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Proton cyclotron waves upstream from Mars: Observations from Mars Global Surveyor

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ABSTRACT

We present a study on the properties of electromagnetic plasma waves in the region upstream of the Martian bow shock, detected by the magnetometer and electron reflectometer (MAG / ER) onboard the Mars Global Surveyor (MGS) spacecraft during the period known as Science Phasing Orbits (SPO). The frequency of these waves, measured in the MGS reference frame (SC), is close to the local proton cyclotron frequency. Minimum variance analysis (MVA) shows that these 'proton cyclotron frequency' waves (PCWs) are characterized – in the SC frame – by a left-hand, elliptical polarization and propagate almost parallel to the background magnetic field. They also have a small degree of compressibility and an amplitude that decreases with the increase of the interplanetary magnetic field (IMF) cone angle and radial distance from the planet. The latter result supports the idea that the source of these waves is Mars. In addition, we find that these waves are not associated with the foreshock and their properties (ellipticity, degree of polarization, direction of propagation) do not depend on the IMF cone angle. Empirical evidence and theoretical approaches suggest that most of these observations correspond to the ion–ion right hand (RH) mode originating from the pick-up of ionized exospheric hydrogen. The left-hand (LH) mode might be present in cases where the IMF is almost perpendicular to the Solar Wind direction. PCWs occur in 62% of the time during SPO1 subphase, whereas occurrence drops to 8% during SPO2. Also, SPO1 PCWs preserve their characteristics for longer time periods and have greater degree of polarization and coherence than those in SPO2. We discuss these results in the context of possible changes in the pick-up conditions from SPO1 to SPO2, or steady, spatial inhomogeneities in the wave distribution. The lack of influence from the Solar Wind's convective electric field upon the location of PCWs indicates that, as suggested by recent theoretical results, there is no clear relation between the spatial distribution of PCWs and that of pick-up ions.

1. Introduction

Our Solar System is embedded in a plasma flow emanating from the Sun, known as the Solar Wind. The Solar Wind expands into the Solar System reaching supersonic speeds at a few solar radii from the Sun. The obstacles in its path can be classified into three types: absorbers (for example, unmagnetized asteroids or the Moon) where the Solar Wind interacts directly with their surface, obstacles with intrinsic magnetic fields (such as the Earth and Jupiter), and objects with no intrinsic magnetic field and whose atmospheres directly interact with the Solar Wind. In this group we find planets like Venus and Mars, Saturn's satellite Titan, and also active comets.

The interaction between the atmosphere of a non-magnetic obstacle and the Solar Wind can be described essentially as a non-collisional interaction between a magnetic plasma wind and a neutral cloud being ionized by solar radiation and charge-exchange with the Solar Wind plasma. An atmospheric obstacle such as Mars's atmosphere generates an induced magnetosphere (Acuña et al., 1998; Bertucci et al., 2005), which has its origin in the exchange of energy and momentum between the Solar Wind and the planetary ions. The induced magnetosphere is preceded by a bow shock because of the supersonic nature of the Solar Wind.

However, the interaction can start far beyond the bow shock because particles from the exosphere (mainly hydrogen) (Chaufray et al., 2008) are ionized several planetary radii away from the object. These particles are ionized mostly by photo-ionization and charge exchange (Modolo et al., 2005), which add a small amount of energy to the ions with respect to their parent neutrals. As the latter are approximately at rest with respect to the planet, the ions' planetocentric velocities are also considered

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to be negligible. These newborn ions start gyrating around the interplanetary magnetic field (IMF) while preserving their parents neutral's parallel velocity. In the planet's frame the gyrating ions also drift perpendicular to $\vec{B}$ and $\vec{E}_c$ ($\vec{E}_c = -\vec{v} \times \vec{B}$).

The physics of planetary ion pick-up is exactly the same as the one seen at comets and about which there is a vast literature (e.g., Mazelle and Neubauer, 1993; Tsurutani et al., 1989; Tsurutani, 1991; Gary, 1991, and references therein). These newborn ions represent a non-thermal component of the total ion distribution function which is unstable to the generation of electromagnetic waves (Wu and Davidson, 1972; Wu and Hartle, 1974). The instability and wave polarization resulting from the pick up process depends on the IMF cone angle $\alpha_{V,B}$, which is the angle between the solar wind velocity (V_{SW}) and the IMF at the time of pick-up (Tsurutani and Smith, 1986; Tsurutani et al., 1987). If V_{SW} is parallel to the IMF, the newborn ions will form a beam in the solar wind frame and the electromagnetic ion–ion right-hand (RH) resonant instability will be predominant (Gary, 1993). On the other hand, if V_{SW} is perpendicular to the IMF, the newborn ion distribution function will drive the electromagnetic ion–ion left-hand (LH) mode unstable. Both instabilities have maximum growth rates at $\vec{k} \times \vec{B} = 0$, where $\vec{k}$ is the propagation wave number. At moderate angles of $\alpha_{V,B}$ the RH instability is still predominant. Brinca and Tsurutani (1989) found that the maximum growth rate of the LH instability is larger than that of the RH instability for $\alpha_{V,B} > 75^\circ$, whereas, according to Convery and Gary (1997), Gary and Madland (1988), this cutoff cone angle is $\alpha_{V,B} = 90^\circ$.

