45

Does a Magnetosphere Protect the Ionosphere?

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ABSTRACT

This chapter reviews observation at Venus, Earth, and Mars related to ionospheric ion outflow. We compare observations made around these three planets – Venus and Mars, which are unmagnetized, and Earth, which is magnetized – in order to assess the protective effect of planetary magnetic fields on ionospheric ion outflow. We discuss the measured flux of outflowing ionospheric ions, the energy transfer from the solar wind to the ionosphere and the fate of outflowing ionospheric ions. Our conclusion is that there is no observational evidence that, under current conditions, Earth's magnetic field can protect its ionosphere from losing material any better than the induced magnetospheres of Venus and Mars. However, extrapolating this result to geological timescale or to other planets must be made with care due to the complexity of the processes associated with ionospheric ion outflow.

45.1. INTRODUCTION

Among the many conditions that make a planet able to sustain life as we know it, the presence of a thick enough atmosphere and of liquid water seems necessary. The evolution and stability of planetary atmospheres depend on the interactions at their interface with the surface of the planet and with space. In the latter case, the loss of ions from the ionosphere may have significantly impacted planetary atmospheres as it is universal in our solar system throughout its history (Lundin et al., 2007, Lammer, 2008).

In the solar system, Earth is currently the only planet with an atmosphere rich in water. Venus and Mars, despite their relatively similar mass and distance to the Sun, provide very different conditions. Contrary to Earth, they are depleted of water and have CO_2-rich atmospheres, very hot and dense for Venus and cold and tenuous for Mars. Many factors could have impacted the evolution of the atmospheres of these three planets (see the review Lammer et al., 2018). Among them, a difference in the ionospheric ion escape rate has been suggested as a potentially significant contributor to the diverging evolution of the atmospheres of these three planets, in particular in the young solar system when the Sun was more active than nowadays (Lammer et al., 2008). It has been alleged that the presence or absence of a large-scale magnetic field on a planet plays a role in the evolution of atmospheres. Indeed, the intensity and morphology of planetary magnetic fields affect the interaction of the planets with stellar winds and thus the escape of ionized material from their atmospheres (Lundin et al., 2007). Magnetized planets like Earth are surrounded by large-scale magnetospheres that isolate them from direct interaction with stellar winds. On the other hand, unmagnetized planets like Venus and Mars, despite the existence of crustal magnetic fields (for Mars) or of an induced magnetosphere (see Chapter 25 of this volume for Mars) interact more directly with solar wind. The paradigm has always been that a large-scale magnetic field prevents the atmospheres from being blown off by the stellar wind and thus protects the atmosphere of planets

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(Lundin et al., 2007, and references therein). However, recent observations around Earth, Mars and Venus challenge it.

In this chapter, we address the question of the protective effect of planetary magnetic field on planetary atmospheres. This is too vast a domain to be exhaustively treated in a book chapter. We will focus on observational results since modeling ionospheric outflow, despite impressive recent developments, remains challenging, in particular due to the inherent difficulty to model the coupling between the ionosphere, the solar wind, and the magnetosphere (Glocer et al., 2009, Welling and Liemohn, 2016). In this chapter we will focus on results based on observations made at Venus, Earth, and Mars and discuss how they can constrain the role of intrinsic magnetic fields in protection of planetary atmospheres. After a short summary of ion outflow processes (section 45.2), we will review the most recent observations related to ion outflow around Venus, Earth, and Mars (section 45.3). Based on these observations, we will then discuss more specifically the influence of the planetary magnetic moment on ionospheric ion outflow and the atmospheric net loss rate (section 45.4).

45.2. MAIN OUTFLOW PROCESSES

Atmospheric erosion can result from the escape of neutral or charged particles. In this chapter we focus on the escape of charged particles only as it is directly affected by the magnetic environment of the planets – contrary to neutral escape. The escape of neutral particles at Earth, Mars, and Venus mostly results from two processes, Jeans escape and dissociative recombination. Jeans escape refers to the escape of the tail of the thermal distribution, which has a kinetic energy higher than the escape velocity. For those three planets, Jeans escape is efficient for hydrogen atoms only. The second neutral particle escape process is caused by the dissociative recombination of molecular oxygen ions. It is only efficient at Mars and its rate is still debated. For hydrogen, the neutral and ion escape rates are of the same order of magnitude. For heavier species, ion escape dominates with the exception of oxygen escape at Mars, where dissociative recombination may induce a significant loss of neutral oxygen (see Figure 45.2 and Gunell et al., 2018).

45.2.1. Unmagnetized Planets

Around an unmagnetized planet with an atmosphere an induced magnetosphere is formed by induced currents in the ionosphere (see Chapter 25 of this volume for Mars). The ionospheres of the unmagnetized planets are thus not magnetically connected to the solar wind, but the magnetosphere outer boundary is located closer to the planet than for magnetized planets. Here we briefly list the main ion outflow mechanisms at play at Venus and Mars. The escape routes for various unmagnetized bodies are discussed in Brain et al. (2016) and ion outflow processes from unmagnetized planets are discussed in more details in Chapter 28 of this volume.

For unmagnetized bodies, the stellar wind can interact directly with the upper layers of the atmosphere. Ion pickup refers to the capture by the solar wind of atoms of the exosphere ionized by the solar wind outside of the magnetosphere. The significance of this process depends on the amount of neutral atoms located outside of the magnetosphere. It is thus largely determined by the scale height of neutrals, and thus by both the mass of the planet, the temperature, atomic mass, and composition of the atmosphere, and may be of different importance for different species. For instance, if Earth had no magnetic field, it would be significant for hydrogen atoms only, as heavier atoms like oxygen have a lower scale height. It is negligible for magnetized planets, as their magnetosphere extends well beyond the exobase.

Atmospheric sputtering is caused by ionospheric ions swept up and accelerated by the solar wind that then reimpact the ionosphere, colliding with exospheric atoms, giving them enough energy to escape the planet (Luhmann and Kozyra, 1991). The ion gyroradius decreases with an increasing magnetic field. Consequently, the region from which newborn ions can reach the exobase shrinks with increasing planetary magnetic moment. Also, the magnetosphere shields this region from the convective electric field of the solar wind. Sputtering therefore decreases with an increasing magnetic moment. The gyroradius is larger for oxygen ions than for protons, and the sputtering efficiency is higher for ions sputtering their own neutrals. Only oxygen ions sputtering neutral oxygen are significant for Venus and Mars.

