Proton cyclotron waves at Mars: Exosphere structure and evidence for a fast neutral disk

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Received 8 March 2006; revised 13 October 2006; accepted 25 October 2006; published 6 December 2006.

[1] Mars is an unmagnetized planet whose hydrogen exosphere extends into the solar wind, creating proton cyclotron waves. Mars Global Surveyor data reveal the occurrence of waves to be extensive and often intermittent at large distance, indicating that the exosphere is time varying or non-spherical. When the region of wave occurrence is examined in a magnetic-electric coordinate system, a strong asymmetry in the occurrence of these waves is seen in the direction of the interplanetary electric field. The extensive, yet asymmetric and intermittent, occurrence of waves can be understood if, after protons are first picked up near Mars, the ions are neutralized by charge exchange and transported across field lines to distant regions, allowing the pickup process to extend far from Mars on only one side of the planet. Thus the exosphere of Mars appears to extend in a disk of fast hydrogen atoms both downstream and to the side of Mars in the direction of the interplanetary electric field. Citation: Wei, H. Y., and C. T. Russell (2006), Proton cyclotron waves at Mars: Exosphere structure and evidence for a fast neutral disk, Geophys. Res. Lett., 33, L23103, doi:10.1029/2006GL026244.

1. Introduction

[2] Mars does not generate a global planetary magnetic field, but its ionosphere interacts with the solar wind, resulting in a unique plasma environment consisting of a bow shock to slow down the solar wind, a magnetosheath, a magnetic pileup region where the solar wind magnetic field drapes around Mars, and an ionosphere [Nagy et al., 2004]. The bow shock is quite close to the planet and the average subsolar shock distance is only about 1.5 Rₘ from the center of Mars [Russell, 1979; Trotignon et al., 1991, 2006; Vignes et al., 2000]. Due to the small size of the bow shock, the Martian hydrogen exosphere extends outside the bow shock into the solar wind. Proton cyclotron waves are created when the hydrogen atoms are ionized and accelerated by the solar wind electric field. Such waves were first reported by Russell et al. [1990] when the Phobos mission arrived at Mars. These waves were detected about 2–3 Rₘ in front of Mars, were left-hand elliptically polarized and propagated at a small angle to the magnetic field [Russell et al., 1990]. Russell et al. [1990] suggested that the waves grew from the free energy provided by ring-beam protons created when the newly ionized protons were accelerated by the solar wind electric field. Observations of a proton ring-beam distribution by Phobos’ ASPERA instrument supported the hypothesis that the proton-cyclotron waves were associated with the solar wind picking up newly-ionized hydrogen from the Martian exosphere [Barabash et al., 1991]. Mars Global Surveyor (MGS) also observed such waves with similar frequencies, polarizations and propagation angles, but these waves were observed over more extensive regions and often with larger amplitude than the Phobos’ observations [Brain et al., 2002; Mazelle et al., 2004]. In the MGS data, the wave events are observed not only in the magnetosheath and close to Mars, but also up to 15 Rₘ, which is an unusually large distance for an exosphere. At distances far from the planet (e.g. more than 3 Rₘ), the waves are often intermittent, lasting for a few minutes to tens of minutes, which is not expected if the exosphere is quasi-spherical and in steady state. To understand the extensive and intermittent behavior of the waves, this paper examines proton-cyclotron wave events observed by the MGS magnetometer to determine their occurrence statistics. From these properties, we propose a hypothesis for the exospheric structure and its production that explain the large distance to which the waves are observed and why they are often seen intermittently.

2. Data Analysis and Explanation

[3] Proton cyclotron waves are observed extensively around Mars in the MGS data. Figure 1 shows the time series and power spectrum of an example of event on 27 December 1997. The waves lasted for about 17 minutes and the peak frequency is about 0.83 of the local proton gyrofrequency. By using a wave analysis program based on the Means method [Means, 1972], the wave is found to be left-handed with an ellipticity of −0.79, a polarization of 93% and a propagation angle of 22 degrees to the magnetic field. The location of this event is about 11 Rₘ from center of Mars. If the exosphere at these distances were spherically uniform we would expect wave generation to be continuous rather than intermittent as it is observed to be. Furthermore we would not expect the exosphere to extend this far. To determine why such waves are both intermittent and occur far from Mars, 85 wave events were selected to examine the statistical properties of the wave occurrence. These events were selected from 9 of the pre-mapping orbits, the so-called AB1 phase of the mission. The criteria were a wave frequency within 20% of the local proton gyrofrequency, left-handed with a polarized power greater than 70%, ellipticity less than −0.7 and propagation angle within 30 degrees of the magnetic field.

