THE MARTIAN UPPER ATMOSPHERE

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Abstract:
The most relevant aspects of the Martian atmosphere are presented in this paper, focusing on the almost unexplored upper atmosphere. We summarize the most recent observations concerning this region, as well as the numerical models used to its study.

Special attention is devoted to the only ground-to-exosphere General Circulation Model existing today for Mars, the LMD-MGCM. The model and its extension to the thermosphere are described and the strategies used for its validation are shortly discussed. Finally, we briefly present some comparisons between the results of the model and the observations by different spacecrafts.

Keywords: Mars atmosphere – Thermosphere – General Circulation Models.

1 Introduction

1.1 Main features of the Martian atmosphere

Our knowledge of the Martian atmosphere has increased dramatically in the last 3-4 decades as a result of an international effort of exploration (more than 20 spacecrafts have been launched to Mars since the first secret attempts by the Soviet Union in 1960, although only about half of them have been successful) and of the increasing sophistication of the theoretical models devoted to its study. Nowadays we know that the Martian atmosphere, mostly composed of CO_2, is very thin (pressure surface of about 6 mb) when compared to the Earth (1 bar) and Venus (95 bar) [1] and has a surface temperature that oscillates between 140 and 300 K [2]. The inclination of its axis of rotation (similar to the terrestrial) and the high eccentricity of the Martian orbit induce a seasonal cycle more intense than the terrestrial one.

A typical thermal profile for the Martian atmosphere is shown in Figure 1. Due to the small amount of water in the Martian atmosphere, the decrease of temperature with altitude in the troposphere follows the dry adiabatic [3]. The Martian atmosphere does not have an stratosphere like the terrestrial one. The reason is that the amount of ozone in the Martian atmosphere is too small to produce a noticeable heating. However, when the dust load is high enough, the heating induced by the dust can produce thermal inversions similar to a stratosphere. The lower thermosphere is characterized by a strong increase of temperature with altitude, due to the absorption of UV solar radiation, while in the upper thermosphere the temperature tends to an asymptotic value due to the high efficiency of the thermal conduction, that suppresses temperature gradients.

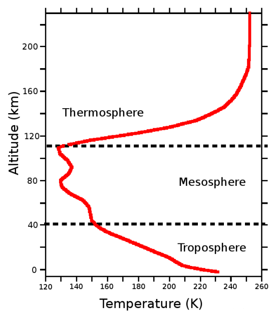

Figure 1: Typical temperature profile of the Martian atmosphere

There are two features of the Martian atmosphere that make it unique in the solar system: the CO_2 cycle and the dust storms.

The CO_2 cycle consists in the interchange of this constituent between the atmosphere and the polar reservoirs in response to the annual change in the insolation of the surface [4]. In winter, the atmospheric temperatures in the polar regions are so low that CO_2 condenses and is deposited on the surface, subliming in spring with the rising temperatures. This cycle affects an important fraction (about one third) of the atmospheric CO_2, producing remarkable seasonal variations in the surface pressure, that were already detected by the Viking landers [5].

The importance of the presence of dust in the Martian atmosphere was first unveiled by the soviet Mars 2 and Mars 3 spacecrafts, lost due to a dust storm [6]. Today we know that the amount of dust suspended in the atmosphere is higher during Southern hemisphere summer (corresponding to the perihelium of the Martian orbit), with an annual cycle approximately repetitive. However, important interannual variations can occur [7]. During perihelium local dust storms are formed, that can eventually join and produce a global, planet-encircling dust storm. The mechanisms to form these global storms are currently not well known. The dust absorbs the infrared radiation and can affect the thermal structure of the atmosphere [3].

1.2 The Martian upper atmosphere

On behalf of the intense international exploratory effort from the second half of the 20th century, it is only in the last years that the upper atmosphere has begun to be explored. In this work, we will refer as "upper atmosphere" to the region with altitudes between about 80 and 250 km, that is, referring to the Figure 1, the upper mesosphere and the thermosphere.

