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Plasma Depletion Events in the Martian Ionosphere: Insights From Conjugate MAVEN and Mars Express Observations

P. Basuvaraj,[1] F. Němec,[1] C. M. Fowler,[2] L. Regoli,[3] Z. Němeček,[1] and J. Šafránková[1]

[1] Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic.
[2] Department of Physics and Astronomy, West Virginia University, Morgantown, WV, USA.
[3] Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.

Abstract. Using in situ measurements, the MAVEN spacecraft has identified approximately 1,000 plasma depletion events (PDEs) occurring in the ionosphere of Mars between October 2014 and May 2021. PDEs are regions characterized by significantly reduced plasma density, with their formation mechanisms, evolution, and spatial extent still not well understood. We analyze simultaneous local electron density measurements obtained by the MARSIS instrument onboard the Mars Express spacecraft with the aim to identify possible conjugate events, and to estimate the spatio-temporal scales of PDEs. We identified 13 closest encounters between MAVEN-detected PDEs and Mars Express observations. These contain two conjugate events, showing that PDEs can extend spatially up to 750 km and persist for at least 4 hours.

Introduction

The Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft [*Jakosky et al.*, 2015] orbiting Mars recently identified an intriguing ionospheric anomaly termed Plasma Depletion Events (PDEs) [*Basuvaraj et al.*, 2022b]. These events involve localized reductions in ionospheric ion densities by at least one order of magnitude over a short vertical extent (typically spanning a few tens of kilometers), potentially representing a significant loss mechanism within the Martian ionosphere. PDEs are observed sporadically and independently of seasonal variations, often accompanied by elevated electron temperatures and electrostatic fluctuations [*Basuvaraj et al.*, 2024]. However, their precise causal mechanisms, detailed characteristics, and spatio-temporal behavior remain poorly understood. Investigating the spatial extents and lifetimes of large-scale ionospheric irregularities, such as plasma depletion events, with a single spacecraft presents significant challenges [*Collinson et al.*, 2019]. This necessitates multi-point observations to accurately determine their spatial and temporal dimensions. Such observations could provide valuable insights into the nature of PDEs, crucial for improving our understanding and developing accurate models of their formation. This study aims to identify potential simultaneous observations of PDEs using data from the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) onboard the Mars Express (MEX) spacecraft [*Gurnett et al.*, 2005; *Picardi et al.*, 2005].

Data Set

We utilize in situ measurements from the Neutral Gas and Ion Mass Spectrometer (NGIMS; *Mahaffy et al.* 2015) instrument aboard the MAVEN spacecraft. The NGIMS instrument is a quadrupole mass spectrometer, measuring the atmospheric ion and neutral composition within the mass range of 2–150 amu [*Benna et al.*, 2015]. A list of 1,125 PDEs identified in MAVEN NGIMS instrument data is retrieved from *Basuvaraj et al.* [2022a].

The MARSIS instrument onboard MEX is a topside ionospheric sounding radar that can provide both remote and local electron density measurements of the Martian ionosphere [*Gurnett et al.*, 2005]. The electron density data are retrieved from ionograms recorded by the MARSIS instrument in an active ionospheric sounding (AIS) mode during each periapsis pass. These passes, which occur during a portion of MEX's ≈7-hour orbit, typically last about 40 minutes. During this time, the spacecraft covers altitudes below 1300 km as it descends to its periapsis and then ascends back to higher altitudes

