

Solar Cycle and Seasonal Variability of the Martian Thermosphere-Ionosphere and Associated Impacts upon Atmospheric Escape

S. W. Bougher, A. Valeille, M. R. Combi and V. Tennishev

University of Michigan, Ann Arbor

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ABSTRACT

A growing body of evidence supports an ancient Mars having a milder, wetter climate, suggesting that its atmosphere was once more substantial than it is today. The fate of the lost atmosphere and water is a major unanswered question. Is the “lost” water sequestered in the crust at all latitudes, or did much of it escape to space? While available measurements and theoretical studies suggest that a number of atmospheric escape processes are at work today, little is known about their efficacy, including temporal variations driven by the solar cycle and Mars seasons. Selected 3-D simulations are presented and illustrate the coupling between the thermosphere-ionosphere system and the exosphere leading to predictions of the oxygen corona and hot oxygen escape (a major component of atmospheric loss for present day Mars).

INTRODUCTION

The Mars thermosphere (~100-200 km) is an intermediate atmospheric region strongly impacted by coupling below with the lower atmosphere (e.g. seasonal inflation/contraction, gravity waves, planetary waves, dust storms) and coupling above with the Sun (solar soft X-ray, EUV, and UV fluxes, and solar wind particles) [see Bougher, 1995; Bougher et al., 2000; 2002]. The thermospheric layer extends from the top of the middle atmosphere (mesopause) to the beginning of outer space (exobase). The thermosphere is also distinguished by a transition region called the homopause (~115-130 km), below which atomic and molecular constituents are well mixed [see Stewart,

1987; Bougher et al., 2000]. Above, in the heterosphere, individual species begin to separate according to their unique scale heights via molecular diffusion. Mars' thermosphere is dominated by CO₂ and its dissociation products O and CO, as well as N₂. Finally, the thermosphere is the topmost completely bound layer of the atmosphere; i.e. above in the exosphere, the lightest species may form an extended hot corona and escape to space.

The Mars dayside thermosphere is characterized by temperatures which increase dramatically with altitude above the mesopause (~90-110 km), largely due to solar EUV-UV heating, while approaching an asymptotic and maximum value at the exobase (~170-200 km). This deposited heat is conducted downward toward the mesopause (molecular thermal conduction), where it is partially radiated away to space by CO₂ 15-micron emission. Finally, global scale winds transport atomic and molecular constituents around the planet, as well as dayside produced heat, giving rise to an intricate feedback of global composition, temperature, and wind fields [see Bougher et al., 2000; 2006; 2009].

Embedded within the thermosphere is the ionosphere, a weakly ionized plasma. The charged particles that make up the Mars ionosphere (e.g. O₂⁺, CO₂⁺, O⁺, NO⁺) are formed by (1) EUV ionization and subsequent photo-electrons that operate on local neutral thermospheric species (e.g. CO₂, N₂, CO, O, etc), and (2) ion-neutral photochemical reactions. Since Mars lacks a significant intrinsic magnetic field, the solar wind (particles, fields and flow) interacts with the Mars near-

space environment (including the thermosphere, ionosphere and exosphere), resulting in ionization, neutral heating, pickup ion escape, ion outflow, hot species escape and ion sputtering [see Chassefiere and LeBlanc, 2003].

The Mars thermosphere-ionosphere system can change dramatically over time since this atmospheric region is controlled by highly variable components of the Sun's energy output composed of both electromagnetic radiation (0.1-200 nm) and the solar wind [e.g. Bougher et al., 2002]. The amount of the most important soft X-ray (0.1-5 nm) and EUV (5-110 nm) solar radiation heating the Mars thermosphere (and/or forming its ionosphere) varies significantly over time. These temporal variations result from the changing heliocentric distance (due to orbital eccentricity), the planet's obliquity (determining the local season), and the changing solar radiation itself. Both solar rotation (~27-day) and solar cycle (~11-year) variations of the soft X-ray and EUV fluxes are significant (up to factors of ~2 to 10), producing dramatic variations in global thermospheric temperatures, composition, and winds [e.g. Bougher et al., 2000; 2002; 2009; Forbes et al., 2006; 2008], as well as ionospheric densities [e.g. Fox et al., 1995].

Mars with its weak gravity (unlike Venus and Earth) permits an extended corona of light species and the escape of its lighter constituents from its exosphere. The local exobase level can be defined as the level above which an escaping particle moving along a radial direction will encounter one collision on average [Valeille et al., 2009c]. For a single constituent upper atmosphere, this is equivalent to the standard definition of the exobase level, where the collision mean free path equals the temperature scale height of the constituent [e.g. Schunk and Nagy, 2000]. An understanding of the Martian exosphere is important for determining the shape and extent of its coronae, for evaluation of atmospheric ion and neutral escape rates, and for estimating the global loss of water over Mars history [e.g. Valeille et al., 2009b; 2009d].

