Response of the Martian ionosphere/thermosphere to solar radiation, the solar wind and crustal magnetic fields: Space weather at Mars

Introduction

Space weather is a colloquial name of the effects of variable impact of the solar photons, solar wind particles and interplanetary magnetic field upon the Earth's environment. In particular, the coronal mass ejections, solar flares, co-rotating high-speed streams, magnetic field re-connections all significantly disturb the geomagnetic field, ionosphere and thermosphere.

Mars and Venus – two of three terrestrial type planets in the solar system - have atmospheres primarily composed of carbon dioxide and atomic oxygen. As far as the ionosphere and atmosphere of Mars and Venus are not protected by the planetary magnetic fields from the solar wind (SW), they are exposed to the solar corpuscular radiation and the interplanetary magnetic field (IMF). Therefore, the ionosphere and atmosphere at Mars and Venus seem to similarly respond to solar radiation (both electromagnetic and corpuscular) except for the effects caused by the planetary gravity and orbit.

Because the gravity of Mars is weaker than that of Venus, the corona (halo) of superthermal neutrals has to be more extended at Mars than at Venus. In particular, within the altitude range 300-400 km, the density of the Martian atmosphere is larger than the neutral atmosphere density at Venus (Breus et al….). Due to the extended atmosphere of Mars, the SW/atmosphere interaction can be potentially the most intensive and comet-like among the solar system planets.

The most recent observations at Mars made by NASA's Mars Global Surveyor (MGS), NASA's Mars Rovers, and ESA's Mars Express (MEX) clearly indicate that liquid water was indeed present on the Martian surface in substantial amounts in the past. Some liquid water existed within 0.5 Ga following the period when the large impact basins like Hellas and Argyre were formed. Liquid water implies warmer climate than it is today, and, consequently, the large amount of carbon dioxide in the atmosphere, which survived the catastrophic impacts. During the following evolution of the Martian atmosphere, water and carbon dioxide must be either hidden somewhere or lost to space. The buried water ice has been recently discovered by MEX MARSIS experiment so that some amount of water was really hidden under the surface of Mars. The rest of the Martian atmosphere might be lost to space.

Planetary magnetic fields are indicators of the status of the planetary interior. Near Venus, the magnetic fields (both large-scale and small-scale) have been detected by the magnetometer onboard Pioneer-Venus Orbiter (PVO). The subsequent analysis has shown that these magnetic fields originate from the SW/IMF interaction with the ionosphere and atmosphere of Venus. Thus, at Venus, even the remnant magnetic fields are not found. Presumably, the planetary dynamo was not effective in the past and the Venusian atmosphere/ionosphere is exposed to SW all the history long.

In contrast, at Mars, the magnetic fields connected with the remnant magnetization of the crust have been discovered (Acuna et al, 1998; 2001; Connerney et al, 1999; Ness et al, 1999; 2000). The magnetic anomalies concentrate in the Southern hemisphere of Mars. However, the magnetic anomalies are especially weak in and around the Hellas and Argyre impact basins. This suggests that Hellas and Argyre had been demagnetized and the Martian dynamo had ceased ~4.0 Ga ago assuming that Hellas and Argyre are coeval to the prominent large impact basins on the Moon and the Martian crust magnetization insignificantly changed since their formation. The second assumption also implies that the crustal magnetic fields as they are observed now can be extrapolated up to 4 billion years backward.

At Mars, the crustal magnetic fields can interact with the SW so that some areas of the Martian atmosphere and ionosphere are protected from the SW while others are not. The areas where the Martian atmosphere and ionosphere are unprotected from SW and IMF were hypothesized to be Venus-like. Within the areas, which are shielded by the crustal magnetic fields from the space environments, the effects of the crustal fields can be very essential. Thus, Mars provides unique opportunity to identify difference in the response of the atmosphere and ionosphere to the electromagnetic radiation, SW and IMF, which is caused by the remnant magnetization of a planetary crust.

At the initial stage of exploration of Venus and Mars, each spacecraft either flew by or was orbiting planet for a short period (several month). The high-resolution altitude profile of the Martian atmosphere characteristics was initially obtained during the entry of the Viking 1 and 2 landers in the late 70s. Mars Pathfinder and the two Mars Exploration Rovers provided new in situ entry data. However the spatial and temporal coverage that can be achieved with entry probes is very limited. In the Mariner 9 and Viking 1 and 2 radio occultation data, evidence of the effects of processes within the lower atmosphere on the ionosphere/thermosphere of Mars has been already found (Kliore, 1992).

