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Solar wind - ionosphere interaction at Mars and Venus as compared to Earth

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Abstract

Ion heating, acceleration and escape at Mars and Venus occur due to a relatively direct interaction between the solar wind and the planetary ionosphere. At Earth the situation is rather different, as the presence of a strong internal magnetic field causes the separation between the solar wind origin and planetary origin plasma domains, the magnetopause, to be located about 10 R_E away from the planet. Despite this, very effective energy transfer and atmospheric removal does occur over the polar caps of the Earth. At Earth we also have much better observations available so that processes such as wave-particle interaction may be studied in much more detail. We therefore compare plasma observations at Mars, Venus and Earth and discuss similarities and differences. We also discuss the ion flow patterns and escape paths of the three planets, as these must be well known in order to study the ionosphere - magnetosphere response to extreme solar wind events. Extreme events are short lived, so the spacecraft will often not be in an optimal position to observe escaping ions. This must be taken into account when we try to compare the response of the different planetary space environments to particular solar wind events.

1 Introduction

The magnetosphere of the Earth is much larger than the induced magnetospheres of Mars and Venus, see Fig. 1 for a size comparison, cylindrical coordinates are used for all three planets. Earth data is from the Cluster spacecraft (Nilsson et al., 2006), Mars and Venus data from the ASPERA instruments on Mars Express and Venus Express (Nilsson et al., 2011; Nilsson et al., 2012; Nordström et al., 2012). Despite the distance of the magnetopause of Earth from the ionosphere, significant interaction is taking place in the ionospheric projection of the cusp. In the ionospheric cusp significant ion upflow occurs in response to mainly the soft electron precipitation of magnetosheath origin, causing strongly enhanced *F*-region electron temperatures (Nilsson et al., 1996). This outflow in the cusp is the main source of oxygen ions, whereas there is a polar wind of light ions emanating from the entire polar cap. The outflowing plasma is subject to significant heating, mainly due to wave-particle interaction (Waara et al., 2011; Slapak et al., 2011), and some field-aligned acceleration due to the centrifugal acceleration mechanism (Nilsson et al., 2008; Nilsson et al., 2010). The final fate of the outflowing ions can be very different depending on the outflow trajectory, with some oxygen ions being heated and accelerated to several keV energy in the cusp and mantle, whereas some protons remain at an energy of a few eV in the magnetotail lobes. Observations at Mars and Venus also show significant heating of ionospheric plasma, to a few eV energy, at times followed by acceleration up to typically several 100 eV (Nilsson et al., 2012).

2 Ion outflow paths

In Fig. 2 we show flight trajectories of average outflowing ions with white lines in panels a and c, and in panel b we show average flight trajectories of cold ions (a parallel velocity of about 20 km/s and subject to the average observed perpendicular drift). The cold ions correspond to cold ions observed in the magnetotail lobes (Engwall et al., 2009; Nilsson et al., 2010). The colour code in these figures corresponds to the electric field spectral density at the (a) oxygen gyro frequency, (b) proton gyro frequency and (c) the average spectral density for frequencies below 10 Hz. As can be seen the flight trajectories of more energetic ions leads to high altitude where even more ion heating can be expected due to the strong wave activity at the ion gyro frequency. Cold ions remain along flight trajectories with little heating. This is particularly true for protons, where the wave activity at the proton gyro frequency is particularly low over most of the mid-altitude polar

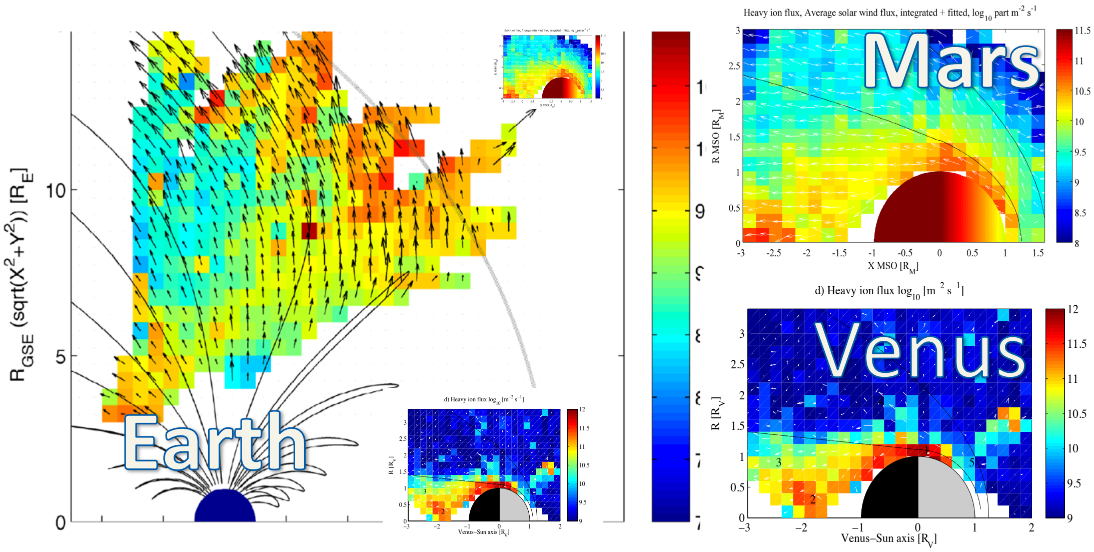

Figure 1: Heavy ion outflow in cylindrical coordinates from Earth, Mars and Venus shown approximately to scale, shown in cylindrical coordinates.

cap.

