Observational Study of Upstream Ion Cyclotron Waves at Mars (Postprint)

Authors: Li Jiawei, Yang Lei, Wu Dejin

Date: 2023-07-14T00:00:00+00:00

Abstract

Ion Cyclotron Wave (ICW) refers to a plasma wave with frequencies near the ion cyclotron frequency. It is widely observed in the Martian upstream region, with satellite measurements showing frequencies predominantly near the proton cyclotron frequency. ICW is a byproduct of ion pickup processes and serves as an indirect indicator of newborn planetary protons. Since its first report in 1990, ICW in the Martian upstream region has garnered widespread attention. This study summarizes the research progress on Martian upstream ICW, encompassing observations of ICW events, generation mechanisms, statistical properties, and future research trends.

Full Text

Observations of Ion Cyclotron Waves in the Upstream of Mars

LI Jia-wei[1;2;3], **YANG Lei**[1;2;3], **WU De-jin**[1;2]
(1 Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023)
(2 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026)
(3 State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190)

Abstract

Ion cyclotron waves (ICWs) are plasma waves with frequencies near the ion cyclotron frequency that exist widely in the Martian upstream region, where satellite observations typically detect frequencies close to the proton cyclotron frequency. ICWs are byproducts of ion pickup processes and serve as indirect signatures of newborn planetary protons. Since their first report in 1990, ICWs upstream of Mars have attracted widespread attention. This review summarizes research progress on Martian upstream ICWs, including observational events, generation mechanisms, statistical properties, and future research trends.

Key words: waves, plasmas, solar wind, planets and satellites: atmospheres, planets and satellites: magnetic fields

1. Introduction

The solar corona, the Sun' s outer atmosphere, expands continuously outward to form a radial plasma flow known as the "solar wind." After propagating several solar radii, the solar wind becomes supersonic and encounters three types of celestial bodies during its journey: (1) bodies that interact directly with the solar wind at their surfaces (such as unmagnetized asteroids or the Moon); (2) bodies with intrinsic magnetic fields (such as Earth and Jupiter); and (3) bodies without intrinsic magnetic fields whose atmospheres interact directly with the solar wind. Mars belongs to the third category.

Mars lacks an intrinsic magnetic field, and its atmosphere interacts directly with the solar wind. Through energy and momentum exchange, the solar wind interacts with the Martian ionosphere to form an induced magnetosphere. Using data from Mars Global Surveyor (MGS), new plasma regions and boundaries have been identified in the Martian space environment. The interaction between supersonic solar wind and the Martian ionosphere creates a bow shock at approximately 1.6 R_M from Mars's center (where R_M is the Martian radius), where the solar wind is sharply decelerated, compressed, and heated. Further inward, the magnetosheath is a region of intense wave activity. The magnetic pileup boundary connects the lower edge of the magnetosheath and is characterized by a sharp increase in interplanetary magnetic field (IMF) strength, marking the outer edge of the magnetic pileup region. The magnetic pileup region features a high-intensity magnetic barrier. The photoelectron boundary separates the ionosphere dominated by photoelectrons from the magnetic pileup region; its altitude correlates with the location of crustal magnetic field sources, and photoelectrons appear primarily in Mars' s southern hemisphere. Together, the ionosphere (Ionosphere, not labeled, below the photoelectron boundary), photoelectron boundary (Photo-Electron Boundary), magnetic pileup region (Magnetic Pileup Region), magnetic pileup boundary (Magnetic Pileup Boundary), magnetosheath (Magnetosheath), bow shock (Bow Shock), and upstream region (Upstream Region) constitute the near-space plasma environment of the Martian atmosphere [Figure 1: see original paper].

Due to Mars' s relatively small gravitational acceleration, its exosphere extends far upstream of the bow shock, so the interaction with solar wind begins at considerable distances from the bow shock. Particles from the exosphere (primarily hydrogen) become ionized several planetary radii away from Mars. These newborn ions are then picked up by the solar wind and excite electromagnetic waves with frequencies very close to the local proton cyclotron frequency—known as "ion cyclotron waves" (ICW). Since hydrogen dominates the particles upstream of Mars, the newborn ions are primarily newborn protons. The ICWs discussed herein are thus proton cyclotron waves (PCW), and pickup ions refer to pickup protons, although other types of ICWs exist upstream of Mars. Russell et al. first observed ICWs upstream of the Martian bow shock by analyzing Phobos 2 satellite data. Subsequent missions have observed numerous ICW events upstream of Mars. Using data from MGS and the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft, upstream ICWs have been studied in detail. These waves exhibit left-handed elliptical polarization in the spacecraft frame with a propagation angle _{kB} $<$ 20° (the angle between wave vector k and background magnetic field B_0), indicating quasi-parallel propagation relative to the background IMF direction.

