The ionosphere of Mars and its importance for climate evolution

A community white paper submitted to the 2011 Planetary Science Decadal Survey

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1. Executive summary

An ionosphere is a weakly ionized region in the atmosphere of a planetary body. The ionosphere of Mars affects, and is affected by, the chemistry, dynamics and energetics of the neutral atmosphere. It is a unique plasma laboratory thanks to Mars' intense, small-scale crustal remanent magnetic fields which rotate with the planet. It is an integral part of the boundary between the planet and the solar wind, spanning the homopause and exobase of the atmosphere. It is consequently involved in many atmospheric loss processes and therefore plays an important role in determining the evolution of the climate and habitability of Mars over geological time. The upcoming MAVEN Mars Scout mission will undoubtedly improve our understanding of the relationship between the primary drivers of the Martian ionosphere (i.e. solar extreme-ultraviolet and X-ray irradiance, the solar wind and the neutral atmosphere), its structure and dynamics, and the escape to space of atmospheric species, but other important questions will remain unanswered. Many of these can be addressed for relatively modest cost.

The importance of the ionosphere of Mars has been recognized in a series of MEPAG goals documents and the most recent Decadal Surveys for both Planetary Science and Space Physics. Our recommendations to the 2011 Planetary Science Decadal Survey can be summarized, in priority order, as:

1) Support the scientific objectives of the MAVEN primary mission and recognize that an extended mission would be scientifically valuable.
2) Acknowledge that exploration of the ionosphere of Mars should not end with MAVEN and request that NASA investigate ways to implement the following, again in order:
    i. Spacecraft-to-spacecraft radio occultation measurements of electron density.
    ii. Ionospheric and atmospheric measurements from surface assets.
    iii. Upstream solar wind monitoring, possibly in collaboration with ESA's Mars Express and China's Yinghuo-1 missions, during MAVEN's mission.
    iv. Measurements of ionospheric electrodynamics (electron, ion, neutral velocities, currents and magnetic fields).
    v. Development of instruments able to measure hot atom escape fluxes.

2. Current state of knowledge: the ionosphere of Mars

The Martian ionosphere is predominantly O_2^+ [1, 2]. Models suggest that O^+ may be the most abundant ion at high altitudes under certain conditions and that N-bearing species, such as NO^+, and metal species derived from meteoroids, such as Mg^+ and Fe^+, may become significant below 100 km [3].

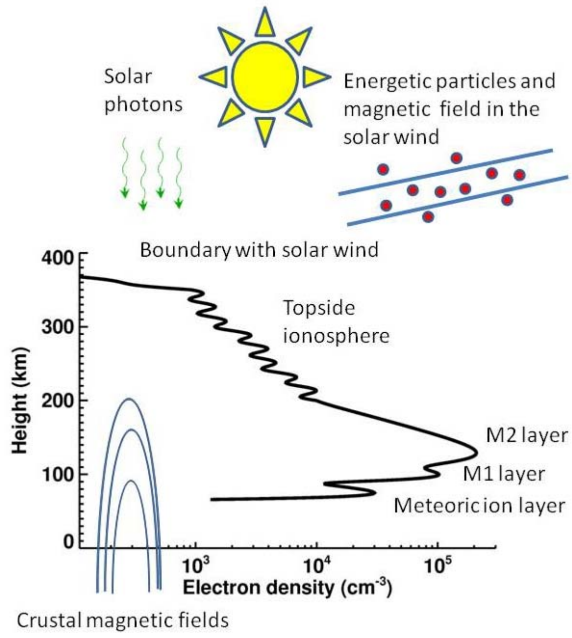

Figure 1: Schematic illustration of the ionosphere of Mars.

The ionosphere can be divided into regions (Fig. 1). A boundary called the magnetic pileup boundary (MPB), which separates solar wind plasma (H^+, He^+) from ions of Martian origin (O^+, O_2^+), occurs near 850 km on the dayside [3, 4]. Another boundary, the photoelectron boundary (PEB), occurs near 400 km. Ions of Martian origin lack distinctive peaks in their energy spectrum above the PEB. The **topside ionosphere** lies above 200 km, where transport processes are significant and the abundances of O and O^+ are relatively large [5, 6]. Below it lies the **M2 layer**, within which the maximum plasma densities over the entire ionosphere are found. Solar extreme-ultraviolet (EUV) photons between 10 nm and 90 nm are responsible for most of the dayside ionization events in the M2 layer and topside. The **M1 layer** lies about two scale heights, or 20 km, below the peak of the M2 layer. Since the flux of EUV photons is greatly attenuated here, X-rays shortward of 10 nm are the ultimate source of plasma in this layer [7, 8]. Yet only 10-20% of ions in the M1 layer are produced directly by photoionization; most are produced by impact ionization due to photoelectrons and secondary electrons. Another plasma layer, the **meteoric ion layer**, is occasionally present near 80 km and is thought to contain atomic metal ions derived from ablating meteoroids [9].

