How Do Meteoroids Affect Venus's and Mars's Ionospheres?

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Recent discoveries in the ionospheres of Venus and Mars of layers of metal ions that have been known to exist on Earth for decades have opened a new area for observationally constrained comparative planetology. These new observations raise four questions, amenable to study with current data and models, whose solutions will collectively answer the titular question of this article.

Meteoroids enter all solar system atmospheres at orbital speeds, ablating as they decelerate (Figure 1a). They deposit exotic species such as magnesium (Mg) and iron (Fe) into planetary upper atmospheres. These metallic species, which are deposited at altitudes where the neutral atmosphere is already weakly ionized by sunlight's ultraviolet photons, can themselves be ionized by sunlight, by chemical reactions with existing atmospheric ions, or directly during ablation. Once ionized into Mg^+ and Fe^+, they form part of the ionosphere, the ionized portion of the upper atmosphere.

Layers of meteoric ions are common in Earth's ionosphere (Figure 1b). Similar, but sporadic, plasma layers been discovered in the past several years in radio occultation measurements of electron density profiles in the ionospheres of Venus and Mars (Figures 1c and 1d). On Earth, meteoric layers are extremely narrow (about 2 kilometers wide), have a typical density of 10^3 ions per cubic centimeter, and occur at altitudes of 90–100 kilometers (corresponding to pressures of ~0.01–0.1 pascal) [*Grebowsky and Aikin*, 2002]. Densities in the example shown in Figure 1b are unusually high. On Venus, meteoric layers are broader (about 10 kilometers wide), have a typical observed density of 10^4 ions per cubic centimeter, and occur at 110-kilometer (~0.1 pascal) altitudes [*Pätzold et al.*, 2009]. On Mars, meteoric layers are also broader (about 10 kilometers wide), also have a typical observed density of 10^4 ions per cubic centimeter, and occur at 90-kilometer (~0.01 pascal) altitudes [*Pätzold et al.*, 2005; *Withers et al.*, 2008]. Meteoric layers are ever present on Earth, yet their densities are highly variable. They are found only sporadically on Venus and Mars.

These observations pose several challenges for understanding meteoric ions in terrestrial planet atmospheres: (1) Why are layers ubiquitous on Earth but not on Venus and Mars? (2) Why are observed layer densities similar on Venus and Mars and apparently larger than on Earth? (3) Why are layers so much narrower on Earth than on Venus or Mars? (4) Why do layers occur at greater pressures on Venus than on Mars?

The most distinctive property of meteoric layers on Earth is their variability: the ±1 standard deviation range about the mean ion density is 1 order of magnitude [*Grebowsky and Aikin*, 2002]. Challenge 1 can be explained if meteoric layers on Venus and Mars are also ubiquitous but are rarely strong enough to detect above the instrumental detection limit of ~10^3 ions per cubic centimeter. If this is the case, it remains a mystery why meteoric ion densities on Venus and Mars are so similar (challenge 2) when the peak ionospheric density is 3 times greater at Venus than Mars. On Earth the effects of wind shear on the transport of plasma along inclined magnetic field lines are thought to be critical for layer formation. Yet how can this process work on Venus and Mars, which do not have global dipole magnetic fields? Perhaps ablation deposits metallic species over an altitude range of one scale height on all three planets, followed on Earth alone by compression to narrower layers due to processes connected with a strong magnetic field (challenge 3). Alternatively, this narrowness could simply be an artifact of the coarse horizontal resolution of radio occultation experiments on Venus and Mars in comparison to data from sounding rockets at Earth. The difference in the pressure levels at which meteoric layers occur on Venus and Mars could be caused by the faster speeds of meteoroids at Venus, which is closer to the Sun than Mars (challenge 4).

Numerical simulations are necessary to interpret observed meteoric ion layers on Venus and Mars, yet they have scarcely been applied to date, with most theoretical work predating the first observations

