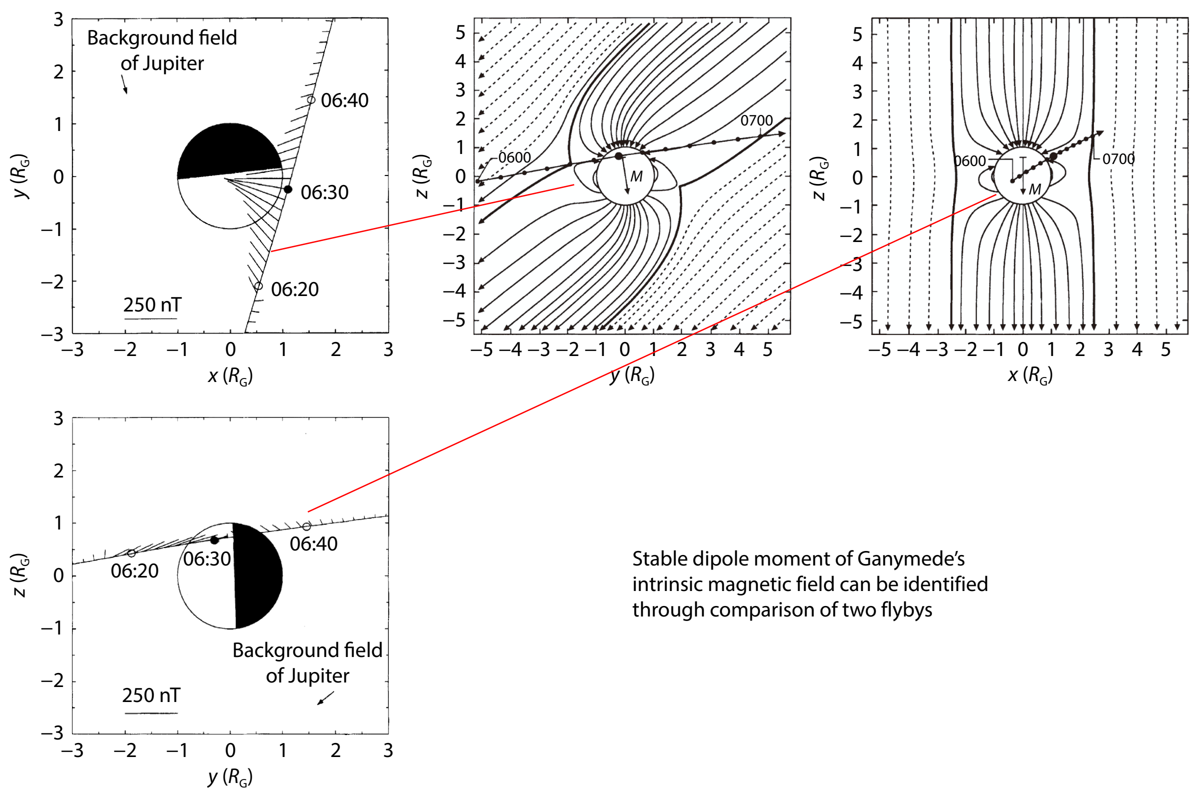

Figure 7. A dipole moment of Ganymede can be identified using magnetic field data of two flybys of Galileo, modified from (Kivelson et al., 1996).

magnetic field. If an unchanged moment can be obtained distinguished from the changing induced magnetic field by the data of different flybys, the intrinsic magnetic field of Io can be identified. In contrast, if only a changing induced magnetic field can be identified, the absence of intrinsic magnetic field may be confirmed.

