Postprint of Observational Study of Ion Cyclotron Waves Upstream of the Martian Bow Shock

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Abstract

Ion cyclotron waves are widely observed upstream of the Martian bow shock. In the spacecraft frame, their frequencies are near the local proton cyclotron frequency, propagating quasi-parallel to the background magnetic field direction, and are associated with the solar wind pickup of newborn H^+ ions in the Martian exosphere. This study, based on magnetohydrodynamic theory, performs a case analysis of ion cyclotron waves observed by the MAVEN spacecraft. Through parameter fitting of plasma density perturbations, velocity perturbations, and magnetic field perturbations, we find that this ion cyclotron wave event can be explained by the superposition of an obliquely propagating fast magnetosonic wave and a parallel propagating Alfvén wave. This work contributes to further understanding the physical nature of disturbances related to ion cyclotron waves observed upstream of Mars and provides guidance for re-modeling and numerical simulation of the underlying plasma physical processes.

Full Text

Observations of Ion Cyclotron Waves Upstream of the Martian Bow Shock

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Abstract

Ion cyclotron waves are widely distributed upstream of the Martian bow shock, with frequencies in the spacecraft frame approaching the local proton cyclotron frequency. These waves propagate quasi-parallel to the background magnetic field and are associated with the solar wind picking up newly ionized H^+ ions from the Martian exosphere. Based on magnetohydrodynamic (MHD) theory, this study presents a case analysis of ion cyclotron waves observed by the MAVEN spacecraft. Through parameter fitting of plasma density perturbations, velocity perturbations, and magnetic field perturbations, we find that this ion cyclotron wave event can be explained by the superposition of obliquely propagating fast magnetosonic waves and parallel-propagating Alfvén waves. This work contributes to a deeper understanding of the physical nature of ion cyclotron wave-related disturbances observed upstream of Mars and provides guidance for re-modeling and numerical simulation of the underlying plasma physical processes.

Keywords: ion cyclotron wave; upstream of Mars; magnetohydrodynamics; fast magnetosonic wave; Alfvén wave; slow magnetosonic wave

1. Introduction

Various plasma waves detected upstream of the Martian bow shock provide important clues about physical processes in the near-Mars environment. Unlike Earth and Venus, waves upstream of Mars originate from two distinct sources: particles reflected from the bow shock or leaked through it, and interactions between the solar wind and the exosphere.

Among these, waves with frequencies near the proton cyclotron frequency in the spacecraft frame—commonly termed ion cyclotron waves—have been extensively studied. Escaping neutral particles from planetary atmospheres, particularly H atoms, provide crucial information for understanding atmospheric composition and evolution throughout the solar system lifecycle. For planets like Mars that lack a global intrinsic magnetic field, the neutral exosphere extends into the solar wind plasma, where neutral H is ionized upstream of the bow shock to form pickup ions that play a significant role in atmospheric escape. Ion cyclotron waves are a byproduct of solar wind pickup of these ions and serve as indirect indicators of newborn planetary protons, making their study essential for understanding Martian atmospheric loss.

Ion cyclotron waves near Mars have been observed by numerous spacecraft. Russell et al. first analyzed observations from the Phobos 2 spacecraft, proposing that these waves are associated with newly ionized H atoms picked up by the solar wind from the Martian exosphere. Subsequent studies using data from Mars Global Surveyor (MGS) and Mars Atmosphere and Volatile Evolution (MAVEN) have further characterized upstream ion cyclotron waves, revealing frequencies very close to the local proton cyclotron frequency with amplitudes ranging from 0.1 to 1 nT. Minimum variance analysis shows these waves exhibit left-handed circular polarization in the spacecraft reference frame, propagate quasi-parallel to the interplanetary magnetic field (propagation angle 20°), and approximate plane waves.