2. Observations of Ion Cyclotron Waves Upstream of Mars

Figure [Figure 2: see original paper] presents an ICW event observed by the MAVEN spacecraft upstream of the Martian bow shock during 16:12:18–16:20:50 UT on November 26, 2018, where SW denotes solar wind. Panels (a)-(d) display the components and magnitude of the magnetic field and solar wind velocity in MSO coordinates (Mars-centered Solar Orbital coordinates: X-axis points from Mars to the Sun, Z-axis is perpendicular to Mars' s orbital plane pointing north of the ecliptic, and Y-axis completes the right-hand system) as measured by the magnetometer (MAG). Panel (e) shows the solar wind ion number density from the Solar-Wind Ion Analyzer (SWIA), with an average density of n_{SW} = 4.3 cm^{-3}. During this interval, all magnetic field components exhibit clear oscillations with wave amplitudes of approximately 0.3 nT. For this event, the average IMF (background magnetic field) is B_0 = [2.6, 2.4, 0.9] nT, the average solar wind velocity is v_{SW} = [344.0, 54.7, 3.6] $\text{km} \cdot \text{s}^{-1}$, and the IMF cone angle (the angle between background magnetic field and solar wind velocity during ion pickup) is 36.0°. The solar wind velocity fluctuations are synchronized with magnetic field fluctuations at the same frequency.

Figure Figure 3: see original paper shows the power spectral density of the transverse magnetic field component B_ (magenta) and compressive magnetic field component B_ (blue) relative to B_0 over a 512 s interval, where the black dashed line indicates the local proton cyclotron frequency. Here, the background magnetic field magnitude is B_0 = 3.7 nT, corresponding to a local proton cyclotron frequency f_c of 0.056 Hz. At a frequency of 0.051 Hz (0.91 f_c), the transverse power spectral density reaches its maximum value, which is 28 times that of the compressive component at the same frequency. To determine the wave polarization properties and propagation direction, Minimum Variance Analysis (MVA) was applied to a subinterval covering three proton cyclotron periods (16:14:50–16:15:44 UT). This method calculates eigenvalues *λj and eigenvectors e_j of the covariance matrix of magnetic field components to characterize wave properties. The ratios* λ_1/λ_2 *1 and* λ_2/λ_3 *» 1 indicate detection of a circularly polarized plane wave. When the* λ_2/λ_3 *ratio satisfies the plane wave assumption, the wave vector k direction is parallel to the eigenvector*

e_3 *associated with the minimum eigenvalue, though its orientation cannot be determined. Figure Figure 3: see original paper displays a hodogram of magnetic field observations in the plane defined by the maximum and intermediate eigenvalue directions during 16:14:50–16:15:44 UT, where* B_1 *and* B_2 *represent magnetic field components along the maximum and intermediate variance directions, respectively. The propagation angle* {kB} (the angle between e_3 and B_0) is 16.0°, indicating that these waves propagate quasi-parallel to the background magnetic field upstream of the Martian bow shock. The wave event exhibits circular polarization ($\lambda_1/\lambda_2 = 1.07$) and near-plane wave properties ($\lambda_2/\lambda_3 = 82.52$) near the proton cyclotron frequency, with wave amplitude $\delta B = 0.5$ nT. The average magnetic field expressed in the MVA basis e_1, e_2, e_3 is B_0*{MVA} = [0.5, 0.7, 3.7] nT, directed inward toward the maximum-intermediate plane. Based on the average rotation direction of magnetic field oscillations relative to* B_0{MVA} (shown by black arrows in Figure Figure 3: see original paper), the wave is left-hand polarized in the spacecraft frame.

3. Generation Mechanism of ICWs Upstream of Mars

ICWs upstream of Mars are primarily generated through the ion pickup process. Ion pickup refers to the acceleration of neutral particles ionized upstream of the Martian bow shock under the solar wind convection electric field, causing them to gyrate around the magnetic field in the solar wind. Since protons dominate upstream of Mars, these pickup ions are produced mainly through charge exchange, photoionization, and electron impact, with charge exchange being the dominant process. After being captured by the solar wind convection electric field, pickup ions mix with upstream solar wind protons and serve as an important non-thermal component, providing free energy to generate or sustain various plasma instabilities and acting as the primary energy source for wave excitation.

Theoretically, two types of instabilities may arise in the plasma frame depending on background conditions such as the IMF cone angle. Newborn ions are initially nearly stationary relative to Mars. In the solar wind frame, these protons have an average velocity approximately equal to -v_{SW}, where v_{SW} is the solar wind velocity. The parallel velocity component v_i = v_{SW} · cos moves along the IMF, while the perpendicular component v_i = v_{SW} · sin causes the ions to gyrate around the IMF, where v_i is the newborn ion velocity in the solar wind frame (protons in this case), v_{SW} = |v_{SW}|, and is the IMF cone angle.

