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Editorial

The solar wind interaction with Mars: Recent progress and future directions

The Sun has a powerful influence on planetary atmospheres. This is especially true for planets lacking a global magnetic field, because the solar wind can interact directly with the upper atmosphere. Neutral particles in the upper atmosphere are ionized by solar photons and through interactions with solar wind charged particles, forming an ionosphere. The newly formed ions move in response to magnetic and electric fields from the solar wind and the ionosphere itself. Likewise, the conducting ionosphere influences the motion of incident solar wind particles. The result is a complex interaction that involves the exchange of particles and energy between the planet and the flowing solar wind plasma in which it is embedded. This interaction persists and evolves throughout the age of the Solar System as both the planetary atmosphere and the Sun evolve.

Mars is not the only unmagnetized planet that interacts with the solar wind; however, it provides a particularly interesting example because it incorporates elements of the interaction at several other solar system bodies. Like Venus, the solar wind interacts directly with the ionosphere. Like comets, the small size of Mars relative to Venus leads to a very extended neutral exosphere that is left exposed to the solar wind and, as it is ionized, significantly modifies the incident plasma flow. Like the Moon, localized crustal magnetic fields shield portions of the planet from interaction with solar wind plasma, and have observable effects on the plasma upstream from the body. Finally, crustal fields form localized "mini-magnetospheres" that enable aspects of Earth-like planetary magnetospheres, including auroral processes.

The first scientific investigations of the solar wind interaction with Mars were conducted in the mid-1960s and 1970s on flyby missions of the US Mariner and the USSR Mars series of spacecraft (see review by Luhmann et al. (1992)). These missions discovered the martian bow shock and the martian ionosphere through radio occultation. The Viking 1 and 2 landers provided the first in situ sampling of the martian ionosphere in the mid-1970s. PHOBOS-2 returned data from Mars' orbit in 1989, including the first measurements of the magnetotail and plasma wake of Mars, and the first measurements of escaping planetary ions (Zakharov, 1992). This mission also provided early hints that interpretation of the plasma environment was not as straightforward as at Venus. For example, there was not a consistent interpretation of the data acquired in the magnetotail, leaving arguments about whether Mars had an intrinsic magnetic field. Thus, it was still surprising when Mars Global Surveyor (MGS) measured intense magnetic fields emanating from highly localized regions of the planet's crust (Acuña et al., 1998). MGS orbited Mars for more than 9 years (nearly a full solar cycle), contributing observations of magnetic fields and suprathermal electrons (Brain, 2006). These observations enabled studies of the entire solar wind interaction region down to ~110 km using data from early aerobraking orbits, and statistical studies of a small portion of the interaction region at ~400 km altitudes using 7 years of mapping data. Most recently, Mars Express (MEX) has measured suprathermal electrons and ions near Mars for more than 5 years, discovering aurora in Mars' crustal fields and measuring atmospheric ion escape rates during solar minimum (Barabash et al., 2006, 2007a; Bertaux et al., 2004). The many years of data collected by MGS and MEX in the past decade have sustained new and exciting research on the solar wind interaction with Mars. The research is supported by coordinated modeling and laboratory experiments. And most fortunately, data now exist from similar instrumentation at multiple plasma environments in the Solar System that enable more direct comparison of plasma interactions (e.g. Mars, Venus, and Titan, at present).

Study of the interaction of the solar wind with unmagnetized planets combines elements of planetary aeronomy and space plasma physics. Study of the planetary consequences of this interaction can involve elements of planetary atmospheres and climate, planetary surface and subsurface chemistry, and planetary interiors. The scientific investigation of the solar wind with Mars, in particular, is motivated by determining the extent to which the solar wind has played a role in climate change on Mars. The plasma interaction at Mars also influences the energetics, dynamics, and chemistry of the ionosphere, exosphere, and upper thermosphere, so is of aeronomical interest. Finally, in situ study of fundamental space plasma processes (e.g. auroral particle acceleration, magnetic reconnection, plasma waves) in a non-terrestrial environment provides good opportunity to test theories for how the processes operate universally.