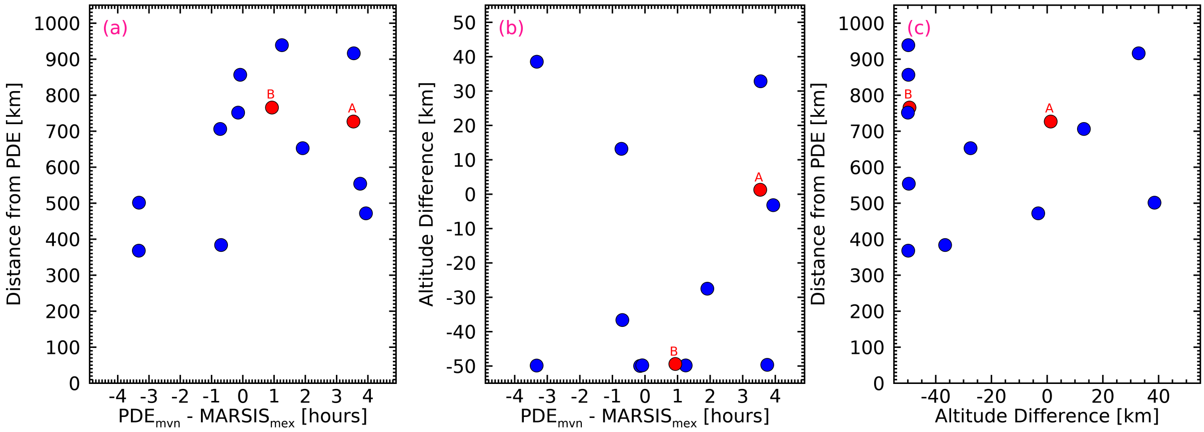

Figure 1. (a) Closest distances of MEX orbits from MAVEN PDEs plotted against their respective time differences. (b) Corresponding altitude differences between MEX orbits and MAVEN PDEs as a function of their respective time differences. (c) Closest distances of MEX orbits from MAVEN PDEs as a function of the corresponding altitude differences. Blue and red circles marks the 13 MEX orbits that closely encountered PDEs. Events A and B represent MEX orbits where simultaneous local electron density measurements are available from both MARSIS and NGIMS.

[*Duru et al.*, 2008]. Locally excited electron plasma oscillations are used to determine the local plasma frequency (f_p) at the spacecraft altitude. The local plasma density (n_e in cm^{-3}) is then calculated from the plasma frequency (f_p in Hz) using the relation $f_p \approx 8980\sqrt{n_e}$ [*Morgan et al.*, 2013; *Duru et al.*, 2008].

Results

Basuvaraj et al. [2022b] demonstrated that the ground traces of PDEs can extend up to a few hundred kilometers, while their vertical traces are on the order of a few tens of kilometers. Taking these limitations into account, we examined MEX orbits near the depletion events identified by MAVEN between October 2014 and May 2021. We required the MEX MARSIS observations to be within $\pm$ 4 hours from the PDE. We further required the great circle path between MEX and the event to be less than 1,000 km, and an altitude difference of MEX and PDE to be less than 50 km. Out of the 1,125 MAVEN PDEs used as a starting point of our analysis, these conditions are fulfilled during 13 MEX orbits with the MARSIS data available. The respective time and spatial differences of MEX measurements and PDEs are shown in Figure 1.

Figure 1a shows the great circle path distances of MEX orbits from MAVEN PDE locations plotted against the time differences between them. The time difference (PDE$_{mvn}$-MARSIS$_{mex}$) is determined as the interval between the PDE peak depletion time and the closest (in terms of the great circle path distance) MEX MARSIS observation. The blue and red solid circles indicate all 13 MEX orbits that closely encountered PDEs. The events shown in red (A and B) represent orbits with electron density depletions possibly corresponding to PDEs observed in the MEX MARSIS data. No such electron density depletions are observed in the remaining 11 orbits. Figure 1b displays the altitude differences determined at the times of the lowest great circle path distances as a function of the respective time differences. Figure 1c depicts the great circle path distances from PDE locations as a function of altitude differences. Event A exhibits a smaller altitude difference despite the time delay of over 3 hours between MAVEN PDE detection and MEX passing, suggesting a considerable duration of the PDE. On the other hand, Event B observations are closely separated in time but at significant great circle path and altitude distances, indicating a large spatial extent of the PDE.

