Planetary and Space Science 58 (2010) 1442–1454

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Transterminator ion flow in the Martian ionosphere

M. Fränz [a,*], E. Dubinin [a], E. Nielsen [a], J. Woch [a], S. Barabash [b], R. Lundin [b], A. Fedorov [c]

[a] Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany
[b] Swedish Institute for Space Physics, 89128 Kiruna, Sweden
[c] Centre dEtude Spatiale des Rayonnements, 31028 Toulouse, France

ARTICLE INFO

Article history:
Received 19 March 2010
Received in revised form
7 June 2010
Accepted 14 June 2010
Available online 22 June 2010

Keywords:
Mars
Ionosphere
Atmospheric escape

ABSTRACT

The upper ionospheres of Mars and Venus are permeated by the magnetic fields induced by the solar wind. It is a long-standing question whether these fields can put the dense ionospheric plasma into motion. If so, the transterminator flow of the upper ionosphere could explain a significant part of the ion escape from the planets atmospheres. But it has been technically very challenging to measure the ion flow at energies below 20 eV. The only such measurements have been made by the ORPA instrument of the Pioneer Venus Orbiter reporting speeds of 1–5 km/s for O^+ ions at Venus above 300 km altitude at the terminator (Knudsen et al., 1980, 1982). At Venus the transterminator flow is sufficient to sustain a permanent nightside ionosphere, at Mars a nightside ionosphere is observed only sporadically. We here report on new measurements of the transterminator ion flow at Mars by the ASPERA-3 experiment on board Mars Express with support from the MARSIS radar experiment for some orbits with fortunate observation geometry. We observe a transterminator flow of O^+ and O_2^+ ions with a super-sonic velocity of around 5 km/s and fluxes of $0.8\times10^9/\mathrm{cm}^2\,\mathrm{s}$. If we assume a symmetric flux around the terminator this corresponds to an ion flow of $3.1\pm0.5\times10^{25}$/s half of which is expected to escape from the planet. This escape flux is significantly higher than previously observed on the tailside of Mars. A possible mechanism to generate this flux can be the ionospheric pressure gradient between dayside and nightside or momentum transfer from the solar wind via the induced magnetic field since the flow velocity is in the Alfvénic regime. We discuss the implication of these new observations for ion escape and possible extensions of the analysis to dayside observations which may allow us to infer the flow structure imposed by the induced magnetic field.

1. Introduction

On the dayside of planets Mars and Venus the upper atmosphere is ionized by solar ultraviolet radiation and an ionosphere is formed (Schunk and Nagy, 2009). This was first observed on Mars by the Mariner 4 spacecraft in 1965 (Kliore et al., 1965; Fjeldbo and Eshleman, 1968) and for Venus by the Mariner 5 spacecraft in 1967 (Kliore et al., 1967; Fjeldbo and Eshleman, 1969). The peak density of ions at low solar zenith angles is observed at an altitude of 130–150 km at both planets. Since the Venus ionosphere has been much better studied than the Mars ionosphere we first summarize the relevant observations at Venus.

General reviews on the Venusian ionosphere can be found in Cravens et al. (1997), Fox and Kliore (1997), and Kar (1996). A more recent summary of models and observations in Fox (2008). The Mariner 5 observations showed surprisingly a highly variable but significant ionosphere on the nightside of Venus, which was later quantified by observations on the Pioneer Venus Orbiter (PVO) (Miller et al., 1980). Since ions are expected to recombine with the ambient electrons during the 58-day night of Venus a steady supply of ions from the dayside must exist to maintain the nightside ionosphere. It was already suggested by McElroy and Strobel (1969) that the transterminator ion flow can deliver this supply. That a significant quantity of ions is indeed transported from the dayside to the nightside across the terminator of Venus was first observed by the Orbiter Retarding Potential Analyzer (ORPA) on board PVO using just a few orbits of observations (Knudsen et al., 1980). These first observations showed a chaotic but generally tailward motion of O^+ ions with velocities of 1–8 km/s. Above 200 km altitude O^+ is the dominant ion species at the terminator, while O_2^+ and H^+ ions contribute less than 10% to the total ion density (Miller et al., 1980). The analysis of these observations was later extended using statistics from 3.5 years of PVO observations to derive the mean transterminator ion flow at Venus as a function of altitude (Knudsen et al., 1982) and later extended to cover solar maximum conditions (Knudsen and Miller, 1992). These statistics showed that the transterminator ion

* Corresponding author. Tel.: +49 5556 979 441.
E-mail address: fraenz@mps.mpg.de (M. Fränz).