Ion outflow can also result from the direct extraction of ionospheric ions across the magnetic field lines of the induced magnetosphere. It may result from several processes that can either extract large plasma blobs from the ionosphere or be associated with a slow drift across magnetic field lines. Note that such cross-field loss is also at play on magnetized planets.

45.2.2. Magnetized Planets

Magnetized planets are surrounded by a large-scale magnetosphere that is an intermediate in the coupling between the stellar wind and the ionosphere. There exist a large variety of magnetospheres, depending on the planet magnetic moment, on the rotation rate of the planet, the presence of rings and satellites, and also the inclination and magnitude of the magnetic dipole.

Here we will focus on outflow processes occurring at Earth, the planet for which we have the best experimental and theoretical knowledge of ion outflow processes (see Chapter 14 this volume). At Earth, the region most favorable for ionospheric outflow is around the magnetic poles where magnetic field lines are connected on one end to the ionosphere and on the other end to the solar wind, which provides a direct escape path along the magnetic field. In the polar cap, plasma escapes by means of a polar wind (Axford, 1968). The polar wind refers to the ion outflow driven by the charge separation between electrons and heavy ions (mostly O^+) on the open field lines of the polar ionosphere. In the classical polar wind theory, this charge separation generates an upward electric field, which drives an upward flow of H^+ and He^+, while other species like O^+ are too heavy to escape. However, observations have shown a significant amount of low-energy O^+ ions upflowing above the polar caps (Nagai et al., 1984; Waite et al., 1985; Abe et al., 1993; Su et al., 1998). This O^+ component could either result from additional acceleration mechanisms (Tam et al., 2007), which are supported by recent observations (Maes et al., 2015), but it is not excluded that it actually corresponds to the low-energy component of polar cusp outflow drifting over the polar cap and mixing with polar wind ions. Polar wind outflow is continuous and the acceleration by the ambipolar electric field is limited to a few tens of eV (Chapter 15 this volume). The cusp region is the part of the dayside polar cap that is magnetically connected to the dayside part of the magnetosphere where solar wind energy and material are transferred to the magnetosphere via dayside reconnection between the solar wind and Earth's magnetic field. Kinetic energy is carried into the cusp by solar wind plasma, and energy can also be transferred by a Poynting flux in the same direction (Strangeway et al., 2005). This energy contributes to the heating of ionospheric particles, leading to their subsequent escape. Cusp outflow occurs on open magnetic field lines and contains a significant amount of O^+ ions in addition to H^+ ions, which can be accelerated to energies up to a few keV (Nilsson et al., 2006). Wave–particle interactions play a significant role in ion acceleration, in particular for O^+ ions via cyclotron resonance (Waara et al., 2011). The third main outflow region on Earth is the auroral oval. While ion outflow occurs on the whole oval, it is more intense and dynamic in the nightside auroral region, which is magnetically connected to the tail plasmasheet, where large amounts of energy can be dissipated during magnetic substorms and storms (Chapter 18 this volume). Auroral ion outflow occurs on closed field lines. In the auroral zone, the upward acceleration of ionospheric ions can either be due to a static electric field parallel to the magnetic field or to wave–particle interactions. Auroral outflow contains a significant proportion of O^+ ions and the particle acceleration can reach a few tens of keVs (Maggiolo, 2015, and references therein).

At lower magnetic latitude, both ends of the magnetic field lines are connected to the ionosphere and outflowing ionospheric ions should flow across the magnetic field to escape. Such cross-field ion escape is at play in the plasmasphere, where the escape of low energy ions (mostly H^+ and He^+) is significant (Chapter 15 this volume; André et al., 2015, and references therein). It can either result from the continuous loss of plasmaspheric material across magnetic field lines, which is referred to as plasmaspheric wind (Dandouras, 2013), or to the formation of plasmaspheric plumes that are associated with the detachment of plasma regions in the afternoon sector of the plasmasphere (Darrouzet et al., 2008).

45.3. ION OUTFLOW RATE: OBSERVATIONS

Spacecraft observations around Venus, Earth, and Mars provide observational evidence of ion outflow around those three planets. We present here a brief summary of loss rates based on those observations. More details are available in review papers and books such as Dubinin et al. (2011) for Mars, Lundin (2011a) and Brain et al. (2016) for Venus and Mars, and Yau and André (1997) and Hultqvist et al. (1999) for Earth. We also refer the reader to the book edited by Nagy et al. (2016) for a more general discussion about the plasma sources of solar system magnetospheres. Note that the outflow rate is somewhat more difficult to estimate for H^+ ions, since they may originate from the solar wind contrary to ions containing an oxygen atom, which are almost exclusively of planetary origin.

45.3.1. Venus (Figure 45.1a)

The Pioneer Venus Orbiter (PVO, 1978–1992) provided the first estimates of the flux of ions escaping Venus' ionosphere. Due to the limitation of the instrumentation onboard the PVO, a direct measurements of the flux of escaping ionospheric ions was not possible. Additional data and indirect methods, using for instance magnetic field measurements or suprathermal electron measurements, had to be used to estimate the ionospheric escape rate. McComas et al. (1986) obtained an escape rate of 6×10^{24} s^{-1} and Brace et al. (1987) a higher value of 5×10^{25} s^{-1}.Direct measurements of the ion escape rate were made available by the Venus Express (VEX) probe (2006–2014). Oxygen escape rate estimates generally fall in the range of 3–6 $\times 10^{24}$ s^{-1} for ions in the energy range 10 eV/q–25 keV/q (Fedorov et al., 2011; Nordström et al., 2013). Lundin et al. (2011) tried to compensate for the difficulty in measuring low-energy ions due to the spacecraft potential. They estimated the oxygen outflow over all