During the last decade there has been a growing interest in this region. The reasons are twofold. First, this region is the scenario of important physical, dynamical and chemical processes, as the absorption of ultraviolet (UV) radiation coming from the Sun, that is the primary heating source of the upper atmosphere [8], the photochemistry, that induces the photodissociation of molecules like CO_2 and O_2 into simpler molecules and/or atoms, and the escape, that is essential to understand the long-term evolution of the whole atmosphere. The region possesses a complex dynamics, with interactions between waves, both created in-situ and propagating from below, and the mean flow [9]. Second, it is in this particular altitude range where the spacecrafts perform their aerobraking maneuvers, using the friction with the atmosphere to decelerate the spacecraft up to the velocity appropriate for the insertion in the required orbit. A detailed knowledge of the density structure is necessary to minimize the risks of this maneuver. Given the scarcity of data, theoretical models, like General Circulation Models (GCMs) are essential for this task.

The latest observations have shown a strong coupling between the lower and the upper atmosphere [10]. During its aerobraking, MGS has observed a longitudinal variation of the density (at constant local time and altitude) mainly composed of wave numbers 2 and 3 [11]. It has been shown [12, 13] that the origin of this structure is the interaction of the solar illumination with the topography and the non-lineal interactions between waves created in-situ and propagating from below. Mars Odyssey has detected, during its aerobraking phase, an increase of temperature with latitude when moving towards the winter pole [14]. The origin of this thermospheric polar warming is a downwelling from the upper thermosphere due to an intense interhemispheric transport, that produces an adiabatic warming [10]. The intensity of this warming is modified by the dust amount in the lower atmosphere [15]. SPICAM on board Mars Express has detected for the first time in Mars the UV emissions of the NO molecule in the nightside [16]. The peak emission is located between 60 and 100 km, with no clear trend with the latitude, longitude, local time or solar activity. This nightglow is produced by the recombination of N and O atoms, that are transported to the nightside mesosphere from the dayside thermosphere, where they are produced by photodissociation of N_2, O_2 and CO_2.

All these processes show a strong coupling between different atmospheric layers and between different process. As we will see, GCMs naturally include these coupling, making them valuable tools to the study of the atmosphere as a global system.

1.3 General Circulation Models for Mars

General circulation models have their origin in the models for meteorological prediction. They simulate the atmosphere by a 3-D grid (longitude-latitude-altitude) in which they solve by numerical methods the governing equations. They can be schematically decomposed in a core that solves the equations of the dynamics and a set of physical processes in form of approximations or parameterizations, to avoid an excessive CPU time consumption. These models include in a natural way the couplings between layers and between physical processes.

However, although these GCMs are very powerful tools, they suffer from a series of limitations that need to be considered when analyzing their results. It is not the lesser the natural unpredictability of the atmosphere, given its chaotic and almost turbulent behavior due to the non-linear character of the equations of the atmospheric physic [17], that originates a day-to-day variability difficult to predict. In many cases, temporal averages are necessary to lessen this problem. Other problems that can be mentioned are the limitations to consider processes with a scale lower than the grid size, and the excessive CPU time consumption. And, in the particular case of the Martian upper atmosphere, the lack of data to contrast the predictions of the models imposes an additional difficulty.

Several GCMs for Mars have been developed since the pioneering work of Leovy and Mintz [18]. Most of them are devoted to the study of the lower atmosphere. For example, we can cite the NASA/AMES-MGCM, used to study the temperature profiles measured by MGS [19], the GFDL Mars-GCM, that has been employed to study the thermal tides [20], or that developed by a French and British consortium, the LMD/AOPP MGCM, used for example to study the polar warming in the lower atmosphere [21]. The only thermospheric GCM until recently, the Mars Thermospheric GCM, developed at NCAR and maintained by the University of Michigan, has been used in studies of comparative terrestrial planet thermospheres [22, 23]. This model has been recently coupled to the NASA/AMES MGCM, with key fields being passed upwards from the NASA/AMES MGCM to the MTGCM, but not the other way around.