Figure 2 shows the plasma density profiles from MAVEN and MEX, corresponding to Event A from Figure 1. Figure 2a displays the density profiles of ionospheric ions (CO_2^+, NO^+, O_2^+, and O^+) measured using the NGIMS instrument. A highlighted yellow region between 405 and 422 km indicates the PDE identified by MAVEN during its inbound orbit over the southern hemisphere of Mars

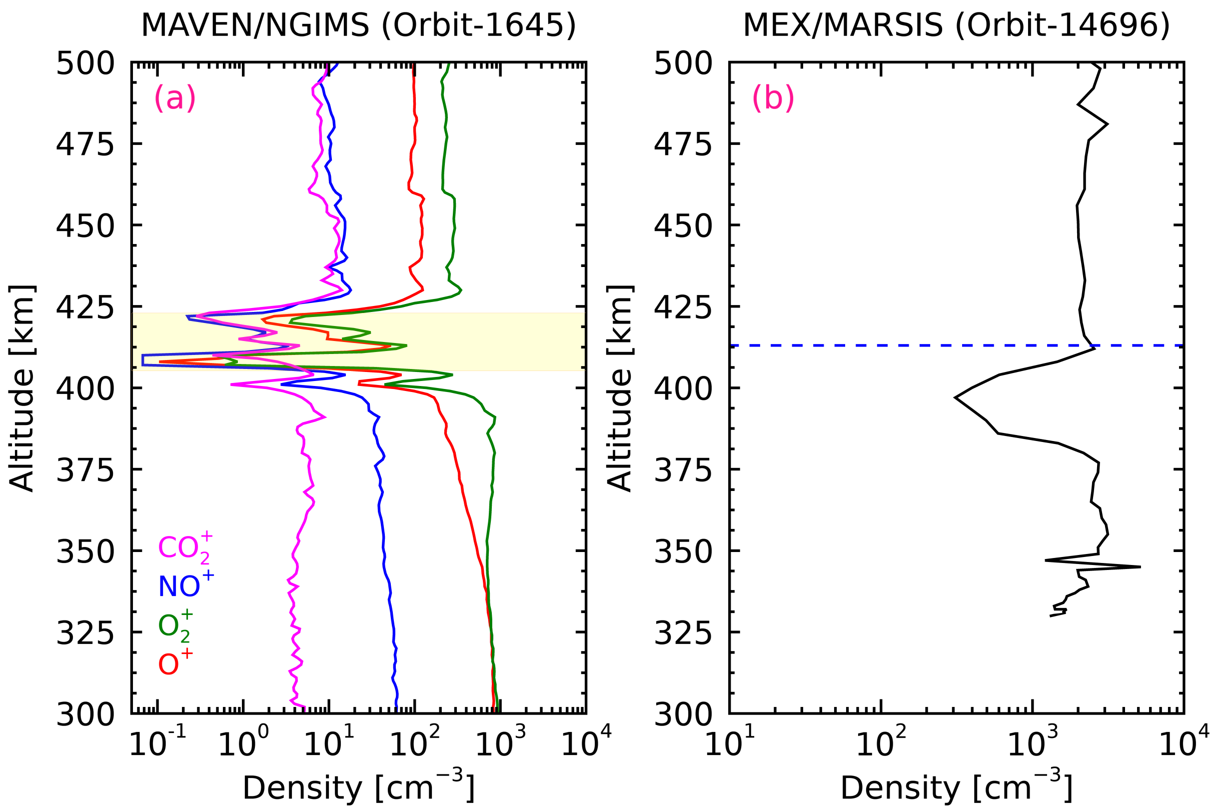

Figure 2. Plasma density profiles from MAVEN and MEX for Event A. (a) Ionospheric ion density profile from MAVEN on 3 August 2015 around 10:37:48 UT. The plasma depletion region is highlighted in yellow. (b) Electron density profile from MEX MARSIS on the same date around 07:05:59 UT, with the blue dashed line indicating the time of the closest PDE approach (great circle path distance of 726 km)