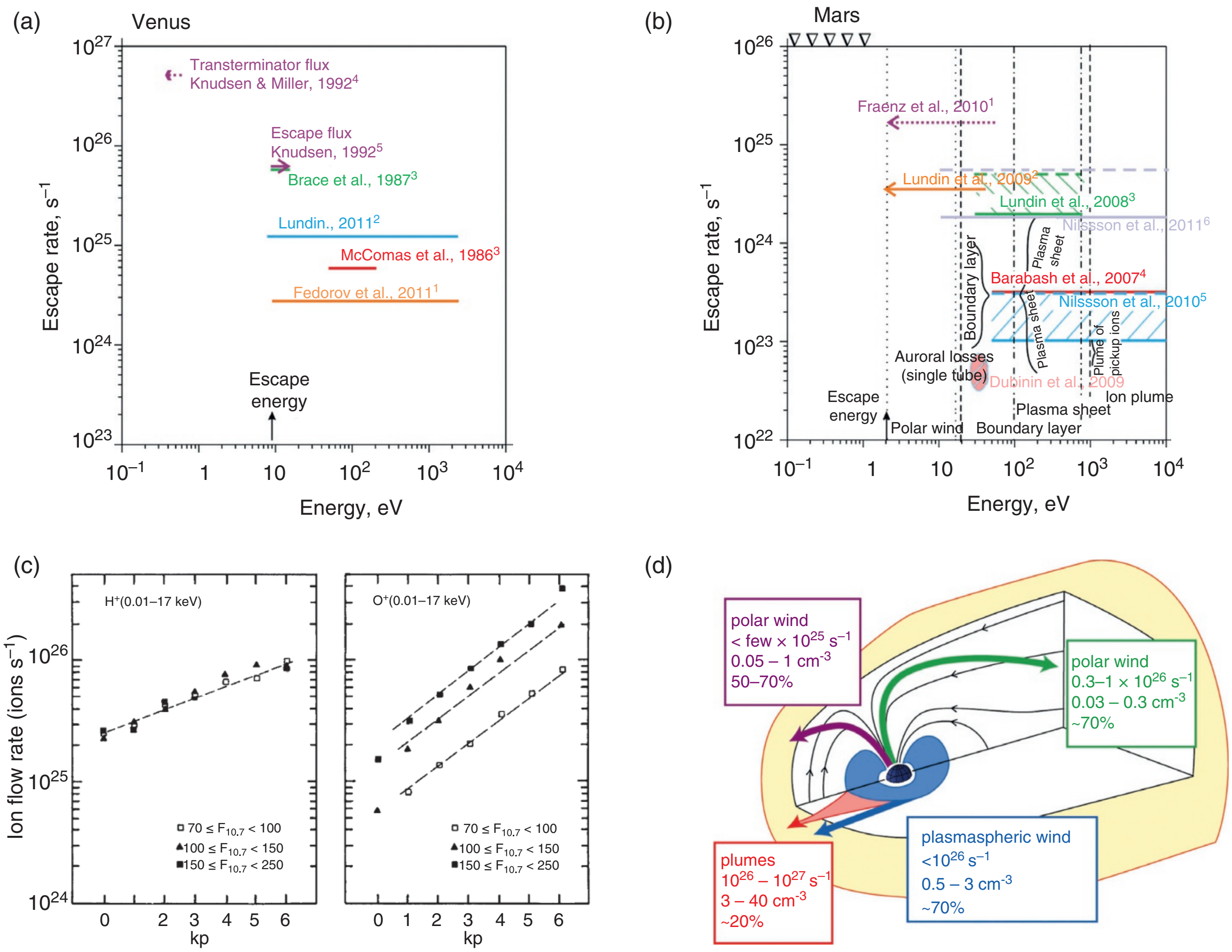

Figure 45.1 Ion outflow rate at Venus (panel a), Mars (panel b), and Earth (panels c and d). (a) and (b) Summary of oxygen loss fluxes on Venus (panel a) and Mars (panel b) evaluated by different authors. From Dubinin et al. (2011); reproduced with permission of Springer Nature. (c) Outflow rate as a function of the Kp index as observed by the DE-1 satellite for H^+ (left) and O^+ (right) for energies between 0.01 and 17 keV integrated over all magnetic local times and invariant latitudes above 56° in both hemispheres. From Yau et al. (1988); reproduced with permission of John Wiley & Sons. (d) Low-energy ion outflow rate in the Earth magnetosphere as estimated from several years of Cluster measurements using the wake method. Sources are indicated, together with order of magnitude outflow rates and densities, and percentage of the time that low-energy ions dominate outside the ionosphere and plasmasphere. From André and Cully (2012); reproduced with permission of John Wiley & Sons.

energies to be 1.2×10^{25} s^{-1}. The ion mass analyzer onboard Venus Express also provided interesting information on the composition of outflowing ions. For instance, Barabash et al. (2007) showed that that ion escape at Venus is dominated by O^+, He^+ and H^+ with an estimated ratio of 1.9 for the H^+/O^+ escape rates and of 0.07 for the He^+/O^+ escape rates. The influence of corotating interactions regions (CIRs) and of interplanetary coronal mass ejections (ICMEs) has been investigated by Edberg et al. (2011). They estimated that they induce an increase in the outflow rate by a factor of ~2 on average. Assuming that CIRs/ICMEs pass by Venus 35% of the time, the authors concluded that 51% of the ion outflow occurs during such active periods.

45.3.2. Mars (Figure 45.1b)

The first direct measurements of the ionospheric outflow from Mars were made by the Phobos 2 spacecraft (1989). Lundin et al. (1989) estimated that Mars is losing oxygen at a rate of $\sim 3 \times 10^{25}$ ions s^{-1}. Later, the Mars Express (MEX) spacecraft was launched in 2003, and it has provided measurements of escaping planetary ions from Mars for a full solar cycle. Nilsson et al. (2011) estimated that the flux of heavy ions (O_2^+, CO_2^+, O^+) escaping Mars during a low solar activity period (2007–2011) was $2.0 \pm 0.2\ 10^{24}$ s^{-1}, which corresponds to a loss of oxygen atoms of $3.0 \pm 0.3\ 10^{24}$ s^{-1}. Lundin et al. (2009) made a stoichiometric analysis of the ion escape. They showed that cold ionospheric ion outflow is dominated by H^+, H_2^+, O^+ and O_2^+ while the average CO_2^+ outflow corresponds to about 10% of the heavy ion outflow. Edberg et al. (2010) performed a statistical analysis of the impact of CIRs on ion outflow from Mars and estimated that it increases the escape rate of heavy ions by a factor of ~2.5 on average, close to the estimate of Nilsson et al. (2011), who found an increase factor of 2.4–2.9 compared to average conditions. Since 2014, the MAVEN spacecraft provides measurements of ion outflow from Mars. Jakosky et al. (2018) estimated the average net loss of O^+ and O_2^+ ions during one Martian year and found that it corresponds to net global loss rate for O atoms of 5×10^{24} s^{-1}, which is in line with Mars Express results.

