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Distant ionospheric photoelectron energy peak observations at Venus

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ABSTRACT

The dayside of the Venus ionosphere at the top of the planet's thick atmosphere is sustained by photoionization. The consequent photoelectrons may be identified by specific peaks in the energy spectrum at 20–30 eV which are mainly due to atomic oxygen photoionization. The ASPERA-4 electron spectrometer has an energy resolution designed to identify the photoelectron production features. Photoelectrons are seen not only in their production region, the sunlit ionosphere, but also at more distant locations on the nightside of the Venus environment. Here, we present a summary of the work to date on observations of photoelectrons at Venus, and their comparison with similar processes at Titan and Mars. We expand further by presenting new examples of the distant photoelectrons measured at Venus in the dark tail and further away from Venus than seen before. The photoelectron and simultaneous ion data are then used to determine the ion escape rate from Venus for one of these intervals. We compare the observed escape rates with other rates measured at Venus, and at other planets, moons and comets. We find that the escape rates are grouped by object type when plotted against body radius.

1. Introduction

Photoionization by sunlight is the principal production process in many planetary ionospheres. As neutrals from the planetary atmospheres are ionized, ions and photoelectrons result. The solar spectrum, together with the composition of the atmosphere, provides photoelectrons with particular energies. The energy of the ionizing photon beyond the ionization potential of the gas gives the emerging photoelectron kinetic energy. In particular, there are peaks in the photoelectron spectrum in the 20–30 eV region, with particular energies for the various ionospheres. A summary of the expected peak energies for Venus, Earth, Mars and Titan is given by Coates et al. (2011) (see Table 1 in reference), based on theoretical ideas including Mantas and Hanson (1979) and Nagy and Banks (1970). The ionosphere is immersed in the Venus–solar wind interaction region, and in this paper we further investigate the interaction between the ionosphere and its environment.

A substantial amount of theoretical and simulation work has been done on the Venus–solar wind interaction, its ionosphere and the morphology of the interaction. On the large scale, the magnetic field configuration at Venus is due to the solar wind interaction with this unmagnetized planet (Luhmann, 1995). A bow shock, where the solar wind slows, is heated, and is deflected around the planet. The Interplanetary Magnetic Field (IMF) penetrates the shock and 'piles up' in front of the planet. The fields interact with the ionosphere as they drape around Venus (Luhmann and Cravens, 1991; Law and Cloutier, 1995). Several simulations have successfully reproduced the large scale features of the interaction, using both MHD (e.g. Ma et al., 2013) and hybrid (e.g. Brecht and Ferrante, 1991; Kallio and Jarvinen, 2012) models. The approaches were compared by Kallio et al. (2011).

Within the Venus ionosphere, the features unique to photoelectron energy spectra include sharp peaks in the primary photoelectron spectrum in the 20–30 eV range. These are from the ionization of neutrals by intense solar HeII 30.4 nm radiation. In addition, a reduction at ~60 eV is predicted due to a drop in the solar spectrum near 16 nm (e.g. Nagy and Banks, 1970; Mantas and Hanson, 1979; Fox, 2007). The peaks in this range are primarily produced by O rather than CO_2, because of the lower altitude of

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Table 1
Plasma loss estimates on 15 September 2009. Rates are in units of ions/s except where noted.

Observation date	E_{esc} H^+	E_{esc} $m=16$	E_{esc} $m=32$	V_{esc} $m=1$	V_{esc} $m=16$	Total	Mass loss (amu s^{-1})
15 Sep 09	8.2×10^{23}	2.1×10^{23}	1.0×10^{23}	1.0×10^{23}	1.2×10^{23}	2.2×10^{23}	2.0×10^{24}

the transition between CO_2 and O at Venus (Schunk and Nagy, 2000; Coates et al., 2008). The primary ionization process clearly introduces specific energy peaks in the energy spectrum (e.g. Gan et al., 1990; Cravens et al., 1980). These specific spectral features can be used to identify ionospheric photoelectrons.

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

Observations of photoelectrons at Venus, Earth, Mars and Titan were summarized by Coates et al., (2011). At Venus, the first well-resolved measurements of ionospheric photoelectrons in the ionosphere were given by Coates et al., 2008 using data from Venus Express. The flux of photoelectrons stayed fairly constant throughout the observation region in the Northern ionosphere, and from this it was inferred that the photoelectrons were produced during the ionization of oxygen at a lower altitude (~200 km) below the observation point (250–700 km). The observed photoelectrons were produced in the denser region of the atmosphere where atomic oxygen is abundant and then transported to the observation altitude.