This special issue of Icarus stems from the AGU and NASA cosponsored Chapman Conference on the Solar Wind Interaction with Mars (SWIM). Eighty-six scientists from past, current, and future spacecraft missions, modelers, theorists, and experimentalists studying Mars and similar bodies gathered in San Diego, CA on 22–25 January 2008. The goals of the conference were to summarize the current state of the field, to identify major unanswered questions, to place recent results into context with others at Mars and other planets, and to move from a phenomenological description of the solar wind interaction with Mars to a physical understanding of the interaction. To address these goals, participants made 54 oral presentations and 42 poster presentations. The conference addressed five science questions. Below, we briefly summarize the 'state of the field' for each question, and identify emerging research areas.

1. *How is the structure of the interaction region formed and maintained?*

The basic structure of the martian plasma interaction region is reasonably well-described, thanks to the many measurements contributed by early spacecraft to visit Mars, and in particular by the two most recent spacecraft to make relevant measurements,

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MGS and MEX. In this interaction, solar wind ions are slowed and deflected around Mars, and a number of different plasma regions and boundaries are formed (see review by Nagy et al. (2004)). These regions can be distinguished by the characteristics (energy, density, composition, etc.) of their resident plasma populations. The interplanetary magnetic field, carried by the solar wind, drapes around the martian atmospheric obstacle and stretches into a two-lobed magnetotail on the night side of the planet.

The many spacecraft measurements have allowed us to determine the location and extent of the different plasma regions, and a fairly robust "steady-state" picture of the martian plasma interaction has emerged. The large amount of new spacecraft data, coupled with advances in the capability of models, has invigorated three new research areas relevant to the structure of the interaction region. These are: (1) the response of the steady-state interaction to different drivers (e.g. solar wind pressure, IMF direction, and solar EUV flux); (2) dynamical processes within the plasma interaction region (e.g. magnetic reconnection, particle acceleration); and (3) detailed physical processes responsible for maintaining the interaction region (e.g. electric fields along plasma boundaries). Investigation in each of these areas has been somewhat hampered by the lack of recent simultaneous ion, electron, and vector magnetic field measurements.

2. *How does the interaction affect upper atmospheric structure and escape?*

A major motivation for studying the solar wind–atmosphere interaction at Mars is the potential relevance this interaction has for long-term climate evolution. Abundant geomorphologic and atmospheric evidence suggests that the martian atmosphere has undergone considerable change over the past several billion years, and that substantial amounts of atmosphere may have been removed (see Jakosky and Phillips, 2001). Atmosphere can be removed in two directions: "down" to the subsurface and polar caps, and "up" to space. Early measurements by the Pioneer Venus Orbiter and by PHOBOS-2 at Mars showed that planetary ions are constantly escaping to space from the atmospheres of unmagnetized planets (e.g. Intriligator, 1989; Lundin et al., 1990). Indirect ground-based and spacecraft measurements and supporting model calculations suggest that neutral particles are also escaping in significant quantities (cf. Fox and Dalgarno, 1980; Nagy et al., 1981). By studying atmospheric escape as it occurs today at Mars, we hope to evaluate how escape has proceeded over solar system history, and the degree to which this atmospheric loss process has been relevant for the evolution of the martian climate. Further, Mars may serve as a laboratory for testing how atmospheric escape processes may operate at other unmagnetized bodies, including exoplanets.

Proper study of atmospheric escape to space at Mars should include the following: (1) determination of the response of the atmospheric reservoirs for escape to different drivers; (2) evaluation of the relative importance of the various processes by which a particle may escape under different conditions; (3) determination of the total atmospheric escape rate under different conditions; (4) assessment of the importance of atmospheric escape over solar system history, relative to other atmospheric loss and source processes. To date, the most progress has been made in area (3), though some progress has been made in all areas.

Recent measurements of planetary ions in the martian wake by Mars Express suggest that atmospheric escape rates are relatively low ($\sim 10^{24}$ ions/s), insufficient to account for long-term climate evolution at Mars even if escape rates were higher early in Mars history (Barabash et al., 2007a). However, it is still unclear what fraction of the total escape this rate represents; substantial amounts of neutral and low energy ions could be escaping that are not represented in the reported rates. Emerging experimental and modeling results demonstrating how ion escape rates vary with solar wind drivers may allow us to more accurately determine the likely escape rates early in martian history (Lundin et al., 2008). Recent attention is also being given to atmospheric escape during extreme events such as solar storms, and to ion loss processes that are not pickup (defined here as acceleration of individual ions to escape energy by the solar wind convection electric field), including low energy ion outflow and bulk plasma escape processes (where portions of ionospheric plasma are removed at once).