on 3 August 2015 around 10:37:48 UT, with a peak depletion altitude of about 414 km. The solar zenith angle at the time of the peak depletion and the average magnetic field magnitude within the depleted region are about 92° and 173 nT, respectively. Figure 2b presents the electron density profile from the MARSIS local electron density measurements, recorded on 3 August 2015 around 07:05:59 UT. The blue dashed line marks the MEX altitude at the time of the closest approach to the MAVEN PDE (in terms of the great circle path distance) within the descending orbit of MEX. This occurred about 3.5 hours before of the MAVEN observations of PDE at nearly the same location (with a great circle path distance of about 726 km). The electron density sharply decreases between altitudes of 377 and 412 km. Within the depleted region, the electron density reaches a minimum of $\approx$309 cm^{-3} at a peak depletion altitude of about 397 km, compared to $\approx$2600 cm^{-3} at the depletion edges. This corresponds to about 90% decrease in the electron number density within the depleted region, roughly consistent with the MAVEN observations. Although difficult to explicitly prove, it seems plausible that MEX observes the same PDE as MAVEN, but significantly earlier.

Figure 3 showcases the plasma density profiles observed by MAVEN and MEX for Event B. The PDE identified by MAVEN, between altitudes of 388 and 464 km on 28 April 2017 around 05:31:39 UT, is depicted in Figure 3a. The peak depletion altitude, about 426 km, occurred near the subsolar region during the outbound orbit of MAVEN, traversing over the southern hemisphere of Mars. It is noteworthy that in this event the plasma densities at altitudes above the event are considerably lower than at altitudes below the event. This might somehow resemble the ionopause-like density drop [*Vogt et al.*, 2015]. However, in the case of an ionopause, the plasma density profile is expected to be monotonic, with no PDE-like local minimum. On the same date around 04:36:59 UT, MEX MARSIS instrument detected a plasma depletion region spanning altitudes of 486 to 577 km during its outbound orbit, as shown in Figure 3b. The peak depletion altitude observed by MEX was about 532 km. Within the depleted

