Space Weather of the Heliosphere: Processes and Forecasts
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The Response of the Martian Atmosphere to Space Weather

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Abstract. Mars lacks a global dynamo magnetic field to shield it from the solar wind and solar storms, so may be especially sensitive to changing space weather compared to Earth. Inputs from the Sun and solar wind have been measured continuously at Mars for 20 years, and intermittently for more than 50 years. Observations of the influence of the variable space weather at Mars include compression and reconfiguration of the magnetosphere in response to solar storms, increased likelihood of aurora and increased auroral electron energies, increased particle precipitation and ionospheric densities during flare and energetic particle events, and increased ion escape during coronal mass ejection events. Continuing measurements at Mars provide a useful vantage point for studying space weather propagation into the heliosphere, and are providing insight into the evolution of the Martian atmosphere and the role that planetary magnetic fields play in helping planets to retain habitable conditions near their surface.

Keywords. planets and satellites: individual

1. Context

Broadly defined, 'space weather' refers to short term variability in the solar particle, field, and photon conditions throughout the heliosphere. By many measures the Martian response to space weather is the best studied in the heliosphere outside of Earth.

Charged particles and heliospheric magnetic fields encounter a much different environment at Mars than they do at Earth (see overview in Brain *et al.* 2017). Unlike Earth, Mars lacks a global dipole magnetic field and solar wind plasma is deflected around the planet in an induced magnetosphere formed through interaction of the solar wind with the conducting ionosphere (Figure 1). This obstacle to the solar wind is weak compared to a global dipole, leading to a more compact magnetosphere relative to the size of the planet. Mars is about half the size of Earth so that the entire interaction region is much smaller than Earth's magnetosphere, and the exosphere of Mars extends into the unperturbed solar wind. The Martian crust contains regions of locally magnetized crust which rotate with the planet and are sufficiently strong that they perturb the canonical picture of an induced magnetosphere, creating an obstacle to the solar wind with elements of the interactions at Venus, comets, and magnetized planets such as Earth.

One can imagine a number of possible space weather effects at Mars. Geophysically, these include compression and reconfiguration of the induced magnetosphere, stripping of atmospheric particles to space, atmospheric heating and chemistry caused by incident solar energetic particles, and aurora. From the perspective of human and robotic exploraton these include disruption of the electrical systems of orbiting and landed spacecraft and instruments (e.g. the infamous and unfortunate failure of the Mars Odyssey radiation detector due to the Halloween solar storm) and hazards to human presence at the surface. Finally, space weather in the form of ionizing radiation could frustrate the development of life at the Martian surface.

