

Spatial distribution of Martian upstream-generated magnetosonic waves observed by Tianwen-1 and their possible wave–particle interactions based on a case study

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Key Points:

- Tianwen-1 observations extend the spatial survey of Martian magnetosonic waves to higher-altitude and more tailward regions.
- Magnetosonic waves are observed predominantly near the Martian bow shock, where the occurrence rate exceeds 50%.
- The wave dispersion and ion resonant energy ranges are strongly controlled by the background magnetic field strength and plasma density.

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Abstract: Using magnetic field and ion measurements from Tianwen-1 acquired between November 2021 and August 2024, we investigate the spatial distribution of Martian magnetosonic (MS) waves and their possible wave–particle interactions. MS wave events are identified using criteria based on frequency range, propagation angle, polarization, compressional power ratio, and event duration. The statistical results show that these waves occur predominantly near the Martian bow shock, where the occurrence rate exceeds 50%. Owing to the high-apogee orbit of Tianwen-1, the present survey also extends its observational coverage to higher-altitude and more tailward regions than previous studies. To further examine the physical properties of these waves, we analyze a representative MS wave event and evaluate its dispersion relation under different background plasma conditions. The results indicate that the wave dispersion is strongly affected by the background magnetic field strength and plasma density, whereas the influence of propagation angle is comparatively weaker within the quasi-perpendicular range. We also estimate the resonant energy ranges for H^+ , O^+ , and O_2^+ ions. The results show clear species-dependent differences, with larger variations for O^+ and O_2^+ than for H^+ under the selected wave and plasma parameters. These findings provide new observational constraints on the role of MS waves in the solar wind interaction with Mars and their potential contribution to ion energization in the Martian plasma environment.

Keywords: Mars; magnetosonic waves; bow shock; Tianwen-1; wave–particle interaction

1. Introduction

Unlike Earth, Mars does not possess a global intrinsic magnetic field. Instead, its plasma environment is controlled by an induced magnetosphere, together with strong localized crustal magnetic fields, mainly in the southern hemisphere. In the absence of a global magnetic shield, the solar wind can directly interact with the Martian upper atmosphere and induced magnetosphere, thereby enhancing energy transfer to planetary ions and facilitating atmospheric escape. Among the various energization processes operating in collisionless plasma, wave–particle interactions are believed to play an important role. Through Landau and

cyclotron resonances, plasma waves can transfer energy and momentum to charged particles, leading to particle heating, acceleration, and escape. Such processes are therefore relevant not only to plasma dynamics in the near-Mars environment, but also to the long-term evolution of the Martian atmosphere and climate (Ergun et al., 2006; Summers et al., 2007a, 2007b; Fowler et al., 2018; Su ZP et al., 2020).

A variety of plasma waves have been observed in the Martian plasma environment, including whistler waves, proton cyclotron waves, and magnetosonic (MS) waves (Russell et al., 1990; Brain et al., 2002; Espley et al., 2005; Romanelli et al., 2013; Wei HY et al., 2014; Ruhunusiri et al., 2015, 2018; Harada et al., 2016, 2019; Halekas et al., 2020; Teng SC et al., 2024). These wave modes are generally associated with different plasma instabilities and exhibit distinct frequency ranges, polarization properties, and propagation characteristics. MS waves are ultra-low-frequency compressional waves supported by magnetic pressure and ion thermal pressure.

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They are typically linearly polarized and propagate at large angles relative to the background magnetic field (Bertucci et al., 2003; Halekas et al., 2011; Collinson et al., 2018). Similar waves have been reported not only around Mars, but also in the plasma environments of Earth, Venus, Mercury, and comets (Russell et al., 1970; Mazelle et al., 1991; Glassmeier et al., 1993; Bertucci et al., 2004; Espley et al., 2004; Boardsen et al., 2009, 2015; Halekas et al., 2011; Ruhunusiri et al., 2015; Fränz et al., 2017; Collinson et al., 2018; Fowler et al., 2018, 2021; Harada et al., 2019; Su ZP et al., 2020; de Souza Franco et al., 2023).

For Mars, MS waves can be broadly divided into two categories according to their frequency and source region. The first category consists of low-frequency waves with frequencies much lower than the local proton cyclotron frequency (e.g., Fowler et al., 2017, 2018; Collinson et al., 2018; de Souza Franco et al., 2023). These waves are generally thought to originate in the upstream solar wind, cross the bow shock, and propagate into downstream regions such as the magnetosheath, magnetic pileup region, and magnetotail. In the following, we refer to these as upstream-generated MS waves. The second category has frequencies close to the local proton cyclotron frequency, and is believed to be generated locally within the Martian plasma environment by unstable ring-beam proton distributions (Harada et al., 2019; Wang J et al., 2023). These waves are referred to as locally generated MS waves. The distinct frequency ranges of two categories suggest different generation mechanisms and physical roles (Wang J et al., 2023).

Previous studies have shown that MS waves can play an important role in the heating and energization of Martian plasma. Fowler et al. (2018) reported large-amplitude MS waves propagating from the magnetosheath into the dayside ionosphere near the subsolar region, where they may contribute to plasma heating. Collinson et al. (2018) suggested that compressional ultra-low-frequency waves driven by the solar wind can excite linearly polarized MS waves in the ionosphere and produce local electromagnetic ringing near the proton cyclotron frequency. These wave processes can in turn energize ionospheric plasma and potentially contribute to atmospheric escape. In addition, MS waves may also create favorable conditions for the generation of whistler-mode waves through temperature anisotropy, thereby affecting the ionospheric electron density and plasma state (Fowler et al., 2018, 2020, 2021; Su ZP et al., 2020). Using Mars Express observations, de Souza Franco et al. (2023) found that MS wave penetration into the ionosphere occurs more frequently during the declining or maximum phases of the solar cycle, on the dayside, during northern autumn equinox, and under moderate solar wind dynamic pressure.

