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Properties of planetward ion flows in Venus' magnetotail

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ABSTRACT

Venus is gradually losing some of its atmosphere in the form of ions through its induced magnetotail. Some of these ions have been reported previously to flow back to the planet. Proposed drivers are magnetic reconnection and deflection of pickup ions in the magnetic field. We analyze protons and oxygen ions with eV to keV energies acquired by the ASPERA-4/IMA instrument throughout the entire Venus Express mission. We find that venusward flowing ions are important in the sense that their density and deposition rate into the atmosphere is of the same order of magnitude as the density and escape rate of downtail flowing ions. Our analysis shows that during strong EUV irradiance, which occurs during solar maximum, the flux of venusward flowing protons is weaker and of oxygen ions is stronger than during weak irradiance. Since such a behavior was observed when tracing oxygen ions through a MHD model, the ultimate driver of the venusward flowing ions may simply be the magnetic field configuration around Venus. Although the pure downtail oxygen flux stays mostly unchanged for all observed EUV conditions, the increase in venusward oxygen flux for high irradiance results in a lower net atmospheric escape rate. Venusward bulk flows are mostly found in locations where the magnetic field is weak relative to the interplanetary conditions. Although a weak field is generally an indicator of proximity to the magnetotail current sheet, these flows do not cluster around current sheet crossings, as one may expect if they would be driven by magnetic reconnection.

1. Introduction

Although Venus itself does not have an internally produced magnetic field, currents within its ionosphere and potentially metallic core are still giving rise to an induced magnetosphere, which includes a magnetotail on the nightside (Dubinin et al., 2013a; Luhmann et al., 2004). The two lobes of the magnetotail are separated by a current sheet. The current sheet coincides with a clear enhancement in the >10 eV electron intensity (Dubinin et al., 2012) but is not very prominent in mission-averaged >10 eV ion densities (Dubinin et al., 2013b).

There is an asymmetry between two hemispheres aligned with the instantaneous direction of the interplanetary electric field (IEF) in the ion properties (Dubinin et al., 2013b; Intriligator, 1989) and magnetic field (Rong et al., 2014; Zhang et al., 2010). Models reproduce this asymmetry by different mechanisms (summarized for example in Du et al., 2013). The Venus Solar Electric (VSE) coordinate system organizes ion measurements well (x aligned with Venus to Sun direction, y with the interplanetary magnetic field component perpendicular to x, and z completing the right-handed system, roughly aligned with the IEF). Another asymmetry in the ion flow directions is along the y-axis of the Venus Solar Orbital (VSO) system. (In VSO x points sunward, $-y$ is along Venus' orbital motion, and z completes the right-handed system, roughly aligned with Venus' spin axis.) The asymmetry was suggested to be caused by Venus' orbital motion relative to the solar wind or the Magnus force (Lundin et al., 2011; Perez-de-Tejada, 2008).

Planetary ions are picked up by the solar wind flow, although not only by the IEF but also by proton lower hybrid waves (Dóbé and Szego, 2007). Not all ions are however flowing downstream. Earlier reports on the observation of venusward bulk flows did not focus on this or they dealt with very brief events

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(Dubinin et al., 2012; Lundin et al., 2011; Masunaga et al., 2013; Nordström et al., 2013; Zhang et al., 2012). A statistical study that explicitly discussed this behavior was done by Dubinin et al. (2013b). Average ion velocities were found to be small and venusward in the $-z_{VSE}$ hemisphere. The VSE coordinate system implies that the magnetospheric configuration is stable during selected time periods. However, the magnetic field especially in the $-z_{VSE}$ hemisphere is very time variable (Rong et al., 2014) and the magnetotail current sheet is often observed to be flapping (Dubinin et al., 2012; Rong et al., 2015). Since this might smear out a correlation between the occurrence of bulk flows in certain directions and proximity to the current sheet, we will look in Section 5.3 for correlations between flows towards Venus and the local magnetic field strength.

The reason why the magnetic field and current sheet location are of interest is because one of the suggested mechanisms for venusward flowing ions is magnetic reconnection, which obviously relates to the magnetic field and usually causes flows close to the current sheet (for Earth see for example Petrukovich et al. (2001), Birn et al. (2011)). Magnetic signatures of reconnection were indeed found at Venus (Dubinin et al., 2012; Volwerk et al., 2010; Zhang et al., 2012). Also at Mars magnetic and electron signatures of reconnection were found (Eastwood et al., 2008; Halekas et al., 2009). Some of the reconnection events at Venus were in combination with planetward flowing ions but these were very brief and close to the limit of the instrument time resolution. Not all venusward flows are therefore necessarily driven by reconnection.

A totally different reason for planetward bulk flows is that they simply emerge from the motion of ions in the magnetic field around Venus. Luhmann and Kozyra (1991) and Curry et al. (2015) trace newly created pickup ions from Venus exosphere through a magnetic field from a MHD model (Ma et al., 2013). Although this approach is not self-consistent, they can derive distribution functions for these ions that are consistent with observations and describe a net precipitation of tens of eV ions into the atmosphere (all over the planet but strongest close to the terminator).

