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Oxygen foreshock of Mars

M. Yamauchi [a,*], R. Lundin [b], R.A. Frahm [c], J.-A. Sauvaud [d], M. Holmström [a], S. Barabash [a]

[a] Swedish Institute of Space Physics (IRF), Box 812, SE-98128 Kiruna, Sweden
[b] Swedish Institute of Space Physics (IRF), Teknikhuset, SE-90187 Umeå, Sweden
[c] Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238, USA
[d] Institut de Recherche en Astrophysique et Planetologie (IRAP), CNRS/Université de Toulouse, 9 avenue du Colonel Roche, BP 44346, F-31028 Toulouse, Cedex 4 France

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ABSTRACT

Mars Express (MEX) has operated for more than 10 years in the environment of Mars, providing solar wind ion observations from the Analyzer of Space Plasmas and Energetic Atoms experiment's Ion Mass Analyser (IMA). On 21 September 2008, MEX/IMA detected foreshock-like discrete distributions of oxygen ions at around 1 keV in the solar wind attached to the bow shock and this distribution was observed continuously up to more than 2000 km from the bow shock. Foreshock-like protons are also observed but at a shifted location from the oxygen by about 1000 km, at a slightly higher energy, and flowing in a slightly different direction than the oxygen ions. Both protons and oxygen ions are flowing anti-sunward at different angles with respect to the solar wind direction. This is the first time that a substantial amount of planetary oxygen is observed upstream of the bow shock. Although rare, this is not the only IMA observation of foreshock-like oxygen: oxygen ions are sometimes observed for a short period of time (<5 min) inside the foreshock region. These observations suggest a new escape channel for planetary ions through the acceleration in the bow shock–magnetosheath region.

1. Introduction

In the solar wind where the interplanetary magnetic field (IMF) points toward the bow shock, a region of ions flowing away from the bow shock with energy higher than the solar wind is sometimes formed (e.g., Asbridge et al., 1968; Eastwood et al., 2005). This phenomenon is the foreshock. Besides the solar wind, there are two types of foreshock ions: high-energy ions with diffuse pitch angle–energy distributions and low-energy ions (up to about 6 times the solar wind energy) with discrete pitch angle–energy distributions. The latter is further subdivided into field-aligned ion beams and gyrating ion flow (Eastwood et al., 2005; Yamauchi et al., 2011). In this paper we consider only the discrete component. The He^{++}/H^{+} ratio of foreshock ions upstream of the Earth's bow shock is lower than the ratio in the solar wind or magnetosheath (Fuselier and Thomsen, 1992). For the magnetospheric component, AMPTE/CCE spacecraft detected energetic O^{+} of more than 40 keV inside the foreshock (Möbius et al., 1986; Krimigis et al., 1986). However, they are interpreted as either the diffuse component that went though the Fermi acceleration inside the bow shock (Möbius et al., 1986) or leakage from the magnetosphere (Edmiston et al., 1982; Krimigis et al., 1986; Sarris et al., 1987; Sibeck et al., 1988). Foreshocks with a discrete component of O^{+} at several keV have never been detected.

The probability of observing foreshocks is different for different planets or objects: they are often observed upstream of the terrestrial and Venus bow shocks, but seldom observed upstream of the Martian bow shock. Phobos-2 observed the foreshock signatures upstream of the Martian bow shock (Dubinin et al., 2000); however, using the Mars Express (MEX) ion mass analyser (IMA) data for the 2004–2005 period, we could not find ion distributions similar to the foreshock ions of the Earth or Venus (Yamauchi et al., 2011) in the dayside upstream region of Mars.

Instead, MEX/IMA detected reflected ions and tailward ion flow, just outside of the bow shock. These ions form a double foot structure outside the bow shock. The first layer (foot) at very close to the bow shock boundary (within about an ion inertia length) is associated with a tailward directed collimated ion flow along the bow shock surface. The second layer is associated with reflected solar wind protons. These reflected solar wind protons continually return to the bow shock for another reflection after gyrating around the interplanetary magnetic field (IMF) (Yamauchi et al., 2011). Such a multiple reflection signature has not been found at Venus, although this could be due to the spatial resolution of the observation (Venus Express traverses the bow shock very quickly compared to MEX). Yamauchi et al. (2011) suggested that the

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

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difference between Venus and Mars comes from the curvature of the bow shock compared to the local ion gyroradius and from the existence of cold ions inside the bow shock (Dubinin et al., 1993).

Although the reflection is considered as a possible mechanism for generating the discrete component of foreshock ions (Gosling et al., 1978; Paschmann et al., 1980; Kucharek et al., 2004), Yamauchi et al. (2011) did not call the reflected ion signature foreshock because (1) the ion distribution was more discrete than ordinary foreshock ions observed at the Earth or Venus, (2) the region where these ions were found was limited to be close to the bow shock, (3) the exact mechanism for reflection still remained as an open question, and (4) foreshock ions might still be formed by mechanisms other than the reflection of the solar wind.

Yamauchi et al. (2012) identified nine cases between 2004 and 2005 where the ion distribution in the foreshock region showed a triple ring structure. The lowest energy ring represents gyromotion around the IMF of pick-up ions that originate from newly ionized exospheric hydrogen. The two extra rings at higher energy represent gyromotion of multiply reflected ions (first and second bounces) around the IMF. The velocity distribution of the pick-up ions was used to identify the magnetic field orientation. The analyses revealed that the reflections could be specular, i.e., without gyration of ions during the trajectory from entering into the bow shock to exiting from the bow shock. Such reflections, i.e., outward accelerations, are possible by an outward directed potential electric field at the bow shock. Since all cases took place at the bow shock flank where the solar wind angle to the bow shock surface is shallow, a strong electric field is not required to reflect 1 keV protons.