Plasma velocities, their associated ionospheric currents and the magnetic fields they induce have not yet been measured directly, although an interpretation of Viking Lander data suggests that **plasma flows upwards in the topside** [10, 11]. As the planet rotates, its powerful crustal remanent magnetic fields produce a time-varying interaction with the solar wind that is unique to Mars [12]. This interaction greatly affects the magnetic topology and ionospheric electrodynamics at regional and smaller lengthscales (<1000 km) in ways that are not well-understood at present [13, 14]. **Martian electrodynamics** is likely to be richly complex because it is governed by winds and the magnetic field, which both vary across a huge range of spatial and temporal scales.

The chemistry, dynamics and energetics of the ionosphere of Mars vary with position and time due to wide variations in solar forcing, atmospheric dynamics and composition, and the magnetic field. Understanding how competing physical processes produce the observed state of the ionosphere is a major unifying theme that underpins the science of the Martian ionosphere. Many atmospheric loss processes, including sputtering by pickup ions, photochemical escape, and ion outflow, involve the ionosphere [15]. Thus **knowledge of the ionosphere of Mars is critical for evaluating the importance of atmospheric escape for the evolution of the planet's climate**. **Put simply, without understanding the Martian ionosphere, we will not understand Mars climate evolution.**

3. Expected contributions from the MAVEN mission

The MAVEN Scout mission, scheduled for launch in October 2013, is currently under development [16]. It is expected to address **many, but not all, of the currently outstanding questions** concerning the ionosphere of Mars.

In particular, MAVEN will:

- Make simultaneous **in situ measurements** of the neutral composition, plasma composition, plasma velocities and electron temperature down to about 150 km (and, occasionally, down to the homopause at 125 km) in order to comprehensively map the chemistry, dynamics and energetics of the ionosphere.
- Characterize the structure of the **nightside ionosphere** in order to determine the importance of trans-terminator transport of plasma and ionization by superthermal particles.
- Observe the ionosphere in a **range of different magnetic environments** in order to determine how magnetic fields affect ionospheric properties and processes, particularly dynamics and energetics.
- Observe the **topside ionosphere and its upper boundaries** in order to determine how energy and momentum are transferred between the solar wind and ionosphere.

4. Questions that will remain after MAVEN's nominal mission

There are some important topics that will not have been adequately addressed at the completion of MAVEN's nominal mission. These include:

(Q1) Solar cycle variations. The states of the ionosphere and upper atmosphere of Mars vary greatly over the 11-year solar cycle, which is significantly longer than the 1 Earth year duration of MAVEN's nominal mission. Theories that can explain such variations are significantly more robust than those that have only been verified over a small range of solar conditions.

(Q2) The ionosphere below 125 km. 93% of MAVEN's periapses will occur at 150 km, which is above the ionospheric peak for solar zenith angles less than 80^{o}. The remaining 7% will occur at 125 km, which is around the ionospheric peak for dayside solar zenith angles, but above the M1 layer and meteoric ion layer. The chemistry, dynamics and energetics of the lower ionosphere will remain poorly observed after MAVEN.

(Q3) Relationships between solar forcings and ionospheric properties. Due to its precessing periapsis, ~30% of MAVEN's orbits will not sample the solar wind at all. During those orbits that do, MAVEN will typically spend ~30% of each orbit in the solar wind. These intermittent solar wind measurements will not be simultaneous with its in situ ionospheric observations. Furthermore, although MAVEN will measure the solar EUV flux in three discrete wavelength ranges (0.1-0.7 nm, 17-22 nm and the Lyman-alpha line at 121.6 nm) and indirectly measure the integrated solar EUV flux via proxies provided by three other instruments, it will not directly measure the entire solar EUV spectrum below 100 nm which is responsible for most plasma production at Mars. Simultaneous solar and ionospheric data are needed to address how solar forcings determine ionospheric properties.

(Q4) Temporal variations. MAVEN's periapsis passes will occur at intervals of 4.5 hours. These observations will not be able to characterize how the ionosphere varies on shorter timescales. Many of the factors that control the ionosphere, including solar irradiance, neutral dynamics and magnetic topology, vary relatively rapidly.

(Q5) Global ionospheric coverage accumulated over short timescales. Accumulation of global ionospheric coverage from MAVEN's periapsis measurements at 4.5 hour intervals will take at least three months, which exceeds most relevant timescales. A synoptic view of the global-scale ionosphere requires the acquisition of distributed measurements at a faster rate.