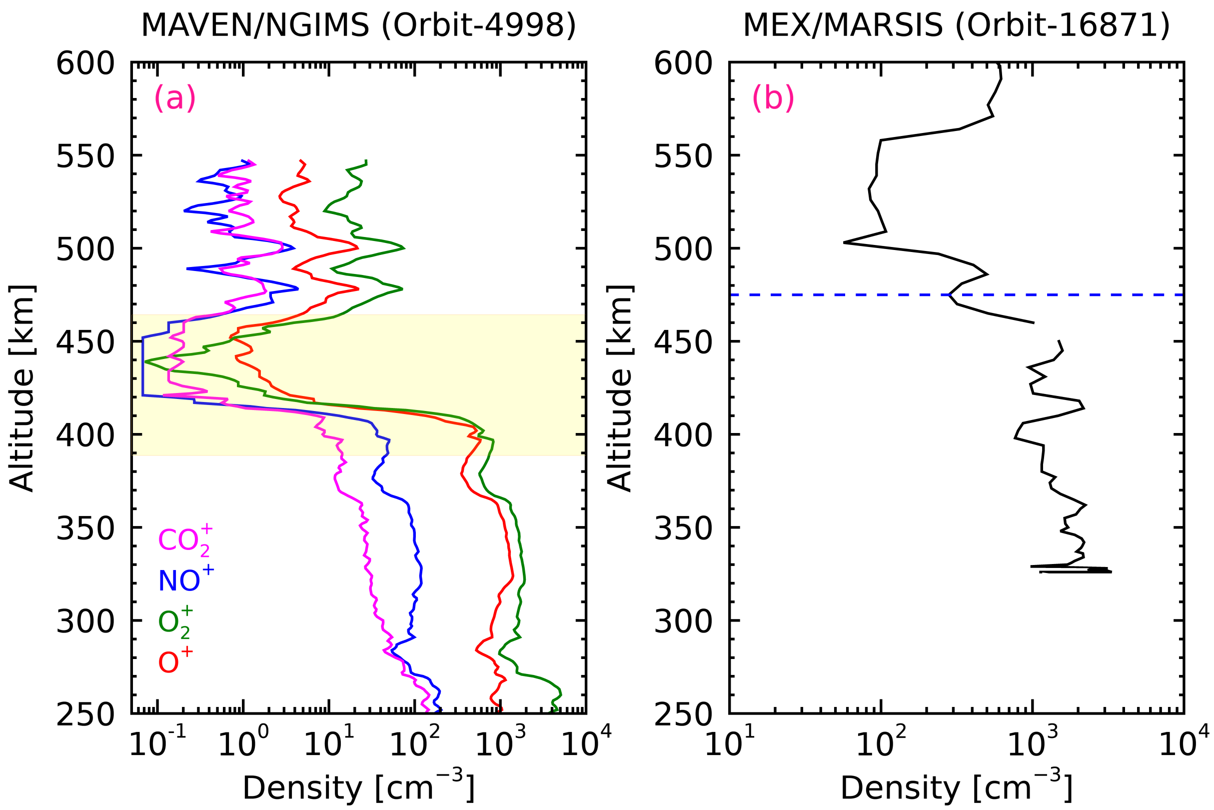

Figure 3. Same as Figure 2 but for Event B. (a) MAVEN ions on 28 April 2017 around 05:31:39 UT. (b) Local electron density measurements by MEX MARSIS on the same date around 04:36:59 UT. At the closest approach, marked by the blue horizontal line, the great circle path distance between MEX and MAVEN PDE is about 765 km.

region, electron densities varied from $\approx$510 cm^{-3} at the depletion edges to about 83 cm^{-3} during the peak depletion, corresponding to the plasma density drop by about 84%. The great circle path between MEX and the MAVEN PDE was about 765 km, and the temporal separation of the two observations was only about 55 minutes.

Discussion

At Earth, ionospheric irregularities span spatial scales from less than a meter to over several hundred kilometers [*Kelley*, 1989], largely influenced by the terrestrial global magnetic field. These irregularities manifest as local fluctuations in plasma density and are detected using diverse instruments and techniques [*Woodman*, 2009; *Tsunoda*, 2010; *Kil*, 2015]. In contrast, Mars lacks an intrinsic magnetic field, and its ionosphere is primarily affected by induced ionospheric and localized crustal magnetic fields [*Gurnett et al.*, 2010; *Withers*, 2009], resulting in distinct dynamics of irregularities such as plasma depletion events (PDEs) [*Basuvaraj et al.*, 2022b]. Although more than 1,000 PDEs have been identified in the MAVEN data, single spacecraft observations limit our understanding of their spatial and temporal variations. Therefore, multi-point observations are crucial to properly assess these.

Using MEX ephemeris and accounting for the MARSIS data coverage, we identified 13 MEX orbits closely aligned with MAVEN PDEs both in time and space. In 11 cases, no significant plasma depletions have been identified. However, Events A and B, presented in Figures 2b and 3b, illustrate significant plasma density depletions detected by MARSIS prior to MAVEN PDEs, potentially representing conjugate observations of the same events. The great circle path distances between MEX and MAVEN PDEs are about 750 km in both cases. The altitude difference in Event A is very low, while the time difference is nearly 4 hours. On the other hand, while the time difference in Event B is only about 1 hour, the altitude difference is about 50 km. Although it is difficult to explicitly prove that the MEX and MAVEN observations indeed correspond to the same PDE events, it seems unlikely that the presented observations of such significant plasma depletions might be a mere coincidence. The presented observations thus suggest that PDEs can extend at least 750 km and persist for up to 4 hours.

Conclusion

We analyzed in situ plasma measurements from the MAVEN and MEX spacecraft to identify possible conjugate observations of MAVEN-detected PDEs between October 2014 and May 2021. Out of 1,125 MAVEN PDEs, 13 closest encounters with MEX MARSIS observations were identified, requiring the great circle path distance between MEX and MAVEN PDE to be less than 1,000 km, time difference less than 4 hours, and the altitude difference less than 50 km. Out of these 13 close encounters, 11 did not contain any significant depletion in the MEX MARSIS data. However, two conjugate events, which occurred on 3 August 2015 and 28 April 2017, revealed comparable plasma depletions in MAVEN and MARSIS. Assuming that these observations indeed correspond to the same PDEs, our findings indicate that PDEs can extend horizontally up to 750 km and persist for at least 4 hours in the Martian ionosphere. Additional simultaneous observations are essential to provide more accurate limits on the spatial and temporal extents of PDEs.

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