The induced magnetospheres of Mars and Venus are much more compact, and we may not expect as large differences depending on the transport path as at Earth. But these induced magnetospheres still have significant structure, mainly depending on the direction of the solar wind electric field. Studies of ion outflow at Venus also show how planetary origin protons and oxygen appear to follow different transport paths (Fedorov et al., 2011; Nordström et al., 2012), so some effects similar to what is seen at Earth does occur. Cold plasma, of too low energy to be measurable by ion spectrometers, are clearly present also at high altitude at least for Earth and Mars. Therefore the question on how and where plasma is heated and accelerated, and what fraction of the plasma which can remain cold, arises when we study all three planets. In order to obtain a truly reliable result we need to understand the processes behind the spatially and temporally variable ion heating and acceleration.

Once ionospheric origin ions reach the high altitude cusp and mantle regions at Earth, they are in an environment with similar magnetic field strength and shape as around the unmagnetised planets Mars and Venus, though the scale size is an order of magnitude larger. This makes it worthwhile to compare the detailed plasma data from the high altitude magnetosphere of Earth to the situation at Mars and Venus. It is likely that similar processes of ion heating through wave-particle interaction occur at Mars and Venus as at Earth, though with lower intensity and resulting in lower final temperatures of the ions.

From Fig. 1 one can see that the strongest heavy ion fluxes at earth are related to the cusp and mantle. Extrapolating these fluxes using the results of (Ebihara et al., 2006; Haaland et al., 2012) we can see that most of these oxygen ions will be lost to interplanetary space rather than transported to the plasma sheet. Such escape can indeed be directly observed for southward IMF using Cluster data (Slapak et al., 2012). During magnetic storms both the outflow and the plasma convection can be expected to increase. The increased plasma convection will bring more plasma to the plasma sheet, resulting in the well known increase in magnetospheric oxygen density during magnetic storms. The important lesson is that whereas changes in tail ion fluxes at Mars and Venus gives a decent picture of changes in ion outflow in response to a solar wind event, at Earth we mainly see a change in the transport pattern. The main part of the outflow will, at least for non-storm conditions, not reach the magnetotail lobes. Outflow response at Earth should preferably be measured in the high altitude cusp and mantle, when the outflowing ions have gained a significant part of the energy they can be expected to gain so that a realistic extrapolation of the flight trajectory can be made. Also for Mars and Venus it is important to at least compare with the average distribution of the ion outflow related to the solar wind electric field direction, so the location of the spacecraft during a particular event will matter for these planets as well.

3 Conclusions

Significant ion outflow and escape of a similar magnitude occur from Mars, Venus and Earth, despite the difference of the strong internal magnetic field of Earth. The strong geomagnetic field causes strong and efficient plasma coupling in the polar cap, whereas the unmagnetised planets have regions of particularly strong coupling, determined by the direction of the solar wind electric field direction. It is therefore worthwhile to compare ion outflow, heating and acceleration not only between Mars and Venus, but also with Earth. We present some similarities and differences and discuss what we can learn from this. We also discuss the limitations of trying to compare planet response to solar wind events based on case studies.

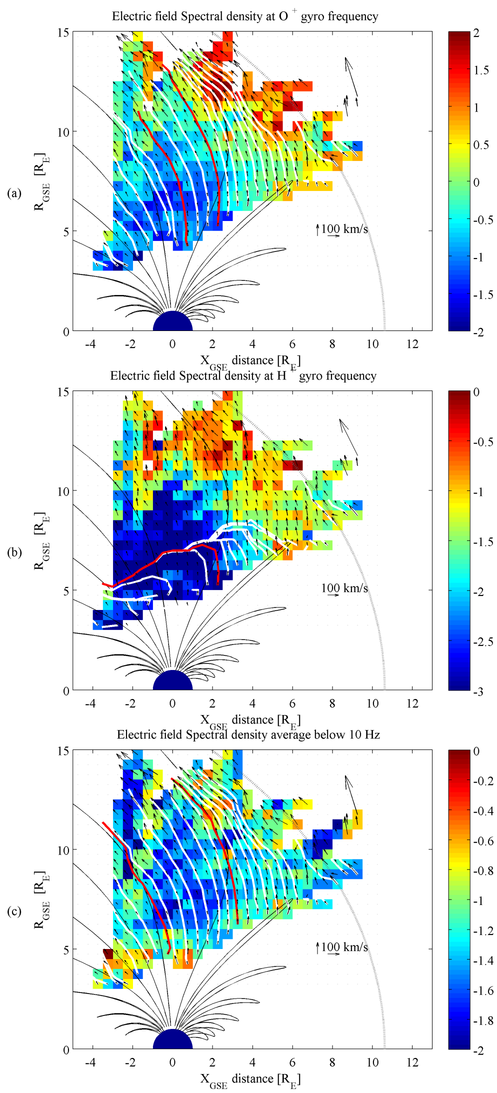

Figure 2: Electric field wave activity at earth in cylindrical coordinates at (a) the oxygen gyro frequency, (b) the proton gyro frequency and (c) the average below 10 Hz.

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