2 The LMD-Mars General Circulation Model

The LMD-MGCM has its origin in the model for the study of the terrestrial climate developed at the Laboratoire de Météorologie Dynamique (Paris University). To adapt this model to Mars, a new radiative transfer code [24] and a CO_2 condensation/sublimation scheme [25] were developed. It includes the radiative effects of CO_2 and dust, a number of subgrid-scale processes, processes of interchange surface-atmosphere and the seasonal cycle of CO_2 and H_2O [21]. Originally, it extended from the surface up to about 80 km.

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In the frame of a joint project of the LMD, the University of Oxford and the Instituto de Astrofísica de Andalucía (IAA, CSIC, Spain) and sponsored by the ESA, the vertical range of the model has been extended up to the upper thermosphere, becoming in this way the first Martian GCM able to study in a self-consistent way the whole atmospheric range from the surface up to the upper thermosphere. This extension has been done in two steps. First, the model was extended up to about 120 km by including the Non-Local Thermodynamic Equilibrium (NLTE) correction to the CO_2 NIR solar heating rate and to the cooling due to 15μm emissions by CO_2 [12]. And in a second step, it was extended up to the thermosphere by adding parameterizations for the physical processes important at these altitudes: Molecular diffusion, thermal conduction [26], photochemistry of the C, H and O families and UV heating [27]. For both extensions, a 1-D model developed at the IAA has been used to implement detailed schemes and to develop and test parameterizations to be included in the GCM.

2.1 The Mars Climate Database

One of the most important applications of this model is the creation of the Mars Climate Database, a compilation of statistics of the results of the LMD-MGCM [28]. This database takes into account both the diurnal and the seasonal variations. Several "scenarios" (combination of different options for the dust load and for the UV solar activity) are included to bracket the very variable conditions of the Martian atmosphere. Statistical tools to estimate the day-to-day variability are also included.

This database is currently being used by most of the active groups in the study of the Martian atmosphere, both as a reference for scientific studies and as a tool in the engineering planning of future missions. It is freely available for the community in DVD format and a simplified version can be found on-line at www-mars.lmd.jussieu.fr

3 Results

3.1 Validation

After extending the LMD-MGCM up to the thermosphere, the first efforts were directed towards validating the model. Different strategies have been used before directly comparing with some of the scarce observational data.

First, a series of sensitivity tests were performed to check if the model reacted as physically expected to modifications in some input parameters or in the absence of some physical processes. These tests allow also for a deeper understanding of the atmosphere as an integrated system. For example, when not including the concentration changes produced by the photochemistry, an increase of temperature was found in the upper atmosphere [27]. The reason is that one of the most important effects of the thermospheric photochemistry is the photodissociation of CO_2 in CO and atomic oxygen. So, when no photochemistry is included, there is more CO_2 than in the "nominal" simulation. Given that CO_2 is more efficient than CO and O in absorbing UV radiation and heating the atmosphere, more CO_2 implies more heating and thus a higher temperature. Another example of these tests can be found in [26], where simulations with and without parameterized orographic gravity waves are presented, concluding that these waves can serve as a coupling mechanism between the lower and the upper atmosphere, modifying the zonal mean winds and interacting with the tides.

And second, a detailed intercomparison campaign with the reference GCM of the Martian thermosphere, the MTGCM, has been performed [29]. In this intercomparison, both models were run using similar forcings and the same input conditions. Three different "scenarios" or sets of input conditions were used, designed to study the atmospheric variability with seasons and with different dust loads. A good overall agreement is found, although some local/regional differences have been identified, expected when comparing models of such a complexity. The detailed results of this intercomparison campaign will be published elsewhere.