The amplitude and occurrence frequency of these ion cyclotron waves decrease with increasing distance from Mars. Researchers attribute wave generation to right-hand resonant interactions with pickup H^+ ions produced by solar wind-exosphere charge exchange. This interpretation is supported by seasonal variations in upstream wave occurrence that correlate with seasonal changes in exospheric neutral H density. Statistical analyses have confirmed enhanced wave occurrence near Martian perihelion and northern winter solstice, a long-term trend related to heliocentric distance variations. This trend may reflect long-term changes in exospheric H density or dust activity affecting lower atmospheric water vapor concentrations, and it is independent of spacecraft spatial coverage or wave selection criteria. Studies also reveal higher occurrence rates at intermediate interplanetary magnetic field cone angles ($20° < \alpha < 45°$), likely resulting from a balance between linear wave growth rates, wave saturation energy, and pickup ion density. Additionally, wave occurrence shows dependence on solar wind density, suggesting that increased charge exchange ionization rates lead to higher newborn proton densities and thus enhanced linear wave growth.

Current observational research on Martian upstream ion cyclotron waves has focused primarily on statistical properties and influencing factors, with event analyses concentrating mainly on magnetic field perturbations. Most studies are statistical in nature, with insufficient investigation of plasma perturbation characteristics and their relationship to magnetic field variations. Moreover, observationally identified "ion cyclotron waves" may not necessarily correspond to the theoretical ion cyclotron wave mode, causing conceptual confusion. This study focuses on the observed characteristics of ion density and velocity perturbations associated with ion cyclotron waves, comparing them with relationships between plasma and magnetic field perturbations predicted by MHD theory for different wave modes to clarify the nature of these plasma disturbances and elucidate the fundamental character of such events.

We first introduce the MAVEN spacecraft and the data used to study upstream ion cyclotron waves. We then employ Fast Fourier Transform and Minimum Variance Analysis (MVA) to analyze the parallel and perpendicular power spectral densities, polarization, and propagation direction of the waves. Finally, based on MHD theory, we derive relationships between plasma perturbations and magnetic field perturbations for different wave modes and compare theoretical predictions with observations.

2. Spacecraft and Data

The MAVEN spacecraft was launched in November 2013, arrived at Mars in September 2014, and completed commissioning to begin its primary one-Earth-year science mission in November 2014. MAVEN’ s magnetic field measurement instrument consists of two independent triaxial fluxgate magnetometers (MAG), each sampling at 32 Hz with 0.25 nT precision. Upstream of the Martian bow shock, ion cyclotron wave frequencies in the spacecraft frame are approximately 0.06 Hz—much lower than the MAG sampling frequency. For this work, we calculate 4 Hz averages from the 32 Hz magnetic field data, as the Nyquist frequency (2 Hz) remains well above the ion cyclotron frequency (~0.06 Hz), satisfying our temporal resolution requirements. MAG field components are expressed in the Mars-centered Solar Orbital (MSO) coordinate system, where the X-axis points from Mars toward the Sun, the Z-axis is perpendicular to Mars’ orbital plane pointing northward, and the Y-axis completes the right-handed system.

The Solar Wind Ion Analyzer (SWIA) onboard MAVEN measures solar wind ions around Mars. SWIA provides 360° × 90° field of view using electrostatic deflection plates in a toroidal energy analyzer, achieving high dynamic range through mechanical attenuators. It delivers high-cadence ion velocity distribution measurements with 14.5% energy resolution, 3.75° × 4.5° angular resolution in the sunward direction (22.5° × 22.5° in other directions), and an energy range of 5-25 keV. In this work, we use SWIA data for solar wind proton velocity and number density in MSO coordinates, sampled at 0.25 Hz.