0032-0633/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2010.06.009

flow at Venus has a mean velocity of about 1–2 km/s at 300 km altitude and increases to 4 km/s at 600 km altitude. Transient velocities up to 8 km/s have been observed. The mean transterminator ion flux was observed to be $2\times10^9/cm^2$ s-sufficient to maintain the nightside ionosphere of Venus. The observations of the PVO ORPA experiment were summarized in Miller and Whitten (1991) who showed that the velocity of ions on the dayside increases with solar zenith angle and that there is a dawn–dusk asymmetry in the flow-pattern (their Fig. 15) for which at the time no explanation was found. Recently Fox and Kasprzak (2007) reported a dawn–dusk asymmetry in the thermosphere which may be related to the asymmetry in the ionospheric flow. Also Fox (2008) showed that new models of the dayside ion production at Venus are in agreement with the transterminator flux at Venus but cannot explain the loss rates of more than 10^{25} ions/s as observed in the tail of Venus by the Venus Express ASPERA-4 instrument (Barabash et al., 2007b).

It was suggested by Cravens et al. (1982) and Whitten et al. (1982) and analyzed by Miller and Knudsen (1987) that the transterminator flux at Venus is controlled by the terminator ionopause altitude and thus by solar wind pressure. The flow speed can be modeled as a function of the pressure gradient between dayside and nightside ionosphere in an inviscid flow model (Elphic et al., 1984). Though ionospheric depletions on the nightside are associated with strong radial magnetic fields, the transterminator transport seems not to be affected by the magnetization state of the ionosphere—though this has not been investigated in detail (Elphic et al., 1985). The reason for the lack of analysis of this dependence is the high variation of magnetization states and the non-coincidence of dayside, nightside and terminator observations by PVO. Analysis of the electron density profiles by the radio occultation experiment on PVO (Woo and Kliore, 1991) suggests that a current with increased density forms at about 200 km altitude in the case of magnetization of the ionosphere which should also influence the transterminator flow. Also magneto-hydrodynamic models suggest that the magnetic pressure gradient force in the upper ionosphere can drive the super-sonic ion flow in the Venus ionosphere (Cravens and Shinagawa, 1991).

At Mars the amount of observations is much smaller since only the Viking landers carried instrumentation to measure constituents and bulk properties of the Martian ionosphere (Hanson et al., 1977; Mantas and Hanson, 1987). General reviews on the Martian ionosphere can be found in Barth et al. (1992), Luhmann et al. (1992), Kar (1996), and Nagy et al. (2004), more recent summaries of models and observations in Withers (2009) and Fox (2009). The nightside ionosphere of Mars was first probed by the radio occultation experiment on the Viking orbiters (Zhang et al., 1990) which showed that on Mars a nightside ionosphere with peak density $>10^4\,cm^{-3}$ was only observed for 40% of the obtained profiles. Since models of the dayside ionosphere suggest that the ion production and flow should be similar to Venus (Fox, 2009) a comparable transterminator flow should be expected at Mars. In general low energy ion flows can best be measured by retarding potential analyzers (RPA) which measure the current excited by the ion flow and are thus not limited by saturation and background noise effects affecting particle counters (see Klenzing et al., 2009, for a recent review on RPAs). Unfortunately the only instrument of this type flown on a Martian mission, the HARP instrument on Phobos-2, was not able to disentangle spacecraft potential effects at low energies and thus was not able to quantify the transterminator flow—though the observations indicated significant low energy ion flow (Shutte et al., 1997; Szegö et al., 1998). The TAUS experiment on Phobos-2 was an ion spectrometer with crude mass resolution and a lower energy limit of 30 eV—thus it was only able to measure the total ion outflow downstream of the planet which was evaluated to be 5×10^{24}/s averaged over all Phobos-2 orbits (Verigin et al., 1991). The ASPERA experiment on the same spacecraft could in principle measure low energy ions and determined the total tailward flow to be 3×10^{25}/s (Lundin et al., 1989). All the Phobos-2 observations were limited by the fact that Phobos-2 did not get closer to the planet than 800 km and below 1000 km on only four orbits.