The magnetic field around Io can be estimate as:

$$\boldsymbol{B} = \boldsymbol{B}_{\mathrm{Io}} + (1 + \eta_{\mathrm{ind}})\,\boldsymbol{B}_0 + \boldsymbol{B}_{\mathrm{ran}} \tag{1}$$

$\boldsymbol{B}_{\mathrm{Io}}$ is the intrinsic magnetic field. $\boldsymbol{B}_0$ is the background magnetic field. η_{ind} is a coefficient that $\eta_{\mathrm{ind}}\boldsymbol{B}_0$ stands for the induced magnetic field. $\boldsymbol{B}_{\mathrm{ran}}$ stands for the noise. If the orbit of each flyby can cover a common region in an Io–Jupiter coordinate but different in the Jupiter's local time, the spatial variation around Io can

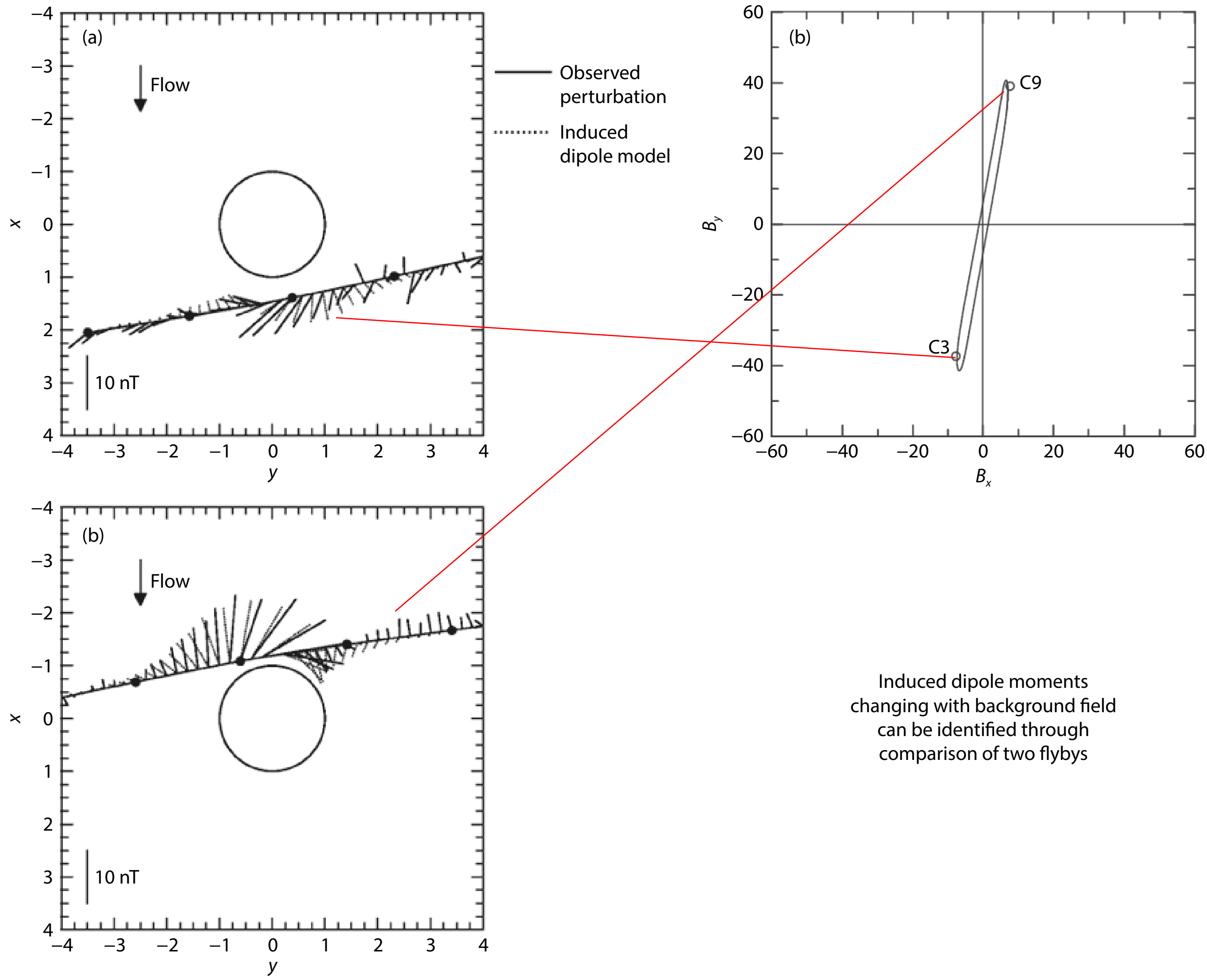

Figure 8. An induced magnetic field of Callisto can be identified using magnetic field data of two flybys of Galileo, modified from (Khurana et al., 1998).

be ignored and the temporal variation can be investigated directly. Each term of Equation (1) may be obtained by fitting the multiple flyby data. If $\boldsymbol{B}_{\mathrm{Io}}$ can be indicated to exist, the intrinsic magnetic field can be indicated to exist. Otherwise, if $\boldsymbol{B}_{\mathrm{Io}}$ can be confirmed to be 0, the absence of an intrinsic magnetic field can be confirmed.