45.3.3. Earth (Figure 45.1c and 45.1d)

Ionospheric ion outflow observations obtained before the launch of the Cluster satellites in 2000 are detailed in the review by Yau and André (1997). The dominant ion species flowing out from Earth ionosphere are H^+, O^+ and He^+. During the most geomagnetically active periods molecular ions like N_2^+, NO^+ and O_2^+ have also been observed. Yau et al. (1988) estimated the integrated ion outflow rate for energies between 0.01 and 17 keV for latitudes above 56° using measurements from the DE-1 satellite (Figure 45.1c). It ranges between ~2.5×10^{25} s^{-1} and 10^{26} s^{-1} for H^+ for low and high geomagnetic activity, respectively. No variation of the H^+ flux with solar UV flux (as parametrized with the F10.7 index) could be evidenced in this energy range. On the contrary, the O^+ flux increases with solar UV flux by a factor of four from low to high solar UV flux levels. The O^+ ion flux also strongly increases with geomagnetic activity (by a factor of ~20 from Kp = 0 to Kp = 6) and ranges between ~5 $\times 10^{24}$ s^{-1} and ~4 $\times 10^{26}$ s^{-1}, depending on solar UV flux and geomagnetic activity. Thermal outflow was investigated with the Akebono spacecraft and the estimated flux is of the order of 10^{24} s^{-1}–10^{25} s^{-1} for O^+ and H^+ (Cully et al., 2003). However, the measurement of such low-energy ions is difficult due to the spacecraft positive charging. A big breakthrough was made by the development of an indirect method to detect low-energy ions using spacecraft potential and electric field measurements (the wake method) (Engwall et al., 2006; André and Cully, 2012; André et al., 2015; Chapter 15 this volume). The use of this method with the Cluster spacecraft led to a significant upward reevaluation of the flux of low-energy ions above the polar cap. New estimates made with this method are in the range of 10^{26} s^{-1}. In addition, Cluster observations at lower latitudes in the plasmasphere (see Chapter 22 this volume) indicate that it is associated with an ion escape rate of a similar magnitude, either through the plasmaspheric wind or via plasmaspheric plumes (Figure 45.1d). The composition of this cold plasma population is inaccessible with the wake method, but it is likely dominated by H^+ and He^+, and may also contain a O^+ component (Maes et al., 2015).

45.3.4. Ion Pickup and Ion Sputtering

Ion pickup and ion sputtering also contribute to the loss of atmospheric material. They are not directly associated with ion outflow but are affected by the magnetic environment around planets. The amount of material lost via ion pickup depends on the number of neutrals in the exosphere that are present outside the magnetosphere. It depends on the altitude profile of the exosphere and on the altitude of the outer boundary of the magnetosphere. Consequently, it is higher for unmagnetized planets for which the induced magnetosphere boundary is located close to the planet. In consequence, ion pickup at Earth is negligible. Estimates of loss via ion pickup for oxygen are of the order of 10^{25} s^{-1} at Venus and Mars and for hydrogen of the order of 5×10^{24} s^{-1} and 2.5×10^{24} s^{-1} for Venus and Mars, respectively (Gunell et al., 2018, and references therein). Ion sputtering is also dependent on the magnetic environment around planets even if it consists in neutral outflow. For Venus Mars, and Earth, sputtering is only significant for oxygen atoms. The corresponding oxygen loss rate is estimated at 5×10^{24} s^{-1} for Venus (Nordström et al., 2013), 3.5×10^{23} s^{-1} for Mars (Chaufray et al., 2007), and 8×10^{23} s^{-1} for Earth (Shematovic et al., 2006).

45.3.5. Case studies: CIRs and CMEs

The outflow rate estimates discussed above were obtained by a statistical analysis of observations made around the planets for long periods of time. They show that the outflow rate at Earth is of the same order of magnitude (typically 10^{25}–10^{26} s^{-1}), if not higher, than the outflow rate at Venus and Mars, even when pickup and sputtering loss are taken into account. It is, however, interesting to compare the outflow rates on different planets for a specific solar event, as done by Wei et al. (2012) for a same CIR that interacted with both Earth and Mars. By comparing Mars Express measurements at Mars and Cluster measurements at Earth, they showed that the increase of the outflow rate on Mars and Earth were of the same order of magnitude. However, their result also indicated that the increase of the O^+ outflow rate under solar wind pressure increase is more pronounced on Mars than it is on Earth. The influence of the strongest Coronal Mass Ejection (CME) of solar cycle 24 on Mars has been studied by Ramstad et al. (2017a) It seems this CME had a limited effect on the outflow rate (with an upper limit of the outflow rate of $10^{25}s^{-1}$) and that its main impact was to increase the escaping ion energy rather than the number flux.

45.4. INFLUENCE OF MAGNETIC MOMENT

45.4.1. On the Energy Transfer from the Solar Wind to the Ionosphere and Ion Outflow

Ion outflow is ultimately driven by the energy input from the star into the planetary atmosphere, in particular in its upper layers, the ionosphere, and the thermosphere. This energy transfer occurs through two main pathways, stellar radiation and stellar winds. Stellar radiation (mostly in the ultraviolet, extreme ultraviolet, and X-ray range) can photodissociate and heat atmospheric constituents. The energy carried by stellar photons is insensitive to the planetary magnetic field. It is the dominant ionization source for planetary neutrals and it drives the formation of the planetary ionosphere. In addition, stellar radiation affects the planetary atmosphere composition and altitude profile by heating the planetary atmospheric neutrals and inducing photochemical reactions.

The energy transfer from the stellar wind to the ionosphere depends on the magnetization of the planet as it occurs through the magnetosphere. Part of this energy is transferred to the planetary atmospheres via particle precipitation (of which electrons are the main energy carriers), waves, and Joule heating (corresponding to the energy dissipated when charged particles drift relative to one another or relative to neutral particles).The presence of a large-scale magnetosphere influences different escape processes in different, and sometimes contradictory, ways. On one hand it can limit the energy transfer into the ionosphere, as it acts like an obstacle that diverts part of the stellar wind energy. However, this shielding is limited and a fraction of the solar wind energy penetrates into the magnetospheric system. The dominant process allowing energy transfer into the magnetosphere is magnetic reconnection, which is effective mostly when the stellar magnetic field is antiparallel to the planetary magnetic field. This energy can then either be deposited directly into the ionosphere or be stored in the magnetosphere and then dissipated during geomagnetic substorms/storms (Chapter 18 this volume). The stellar wind energy that has penetrated into the magnetosphere is not necessarily dissipated in the ionosphere. It can be returned to the stellar wind, for instance via the release of plasmoids in the magnetospheric tail (Koskinen and Tanskanen, 2002). On the other hand, the presence of a magnetosphere, whose dimensions can be much larger than the size of the planet, increases the cross-section of the interaction region with the stellar wind and thus increases the amount of stellar wind energy that can potentially be diverted into the ionosphere. Furthermore, the magnetosphere funnels solar wind energy in specific regions (mainly in the cusp region and the auroral zone), which favors the escape of heavy ions.