The ion–ion RH instability satisfies that the expression $\omega - \vec{k} \cdot \vec{v}^{\,ion}_{//} + \Omega_i$ is approximately zero for moderate $\alpha_{V,B}$ (Gary et al., 1989; Brinca, 1991). In this expression Ω_i is the newborn ion gyrofrequency, $\vec{v}^{\,ion}_{//}$ is the ion drift velocity along the magnetic field $\vec{B}$, and ω and $\vec{k}$ are, respectively, the wave frequency and wave vector in the Solar Wind frame in the case of propagation parallel to $\vec{B}$. As the spacecraft has a negligible planetocentric velocity compared to that of the Solar Wind $\vec{V}_{sw}$, we obtain the following expression:

$$\omega_{sc} = \omega - \vec{k} \cdot \vec{v}^{\,sc}_{//}, \vec{v}^{\,sc}_{//} = -[\vec{V}_{sw} \cdot \hat{k}]\, \hat{k} \qquad (1)$$

where ω_{sc} is the frequency of the plasma wave in the SC frame and $\hat{k} = \vec{k}/|\vec{k}|$.

Since the frequency of the electromagnetic plasma wave in the newborn ion reference frame is $\omega_{ion} = \omega - \vec{k} \cdot \vec{v}^{\,ion}_{//}$, and the velocity of the planetary particle before ionization is negligible with respect to $\vec{V}_{sw}$, we obtain the useful expression:

$$\omega_{sc} = -\Omega_i \qquad (2)$$

where $\Omega_i = (q_i B/m_i)$, with $B = |\vec{B}|$, and q and m being the charge and mass of the newborn ion, respectively. This means that the waves generated by the RH instability are characterized by a frequency which, in the SC frame, is close to the local ion cyclotron frequency with a left-handed polarization.

When the parallel propagating ion–ion LH instability prevails, the Doppler correction is very small and therefore the waves will be observed with a left-hand polarization in both the plasma and SC frames at the local ion cyclotron frequency.

This suggests that the occurrence of waves at the local ion cyclotron frequency of a particular ion species in the SC frame can be associated with the occurrence of the pick up of such ions. In this sense, the presence of plasma waves is, a priori, an important diagnostic tool for the evidence of ionized exospheric particles.

The first observation of PCWs upstream from Mars' bow shock was made by Phobos-2 (Russell et al., 1990). These waves had small amplitudes (~ 0.15 nT), they were left-hand elliptically polarized in the SC frame, and propagated at a small angle to the mean magnetic field. PCWs have also been observed by Mars Global Surveyor (MGS) (Brain et al., 2002; Mazelle et al., 2004). The frequency, polarization and propagation angle of the waves detected by MGS were similar to those determined from Phobos-2 observations, except their amplitude (2–3 times greater). Waves at the local proton cyclotron frequency have also been observed upstream from Venus (Delva et al., 2009) and active comets (Tsurutani, 1991; Mazelle and Neubauer, 1993 and references therein).

The eccentric orbits of MGS during the mission's pre-mapping phase (Albee et al., 2001) allowed observations of PCWs up to $15R_M$ ($1R_M$=3390 km: Mars radius). Brain et al. (2002) performed a statistical analysis of the properties of these waves during the first aerobraking (AB1) and science phasing orbit (SPO) phases. A few years later, Wei and Russell (2006) analyzed 85 events during the AB1 phase and discussed the generation mechanisms at large distances, as well as the possible distribution of waves depending on the direction of $\vec{E}_c = -\vec{v} \times \vec{B}$. Similar analyses were presented by Delva et al. (2009), based on measurements provided by the magnetometer onboard the Venus Express spacecraft during 450 orbits.

In this study we carry out an analysis of the PCWs detected by the magnetometer and the electron reflectometer (MAG/ER) onboard MGS in the region upstream from the Martian bow shock during the mission's SPO phase. We analyze the frequency, propagation and polarization properties of these waves and discuss the generation mechanisms and their relationship to the neutral densities at the exosphere of Mars. We also analyze the spatial distribution of these waves in a magneto-electric coordinate system centered on Mars (MBE). Finally, we study the implications of our results and compare them with recent studies around Mars (Wei and Russell, 2006) and Venus (Delva et al., 2011). This paper is structured as follows. In Section 2 we describe the capabilities and limitations of MAG/ER in characterizing the properties of the PCW's, along with a description of the various methods of analysis that we applied to the measurements. In Section 3 we show typical examples of PCW's as detected by MAG/ER and obtain their properties based on the methods described in Section 2. Next, we show statistical analyses of the amplitude and the spatial distribution of these waves, as well as the Solar Wind IMF cone angle associated with them. In Section 4 we present a discussion of the results, and the theoretical approaches that might explain the generation of these waves. Finally in Section 5 we summarize our conclusions.

2. Upstream waves: analysis methods

MGS entered into orbit around Mars on 11 September 1997 (Albee et al., 2001). During the pre-mapping AB and SPO phases, MGS provided measurements of the Martian environment from the unperturbed Solar Wind down to the neutral atmosphere from 1683 elliptical orbits. After these orbital phases, MGS reached a final circular mapping orbit at 400 km altitude.

MGS carried a combination of a twin-triaxial fluxgate magnetometer system (MAG) and an electron spectrometer used as a reflectometer (ER) (Acuña et al., 1992). MGS did not carry any instruments dedicated to the measurements of ion properties. The magnetometers (MAG) provided fast measurements (32 vectors/s) over a wide dynamic range (from ± 4 nT to ± 65536 nT), and the electron spectrometer (ER) measured the electron fluxes in 30 logarithmically spaced energy channels ranging from 10 eV to