3. Observations of Upstream Ion Cyclotron Waves at Mars

[Figure 1: see original paper]a and b show MAVEN’ s trajectory, the Martian bow shock, and Mars in the MSO X-Y and X-Z planes during 04:00-06:00 UT on December 24, 2014. The red-brown circle represents Mars, and the light blue curve shows the bow shock model from Vignes et al. The spacecraft moved from the red endpoint to the blue endpoint, with the yellow trace indicating the spatial location of the ion cyclotron wave event during 05:10:23-05:12:31 UT at approximately (2, 0.6, -2)R_M, confirming the event occurred upstream of the bow shock.

[Figure 1: see original paper]c and d present Fourier dynamic spectra of the perpendicular (B) and parallel (B) magnetic field components from MAG data during 04:00-06:00 UT. The black curve indicates the local proton cyclotron frequency for a typical magnetic field of (4.72 ± 0.17) nT. The red box highlights the 05:10:23-05:12:31 UT interval analyzed subsequently. The spectra show that throughout the two-hour interval upstream of Mars, the perpendicular power spectral density P[B] greatly exceeds the parallel power spectral density P[B], with P[B] being 10-100 times larger than P[B] near the local proton cyclotron frequency. Both components peak near the local proton cyclotron frequency, characteristic of typical upstream ion cyclotron wave events.

During 05:10:23-05:12:31 UT on December 24, 2014, MAVEN's MAG and SWIA instruments observed an ion cyclotron wave event upstream of the Martian bow shock ([Figure 2: see original paper]). [Figure 2: see original paper]a shows the magnetic field magnitude (black line) from MAG and solar wind proton density (red line) from SWIA, with an average proton density of $n_0 = 12.60\ \text{cm}^{-3}$ during this interval. Because the density measurement resolution is 0.25 Hz—much lower than the 4 Hz magnetic field sampling—we interpolate the magnetic field magnitude |B| onto the density observation times (using cubic spline interpolation for all interpolations in this work). The resulting correlation coefficient between magnetic field and density perturbations is 0.99, with maximum correlation at zero phase lag, consistent with fast magnetosonic wave characteristics in MHD theory.

[Figure 2: see original paper]b, c, and d display the MSO components of magnetic field (black) and solar wind velocity (red) measured by MAG and SWIA. Over this 128 s interval, all magnetic field components exhibit clear oscillations with amplitudes of ~0.5 nT. Averaging yields a background magnetic field $B_0 =$ [4.46, 0.68, 1.79] nT and average solar wind velocity V_{sw} = [-373.11, 26.47, 1.63] $\text{km} \cdot \text{s}^{-1}$, with an interplanetary magnetic field cone angle $\alpha = 25.15°$. Solar wind velocity perturbations correlate with magnetic field perturbations, with correlation coefficients of -0.99, 0.86, and 0.64 in the x, y, and z directions, respectively, suggesting the presence of Alfvén waves propagating along the background magnetic field (see Section 4 for detailed analysis).

[Figure 3: see original paper]a shows the power spectral density P of perpendicular and parallel magnetic field components relative to B_0 for the event in [Figure 2: see original paper]. The blue curve represents the perpendicular component, black the parallel component. The local proton cyclotron frequency f_c is 0.0740 Hz (orange vertical dashed line), corresponding to a proton cyclotron period of 13.51 s; the 128 s duration spans approximately nine cyclotron periods. The perpendicular component' s P peaks at f_{peak} = 0.0827 Hz (1.117 f_c), slightly above the local proton cyclotron frequency, with a peak value 17.28 times that of the parallel component at this frequency. Accounting for MAG measurement uncertainties, the black bar indicates the frequency range 0.8f_c-1.2f_c. The magnetic field oscillation frequency is very close to the local proton cyclotron frequency, with perturbation power concentrated primarily in the direction perpendicular to B_0.