In order to assess the protective effect of a magnetosphere on the stellar wind energy deposition in the ionosphere we consider the energy budget between the stellar wind, the magnetosphere, and the ionosphere.

For unmagnetized planets, the size of the induced magnetosphere is relatively small. For Venus, the induced magnetosphere boundary is located at a distance of ~0.1 Venusian radii (Stenberg Wieser et al., 2015), and for Mars at a distance of ~0.45 Martian radii at the terminator (Bertucci et al., 2011). The cross-section of the induced magnetosphere with the stellar wind is thus only slightly larger than the cross-section of the planet itself, which limits the maximum amount of solar wind energy potentially transferred to the ionosphere. The efficiency of the energy transfer between the solar wind and ion outflow at Mars is discussed in Ramstad et al. (2017b). This study points to an efficient shielding of the ionosphere from the solar wind by the induced magnetosphere. They estimated the outflowing ion kinetic energy using observations from ASPERA-3 onboard MEX. They obtained a coupling efficiency (the ratio between the outflowing ions kinetic energy and the incoming solar wind energy flux) of 2.39 ± 0.95% for the highest values and of 0.67 ± 0.04% for the average value. To our knowledge, this is the only estimate of the coupling between the solar wind and Mars and no estimate of the coupling efficiency at Venus has ever been published.

The size of Earth's magnetosphere is much larger than the induced magnetospheres of Venus and Mars. The magnetopause (the outer boundary of the magnetosphere) is located at distances of 11–15 Earth radii (R_E) at the terminator (Case and Wild, 2013). The large cross-section of Earth's magnetosphere with the solar wind (approximately 350–700 times the cross-section of Earth itself) implies that it can potentially catch more solar wind energy than if Earth had no intrinsic magnetic field. The interaction between the stellar wind magnetic field and the planetary magnetic field result in a variable coupling efficiency depending, in particular, on the relative orientation of these two magnetic fields at the dayside magnetosphere. Part of the solar wind energy can be directly deposited in the ionosphere, in the cusp region for instance, or be accumulated in the magnetosphere.

A large number of coupling functions have been developed to estimate empirically the solar wind input into Earth's magnetosphere (Newell et al., 2007). They have been used to assess the transmission efficiency between the solar wind and the magnetosphere (the ratio between the energy input in the magnetosphere and the solar wind incoming energy). The transmission efficiency is estimated typically between less than 1% and 10% (or even more during strong geomagnetic storms) (Li et al., 2012). Those values depend on the estimates of the magnetospheric effective cross-section, which can be obtained either by assuming that the energy input equals the estimated energy dissipation in the magnetosphere or by using magnetic field models (Ostgaard et al., 2002a). For instance, Knipp et al. (1998) obtained a coupling efficiency of 6.9% for a cross-section of 7^2 R_E^2, Ostgaard et al. (2002a) of 0.3–0.8 % for a typical cross-section of $\pi.10^2$ R_E^2, and Tenfjord and Ostgaard (2013) of 0.6% for a typical cross-section of ~$\pi.25^2$ R_E^2 (they used a varying magnetospheric cross-section at Xgsm = −30 Re from the Petrinec and Russell (1996) magnetopause model). Thus, it seems the shielding effect of the magnetosphere, which diverts most of the incoming solar wind energy, could be balanced by its large cross-section with the solar wind.

In order to estimate the influence of the magnetosphere on the solar wind energy deposition in the ionosphere, we compare estimates of the energy dissipated in the ionosphere with the incoming solar wind energy flux which would intercept Earth if it had no magnetic field. The main energy dissipation channels in the magnetosphere are the ring current, Joule heating, and particle precipitation in the ionosphere, whose contributions to the total energy dissipation are estimated to 15, 56, and 29%, respectively (Østgaard et al., 2002a), which are close to the estimates of Knipp et al. (1998) (17, 60, and 23%). Guo et al. (2012) found slightly different values with an energy dissipation in the ionosphere, lower for high solar wind energy input and ranging between 20 and 80% (with an average around 50%) of the total dissipated energy.

A large part of the magnetospheric energy is thus dissipated in the ionosphere through Joule heating and particle precipitation. The energy flux of precipitating particles can be measured directly. For instance, Newell et al. (2009) estimated the total energy flux precipitating in the auroral zone with Defense Meteorological Satellite Program (DMSP) measurements and found an energy deposition of 10.8 GW during low solar wind driving conditions and 35.7 GW during high solar wind driving condition. By deriving the electron energy deposition (0.1–100 keV) from UV and X-ray emissions in the Northern Hemisphere, Østgaard et al. (2002b) found a relation between the AL index and the electron energy deposition U_A ($U_A[GW] = 4.4\ AL^{1/2} - 7.6$). Energy dissipation via Joule heating can be estimated from measurements or models. It is more debated as estimates can be largely different from one method to another (Palmroth et al., 2005). Joule heating varies strongly with geomagnetic activity and estimates of the Joule heating vary between a few and several hundreds of GW during active periods.

The incoming solar wind energy arriving at Earth is 2.67×10^{-4} $Jm^{-2}s^{-1}$ for a solar wind density of 5 cm^{-3} and a solar wind velocity of 400 kms^{-1}. It corresponds to an energy flux of ~34.1 GW for a cross-section the size of Earth. If Earth had no magnetic field, its cross-section with the solar wind would correspond to the cross-section of its induced magnetosphere, the radius of which is estimated to 1.2 R_E (Gunell et al., 2018). We can thus estimate that an Earth with no magnetic field could receive a maximum available energy from the solar wind of the order of $34.1*1.2^2 = 49.1$ GW on average. Another estimate of the incoming energy based on OMNI data from 1997 to 2010 (Tenjford and Ostgaard, 2013, Table 1) and assuming an average cross-section of the Earth magnetosphere of $\pi.25^2$ R_E gives a similar value of 48.5 GW. To compare the incoming solar wind energy on the induced magnetosphere of an hypothetic unmagnetized Earth, we use the long term averages discussed in Tenjford and Ostgaard (2013), who investigated energy dissipation in the ionosphere between 1997 and 2010. Indeed, the solar wind is highly variable, as is energy dissipation at Earth, which depends on geomagnetic activity and solar wind driving. Furthermore, the accumulation of energy in the magnetosphere implies that energy dissipation in the ionosphere can be delayed. It is thus more relevant to compare long-term averages than to focus on specific events. Tenjford and Ostgaard (2013) estimated that a total of 4.8×10^{19} J were dissipated through Joule heating and of 2.7×10^{19} J through particle precipitation during this period. This gives an average dissipated power of, respectively, 109 GW for Joule heating and 61 GW for particle precipitation, and thus of 170 GW dissipated in the ionosphere in total. This is more than the incoming energy as estimated above. As a 100% transmission efficiency of the stellar wind energy into the ionosphere of an unmagnetized planet seems highly unrealistic, we conclude that the presence of a large-scale magnetosphere around Earth increases the solar wind energy deposition in its atmosphere.