The interaction between planetary protons and solar wind can excite both left-hand and right-hand resonant electromagnetic ion-ion instabilities, depending on the IMF cone angle . For large , the left-hand resonant instability has a larger linear growth rate and is associated with ring-beam or ring velocity distribution functions of pickup protons. Conversely, the right-hand resonant instability is more easily excited at low to moderate cone angles, associated with proton beam or ring-beam distributions.

For both resonant instabilities, the observed wave frequencies in the spacecraft frame contain Doppler shifts due to relative motion between the satellite and solar wind reference frames. Since the satellite’ s velocity relative to Mars’ s center is negligible compared to v_{SW}, the wave frequency observed in the spacecraft frame ω_{SC} is:

$$\omega_{SC} = \omega - k \cdot v_{SC}$$

where ω is the wave frequency in the plasma frame, k is the wave vector, $v_{SC} = -(v_{SW} \cdot \hat{k})\hat{k}$ is the satellite velocity component parallel to the wave propagation direction, and $\hat{k}$ is the unit wave vector. Additionally, the wave frequency in the newborn ion frame is $\omega_i = \omega - k \cdot v_i$.

The right-hand resonant mode satisfies the cyclotron resonance condition, particularly at moderate cone angles:

$$\omega - k \cdot v_i + n\Omega_i = 0;\ n = 1, 2, 3, \cdots$$

where $\Omega_i = q_i|B|/m_i$ is the ion cyclotron frequency, B, q_i, and m_i represent the IMF, ion charge, and mass, respectively, and v_i is the ion velocity along the magnetic field in the solar wind frame. Considering that newborn ions are initially nearly stationary relative to Mars, the right-hand mode wave frequency in the spacecraft frame is $\omega_{SC} = -n\Omega_i$. *Thus, when* $n = 1$ *(fundamental mode), the observed frequency* ω_{SC} approaches the newborn ion cyclotron frequency with polarization opposite to that in the solar wind frame. Since the observed frequency is very close to the local proton cyclotron frequency, these waves are also called PCWs.

For the left-hand resonant mode, the Doppler shift term in the equation is relatively small, and waves generated by left-hand instability can also be observed near the local ion cyclotron frequency with left-hand polarization in the spacecraft frame. Compared to the right-hand resonant mode, these waves are left-hand polarized in both the solar wind and spacecraft frames, whereas the right-hand resonant mode is right-hand polarized only in the solar wind frame but left-hand polarized in the spacecraft frame.

The solar wind pickup process leads to atmospheric loss at Mars. Since ICWs are byproducts of ion pickup, they play an important role in Martian atmospheric loss and serve as indirect signatures of newborn planetary protons. Typically, plasma instruments cannot directly measure or determine mass-loading characteristics. This relationship between ICWs and pickup ions enables plasma waves to serve as a diagnostic tool for determining the extent of mass-loading regions, inferring pickup ion density profiles, and estimating neutral particle loss rates. For example, in studies of ion pickup in the inner magnetospheres of Jupiter and Saturn, empirical relationships between wave energy and pickup ion density from analytical theory and numerical simulations have been used to estimate pickup ion densities in Io’ s torus and production rates in Saturn’ s neutral cloud. Therefore, observational studies of ICWs in near-Mars space have significant scientific importance.

4. Statistical Studies of ICWs Upstream of Mars

4.1. Seasonal Variation of ICWs MGS observations during the Science Phasing Orbits (SPO1, SPO2) revealed strong seasonal variation in ICW occurrence rates, independent of MGS' s spatial distribution near Mars and the IMF cone angle distribution during measurements, but possibly related to temporal variations in hydrogen properties of the Martian exosphere.

Figure Figure 4: see original paper shows ICW occurrence upstream below 20400 km altitude from September 1997 to September 1998, where gray dots represent per-orbit occurrence rates R and black dots show averaged rates . Figure Figure 4: see original paper presents modeled hydrogen density above the Martian South Pole and dayside-averaged hydrogen density at 15400 km altitude for minimum and mean solar activity from August 1997 to October 1998. Key dates include Mars perihelion (PH, 7 January 1998), southern hemisphere spring equinox (SSE, 12 September 1997), southern hemisphere summer solstice (SSS, 6 February 1998), and southern hemisphere autumn equinox (SAE, 14 July 1998). The MGS observations in the southern high-latitude region between solar minimum and mean solar activity show higher ICW occurrence rates near perihelion and southern summer solstice, with average occurrence rates increasing by 70% compared to during autumn and spring equinoxes. Modeled hydrogen density distributions on the Martian dayside and above the South Pole, accounting for ultraviolet thermospheric heating effects, exhibit similar temporal variations. Although ion pickup and plasma wave generation and evolution are complex processes, these observations suggest that temporal variations in ICW occurrence rates can be used to study the temporal evolution of the Martian hydrogen corona and its coupling with the thermosphere.