More recently, Pang SY et al. (2024) used MAVEN observations from October 2014 to May 2023 to investigate upstream-generated MS waves and map their spatial distribution around Mars. They found that such waves occur frequently near the bow shock, in the dayside magnetic pileup region, and in the magnetotail, with larger amplitudes and enhanced peak power spectral density in the dayside magnetosheath and pileup region. However, because of the MAVEN orbital configuration, statistical studies have mainly

been limited to distances of within about 3 Martian radii (R_M). As a result, the spatial distribution of MS waves at larger radial distances, especially in the nightside shock flank and distant magnetotail, remains insufficiently constrained.

Tianwen-1 provides an important opportunity to address this limitation. Owing to its large elliptical polar orbit, the spacecraft can reach altitudes of approximately 2.8–4.3 R_M (Li CL et al., 2021; Zou ZX et al., 2023), extending the observational coverage into the middle and distant magnetotail. This broader coverage makes Tianwen-1 particularly suitable for investigating the large-scale spatial distribution of upstream-generated MS waves. Because the Martian magnetotail is one of the major channels for planetary ion escape, understanding the occurrence and properties of MS waves in these regions is important for evaluating their possible role in ion energization and escape.

In this study, we use Tianwen-1 observations from November 2021 to August 2024 to statistically investigate the spatial distribution and occurrence characteristics of Martian upstream-generated MS waves. We further analyze a representative event to examine its wave properties, dispersion relation, and possible wave–particle interaction characteristics. The remainder of this paper is organized as follows: Section 2 describes the data sets, coordinate transformation, and wave identification procedure; Section 3 presents a representative MS wave event and statistical results; whereas Section 4 summarizes the main conclusions.

2. Data and Methods

The data used in this study were obtained from the Tianwen-1 Mars mission operated by the China National Space Administration (CNSA). As China's first Mars exploration mission, Tianwen-1 successfully entered Martian orbit on 10 February 2021 after a series of interplanetary cruise and braking maneuvers, and has continued orbital operations since then. In this work, we use vector magnetic field measurements from the Mars Orbiter Magnetometer (MOMAG) with a sampling rate of 32 Hz, together with ion measurements from the Mars Ion and Neutral Particle Analyzer (MINPA). The full analyzed interval spans from November 2021 to August 2024.

Before performing the spectral analysis, the magnetic field data were transformed from the Mars-centered Solar Orbital (MSO) coordinate system into the magnetic-field-aligned (MFA) coordinate system in order to better characterize the wave properties (Pang SY et al., 2024, 2026; Jin TF et al., 2024). In the MSO system, the x-axis points from Mars toward the Sun, the z-axis is normal to the Martian orbital plane and points northward, and the y-axis completes the right-handed coordinate system. In the MFA system, the $\mathbf{e}_{||}$ direction is defined to be parallel to the background magnetic field, the $\mathbf{e}_{\perp 1}$ direction is perpendicular to the plane formed by the background magnetic field and the spacecraft position vector, and the $\mathbf{e}_{\perp 2}$ direction completes the right-handed orthogonal basis.

The background magnetic field was obtained by applying a 90-s running average to the original magnetic field data (e.g., Su ZP et al., 2020; Wang J et al., 2023). The unit vector along the background

magnetic field is defined as

$$\hat{\mathbf{e}}_{\parallel} = \frac{\mathbf{B}_0}{|\mathbf{B}_0|},$$

where $\mathbf{B}_0$ is the background magnetic field. The other two orthogonal unit vectors are given by

$$\hat{\mathbf{e}}_{\perp 1} = \frac{\hat{\mathbf{e}}_{\parallel} \times \hat{\mathbf{r}}}{|\hat{\mathbf{e}}_{\parallel} \times \hat{\mathbf{r}}|},$$

$$\hat{\mathbf{e}}_{\perp 2} = \hat{\mathbf{e}}_{\perp 1} \times \hat{\mathbf{e}}_{\parallel},$$

where $\hat{\mathbf{r}}$ is the unit position vector of the spacecraft. Using these basis vectors, the magnetic field can be decomposed into the three MFA components: $B_{\parallel}$, $B_{\perp 1}$, and $B_{\perp 2}$.

We then applied a wavelet transform to the three magnetic field components to obtain their time-frequency power spectra. In addition, the singular value decomposition (SVD) method (Santolík et al., 2003) was used to analyze the wavelet coefficient matrix and estimate the propagation angle and polarization properties of the waves at each frequency. This procedure allows us to determine whether a given wave interval exhibits the quasi-perpendicular propagation, weak ellipticity, and compressional character expected for MS waves.

To identify MS waves, we adopted the selection criteria used by Pang SY et al. (2024). Specifically, candidate events were required to satisfy the following conditions:

- (1) the wave frequency f lies between 0.018 and 0.1275 Hz;
- (2) the wave propagation angle is greater than 50° ;
- (3) the polarization rate is between -0.5 and 0.5 ;
- (4) the power spectral density of the compressional component ($P_{\parallel}$) is more than 3 times that of the transverse components ($P_{\perp 1} + P_{\perp 2}$);
- (5) the event duration is longer than 1.4 min.