3.2 Thermal and wind structure of the Martian upper atmosphere

After these validation exercises, we have exercised the model to study the thermal and wind structure of the Martian upper atmosphere. The longitudinal and latitudinal variation of the temperatures and winds predicted by the model for perihelium conditions (Southern summer) is shown in figure 2. We can clearly appreciate the shape of the terminator (the day-night separation line) and how the summer polar region is constantly illuminated. Maximum temperatures of about 400 K are found in the Equator close to the evening terminator, while the minimum temperatures ($\approx$200 K) are found in the equatorial region close to midnight. The winds diverge from the summer night hemisphere and converge in the Equator before midnight. The energy transported by the winds modifies the distribution of temperatures that would be expected by radiative equilibrium, as described by [23]. A thermospheric polar warming is clearly visible during the night, as observed by Mars Odyssey [14].

The balance between the different heating/cooling terms predicted by the LMD-MGCM can be found in figure 3. The UV heating is the main heating source of the Martian upper atmosphere, and it is mainly compensated at the altitude of its peak by thermal conduction, although there is an important contribution by 15 μm cooling in lower layers, in good agreement with the predictions of the MTGCM [23].

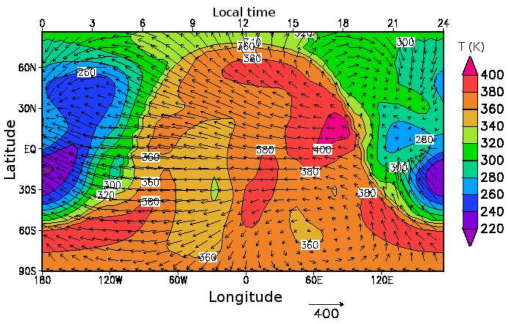

Figure 2: Temperatures (color contours) and winds (arrows) in a constant pressure layer in the upper thermosphere (P≈ 10^{-9} Pa) derived from the LMD-MGCM for perihelium conditions.

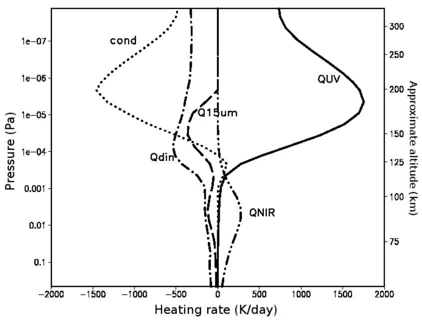

Figure 3: Balance between different heating/cooling terms for perihelium conditions.

3.3 Comparisons with data

In figure 4, we compare the variation of the upper thermospheric temperatures with seasons and with the solar cycle predicted by the LMD-MGCM (solid lines) with the few existing data (symbols) and with the results from the MTGCM (dashed lines), taken from [23]. Temperature is minimum for aphelium and maximum for the perihelium season, as expected. The LMD-MGCM predicts a more intense seasonal variability than the MTGCM, although it has to be taken into account that the results from the MTGCM are for a dust-free lower atmosphere. In spite of predicting reasonably well the temperatures for solar minimum conditions, the LMD-MGCM tends to overestimate the exospheric temperatures for solar medium and maximum conditions. This indicates an overestimation of the UV heating, an underestimation of the 15 μm cooling or the thermal conduction, or the lack of some process. However, given the scarcity of results used for this comparison and their variability, this result needs to be further confirmed, for example with comparisons with SPICAM temperature profiles, as discussed below.