[4] The wave occurrences were first examined in a Sun-State coordinate system with the ℏ₀ direction from Mars to Sun, the ℏ direction to be upward and perpendicular to the Mars orbit plane and the ℏ direction completing a right-
be proportional to the rate of newly created ions \cite{Huddleston1990, Huddleston1998, Huddleston1992}, although the relation can become complicated in a non-linear scenario \cite{Sauer2001, Dubinin2004}. While the locations of wave occurrence suggest a broadly extended hydrogen exosphere around Mars, the intermittent character of the waves for the data set reported here shows that when the MGS spacecraft is far from the planet the exosphere does not last long, at least at any one location. In Figure 2b, the inferred hydrogen density fall-off from the waves power is about $\propto x^{-1.44\pm0.21}$, which is slower than the fall-off $\propto x^{-2}$ expected at a minimum for a high velocity radial expansion in a spherical exosphere, and much slower than if gravity and photo-ionization were taken into account. However, this lower rate of fall-off could occur in an exosphere whose ions were confined to a thick disk which might be perpendicular to the interplanetary magnetic field (IMF), centered on Mars. A thin disk would result in a fall-off of the wave power of $x^{-1}$ for a fast exospheric wind. A thick disk or a slow exospheric wind would result in a more rapid fall-off. The disk-shaped exosphere can also explain why

handed system. Figure 2a shows the wave powers versus their distances along the Sun-Mars line, with running medians over-plotted on it. Figure 2b shows the wave powers versus the cylindrical radial distances from the Mars-Sun line with running medians. The waves are seen to be widespread around Mars and their amplitudes decrease very slowly with distance. In Figure 2b, the fall-off of wave power with radial distance is fitted by least square fits to the function of $y = (0.56 \pm 0.13) \times x^{-1.44\pm0.21}$. We note that on the left hand side where the curves fall rapidly, there should not be a good fit to the median because the median is calculated over a wide interval compared to the scale length for the change in slope of the curve.

Since the proton cyclotron waves are associated with picked-up protons, the region in which waves are observed indicates where the exospheric hydrogen is picked up. According to quasi-linear theory, the wave power should

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{Figure 1. (a) Time series of magnetic field measured by Mars Global Surveyor during period which proton cyclotron waves are observed in solar wind. (b) Power spectrum of time series shown in Figure 1a, illustrating peak in spectral density near local proton gyrofrequency.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure2.png}
\caption{Figure 2. (a) Variation of proton cyclotron wave power versus distance along the Sun-Mars line. Horizontal lines show running medians. (b) Variation of proton cyclotron wave power versus the cylindrical radial distance from the Mars-Sun line. Horizontal lines show running medians. Dashed line fit the data fall-off by least square method.}
\end{figure}
the waves are observed intermittently. Since waves will be observed only when the spacecraft is inside the exospheric disk, and not when the spacecraft moves outside, the waves appear intermittent during an orbit as the IMF direction rotates about the solar wind flow direction. For cases when waves appear to be continuous for hours [Mazelle et al., 2004; Bertucci et al., 2005], spacecraft orbit must be continuously inside the disk of the extended exosphere. This can happen most readily when the spacecraft is closest to Mars.

To gain insight into how the hydrogen is transported to distant regions, the events are examined in a magnetic-electric coordinate system, whose interplanetary magnetic field $B_{\text{total}}$ is large enough to neglect the inaccuracy of $B_{\text{total}}$. In this coordinate system, $\hat{x}$ direction is from Mars to Sun, $\hat{y}$ direction is in $\hat{x} \times \hat{B}$ and $\hat{z}$ direction completes a right-handed system. Thus by assuming solar wind flow in $\hat{x}$ direction, $\gamma$ axis is along the direction of interplanetary electric field; $\gamma$ axis lies along the direction of the component of $\hat{B}$ perpendicular to $\hat{x}$ (label as $B_{\text{perp}}$ in the plot).

Figure 3. Distribution of wave occurrence in an electromagnetic coordinate system, whose interplanetary magnetic field $B_{\text{total}}$ is large enough to neglect the inaccuracy of $B_{\text{total}}$. In this coordinate system, $\hat{x}$ direction is from Mars to Sun, $\hat{y}$ direction is in $\hat{x} \times \hat{B}$ and $\hat{z}$ direction completes a right-handed system. Thus by assuming solar wind flow in $\hat{x}$ direction, $\gamma$ axis is along the direction of interplanetary electric field; $\gamma$ axis lies along the direction of the component of $\hat{B}$ perpendicular to $\hat{x}$ (label as $B_{\text{perp}}$ in the plot).

[6] To gain insight into how the hydrogen is transported to distant regions, the events are examined in a magnetic-electric coordinate system with the $\hat{x}$ direction from Mars to Sun, the $\hat{y}$ direction along $\hat{x} \times \hat{B}$ and the $\hat{z}$ direction completing a right-handed system. If the solar wind velocity is assumed to be in the $\hat{x}$ direction in this magnetic-electric coordinate system, then the $\gamma$ axis is along the interplanetary electric field direction and the $\gamma$ axis lies along the direction of the component of $\hat{B}$ perpendicular to $\hat{x}$. However, the coordinate transform is derived from the interplanetary magnetic field direction as well as the spacecraft position. The magnetic field is not known as accurately as the spacecraft location relative to Mars. Since the MGS magnetometer data during this period also included a contribution from the illuminated solar panels with an estimated size of about 1 nT [Acuña et al., 2001], wave events in the background of weak interplanetary magnetic field could have strongly biased locations in magnetic-electric coordinates. For events with stronger interplanetary magnetic field $B_{\text{total}}$, the uncertainty of observed magnetic field directions should have less influence.