Investigation of atmospheric escape at Mars has been hampered by the lack of simultaneous measurements and supporting fully-integrated models of the drivers, atmospheric reservoirs, and escaping particles. Only when these measurements are obtained will it become realistic to determine whether escape-related processes have been important for martian climate evolution.

3. *How do crustal magnetic fields affect the interaction locally and globally?*

The presence of strongly magnetized regions of the crust and apparent lack of a global dynamo magnetic field today provides clues about the structure, composition, and evolution of the martian interior and subsurface. Crustal fields also influence the upper atmosphere and plasma interaction region, on local scales and perhaps on global scales (see Brain, 2006). The strongest crustal magnetic fields supply sufficient magnetic pressure to stand off the solar wind well above the ionosphere in some locations, shielding the atmosphere from solar wind-related ionization processes. Further, crustal field lines should interact with solar wind magnetic field lines, creating complex magnetic topologies at Mars where some sheltered regions of the atmosphere lie immediately adjacent to regions magnetically connected to solar wind plasma populations.

Investigation of crustal field influences on the atmosphere and plasma environment is relatively new, since crustal fields were not discovered at Mars until 1997. But a few areas in particular might be addressed in the coming years using existing observations and models. First, ongoing studies should determine the extent of the influence of crustal fields on the plasma environment. Next, the influence of crustal fields on atmospheric escape rates is beginning to be addressed by models. Recent global simulations find that crustal fields decrease the total ion escape rate (Ma et al., 2002; Harnett and Winglee, 2006), suggesting that regional atmospheric shielding effects are more important than the increased access to the solar wind that vertical open magnetic field lines in crustal field regions provide. However, it is still unclear whether these simulations contain sufficient spatial or temporal resolution to fully capture crustal field effects. Third, observations by MGS and MEX show that crustal fields influence the chemistry and dynamics of the upper atmosphere. Auroral processes operate at Mars, depositing energy and particles into the night side atmosphere that should alter it in certain locations (Bertaux et al., 2004; Fillingim et al., 2007). MEX radar observations also show that ionospheric densities and total electron content are increased in likely regions of open crustal magnetic field, both on the day side and at night (Gurnett et al., 2005; Safaeinili et al., 2007). Fourth, regional effects of crustal fields continue to be investigated, not only in the steady-state picture, but as external conditions change and as the orientation of Mars with respect to the Sun changes (both daily and seasonal effects).

4. *What can models teach us about the physics and variability of the system?*

Early models of the global plasma interaction at Mars provided adequate approximations for the macro-scale structure of the plasma interaction region, based on limiting physical assumptions (e.g. Spreiter et al., 1970). Increases in computational power in recent years have allowed today's global plasma models to employ more sophisticated physical schemes at ever-improving temporal and spatial resolution, with the goal of truly understanding the physics of the interaction. In addition to the early gasdynamic models that considered the solar wind entirely as a fluid that carried its magnetic field with it, there are now multiple models that employ MHD, Hall MHD, multifluid MHD, and hybrid physical assumptions. Many of these models have sufficient resolution to couple the plasma interaction with the ionosphere, and include ionospheric chemistry and physics. In addition, there are several other types of models relevant for the study of the martian plasma interaction, including test particle models for ions near Mars, Monte Carlo models for the martian exosphere, models for neutral and/or charged particle deposition in the atmosphere, ionospheric models, and self-consistent models for the neutral upper atmosphere. Each of these models has strengths and weaknesses, and the potential to place observations into context and make predictions for future observations to verify.

Recent modeling efforts have focused on both the physics and the variability of the martian system. Most global plasma modeling efforts have addressed the issue of atmospheric escape to space, providing escape rates for planetary ions, and variability in escape rates introduced by changes in solar EUV and solar wind conditions, or the presence of crustal magnetic fields. But it is still uncertain whether all of these models are appropriate tools to use when studying atmospheric escape. It is not clear that any model captures all of the escape processes for ions, and many models use boundary conditions or limiting assumptions that may preclude appropriate estimates of escape. The models are also used for other purposes, including all of the areas described in the sections above.