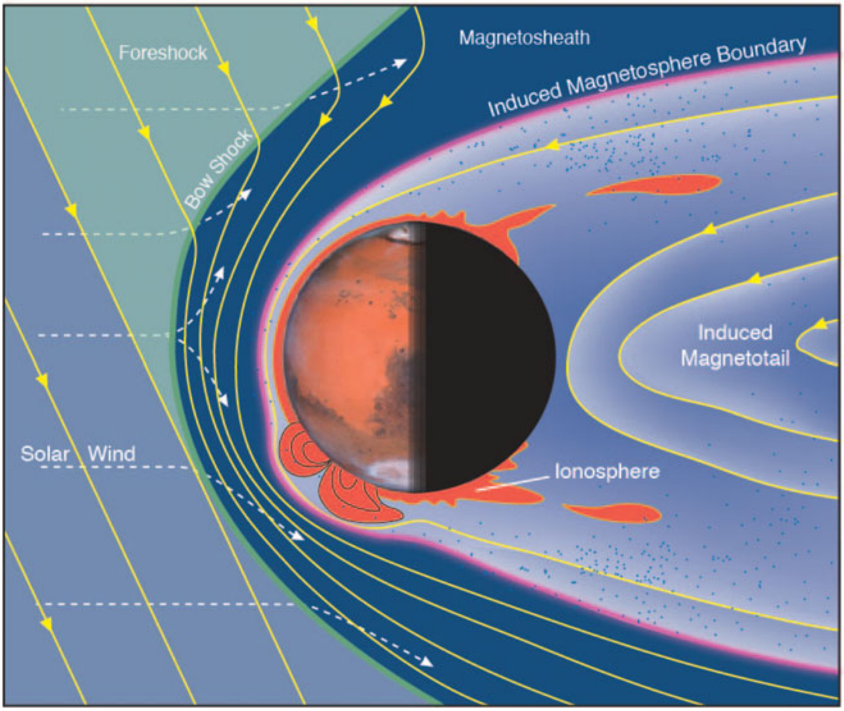

Figure 1. Diagram of the interaction of the Martian upper atmosphere with the solar wind, from Brain *et al.* (2017).

2. Space Weather Inputs

More than a dozen spacecraft missions since 1965 have made observations at Mars relevant to space weather, the magnetosphere, and the upper atmosphere. The first of these (Mariner 4, 6, 7, 9, Mars 2, 3, 5, Viking, and Phobos 2) sampled the environment near Mars in situ, and established Mars as likely to be an induced magnetosphere with at most a weak global dipole field. The Phobos 2 mission also determined that Martian atmosphere was escaping to space in respose to the interaction with the solar wind (Lundin *et al.* 1989).

Following these early missions, there has been continuous measurement of space weather at Mars since 1997, with observations supplied by Mars Global Surveyor (MGS), Mars Express (MEX), and the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission. Observations from these three spacecraft comprise the longest continuous record of space weather observations at a solar system object other than Earth.

Though there is a continuous measurement record at Mars extending back two decades, the observations from MGS and MEX are less complete than those of MAVEN. For example, MGS directly measured only magnetic field and suprathermal electrons, and indirectly measured energetic ($\sim 20 - 50$ MeV) ions via its instrument backgrounds. Additionally, most of its nine year mission was spent in orbit close to the planet, so that undisturbed solar wind was not sampled directly. Mars Express has an elliptical orbit that enters the solar wind, but directly measures suprathermal electrons and ions, and indirectly measures energetic ions via instrument backgrounds. MAVEN, by contrast, has both an elliptical orbit that enters the solar wind and directly measures all of the relevant space weather drivers (Figure 2).