PVO was the first planetary mission for which the plasma environment was monitored for approximately a full solar activity cycle. However, the pericenter of the PVO orbit was down to the main ionospheric electron density peak only at the beginning and end of the mission. During those two periods the solar activity was higher than on average. Thus, at Venus, the evolution of the ionosphere/thermosphere and the magnetic fields in the ionosphere has not yet been fully observed. Observations during future Venus Express mission will be complementary to the PVO observations.

Continuous monitoring of the Martian ionosphere/atmosphere and magnetic fields began when the Mars Global Surveyor (MGS) was inserted into orbit in September 1997. As today, the ionosphere and magnetic fields are continuously observed during approximately half of the solar activity cycle. This is more than 3 Martian years and allows also studies of seasonal variations. Several other satellites have been entered into orbit around Mars since 1999, which allow simultaneous observations in different locations.

In 1999 MGS started circular mapping orbits, which provides global coverage of the magnetic fields every approximately 28 days or so. The radio occultation experiment and spacecraft accelerometer experiment during the aerobraking phase provide good global coverage of the Martian atmosphere/thermosphere (Tyler et al, 1992; 2001; Keating et al, 1998; Withers, Bougher and Keating, 2003). Airglow spectroscopy and radiometry are other methods for remote sensing of upper atmospheres of the planets. For instance, NO and O_2 emissions are important tracers of atmospheric transport at high altitudes at Mars (Bertaux et al, 2005a; 2005b). The MGS electron reflectometer data also have a potential for remotely probing the density of the Martian exosphere (Lillis et al, 2003; 2005). Numerical models can provide an intelligent extrapolation procedure for both space and time. Entry data and measurements from orbit are providing the data needed to test our understanding and our advanced modeling of Mars atmospheric processes (Zurek et al, 2005).

The pericenter altitude determines the minimal altitude at which the atmosphere density can be derived from the accelerometer data. It was 100-120 km in the case of MGS. The maximal altitude is set by the accelerometer sensitivity and was approximately 160 km (Withers, Bougher and Keating, 2003). MGS accelerometer obtained over 1000 vertical structures of the atmospheric density, scale height, temperature, and pressure on the day-side in the Northern hemisphere, and on both the day and night-side in the Southern hemisphere. Mars Odyssey accelerometer obtained the first vertical structures near the North Pole and of the night-side of Mars in the Northern hemisphere: over 600 vertical structures of the Martian atmosphere between 100 and 170 km. Thus, the vertical structure of the upper atmosphere has been mapped globally on the day and night-side. In which are interpreted as non-migrating planetary-scale waves propagating up from below, have been discovered (Keating et al, 2000; Forbes and Hagan, 2000; Forbes et al, 2001;2002; Wilson 2002; Withers, Bougher and Keating, 2003). Coupling between lower and upper atmosphere has been also established from studies of the strong response of the upper atmosphere to Martian dust storms (Keating et al, 2005).

The MGS radio occultation experiment has been described in detail in Tyler et al (2001). It yields the neutral atmosphere density, pressure and temperature versus absolute radius from Mars' center of mass up to altitudes 40-45 km with vertical resolution in the range 0.5–1 km. The time span of the data allows studying of the meridional, seasonal and interannual variability (Tyler et al, 2001; Hinson et al, 2001; Hinson and Wilson, 2004). In addition to the lower atmosphere, the MGS radio occultation experiment senses the ionosphere. The geometry restricts the ionosphere observations to a region near the terminator. Sometimes the ionosphere cannot be detected because the electron density is too low for X-band radio signal used. However, the dense sampling of the ionosphere facilitates studies of the longitudinal, SZA /latitudinal and local time variations. Significant longitudinal variations in the altitude of the peak electron density, which have been found, have been shown to be caused by the large-scale non-migrating tidal waves in the thermosphere (Bougher et al, 2001; 2004). Thus, the longitudinal variations of the altitude of the peak electron density also indicate the coupling between the lower atmosphere and the thermosphere.

The Mars general circulation model (MGCM) of NASA Ames, Geophysical Fluid Dynamics Laboratory (GFDL) and French Laboratoire de Météorologie Dynamique (LMD) were used to study polar warming and thermal tides (Wilson 1997; Joshi et al, 2000; Forbes et al, 2002). For modeling the Martian atmosphere above the thermopause, a class of thermospheric model has been developed by Bougher et al. (1990; 1999; 2000). According to Lewis (2003), there is a practical necessity to couple the upper atmosphere model to output from a (MGCM) for the lower and middle atmosphere, usually via a boundary between 50–100 km altitudes. Recently the models extending from the surface to the atmosphere above the thermopause (the top-side boundary of calculation domain at altitudes 120 km (Angelats i Coll, et al, 2004), 160-180 km (Moudden and McConnell, 2005) and 240 km (Angelats i Coll, et al, 2005) have been developed.

