Planetary and Space Science 113-114 (2015) 385–394

Contents lists available at ScienceDirect

Planetary and Space Science

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

Ionospheric photoelectrons at Venus: Case studies and first observation in the tail

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ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form
11 September 2014
Accepted 27 January 2015
Available online 16 February 2015

Keywords:
Venus
Ionosphere
Photoelectrons
Solar wind
Escape

ABSTRACT

The presence of photoelectrons in ionospheres, including that of unmagnetised Venus, can be inferred from their characteristic spectral peaks in the electron energy spectrum. The electrons within the peaks are created by the photoionisation of neutrals in the upper atmosphere by the solar HeII 30.4 nm line. Here, we present some case studies of photoelectron spectra observed by the ASPERA-4 instrument aboard Venus Express with corresponding ion data. In the first case study, we observe photoelectron peaks in the sunlit ionosphere, indicating relatively local production. In the second case study, we observe broadened peaks in the sunlit ionosphere near the terminator, which indicate scattering processes between a more remote production region and the observation point. In the third case study, we present the first observation of ionospheric photoelectrons in the induced magnetotail of Venus, which we suggest is due to the spacecraft being located at that time on a magnetic field line connected to the dayside ionosphere at lower altitudes. Simultaneously, low energy ions are observed moving away from Venus. In common with observations at Mars and at Titan, these imply a possible role for the relatively energetic electrons in producing an ambipolar electric field which enhances ion escape.

1. Introduction

Ionospheric photoelectrons are usually observed in sunlit ionospheres. They have been observed in several solar system contexts, including Earth (e.g. Coates et al., 1985), Mars (Frahm et al., 2006a), Titan (e.g. Coates et al., 2007), in Saturn's ring ionosphere (Coates et al., 2005) and in Saturn's inner magnetosphere (Schippers et al., 2009). When observed, they usually indicate local production of photoelectrons, but may also be indicative of a magnetic connection to regions where ionisation is occurring (e.g. Coates et al., 1985; Frahm et al., 2006b; Coates et al., 2007).

The first observation of distinct ionospheric photoelectron peaks by the ESA Venus Express spacecraft (VEx) was found in data from 18 May 2006 (Coates et al., 2008). The ionospheric electron component of the plasma is characterised by a high peak of electron flux occurring mainly due to solar photoionisation below 60 eV. This flux is relatively intense compared to the background. The solar spectrum contains discrete spectral lines (see for example solar spectrum in Gibson (1973)). In the ionosphere of Venus, the dominant solar EUV helium line at 30.4 nm causes photoionisation of atmospheric carbon dioxide and atomic oxygen, yielding electrons that populate a narrow energy range of the electron spectrum (e.g. Mantas and Hanson, 1979). The analysis by Coates et al. (2008) indicated that the photoelectrons observed by VEx were mainly due to ionisation of oxygen at altitudes lower than the spacecraft and subsequently transported to the observation point.

Similar ionospheric photoelectrons have been observed at Mars (mainly from the ionisation of CO_2, Frahm et al., 2006a, 2006b) and at Titan (from ionisation of N_2, Coates et al., 2007). At Titan, photoelectrons observed in the tail on Cassini's T9 encounter were used to infer a magnetic connection to the sunlit ionosphere at lower altitude (Coates et al., 2007), which was supported by a comparison of the magnetometer data with an MHD model showing that magnetic connection was indeed possible in that case (Wei et al., 2007). Similar photoelectron peaks are also observed in the tail region of Mars (Frahm et al., 2006a) inferring magnetic connection to Mars and transport from the Martian dayside ionosphere (Liemohn et al., 2006).

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http://dx.doi.org/10.1016/j.pss.2015.01.019
0032-0633/

The theory of photoelectron generation at Venus is similar to that detailed for Mars by Mantas and Hanson (1979). For Venus, there are two main species (carbon dioxide and atomic oxygen) interacting with the 30.4 nm HeII solar line, each generating a multiple of possible parent states and ejecting electrons as described in the following equations:

$$CO_2+h\nu\rightarrow CO_2^+ + e^- \begin{cases} X^2\Pi_g \text{ ionisation potential } 13.8\ eV\rightarrow 27.0\ eV \text{ electron} \\ A^2\Pi_u \text{ ionisation potential } 17.7\ eV\rightarrow 23.1\ eV \text{ electron} \\ B^2\sum_u^+ \text{ ionisation potential } 18.1\ eV\rightarrow 22.7\ eV \text{ electron} \\ C^2\sum_g^+ \text{ ionisation potential } 19.4\ eV\rightarrow 21.4\ eV \text{ electron} \end{cases} \quad (1)$$

Padial et al. (1981):

$$O+h\nu\rightarrow O^+ + \boldsymbol{e}^- \begin{cases} ^4S \text{ ionisation potential } 13.62\ eV\rightarrow 27.16\ eV \text{ electron} \\ ^2D \text{ ionisation potential } 17.10\ eV\rightarrow 23.68\ eV \text{ electron}. \\ ^2P \text{ ionisation potential } 18.50\ eV\rightarrow 22.28\ eV \text{ electron} \end{cases} \quad (2)$$

Mantas and Hanson (1979):

Because atomic oxygen is the dominant species at ionospheric altitudes near the exobase at ~200 km (Fox and Bougher, 1991; Fox and Sung, 2001), the photoelectron population observed at Venus Express altitudes (250–700 km in the Coates et al. (2008) case) is dominated by the atomic oxygen source (Coates et al., 2008). In particular, models have shown that detailed modelling of the Venus atmosphere can generate electron spectra showing electron flux peaks in the 22–24 and 27 eV range (McCormick et al., 1976; Cravens et al., 1980; Knudsen et al., 1980; Spenner et al., 1997).