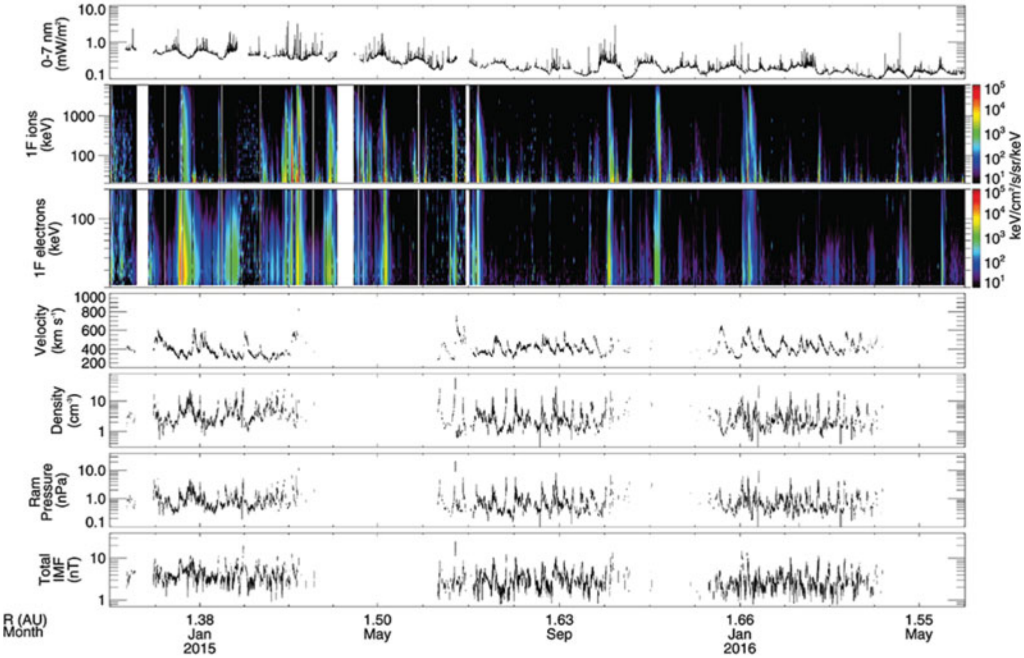

Figure 2. Space weather inputs to the Martian magnetosphere and upper atmosphere as measured by MAVEN, including EUV photon flux, solar energetic ions and electrons, solar wind velocity, density, and pressure, and interplanetary magentic field strength (Lee *et al.* 2017).

3. Martian Consequences of Space Weather

The long baseline of relevant observations at Mars has allowed the community to associate changing space environment conditions with the response of the Martian magnetosphere and upper atmosphere. Additionally, the measurements of the Martian system have allowed the community to validate models that can be used to predict the response of Mars to space weather. Here we broadly describe four categories of response.

Magnetospheric Reconfiguration - The Martian magnetosphere is comprised of several distinct plasma regions separated by plasma boundaries roughly analogous to those in Earth's magnetosphere (see Figure 1). Boundaries such as the collisionless bow shock and the Induced Magnetosphere Boundary (IMB, with some similarities to Earth's magnetopause) can become compressed in response to changing conditions in the solar wind. For example, as a Coronal Mass Ejection (CME) passes Mars these boundaries are pushed closer to the planet on the dayside, and flare away from the planet much less than during undisturbed periods (e.g. Crider *et al.* 2005; Jakosky *et al.* 2015). Figure 3 shows MHD simulation results during a CME that passed Mars in March of 2015 (Jakosky *et al.* 2015). The model agrees well with MAVEN observations along the orbit track, giving confidence that the model results are trustworthy elsewhere, and further shows a compressed and less flared magnetsphere after the arrival of the CME at Mars. Additional simulations show a complex magnetic field topology close to Mars that changes significantly during different phases of the CME passage (Luhmann *et al.* 2017). MEX observations show similiar evidence of compression of the plasma regions near Mars, with rapid compression during and after the CME shock in 2008, followed by a more gradual 'relaxation' of the plasma boundaries during the fast stream that followed (Sanchez-Cano *et al.* 2017).

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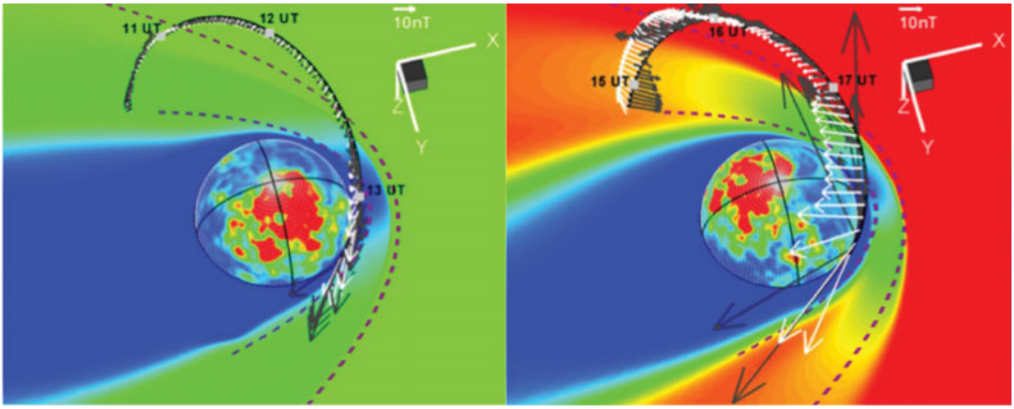

Figure 3. MHD simulations of the Martian solar wind interaction before and immediately following the passage of a CME at Mars. Crustal magnetic field strength is colored on the planet, and the simulated plasma flow speed is shown in the Mars equatorial plane, as viewed from above the southern hemisphere. Nominal bow shock and IMB locations are shown as dashed lines. The MAVEN trajectory is shown in black, with superposed measured (black) and modeled (white) magnetic field vectors. From Jakosky *et al.* (2015).