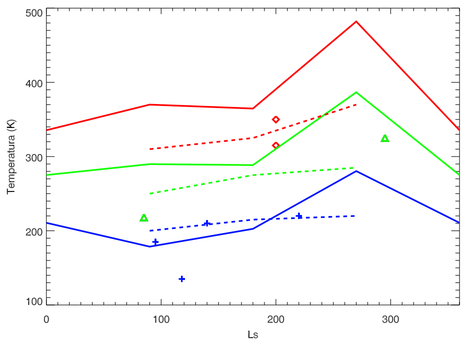

Figure 4: Variation of equatorial temperatures in the upper thermosphere at LT=15 given by the LMD-MGCM (solid lines) and by the MTGCM (dashed lines, taken from [23]) for solar minimum (blue), average (green) and maximum (red) conditions. The different symbols represent the observations: red squares for solar maximum conditions (Mariner 6 and 7), green triangles for solar average conditions (Mariner 9 and phase 2 of aerobraking of MGS) and blue crosses for solar minimum conditions (Viking Landers 1 and 2, Mariner 4 and phase 1 of aerobraking of MGS).

Maybe the most interesting application of these models is the comparison with data, that is doubly useful as a validation exercise for the model, revealing its weak points that need to be improved, and allowing a deeper understanding of the data.

A good example of this merging between data and models is the study with the LMD-MGCM of the density measured by MGS during its aerobraking. A good agreement between the data and the predictions from the model is found, although the density is underestimated by the model in the polar regions [12]. The wave structure obtained by MGS is nicely reproduced by the model, allowing to perform a Fourier decomposition of the results and confirming the importance of the non-migrating tidal components (that is, those components not directly excited by the Sun). The origin of these components is the interaction of the solar illumination with the topography and the wave-wave interactions, coupling the lower and the upper atmosphere [12].

We are currently using the model for the analysis of some other sets of data about the Martian upper atmosphere, that we briefly mention below:

SPICAM on board Mars Express has performed the first remote sensing observations of the upper Martian atmosphere, using the technique of stellar occultation [30].

About 600 profiles have been obtained during more than one Martian year, with a good latitudinal and longitudinal coverage. We are right now comparing the SPICAM profiles with results from the MCD, which will tell us for the first time the accuracy of the model at this altitude range, previously unexplored.

As mentioned above, SPICAM has also observed for the first time the NO nightglow in Mars [16]. In order to study this phenomenon with the LMD-MGCM we are currently working in the extension of the photochemical module to include the chemistry of the Nitrogen family. This will allow to simulate the production of N atoms in the dayside thermosphere and its recombination with O in the nightside mesosphere. By comparing this recombination rate with the one inferred from SPICAM NO nightglow observations, we will hopefully be able to constrain the dynamics, in particular the day-night transport.

In the future, we plan to use other recent observations to further validate our model. In particular, the emissions by CO_2 and O_2 measured by OMEGA on board Mars Express will be very valuable to constrain the concentrations predicted by the LMD-MGCM.

4 Summary and conclusions

General Circulation Models are very valuable tools for the study of planetary atmospheres. Given the strong coupling between the Martian lower and upper atmosphere, it is very important to study this complex system with a ground-to-exosphere model, able to study in a self-consistent way the coupling between atmospheric layers and between physical processes. With this in mind, the GCM developed at the LMD has been extended up to the thermosphere, in collaboration with the Instituto de Astrofísica de Andalucía, by adding the physical processes relevant for these altitudes.

This model has been (and is still being) carefully validated. First, a series of sensitivity tests has been performed to assess the behavior of the model when some input parameters are modified or in the absence of certain processes. Second, a detailed intercomparison with the reference GCM of the Martian thermosphere, the MTGCM, has shown a general agreement between the models. And third, we have compared the results from the model with the most recent observations of the Martian upper atmosphere.

The model reproduces the density measured during the aerobraking of MGS, although an underestimation is obtained in the polar regions. This has allowed us to confirm the importance of the non-migrating components to produce the observed wave structure. Comparisons with the exospheric temperatures measured by different spacecrafts and its variation with season and solar cycle shows that the model overestimates the exospheric temperature, at least for solar average and maximum conditions. This is a preliminary result that needs to be confirmed by comparing with the more complete data set of temperatures in the thermosphere, obtained by SPICAM.

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