We apply MVA to investigate the polarization characteristics and propagation direction. Calculating the covariance matrix eigenvalues and eigenvectors for the 128 s interval yields eigenvalues $\lambda_1 = 0.253$, $\lambda_2 = 0.224$, $\lambda_3 = 0.017$ with corresponding eigenvectors e_1 = [-0.25, 0.97, 0.07], e_2 = [-0.16, -0.11, 0.98], e_3 = [0.95, 0.24, 0.18]. The ratio λ_1/λ_2 characterizes circular polarization, while λ_2/λ_3 indicates planarity; for plane waves, λ_2/λ_3 is typically large. When λ_2/λ_3 » 1, the eigenvector e_3 corresponding to the minimum eigenvalue approximates the wave vector k direction.

MVA results are shown in [Figure 3: see original paper]b and c, which display magnetic hodograms in the maximum-intermediate and intermediate-minimum variance planes for 05:10:35-05:11:20 UT. B_1, B_2, B_3 represent magnetic field components along maximum, intermediate, and minimum variance directions. The average magnetic field expressed in eigenvector coordinates is B_0_{MVA} = [-0.34, 0.98, 4.74] nT (marked with ×), lying in the maximum-intermediate (e_1-e_2) plane. Red and black dots indicate start and end points of sub-intervals. [Figure 3: see original paper]b shows left-hand polarization in the spacecraft frame. The event exhibits nearly circular polarization (λ_1/λ_2 = 1.13) and plane wave characteristics (λ_2/λ_3 = 13.16). The wave amplitude δB = 0.486 nT is determined from √(λ_1 - λ_3), and the angle between propagation direction e_3 and B_0 is = 12.37°, indicating quasi-parallel propagation. All observed characteristics match previously reported properties of upstream ion cyclotron waves.

4.1 Relationship Between Plasma and Magnetic Field Perturbations

We select a field-aligned coordinate system with background magnetic field along the z-axis ($B_0 = B_0\hat{z}$) and wave vector k components in the x-z plane (k = k_xẋ + k_zẑ, k_y = 0), with the y-axis completing the right-handed system. Here is the angle between k and B_0. In this coordinate system, MHD wave velocity perturbations (δv_x, δv_y, δv_z) can be expressed as:

$$\begin{vmatrix} \omega^2 - v_A^2 k_z^2 & 0 & 0 \\ 0 & \omega^2 - c_{ms}^2 k^2 & (c_s^2 - v_A^2) k_x k_z \\ 0 & (c_s^2 - v_A^2) k_x k_z & \omega^2 - c_s^2 k_x^2 - v_A^2 k_z^2 \end{vmatrix} = 0,$$

where ω is wave frequency, v_A = B_0/√($_0$ m_i n_0) is the Alfvén speed (n_0 = background ion density, m_i = ion mass, $_0$ = vacuum permeability), c_s = √(γP_0/ $_0$) is sound speed (γ = polytropic index, P_0 = background pressure, $_0$ = background ion density), and c_{ms} = √(c_s^2 + v_A^2) is the magnetosonic speed. Equation (1) has three solutions corresponding to three MHD wave modes: Alfvén waves, fast magnetosonic waves, and slow magnetosonic waves.

The Alfvén wave dispersion relation is:

$$\omega = \pm k_z v_A,$$

where ± indicates k_z parallel/antiparallel to B_0. From equations (1) and (2), Alfvén wave velocity perturbations are in the y-direction with:

$$\delta v_y / v_A = \mp \delta B_y / B_0,$$

and no magnetic field perturbations or density perturbations along the background field direction.

The magnetosonic wave dispersion relation is:

$$\omega^2 = \frac{1}{2} k^2 (c_s^2 + v_A^2) \left[1 \pm \sqrt{1 - \frac{4 c_s^2 v_A^2 \cos^2\theta}{(c_s^2 + v_A^2)^2}} \right],$$

where + represents fast magnetosonic waves and - represents slow magnetosonic waves. Combining MHD continuity and momentum equations with equation (1) yields relationships between velocity and magnetic field perturbations:

$$\delta v_x = -\frac{v_{ph} \cos\theta}{B_0} \frac{\omega^2 - v_A^2 k_z^2}{\omega^2 - c_s^2 k_x^2 - v_A^2 k_z^2} \delta B_x,$$