Ionospheric Enhancements - Planetary ionospheres are formed chiefly through photoionization of atmospheric neutrals by EUV and X-ray photons from the Sun, with a secondary source of ionization from particle precipitation into the atmosphere. Solar flares generate short but intense bursts of radiation at these energies that can cause additional ionization in a planet's upper atmosphere. Radio soundings of the Martian atmosphere during flare periods by MGS have shown an increase in both the peak ionospheric electron density (Gurnett *et al.* 2005), and in a soft X-ray peak near 100 km altitudes as shown in Figure 4 (Mendillo *et al.* 2006). Ionospheric densities have been observed to increase by as much as 200% in response to a flare. In addition, solar energetic particles accelerated during flares or CMEs encounter the Martian atmosphere and can increase ionization. Radar soundings of the Martian ionosphere by MEX have shown that the total electron content of the ionosphere increases substantially during both flares and some SEP events (Morgan *et al.* 2006).

Aurora - One consequence of energetic particle precipitation at Earth is aurora. Mars similarly hosts UV auroral emission, both in localized crustal magnetic field regions (Bertaux *et al.* 2005) and throughout the entire atmosphere, including far from crustal fields (Schneider *et al.* 2015). This latter aurora, termed 'diffuse aurora', is clearly associated with the presence of populations of solar energetic electrons near Mars, and is therefore a direct response to space weather. Aurora in crustal fields are more directly analogous to terrestrial aurora, and result from locally energized electron populations accelerated into the Martian atmosphere in cusp regions (Lundin *et al.* 2006; Brain *et al.* 2006). The brightest example of UV emission from crustal field aurora occurred during a SEP event (Brain *et al.* 2006), and the most energetic electron distributions in cusps tend to occur during periods of ehnanced SEP flux. Like ionospheric enhancements, aurora indicate enhanced energy input into the Martian ionosphere and upper atmosphere during space weather events.

Atmospheric Escape - Measurements from Phobos 2, Mars Express, and MAVEN all show that Martian atmospheric ions are escaping to space (e.g. Lundin *et al.* 1989;

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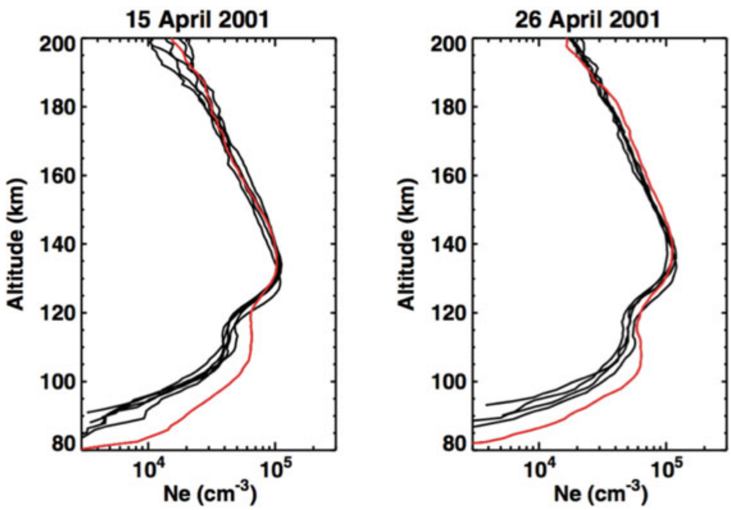

Figure 4. Electron density altitude profiles of the Martian upper atmosphere obtained via radio sounding by the MGS spacecraft for two time periods in 2001. A single profile occuring during a soft X-ray flare is colored red in each time period. From Mendillo *et al.* (2006).