For all wave intervals identified using the above criteria, we calculated their occurrence rate as a function of spacecraft location. For the current statistical analysis, only magnetic field intervals with continuous durations longer than 30 min were used in order to reduce the influence of data gaps and interpolation on the spectral analysis. As a result, the occurrence-rate survey shown in Section 3.2 is based on data from 16 November 2021 to 30 August 2024, which is a fraction of the full observation interval. To further investigate the physical implications of the observed waves, we selected a representative event and analyzed its dispersion relation for cold plasma wave assumption (Stix, 1992; Swanson, 2003). We can obtain the wave number k and the wave dispersion function by using Stix parameters and Maxwell equations. Then, we further investigate the possible wave-particle interactions. For the general resonance condition, $\omega - k_{\parallel}v_{\parallel} = N\Omega_c$, ω is the wave frequency, $k_{\parallel}$ and $v_{\parallel}$ are the wave number and the particle velocity parallel to magnetic field B , respectively; N is the resonance order, $N = 0$ corresponds to the Landau resonance, and the other N values correspond to cyclotron resonances; Ω_c is the geofrequency of the Martian ions. In summary, we perform the dispersion relation and resonance-energy calculations by using the observed wave frequency together with background plasma parameters repre-

sentative of the event interval. We estimated the resonant energy ranges for different ion species under the selected background conditions in order to provide a preliminary assessment of the possible energy exchange process associated with the wave event.

3. Results

3.1 Tianwen-1 Observations

Figure 1 shows the plasma environment observed by Tianwen-1 between 12:30 and 13:30 UT on 6 October 2023, during a representative MS wave event. Figures 1a–1c present the spacecraft trajectory in the MSO coordinate system, with the direction of motion indicated from blue to red. Figure 1d shows the spacecraft altitude, which decreased from approximately 10,000 km to 8000 km during this interval. According to the orbit location relative to the nominal plasma boundaries, Tianwen-1 was moving within the Martian magnetosheath. Figures 1e and 1f display the magnetic field components in the MSO and MFA coordinate systems, respectively. The background magnetic field strength during this interval was approximately 10 nT. Figures 1g–1i show the ion energy spectrograms of H^+ , O^+ , and O_2^+ , respectively. The proton flux is much stronger than those of O^+ , and O_2^+ , and is mainly concentrated in the energy range from about 500 to 5000 eV.

Figure 2 presents the MS wave interval selected using the criteria described in Section 2. The wave event occurred from 12:53 UT to 13:11 UT and lasted for about 18 min. Figure 2a shows the total magnetic field power spectral density obtained from the wavelet analysis, and Figure 2b gives the ratio of the compressional power to the transverse power. At the selected MS wave frequencies, the compressional component is clearly dominant, with the power ratio exceeding 3, indicating the compressional nature of the wave. Figures 2c–2e show the power spectral density, polarization parameter, and propagation angle of the identified MS wave, respectively. The polarization parameter remains within ± 0.5 , whereas the propagation angle is generally larger than 80° , indicating that the wave is quasi-linearly polarized and propagates nearly perpendicular to the background magnetic field. Figure 2f shows the wave amplitude derived by integrating the selected wave power spectral density. The maximum wave amplitude reaches 1.27 nT, corresponding to approximately 12.7% of the background magnetic field strength.

3.2 Spatial Distribution

To investigate the spatial distribution of Martian MS waves, we applied the identification procedure described above to magnetic field intervals with continuous durations longer than 30 min—that is, intervals without data gaps within each continuous half-hour segment. For the current statistical survey, the analyzed data set covers the period from 16 November 2021 to 30 August 2024.

Figure 3a shows the spatial distribution of identified MS wave samples; Figure 3b shows the spatial distribution of all valid samples during the same interval; and Figure 3c gives the corresponding occurrence rate. The distributions are displayed in the