However, the above studies did not consider wave polarization characteristics or compressive power spectral density near the proton cyclotron frequency. MAVEN observations provide more comprehensive coverage of Mars, enabling stricter criteria for ICW identification and further investigation incorporating wave frequency and polarization properties, which confirmed the seasonal variation of ICW occurrence upstream of Mars with more frequent observations near perihelion. Simulated hydrogen density profiles at higher altitudes also show similar long-term trends consistent with temporal variations in ICW occurrence rates.

Mars Express data showing higher pickup ion occurrence rates near perihelion support the correlation between ICW occurrence and heliocentric distance. Studies also reveal similar long-term trends in temporal variations of exospheric hydrogen column density, with hydrogen density upstream of the bow shock being an order of magnitude larger near perihelion than at aphelion. However, there is a time lag between Mars reaching perihelion, peak exospheric hydrogen density, and peak ICW occurrence rates, possibly due to delayed response of the upper atmosphere to solar input or seasonal effects combined with solar extreme ultraviolet flux influence. In the region one to two thousand kilometers upstream of Mars, simulated profiles of upper exospheric hydrogen density correlate more closely with temperature variations at the exobase, which depend on solar EUV flux. MAVEN' s Extreme Ultraviolet Monitor observations show irradiance trends similar to long-term variations in exospheric hydrogen density, with stronger irradiance at smaller heliocentric distances. Under dense exospheric hydrogen conditions near perihelion, increased ionization of Martian particles may enhance newborn ion density, providing more energy to excite ICWs and resulting in higher occurrence rates. Additionally, the average delay between hydrogen density peaks and ICW occurrence peaks is 25 days, with asymmetric growth and decay times for ICW abundance, partially due to seasonal sampling biases near perihelion and northern winter solstice.

Dust activity and atmospheric upwelling significantly affect water vapor concentration variations in the lower Martian atmosphere, consequently influencing exospheric hydrogen. Observations show that Martian dust storms increase lower atmospheric opacity, with regional dust storms raising near-surface atmospheric temperatures by 15–20 K and planet-encircling dust storms increasing temperatures by 30–40 K. Dust storm effects can amplify large-scale atmospheric circulation, mixing water vapor from near the Martian surface into the higher thermosphere. Consequently, initially high water vapor concentrations in the lower atmosphere may affect the hydrogen exosphere. ICWs occur more frequently during dust storm seasons each Martian year. During June–July 2018 (2–3 months before the third perihelion of that year), ICW occurrence showed a smaller secondary peak (20%), compared to no similar secondary peaks exceeding 15% observed several months before perihelion in other Martian years. This minor peak around July 2018 is at least associated with the global dust storm of summer 2018, the first such event since 2007.

4.2. Global Distribution of ICWs Analysis of MGS sampling data during the first aerobraking (AB1) phase revealed that ICWs occur over a wide range near Mars, often intermittently at large distances, suggesting that the Martian exosphere is time-varying or non-spherical, appearing to extend downstream and to one side of Mars as a disk composed of fast hydrogen atoms aligned with the interplanetary electric field direction.

Figure [Figure 5: see original paper] shows the spatial distribution of wave occurrence in an electromagnetic coordinate system (x-direction from Mars to Sun, y-direction along x × B, z-direction completing a right-handed system) for IMF magnitude B_{total} > 5.6 nT. Assuming solar wind flows along the negative x-axis, the y-axis represents the interplanetary electric field direction (E), and the z-axis lies along the component of B perpendicular to x (B_{perp}). ICWs occur frequently in the +E hemisphere but are not observed in the -E hemisphere, indicating strong asymmetry in ICW occurrence along the interplanetary electric field direction in this coordinate system. If protons are first picked up near Mars, then neutralized through charge exchange and transported along magnetic field lines to distant regions, the pickup process would occur only on one side of Mars extending far downstream, creating the extensive, asymmetric, and intermittent nature of ICW occurrence. Extensiveness refers to ICW occurrence at large distances from Mars, asymmetry refers to the non-uniform distribution along the interplanetary electric field direction (existing only in the positive electric field direction), and intermittency refers to short wave durations. For wave events lasting several hours, the spacecraft must remain within the extended exosphere, which occurs most readily when close to Mars, where waves persist in near-Mars space (2-6 R_M). This asymmetry demonstrates that electric and magnetic fields in the solar wind play important roles in transporting exospheric hydrogen. Stronger IMF yields greater observed asymmetry, with ICW distribution asymmetry becoming more pronounced for events with stronger background magnetic fields. Numerical simulations have also identified this asymmetry in ICW distribution along the interplanetary electric field direction, attributable to finite Larmor radius effects (approximately 0.3 R_M for solar wind speeds of ~440 km/s and background magnetic field strength of ~5 nT), where protons lost through collisions with the lower atmosphere when near Mars.