Barabash *et al.* 2007; Brain *et al.* 2015). The rate of atmospheric escape varies with the driving solar and solar wind conditions - a result that is also supported by global plasma models of Mars. It is difficult for an orbiting spacecraft to measure a change in the global escape rate during a CME or SEP event due to a the limited coverage of the region over which escape occurs during the duration of the event. However, multiple studies suggest that escape rates increase during extreme events. The MEX instrument background rates increased strongly during a CME that encountered both Venus and Mars in 2006, indicating the presence of substantial SEP fluxes during the CME (Futaana *et al.* 2008). Escaping ion fluxes increased by 1-2 orders of magnitude during this time period, but this measurement is complicated by the presence of the very instrument backgrounds that indicated that a disturbed period occurred. Similarly, a moderate CME in March 2015 was observed by MAVEN, during which escaping ion fluxes on the dayside of the planet were enhanced by an order of magnitude or more (Jakosky *et al.* 2015). Continued work is currently underway to separate the influences of: the different phases of a CME, SEPs vs. increased magnetic field in the solar wind, and different geometries for CMEs encountering Mars.

4. Applications

As described above, studies of space weather at Mars reveal the response of the Martian atmosphere and near space environment to changing conditions at the Sun. But they also offer the opportunity to address several larger scientific questions.

First, the location of Mars at 1.5 AU provides an additional vantage point from which to study the propagation of the solar wind into the heliosphere. Multipoint measurements comparing conditions at Mars and Earth (in addition to Mercury, Venus, and other locations) provide useful constraints for the validation of models of CME and solar wind propagation (e.g. Falkenberg *et al.* 2011; Dewey *et al.* 2016).

Next, comparisons of the space weather response of Mars to that of Earth may teach us about the importance of a global planetary magnetic field in regulating the interaction of a planet's atmosphere with its space environment. For example, a comparison of

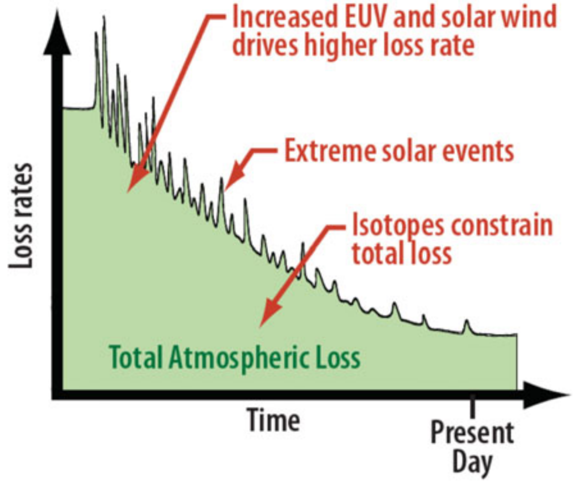

Figure 5. Cartoon showing how atmospheric loss rates from Mars have changed over time. Early in Martian history loss rates were likely to have been both greater in response to larger solar EUV flux and a more robust solar wind, and more variable in response to higher solar activity in the form of flares and CMEs. Courtesy NASA's MAVEN mission.

atmospheric escape at Earth and Mars in response to drivers from the Sun may reveal whether the presence of a global dipole planetary magnetic field reduces atmospheric loss. Of course this comparison is complicated by a number of additional differences between Earth and Mars (e.g. planetary size, heliocentric distance, etc.). Therefore, studies of Mars alone that compare escape from magnetized and unmagnetized regions of the planet present an appealing alternative to Earth-Mars comparisons.

Third, studies of atmospheric escape under different conditions at Mars can be used to understand how the different escape processes vary in response to drivers. With this understanding, it becomes possible to make simple estimates of atmospheric escape rates at earlier epochs in Martian history, when the driving conditions were different (Figure 5). This is important because abundant evidence points to an early Mars that was more habitable than that of today - where liquid water was stable on the surface for long periods of time. In short, space weather observations at Mars today help us to understand the history of the planet's habitability.

Finally, we can treat Mars as a laboratory for measuring space weather influences at unmagnetized planets in our galaxy. By gaining insight into the physical processes at work in the Martian response to space weather, we can port our understanding over to the myriad objects currently being discovered orbiting other stars. With knowledge of a star's properties we can apply the lessons learned at Mars to estimate whether a planet is likely to retain a habitable atmosphere.

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