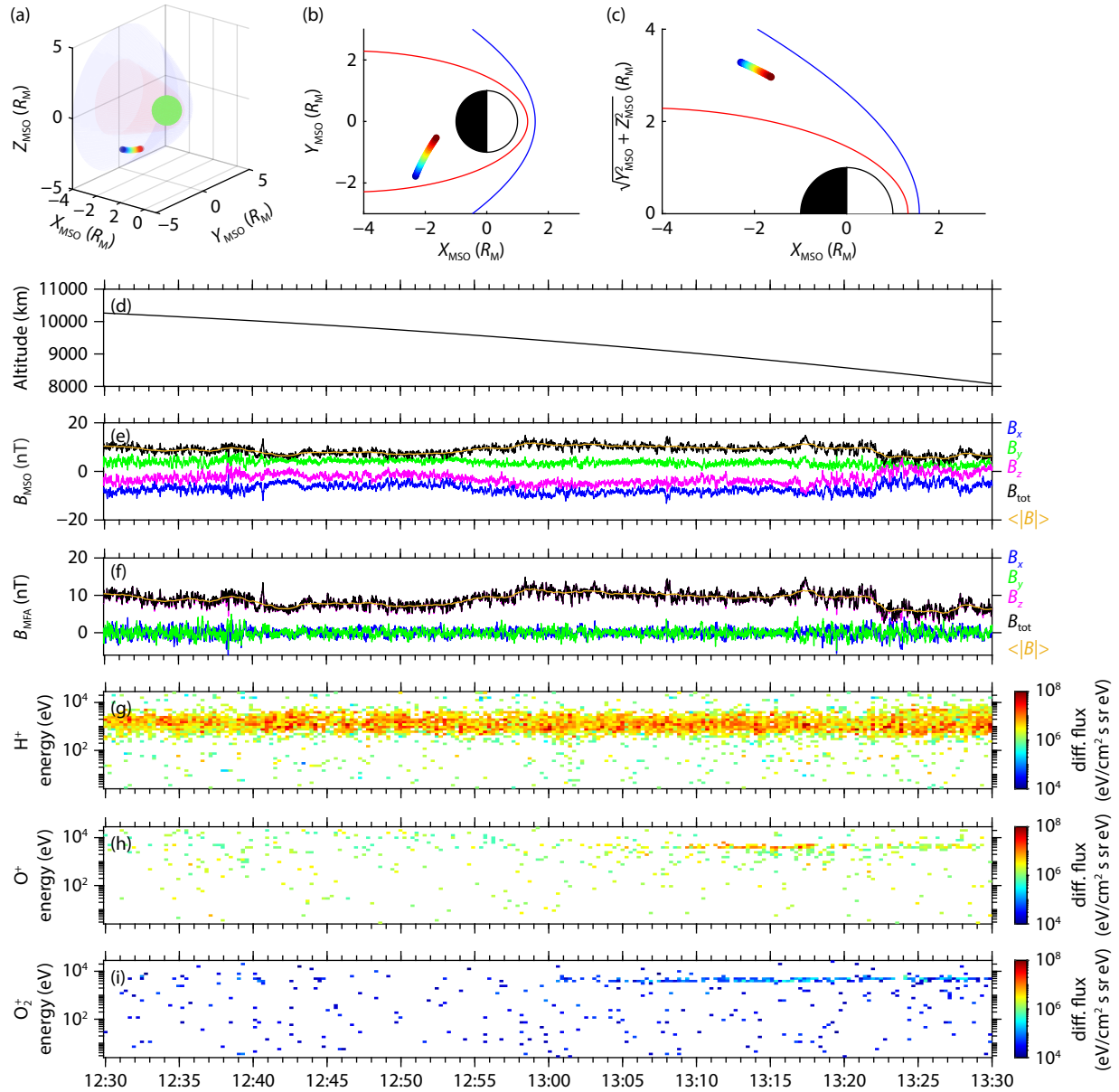


Figure 1. Plasma environment observed by Tianwen-1 between 12:30 and 13:30 UT on 6 October 2023. (a) Three-dimensional spacecraft trajectory in the Mars-centered Solar Orbital (MSO) coordinate system. The green sphere represents Mars. The nominal magnetic pileup boundary and bow shock are shown for reference. (b–c) Projections of the trajectory onto the X – Y and X – ρ planes in the MSO frame, where $\rho = \sqrt{Y_{\text{MSO}}^2 + Z_{\text{MSO}}^2}$. White and black indicate the dayside and nightside of Mars, respectively. The spacecraft moves from the blue segment toward the red segment. (d) Spacecraft altitude. (e) Magnetic field components B_x , B_y , B_z , and total field B_{tot} in the MSO frame, together with the 90-s running average of B_{tot} . (f) Magnetic field components and total field in the MFA frame, together with the 90-s running average of B_{tot} . (g–i) Energy spectrograms of H^+ , O^+ , and O_2^+ , respectively.

X – ρ plane of the MSO coordinate system, where

$$\rho = \sqrt{Y_{\text{MSO}}^2 + Z_{\text{MSO}}^2}.$$

The domain was divided into bins of $0.1 \times 0.1 R_M$, where $R_M = 3395$ km. The occurrence rate in each bin was calculated as the ratio of the number of identified MS wave samples to the total number of valid samples.

As shown in Figure 3, the MS waves observed by Tianwen-1 occur predominantly near the Martian bow shock, where the occurrence

rate exceeds 50% in some regions. This result is consistent with the interpretation that these waves are closely associated with the upstream solar wind and bow shock interaction. At the same time, the Tianwen-1 orbit extends the observational coverage to larger radial distances, providing additional constraints on the occurrence of MS waves in more distant flank and tailward regions. As shown in Figure 3c, the probability of magnetosonic waves occurring in the distant nightside magnetotail remains above approximately 20%. Despite the limited number of extended data points resulting from our strict 30-minute continuous data criterion, this quantita-

