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Comparative Planetology: How Effective is an Intrinsic Magnetic Field in Shielding a Planetary Atmosphere?

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Abstract

It is often argued that an intrinsic planetary magnetic field will shield a planetary atmosphere from erosion by the solar wind. In terms of ionospheric escape it is somewhat surprising, then, to note that for the present era the globally averaged ion escape rates for Venus, Mars and the Earth all lie in the range 10^{24} to 10^{26} s^{-1}, with the unmagnetized planets tending to fall at the lower end of this range. While the escape processes may be different for the magnetized and unmagnetized planets, the similarity in rates does suggest that the magnetic shield hypothesis should be revisited, with possible implications for escape rates over geological times.

1. Introduction

The contemporary atmospheres of the terrestrial planets are very different. In particular, the Earth has a substantial amount of water in the atmosphere, while Venus and Mars are essentially dry. It is often assumed that this is because the Earth's intrinsic magnetic field shields the atmosphere from direct interaction with the solar wind. Here we will revisit that hypothesis.

We will first discuss the various pathways for escape and associated rates for Venus and Mars in Section 2 , and then for the Earth in Section 3. We will summarize the discussion in Section 4. In particular we will note that the presence of an intrinsic magnetic field need not shield the atmosphere.

2. Ion Escape Processes at Venus and Mars

At Mars the escape velocity is only 5 km/s, as opposed to > 10 km/s at Venus and the Earth. For Mars processes such as dissociative recombination of O_2^+ ions can consequently result in significant escape of energetic neutral oxygen atoms from the atmosphere [3], with rates of the order 10^{26} s^{-1}. At Venus, on the other hand, dissociative recombination does not provide sufficient energy to overcome the gravitational potential, and the primary atmosphere escape processes involve interactions of the ionosphere with the solar wind.

Luhmann and Kozyra [4] have discussed one of the primary loss processes that involve the solar wind: pick up and sputtering. In this context pick-up is the process whereby neutral atoms are ionized and picked-up by the solar wind motional electric field. A large fraction of these ions impact the ionosphere since their gyro-radius in the solar wind is smaller or comparable to the planetary radius. But on impacting the atmosphere these ions cause sputtering, thereby enhancing the escape of neutrals and also augmenting the neutrals available for ionization within the solar wind. It is estimated that the pick-up and sputtering escape fluxes are of the order $2x10^{25}$ s^{-1} at both Venus and Mars [4].

At Venus and Mars the planetary ionosphere interacts directly with the solar wind, forming an induced magnetotail. Case studies [5] and statistical studies [7] of escaping ions observed within the magnetotail both indicate a total escape rate of heavy ions of the order $4x10^{24}$ s^{-1} at Mars. The rates appear to be higher at Venus [1], of the order 10^{25} s^{-1}.

Because there are remanent field anomalies at Mars, unlike Venus, there is also evidence for acceleration of escaping ions through auroral processes. But the regions of auroral acceleration are relatively small, and the average escape rate is of the order 10^{23} s^{-1} [2].

3. Terrestrial Ion Escape Processes

There have been many studies of outflowing ions in the terrestrial magnetosphere. The outflowing ions can very high fluxes, of the order 10^{26} s^{-1} [9], although this is dependent on the solar cycle. One of the strongest source regions appears to be the dayside cusp, where significant fluxes of 100 eV electrons and large field-aligned currents flow. Strangeway et al. [8] have estimated that for one strong outflow interval, fluxes of of the 10^{26} s^{-1} were observed to be flowing out of the cusp-region ionosphere. Large fluxes of energetic ions of ionospheric origin have also been observed in the magnetotail [6].

The escape process is more indirect, unlike the unmagnetized planets. The process is multi-step, with the incoming particle and electromagnetic energy associated with reconnection at the magnetopause flowing down field-lines and heating the topside ionosphere. But this heating is relatively inefficient, and does not provide sufficient energy to overcome the gravitational potential, only causing upwelling. Wave heating is required to transversely accelerate the ions. The resultant magnetic mirror force then allows the ions to escape. Additional acceleration may also occur at higher altitudes [6].

Even though the ions may initially escape the gravitational potential well it is still not clear that the ions necessarily escape. Some of the ions may have sufficient energy so that even though they are convected towards the plasmasheet, they encounter the plasmasheet beyond the distant reconnection line and are therefore lost. Those ions that enter the plasmasheet may either be scattered back into the ionosphere via waves, or form part of the ring current. Charge exchange could enhance the escape of these ions as neutrals, and changes in convection associated with magnetospheric activity may bring some of the ring current and plasmasheet ions to the magnetopause, where they are lost to the solar wind.

4. Summary and Conclusions

The presence of an intrinsic magnetic field need not shield a planetary atmosphere. At Venus and Mars the solar wind interacts directly with the ionosphere. At the Earth the interaction is indirect, being mediated by reconnection at the magnetopause. But contemporary escape fluxes are similar for the three planets. Given the variability of the Sun, determining how these loss rates vary over the age of the solar system is complicated. Invoking a magnetic shield does not appear to be sufficient to explain the differences in the atmospheres of the terrestrial planets.

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