Peaks in the electron spectrum generated near the exobase must have a conduit in order for them to be transported in altitude to the point of observation without changing their energy spectrum. This conduit is the magnetic field (cf. Coates et al., 1985, 2007; Frahm et al., 2006a, 2006b).

Pioneer Venus Orbiter (PVO) observations have shown that there is no intrinsic magnetic field at Venus (Slavin et al., 1980; Russell et al., 1980; Phillips and Russell, 1987). There is, however, an induced magnetosphere caused by the interaction of the solar wind with the outer atmosphere of the planet. The interaction causes the solar wind magnetic field to be draped around Venus (Luhmann and Cravens, 1991; Law and Cloutier, 1995). In our region of interest, the draped field lines may be connected to the dayside ionosphere at times. The draping region is complex with an intermediate boundary called the magnetic barrier, or plasma mantle (Spenner et al., 1997) or transition region (Coates et al., 2008). PVO observed the solar wind interaction with Venus but the resolution of the electron measurements was insufficient to reveal the photoelectron peaks (e.g. Knudsen et al. (1980) and the model comparisons shown in Spenner et al. (1997)). The VEx ASPERA-4 ELS is the first instrument which has observed peaks in the ionospheric electron spectrum. This is a result of the ~8% energy resolution and the differential measurements performed by ELS as described below.

A detailed comparison of a multi-stream kinetic model with ASPERA-ELS photoelectron data was performed by Cui et al. (2011). The comparison indicated good agreement between the observed and modelled photoelectron peak energies and flux decrease features, and fair agreement between the observed and modelled absolute fluxes when the magnetic field direction is included.

In this paper, we present clear evidence for ionospheric photoelectrons in the tail of Venus, indicating that there exists, at times, magnetic connectivity between the dayside Venus ionosphere and its tail.

2. Instrument

VEx was launched on 09 November 2005. It arrived at Venus on 11 April 2006. The spacecraft payload comprises seven experiments, including ASPERA-4, the Analyzer of Space Plasma and EneRgetic Atoms (Barabash et al., 2007). The ASPERA-4 experiment is composed of four instruments, two of which measure neutral particles (the Neutral Particle Detector, NPD, and the Neutral Particle Imager, NPI), one measuring ions (the Ion Mass Analyzer, IMA), and one measuring electrons (the ELectron Spectrometer, ELS).

The ELS measures the electron population near Venus between 0.8 eV and 30,000 eV. The lowest energy of observation is dependent on the charging of the spacecraft. The spacecraft potential in turn, depends on the flux of the local electrons in the plasma, and the characteristic energy of the plasma. These values change as VEx orbits and samples various plasma regions from a 66,000 km apoapsis to a periapsis in the 250–350 km range (see Titov et al., 2006). During its sampling of the electron plasma around Venus, we have used the ELS to search for evidence of ionospheric photoelectrons.

The data used in this paper come from the ELS and IMA instruments of the ASPERA-4 experiment (Barabash et al., 2007). The electron-optical design of the ELS is a top hat analyser and a collimator system with a nominal $360^\circ\times 4^\circ$ field of view (Barabash et al., 2007). Small non-concentric differences between the ELS sectors occurred during manufacture causing slight sector differences (Collinson et al., 2009) which are compensated for by the instrument calibration. A scanner enables increased angular coverage so that ELS sweeps out the entire sky; however, about a quarter of the sky is blocked by the spacecraft. Particles enter the instrument through a collimator, passing a set of baffles which confine the incoming electrons. This baffling system includes a very effective light trap. Electrons of a particular energy are selected by applying a voltage to the inner hemisphere corresponding to the energy divided by the analyser k-factor, with the outer hemisphere at ground. Any electrons of lower or higher energies than the energy passband (~8% $\Delta E/E$ at FWHM) will impact the sides of the hemispheres and not pass through to the detector. The selected electrons which traverse the inner hemisphere gap impact a microchannel plate (MCP) detection system via a programmable decoupler screen. Each incoming electron is multiplied by the MCP, causing the impact of $\sim 10^6$ electrons onto a discrete anode. The anode at which they are measured corresponds to the particle entering at the opposite side of the instrument. There are 16 anodes on ELS, each designed to cover a 22.5° portion of the 360° azimuthal field of view. For the observations shown in this paper, ELS sweeps through 127 logarithmically spaced steps, covering the complete range of energies from 0.8 to 30,000 eV in 4 s. Data from anode 11 is presented here as it is one of the least affected by obscuration by, and photoemission of, electrons from the spacecraft.

The ASPERA-4 IMA instrument (Barabash et al., 2007) is an electrostatic–magnetic momentum analyser covering an energy range from 10 to 36,000 eV. There are three stages to the electrostatics: (1) incoming ions are elevation analysed within the angular range of $\pm 45^\circ$ (about every 5.6°), (2) electrostatic deflection through a top-hat analyser energy filters the ions, and (3) ions are then accelerated into the magnetic section. The magnetic section is an orange-segment arrangement causing momentum deflection in the radial direction, resulting in mass discrimination up to about 40 amu. IMA accumulates ion counts in bins of 16 elevation angles, 16 azimuthal angles, 32 mass channels and 96 energies every 192 s. In this paper, as well as ion spectrograms summed over all sectors, we present pitch angle distributions of O^+ organised parallel and perpendicular to the magnetic field (e.g.