[7] Figure 3 shows the location of the waves in the y-z plane (i.e. the $E - B_{\perp}$ plane) for $B_{\text{total}}$ stronger than 5.6 nT which means the uncertainty of the magnetic field direction is about $\pm 10^\circ$ and the uncertainty perpendicular to the flow somewhat larger. The 17 events with strong $B_{\text{total}}$ are all on one side of Mars in the positive direction of interplanetary electric field, as shown in Figure 3. The probability of this occurring by chance for 17 independent data points is $\sim 10^{-5}$. This asymmetry indicates that the electric and magnetic fields in the solar wind play a role in transporting the exospheric hydrogen even it is neutral. If this hypothesis is true, the observed asymmetry should be greater the stronger is the interplanetary magnetic field, i.e. the larger is the difference between the spacecraft field and IMF. This is tested in Figure 4 that shows that the asymmetry becomes more obvious for wave events with stronger background $B_{\text{total}}$, giving additional support to the suggestion that the solar wind electric and magnetic fields play a role in developing an extensive hydrogen exosphere.

[8] The exosphere consists of neutral atoms that should not be affected by the magnetic and electric fields. If these particles are so controlled, they must have been ionized at one point in time. Figure 5 illustrates a mechanism which can explain how the Martian hydrogen exosphere could be accelerated. Due to the small size of Martian bow shock and the large scale height of hydrogen in Martian atmosphere, the hydrogen exosphere can extend outside the bow shock. In the solar wind, the exospheric hydrogen can be ionized by impact ionization, photo ionization and charge exchange with solar wind protons. To see waves at large distance regions requires the particles to be transported a long way from their origin at Mars. Since protons cannot be transported across the field lines, the proton cyclotron waves observed in distant regions implies that the accelerated particles producing the waves must have been neutralized after their initial acceleration presumably by charge exchange near Mars, and the neutrals transported to distant regions where they were re-ionized to produce cyclotron waves. Before the first-step ionization, the exospheric hydrogen atoms are assumed to have small thermal velocity.

Figure 4. The asymmetry of wave occurrence in the direction of interplanetary electric field versus the strength of interplanetary magnetic field $B_{\text{total}}$. 

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Figure 5. Mechanism for producing an extended exosphere around Mars. Close to the planet, exospheric hydrogen is ionized and then accelerated by the solar wind electric field, creating proton-cyclotron waves near Mars. Charge exchange produces fast neutrals, which are transported to distant regions where they get re-ionized and generate cyclotron wave downstream of the planet and far to (only) one side of Mars.

compared with solar wind velocity. When they are ionized and create proton cyclotron waves, the wave frequencies should have very small Doppler shift under assumption of wave propagating nearly parallel to IMF because of the negligible thermal velocities of pickup protons. In the meanwhile waves are created around the local proton gyrofrequencies; these pickup protons are accelerated in direction perpendicular to IMF to a maximum of 2V_{SW} / gyrofrequencies; these pickup protons are accelerated in direction perpendicular to IMF to a maximum of 2V_{SW} [Huddleston et al., 1997]. Thus when these protons are neutralized and become neutrals, these neutrals should have their initial velocity nearly perpendicular to the direction of IMF. And the neutral transport region should create a disk of neutrals perpendicular to the interplanetary magnetic field, in the plane containing both Mars and the solar wind electric field vector. In a uniformly magnetized medium, the period of motion as a neutral merely translates the particle preserving the pitch angle and gyro phase. Thus when these neutrals are re-ionized, these ions’ initial velocities are dominant in the direction perpendicular to IMF so that the cyclotron waves created by them are still near the local proton gyrofrequency.

In this mechanism, ion cyclotron waves can be produced downstream and to the side of the planet, and the orientation of this wave-production disk is controlled by the direction of the interplanetary magnetic field with an asymmetry in the direction of interplanetary electric field.

3. Discussion and Conclusions

MGS observations show that proton cyclotron waves occur extensively around Mars but at large distances they occur intermittently and asymmetrically. The wave occurrence pattern in turn indicates that the Martian hydrogen exosphere cannot be spherically symmetric but disk-shaped with asymmetry in the direction of the interplanetary electric field. In order to travel across the magnetic field the picked up ions must be neutralized near where they are picked up. Thus the top of Mars exosphere appears to extend in a disk to high altitude, with its orientation controlled by the interplanetary magnetic field. The rocking back and forth of this disk as the IMF changes can account for why the waves appear to turn on and off so frequently.

The asymmetry in the direction of interplanetary electric field is also found in numerical modeling results [Brecht, 1990; Modolo et al., 2005]. The cause of the asymmetry in the simulations can be attributed to the effects of finite Larmor radius which is about 0.3 R_{M} for pickup proton (e.g. for V ∼ 440 km/s, B ∼ 5 nT), so that when the protons are picked up close to Mars the protons on the left side of Mars in Figure 5 are easily lost by collisions into the lower atmosphere. This is different than the much larger asymmetry discovered herein, although also created by the same root cause, the interplanetary electric field.

References


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