Planetary and Space Science 113-114 (2015) 369–377

Contents lists available at ScienceDirect

Planetary and Space Science

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

Proton and alpha particle precipitation onto the upper atmosphere of Venus

G. Stenberg Wieser [a,*], M. Ashfaque [a,b], H. Nilsson [a], Y. Futaana [a], S. Barabash [a], C. Diéval [c], A. Fedorov [d], T.L. Zhang [e]

[a] *Swedish Institute of Space Physics, Kiruna, Sweden*
[b] *Pakistan Space & Upper Atmosphere Research Commission, Karachi, Pakistan*
[c] *Department of Physics and Astronomy, University of Iowa, IA, USA*
[d] *IRAP, CNRS, Toulouse, France*
[e] *Space Research Institute, Graz, Austria*

ARTICLE INFO

Article history:
Received 28 February 2014
Received in revised form
30 October 2014
Accepted 27 January 2015
Available online 7 February 2015

Keywords:
Venus
Proton precipitation
Alpha-particle precipitation
Induced magnetosphere
Solar wind interaction

ABSTRACT

We study the precipitation of protons and alpha-particles onto the upper atmosphere of Venus, using particle data recorded by the Venus Express spacecraft inside the induced magnetosphere. Our investigations are limited to the dayside close to the terminator. We observe on average a net downward flux of protons, which originate partly from the planetary atmosphere and partly from the solar wind. We present median energy spectra of the precipitating protons divided into two energy ranges, 10–100 eV and 100 eV–30 keV. The total dayside precipitation of solar wind protons is estimated to be $3\times10^{22}\ \mathrm{s}^{-1}$, assuming only protons with energies above 500 eV will reach the exobase. Downgoing protons are frequently observed but only in 3% of the available data records we see He^{2+}. These observations are made close to the induced magnetosphere boundary and we argue that at lower altitude the countrates for alpha-particles fall below detection limits. We estimate the precipitation of He^{2+} onto the dayside exobase to be $1\times10^{21}\ \mathrm{s}^{-1}$, which is not enough enough to replace the helium escaping from the planet.

1. Introduction

Venus has no intrinsic magnetic field and the solar wind can directly interact with its atmosphere. As the solar wind and its frozen-in interplanetary magnetic field encounters the planet, electrical currents are set up in the ionosphere and the so-called induced magnetosphere is formed. The solar wind is diverted around this obstacle, and the field lines of the interplanetary magnetic field drape around the planet forming an elongated magnetotail on the night-side. On the dayside, the magnetic field piles up and creates a magnetic barrier, which shields the atmosphere/ionosphere from erosion by the solar wind (e.g. Luhmann, 1986).

The magnetic barrier is, however, not impermeable; if the gyro radii of the approaching solar wind ions are comparable in size to the thickness of the barrier ions can gyrate through. This is a precipitation mechanism suggested to be in operation on Mars, where solar wind particles are observed deep inside the ionosphere of the planet (Lundin et al., 2004; Diéval et al., 2012a, 2013a; Stenberg et al., 2011).

Precipitating solar wind ions may transfer matter, energy and momentum from the solar wind to the upper atmosphere. For example, precipitating solar wind He^{2+} could be an important source of atmospheric helium for both Mars and Venus. On both planets $^{4}\mathrm{He}$ is produced by radioactive decay of uranium and thorium in the interior of the planets, which slowly seeps through the rock and outgases to the atmospheres. Models suggest, however, that the neutral helium formed this way is not sufficient to explain the amounts of helium actually observed in the atmospheres (Krasnopolsky and Gladstone, 2005), considering observed escape rates. He^{2+} from the solar wind may be the additional source needed to balance the outflow. For Mars both observations (Stenberg et al., 2011) and models (Chanteur et al., 2009; Modolo et al., 2005) indicate this might be the case. Models also suggest the magnetic field strength in the magnetic barrier regulates the net inflow and energy deposition of both protons and He^{2+} both on Mars and on Venus (Shematovich et al., 2011, 2013, 2014).

Ions of planetary origin can also precipitate and have significant atmospheric effects. For example, O^{+} ions may first be extracted from the ionosphere and then accelerated by the convective electric

---

[*] Correspondence to: Swedish Institute of Space Physics, Box 812, SE-98128 Kiruna, Sweden.
E-mail address: gabriella@irf.se (G. Stenberg Wieser).

http://dx.doi.org/10.1016/j.pss.2015.01.018
0032-0633/

field of the solar wind before they re-enter the upper atmosphere (Luhmann and Kozyra, 1991). Due to their heavy mass they carry significant momentum, which is transferred to the heavy components of the atmosphere in elastic collisions and kicks them off. Sputtering effects of elastic collisions of precipitating lighter ions, such as protons, should not be important for heavy species, but maybe for lighter species.

Measurements from Pioneer Venus Orbiter (PVO) reveal that the Venusian ionosphere is very sensitive to variations in the solar wind. They also show that low energy H^+ ions (<10 km/s) is an important component of the dayside upper ionosphere of Venus, even dominating in the predawn region. Due to instrument limitations identification of protons above 100 eV was unfortunately not possible (Taylor et al., 1980). Modeling the solar wind interaction with Venus (Cloutier and Daniell, 1979) suggest that the ionosphere could at most absorb a few per cent of the solar wind flux, except when there are rapid transients in the solar wind parameters. Gombosi et al. (1980) use data from Pioneer Venus Orbiter to calculate the solar wind absorption on Venus. Their calculation says 0.3% of the solar wind will be absorbed. Based on Venus Express observations of the position of the Venusian bowshock Zhang et al. (2007) claim that very little or no solar wind enters the induced magnetosphere at least during solar minimum conditions. Other modelling efforts, however, suggest that even on Venus the precipitating solar wind He^{2+} should play an important role for the helium balance on the planet (Krasnopolsky and Gladstone, 2005).