Three areas in particular hold promise for future studies. First, with the proliferation of new models employing different physics there is outstanding opportunity to determine the physics responsible for different aspects of spacecraft measurements. This can be achieved by comparing multiple models using the same initial and operating conditions; such comparisons are currently being pursued by the community. Further, these comparisons can help to place "error bars" on modeled atmospheric escape rates, for comparison with measurements. Second, application of any single model to multiple solar system bodies (e.g. Mars, Venus, Titan) should help us to distinguish the important features of the interaction region at each body, and the reasons for differences between the bodies. Finally, the integration and exchange of information between different types of models may help us to understand the entire martian system (thermosphere, ionosphere, exosphere, plasma interaction region), and the many connections between different parts of the system. Such efforts are in their infancy today, and it remains to be seen whether this approach is viable.

5. *How does the martian environment compare to other solar system bodies?*

Each of the questions discussed above has the underlying goal of understanding the martian system more completely. But, as mentioned above, the martian plasma interaction has elements of the plasma interactions at Venus, Titan, comets, and even Earth. Venus and comets are like Mars, except with different size (so that the atmosphere is more or less extended and ion length scales are smaller or larger relative to the size of the different plasma regions). Titan is like Mars, except the atmospheric composition is different and the directions of the Sun and incident plasma vary with respect to each other. Earth is like Mars, except the magnetosphere is global rather than local. Fortunately, spacecraft have visited each of these bodies, and we are able to compare the measurements in order to learn more about planetary plasma interactions in general.

There are two attractive frontier research areas for comparative studies. First, as discussed above, the use of models for comparative studies is becoming increasingly feasible. Several global plasma models used recently for Mars have also been recently applied to one or more of these other bodies (e.g. Kallio et al., 2008; Ma et al., 2006; Modolo and Chanteur, 2008), and it would be beneficial to perform side-by-side comparisons of similar initial conditions at multiple bodies. Second, Mars and Venus Express are providing a great opportunity to learn more about both Mars and Venus using measurements from identical and highly similar instruments in orbit around both bodies simultaneously (Barabash et al., 2007a,b).

The papers in this special issue all deal with one or more of the five questions outlined above, and collectively demonstrate that studies of the martian upper atmosphere and solar wind interaction are progressing at a rapid pace. This research area is in the middle of an exciting time. An influx of new measurements has moved the field from data-poor to data-rich over the course of the last decade. The many new computer models and increased computational resources have enabled ever-more detailed exploration of the physics in the interaction region and the connections between the martian upper atmosphere, ionosphere, and surrounding plasma. And increasing collaboration between scientists with many different perspectives (e.g. terrestrial vs. planetary scientists, experimental vs. computational or theoretical scientists, aeronomers vs. space physicists, and scientists associated with different spacecraft) is allowing new discoveries to be made from "old data".

Even in the absence of a dedicated mission for this research area, there is much still to be done. Existing observations will continue to be mined for new information for many years, and rapidly improving models applied to place them in context. Here we identify two of the most notable challenges facing the community as we go forward.

First, the community should continue to strive to fully understand the connections between the different parts of the system under different conditions. There has been great progress toward understanding "each part of the whole" over the past several years. But despite the abundance of recent data returned by MGS and MEX, the community still does not have much-needed simultaneous observations of the solar and solar wind drivers, the martian upper atmosphere and ionosphere, and plasma near Mars. These observations, if obtained at sufficient spatial and temporal resolution, should allow us to determine how the entire system responds to the Sun. It is hoped that an upcoming mission to Mars, such as the MAVEN mission currently being developed for launch in 2013, will provide these measurements.

Second, the community should be cognizant of recent advances in other relevant research areas, and should take care to embrace new ideas and not to insulate itself. For example, the study of plasma processes near Mars is likely to benefit from new discoveries made by terrestrial space physics missions or at other planets. Similarly, studies of atmospheric escape to space at Mars should strive to place their research in context with what is being learned about other source or loss processes, and the likely state of the martian atmosphere at different epochs.

In summary, studies of the solar wind interaction at Mars (SWIM) like those included in this special issue are relevant to martian climate evolution, the state of the upper atmosphere, and fundamental space plasma processes. Our understanding of the plasma environment continues to grow, thanks to recent spacecraft measurements, recent advances in modeling capability, and broad collaboration of planetary scientists with a wide range of expertise.

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