However, Romanelli et al. found that during MGS' s SPO1 and SPO2 phases, the spatial distribution of ICWs within 6 R_M of Mars' s surface appears independent of the solar wind convection electric field direction. Moreover, ICWs can be observed even in the negative interplanetary electric field direction. One explanation is that ICW distribution does not necessarily follow pickup ion distribution, as the wavelengths of ICWs generated by pickup ions are planetary in scale, and ion density cannot be uniform over such large distances. This discrepancy with Wei et al.' s results may stem from different sampling regions during MGS' s AB1 and SPO phases. Figure [Figure 6: see original paper] shows MGS SPO orbit trajectories with ICW occurrence in the MBE coordinate system, where solid and hollow circles correspond to SPO1 and SPO2 orbits, respectively. The left panel is color-coded by wave amplitude, and the right panel by IMF cone angle. The MBE coordinate system differs from the electromagnetic coordinate system described earlier, being centered on Mars with Z_{MBE} axis parallel to E_c (solar wind convection electric field), X_{MBE} axis antiparallel to v_{SW}, and Y_{MBE} completing the right-hand system. Sixty percent of waves occur above the Z_{MBE} = 0 plane and 40% below, while the spacecraft spends 48% and 52% of time in the positive and negative hemispheres of the solar wind convection electric field, respectively. Thus, ICW spatial distribution appears unaffected by the solar wind convection electric field, and neither wave amplitude distribution nor IMF cone angle _V;B shows electric field dependence, with ICWs observed even when E_c is relatively weak.

Figure [Figure 7: see original paper] shows the distribution of wave events in the electromagnetic coordinate system xy-plane. The right panel displays events with background field > 4 nT, revealing more ICWs on the positive electric field side. The left panel shows no obvious asymmetry in wave spatial distribution along the electric field direction, but the right panel indicates higher occurrence rates on the positive electric field side for waves downstream of Mars (x < 0).

ICWs appear in both positive and negative electric field directions at Mars, but occur more frequently in the positive electric field direction when the background magnetic field is strong. Wei et al. proposed that ion pickup occurs at distances greater than one gyroradius from Mars, allowing local pickup ions and/or fast neutral ions to reach the negative electric field side without being lost in the Martian atmosphere. Therefore, ICWs observed far from Mars may originate from pickup processes in a very tenuous exosphere or from re-ionization of fast neutral particles generated near Mars. Statistically, more wave events appear on the positive electric field side, suggesting that the process described in Wei et al.' s original fast neutral disk model may be at work and likely dominated by newborn ions generated within one gyroradius of Mars.

4.3. Relationship Between ICW Occurrence Rate and IMF Cone Angle

The IMF cone angle, also called the pickup angle, is defined as the angle between the magnetic field direction and the Sun-Mars line (x-axis) when solar wind flows along the Sun-Mars line (denoted as angle BR). Bertucci et al. studied the relationship between pickup angle and ICW occurrence rate for background field strengths > 4 nT. Figure Figure 8: see original paper shows the histogram of pickup angles for all MGS AB1 orbit data, Figure Figure 8: see original paper shows the distribution only for ICW events, and Figure Figure 8: see original paper gives the temporal percentage of ICW occurrence (normalized occurrence rate) at different pickup angles. The normalized ICW occurrence rate peaks near a pickup angle of 45°.

MAVEN data from October 2014 to February 2020, covering three consecutive Martian years, were divided into six groups: HR1, HR2, and HR3 for data near perihelion at similar longitudes, and LR1, LR2, and LR3 for data near aphelion at similar longitudes. Figure [Figure 9: see original paper] (left panel) shows ICW occurrence rate as a function of IMF cone angle from October 2014 to February 2020, while the right panel displays ICW occurrence rates for HR1 (orange), HR2 (green), and HR3 (purple) groups as a function of IMF cone angle . HR1 and HR2 groups show higher ICW occurrence rates at medium-low cone angles (20° < < 45°), whereas HR3 group shows higher occurrence across a slightly larger IMF cone angle range (0° < < 60°, right panel). Excluding MAVEN data from July 20 to September 15, 2018 (corresponding to the duration of the global dust storm), the distribution of ICW occurrence rates in the HR3 group shows no significant change from HR1 and HR2. The right panel of Figure [Figure 9: see original paper] reveals that the peak occurrence rate at = 22.5° in the left panel primarily comes from HR1 contributions, likely due to seasonal sampling biases near perihelion and northern winter solstice. For instance, the peaks in ICW occurrence rates for HR1 in the right panel and in the left panel vary with the selected magnetic field strength range. When considering IMF > 4 nT, the distribution of occurrence rates with cone angle shows better consistency, with peaks near = 22.5° appearing each Martian year. Despite this variation, ICW occurrence rates remain consistently high for IMF cone angles below 45°, possibly resulting from a balance between relevant saturated wave energy, characteristic growth times, and newborn planetary proton density. For example, the ion-ion right-hand instability typically has relatively large wave saturation amplitudes and long growth times when $< 75°$, but requires lower pickup ion densities compared to resonant plasma instabilities at large IMF cone angles. Therefore, the observed peak in ICW occurrence rates at medium-low IMF cone angles may represent a net result of different growth times and planetary ion density thresholds in plasma instability processes.