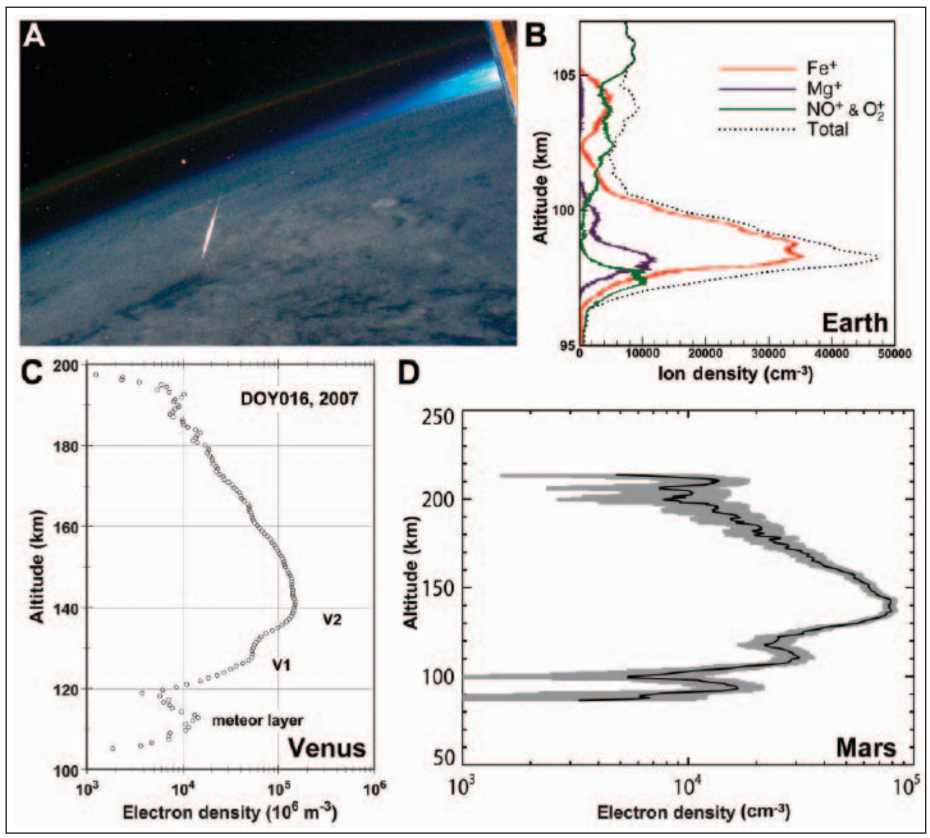

Fig. 1. (a) A fireball meteor in Earth's atmosphere augmenting metal ion densities in the ionosphere, as viewed from the International Space Station (ISS). Credit: Ron Garan, ISS Expedition 28 Crew, NASA. (b) Meteoric ion densities measured above Puerto Rico by a rocket-borne mass spectrometer. In these postsunset measurements (2145 local time), photo-produced plasma (NO^+ and O^+) at these E *region altitudes is sparse. Note the narrow width (about 2 kilometers) of the meteoric layer and its large peak density of 5×10^4 ions per cubic centimeter. Reproduced from Figure 8.11 of* Grebowsky and Aikin *[2002]. (c) Meteoric layer seen in the dayside ionosphere of Venus on day 16 of 2007 by the Venus Express radio science experiment. The meteoric layer occurs at 110-kilometer altitude and has a peak density of 10^4 ions per cubic centimeter. It is distinctly separated from the main photochemical layers V1 and V2 of the ionosphere, which are produced by solar soft X-rays and extreme ultraviolet photons, respectively, and which contain O^+ ions. Reproduced from Figure 2 of* Pätzold et al. *[2009]. (d) Meteoric layer seen in the dayside ionosphere of Mars by the Mars Global Surveyor radio science experiment. The meteoric layer occurs at 90-kilometer altitude and has a peak density of 10^4 ions per cubic centimeter. It is distinctly separated from the main photochemical layers M1 (110 kilometers) and M2 (140 kilometers) of the ionosphere, which are produced by solar soft X-rays and extreme ultraviolet photons, respectively, and which contain O^+ ions. Reproduced from Figure 2 of* Withers et al. *[2008].*

[*Pesnell and Grebowsky*, 2000; *Molina-Cuberos et al.*, 2003; *Whalley and Plane*, 2010]. At Mars, but not Venus, gross layer characteristics are reproduced accurately by current models. To date, all work has involved one-dimensional models simulating a nominal meteoroid influx at a nominal solar zenith angle into a nominal neutral atmosphere. Topics as fundamental as how meteoric ion densities depend on incident meteoroid flux, meteoroid velocity, or solar zenith angle have not been explored. Models have not been adjusted or tuned to reproduce observed meteoric layers nor used to explore why meteoric layers are observed only sporadically, not ubiquitously, on Venus and Mars. Further studies using models to explore these issues will help scientists better understand how meteoroids affect the ionospheres of terrestrial planets.

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