$$\delta v_z = \frac{v_{ph} \cos\theta}{B_0} \frac{(c_s^2 - v_A^2) k_x k_z}{\omega^2 - c_s^2 k_x^2 - v_A^2 k_z^2} \delta B_x,$$

and density perturbations:

$$\delta n = n_0 \frac{k_x}{\omega} \delta v_x.$$

Equations (3), (5), and (6) show that for these three MHD wave modes, velocity perturbation magnitudes are proportional to corresponding magnetic field perturbations with different proportionality coefficients and either positive or negative correlations. These relationships allow calculation of theoretical velocity and density perturbations from observed magnetic field perturbations for direct comparison with observations to identify Alfvén and fast/slow magnetosonic waves.

4.2 Comparison Between MHD Theory and Observations

To compare theoretical density and velocity perturbations with observations, we first transform MAG and SWIA measurements from MSO coordinates to the field-aligned coordinate system. Since SWIA' s measurement resolution differs from MAG' s, we interpolate magnetic field components onto plasma measurement times. Background plasma parameters used in theoretical calculations are listed in , derived from averaging MAVEN observations during 05:10:23-05:12:31 UT on December 24, 2014. For Alfvén waves, stronger background magnetic fields and lower background proton densities yield larger phase speeds, while velocity perturbations increase with decreasing proton density but are independent of background magnetic field. For magnetosonic waves, the relationships become more complex, with velocity and density perturbations depending on background magnetic field, density, and temperature.

Table 1. Background Plasma Physical Parameters

Parameter	Value
Background proton number density	$(12.60 \pm 0.40)\ \mathrm{cm}^{-3}$
Background proton temperature	$(1.38 \pm 0.07) \times 10^{5}\ \mathrm{K}$
Thermal to magnetic pressure ratio	2.56 ± 0.03
Background pressure	$(2.41 \pm 0.20) \times 10^{-11}\ \mathrm{Pa}$
Alfvén speed	$(29.86 \pm 0.57)\ \mathrm{km \cdot s^{-1}}$
Sound speed	$(33.79 \pm 0.86)\ \mathrm{km \cdot s^{-1}}$

Using fast magnetosonic wave theory, we substitute background plasma parameters and interpolated MAG magnetic field data into equations (5)-(7) to obtain theoretical density and velocity perturbations. [Figure 4: see original paper] compares these with SWIA observations for a fast magnetosonic wave phase speed v_{ph} = 35.59 $\mathrm{km \cdot s^{-1}}$. Black lines represent theoretical values (superscript t), red lines observations (superscript o). [Figure 4: see original paper]a compares density perturbations; [Figure 4: see original paper]b-d compare x, y, and z velocity perturbation components. Density and z-velocity perturbation theoretical values match observed trends but differ significantly in magnitude: observed density perturbations are within \$±1*cm*^{-3}\$ versus theoretical \$±6*cm*^{-3}\$; observed z-velocity perturbations are within \$±2*km*·*s*^{-1}\$ versus theoretical \$±20*km*·
s{-1}.*Whilephaseagreementisexcellent, amplitudediscrepanciesarelarge.Forx − velocityperturbations, aphaseshiftexistsbetweenthe*
1}\$). However, y-velocity perturbations observed at \$±7*km* · *s*^{-1}\$ are theoretically zero for pure fast magnetosonic waves.

Under the pure fast magnetosonic wave model, significant discrepancies exist between theoretical and observed density and z-velocity perturbations. This may arise from the k-direction influence and the high correlation between velocity and magnetic field perturbations, suggesting contamination by Alfvén waves propagating along the background magnetic field. The observed y-velocity perturbations likely result from such Alfvén waves.

