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Foreshock ions observed behind the Martian bow shock

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ABSTRACT

The Mars Express Analyzer of Space Plasmas and Energetic Atoms experiment contains ion and electron instruments for conducting plasma measurements. On January 23, 2012, during in-bound travel of Mars Express in the southern hemisphere of Mars from its dawn side toward periapsis at dusk, the plasma instruments measured foreshock-like ion beams extending from outside the bow shock and into the magnetosphere, continuing to a distance of about a proton gyroradius from the bow shock. These ion beams were mostly protons, were observed to have energies greater than solar wind protons, and were not gyrating, in agreement with reflections of the solar wind proton beam. Furthermore, in the foreshock region the ion energy gradually decreased toward the magnetosheath, in agreement with an acceleration by outward-directed electric field in the bowshock. The observations also suggest that this electric field exists even inside the magnetosheath within the distance of a proton gyroradius from the bow shock.

1. Introduction

The solar wind forms a magnetospheric cavity around Mars. This magnetosphere results from an induced interaction of the solar wind with the upper atmosphere of Mars. The upper atmosphere of Mars ionizes and creates an ionosphere where currents flow to create the induced magnetic field. This causes the solar wind to be deflected around the planet. A shock is formed in front of the planet to deflect the solar wind around the planet. Between this bow shock and the ionosphere is a magnetosheath where the solar wind is diverted around the planet (Luhmann et al., 1995).

The solar wind fluctuates in velocity and density. Variations are observed over a wide range of time scales as the solar wind contains a variety of types of wave activity (Feynman, 1985). At Earth, factor of two pressure pulses of scale up to about 36,000 km wide have been observed in the solar wind which penetrate into the magnetosheath (Hietala et al., 2012). Inside the Earth's magnetosheath, plasmoids of higher momentum density than the surrounding plasma have been observed which can penetrate into the magnetoshere (Gunell et al., 2012). These observations coupled with the observations of waves in the magnetosheath of Mars (Espley et al., 2004, 2005; Winningham et al., 2006), all suggest a measure of similarity in the interactions of the solar wind with Earth and Mars.

Part of the solar wind interaction that creates the bow shock can create a foreshock region of reflected and accelerated electrons and ions. The foreshock is dependent on the interplanetary magnetic field (IMF) and its connection to the bow shock. When the angle between the IMF and bow shock normal is greater than 45°, the shock is quasi-perpendicular and the foreshock region is restricted to near the shock foot (Bale et al., 2005). For an angle less than 45°, the shock is termed quasi-parallel (Burgess et al., 2005) and the foreshock has a much larger domain. For quasi-parallel shocks, the electron foreshock is observed antisunward of the sunward-most IMF field line which connects to the bow shock (Eastwood et al., 2005; Yamauchi et al., 2011) with the ion foreshock more tailward than this location (see examples, Burgess, 1995, Figure 5B.1; Parks, 2004, Figure 10.11; Eastwood et al., 2005, Figures 2.1 and 2.3, Otto, 2006, Figure 6.9). Near the upstream boundary, separation between the electron and ion foreshock regions are related to the angle between the IMF and bow shock normal. It has been found at the Earth that this angle is less than 90° for electrons and less than 70° for ions, which is suggested by Burgess (1995) to be due to the acceleration mechanism for ions being less efficient than for electrons; however, the details may depend on the size and shape of the bow shock.

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Foreshock ions are observed near the bow shock and can flow upstream of the planet in the solar wind; however, it is important to note that foreshock ions are observed in the foreshock region. The classifications of foreshock ions, which are both discrete and diffuse, are termed “reflected”, “intermediate”, and “diffuse” (Bale et al., 2005; Burgess et al., 2005; Pachmann et al., 1981). Foreshock ions have been explained by acceleration following reflections off the bow shock (Burgess and Schwartz, 1984; Oka et al., 2005; Yamauchi et al., 2015) and wave–particle interactions (Meziane et al., 2001; Mazelle et al., 2003). Reflection may take several forms including ion beams and ring distributions (Yamauchi et al., 2006, 2008, 2011, 2012) with energies several times the energy of the solar wind (Eastwood et al., 2005).

Eastwood et al. (2005) summarized observations of electron foreshock distributions as generated from electron beams or waves. Basically since the electron distribution is thermally dominated (as opposed to the kinetic energy-dominated ion distribution), foreshock electrons appear as a high energy tail on the main solar wind electron distribution, with more energetic electrons observed near the tangent to the shock and less energetic electrons deeper in the electron foreshock. Waves are also observed in the electron foreshock region, shifting frequency deeper in the electron foreshock compared to the tangent point. Thus, distinguishing between the addition of an electron beam and wave–particle interactions to the solar wind electron distribution is difficult.

