Planetary and Space Science 76 (2013) 10–27

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

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

Energy distribution asymmetry of electron precipitation signatures at Mars

Y.I.J. Soobiah [a,b,*], S. Barabash [a], H. Nilsson [a], G. Stenberg [a], R. Lundin [a], A.J. Coates [b], J.D. Winningham [c], R.A. Frahm [c]

[a] Swedish Institute of Space Physics, Institutet för rymdfysik (IRF), Kiruna, Sweden
[b] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, UK
[c] Southwest Research Institute, San Antonio, TX, USA

ARTICLE INFO

Article history:
Received 25 November 2011
Received in revised form
26 October 2012
Accepted 29 October 2012
Available online 7 November 2012

Keywords:
Mars
Solar wind
Electron precipitation
Martian crustal magnetic fields
Ionospheres
Aurora

ABSTRACT

The different types of asymmetry observed in the energy distributions of electrons and heavy-ions (M/Q=16-44) during signatures of electron precipitation in the Martian ionosphere have been classified. This has been achieved using the space plasma instrumentation of MEX ASPERA-3 from peri-centre altitude to 2200 km. ASPERA-3 ELS observes signatures of electron precipitation on 43.0% of MEX orbits. Unaccelerated electrons in the form of sudden electron flux enhancements are the most common type of electron precipitation signature at Mars and account for ~70% of the events observed in this study. Electrons that form unaccelerated electron precipitation signatures are either local ionospheric electrons with enhanced density, or electrons transported from another region of ionosphere, solar wind or tail, or a combination of local and transported electrons. The heating of electrons has a strong influence on the shape of most electron energy spectra from accelerated precipitation signatures. On most occasions the general flow of heavy-ions away from Mars is unchanged during the precipitation of electrons, which is thought to be the result of the finite gyroradius effect of the heavy-ions on crustal magnetic field lines. Only ~17% of events show some form of heavy-ion acceleration that is either concurrent or at the periphery of an electron precipitation signature. The most common combination of electron and heavy-ion energy distributions for signatures of electron precipitation involves electrons that visually have very little asymmetry or are isotropic and heavy-ions that have a upward net flux, and suggest the upward current associated with aurora. Due to a lack of reliable measurements of electrons travelling towards Mars, it is likely we miss further evidence of upward currents. The second most common combination of electron and heavy-ion energy distributions for signatures of electron precipitation, are those distributions of electrons that are asymmetric and have an net upward flux, with distributions of heavy-ions that also have a net upward flux. Energy distributions of heavy-ions with a net flux towards Mars occur half as often as heavy-ions with an upward net flux. There is also evidence to suggest we observe downward currents during electron precipitation signatures when we find energy distributions of electrons that are asymmetric and have an upward net flux, combined with energy distributions of heavy-ions that have a downward net flux. Wave particle interactions and downward parallel electric fields may be responsible for electrons that display a large amount of asymmetry in the upward direction of the energy distribution and have a upward net flux.

1. Introduction

Since the discovery that Mars has the remanent magnetisations of an ancient dynamo imprinted on its crust (Acuña et al., 1998), it has been conceivable that the otherwise non-magnetised planet could host mechanisms that energise plasma and accelerate particles, typically related to planets with strong intrinsic magnetic fields. Indeed, in 2005 the Mars EXpress (MEX) Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM) Ultra-Violet (UV) spectrometer (Bertaux et al., 2004) made the first observations of localised auroral emissions from the nightside atmosphere of Mars over regions of strong crustal magnetic fields (Bertaux et al., 2005). Further processes akin to a planet with a strong dipole magnetic field have been found in observations of magnetic reconnection (Eastwood et al., 2009; Halekas et al., 2009), and flux rope formation at Mars (Brain et al., 2010; Morgan et al., 2011).

The processes that occur at the low altitudes of the Martian ionosphere and also in the region of the crustal magnetic fields

* Corresponding author at: Swedish Institute of Space Physics, Institutet för rymdfysik (IRF), Kiruna, Sweden. Tel.: +44 7772955534.
E-mail addresses: ysoobiah@googlemail.com (Y.I.J. Soobiah), stas.barabash@irf.se (S. Barabash), hans.nilsson@irf.se (H. Nilsson), gabriella.stenberg@irf.se (G. Stenberg), rickard.lundin@irf.se (R. Lundin), ajc@mssl.ucl.ac.uk (A.J. Coates), d.winningham@mac.com (J.D. Winningham), rfrahm@swri.edu (R.A. Frahm).

0032-0633/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pss.2012.10.014

are far from being understood. As a result, little is known about the mechanisms responsible for the aurora that have been observed in the Martian atmosphere.