It is generally believed that atmospheric escape from unmagnetized planets via downtail flowing ions is scaling with upstream plasma and solar parameters. For example, Ramstad et al. (2015) found a factor ≤ 3 correlation between the escape at Mars and solar wind density and EUV irradiance. The extreme conditions during coronal mass ejections (CME) and corotating interaction regions (CIR) enhance the escape from Mars by an order of magnitude (Dubinin et al., 2009; Futaana et al., 2008; Wei et al., 2012). CMEs and CIRs can cause similar enhancements at Venus (Luhmann et al., 2007) but there are also many reported cases where the increase is at best a factor < 2 (Edberg et al., 2011; Luhmann et al., 2008; McEnulty et al., 2010). All of these studies are on net escape rates or approximations thereof. They do not separate downtail from planetward bulk flows. While the net escape is an important quantity to understand the atmospheric evolution of terrestrial planets, its scaling with upstream and solar parameters may be misleading since the drivers of flows in the two directions are probably different. While it is known (Dubinin et al., 2013b) that the venusward bulk flows are well organized depending on the direction of the IMF, it is an open question if there are conditions in the solar wind that trigger or states of Venus' ionosphere that promote such flows. Since this may shed light on the physical mechanisms that drives ions toward Venus and since it is useful to understand the scaling of the escape rate, we therefore study correlations with the upstream parameters and the EUV irradiance in Section 5.1.

The structure of our paper is as follows: We start with a case study of venusward bulk flows in Section 3 to set the basis for the statistical study that follows. One of the properties found in the case study is that the flow directions of different species are not always aligned, which is confirmed statistically in Section 4. Section 5 analyzes how the fluxes correlate with upstream and solar parameters and where they occur. We discuss the implications of the venusward bulk flows on atmospheric escape in Section 6. At the end we briefly compare our findings with predictions for different mechanisms that were proposed to drive planetward flows (Section 7).

2. Data set and processing

2.1. Ions and plasma moments

We use ion data from the Venus Express (VEX) spacecraft spanning from its arrival in 2006 until the end of the mission in 2014. VEX completed over 3000 orbits in this period, each with closest approach near Venus's north pole. The main instrument used in this study is the Ion Mass Analyzer (IMA), which is part of the ASPERA-4 package (Barabash et al., 2007). IMA is an electrostatic analyzer with magnetic separation. It measures ions between 10 eV/Q and 36keV/Q in 96 steps (with Q being the ion charge number). The spacecraft motion ($<$ 10 km/s) allows to measure ions in the spacecraft velocity direction that have lower energies ($>$ 6 eV/M for $Q = 1$, no spacecraft potential, and nucleon number M). Spacecraft motion and the elevation scan cause the energy coverage to be direction dependent. IMA measures the full 360° azimuthal range and scans over 90° in elevation for most energies. Some directions are obscured by the spacecraft. Integration of a full velocity distribution takes 3.2min. IMA resolves protons, alpha particles, and "heavy" ions (defined here as $M/Q \gtrsim 16$ like O^+ and O_2^+). In order to calculate velocities and densities we assume for simplicity that all heavy ions are O^+.

Number density n and bulk velocity $\langle\vec{v}\rangle$ of the ions are calculated by numerically integrating over each measured distribution (Fränz et al., 2006). In Section 5 we will calculate the ion flux from the product of number density and bulk velocity. Measurements where the incomplete directional coverage is an issue for the numeric integration are removed. This is discussed in Appendix A together with other details of the data processing. Our background heavy ion density is ≈ 0.01 cm^{-3}. We therefore consider ion densities below this either as zero (when calculating escape rates and mean densities) or as invalid (when studying occurrence and fluxes of bulk flows in defined directions), depending on the case. We show maps of some plasma moments in Fig. 1.

Please note that we express velocity vectors and flow directions in a coordinate system where the x-axis points downtail, opposite to the usual Venus Solar Orbital (VSO) frame, where x points sunward. We will refer to the x-axis also as the "downtail axis".

2.2. Magnetic field and current sheet crossings

Magnetic field data is provided by the Venus Express magnetometer MAG (Zhang et al., 2006). It consists of two triaxial fluxgate magnetometers, one on a boom, one on the spacecraft. We use data with 4s time resolution.

One of our uses of the magnetic field is to identify when VEX is crossing the magnetotail current sheet. We automatically search these crossings for times where VEX is on the nightside ($x < 0$) and has a cylindrical distance ρ from the x-axis of $\rho \leq 0.7R_V$ (with the Venus radius $R_V = 6051.8$ km). Our requirement for a current sheet crossing is that the total magnetic field B_{tot} drops below 5nT during a certain time interval and that the component B_x is changing from −5nT to +5nT (or in the opposite direction) during the same time interval. The interval is selected to be 96 s, half the IMA integration period. We repeat the search for intervals that are