4.4. Variation of ICW Amplitude Analysis of MAVEN-observed ICW events reveals that ICW amplitudes primarily range between 0.1–1.0 nT. Figure [Figure 10: see original paper] shows the median amplitude of upstream ICWs for HR1 (orange), HR2 (green), and HR3 (purple) groups as a function of X_{MSO} (left panel) and altitude (right panel). The amplitude decreases with increasing distance from Mars for all HR groups, indicating these waves originate from near-Mars space. In contrast, the right panel shows that the HR1 curve amplitude first increases then decreases with altitude, the HR2 curve amplitude decreases overall with altitude, and the HR3 curve amplitude first decreases then increases with altitude, demonstrating that HR curve amplitudes do not necessarily decrease with increasing altitude. Additionally, researchers using MAVEN data from October 2014 to November 2018 found no consistent, clear variation of wave amplitude with altitude.

Figure [Figure 11: see original paper] shows MGS observations of the relationship between ICW amplitude and altitude for SPO orbits. Wave amplitudes were estimated from power spectral density centered at the proton cyclotron frequency with a width of 0.015 Hz. Cyan crosses and brown circles correspond to waves appearing in SPO1 and SPO2 orbits, respectively. The black curve shows average amplitudes within 0.5 R_M, revealing a decreasing trend in wave amplitude with increasing distance.

The differences between MAVEN and MGS observations may result from varying solar wind and Martian conditions affecting ICW amplitudes each Martian year, such as pickup ion rates, pickup velocities, pickup geometry, and wave growth times. MGS' s preset orbit reached up to 15 R_M, significantly different from MAVEN's altitude coverage. Future studies combining satellite observations and numerical simulations should analyze the relationship between wave amplitude and radial distance from Mars.

The left panel of Figure [Figure 10: see original paper] shows a continuous decrease of 0.15 nT in median wave amplitude across the three HR groups, which is unlikely due to spatial sampling bias in MSO coordinates since each HR group covers similar X_{MSO} and altitude ranges. Within MAVEN' s orbital spatial range, ICW amplitudes from three consecutive Martian years (HR1-HR3) show an overall decreasing trend with X_{MSO} and altitude, with similar results for Y_{MSO} and Z_{MSO} coordinates. Furthermore, no significant differences in solar wind conditions exist between HR groups, suggesting solar wind conditions may not be related to the decreasing trend in ICW amplitudes each Martian year. The amplitude decrease may be associated with physical processes in the Martian bow shock foreshock region, asymmetry in solar wind convection electric field effects on newborn protons, or responses of the Martian atmosphere to changes in solar wind velocity, proton density, proton flux density, and/or solar cycle effects.

Figure [Figure 12: see original paper] shows the median amplitude of upstream ICWs for HR1 (orange), HR2 (green), and HR3 (purple) groups as a function of IMF cone angle . The HR1 group shows decreasing wave amplitude with increasing IMF cone angle, while HR2 and HR3 groups show weaker decreasing trends. Previous studies based on MGS and MAVEN observations found amplitude dependence on IMF cone angle. Wave amplitude is generally thought to be related to the energy of local pickup ion populations, making the spatial and temporal distribution of observed wave amplitudes a diagnostic of local exospheric structure and loss rates. One-dimensional numerical hybrid simulations of the Martian plasma environment reveal a complex relationship between wave amplitude and ion pickup rate, showing that observed local ICW amplitudes may be more complicated because instability growth times are long compared to wave propagation times near Mars. Additionally, upstream ICWs are found to be in a growing rather than saturated state, with saturated wave energy decreasing as cone angle increases. However, MGS observations do not support this relationship between IMF cone angle and wave amplitude, consistent with results from HR2 and HR3 groups.

The differences between HR groups may be related to variations in wave frequency distributions, as different frequencies correspond to different saturation levels. For example, assuming IMF cone angle = 0°, ICWs must experience at least ten gyroperiods to reach saturation. For a wave with frequency f = 0.06 Hz and v_{SW} = 400 km/s, the wave must propagate a distance of 20 Martian radii before saturation. Higher-frequency ICWs can saturate within shorter distances. Restricting analysis to frequencies above 0.07 Hz yields similar frequency distributions across the three HR groups, focusing on ICWs more likely to be saturated and resulting in three curves showing stronger decreasing trends with similar slopes. Therefore, variations in wave frequency distributions between HR groups may explain the different trends observed each Martian year and reconcile differences between previous studies.