On the other hand, as the space environment around Io is harsh, if wanting to fly by Io in nearer orbits than Galileo, the multi-spacecraft strategy may be considered to make sure at least one spacecraft can survive by flying by Io in high altitude. The spacecraft can carry multiple small probes and throw them multiple times to obtain time-varying data, or carry a battery-powered probe and throw it to fly orbiting Io. However, we should note that the engineering constraints of these methods are uncertain, and the accurate control of each flybys' orbits is also very challenging. Since no prior missions have attempted similar explorations, further professional discussions are needed to clarify relevant engineering constraints. Besides, the detection method presented here is qualitative, and additional detailed simulations are required to confirm its ability to detect a potential weak intrinsic magnetic field and determine its detection accuracy. If the noise is large enough, the presence or absence of a constant $\boldsymbol{B}_{\mathrm{Io}}$ may be hard to be confirmed and only the upper limit can be obtained. Nevertheless, a new detection indicating the temporal variation with nearer orbits is supposed to provide new insights into Io's inner processes and the interactions with the magnetosphere.

3.2 Mass Balance of Neutral and Charged Particles Potentially Indicating the Source of Inner Radiation Belt

The mass balance of particles in the inner radiation belt can be investigated by detecting the motions and distributions of neutral and charged particles. This may help investigate the origin of particles in the inner radiation belt. For example, the sulfur ions have two potential origins, injection of charged particles and ionization of local neutral particles. The motions of sulfur ions can indicate the injection of sulfur ions, the distribution of neutral sulfur particles can indicate the ionization of neutral particles, and the motions of neutral particles can indicate the origin of neutral particles. If the detection can figure out these processes, different potential origins of sulfur ions in the inner radiation belt can be quantitatively analyzed.

Here gives a simple way of estimation:

$$\Delta n_{\mathrm{Si}} = n_{\mathrm{Siin}} + \eta_{\mathrm{i}} \left(n_{\mathrm{Sn}} + n_{\mathrm{Snin}} - n_{\mathrm{Snlo}} \right) - n_{\mathrm{Silo}} \quad (2)$$

Δn_{Si} is the variation of sulfur ion contents. n_{Siin} is the injection of sulfur ions. η_{i} is the ionization rate of neutral sulfur particles. n_{Sn} is neutral sulfur particle contents. n_{Snin} is the injection of neutral sulfur particles. n_{Snlo} is the loss of neutral sulfur particles. n_{Silo} is the loss of sulfur ions. Some terms can be estimated utilizing the data or model of the distribution and motions of charged and neutral particles, like Δn_{Si}, n_{Siin}, n_{Sn} and n_{Snin}. Other terms can be estimated through Equation (2). The origin of the charged and neutral particles in this region can therefore be estimated, which can help understand the source of the inner radiation belt.

3.3 Periodicities Potentially Indicating Controllers of Distant Magnetotail

When comparing the influence on the distant magnetotail from Jupiter system and solar wind, the periodicities can serve as indicators. The most influential periodicity of the Jupiter system is the ~10 hours period, generated by the corotation and flapping of charged particles due to the rotation and magnetic dip of Jupiter. The Sun rotates in a period of about 25 days, which is much longer than Jupiter's 10 hours period. Therefore, the periodicities changing from 10 hours in Jupiter's magnetosphere (e.g. Vasyliunas, 1983) to 25 days in 9000 R_{J} (Lepping et al., 1983) may indicate the controller changing from Jupiter system to solar wind.