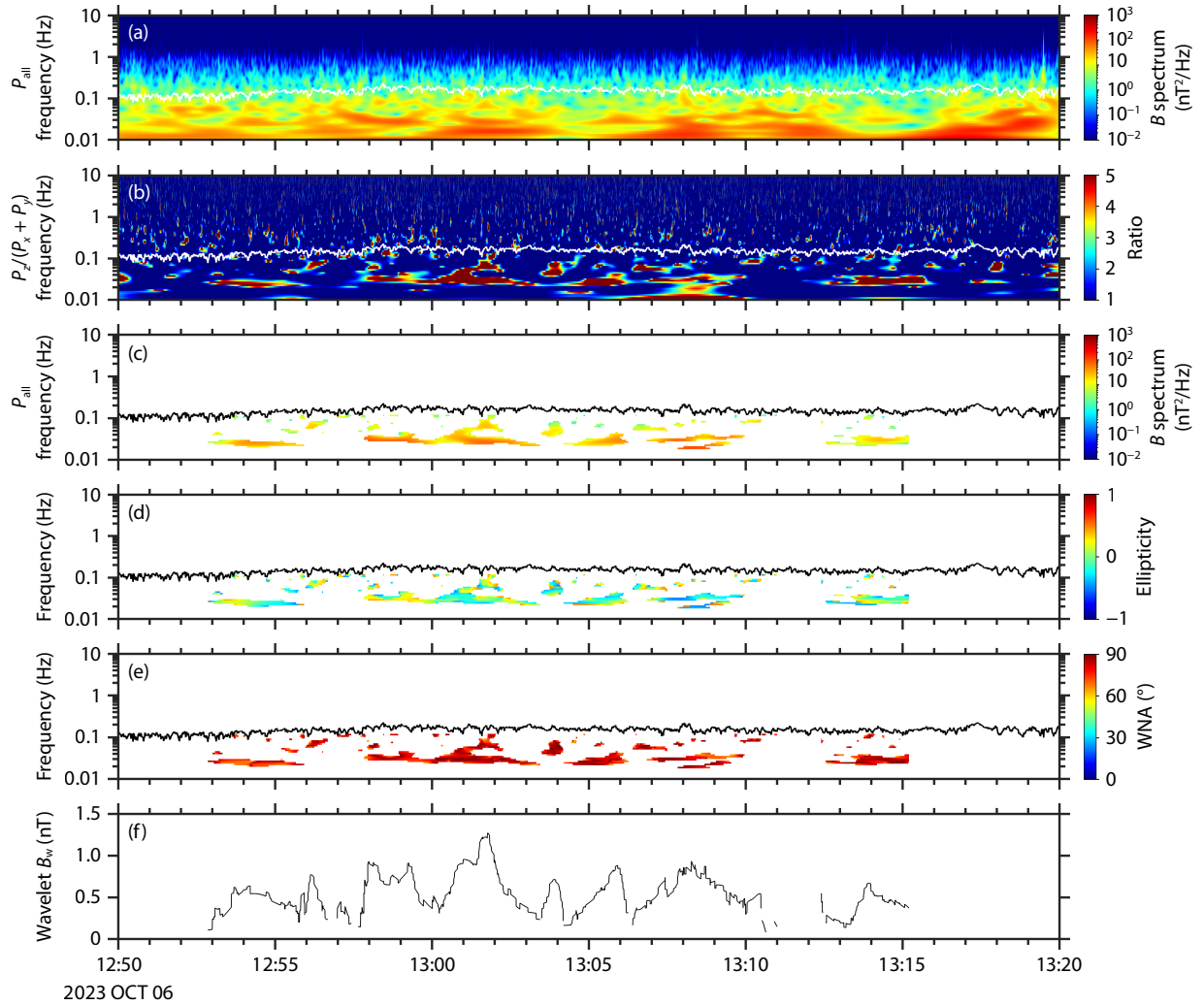


Figure 2. Upstream-generated MS wave event observed by Tianwen-1 between 12:50 and 13:20 UT on 6 October 2023. (a) Magnetic field power spectrum (P_{all}) from the wavelet transform. (b) Ratio of the compressional (P_z) to transverse ($P_x + P_y$) magnetic power spectral density, the suffix x, y and z referring to components in MFA frame. The lower four panels show the parameters of the identified MS wave interval: (c) magnetic field power spectrum; (d) frequency–time spectrogram of polarization parameter; (e) frequency–time spectrogram of wave normal angle (WNA); and (f) wave amplitude (B_w). The white (black) solid line marks the local proton gyrofrequency.

tive finding indicates a persistently high likelihood of MS wave generation or propagation into this newly mapped tailward region, contrasting with the dayside-dominant distribution previously observed at lower altitudes.

3.3 Wave–Particle Interactions

We further examined the possible interaction between the identified MS wave and charged particles during the event shown in Figure 2. Figures 4a–4c show the total magnetic field strength, the wave propagation angle, and the wave spectrum during the event interval, respectively. The average magnetic field strength is about 10 nT. Figure 4b shows the wave propagation angle corresponding to the spectral peak at each time, and the values are mainly distributed between 60° and 90°, with an average of about 80°. This confirms that the wave propagates in a quasi-perpendicular direction relative to the background magnetic field.

Figure 4c presents the distribution of the power spectral density

within the associated frequency range. A clear spectral peak appears at approximately 2.5–4.5 Ω_{O^+} , corresponding to a frequency of about 0.0302 Hz, or roughly 3.2 f_{co} , where f_{co} is the O^+ cyclotron frequency ($f_{co} = 0.0095$ Hz).

According to the spectral characteristics of this event, we evaluated the wave dispersion relation and examined its dependence on several background parameters. During the calculation, based on the density distribution of each ion in Martian space mentioned by Fan K (2020), the ion density ratio of H^+ , O^+ and O_2^+ in the study area is estimated to be about 10:0.03:0.1. Figure 5a presents the dispersion relation calculated for different magnetic field strengths ($B = 5, 10, 15, 20$, and 25 nT), assuming an electron density of $N_e = 10 \text{ cm}^{-3}$ and a propagation angle of $\psi = 80^\circ$ (Fu S et al., 2019; Su ZP et al., 2020; Zhou RX et al., 2020, 2022; Yang JT et al., 2026). The results show that the background magnetic field strength has a strong influence on the dispersion relation. Figure 5b shows the dispersion relation for different electron densities