Burlaga noted discrepancies between discontinuity normals estimated from Explorer 33 and 35 data and those from MVA. In solar wind rotational discontinuity studies, angles between MVA-determined normals and those from other methods range from 0.8° to 51.9°, indicating substantial uncertainty in MVA wave vector k estimation. To find an improved wave vector direction, we rotate the field-aligned coordinate system in the plane perpendicular to B_0 (the z-axis) by angle while varying the angle between B_0 and k. We also consider mixing of Alfvén waves with different amplitude proportions in the x and y directions of the field-aligned coordinate system. Through parameter searching using equations (2)-(6), we compare theoretical and observed perturbations to find optimal parameters: $= 63° \pm 1°$, $= 95° \pm 1°$, with fast magnetosonic wave amplitudes comprising 45% in the x-direction and 1% in the y-direction, while Alfvén waves comprise 55% in x and 99% in y. The fitted results are shown in [Figure 5: see original paper].

[Figure 5: see original paper] compares SWIA density and velocity perturbations with theoretical values from the superposition of fast magnetosonic and Alfvén waves for $= 63°$, $= 95°$ (v_{ph} = 48.87 km • s^{-1}). Density and z-velocity perturbations show excellent agreement in both magnitude and phase. The x-velocity perturbation represents a superposition of both wave modes; shifting theoretical values right by 4 s yields good agreement. The angle between the k vector from MVA and the optimal fast magnetosonic wave vector k'is 64.73°. The y-velocity perturbation is dominated by Alfvén waves, with similar waveforms and a phase shift resolved by shifting theoretical values left by 4 s, showing better amplitude agreement than [Figure 4: see original paper].

Table 2 lists perturbations and relative perturbations for the studied event (derived from standard deviations), showing that density, magnetic field, and velocity perturbations are small relative to background values ($ $9.83%), satisfying MHD linear approximation requirements.

5. Summary and Discussion

MAVEN observations upstream of the Martian bow shock show that the perpendicular magnetic field perturbation power spectrum greatly exceeds the parallel component, with spectral peaks near the proton cyclotron frequency. The event exhibits left-hand polarization and near-plane wave characteristics, representing a typical ion cyclotron wave event. Plasma number density correlates positively with magnetic field strength (correlation coefficient 0.99), while solar wind velocity perturbations correlate with magnetic field perturbations in x, y, and z directions (coefficients -0.99, 0.86, and 0.64) with phase differences.

According to fast magnetosonic wave theory, density and velocity perturbations can be calculated from observed magnetic field perturbations using equations (5)-(7). MVA yields a wave propagation direction quasi-parallel to the background field ($= 12.37°$). However, in this field-aligned coordinate system, pure fast magnetosonic wave theoretical values differ significantly from observations, likely due to uncertainties in the k-direction determined by MVA, which can deviate by 0.8°-51.9° from other methods.

To reduce discrepancies between theoretical and observed velocity perturbations, we assume perturbations perpendicular to B_0 result from superposition of fast magnetosonic and Alfvén waves. By varying and coordinate rotation angle through parameter searching, we obtain optimal parameters (= 63°, = 95°) that yield much better agreement between theory and observations. This suggests the observed ion cyclotron wave event can be explained by superposition of parallel-propagating Alfvén waves and oblique fast magnetosonic waves (= 63°). The Alfvén wave component likely originates from Alfvén waves in the solar wind.

Future work should pursue two directions: (1) Statistical studies of such events across different regions of Mars space, as our detailed analysis of a single event may have limited generality. Comprehensive analysis of more events is needed to determine whether these properties are universal or location-specific in the bow shock downstream, induced magnetosphere, and magnetosheath. (2) Theoretical interpretation of wave modes and perturbation characteristics in these different Martian space environments based on statistical studies, which will improve understanding of wave properties and deepen our comprehension of solar wind-Mars interactions from a wave perspective.