The comparison of influence from Jupiter system and solar wind can therefore be estimated as

$$\eta = \frac{p_{10\mathrm{h}}}{p_{25\mathrm{d}}}, \quad (3)$$

$p_{10\mathrm{h}}$ and $p_{25\mathrm{d}}$ are the power spectral density of 10 hours period and 25 days period, respectively. In Jupiter's magnetosphere, the 10 hours period dominates almost all processes while the 25 days period is much less significant. Therefore, in Jupiter's magnetosphere, $p_{10\mathrm{h}}$ is much larger than $p_{25\mathrm{d}}$, and η is much larger than 1. On the contrary, at 9000 R_{J}, the 25 days period is much more significant than 10 hours period. Therefore, at 9000 R_{J}, $p_{10\mathrm{h}}$ is much smaller than $p_{25\mathrm{d}}$, and η is much smaller than 1. From Jupiter's magnetosphere to 9000 R_{J}, the variation of η can indicate the variation of controller. In fact, the particle data has shown this kind of change, as shown in Figure 4, while the specific processes and mechanisms remain unknown. If the magnetic field in the distant magnetotail can be investigated, the electromagnetic processes can be analyzed by combining magnetic field data and particle data. Besides, a new period of 3 h or 6 h has been identified in Jovian system (Gu WD et al., 2023; Schok et al., 2023), which can be a new indicator.

4. Opportunities in Tianwen-4 era

In the coming decades, Tianwen-4 will systematically explore Jovian system, offering unique opportunities to expand our insight about the Jupiter wind. Tianwen-4 may help address the gaps described in section 2 by the methods described in Section 3, as discussed below, which will help establish a cognitive system about the Jupiter wind and further study the concept of planet wind. The potential simultaneous observations of spacecraft and Lenghu planetary telescope can also bring new insights (Deng et al., 2021; Zou et al., 2024).

(1) Whether Io's weak intrinsic magnetic field exists or not is an open question about the inner processes of Io and the source of Jupiter wind. But it is hard to confirm based on the existing observations. If a future mission can fly by Io multiple times, it will have good chances to provide new insights of Io through methods introduced in Section 3.1. If the future mission can take multiple small probes and throw them in every Io flyby, whether Io has an intrinsic dynamo magnetic field or a new upper limit of it may be confirmed utilizing the multiple observations. Besides, the environment around Io can also be further investigated based on the new data in the nearer regions of Io, which can help further understand the evolution of Jupiter wind.

(2) The neutral particles from Io are important components of Jupiter wind and participate in the evolution of Jupiter wind. The detection of neutral particles may shed light on unknown processes like the source of inner radiation belt. However, the detection of neutral particles is lacking, maybe due to the lower priority or technical difficulties. If a future mission can bring in-situ detections of the distributions and motions of neutral and charged particles by carrying neutral and charged particle investigation instruments or telescopes, these data will shed light on the unsolved problems as discussed in Sections 2.2 and 3.2.

(3) The electromagnetic processes along the distant magnetotail may indicate the controlling factors and evolution of Jupiter wind along the distant magnetotail. The charged particles along the distant magnetotail have been detected (McComas et al., 2007), while the magnetic field along the distant magnetotail remains unknown. If a future mission can detect the distant magnetotail at least further than 200 R_{J} carrying magnetic field and particle investigation instruments (further than the orbit of Galileo mission which carried magnetic field and particle investigation instruments), it will offer unique opportunities to further investigate the distant magnetotail. Using the potential data in distant magnetotail from upcoming missions, the controlling factors and evolution of the Jupiter wind along the distant magnetotail can be further studied. Besides, the high-resolution simulations can also shed light on studying distant magnetotail (e.g. Zhang BZ et al., 2019).

5. Conclusions

Jupiter wind represents more than an interesting circulation system within a single planetary magnetosphere. It embodies a new paradigm for understanding how planetary systems operate as integrated circulation networks. By framing the diverse processes of the Jovian system—from Io's interior dynamics and volcanic activity through magnetospheric plasma physics to distant magnetotail evolution—as interconnected stages, we gain new insights into the fundamental physics governing planetary environments. The three critical knowledge gaps identified in this analysis—source electromagnetic control, intermediate neutral particle processing, and distant evolution under competing influences—form a coherent investigative framework that can be systematically addressed.