(Q6) Hot atom escape fluxes. Theoretical models suggest that hot neutral atoms, such as hot N and O, which are produced by the dissociative recombination of molecular ions, such as N_2^+ and O_2^+, and serve as tracers of ionospheric processes, are the major component of atmospheric escape from Mars [15, 17]. The Mars Express (MEX) energetic neutral atom (ENA) imager detected only the low-flux, high-energy tail of this population and MAVEN's only measurements of hot atoms will be vertical abundance profiles derived from UV spectra. The UV spectrometers on Venus Express and Mars Express have shown that measuring such profiles accurately is challenging - yet the derived escape fluxes are highly sensitive to the measured vertical abundance profiles.

(Q7) Coupling between the neutral atmosphere and ionosphere. Strong interactions are expected between the Martian neutral atmosphere and ionosphere. For instance, atmospheric tides shift the M1 and M2 layers vertically and the ionosphere influences neutral winds via ion-drag [18]. Relationships between neutral and ionospheric chemistry will be investigated by the MAVEN payload, but dynamical coupling will not. A wide variety of electrodynamical processes are likely to occur with a range of length and time scales in the unique Martian magnetic environment.

5. Looking beyond MAVEN's nominal mission

The science of the Martian ionosphere can be advanced at relatively low cost and risk by a **range of small instrument packages** that could be flown as parts of upcoming missions without requiring dedicated spacecraft. Acquisition of these measurements need not wait until after the completion of the MAVEN mission.

(M1) High cadence measurements from the Martian surface of **magnetic fields** induced by ionospheric currents (Q2, Q4).

(M2) High cadence vertical profiles of **electron density below the main peak** (Q2, Q4).

(M3) High cadence measurements of **total electron content** at one geographic location (Q4).

(M4) **All-sky airglow images** from the Martian surface, preferably viewing a magnetic cusp, at specific wavelengths, such as 557.7 nm and 630.0 nm emissions from excited O (Q4).

(M5) **Upstream measurements** of solar wind conditions (electrons and ions from ~20 eV to ~10 MeV; the interplanetary magnetic field) and the solar irradiance spectrum made simultaneously with ionospheric measurements. MEX and the Chinese Yinghuo-1 payload may be able to provide partial upstream measurements for MAVEN (Q3), even though MEX does not have a magnetometer.

(M6) Widely distributed and frequent **orbiter-to-orbiter radio occultation measurements** of vertical profiles of electron density (Q5).

(M7) In situ data on **neutral winds, ion velocities**, plasma density and magnetic field (Q7).

Q1 on solar cycle variations can be addressed by a **long-duration extension** of MAVEN. No instrument currently exists that can measure hot atom escape fluxes and address Q6 directly. The definition and development of such an instrument should be a priority for the PIDDP and MIDP programs. If the hardware required for orbiter-to-orbiter radio occultations (M6) is flown on a lander and an orbiter instead, then line-of-sight total electron content can be measured.

Table 1: Instrument packages for ionospheric observations (estimated resources are approximate)

Instrument package	Individual components	Measurements	Scientific questions addressed	Mass (kg)	Power (W)	TRL	Cost ($M)
Surface package for ionospheric studies	Magnetometer	Magnetic fields induced by ionospheric currents	Q2, Q4, Q7	0.7	3.0	9	0.8
	Ionosonde	Bottomside electron density profiles	Q2, Q4	6.2	8.5 (av.)	6*	10.5
	* - Most subsystems at TRL6, antenna at lower TRL						
	Riometer	Relative total electron content	Q4	0.2	0.1	4	?
	All-Sky Camera	Optical emissions from products of neutralization	Q4	6.0	6.0	7	5.0
Upstream solar monitor	Magnetometer	Direction and strength of interplanetary magnetic field	Q3	0.7	3.0	9	0.8
	Solar Wind Ion Analyzer	Energy and angular distribution of solar wind ions (20 eV-20 keV)	Q3	1.8	1.0	8	1.3
	Solar Wind Electron Analyzer	Energy and angular distribution of solar wind electrons (20 eV-20 keV)	Q3	1.6	1.0	9	0.8
	Solar Energetic Particles Instrument	Spectrum of energetic electrons (20 keV-1 MeV) and ions (20keV-10 MeV)	Q3	1.2	1.8	9	1.5
	Solar EUV Spectrograph	Solar spectrum (0.1- 100 nm) with resolution comparable to GOES-R EUVS instrument	Q3	10.0	10.0	7	15.0
	Digital Processing Unit	N/A	N/A	3.0	2.0	9	1.5
	Total	N/A	N/A	18.3	18.8	>7	20.9
Spacecraft-to-spacecraft radio occultations	Ultrastable Oscillator - on each spacecraft	Vertical profiles of electron density (if orbiter-to-orbiter; total electron content if lander-to-orbiter)	Q5	2 x 1.0	2 x 3.0	9	2 x 1.5
	Receiver - on one spacecraft			1.0	N/A	9	0.3
Coupled ion-neutral dynamics investigation	Ion Velocity Meter and Neutral Wind Meter	Plasma density, neutral wind, ion velocity	Q4, Q7	8.0	15.5	9	7.7
	Magnetometer	Direction and strength of magnetic field	Q4, Q7	0.7	3.0	9	0.8