The volatile escape processes estimated to be important for Mars today and during its last 3.8-Gyr are well described in the literature [e.g. Chassefiere and LeBlanc, 2004; Barabash et al., 2007; Lundin et al., 2008]. These processes include: (1) hot atom escape resulting primarily from dissociative recombination (DR) of molecular ions (e.g. O_2^+ , CO^+ , N_2^+), (2) bulk ion outflows created by solar-wind induced fields in the ionosphere, (3) pickup ion escape (accelerated by the solar wind B-field) resulting from photo-ionization, electron impact ionization and charge exchange of exospheric neutrals, and (4) sputtering caused by precipitation of pick-up ions into the Mars atmosphere ejecting neutrals to space. Each of these mechanisms is

regulated to some degree by the changing solar EUV radiation. However, no comprehensive observational study of these escape processes has ever been undertaken.

Instead, a suite of multi-dimensional models has been used to simulate each of these escape processes (including variations over the solar cycle and with Mars' seasons), thereby providing estimates of individual escape rates for modern Mars (see Figure 1). The interconnectedness of these escape processes is just now being investigated as specific model outputs are sequentially linked to subsequent model inputs, as illustrated in Figure 1. For this paper, we investigate the linkage between thermosphere-ionosphere and exosphere models, leading to predictions of hot oxygen escape rates and the extent of the hot oxygen corona.

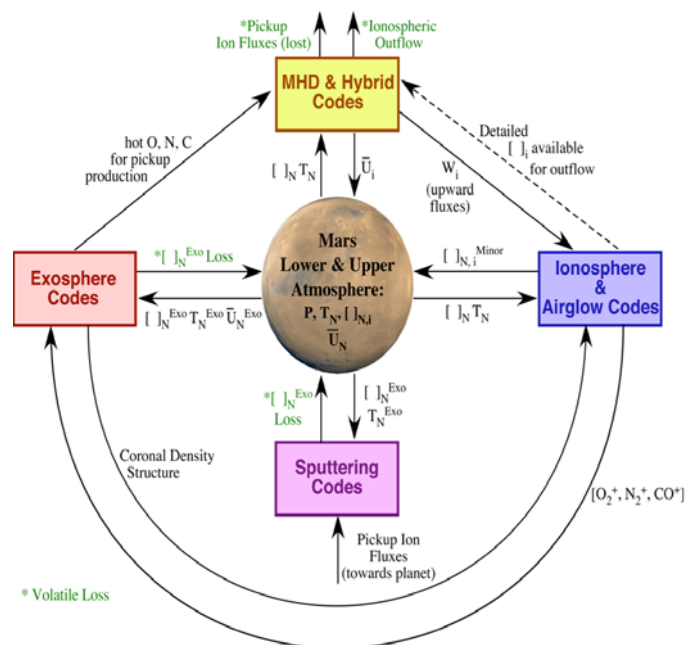


Figure 1. Mars upper atmosphere model inter-connections for the simulation of volatile escape rates.

Processes that shape the exosphere and the Martian hot corona originate deep in the thermosphere-ionosphere. As a result, spatial (asymmetries in the density, temperature and wind structure) and temporal (e.g. solar cycle and seasonal) variations of the thermosphere-ionosphere system strongly impact the production and subsequent distribution of hot oxygen atoms in the exosphere and their escape from the planet. In this paper, modern 3-D modeling tools are described, coupled thermosphere-ionosphere and exospheric simulations are presented [from Valeille et al., 2009c, 2009d], and corresponding upper atmosphere results are illustrated. Finally we evaluate the implications of this strong coupling of the Mars thermosphere-ionosphere with the exosphere, in particular the resulting variations in atmospheric escape rates.

MODELING TOOLS

In this section, the two models used together in our approach, the Mars Thermospheric General Circulation Model (MTGCM) and the Direct Simulation Model Carlo (DSMC) code, are presented along with a summary of the main assumptions used in the description of the Martian upper atmosphere. Both thermosphere-ionosphere and exosphere models, as well as how they are coupled, were recently presented in detail in several papers [Valeille *et al.*, 2009a, 2009b, 2009c; 2009d].

MTGCM CODE. The MTGCM is a finite difference primitive equation model that self-consistently solves for time-dependent neutral temperatures, neutral-ion densities, and three component neutral winds over the Mars globe (e.g., Bougher *et al.* 1999, 2000, 2002, 2004, 2006; 2008; Bell *et al.* 2007). The MTGCM hydrodynamic code is adapted from the NCAR Thermospheric General Circulation Model (TGCM) framework for the Earth (see Bougher *et al.*, 2002; 2008).

