Planetary and Space Science 119 (2015) 54–61

Contents lists available at ScienceDirect

Planetary and Space Science

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

Seasonal variation of Martian pick-up ions: Evidence of breathing exosphere

M. Yamauchi [a],*, T. Hara [b], R. Lundin [c], E. Dubinin [d], A. Fedorov [e], J.-A. Sauvaud [e], R.A. Frahm [f], R. Ramstad [a], Y. Futaana [a], M. Holmstrom [a], S. Barabash [a]

[a] Swedish Institute of Space Physics (IRF), Box 812, SE-98128 Kiruna, Sweden
[b] Space Sciences Laboratory, University of California, Berkeley, CA, USA
[c] Swedish Institute of Space Physics (IRF), Teknikhuset, SE-90187 Umea, Sweden
[d] Max-Planck-Institut fur Sonnensystemforschung, Justus-von-Liebig-Weg 3, DE-37077 Göttingen, Germany
[e] Institut de Recherche en Astrophysique et Planetologie (IRAP), CNRS/Universite de Toulouse, 9 avenue du Colonel Roche, BP 44346, F-31028 Toulouse, Cedex 4 France
[f] Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238, USA

ARTICLE INFO

Article history:
Received 16 February 2015
Received in revised form
8 September 2015
Accepted 9 September 2015
Available online 21 September 2015

Keywords:
Pick-up ions
Mars Express
Exosphere
Hydrogen corona
Solar UV effect
Seasonal variation
Solar cycle
Atmospheric escape
ASPERA-3

ABSTRACT

The Mars Express (MEX) Ion Mass Analyser (IMA) found that the detection rate of the ring-like distribution of protons in the solar wind outside of the bow shock to be quite different between Mars orbital summer (around perihelion) and orbital winter (around aphelion) for four Martian years, while the north–south asymmetry is much smaller than the perihelion–aphelion difference. Further analyses using eight years of MEX/IMA solar wind data between 2005 and 2012 has revealed that the detection frequency of the pick-up ions originating from newly ionized exospheric hydrogen with certain flux strongly correlates with the Sun–Mars distance, which changes approximately every two years. Variation due to the solar cycle phase is not distinguishable partly because this effect is masked by the seasonal variation under the MEX capability of plasma measurements. This finding indicates that the variation in solar UV has a major effect on the formation of the pick-up ions, but this is not the only controlling factor.

1. Introduction

Planetary ionospheres and exospheres are affected by the flux from solar extreme ultraviolet (EUV) radiation because the energy required for ionizing atoms or neutrals corresponds to the energy of EUV (Chapman, 1931). As a result, all models of planetary ionospheres and exospheres predict a strong dependency of the ionospheric/exospheric density (at given altitude) on the solar EUV flux (e.g., Lammer et al., 2009; Bougher et al., 2014; Chaufray et al., 2015). For example, the density distribution and behavior of ions above the ionosphere (e.g., escape) are expected to depend on the solar EUV flux.

Observations support the expected dependence of the ionospheric condition and of the resultant ion escape on the solar EUV flux. For the Earth, the ionospheric density changes by an order of magnitude between the solar maximum and minimum in the established International Reference Ionosphere (e.g., Bilitza et al., 2014), and the resulting escape rate of ionospheric oxygen (O^+) is found to vary by more than an order of magnitude between low F10.7 (proxy for EUV flux) and high F10.7 index (Cully et al., 2003). On Venus, the observed ionopause location changes drastically between the solar maximum and minimum, and this change is attributed mainly to the EUV difference (Zhang et al, 1990). The escape rate of the planetary hot ions from the nightside of Mars also depends on the F10.7 flux (Lundin et al., 2013). Lundin et al. (2013) further obtained the escape rate as a simple function of the F10.7 index and the sunspot number.

Planetary ion escape also depends on the extent of the planet's exosphere because the exospheric neutrals that are exposed to the solar wind are lost by a pick-up mechanism (e.g., Luhmann and Kozyra, 1991; Barabash et al., 1991; Dubinin et al., 2006) as soon as they are ionized by the solar EUV, by charge exchange, or by the electron impact ionization. Inversely, refilling of exospheric neutrals that are lost after the ionization causes a faster expansion rate of the exosphere. Therefore, the solar EUV flux strongly influences

---

* Corresponding author. Tel.: +46 980 79120; fax: +46 980 79050.
E-mail address: M.Yamauchi@irf.se (M. Yamauchi).

http://dx.doi.org/10.1016/j.pss.2015.09.013

the loss rate of the exosphere through both the ionization efficiency and the exospheric scale height.

In such EUV-dependent loss processes, the amount of ionized exospheric neutrals inside the solar wind (including the magnetosheath) is the key number that is important in estimating the total escape of ions of exospheric origin and the dependence of this escape rate on seasonal/solar cycle variations. Among Earth, Venus, and Mars, the role of this mechanism and its seasonal/solar cycle dependence is most dominant at Mars, because the weak gravity of Mars and the large extent of its exosphere beyond the magnetopause or ionopause, causes the exosphere to be exposed to the solar wind.

There are some observations relating how much the Martian exosphere and relevant ion production vary with the solar EUV flux. Using electron data at 390 km altitude from the Mars Global Surveyor (MGS), Forbes et al. (2008) reported nearly two-year variations of the electron density and temperature, and this variation was more evident than the solar cycle variation (see also Bruinsma et al., 2014). Chaffin et al. (2014) used Lyman-alpha emission observed by the Mars Express (MEX) (Chicarro et al, 2004) ultraviolet spectrometer (Bertaux et al., 2006), and showed that the estimated exospheric temperature changed more drastically than the expected change from the EUV variation (see also Chaufray et al., 2009; Clarke et al., 2014). Bertucci et al. (2013) analyzed MGS magnetic field data during one year (from September 1997 to September 1998) and showed that proton cyclotron waves upstream of the bow shock (indication of generation of exospheric-origin cold protons) are observed most frequently during perihelion. However, no direct ion observations have been reported on the solar EUV dependency of the amount of ionized exospheric neutrals in the solar wind.