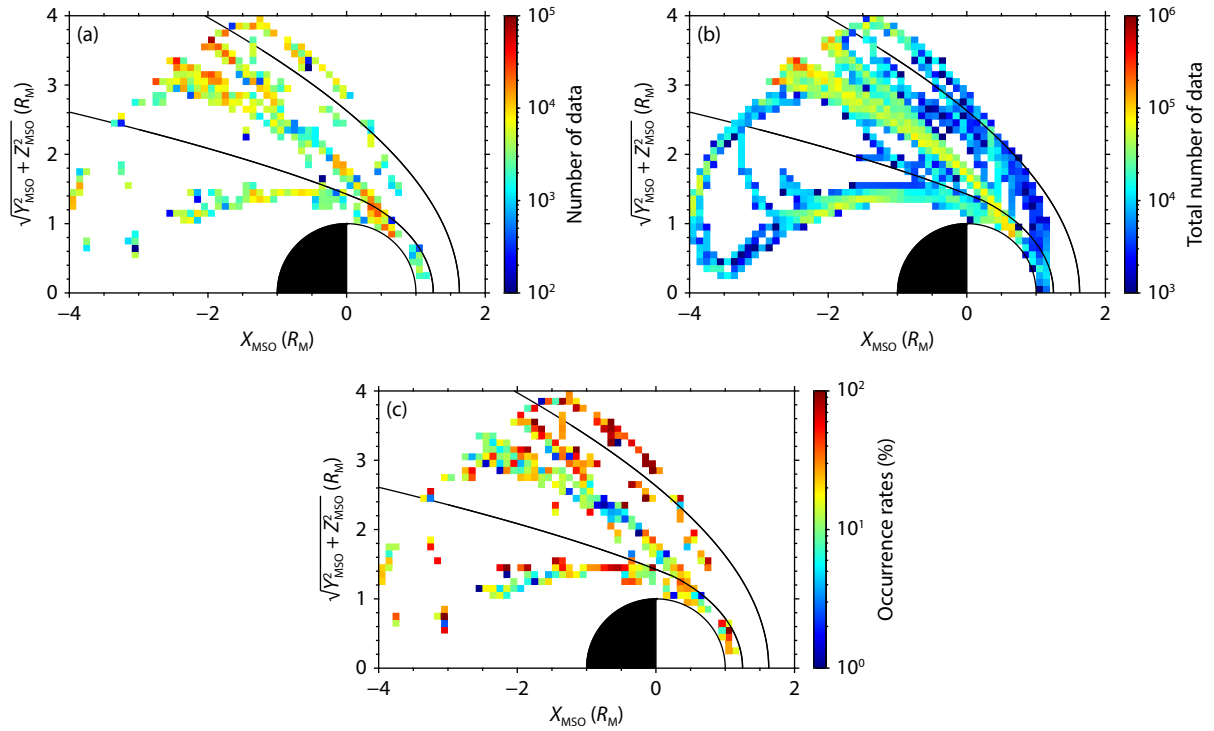


Figure 3. Spatial distribution of Martian MS waves identified in Tianwen-1 observations. (a) Number of identified MS wave samples. (b) Total number of valid samples. (c) Occurrence rate of MS waves. The black curves indicate the nominal bow shock and magnetic pileup boundary proposed by Trotignon et al. (2006).

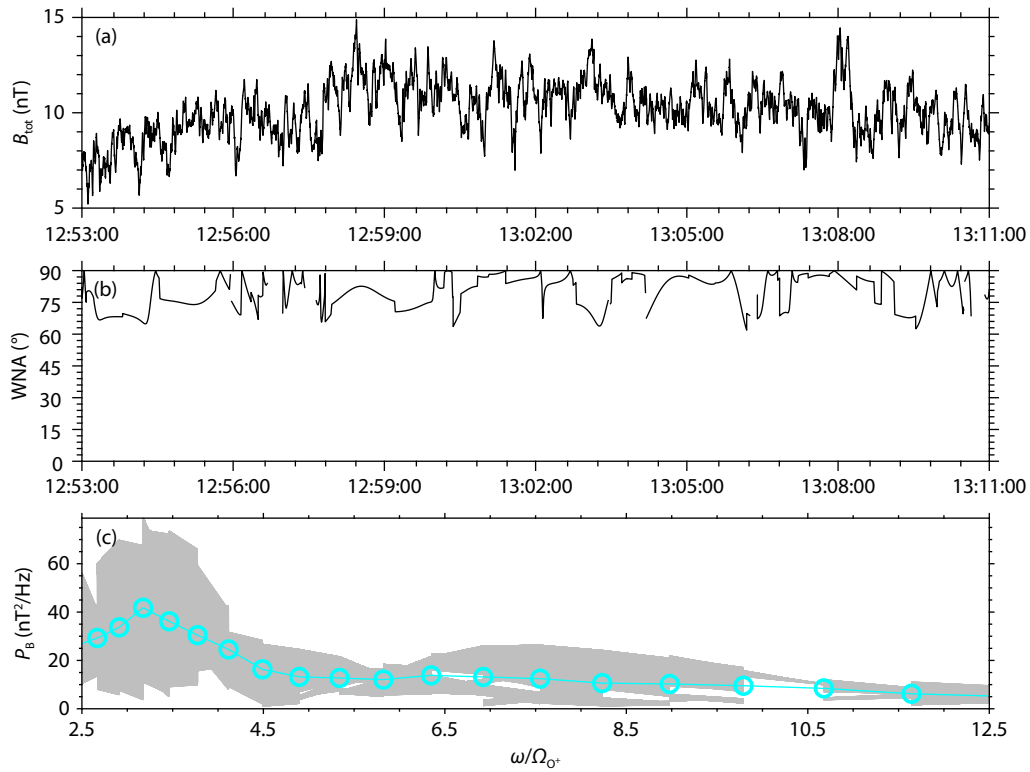


Figure 4. Frequency-domain analysis of the representative magnetosonic wave event. (a) Total magnetic field strength in the MSO frame. (b) Wave propagation angle as a function of time. (c) Power spectral density as a function of frequency between 12:58 and 13:07 UT. The gray shaded region shows the distribution of power spectrum (P_B) curves at different times, and the blue symbols indicate the average power spectrum. Ω_{O^+} denotes the gyrofrequency of O^+ ions.