The magnetic fields connected with the remnant magnetization can form mini-magnetospheres. The outermost magnetic field lines can be open after reconnection. Particle precipitation occurs near magnetically connected points. The precipitation into the thermosphere is an additional local energy source and the effects of the particle precipitation can interfere with the effects of the lower-to-upper atmosphere coupling. Just recently, the intense aurora caused by strongly localized precipitation of solar wind (SW) particles into the Martian atmosphere has been discovered by SPICAM experiment onboard Mars Express (Bertaux et al, 2005c). The vertical and horizontal dimensions of a mini-magnetosphere are controlled by the SW dynamic pressure while the energy input of the SW precipitation is proportional to the energy flux of SW particles at the orbit of Mars. Next, the reconnection and the SW variability drive currents within the Martian ionosphere. Knipp, Tobiska and Emery (2005) have shown recently that, in the case of the Earth, the Joule dissipation of these currents is a main cause of variability of the energy input into the thermosphere, and, sometimes, can compete with the EUV radiation as a dominant heating mechanism. Next, the relative energy input of the precipitation and Joule heating vary with the solar activity. Consequently, the analysis of the long-term variability of the SW and draped IMF in the MPB region is required for both predicting status of the Martian thermosphere especially at smaller scales and comparative studies of the terrestrial type planets. The recent MGCMs, which extend from the surface to the atmosphere above the thermopause, ignore the precipitation and Joule heating which can be significant contributors to the energy balance in the regions with crustal magnetic fields. The analysis of the thermosphere response to the SW/IMF variability is, therefore, also necessary for checking accuracy and further improvements of the atmosphere/thermosphere models recently developed.

Kinetic and test-particle simulations of the Mars – solar wind interaction, which assumed the lack of a global magnetosphere at Mars, suggest that solar wind absorption by the Martian atmosphere may be an important energy source for the upper atmosphere (see, for example, *Kallio et al.*, 1997). According to the models, some of the solar wind ions (mainly protons and alphas) directly impact the upper atmosphere of Mars (*Kallio and Janhunen* [2001], *Kallio et al.*, [1997]). Others undergo charge exchange reactions with ambient exospheric and thermospheric neutrals, particularly hydrogen and helium, and then impact the exobase as energetic neutral atoms (ENAs) (*Kallio et al.*, [1997]). In both cases, solar wind energy is "directly" deposited into the upper atmosphere resulting in increasing ionization rates and UV emissions [*Kallio and Barabash*, 2000]. ENAs generated as a product of the SW interaction with the extended Martian exopshere also provide means of "imaging" the solar wind interaction.

Thus, the analysis and reconciliation of all the past and present data is particularly important for studies of the long term evolution of the Martian atmosphere including water losses from the outer layers of Martian crust. The following aspects of experimental, theoretical and numerical studies of the response of the Martian ionosphere/atmosphere are of principal interest and are discussed in this paper:

1) The limitations and advantages of various versions of the radio occultation experiment, which provided the bulk of the data regarding status of the ionosphere/atmosphere at Mars; the comparison of recent experiment with topside sounder (the MARSIS experiment of MEX mission) with the radio occultation

experiments in order to find possibilities to reduce internal limitations of each experiment and develop procedure of complementary analysis of the data.

2) Sources of the energy responsible for the Martian atmosphere heating and ionization and available data regarding these energy sources; proxies of the solar EUV radiation and SW characteristics near Mars, which are based on the solar EUV fluxes and SW characteristics measured near the Earth or the MAG/ER magnetic field measurements within the MPR at Mars.
3) Interpretation of radio occultation electron density measurements in order to obtain the neutral atmosphere characteristics in the vicinity of the main peak of the electron density (neutral atmosphere scale-height, neutral atmosphere density and shape of isodensity lines) and electron temperature in the ionosphere region where day-to-night plasma transport is ineffective.
4) Magnetic fields observed during MAG/ER experiment onboard MGS, discrimination of the induced component of the fields, and modeling of crustal magnetic fields within the Martian ionosphere. Goodness of the numerous models of the crustal magnetic fields for the interpretation of experimental data regarding the ionosphere at Mars. Mini-magnetospheres at Mars and structure of the magnetic field fluxes near Mars.
5) Effects of the lower-to-upper atmosphere coupling (vertical propagation of tidal waves) observed near the main ionization peak at Mars and their importance for the interpretation of the variability of the ionosphere/atmosphere caused by the solar EUV radiation, SW and crustal magnetic fields recently discovered on Mars.
6) Variability of the ionosphere/atmosphere parameters related with the variable EUV radiation (SZA, Martian local time, seasonal and solar cycle effects) and SW (SZA and solar cycle effects).
7) Variability of the ionosphere/atmosphere parameters caused by the formation of the mini-magnetospheres and magnetic field reconnections followed by the SW particle precipitations.