Mars Express has over 10 years of observations at Mars, including ion mass analyzer (IMA) observations of the solar wind outside the bow shock. In this region, IMA is capable of observing the pick-up ions of exospheric origin (Dubinin et al., 2006; Yamauchi et al., 2006; 2008) as well as reflected solar wind (Yamauchi et al., 2011, 2012). Although there are some operational and observational restrictions in detecting the pick-up ions by IMA, the length and quality of the IMA data are sufficient to statistically diagnose seasonal and solar cycle variations.

2. Instrument

The MEX Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment contains one ion instrument (IMA), one electron instrument (Electron Spectrometer: ELS), and two instruments to measure energetic neutral atoms.

During more than 10 years of operation, the IMA energy-sweep scheme changed several times to emphasize different regions of the ion energy spectrum (the energy scan from the highest energy to the lowest energy with 12 s cycle was unchanged). Before 30 April 2007, IMA intended to cover a downgoing energy range of 30 keV/q to 10 eV/q with 96 logarithmically scaled energy steps (from about 3 kV to about 1 V potential drop within two spheres of the electrostatic analyzer between which ions travel (Barabash et al., 2004, 2006)), but it turned out that IMA could not accurately determine ions with energies less than 100 eV. Therefore, the IMA energy sweep scheme was reset for the energy range from 30 keV/q to 50 eV/q with 76 logarithmically scaled energy steps and then from 50 eV/q to 10 eV/q in 20 linearly scaled energy steps between 30 April 2007 and 16 November 2009 (Lundin et al., 2009), and from 20 keV to 50 eV/q with 66 logarithmically scaled energy steps and then from 50 eV to -20 eV/q in 30 linearly scaled energy steps after 16 November 2009. This -20 eV/q setting allows IMA to measure ions close to the spacecraft potential and the linear stepping range decreases the rate of voltage decay, allowing the power supply to settle the targeted voltage for an accurate energy measurement.

After completion of the energy scan every 12 s, IMA executes a scan step in elevation. The IMA elevation covers the angular range from $-45°$ to $+45°$ (elevations 0–15) in 192 s using an electrostatic deflection system with about 5° elevation resolution. After 30 April 2007, elevation scanning is disabled on the portion of the energy sweep below 50 eV/q. Since the detection of pick-up ions requires ion measurements at an energy range around the solar wind energy, i.e., from sub-keV to several keV (Yamauchi et al., 2006, 2008; Hara et al., 2013), changes in the energy sweep and elevation scanning do not affect the present study.

IMA also contains a magnetic deflection system (supported by 16 identical permanent magnets) which separates the ions according to M/q after they are electrostatically analyzed. IMA simultaneously measures ions up to 40 amu/q, which spread across a microchannel plate (MCP) sensor depending on the ion energy and M/q, into 32 mass channels. By accelerating ions that went through the energy analyzer before entering the mass analyzer (post acceleration), the mass resolution can be changed between low, medium, and high resolutions (corresponding to high, medium, and no post acceleration, respectively). The low mass-resolution mode is best for detecting the low mass ions like H^+ and He^+, while in the high mass-resolution mode, the solar wind protons are often completely deflected to outside the sensor area. Therefore, one may not mix IMA data taken during different mass-resolution modes for statistical studies. Note that light ions which are deflected outside the sensor area are reflected back from the outer wall of IMA, reaching the sensor in the central area of the MCP, and generating counts in the incorrect mass channels.

MCPs that are used in many medium-energy (around 1 keV) ion sensors including IMA often degrade after long exposure to intense ion beams such as those from the solar wind and radiation belt (e.g., Yamauchi et al., 2013). However, the efficiency of MEX/IMA has not degraded during more than 10 years of operation since the accumulated total count over 10 years was much lower than the specification for the IMA/MCP (In fact, the MCP bias voltage did not require adjusting in order to maintain sensitivity). Therefore, all data collected during 2005–2012 (more than 10000 inbound or outbound traversals across the bow shock) may be treated equally.

ASPERA-3 electrons are measured with Electron Spectrometer (ELS). With angular acceptance width of 4°, ELS covers an energy range from 0.5 eV to 20 keV and is capable of helping identification of bow shock and foreshock, and hence confirming IMA observations of pick-up ions.

Both IMA and ELS are top-hat instruments with 360° azimuthal field of view, divided into 16 sectors (0-15), each 22.5° wide. Note that some reports that have used IMA data refer to different sector numbering (1–16), whereas this paper uses numbering of 0–15 (the same as Yamauchi et al., 2006, 2011). For details of the IMA and ELS instruments, see Barabash et al. (2004, 2006), Fedorov et al. (2006), and Frahm et al. (2006a, 2006b).

3. Analysis methods and restrictions

In the IMA energy–time spectrograms, pick-up ions form a clear ring distribution display (an energy arch) in an energy-azimuth/elevation angle scan at about 2–5 times the solar wind proton energy (Yamauchi et al., 2006, 2008). However, its appearance varies depending on the intensity. Fig. 1 shows three consecutive outbound traversals from the bow shock to upstream solar wind, in which one can recognize the ring-like distribution of pick-up ions at around 3–4 keV in the second traversal (Fig. 1b) as