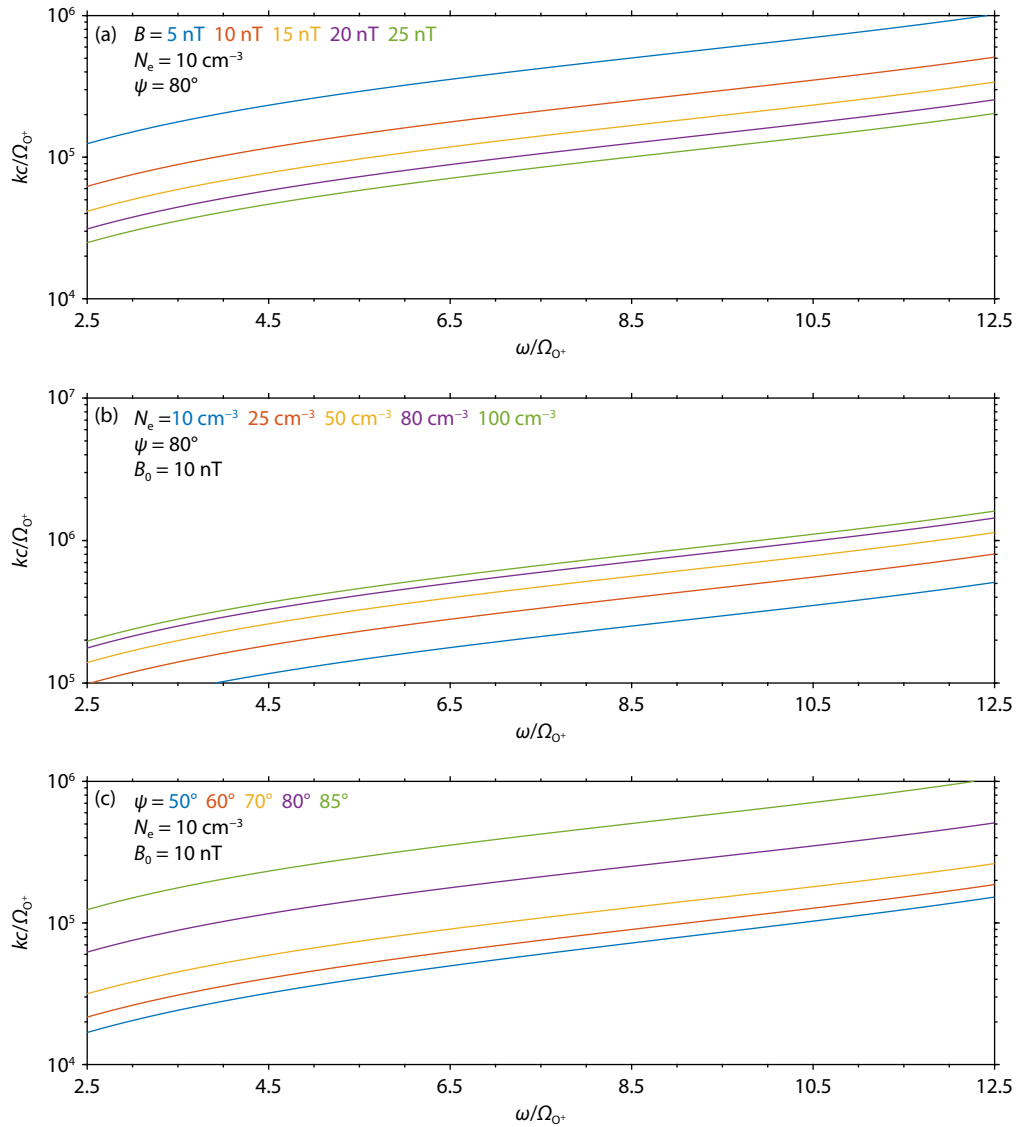


Figure 5. Dispersion relation analysis under different background conditions. (a) Dependence of normalized wave number kc/Ω_{O^+} on normalized angular frequency ω/Ω_{O^+} for different background magnetic field strengths; (b) same as (a), but for different electron densities; (c) same as (a), but for different wave propagation angles. k and c refer to the wave number and velocity of light in the vacuum, respectively.

($N_e = 10, 25, 50, 80$, and 100 cm^{-3}) with the magnetic field fixed at $B_0 = 10 \text{ nT}$ and the propagation angle fixed at $\psi = 80^\circ$. In contrast, the electron density has a significant effect on the dispersion relation. Figure 5c shows that the dependence on propagation angle is comparatively stronger when the magnetic field strength and density are fixed at $B_0 = 10 \text{ nT}$ and $N_e = 10 \text{ cm}^{-3}$, respectively, and the angle is varied within the quasi-perpendicular range ($\psi = 50^\circ, 60^\circ, 70^\circ, 80^\circ$, and 85°).

Figure 6 shows the resonant energy ranges for H^+ , O^+ , and O_2^+ ions at different pitch angles and resonance orders. The colored regions indicate the parameter ranges in which resonance can occur, allowing rapid exchange of energy and momentum between the wave and particles. The results show clear ion-species-dependent differences in the resonance patterns. The estimated resonance energy ranges exhibit a clear dependence on the ion species. All three ions show significant variations across

different resonance orders. The resonance energy range for H^+ gradually increases from 10^{-10^3} eV to 10^{-10^5} eV . For O^+ , the resonance energy range progressively shifts from 10^2 – 10^4 eV ($N = 0$), to 1 – 10^2 eV ($N = 1$), and further broadens to 10^{-1} – 10^3 eV ($N = 2$). Similarly, the resonance energy range for O_2^+ shows substantial differences, shifting from 10^2 – 10^4 eV ($N = 0$) to 1 – 500 eV ($N = 2$). These pronounced species- and order-dependent differences suggest that, under Martian plasma conditions, MS waves interact with different heavy ions through highly selective energy pathways. This suggests that, under the plasma conditions of this event, the possible wave–particle interaction pathways differ significantly among ion species. For H^+ , the MINPA measurements in Figure 1g show energy concentrations primarily between 10^2 and 10^4 eV . This observed population effectively overlaps with the theoretically calculated resonant energy ranges shown in the first row of Figure 6, suggesting active wave–particle resonance. Similarly, the energy ranges of the resonance regions for O^+ and O_2^+