This situation changed with the arrival of the Mars Express spacecraft at the planet in 2004. Mars Express carries the radar instrument MARSIS to determine local electron density and magnetic field intensity as well as top-side ionospheric electron density profiles (Gurnett et al., 2005; Nielsen et al., 2006). In addition the thermal ion spectrometer ASPERA-3 observes ions with mass separation down to energies of 10 eV (Barabash et al., 2006)—though observation at energies below 200 eV is only possible since an instrument reconfiguration in May 2007. The ASPERA-3 electron sensor can determine the spacecraft potential by identification of photo-electron spectral lines (Frahm et al., 2006). Previous analyses of the ASPERA-3 ion data concentrated on observations of the tailward ion outflow outside of the ionosphere to avoid the problems of measurements at very low energies (Barabash et al., 2007a; Carlsson et al., 2006). The low energy measurements since May 2007 have been used by Lundin et al. (2008b) to determine the total ion outflow at solar minimum (3.3×10^{24}/s) and the mean O_2^+/O^+-ratio in the outflow (2/3) (Lundin et al., 2009). But it could not be shown whether the acceleration of ions happens inside or outside of the ionosphere. In the following we try for the first time to use the combined observations of the MARSIS and ASPERA-3 experiments to determine the transterminator flow in the upper ionosphere of Mars.

2. Instruments

The MEX spacecraft is in a highly eccentric polar orbit around Mars with periapsis and apoapsis of ~275 and 10 000 km, respectively. The ASPERA-3 (Analyzer of Space Plasma and Energetic Atoms) experiment is a combination of in situ and remote diagnostics of atmospheric escape induced by the solar wind. It comprises the Ion Mass Analyzer (IMA), ELectron Spectrometer (ELS), Neutral Particle Imager (NPI) and Neutral Particle Detector (NPD) (Barabash et al., 2006). The Ion Mass Analyzer (IMA) determines the composition, energy and angular distribution of ions in the energy range $\approx10\,eV/q-30\,keV/q$. Mass (m/q) resolution is provided by combination of the electrostatic analyzer with deflection of ions in a cylindrical magnetic field set up by permanent magnets. A new patch uploaded on 1 May 2007 has further improved the IMA performance, extending the energy range down to cold/low-energy ions (≤10 eV). In the energy range ≥50 eV, it measures fluxes of different (m/q) ion species with a time resolution of 192 s and a field of view of $90^\circ\times360^\circ$ (electrostatic sweeping provides elevation coverage $\pm45^\circ$). The measurements of the cold/low-energy component (≤50 eV) are carried out without the elevation coverage but with an increased time-resolution of these 2D-measurements of 12 s. The field of view for low-energy ions is $6^\circ\times360^\circ$ with an azimuthal angular resolution of 22.5°. The effective energy resolution of the ion sensor is $\delta E/E=9\%$, the nominal mass resolution $\delta M/M=10\%$ is in principal sufficient to discriminate between O^+ and O_2^+ ions. In practice scattering within the ion optics and saturation of the sensor at high ion fluxes reduces mass resolution at low energies to $\delta M/M\sim30\%$. The ELS sensor measures 2D distributions of the electron fluxes in the energy range 1 eV–20 keV ($\delta E/E=8\%$) with a field of view of $4^\circ\times360^\circ$ and a time resolution of ~4 s. A grid usually biased