In this paper we investigate the precipitation of protons and He^{2+} and we make rough estimates of the size of the average net precipitating fluxes onto the upper parts of the atmosphere of Venus using direct measurements of the precipitating particles. Our primary goal is to investigate the precipitation of particles originating from the solar wind. The protons, however, do not come with a label announcing their origin. In order to distinguish planetary origin protons from solar wind protons we divide the precipitation events into four different classes. By comparing the energies of the precipitating protons to the energies of simultaneously observed heavier ions we find that some of the observed events are examples of solar wind precipitation. We also search for the presence of He^{2+} ions inside the induced magnetosphere. We examine the dependence of the solar wind precipitation on upstream solar wind conditions and the direction of the convection electric field, and we present average energy spectra for the precipitating H^+ ions. Based on our findings we discuss similarities and differences between solar wind precipitation on Venus and Mars.

2. Instrumentation

We use data from the Ion Mass Analyzer (IMA), which is part of the ASPERA-4 instrument (Barabash et al., 2007) onboard Venus Express. IMA is capable of resolving ion direction, E/q, and m/q (E being energy, m denotes mass and q is the electrical charge).

Ion energies are separated in a top hat electrostatic analyzer, scanning from 10 eV/q to 36 keV/q in 96 steps with an energy resolution of 7%. The top hat analyzer has a full 360° cylindrical symmetry. Behind the electrostatic analyser all particles have the same energy per charge value. Ion masses are separated by a circular magnetic separation system. The radial deviation of the ion trajectories at the exit of the magnetic field region then corresponds to mass per charge.

IMA gives an instantaneous field of view of $6^\circ \times 360^\circ$ in the azimuthal plane, which is divided into 16 azimuthal sectors. An electrostatic deflector system steps through 16 elevation angles in the interval $\pm 45^\circ$ measured from the azimuthal plane, resulting in a total field of view of $90^\circ \times 360^\circ$. Hence, IMA provides ion fluxes in a 2D plane with a time resolution of 12 s and a complete distribution (one IMA scan) is produced every 192 s.

The local magnetic field is recorded by the magnetometer (MAG) (Zhang et al., 2006). MAG measures the magnetic field vector and in this study we use the 4-s resolution data product.

3. Data set and method

Our aim is to investigate the precipitation of H^+ and He^{2+} ions onto the upper atmosphere of Venus. In particular we want to estimate the contribution of the solar wind H^+ to the total H^+ precipitation. We choose to examine full scans observed by IMA (192 s, $90^\circ \times 360^\circ$ field of view) inside the induced magnetospheric boundary (IMB). We also restrict our investigations to the dayside. Due to the orbit of Venus Express the time spent in this region is very short and during each 24 h orbit only a few full distributions are obtained. The observations are also confined to a region close to the North pole (cf. Fig. 1).

The draping of the solar wind around the planet causes a pile-up of magnetic field and the crossing of this magnetic barrier could be used as a indicator of the entry into the induced magnetosphere. However, the magnetic barrier is not always evident in the data, at least not at the high solar zenith angles where our measurements are made. Instead we use the presence of low energy heavy ions as evidence that we crossed the IMB. We consider all ions with $m/q \geq 8$ as heavy. Hence, in this study we define the ionosphere passage as the interval of each orbit starting from the first observations of such heavy ions with integrated fluxes larger than $10^5\,\mathrm{cm^{-2}\,s^{-1}}$ below 100 eV, and ending with the last detection of such low energy heavy ions. Each boundary identification is inspected manually and occasionally adjusted since contamination of the data sometimes cause a false ionospheric signal. We use data from the entire year 2007 as an example of solar minimum conditions. The total number of scans

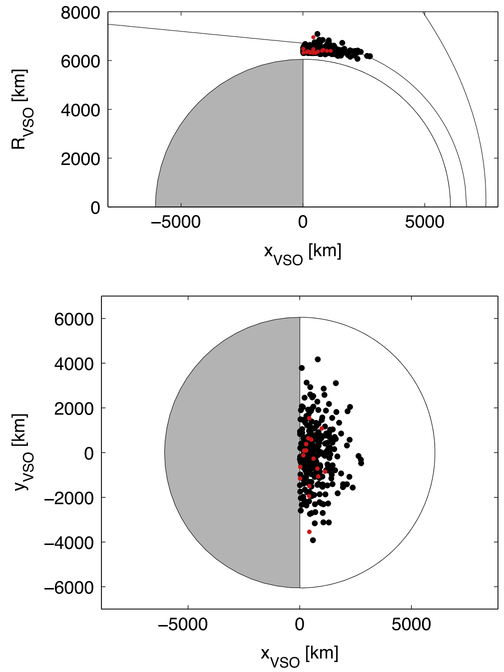

Fig. 1. Location of the H^+ precipitation events in the VSO frame. The top panel shows the position of the events in the $x_{VSO}-R_{VSO}-$plane, where $R_{VSO}=\sqrt{y_{VSO}^2+z_{VSO}^2}$. The two solid lines corresponds to models of the IMB (inner) and the bowshock (outer). The bottom panel shows the view from above the north pole. The red dots show the location of the spacecraft during scans where no precipitating protons were observed.