5. Summary and Outlook

Mars’ s lack of an intrinsic magnetic field allows direct interaction between its atmosphere and solar wind, creating a unique plasma environment. In the upstream region of the Martian bow shock, hydrogen diffusing into interplanetary space becomes ionized and is picked up by the solar wind. These pickup ions mix with upstream solar wind protons, providing free energy to generate or sustain various plasma instabilities and producing plasma waves with frequencies near the proton cyclotron frequency. Theoretically, two instability processes may arise in the plasma frame depending on the IMF cone angle. For both resonant instabilities, observed wave frequencies contain Doppler shifts. Left-hand instability waves are left-hand polarized in both solar wind and spacecraft frames, while right-hand resonant modes are right-hand polarized only in the solar wind frame but left-hand polarized in the spacecraft frame.

Since Russell et al. first observed ICWs upstream of the Martian bow shock, statistical analyses using magnetic field and plasma data from multiple Mars missions have confirmed that ICWs occur more frequently near each Martian perihelion and northern winter solstice. This long-term trend correlates with Mars’ s heliocentric distance, possibly due to long-term variations in exospheric hydrogen density or dust activity affecting water vapor concentration in the lower atmosphere. This trend is independent of satellite spatial coverage and ICW selection criteria biases.

In the spacecraft frame, observed ICWs propagate primarily quasi-parallel to the background magnetic field direction, with amplitudes ranging from 0.1–1.0 nT and elliptical left-hand polarization. Studies also find higher ICW occurrence rates at medium-low IMF cone angles (20° < < 45°). This preference for IMF cone angle ranges may result from a balance between relevant linear wave growth rates, wave saturated energy, and absorbed proton density.

The average delay between exospheric hydrogen density peaks and ICW occurrence peaks is 25 days, with asymmetric growth and decay times for ICW abundance. The reasons remain unclear, and future research should focus on analyzing temporal lags between Mars perihelion, exospheric hydrogen density peaks, and ICW occurrence peaks. Such studies will improve understanding of the relationship between exospheric hydrogen density and upstream ICWs, provide observational constraints on these phenomena’ s timescales, help better understand the physical processes coupling the Martian plasma environment with solar wind, and provide references for analyzing interactions between solar wind and other planetary atmospheres.

ICW amplitudes decrease with distance from Mars along the Sun-Mars line but do not necessarily decrease with increasing altitude. Future research should combine multi-satellite observations and numerical simulations to analyze the relationship between ICW amplitude and radial distance from Mars. The decreasing median ICW amplitude over three consecutive Martian years may be related to physical processes in the Martian bow shock foreshock region, effects of solar wind electric field on newborn proton asymmetry, and responses of the Martian atmosphere to varying solar inputs or solar cycle effects, all requiring further investigation.

References

[1] Romanelli N, Bertucci C, Gómez D, et al. P&SS, 2013, 76: 1
[2] Yamauchi M, Hara T, Lundin R, et al. P&SS, 2015, 119:
[3] Bertucci C, Mazelle C, Acuña M H. JASTP, 2005, 67:
[4] Kim E J, Sohn J D, Yi Y, et al. JASS, 2011, 28: 17