On the other hand, many past observations (including those described above) do not exclude local acceleration of ambient ions inside the bow shock–magnetosheath region as an alternative mechanism of forming the foreshock ions, such as wave–particle interactions (Tanaka et al., 1983; Mazelle et al., 2003; Meziane et al., 2004). If cold ions exist inside this acceleration region (in the bow shock–magnetosheath), its behavior could give hint to the acceleration mechanism because potential acceleration energizes cold ions whereas Lorentz force acceleration will not. The Martian bow shock is a good candidate for holding such cold ions (Dubinin et al., 1993), originating from ionized exospheric atoms (coronas). Since the foreshock acceleration mechanism must equally influence such cold ions as well as the solar wind, the cold ion (particularly if it is oxygen) provides extra information about the foreshock acceleration mechanisms.

On 21 September 2008, MEX/IMA detected foreshock-like oxygen ions (O^+) at around 1 keV as intense as protons (H^+), and extending outward from the dayside bow shock. This is the first time that intense O^+ at that energy is observed upstream of the dayside bow shock, including the other planets (for Earth the energy would be much higher). The observation also indicates for the first time that a substantial amount of low-energy O^+ may exist at the bow shock location of Mars. Furthermore, the O^+–H^+ difference provides new information on the acceleration mechanism of the foreshock.

2. Instrument

MEX carries one ion instrument (IMA) and one electron instrument (Electron Spectrometer: ELS). IMA measures ions below 30 keV/q in a 96 step energy sweep every 12 s. The low energy limit and scaling had changed several times during the mission, but the energy stepping above 50 eV remained logarithmic. ELS covers an energy range from 0.5 eV to 20 keV and has several different measurement modes. For the data presented in this paper, ELS measures electrons logarithmically in a 127 step energy sweep every 4 s. Both IMA and ELS are top–hat instruments with a 360° field of view, divided into 16 azimuthal sectors (0–15), each 22.5° wide. The angular acceptance width at the entrance is 4.6° for IMA and 4° for ELS. After completion of each energy scan, IMA also steps the entrance direction, which ranges from −45° to +45° (elevations 0–15) in 192 s using an electrostatic deflection system. Unfortunately, some of IMA's field-of-view (FOV) is blocked by the spacecraft and disappearance of expected counts in the IMF's FOV could sometimes be due to this blockage.

IMA has three mass-resolution modes for detecting different ion species up to 40 amu/q. These three modes have completely different low-energy limits that can detect low-energy protons (the lowest mass-resolution mode is the most favorable for proton detection). For details of the IMA and ELS instruments, see Barabash et al. (2006), Fedorov et al. (2006), and Frahm et al. (2006a, 2006b).

3. Observation

Fig. 1 shows the IMA and ELS observations (energy–time spectrograms) of the outbound traversal of the bow shock from the ionosphere to the solar wind on 21 September 2008. Fig. 2 shows the spacecraft trajectory that corresponds to Fig. 1, indicating that the spacecraft traversed the bow shock nearly radially outward during this bow shock crossing. Fig. 3 shows IMA's FOV at around 01:40 UT of this traversal. From around 01:15 UT to around 01:20 UT, the solar wind was nearly entirely blocked by the spacecraft, and this blockage diminished as the spacecraft moved away from pericenter. Therefore, one may not discuss the intensity of the solar wind for this traversal.

The top two panels of Fig. 1 show the average energy flux accumulated from all azimuthal sectors for the electrons and ions. The lower panels of Fig. 1 show count rates of protons (upper four panels) and heavy ions (lower four panels) from neighboring azimuthal sectors (sectors are common for the protons and heavy

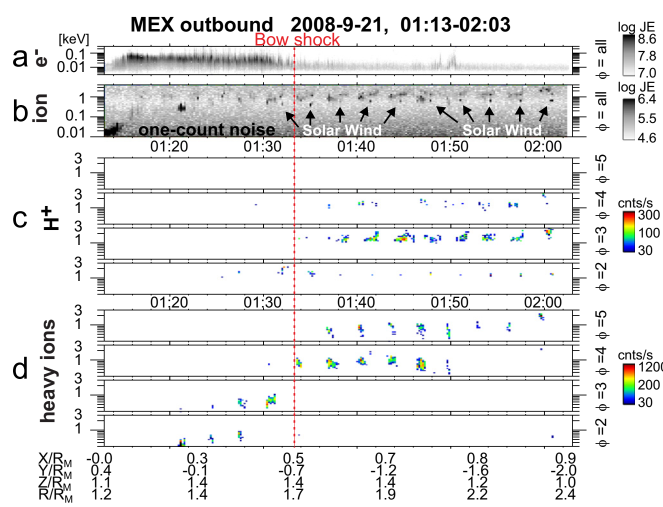

Fig. 1. Observations of foreshock ions during 21 September 2008. Energy–time spectrograms of energy flux (keV cm^{-2} s^{-1} keV^{-1}) for (a) total electron and (b) total ions, and count rate for (c) H^+ at different azimuthal sectors and (d) O^+ at different azimuthal sectors observed by ELS and IMA. Note that this paper uses numbering of 0–15 in the same order as Yamauchi et al. (2006, 2008, 2011, 2012) but some papers used numbering of 1–16. The nearly 3 min (192 s) cycle in the IMA data is due to the scanning cycle in the elevation direction from −45° to +45°. Solar wind protons are observed at around 0.6 keV near 0° elevation angle. The unit R_M is the Mars radius (3397 km). A short burst of electron at around 01:50 UT is consistent with a direct magnetic connection to the bow shock during this short period.