In the case of planets with global dipole magnetic fields, such as the Earth, Saturn and Jupiter, auroral emissions occur as a result of atoms and molecules in the respective atmospheres undergoing excitation after collisions with precipitating electrons (McIlwain, 1960). At the Earth auroral emissions appear in either diffuse or discrete forms. The former results from electrons typically of plasma sheet origin moving along the Earth's magnetic field until contact is made with the upper atmosphere. The precipitation of electrons from the plasma sheet is thought to occur mainly from pitch angle diffusion as particles interact with electrostatic electron cyclotron harmonic (ECH) waves (Johnstone et al., 1993; Villalón et al., 1995) or the scattering of electrons by whistler mode waves (Lyons et al., 1974; Horne and Thorne, 2000). The sharp, bright and discrete form of aurora occurs when the electrons responsible for the auroral emissions have been accelerated. The type of acceleration most explored in research involves a quasi-static field-aligned potential drop that accelerate electrons over a narrow range in energy, thus forming what is known as a mono-energetic peak. The potential drop facilitates electrons transported over large distances via an upward current to reach the low altitudes where auroral emissions take place (Gurnett and Frank, 1973). It has been established that this process occurs as part of a larger current system that closes through the Pedersen and Hall currents in the ionospheres and a return parallel current to a dynamo at higher altitudes (Johansson et al., 2006). These current systems are responsible for transporting large amounts of energy and momentum within the magnetospheres of the magnetised planets and is therefore of great importance. For Earth and Saturn, the current system is powered by an external dynamo in the solar wind and for Jupiter the source is internal to the planet's magnetosphere. Acceleration of electrons can also be observed over a wide range or broad band of energies, as associated with dispersive Alfvén waves (DAWs) (Ergun et al., 1998; Chaston et al., 2003). For the Earth, modelling by Newell et al. (2009), shows that diffuse aurora may account for 70% of the precipitating particle energy flux into the high-latitude ionosphere.

SPICAM observes an auroral signal as a sudden increase in the intensity of the nightglow from the Martian atmosphere. Leblanc et al. (2006) have calculated this is most probably produced by electrons with a peak energy of a few tens of eV and not by electrons that have been accelerated. This would suggest the aurora at Mars is more comparable to the Earth's diffuse aurora. Studies by Haider et al. (1992, 2007) and Seth et al. (2002), support such a possibility by demonstrating nightglow emissions at Mars would occur from the precipitation of unaccelerated solar wind electrons onto the atmosphere. However, evidence has been mounting that the UV emissions observed by SPICAM at Mars could also be associated with similar processes that occur in regions of the cusp/polar magnetic field of the Earth during discrete aurora. The first such example was of peaked electron distributions on open magnetic field lines indicative of acceleration by a current system similar to that found during the Earth's discrete aurora (Brain et al., 2006). This was followed by the detection of an "inverted-V" shape in the energy–time distribution of electrons and ions, with electrons moving downward and ions upward in the high altitude deep shadow of Mars, indicative of acceleration and the current from a parallel electric field (Lundin et al., 2006a). Further observations then revealed density depletions alongside peaked electron distributions and beams of O^+ ions that have a missing cold component, indicative of long-lived active auroral type flux tubes (Dubinin et al., 2009).

Despite the similarities in the properties of accelerated particles found at Mars and the Earth, there is a great amount of uncertainty as to whether the observations at Mars are the result of a direct analogy with the auroral current systems of the Earth. This is due to the difference of the Martian ionosphere, which has high values of Pedersen conductivity. Modelling by Dubinin et al. (2008b) shows that the high conductance of the Martian ionosphere would leave the electric currents that couple the Martian ionosphere and the induced magnetosphere prone to short circuit.

Previous attempts were made by Leblanc et al. (2008), to compare UV observations of Martian aurora by SPICAM in its nadir orientation with in situ electron and ion measurements by MEX Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) Electron Spectrometer (ELS) and Ion Mass Analyzer (IMA) instruments and electron content as measured by the MEX MARSIS Radio Sounder. The study found a very good correlation between the locations of aurora with regions that were least probable to be on closed field lines from the crust, as well as a simultaneous correlation to increased electron content and precipitating electron flux at these locations. However, the SPICAM observations of the aurora did not show any corresponding ion signal from IMA measurements. This was possibly due to the lack of complimentary viewing direction between that of the SPICAM instrument with the aperture plane of IMA. Previous studies of "inverted-V" signatures using ELS and IMA were restricted by an earlier energy table of IMA before May 2007, which did not adequately resolve ion measurements below 50 eV. As a result, possible observations of heavy planetary ions as they begin to accelerate from low altitudes were missed. Without observing ion beams in conjunction with SPICAM UV observations of Martian aurora or in the low altitudes regions associated with the aurora, it is not possible to assess the current systems responsible for the Martian aurora and therefore to know with certainty that a similar mechanism for creating aurora at the Earth is present at Mars.

Hence, this paper will survey accelerated and unaccelerated electron signatures of electron precipitation as could lead to the Martian aurora, to assess the different mechanisms that lead to electron precipitation. Using the ASPERA-3 ELS and IMA instruments we will compare the energy distributions in differential energy flux (DEF) of electrons and heavy-ions at the times of these signatures. The study will make use of IMA's updated energy table that allows for increased energy resolution of ion measurements below 50 eV. By comparing the energy distributions of electron and heavy-ions with the new energy table of IMA, we will search for evidence of upward flowing ion beams from peri-centre altitude, ~ 275 km, up to altitudes of 2200 km and further evidence of Earth-like auroral acceleration processes and current systems around Mars.

A study by Nilsson et al. (2012), of average ion distribution functions around Mars, shows that there is a general outflow of ions from the Martian ionosphere, with greater amounts of cold plasma close to the planet. On average, ions are observed flowing away and towards Mars. In this study, we will look at the combination of energy distributions of electrons and heavy-ion during signatures of electron precipitation and will attempt to classify different types of particle distribution asymmetries.

2. Instrumentation

We present data from the ELS and IMA, the two plasma instruments on MEX ASPERA-3 (Barabash et al., 2004), to study the energy distributions of electrons and heavy-ions during signatures of electron precipitation at Mars. ELS is a compact spherical top-hat electrostatic analyzer and collimator system, and measures electrons in the energy range of 1–20 keV with an energy resolution of $\Delta E/E = 8\%$. ELS has a time resolution of 4 s, which it takes to complete a sweep of 128 energy levels. The intrinsic field of view for ELS is $4^\circ \times 360^\circ$ and is divided in to