45.4.2. On the Outflow Rate

Recently, we presented a study where we investigated the dependence of escape processes at Venus, Earth, and Mars on the planetary magnetic moment (Gunell et al., 2018). We varied the magnetic moment of three fictitious planets with atmospheric properties similar to the present day atmospheres of Venus, Earth, and Mars and investigated the influence of their magnetic moment on the erosion of their atmospheres. We made a semi-empirical model of the outflow process based on measurements made around those three planets and on a magnetic field model. This empirical model describes the variation of the total escape rate of the main outflow processes as a function of the planetary magnetic moments. Seven outflow processes are taken into account: Jeans escape, dissociative recombination, cross-field ion loss, ion pickup, sputtering, polar wind, and polar cusp escape. The last five of these processes are dependent on simple properties of the planetary magnetosphere (the magnetopause standoff distance, the solid angle of the polar cap, and the cross-section of the magnetosphere), which dependence on the planetary magnetic moment is simulated assuming a magnetic field model and solar wind dynamic pressure balance. The final outcome of this study is displayed in Figure 45.2 and can be summarized as follows: the outflow rate for those three fictive planets is relatively similar when those planets are unmagnetized and when they have a very strong dipolar moment (with the same magnitude as Jupiter). For dipolar moments similar to the present day Earth magnetic moment, the escape rate is actually slightly higher than in the unmagnetized configuration.

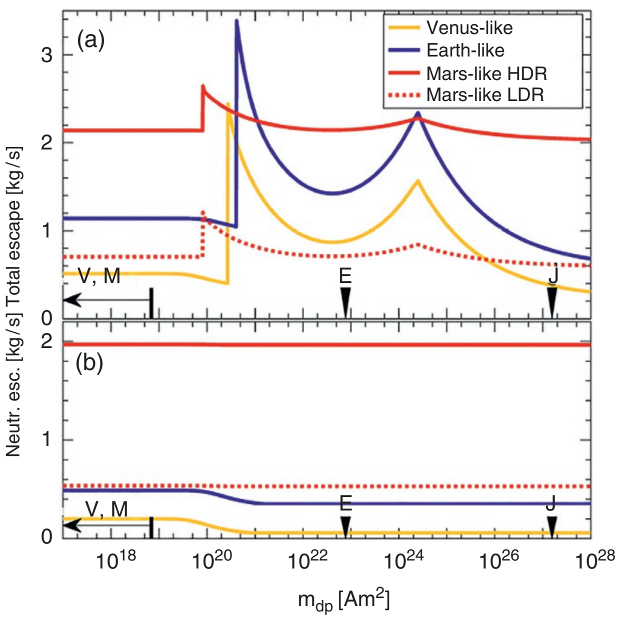

Figure 45.2 Mass escape rates for Venus-like, Earth-like, and Mars-like planets: (a) total mass escape rates. (b) neutral mass escape rates. For escape from Mars, the two curves represent high (HDR) and low (LDR) estimates of dissociative recombination of molecular oxygen. The magnetic moments of present-day Earth and Jupiter are marked on the horizontal axis for reference. The horizontal arrow indicates the unmagnetized character of Venus and Mars. From Gunell et al. (2018); licensed under CC BY 4.0.

Interestingly, there were two peaks of the escape rate. The one at low magnetization levels (a few percent or less of the magnetic moment of present-day Earth) is associated with a peak of the polar wind outflow and is dominated by hydrogen. It corresponds to a magnetization level the size of which the polar cap maximizes. The peak at high magnetization levels (about thirty times the magnetic moment of present-day Earth) corresponds to a peak of cusp ion outflow and is dominated by oxygen. As the magnetic moment of a planet increases, the size of its magnetosphere increases and so does the amount of stellar wind energy captured by the magnetosphere and deposited in the cusp region. This increases the cusp outflow until it reaches the maximum that can be supplied by the ionosphere. The decrease of the cusp outflow for higher magnetic moment is caused by the decrease of the size of the cusp region in this saturation regime. This study shows that the variation of atmospheric escape with magnetic moment is complex and that the amount of material extracted from the atmosphere is maximum when the planets are magnetized, not when they are unmagnetized. The two peaks identified in this study are associated with escape rates a few times higher than the escape rate for unmagnetized planets. The escape rate for current solar and atmospheric conditions on Venus, Earth, and Mars remains relatively limited (a few kg s^{-1}) whatever their magnetization level and could at maximum have removed as much as one Earth atmosphere from those three planets.

45.4.3. On the Return Rate

In addition to their effect on the energy transfer from the stellar wind to the ionosphere and on charged particles outflow, planetary magnetic fields may prevent atmospheric erosion by trapping ionospheric ions and returning part of them to the atmosphere. Neutral atmospheric particles are considered as escaping a planetary body if they have a sufficient kinetic energy to overcome the escape energy of its gravitational field. This criterion is, however, inapplicable to ionized particles, which are sensitive to electric and magnetic forces and which can remain trapped in the magnetosphere even if they have a kinetic energy well above the escape energy. On unmagnetized planets, ion trapping in the magnetosphere is expected to be limited due to the small size of the induced magnetosphere. The vast majority of ions escaping unmagnetized planets with a velocity above the escape velocity are directly dragged away from the planet by the stellar wind. On the contrary, magnetized planets are surrounded by a magnetosphere which can trap ions efficiently – even those with an energy well above the escape energy. On Earth, the observation of a significant amount of trapped O^+ ions with energies of the order of a few to tens of keVs in the magnetosphere provides clear evidence for this process (Maggiolo and Kistler, 2014). Once trapped in the magnetosphere, ionospheric ions can be energized and transported and some of them will eventually return to the ionosphere (see the review by Kronberg et al., 2014). It implies that the flux of outflowing ions does not necessarily correspond to a net loss of the atmosphere. There are two ways to estimate the net loss rate of the atmosphere of magnetized planets: estimating the flux of ionospheric ions escaping the magnetosphere, or measuring the return flux of ionospheric ions in the atmosphere and subtracting it from the outflow rate.

