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Distribution of meteoritic ions in the upper atmosphere of Mars as observed by MAVEN's mass spectrometer

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Abstract

The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission made the first in situ detection of the continuous presence of Na^+, Mg^+, and Fe^+ at Mars. The measured density distributions revealed that these metal ions are well-mixed with the neutral atmosphere at altitudes where no mixing process is expected. Additionally, isolated metal ion layers mimicking Earth's sporadic E layers were regularly observed despite the lack of a strong magnetic field as required at Earth. Finally, the metal ion distributions are coherent enough to always reveal the signature of atmospheric gravity wave signatures.

1. Introduction

The formation of metal ions and their associated ionospheric layers by the ablation of meteoroids has been extensively observed in Earth's upper atmosphere, and metal ions such as Mg^+, Fe^+, Na^+, Al^+, Ca^+, and Ni^+, have been detected in the ionosphere [1, 2]. Several models mapped the chemical pathways by which these metal ions are recycled and ultimately removed [3]. Although well studied, the major characteristics of the metal ion layers are their complex structure and temporal variations. Interest in them persists because of the clues and frequent discoveries they provide for exploring meteoric properties, atmospheric dynamics, fundamental chemical processes, and ionospheric structures at low altitudes [4, 5].

Similar mechanisms were predicted to form metal ions in the Martian ionosphere as the result of the high-speed deposition and subsequent ablation of solar system dust particles. Evidence for this is based on radio occultation measurements by orbiting spacecrafts of isolated electron density layers sometimes seen below the main ionospheric peak [6]. The new in-situ observations taken by MAVEN's Neutral Gas and Ion Mass Spectrometer (NGIMS) show for the first time that the metal ions are indeed a ubiquitous ionospheric feature and do not only arise from exceptional meteoroid events like the close passage of comet Siding Spring in mid-October 2014. Several metal ion species and their isotopes have been, and are, continuously observed by NGIMS at low altitudes on most of MAVEN's orbits since the start of the mission in September 2014.

2. Observations

The NGIMS instrument has been collected data on metal ions during every other periapsis passage (every ~9 hours). While all metallic species and their ion oxides in the range of 23 – 86 Da are targeted by these observations, only Na^+, Mg^+, and Fe^+ were regularly detected. Figure 1 depicts the entire ensemble of Na^+, Mg^+, and Fe^+ measurements from MAVEN over the two years spanning from September 2014 to September 2016.

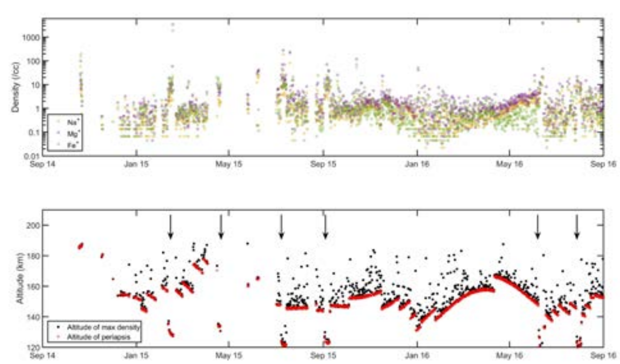

Figure 1: Orbit-by-orbit set of NGIMS measured Na^+, Mg^+, and Fe^+ maximum concentrations from September 2014 to September 2016. The altitude of each orbit's periapsis and the altitude of the maximum metal ion density of each orbit are shown on the bottom. Arrows mark the period of the deep-dip campaigns (larger figure provided in [7]).

As on Earth [8], the dominance of Mg^+ or Fe^+ on Mars changes with time. At either planet, one might expect Fe^+ to be less dominant with increasing altitude because of the mass separation from diffusion processes.

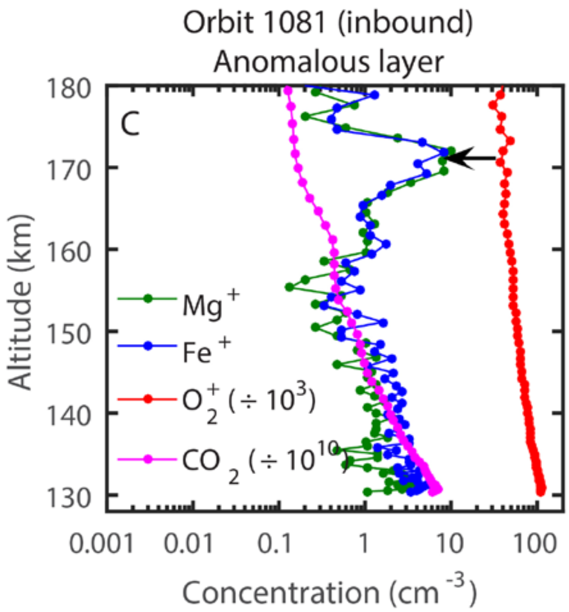

Figure 2: Characteristic structures of metal ion seen on a typical deep dip orbit. Relevant measurements of the main ionosphere ion O_2^+ and the major CO_2 neutral species are also shown. The dropoff of the metal ion concentrations follows closely the CO_2 scale heights. Isolated high-altitude metal ion peaks are pointed to. These density peaks are sometimes associated with ambient ionosphere disturbances at night and near the terminator.

Figure 2 shows samples of the metal ion altitude structures observed along orbits from "deep-dip" campaigns when periapsis was below 130 km altitude. Typically, the concentrations of metal ions at the lowest altitudes are < 10 cm^{-3} and exhibit an average orderly-like decrease with altitude. This decay of the metal ion densities with altitude tends to match closely the falloff of the neutral atmosphere concentration. The close similarity of CO_2 and metal ion scale heights indicates a well-mixed atmosphere with the metal ions behaving like inert minor atmospheric species. Such close correlation in scale heights would be expected if these data taken below the homopause (located below 130 km) where the atmosphere is well mixed through turbulent diffusion, but not well above the homopause where molecular diffusion is expected to take over, resulting in gravity mass separation of the heavy Fe^+ from the lighter Mg^+. High-altitude sporadic metal ion layers are also encountered. These layers are seen as nearly order of magnitude density enhancements above the altitude decreasing background profiles.

At Earth, the generation of isolated metal ion layers, above the main meteoric ion layer, requires the control of ions by neutral winds, or magnetospheric-induced electric fields, in a large magnetic field background [8, 9]. However, Mars has no intrinsic global magnetic field and the strength of the Martian surface remanent magnetic fields appears mostly insufficient to support any known terrestrial formation mechanism.

In addition to the well-mixing of the metal ions with the neutral atmosphere, the NGIMS observations reveal oscillations in the metal ion concentration profiles on most orbits. There is compelling evidence that these oscillations reflect the responses of the metal ions to atmospheric gravity waves. The observed waves in the metal concentrations along the MAVEN orbit have wavelengths of ~80 km along the nearly horizontal spacecraft trajectory near periapsis, which are the typical scale lengths for vertically propagating, horizontal gravity waves [10].

3. Summary and Conclusions

The in situ metal ion measurements at Mars have revealed new facets of how the ablated residues from interplanetary dust particles can interact with a planetary atmosphere. These observations leave us with several interesting puzzles to unravel. The main two being the absence of gravitational separations of the metal ions with altitude in the region where molecular diffusion is supposed to dominate; and the unknown source of the observed isolated metal ion layers in the absence of an intrinsic planetary magnetic field.

Acknowledgements

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