The modern MTGCM code contains prognostic equations for the major neutral species (CO_2 , CO , N_2 , and O), selected minor neutral species (Ar , NO , $\text{N}^{(4)\text{S}}$, O_2), and several photo-chemically produced ions (e.g. O_2^+ , CO_2^+ , O^+ , and NO^+ below 180 km). All fields are calculated on 33 pressure levels above 1.32 microbar, corresponding to altitudes from roughly 70 to 300 km (at solar maximum conditions), with a $5^\circ \times 5^\circ$ resolution in latitude and longitude. The vertical coordinate is log pressure, with a vertical spacing of 0.5 scale heights. Key adjustable parameters which can be varied for MTGCM cases include the F10.7 or E10.7-cm index (solar EUV/UV flux variation), the heliocentric distance and solar declination corresponding to Mars seasons. A fast non-Local Thermodynamic Equilibrium (NLTE) 15-micron cooling scheme is implemented in the MTGCM, along with corresponding near-IR heating rates (Bougher *et al.* 2006). These inputs are based upon detailed 1D NLTE model calculations for the Mars atmosphere (e.g., Lopez-Valverde *et al.* 1998).

A simple dayside photochemical ionosphere is formulated for the MTGCM, including the major ions. Key ion-neutral reactions and rates are taken from Fox and Sung (2001); empirical electron and ion temperatures are adapted from the Viking mission for various solar conditions. The ionization rates required for the production rates are calculated self-consistently, making use of specified solar EUV fluxes. Nightside ions are not yet simulated, but will require either day-to-night ion drifts from modern magneto-hydrodynamic (MHD) models (e.g., Ma *et al.* 2004), or energetic electron precipitation sources of nightside ionization (e.g., Fillingim *et al.* 2007).

The MTGCM is driven from below by the NASA Ames Mars MGCM code (Haberle *et al.* 1999) at the 1.32-microbar level (near 60-80 km). This coupling allows both the migrating and non-migrating tides to cross the MTGCM lower boundary and the effects of the expansion and contraction of the Mars lower atmosphere to extend to the thermosphere. The entire atmospheric response to simulated dust storms can also be calculated using these coupled models. Key prognostic variables are passed upward from the MGCM to the MTGCM at the 1.32-microbar level at every MTGCM grid point: temperatures, zonal and meridional winds, and geopotential heights. These two climate models are each run with a 2-minute time step, with the MGCM exchanging fields with the MTGCM at this frequency.

This coupled model configuration has been validated using an assortment of spacecraft observations, including Mars Global Surveyor (MGS), 2001 Mars Odyssey (MO), Mars Reconnaissance Orbiter (MRO), and Mars Express (MEX) mesosphere, thermosphere and/or ionosphere data sets (Bougher *et al.* 1999, 2000, 2004, 2006; McDunn *et al.*, 2009). Recently, Bougher *et al.*, (2009) presented predictions for dayside, low-to-mid latitude exospheric temperature variations over the solar cycle and Mars seasons. These computed variations are in reasonably good agreement with available aerobraking, airglow, and orbital drag measurements (e.g., Keating *et al.* 1998, 2007; LeBlanc *et al.*, 2006; Forbes *et al.* 2008). In general, the global wind patterns simulated by the MTGCM reveal very strong summer-to-winter inter-hemispheric Hadley circulations that are consistent with observed NO nightglow (Bertaux *et al.* 2005) and winter polar warming (Bougher *et al.* 2006) features. Finally, no downward coupling is presently activated between the MGCM and the MTGCM. However, the impacts of lower atmosphere dynamics upon the upper atmosphere are dominant.

DSMC CODE. The DSMC model is a 3D simulator that solves for the coupled thermosphere/ionosphere and exosphere system using an altitude-based coordinate system. Instead of assuming a strict separation between collision and collisionless domains, the DSMC model considers a collision transitional domain (135 to 600 km altitude) where the momentum exchange within the flow is still important but the collision frequency is not high enough to maintain equilibrium in the flow (see Table 1). The DSMC code provides a complete set of the exospheric macroscopic parameters for hot oxygen, its escape flux, and its return flux to the thermosphere.

With the DSMC method, a gas flow is represented by a set of (usually millions) model particles moving in phase space. A probabilistic technique is used to sample the state of collision partners after a

momentum exchange event, to simulate scattering and chemical reactions. The approach is based on solving the Boltzmann equation and, hence, is valid for all gas flow regimes presented in the domain of study.