Measuring the amount of ionospheric ions escaping the magnetosphere is complex due to the large spatial extent of the magnetospheric interface with the solar wind. Seki et al. (2001) studied the net mass exchange budget of Earth's magnetosphere with the interplanetary space using observations from the Geotail spacecraft. They considered four escape routes (Figure 45.3): (i) cold plasma drift to the dayside magnetopause (plasmaspheric plumes), (ii) energetic particle drift to the dayside magnetopause (energetic ring current particles and dayside plasma sheet), (iii) tailward plasma flows in the nightside plasma sheet, and (iv) tailward ion beams in the lobe/mantle region. Seki et al. (2001) estimated total O^+ loss rate through these four routes to be about $\sim 5 \times \cdot 10^{24}\ s^{-1}$. Based on this estimate, the authors concluded that only 2% of the ionospheric ions escaping the ionosphere are actually lost in the solar wind while the other 98% are returned to the ionosphere, suggesting that the protective effect of the magnetosphere consists mainly in its capacity to return ionospheric ions into the atmosphere. However, later studies point to a higher ionospheric ion loss rate from the magnetosphere to the solar wind. For instance, Echer et al. (2008), estimated that the loss of O^+ through the plasma sheet boundary layer of the magnetotail alone can be about $\sim 4 \times \cdot 10^{24}\ s^{-1}$, suggesting a higher total loss rate than estimated by Seki et al. (2001).

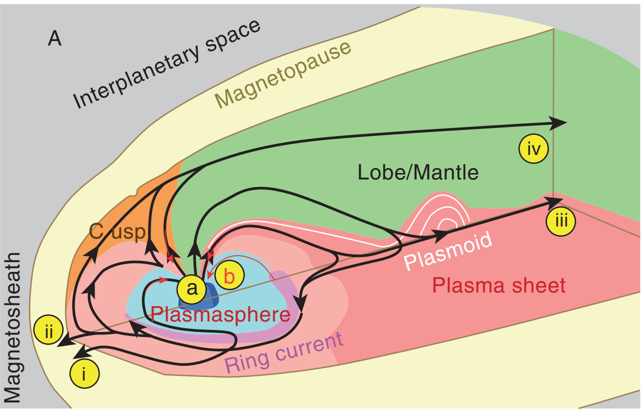

Figure 45.3 Ionospheric ions escape routes from the Earth's magnetosphere (see text for the definition of the four main escape routes). From Seki et al. (2001).

It is mainly the loss rate of ionospheric ions originating from the cusp and polar cap region that has been reconsidered during the last years. Of particular interest were the observations made by the Cluster satellites, whose polar orbit and mass discriminating ion detector allowed a much better characterization of the fate of ionospheric ions escaping from the cusp and polar cap region along the open magnetic field lines of the magnetosphere. Direct loss of ionospheric material into space is facilitated on open magnetic field lines, like for cusp outflow and polar wind outflow. The fate of those ionospheric ions depends on their trajectory, i.e. on the ratio between their field-aligned velocity and their horizontal drift velocity (at which magnetic field lines are convected toward the central plasma sheet). If convection is strong compared to the field-aligned velocity of the ions, they will be trapped on closed plasma sheet field lines close enough from Earth (i.e. earthward of the typical location of the reconnection site in the tail where open magnetic field lines reconnect to form closed plasma sheet field lines, also referred to as the neutral point). Such particles can eventually be returned to the atmosphere. In the opposite situation, ions flow fast enough along magnetic field lines and are most likely lost in interplanetary space, either directly through the lobes or by the ejection of plasmoids in the far plasma sheet (respectively route (iv) and (iii) as defined in Seki et al., 2001).

Slapak et al. (2012, 2013) provided evidence that the acceleration in the cusp region can lead to escape at the dayside magnetopause. They estimated that a significant fraction of cusp ions are accelerated sufficiently to escape through the dayside magnetopause, with a total escape flux of $\sim 7 \times \cdot 10^{24}\ s^{-1}$. Note that ions lost via this route do not even transit through the magnetotail.

Furthermore, the loss rate of ionospheric ions through the cusp into the magnetotail has been revised upwards. Nilsson et al. (2012) showed that a majority of the cusp O^+ flux is sufficiently accelerated to escape into interplanetary space. Slapak et al. (2015) confirmed that the fraction of O^+ ions that might be brought back to the atmosphere is a low percentage and that it has a negligible effect on the total direct escape in the magnetosheath. Slapak et al. (2017) quantified the O^+ ion loss down the magnetotail. They estimated that the flux of O^+ in the plasma mantle, sufficiently fast to escape down the magnetotail and reach beyond the neutral point, is nearly three times larger than the O^+ flux in the dayside magnetosheath. They determined the dependency on geomagnetic activity of ion escape through this route with the following empirical formula $\sim 3.9 \times 10^{24} \exp(0.45\ \mathrm{Kp})(s^{-1})$. It corresponds to a 1–2 orders of magnitude range of variation depending on geomagnetic activity conditions. The extrapolation of this result, including escape via the dayside magnetosheath, indicates an average O^+ escape of $3 \times 10^{26}\ s^{-1}$ for the most extreme geomagnetic storms. This lead the authors to conclude that, in contrast to the conclusion of Seki et al. (2001), the total O^+ loss from the cusp region since Earth was young until today is roughly equal to the amount of the present atmospheric oxygen content.

As discussed above, there is now clear evidence that cusp outflow is associated with a significant direct ion loss into the interplanetary space, as most of these ions are fast enough to flow downtail without being trapped on closed field lines. Such a mechanism is less efficient for polar wind ions whose velocity is much lower. The fate of those low-energy ions escaping from the polar ionosphere has been investigated with the Cluster satellites using the wake method. Haaland et al. (2009, 2012) investigated the transport path of low energy ions using Cluster observations in the lobe region. They compared the ion field-aligned velocity with the convection velocity, i.e. the velocity that brings them toward the plasma sheet closed field lines. These observations show that direct loss of cold ions is significant, corresponding on average to ~10% of the upward flux above the polar cap or ~$10^{25}\ s^{-1}$. This direct loss has its maximum during geomagnetically quiet periods when the convection velocity is the lowest. Of particular interest for the fate of cold ions flowing in the lobe region is centrifugal acceleration, which has been shown to be efficient in accelerating those ions up to high altitudes (Nilsson et al., 2008), contributing to increasing their field-aligned velocity and thus their capacity to escape directly into interplanetary space.