References

[1] Wei H Y, Russell C T, Zhang T L, et al. P&SS, 2011, 59: 1039
[2] Wei H Y, Cowee M M, Russell C T, et al. JGRA, 2014, 119: 5244
[3] Acuña M H, Connerney J E P, Wasilewski P, et al. JGR, 2001, 106: 403
[4] Anderson D E, Hord C W. JGR, 1971, 76: 6666
[5] Chaufray J Y, Bertaux J L, Leblanc F, et al. Icar, 2008, 195: 598
[6] Yun X, Fu S, Ni B, et al., ApJ, 2022, 929: 105
[7] Russell C T, Luhmann J G, Schwingenschuh K, et al. GRL, 1990, 897: 900
[8] Brain D A, Bagenal F, Acuña M H, et al. JGRA, 2002, 107: 1076
[9] Liu D, Yao Z, Wei Y, et al. E&PP, 2020, 4: 51
[10] Mazelle C, Winterhalter D, Sauer K, et al. SSRv, 2004, 111: 115
[11] Romanelli N, Bertucci C, Gómez D, et al. P&SS, 2013, 76: 1
[12] Romanelli N, Mazelle C, Chaufray J Y, et al. JGRA, 2016, 121: 11
[13] Wei H Y, Russell C T, GeoRL, 2006, 33: 23103
[14] Bertucci C, Romanelli N, Chaufray J Y, et al. GeoRL, 2013, 40: 3809
[15] Romeo O M, Romanelli N, Espley J R, et al. JGRA, 2021, 126: 28616
[16] Bhattacharyya D, Clarke J T, Bertaux J L, et al. GeoRL, 2015, 42: 8678
[17] Chaffin M S, Chaufray J Y, Stewart I, et al. GeoRL, 2014, 41: 314
[18] Halekas J S. JGRE, 2017, 122: 901
[19] Rahmati A, Larson D E, Cravens T E, et al. JGRE, 2018, 123: 1192
[20] Yamauchi M, Hara T, Lundin R, Dubinin E, et al. P&SS, 2015, 119: 54
[21] Bhattacharyya D, Clarke J T, Chaufray J Y, et al. JGRA, 2017, 122: 11
[22] Chaffin M S, Deighan J, Schneider N M, et al. NatGe, 2017, 10: 174
[23] Clarke J T, Bertaux J L, Chaufray J Y, et al. GeoRL, 2014, 41: 8013

[24] Clarke J T, Mayyasi M, Bhattacharyya D, et al. JGRA, 2017, 122: 2336
[25] Fedorova A, Bertaux J L, Betsis D, et al. Icar, 2018, 300: 440
[26] Fedorova A A, Montmessin F, Korablev O, et al. Sci, 2020, 367: 297
[27] Heavens N G, Kleinböhl A, Chaffin M S, et al. NatAs, 2018, 2: 126
[28] Jakosky B M, Lin R P, Grebowsky J M, et al. SSRv, 2015, 195: 3
[29] Connerney J E P, Espley J, Lawton P, et al. SSRv, 2015, 195: 257
[30] Halekas J S, Taylor E R, Dalton G, et al, SSRv, 2015, 195: 125
[31] Vignes D, Mazelle C, Rème H, et al. GeoRL, 2000, 27: 49
[32] Halekas J S, Ruhunusiri S, Vaisberg O L, et al. JGRA, 2020, 125: 28221
[33] Belcher J W, Davis L. JGR, 1971, 76: 3534
[34] Alfvén H. Natur, 1942, 150: 405
[35] Sonnerup B U Ö, Scheible M. ISSIR, 1998, 1: 185
[36] Song P, Russell C T. SSRv, 1999, 87: 387
[37] Wolfgang B, Rudolf A T. Basic Space Plasma Physics, London: Imperial College Press, 1997: 220
[38] Denskat K U, Burlaga L F, JGR, 1977, 82: 2693
[39] Yang Y H, Chao J K, Yang L, et al. JGRA, 2019, 124: 7744
[40] Bruno R, Carbone V. LRSP, 2013, 10: 2

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