One particular aspect of photoelectron observations, seen at all four objects, is the observations of ionospheric photoelectrons at locations well away from their production point, as well as locally in the ionosphere near the production point. These remote locations include the Earth's magnetosphere (at up to 6.6 R_E, Coates et al., 1985), in the Martian tail (at up to 3 R_M, Frahm et al., 2006a, 2006b; Coates et al., 2011), in Titan's tail (at up to 6.8 R_T, Coates et al., 2007; Wellbrock et al., 2012) where the observations were used to estimate ion loss rate (Coates et al., 2012), and at Venus (at up to 1.45–1.5 R_V, Tsang et al., accepted for publication; Coates et al., 2011). Tsang et al. (accepted for publication) also observed that at times near and beyond the terminator, the clear two-peak signature observed on the day side broadens into one peak, perhaps the result of scattering processes between the production and observation point (Jasperse, 1977; Jasperse and Smith, 1978). At Mars, photoelectron peaks were used to estimate the total loss rate of electrons from the Martian ionosphere, which was then suggested to be equal to the ion loss rate (Frahm et al., 2010). At Venus, escape rates appear to be dependent on upstream conditions (e.g. Brace et al., 1987, Barabash et al., 2007b; McEnulty et al., 2010).

In this paper, we present new case studies of photoelectrons seen in the Venus tail at larger distances than seen previously, and we make a new estimate of the ion escape flux from Venus using these measurements. We also summarize the observed plasma escape rates at various objects throughout the solar system as derived from in-situ measurements by spacecraft, and for the first time order these observed rates by body mass.

2. Instrumentation

We use data from the Electron Spectrometer (ELS) and the Ion Mass Analyzer (IMA), part of the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4) experiment on ESA's Venus Express (VEx) spacecraft (Barabash et al., 2007a). The ELS has an energy resolution of 8%, designed to provide well resolved measurements of photoelectrons at Venus (Barabash et al., 2007a; Coates et al., 2008).

3. Ionospheric photoelectrons in the Venus tail region

The first measurements of photoelectrons in the Venus tail region were given by Tsang et al., accepted for publication, which studied Venus Express data on 3, 4, and 30 June 2006, where photoelectrons were observed at 1.45 R_V in the tail region. An additional example with photoelectrons seen at 1.5 R_V on 20 April 2008 by Venus Express was shown by Coates et al. (2011). During this pass, photoelectrons were observed in the local ionosphere (interval A) as well as in the tail of Venus (interval B), and averaged spectra were shown from both intervals (Coates et al., 2011, Fig. 3). These tail photoelectrons were also associated with an increased flux of low energy ions. This led to the suggestion that polar wind-type escape along the draped magnetic field around Venus may be occurring, associated with an ambipolar electric field set up by relatively energetic photoelectrons (Hartle and Grebowsky, 1995; Coates et al., 2008, 2011).

Hybrid simulations of the Venus environment (Jarvinen et al., 2012) showed that draped fields with the suggested configuration were possible for suitable upstream conditions, at least early during interval B. Similar studies were done at Mars (Liemohn et al., 2006) and at Titan (Wellbrock et al., 2012). These simulations support the hypothesis that such field morphology is consistent with the observations.

We now present two new examples where ionospheric photoelectrons are seen in the tail: 8 May 2013 and 15 September 2009. These additional events are not the result of a full survey of the data, which is beyond the scope of the current paper. However, the two new events are measured (1) in the dark tail and (2) at larger distance along the tail, providing significant additional case studies.

3.1. 8 May 2013

Three types of plots are shown in Fig. 1. These are: the VEx orbital trajectory shown at the lower right, the ion and electron spectrogram at the lower left, and selected electron spectra at the top. Utilizing both the particle spectrograms and the orbital trajectory, VEx travels from the tail region (where intervals of relatively high energy solar wind halo/strahl electrons are seen, up to 0400 UT, and then again during an intensification at ~0405 UT), through ionospheric plasma in the tail (before the terminator at ~0425 UT) and then traversing the dayside ionosphere (0425-0431 UT), out to the magnetosheath (0431-0446 UT) then into the solar wind after the bow shock crossing at 0446 UT.

At various locations within the ionosphere, individual electron spectra highlight the observed distributions. The spectra A and B are measured before the terminator, with spectrum C measured just after the terminator. In all the spectra A, B and C, a broad peak structure in energy is observed between 10 and 20 eV, with some further detail also seen (2 peaks in spectra A and C in particular). We interpret the peaks in spectra A, B and C as due to ionospheric photoelectrons. Spectrum A in particular represents ionospheric photoelectrons observed in the dark tail region. Spectrum B appears somewhat broadened in energy; as found by Tsang et al. (accepted for publication), this may be due to scattering processes (Jasperse, 1977; Jasperse and Smith, 1978) between the production site in the dayside ionosphere and the observation site at the spacecraft. This may differ depending on which field line is being sampled.