	Kn<<1	Kn~1	Kn>>1
Model	DSMC (Boltzmann equations)		
Inputs	MTGCM		no
Mesh	Structured	Unstructured	
Location	Thermosphere	Exosphere	
Collision	Transitional domain		Collisionless
Hot O Production	yes		no
Altitude (km)	135	200 600	7000

Table 1: Illustration of the method for combining hydrodynamic (MTGCM) and kinetic (DSMC) models to describe rigorously both transitional and collisionless regions. The Knudsen number, $Kn = \lambda/H$, is a dimensionless number defined as the ratio of the molecular mean free path length λ to the scale height H . Collisionless kinetic theory models, used to describe the exosphere, are valid in the limit $Kn \rightarrow \infty$; whereas hydrodynamic models, such as the MTGCM, are used to describe the thermosphere and are valid when the mean free path λ is very small and $Kn \rightarrow 0$. However the Boltzmann equation of kinetic theory is valid for the whole range of Knudsen numbers and is solved by the DSMC code. Adapted from Valeille et al., [2009a].

The main constituents of the Mars upper thermosphere are carbon dioxide and atomic oxygen. The trajectory of each hot oxygen atom in the gravitational field of Mars is traced from collision to collision until it escapes at 3 Mars radii, becomes part of the ‘cold’ thermosphere when its speed falls below $V_{\text{threshold}}$ (which is defined as twice the local thermal speed in the transitional domain) [Valeille et al., 2009a], or becomes ionized in the sunlit portion of the exosphere. Scattering collisions are approximated as elastic hard sphere encounters.

For present conditions at Mars, O_2^+ dissociative recombination is by far the most important source of hot oxygen in the Martian thermosphere. The cumulative effect of the escape processes resulting from the interaction of the solar wind with the Martian corona (including sputtering and ion escape) appears to be smaller by at least one order of magnitude than the contribution due to O_2^+ DR at the present epoch [e.g. *Leblanc and Johnson*, 2001; *Chaufray et al.*, 2007]. The excess energies and the measured branching ratios of *Kella et al.* [1997] are used to compute the main branches of the O_2^+ DR reaction. It is important to note that the O_2^+ DR reaction rate coefficient presently used by the thermosphere/ionosphere model (MTGCM) for O_2^+ loss and by the exosphere model (DSMC) for the hot O source are consistent [Valeille et al., 2009a, 2009b, 2009c, 2009d]. In this work, this common rate is taken from *Mehr and Biondi* [1969]:

$$\begin{cases} \alpha = 1.95 \times 10^{-7} (300/T_e)^{0.7} \text{ cm}^3 \text{ s}^{-1} & \text{for } T_e < 1200 \text{ K} \\ \alpha = 0.75 \times 10^{-7} (1200/T_e)^{0.56} \text{ cm}^3 \text{ s}^{-1} & \text{for } T_e > 1200 \text{ K} \end{cases}$$

The DSMC code uses an unstructured mesh of tetrahedral cells that allows a pertinent description of the domain around complex 3D bodies. It can be easily adapted to the physical features of the problem, and takes into account the variations of the outputs of interest. The three spatial dimensions of a typical cell of the mesh shall match the three local characteristic lengths of the 3D problem. The angular resolution matches that of the MTGCM model, being a 5° x 5° grid (*i.e.* about 300 km x 300 km at the equatorial surface) all across the simulation domain. However, to capture the critical variations in density with altitude satisfactorily, the radial resolution should be less than about one half to one third of the local temperature scale height in the transitional domain. The mesh provides uniformly spaced cells distributed radially from the inner boundary (at 135 km) to 200 km with a 4 km altitude resolution, followed by exponentially distributed cells beyond the 200 km altitude, as shown in Table 1. This allows for an approximately constant number of atmospheric particles per cell (mostly ~20-40 particles per cell). Each of those stretched hexagonal cells is then split into six tetrahedral cells.

The two main processes for the generation of the exospheric population, *i.e.* production (via O_2^+ DR) and collision (with O and CO₂ background species), are well simulated. The size of the simulation domain is limited to 3 Mars radii, the domain of interest of most studies, in order to limit the computational time and to keep the two-body approximation valid. A total of about 500 000 cells, or 30 million particles, is simulated.

MODEL RESULTS

SOLAR CYCLE VARIATIONS AT EQUINOX.

MTGCM. Thermosphere-ionosphere model results are presented first for Equinox (Ls = 180) conditions to illustrate the variations of the density, temperature and wind distributions due to solar activity.

Figure 2 illustrates exobase height temperature and super-imposed horizontal wind distributions for: (a) solar minimum (at 170 km) and (b) solar maximum (at 185 km) conditions. Note that sub-solar (noon, equatorial) temperatures vary from 170-180°K (solar minimum) to 280-290°K (solar maximum). Horizontal winds appear to diverge from mid-afternoon (near the equator) and converge on the nightside and at high dayside latitudes. Divergent (upwelling) winds are predicted to cool the dayside while convergent (subsiding) winds are estimated to warm the nightside and high latitudes [e.g. Bougher et al., 2006; 2009;