A substantially greater leap in knowledge could be achieved by an aeronomy constellation mission that provides **long-duration simultaneous multi-point measurements** of conditions upstream, in the ionosphere, and downstream. This will require significant resources and should not be implemented until after the completion of MAVEN's nominal mission.

(M8) **Aeronomy constellation mission** (At least Q1, Q3, Q4, Q5, Q7).
(1) Upstream measurements at high cadence of (a) velocity, composition and density of the solar wind; (b) fluxes and energy spectra of solar energetic particles; (c) magnitude and direction of interplanetary magnetic field; and (d) solar irradiance.
(2) Downstream measurements of the loss rates of atmospheric species as functions of energy (ranging from escape energies of ~eV to tens to keV), composition (H, O, CO, N_2, CO_2) and angular distribution for ions and neutrals. These measurements should range across all latitudes and local times, but focus on downstream regions.
(3) Measurements at high cadence of ionospheric conditions, including vertical profiles of electron density and velocity, ion density, velocity and composition, neutral density, winds and composition, and in situ electric and magnetic field measurements.

Finally, **theoretical models are vital tools** for the interpretation of observations. For the Earth, state-of-the-art ionospheric simulations include data assimilation, three-dimensional models, and coupling between the ionosphere, neutral atmosphere and solar wind. The scientific return on new ionospheric measurements will be maximized if Martian models approach the sophistication of their terrestrial counterparts [18, 19]. A reference ionosphere would also serve as a valuable common benchmark for analyses.

6. Conclusions & recommendations

The ionosphere of Mars forms an important part of the Mars system. It plays a key role in the volatile escape processes that have dehydrated Mars over solar system history. It is closely coupled to the atmosphere of Mars, especially the thermosphere, and to the regions where the solar wind mixes with plasma of planetary origin. Comparative study of planetary ionospheres and upper atmospheres has been, and will continue to be, a fruitful area of planetary science [20, 21, 22, 23, 24]. The unusual magnetic field at Mars makes the ionosphere of Mars particularly valuable for comparative studies.

The success of the Mars Exploration Program is due to its cohesion as a program. Later missions are defined and implemented in response to earlier discoveries. For example, Opportunity landed on a hematite-rich region discovered by MGS and Phoenix performed in situ analysis of buried ice discovered by Odyssey. The MAVEN Scout mission, scheduled for launch in 2013, is expected to address many, but not all, of the currently outstanding questions concerning the ionosphere of Mars. Accordingly, planning for missions that can build upon the discoveries of MAVEN should not be neglected.

In priority order, we recommend that the Decadal Survey committee:

1) **Reiterate support for the scientific objectives that will be addressed by MAVEN**. We find that successful implementation of the MAVEN mission is the most valuable step that NASA can take in the near-term related to the science of the ionosphere of Mars.
2) Affirm that **extension of the MAVEN mission** beyond one Earth year, at least for the declining phase of the solar cycle, will be scientifically valuable. A full solar cycle would be even better.

3) Request that NASA determine the resources required to implement a **spacecraft-to-spacecraft radio occultation experiment at Mars** using existing or future orbiters and that NASA consider making such experiments a routine feature of its network of Martian orbiters.
4) Recognize that **valuable ionospheric and atmospheric science measurements can be made from surface assets** on Mars, even when the prime objectives of those assets relate to the Martian surface and subsurface.
5) Request that NASA **investigate ways to obtain upstream monitoring during MAVEN's mission**, such as an extended mission for Mars Express, coordination with the Chinese Yinghuo-1 mission, a small dedicated satellite piggybacking on MAVEN's launch vehicle, or small instruments on Mars Science Orbiter (2016).
6) Acknowledge that the **electrodynamics** (velocities of ions, electrons and neutrals, currents and induced magnetic fields**) of Mars merit observation** due to their complexity, variability, uniqueness, and importance for ionosphere-thermosphere coupling.
7) Identify direct measurements of **hot atom escape fluxes** as a priority for MIDP and PIDDP.
8) Acknowledge that **scientific exploration of the ionosphere of Mars should not end with MAVEN** and that appropriate planning for possible missions responsive to MAVEN's discoveries, such as an aeronomy constellation mission, should be undertaken in the next decade.

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