Addressing these gaps will convert a largely descriptive inventory into a predictive architecture. Discriminant observational signatures—stability or proportional variability of low-degree magnetic moments around Io, spatial–temporal correlations between neutral and charged particles, and radial evolution of periodic power ratios—supply the testable predicates needed to elevate the paradigm. Each signature links a physical process (interior electromagnetic action, neutral–ion conversion efficiency, Jovian vs solar forcing competition) to a measurable metric, enabling falsifiability rather than purely analogical argument.

These gaps relate to the source and evolution of Jupiter wind, yet they remain poorly understood up to now due to the limited observations. The future missions, like Tianwen-4, will have good chances to overcome the challenges in detections and provide new observations to figure out these gaps. With the future data from future Jovian system investigation missions, the understanding of Jupiter wind and planet wind will achieve significant and long-term development.

References

Bagenal, F., and Sullivan, J. D. (1981). Direct plasma measurements in the Io torus and inner magnetosphere of Jupiter. *J. Geophys. Res.: Space Phys.*, *86*(A10), 8447–8466. https://doi.org/10.1029/JA086iA10p08447

Biermann, L. (1951). Kometenschweife und solare Korpuskularstrahlung. *Z. Astrophys.*, *29*, 274–286.

Biermann, L. (1952). Entstehung von Magnetfeldern in bewegten Plasmen. *Ann. Phys.*, *445*(8), 413–417. https://doi.org/10.1002/andp.19524450802

Biermann, L. (1957). Solar corpuscular radiation and the interplanetary gas. *Observatory*, *77*, 109–110. https://doi.org/10.4159/harvard.9780674366688.c28

Bolton, S. J., Lunine, J., Stevenson, D., Connerney, J. E. P., Levin, S., Owen, T. C., Bagenal, F., Gautier, D., Ingersoll, A. P., … Thorpe, R. (2017). The Juno Mission. *Space Sci. Rev.*, *213*(1–4), 5–37. https://doi.org/10.1007/s11214-017-0429-6

Carberry Mogan, S. R., Liuzzo, L., Poppe, A. R., Simon, S., Szalay, J. R., Tucker, O. J., and Johnson, R. E. (2023). Callisto's atmosphere: The oxygen enigma. *J. Geophys. Res.: Planets*, *128*(9), e2023JE007894. https://doi.org/10.1029/2023JE007894

Connerney, J. E. P., Timmins, S., Oliversen, R. J., Espley, J. R., Joergensen, J. L., Kotsiaros, S., Joergensen, P. S., Merayo, J. M. G., Herceg, M., … Levin, S. M. (2022). A new model of Jupiter's magnetic field at the completion of Juno's Prime Mission. *J. Geophys. Res.: Planets*, *127*(2), e2021JE007055. https://doi.org/10.1029/2021JE007055

Deng, L. C., Yang, F., Chen, X. D., He, F., Liu, Q. L., Zhang, B., Zhang, C. G., Wang, K., Liu, N., ... Pan, J. (2021). Lenghu on the Tibetan Plateau as an astronomical observing site. *Nature*, *596*, 353–356. https://doi.org/10.1038/s41586-021-03711-z

Gu, W. D., Yao, Z. H., Pan, D. X., Xu, Y., Zhang, B., Delamere, P. A., Fu, S. Y., Xie, L., Ye, S. Y., … Wei, Y. (2023). Hourly periodic variations of ultralow-frequency (ULF) waves in Jupiter's magnetosheath. *J. Geophys. Res.: Planets*, *128*(2), e2022JE007625. https://doi.org/10.1029/2022JE007625

Gu, W. D., Yao, Z. H., Wei, Y., Qin, T. S., Zhang, B. Z., Xu, Y., Dunn, W. R., Delamere, P. A., and Chen, Y. N. (2024). A survey of magnetic field line curvature in Jovian dawn magnetodisc. *Geophys. Res. Lett.*, *51*(1), e2023GL106971. https://doi.org/10.1029/2023GL106971

Hall, C. F. (1974). Pioneer 10. *Science*, *183*(4122), 301–302. https://doi.org/10.1126/science.183.4122.301