[5] Mitchell D L, Lin R P, Rème H, et al. LPI, 2002, 33: 2029
[6] Garnier P, Steckiewicz M, Mazelle C, et al. JGRA, 2017, 122: 10
[7] Nagy A F, Winterhalter D, Sauer K, et al. SSRv, 2004, 111: 33
[8] Chaufray J Y, Bertaux J L, Leblanc F, et al. Icar, 2008, 195: 598
[9] Anderson Jr DE, JGR, 1974, 79: 1513
[10] Connerney J E P, Espley J, Lawton P, et al. SSRv, 2015, 195: 257
[11] Russell C T, Luhmann J G, Schwingenschuh K, et al. GeoRL, 1990, 17: 897
[12] Bertucci C, Romanelli N, Chaufray J Y, et al. GeoRL, 2013, 40: 3809
[13] Brain D A, Bagenal F, Acuña M H, et al. JGRA, 2002, 107: 1076
[14] Liu D, Yao Z, Wei Y, et al. E&PP, 2020, 4: 51
[15] Mazelle C, Winterhalter D, Sauer K, et al. SSRv, 2004, 111: 115
[16] Romanelli N, Mazelle C, Chaufray J Y, et al. JGRA, 2016, 121: 11113
[17] Wei H Y, Russell C T. GeoRL, 2006, 33: L23103
[18] Wei H Y, Russell C T, Zhang T L, et al. P&SS, 2011, 59:
[19] Wei H Y, Cowee M M, Russell C T, et al. JGRA, 2014, 119: 5244
[20] Romeo O M, Romanelli N, Espley J R, et al. JGRA, 2021, 126: e2020JA028616
[21] Sonnerup B U Ó, Scheible M. ISSIR, 1998, 1: 185
[22] Zhang M H G, Luhmann J G, Nagy A F, et al. JGRE, 1993, 98: 3311
[23] Rahmati A, Larson D E, Cravens T E, et al. JGRE, 2018, 123, 1192
[24] Wu C S, Davidson R C. JGR, 1972, 77: 5399
[25] Wu C S, Hartle R E. JGR, 1974, 79: 283
[26] Tsurutani B T, Brinca A L, Buti B, et al. JGRA, 1989, 94: 29
[27] Tsurutani B T. GMS, 1991, 61: 189
[28] Brinca A L. GMS, 1991, 61: 211
[29] Gary S P. SSRv, 1991, 56: 373
[30] Mazelle C, Neubauer F M. GeoRL, 1993, 20: 153
[31] Sauer K, Dubinin E, McKenzie J F. GeoRL, 2001, 28:
[32] Sauer K, Dubinin E. GeoRL, 2003, 30: 2192
[33] Cowee M M, Gary S P, Wei H Y. GeoRL, 2012, 39: L08104
[34] González-Galindo F, López-Valverde M A, Angelats I Coll M, et al. JGRE, 2005, 110: E09008
[35] Brinca A L, Tsurutani B T. JGRA, 1989, 94: 13565
[36] Convery P D, Gary S P. JGRA, 1997, 102: 2351
[37] Gary S P, Madland C D. JGRA, 1988, 93: 235
[38] Gary S P, Akimoto K, Winske D. JGRA, 1989, 94: 3513
[39] Gary S P. *Theory of Space Plasma Microinstabilities.* Cambridge: Cambridge University Press, 1993: 193
[40] Huddleston D E, Strangeway R J, Warnecke J, et al. JGRE, 1998, 103: 19887
[41] Cowee M M, Omidi N, Russell C T, et al. JGR, 2009, 114: A04219
[42] Leisner J S, Russell C T, Wei H Y, et al. JGRA, 2011, 116: A09235
[43] Albee A L, Arvidson R E, Palluconi F, et al. JGRE, 2001, 106: 23291
[44] Halekas J S. JGRE, 2017, 122: 901
[45] Chaufray J Y, Gonzalez-Galindo F, Forget F, et al. Icar, 2015, 245: 282

[46] Eparvier F G, Chamberlin P C, Woods T N, et al. SSRv, 2015, 195: 293
[47] Thiemann E M B, Chamberlin P C, Eparvier F G, et al. JGRA, 2017, 122: 2748
[48] Bhattacharyya D, Clarke J T, Bertaux J L, et al. GeoRL, 2015, 42: 8678
[49] Bhattacharyya D, Clarke J T, Chaufray J Y, et al. JGRG, 2017, 122: 11756
[50] Bhattacharyya D, Chaufray J Y, Mayyasi M, et al. Icar, 2020, 339: 113573
[51] Chaffin M S, Chaufray J Y, Stewart I, et al. GeoRL, 2014, 41: 314
[52] Clarke J T, Bertaux J L, Chaufray J Y, et al. GeoRL, 2014, 41: 8013
[53] Clarke J T, Mayyasi M, Bhattacharyya D, et al. JGRA, 2017, 122: 2336
[54] Smith M D. Icar, 2009, 202: 444
[55] Aoki S, Vandaele A C, Daerden F, et al. JGRE, 2019, 124: 3482
[56] Chaffin M S, Deighan J, Schneider N M, et al. NatGe, 2017, 10: 174
[57] Fedorova A, Korablev O, Bertaux J L, et al. JGRE, 2006, 111: E09S08
[58] Fedorova A A, Korablev O I, Bertaux J L, et al. Icar, 2009, 200: 96
[59] Fedorova A, Bertaux J L, Betsis D, et al. Icar, 2018, 300:
[60] Fedorova A A, Montmessin F, Korablev O, et al. Science, 2020, 367: 297
[61] Heavens N G, Kleinböhl A, Chaffin M S, et al. NatAs, 2018, 2: 126
[62] Maltagliati L, Montmessin F, Fedorova A, et al. Science, 2011, 333: 1868
[63] Maltagliati L, Montmessin F, Korablev O, et al. Icar, 2013, 223: 942
[64] Sánchez-Lavega A, Del Río-Gaztelurrutia T, Hernández-Bernal J, et al. GeoRL, 2019, 46: 6101
[65] Brecht S H. GeoRL, 1990, 17: 1243
[66] Modolo R, Chanteur G M, Dubinin E, et al. AnGeo, 2005, 23: 433
[67] Mazelle C X, Meziane K, Mitchell D L, et al. GeoRL, 2018, 45: 3768
[68] Meziane K, Mazelle C X, Romanelli N, et al. JGRA, 2017, 122: 1531