Thanks to its polar orbit at relatively high altitude (several Earth radii), the Cluster satellite allowed a much better characterization of the fate of ionospheric ions outflowing above the polar ionosphere, i.e. the relatively energetic and oxygen rich population escaping in the cusp region and the low-energy polar wind outflow above the polar cap. For both, results obtained in the 2010s and based on several years of measurements points toward a significant loss rate in the interplanetary space.

The dominant plasma reservoir in the magnetosphere is the plasma sheet. It contains substantial amounts of ions of ionospheric origin, as shown by the presence of a significant proportion of O^+ ions. The amount of ionospheric material in the plasma sheet increases with geomagnetic activity (Maggiolo and Kistler, 2014), consistent with the increase of the flux of outflowing ions and with the enhanced convection towards the plasma sheet during active periods. Ionospheric ions entering the plasma sheet farther away than the neutral point are ejected into the solar wind. Otherwise, they are transported toward Earth, where they eventually precipitate in the ionosphere. The main precipitation region corresponds to the auroral zone, magnetically connected to the plasma sheet. Precipitation can also occur in the radiation belt and ring current region, at lower magnetic latitude, but there the number flux of precipitating particles is negligible compared to the flux in the auroral zone. Particle precipitation in the auroral zone has been studied extensively by Newell et al. (2009) using 10 years of DMSP observations at low-altitude (~850 km). They estimated the flux of precipitating ions in the auroral zone to be of the order of $2.4 \times 10^{24}\ s^{-1}$ for low solar wind driving and of $4.1 \times 10^{24}\ s^{-1}$ for high solar wind driving (Figure 45.4). Among these precipitating ions, part of them (mostly H^+ ions) originate from the solar wind, implying that the return flux of ionospheric ions is actually lower than the flux of precipitating ions measured by DMSP. The average flux of precipitating ions in the ionosphere is at least one order of magnitude lower than the flux of outflowing ionospheric ions on Earth and points towards a

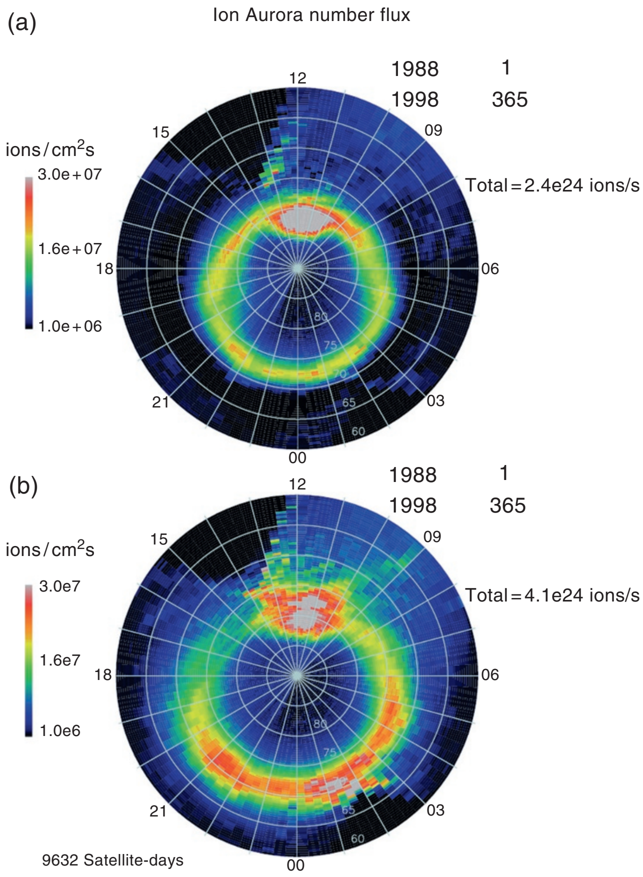

Figure 45.4 Total precipitating ion number flux in the auroral zone as observed by the DMSP satellites; the top panel is for low solar wind driving conditions and the bottom panel for high solar wind driving conditions. From Newell et al. (2009); reproduced with permission of John Wiley & Sons.

low return rate of ionospheric ions. Obviously, these are averaged values of the dominant ion precipitation channel in the atmosphere and it is likely that during active periods, when the precipitation in the nightside ionosphere is intense, the precipitating flux is well above those values. However, such very active periods have a limited duration and are also associated with a dramatic increase of the flux of outflowing ionospheric ions.

To summarize, recent extensive observations at high altitude in the lobe region show that most of the cusp outflow and a non-negligible part of polar wind outflow converts into direct loss in the interplanetary space. Furthermore, low-altitude observations indicate that the average precipitating flux of ions in the atmosphere is well below the typical flux of outflowing ionospheric ions. This implies that the presence of a large-scale magnetosphere at Earth is not sufficient to induce a significant return of outflowing ionospheric ions.

45.5. CONCLUSION

We reviewed satellite observations related to ion outflow around Venus, Earth, and Mars. From those observations we do not find any evidence of a protective effect of the presence of a large-scale magnetic field on ion outflow. In particular we showed that:

- The presence of a magnetosphere does not decrease the amount of solar wind energy that is deposited in Earth's ionosphere.
- The ion outflow rates from Venus, Earth, and Mars are relatively similar (if not higher on Earth).
- The ion return rate at Earth is low, which indicates that the magnetosphere is not efficient at returning outflowing ions into the ionosphere.

It is thus clear that the old paradigm of the protective effect of planetary magnetic fields on atmospheric planets is not supported by our current observational knowledge of ionospheric ion outflow around Venus, Mars, and Earth.

One must, however, be careful when extrapolating those observations to other planetary systems or to the past history of Venus, Mars, and Earth. Ion outflow processes depend on several parameters, in particular the atmospheric temperature and composition, the characteristics of the stellar wind and the spectral properties of the star, and the magnitude of the planetary magnetic field. Those properties are not known accurately for exoplanets or the solar system in the past. Furthermore, due to their complexity, it is extremely difficult to guess how outflow processes will respond to a modification of their drivers. That being said, based on the knowledge we have today, there is no reason to believe that a planet needs magnetization to protect its atmosphere.

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