Jia, X. Z., Kivelson, M. G., Khurana, K. K., and Walker, R. J.. (2010). Magnetic fields of the satellites of Jupiter and Saturn. *Space Sci. Rev.*, *152*(1–4), 271–305. https://doi.org/10.1007/s11214-009-9507-8

Khurana, K. K., Kivelson, M. G., Stevenson, D. J., Schubert, G., Russell, C. T., Walker, R. J., and Polanskey, C. (1998). Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto. *Nature*, *395*(6704), 777–780. https://doi.org/10.1038/27394

Khurana, K. K., and Schwarzl, H. K. (2005). Global structure of Jupiter's magnetospheric current sheet. *J. Geophys. Res.: Space Phys.*, *110*(A7), A07227. https://doi.org/10.1029/2004JA010757

Khurana, K. K., Jia, X. Z., Kivelson, M. G., Nimmo, F., Schubert, G., and Russell, C. T. (2011). Evidence of a global magma ocean in Io's interior. *Science*, *332*(6034), 1186–1189. https://doi.org/10.1126/science.1201425

Kim, T. K., Ebert, R. W., Valek, P. W., Allegrini, F., McComas, D. J., Bagenal, F., Connerney, J. E. P., Livadiotis, G., Thomsen, M. F., … Bolton, S. J. (2020). Survey of ion properties in Jupiter's plasma sheet: Juno JADE-I observations. *J. Geophys. Res.: Space Phys.*, *125*(4), e2019JA027696. https://doi.org/10.1029/2019JA027696

Kivelson, M. G., Khurana, K. K., Russell, C. T., Walker, R. J., Warnecke, J., Coroniti, F. V., Polanskey, C., Southwood, D. J., and Schubert, G. (1996). Discovery of Ganymede's magnetic field by the Galileo spacecraft. *Nature*, *384*(6609), 537–541. https://doi.org/10.1038/384537a0

Kollmann, P., Paranicas, C., Clark, G., Mauk, B. H., Haggerty, D. K., Rymer, A. M., Santos-Costa, D., Connerney, J. E. P., Allegrini, F., … Bolton, S. (2017). A heavy ion and proton radiation belt inside of Jupiter's rings. *Geophys. Res. Lett.*, *44*(11), 5259–5268. https://doi.org/10.1002/2017GL073730

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

Kurth, W. S., Sullivan, J. D., Gurnett, D. A., Scarf, F. L., Bridge, H. S., and Sittler, E. C. Jr. (1982). Observations of Jupiter's distant magnetotail and wake. *J. Geophys. Res.: Space Phys.*, *87*(A12), 10373–10383. https://doi.org/10.1029/JA087iA12p10373

Lepping, R. P., Desch, M. D., Klein, L. W., Sittler, E. C. Jr., Sullivan, J. D., Kurth, W. S., and Behannon, K. W. (1983). Structure and other properties of Jupiter's distant magnetotail. *J. Geophys. Res.: Space Phys.*, *88*(A11), 8801–8815. https://doi.org/10.1029/JA088iA11p08801

Mauk, B. H., Clark, G., Gladstone, G. R., Kotsiaros, S., Adriani, A., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., … Rymer, A. M. (2020). Energetic particles and acceleration regions over Jupiter's polar cap and main aurora: A broad overview. *J. Geophys. Res.: Space Phys.*, *125*(3), e2019JA027699. https://doi.org/10.1029/2019JA027699

McComas, D. J., Allegrini, F., Bagenal, F., Crary, F., Ebert, R. W., Elliott, H., Stern, A., and Valek, P. (2007). Diverse plasma populations and structures in Jupiter's magnetotail. *Science*, *318*(5848), 217–220. https://doi.org/10.1126/science.1147393

Parker, E. N. (1958a). Dynamics of the interplanetary gas and magnetic fields. *Astrophys. J.*, *128*, 664. https://doi.org/10.1086/146579

Parker, E. N. (1958b). Dynamical instability in an anisotropic ionized gas of low density. *Phys. Rev.*, *109*(6), 1874–1876. https://doi.org/10.1103/physrev.109.1874

Parker, E. N. (1958c). Cosmic-ray modulation by solar wind. *Phys. Rev.*, *110*(6), 1445–1449. https://doi.org/10.1103/physrev.110.1445