As a special feature of Martian bow shock, where the proton kinetic gyroradius (about 1000 km) and the existence of cold protons of exospheric origin can no longer be ignored, the reflected solar wind ions cause multiple foot structures at the bow shock (the shock foot is where the magnetic field gradually increases in front of the main shock). Sometimes it is difficult to distinguish the reflected solar wind ions from the exospheric origin pick-up ions which form a ring distribution (Yamauchi et al., 2011, 2012). The ring ion distribution, seen at comets and in planetary magnetospheres (e.g. Coates, 2012 and references therein) is a unique feature seen in the Martian foreshock and is a result of the curvature of the Mars bow shock compared to the local ion gyroradius. In Yamauchi et al. (2011, 2012), the reflected ions have nearly the same energy from the bow shock boundary to about one gyroradius into the solar wind, indicating that the reflection (acceleration) process takes place inside the bow shock, but the internal processes and location were not discussed. With Mars Express (MEx), it is actually possible to trace such acceleration process inward from the bow shock thanks to the large proton gyroradius at Mars and the slow traverse velocity of the spacecraft (due to the low gravity of Mars).

In this paper we present results from observations of foreshock-like ions which were detected both in the classical foreshock region and are continually observed as the spacecraft passes inside the bow shock at Mars to at least 800 km inside the magnetosheath. We begin by briefly discussing the instrumentation which made the observations and how this instrumentation is orientated with respect to the solar wind and Mars. This is necessary to understand the observations, which are presented next, followed by a discussion of the possible sources of the observed foreshock-like ions. Lastly, investigations for the future are discussed.

2. Instrumentation

Plasma is measured on the Mars Express (MEx) spacecraft (Chicarro et al., 2004) by the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment (Barabash et al., 2004, 2006). ASPERA-3 contains four instruments, one measuring ions, one measuring electrons, and two measuring neutral particles. The electron and neutral measurements are conducted on a scanner. This study focuses on the measurement of the ions and electrons in the foreshock, bow shock, and magnetosheath.

Ions are measured by ASPERA-3 using the Ion Mass Spectrometer (IMA). IMA has a top hat energy deflection system coupled with an elevation analyzer at the entrance and a magnetic momentum analyzer at the exit. During its operation, IMA has undergone several operational changes. For the ion data used in this study, ions between 50 eV and about 20 keV are measured logarithmically in 66 energy steps and linearly below 50 eV to -20 eV in 30 steps. Thus, there are a total of 96 energy steps in an energy sweep measuring the ion spectrum. IMA measures ions in 360° of azimuth with 16 angular sectors, each 22.5° wide. In elevation, IMA measures ions from $-45°$ to $+45°$ when energies are above 50 eV in 16 elevation sectors, each about 5.6° wide. Below 50 eV, elevation scanning is disabled and the ions are measured from the central plane at 0° elevation about 5.6° wide. The momentum analyzer accelerates the energy-angle analyzed ion beam, sending it through an orange-section style magnetic field where the ions are separated by momentum and are detected in a 32 mass channel array. Ions up to 40 amu are collected by IMA, simultaneously. The entire energy-angle-mass array is accumulated in 192 s. Each energy-azimuthal angle scan at a single elevation angle occurs in 12 s.

Electrons are measured by ASPERA-3 using the Electron Spectrometer (ELS). ELS is a spherical top hat analyzer which is mounted on a scanner. For these data, the scanner angle was fixed so that the ELS and IMA central plane are roughly perpendicular. The ELS measures in a central plane of 360° with 16 azimuth bins, each 22.5° wide. Perpendicular to the central plane of ELS, the angular width is $\pm 2°$. For these data, ELS operated in its survey mode, where a 127 energy step spectrum is measured from 0.5 eV to about 20 keV logarithmically in 4 s.

Both the ion and electron data presented here have the background estimated and removed. In both cases, background is estimated by accumulating signals above 10 keV for a time period which is 300 s for ELS and 192 s for IMA. These accumulated signals are assumed to represent background noise within the microchannel plate (MCP) sensors for each instrument. Accumulated signals are normalized to the instrument's accumulation period and then subtracted from each measurement before scientific units are calculated.

3. Orientation

The spacecraft entered the Mars system on the dawn side in the southern hemisphere and preceded to periapsis on the dusk side of Mars at about 2343 UT. Figure 1 aids in visualizing the MEx trajectory. Shown are views in the Mars Solar Orbital (MSO) coordinate system in the MSO X–Y (a), X–Z (b), and Z–Y (c) planes as well as in cylinderical coordinates. MSO distances are given in km and relate to the cylindrical radius $\rho = \mathrm{sqrt}(Y^2 + Z^2)/R_{Mars}$, where $R_{Mars} = 3397$ km and the X distance in the cylindrical Fig. 1d is given in Mars radii. The average locations of the bow shock and the Magnetic Pileup Boundary (MPB) (Vignes et al., 2000) are indicated on Fig. 3d. The average position of the bow shock occurs at about 2222 UT and the average position of the MPB occurs at about 2307 UT. The MPB is defined using a magnetometer and since MEx contains no magnetic field experiment, MEx can only define the Induced Magnetospheric Boundary (IMB) (Lundin et al., 2004) from the particle signatures. However, the MPB and IMB are very nearly colocated.

Magnetic anomalies are most extreme in the southern hemisphere at a planetodetic longitude of 180°, and reach the magnetic