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Ionospheric plasma acceleration at Mars: ASPERA-3 results

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Abstract

The Analyzer of Space Plasma and Energetic Atoms (ASPERA) on-board the Mars Express spacecraft (MEX) measured penetrating solar wind plasma and escaping/accelerated ionospheric plasma at very low altitudes (250 km) in the dayside subsolar region. This implies a direct exposure of the martian topside atmosphere to solar wind plasma forcing leading to energization of ionospheric plasma. The ion and electron energization and the ion outflow from Mars is surprisingly similar to that over the magnetized Earth. Narrow "monoenergetic" cold ion beams, ion beams with broad energy distributions, sharply peaked electron energy spectra, and bidirectional streaming electrons are particle features also observed near Mars. Energized martian ionospheric ions (O^+, O_2^+, CO_2^+, etc.) flow in essentially the same direction as the external sheath flow. This suggests that the planetary ion energization couples directly to processes in the magnetosheath/solar wind. On the other hand, the beam-like distribution of the energized plasma implies more indirect energization processes like those near the Earth, i.e., energization in a magnetized environment by waves and/or parallel (to B) electric fields. The general conditions for martian plasma energization are, however, different from those in the Earth's magnetosphere. Mars has a weak intrinsic magnetic field and solar wind plasma may therefore penetrate deep into the dense ionospheric plasma. Local crustal magnetization, discovered by Acuña et al. [Acuña, M.J., Connerey, J., Ness, N., Lin, R., Mitchell, D., Carlsson, C., McFadden, J., Anderson, K., Rème, H., Mazelle, C., Vignes, D., Wasilewski, P., Cloutier, P., 1999. Science 284, 790–793], provide some dayside shielding against the solar wind. On the other hand, multiple magnetic anomalies may also lead to "hot spots" facilitating ionospheric plasma energization. We discuss the ASPERA-3 findings of martian ionospheric ion energization and present evidences for two types of plasma energization processes

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responsible for the low- and mid-altitude plasma energization near Mars: magnetic field-aligned acceleration by parallel electric fields and plasma energization by low frequency waves.

Keywords: Mars, atmosphere; Ionospheres; Magnetospheres

1. Introduction

Energization and escape of ionospheric plasma from the inner planets in the Solar System is the result of external forcing by the expanding solar corona plasma—the solar wind. For a strongly magnetized planet like the Earth the solar wind forcing is indirect, direct penetration of solar wind plasma to the upper atmosphere/ionosphere only taking place in two narrow dayside region—the polar cusps. Weakly magnetized planets like Venus and Mars behave more like comets, the entire dayside atmosphere/ionosphere representing a target for solar wind forcing, directly transferring energy and momentum to the ionosphere (e.g., Luhmann and Bauer, 1992). Solar wind forcing of a planetary atmosphere/ionosphere leads to loss of planetary matter, a planetary wind. The processes leading to such losses are essentially the same for all non-magnetized objects, including the more visible losses observed in the tail of comets. The question is rather, how different are the escape processes between magnetized and non-magnetized objects?

The escape and total loss of planetary volatiles from Mars has been subject for discussions ever since the confirmation of a "dry" planet in the late 1960 and early 1970. Various reasons for water drainage have been proposed such as catastrophic impact, Jeans escape and hydrodynamic escape (e.g., Melosh and Vickery, 1989; Chassifiere, 1996; Kerr and Wetter, 2000). In addition non-thermal escape due to solar wind forcing has been proposed (e.g., McElroy et al., 1977; Pérez-de-Tejada, 1987; Luhmann and Bauer, 1992). Based on the ASPERA findings from Phobos-2 (Lundin et al., 1989) the non-thermal ion escape was estimated to ≈ 1 kg/s. The ion composition of the non-thermal ion escape at Mars, the planetary wind, is a mix of O^+ and ionized molecules such as O_2^+ and CO_2^+ (Norberg et al., 1993). The major portion of the outflow was found to have energies below a few hundred eV, the outflow concentrated along the flanks of the martian tail (Lundin and Dubinin, 1992). On the other hand, observations in the central tail of Mars, the plasma sheet, frequently displayed ions beams accelerated up to several keV (e.g., Lundin et al., 1990; Verigin et al., 1991). The central tail of Mars is therefore of particular interest with regard to the acceleration of plasma.

The plasma tail of a "non-magnetized" planet like Mars contains a mix of planetary and solar wind plasma, with a strong preference of planetary plasma in the inner tail (Lundin et al., 1989, 1990). This suggests that the induced magnetic field of a non-magnetized planet provide some shielding against solar wind penetration, at least in the nightside-tail region. However, the induced magnetic shielding appears to be less effective in the dayside and flank regions. The solar wind can penetrate deep into the dayside ionosphere, down to some 270 km altitude (Lundin et al., 2004). The solar wind is also effectively interacting directly or indirectly with ionospheric plasma along the entire flanks of the induced magnetosphere of Mars, especially inside what has been termed the mass-loading boundary (e.g., Lundin et al., 1991). Notice that the mass-loading boundary is not synonymous with the magnetic pile-up boundary, MPB (Vignes et al., 2000), or the induced magnetosphere boundary, IMB (Lundin et al., 2004). IMB is defined as the envelope of the induced martian magnetosphere, marking a stopping boundary for solar wind plasma, the interior dominated by plasma of planetary origin. We note that this is only partly true because of the temporary access of solar wind plasma inside IMB (Lundin et al., 2004). Although the MPB (from B-field) and IMB (from particles) are conceptually different, they may yet represent the same boundary in space. On the other hand, the mass-loading boundary represents a smooth sheath transition region lying outside of MPB/IMB. Inside the mass-loading boundary the sheath plasma show signatures of heavy mass-loading, i.e., a gradual velocity decrease inwards (Lundin et al., 1991). From a kinetic point of view mass loading represents a direct or indirect transfer of energy and momentum from the solar wind to the planetary plasma (Pérez-de-Tejada, 1987, 1998). Such a kinetic approach is useful for the overall energy and momentum transfer, but it does not provide any details of the process that leads to such a direct or indirect forcing.

Localized energization and loss processes such as wave-particle interaction and quasi-static electric fields are well known in the Earth's magnetosphere (see, e.g., book edited by Paschmann et al., 2002). The question is, do similar processes take place in the martian plasma environment? Furthermore, does the induced magnetic field, or the crustal magnetic play a role in the plasma energization at Mars?

The crustal magnetic field at Mars is an intriguing phenomena (Acuña et al., 1999). The field strength is apparently sufficient to magnetize the ionospheric plasma and to enable plasma access and energization processes like those above the Earth. The crustal magnetic field at Mars provide localized dayside shielding fending off the solar wind, but leaves at the same time open throats (cusps) where solar wind have focused access (Krymskii et al., 2002; Brain et al., 2005). In the latter case a magnetized ionospheric plasma is subject to localized external forcing, the diverging magnetic field geometry facilitating upward energization and outflow of ionospheric plasma. The scattered multipole surface magnetic field at Mars therefore acts as both protection against and site for ionospheric plasma outflow (Brain et al., 2005), the net global effect for the outflow yet to be determined. Magnetic flux tubes from martian magnetic anomalies swept tailward by the solar wind (Mitchell et al., 2001) should also play a role in the energization and outflow of ionospheric plasma (Brain et al., 2005). Here again a diverg-