Roth, L., Saur, J., Retherford, K. D., Strobel, D. F., Feldman, P. D., McGrath, M. A., and Nimmo, F. (2014). Transient water vapor at Europa's south pole. *Science*, *343*(6167), 171–174. https://doi.org/10.1126/science.1247051

Roussos, E., Allanson, O., André, N., Bertucci, B., Branduardi-Raymont, G., Clark, G., Dialynas, K., Dandouras, I., Desai, R. T., … Yao, Z. H. (2022). The in-situ exploration of Jupiter's radiation belts. *Exp. Astron.*, *54*(2–3), 745–789. https://doi.org/10.1007/s10686-021-09801-0

Samanta, T., Tian, H., Yurchyshyn, V., Peter, H., Cao, W. D., Sterling, A., Erdélyi, R., Ahn, K., Feng, S., … Chen, Y. J. (2019). Generation of solar spicules and subsequent atmospheric heating. *Science*, *366*(6467), 890–894. https://doi.org/10.1126/science.aaw2796

Saur, J. (2004). Turbulent heating of Jupiter's middle magnetosphere. *Astrophys. J.*, *602*(2), L137–L140. https://doi.org/10.1086/382588

Saur, J., Neubauer, F. M., Connerney, J. E. P., Zarka, P., and Kivelson, M. G. (2004). Plasma interaction of Io with its plasma torus. In F. Bagenal, et al. (Eds.), *Jupiter: The Planet, Satellites and Magnetosphere* (pp. 537–560). Cambridge:

Cambridge University Press.

Schok, A. A., Delamere, P. A., Mino, B., Damiano, P. A., Zhang, B., Sciola, A., Sorathia, K., Wing, S., Johnson, J. R., … Brambles, O. (2023). Periodicities and plasma density structure of Jupiter's dawnside magnetosphere. *J. Geophys. Res.: Planets*, *128*(2), e2022JE007637. https://doi.org/10.1029/2022JE007637

Schubert, G., Anderson, J. D., Spohn, T., and McKinnon, W. B. (2004). Interior composition, structure and dynamics of the Galilean satellites. In F. Bagenal, et al. (Eds.), *Jupiter: The Planet, Satellites and Magnetosphere* (pp. 281–306). Cambridge: Cambridge University Press.

Sittler, E. C. Jr., Lepping, R. P., Mauk, B. H., and Krimigis, S. M. (1987). Detection of a hot plasma component within the core regions of Jupiter's distant magnetotail. *J. Geophys. Res.: Space Phys.*, *92*(A9), 9943–9948. https://doi.org/10.1029/JA092iA09p09943

Southwood, D. J., and Kivelson, M. G. (1982). Charged particle behavior in low-frequency geomagnetic pulsations, 2. Graphical approach. *J. Geophys. Res.: Space Phys.*, *87*(A3), 1707–1710. https://doi.org/10.1029/JA087iA03p01707

Spohn, T. (1997). Tides of io. In H. Wilhelm, et al. (Eds.), *Tidal Phenomena* (pp. 345–377). Berlin, Heidelberg: Springer. https://doi.org/10.1007/BFb0011471

Thomas, N., Bagenal, F., Hill, T. W., and Wilson, J. K. (2004). The Io neutral clouds and plasma torus. In F. Bagenal, et al. (Eds.), *Jupiter: The Planet, Satellites and Magnetosphere* (pp. 561–591). Cambridge: Cambridge University Press.

Vasyliunas, V. M. (1983). Plasma distribution and flow. In: A. J. Dessler (Ed.), *Physics of the Jovian Magnetosphere* (pp. 395–453). New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511564574.013

Wei, Y., Fraenz, M., Dubinin, E., Woch, J., Lühr, H., Wan, W., Zong, Q. G., Zhang, T. L., Pu, Z. Y., … Dandouras, I. (2012). Enhanced atmospheric oxygen outflow on Earth and Mars driven by a corotating interaction region. *J. Geophys. Res.: Space Phys.*, *117*(A3), A03208. https://doi.org/10.1029/2011JA017340