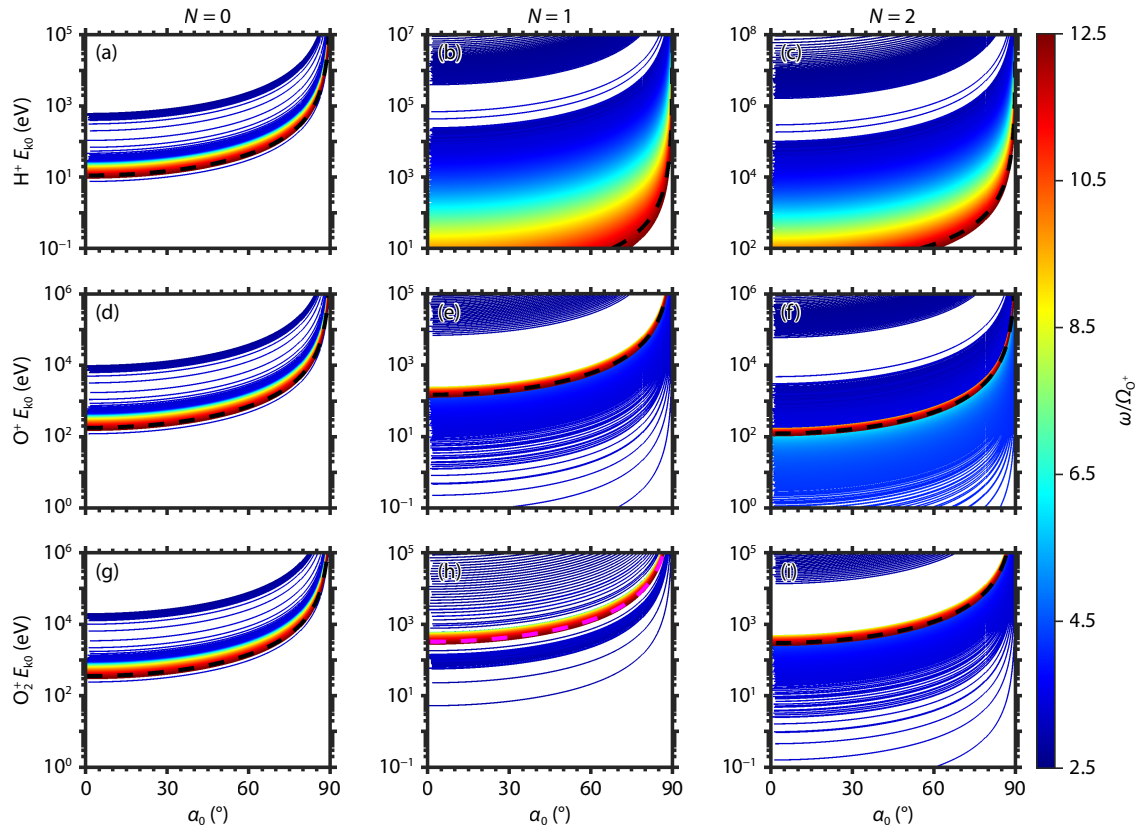


Figure 6. Resonant energy (E_{k0}) ranges of different ion species at various pitch angles. Rows correspond to H^+ , O^+ , and O_2^+ , and columns correspond to resonance orders $N = 0, 1$, and 2 . The colored regions indicate the resonance ranges, and the dashed line marks the cyclotron resonance condition.

overlap with their respective observed ion distributions in Figure 1. Notably, for O^+ , a visible flux enhancement at approximately 10^4 eV is observed between 13:10 and 13:20 UT, which may be an observational signature of energy exchange with the MS fluctuations. However, due to the resolution limitations of MINPA, more detailed particle measurements are required in future studies to definitively quantify the direction and efficiency of this energy transfer.

4. Conclusions

In this study, we used Tianwen-1 magnetic field observations, together with ion measurements for a representative event, to investigate the spatial distribution and possible wave–particle interactions of Martian magnetosonic waves. The main conclusions are summarized as follows:

- (1) Based on the event selection criteria adopted in this study, MS waves observed by Tianwen-1 are found predominantly near the Martian bow shock, where the occurrence rate exceeds 50% in some regions. Owing to the high-apogee orbit of Tianwen-1, the present analysis also extends the observational coverage to more distant flank and tailward regions.
- (2) For the representative event analyzed here, the wave dispersion relation is strongly influenced by the background magnetic field strength and propagation angle plasma density, whereas the effect of plasma density is comparatively weaker within the quasi-

perpendicular range considered in this study.

- (3) The estimated resonant energy ranges show clear ion- and species-dependence. All three ions show significant differences across different resonance orders. This suggests that MS waves may interact with different ion species in distinct ways under Martian plasma conditions.

This study is subject to several limitations. To reduce the potential influence of data interpolation on the spectral analysis, we only used continuous magnetic field intervals longer than 30 min, which restricted the amount of data available for the statistical survey. In future work, a quantitative evaluation of the effects of different interpolation schemes may allow a broader data set to be included and improve the statistical robustness of the results. In addition, coordinated observations from Tianwen-1 and MAVEN could provide a valuable opportunity to further examine the role of MS waves in ion energization by comparing wave and particle measurements obtained under similar plasma conditions.

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Data Availability Statement

The Tianwen-1 magnetic field and particle data used in this study were provided by the corresponding mission and instrument teams. Information on data access and availability should be updated here according to the applicable data policy of the Tianwen-1 mission before submission.

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