Wei, Y., Pu, Z. Y., Zong, Q. G., Wan, W. X., Ren, Z. P., Fraenz, M., Dubinin, E., Tian, F., Shi, Q. Q., … Hong, M. H. (2014). Oxygen escape from the Earth during geomagnetic reversals: Implications to mass extinction. *Earth Planet. Sci. Lett.*, *394*, 94–98. https://doi.org/10.1016/j.epsl.2014.03.018

Wei, Y. (2024). Planet wind: Planetary evolution dominated by electromagnetic forces. *Sci. China Earth Sci., 67*(10), 3331–3336. https://doi.org/10.1007/s11430-024-1419-y

Xu, Y., Arridge, C. S., Yao, Z. H., Zhang, B., Ray, L. C., Badman, S. V., Dunn, W. R., Ebert, R. W., Chen, J. J., … Wei, Y. (2024). In situ evidence of the magnetospheric cusp of Jupiter from Juno spacecraft measurements. *Nat. Commun.*, *15*(1), 6062. https://doi.org/10.1038/s41467-024-50449-z

Yao, Z. H., Dunn, W. R., Woodfield, E. E., Clark, G., Mauk, B. H., Ebert, R. W., Grodent, D., Bonfond, B., Pan, D. X., … Bolton, S. J. (2021). Revealing the source of Jupiter's x-ray auroral flares. *Sci. Adv.*, *7*(28), eabf0851. https://doi.org/10.1126/sciadv.abf0851

Yao, Z. H., Bonfond, B., Grodent, D., Chané, E., Dunn, W. R., Kurth, W. S., Connerney, J. E. P., Nichols, J. D., Palmaerts, B., … Bolton, S. J. (2022). On the relation between auroral morphologies and compression conditions of Jupiter's magnetopause: Observations from Juno and the Hubble space telescope. *J. Geophys. Res.: Space Phys.*, *127*(10), e2021JA029894. https://doi.org/10.1029/2021ja029894

Yao, Z. H., Guo, R. L., Wei, Y., Bonfond, B., Grodent, D., Zhang, B. Z., Dunn, W. R., and Pu, Z. Y. (2024). Recent advances in the magnetic reconnection, dipolarization, and auroral processes at giant planets from the perspective of comparative planetology. *Earth Planet. Phys.*, *8*(5), 659–672. https://doi.org/10.26464/epp2024017

Zhang, B. Z., Sorathia, K. A., Lyon, J. G., Merkin, V. G., Garretson, J. S., and Wiltberger, M. (2019). GAMERA: A three-dimensional finite-volume MHD solver for non-orthogonal curvilinear geometries. *Astrophys. J. Suppl. Ser.*, *244*(1), 20. https://doi.org/10.3847/1538-4365/ab3a4c

Zhang, B. Z., Delamere, P. A., Yao, Z. H., Bonfond, B., Lin, D., Sorathia, K. A., Brambles, O. J., Lotko, W., Garretson, J. S., … Lyon, J. G. (2021). How Jupiter's unusual magnetospheric topology structures its aurora. *Sci. Adv.*, *7*(15), eabd1204. https://doi.org/10.1126/sciadv.abd1204

Zhang, B. Z., Yao, Z. H., Brambles, O. J., Delamere, P. A., Lotko, W., Grodent, D., Bonfond, B., Chen, J. J., Sorathia, K. A., … Lyon, J. G. (2024). A unified framework for global auroral morphologies of different planets. *Nat. Astron.*, *8*(8), 964–972. https://doi.org/10.1038/s41550-024-02270-3

Zhong, J., Wan, W. X., Wei, Y., Fu, S. Y., Jiao, W. X., Rong, Z. J., Chai, L. H., and Han, X. H. (2014). Increasing exposure of geosynchronous orbit in solar wind due to decay of Earth's dipole field. *J. Geophys. Res.: Space Phys.*, *119*(12), 9816–9822. https://doi.org/10.1002/2014JA020549

Zou, Y. Q., He, F., Zheng, S. S., Yu, L., Yao, Z. H., Rong, Z. J., and Wei, Y. (2024). Prospects for Jovian seismology with the Lenghu planetary telescope. *Earth Planet. Phys.*, *8*(5), 703–710. https://doi.org/10.26464/epp2024043