Martian Upper Atmosphere CO2 Profiles as Measured by the MAVEN Spacecraft and Simulated by the MGITM

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1. Introduction

On November 28, 1964, the Mariner 4 spacecraft was launched from Earth and set on a path towards Mars. It was the first successful mission dedicated solely to the exploration of the planet's environment, and it was also the first spacecraft to take pictures of another planet and return them from deep space. Interest in our planetary neighbor has continued to increase as evidenced by approximately thirty successful spacecraft missions designed to explore the system since Mariner 4. From the surface, rovers and landers can analyze soil composition, topology, and low-altitude weather conditions. From the sky, spacecraft can analyze the atmosphere's chemical composition, study how the system interacts with the solar wind, and observe seasonal effects on global- and local-scale structures. Of the many reasons it is important this research be done, one is to learn about Mars' long-term history. We want to understand things like why it lost its atmosphere, how it came to have no global magnetic field, and whether or not life could have ever been supported there. Equipped with a better understanding of how this dusty, red planet has transformed over its lifetime, we may be able to address these questions, and perhaps in the future use such knowledge to visit it.

2. Background and Methods

2.1 Upper Martian Atmosphere and MAVEN

Mars has an atmosphere comprised of distinct regions, the separation of which is organized by altitude and distinguished by various physical processes and characteristics. Our work here focuses on understanding the chemical structures of two such regions - the thermosphere and the ionosphere - and how their constituents vary with altitude throughout both time and space. The thermosphere (~100-200 km from the surface) is coupled with the atmosphere below via phenomena such as gravity waves and dust storms, and from above it is greatly influenced by solar radiation and solar wind particles (Bougher, Cravens, et al, 2015). The ionosphere (~80-400 km) generally consists of weakly-ionized plasma affected most significantly by the chemistry and dynamics of the neutral atmosphere and ultimately by the Sun. Together, these regions comprise the upper atmosphere. To study it, we use data collected by instruments on board NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission spacecraft (Figure 1) which has been orbiting the planet since late 2014 and continues to this day.

MAVEN orbits Mars in a highly elliptical orbit designed specifically to meet the science requirements of the mission (Figure 2). When it is closest to the surface (periapsis), it is able to make in-situ measurements of the upper atmosphere. When it is farthest from the surface (apoapsis), it is able to make global-scale, remote measurements. During each orbit, the spacecraft travels latitudinally with only a slight variation in longitude during a single orbit. Over successive orbits, due to the rotation of the planet, this flight path observes a broad range of longitudes. Doing this allows MAVEN to analyze both transient and spatial environmental conditions, something unique to this mission. As of this writing, there have been nine *Deep Dip* campaigns where the spacecraft's flight path has been manipulated to reach lower-than-normal altitudes (e.g. ~120-135 km) at periapsis. This is imposed to make possible the measurement of different processes occurring lower in the Martian atmosphere, and it typically lasts no longer than five days (~20 orbits) before being returned to normal orbit.

2.2 EUVM and Solar Occultation

This summer, we have focused on data collected through novel, remote measurements made by MAVEN's Extreme Ultraviolet Monitor (EUVM) (Figure 3). The EUVM is made up of three photometers which measure incoming photons (light) from the Sun. Each is tuned to a specific extreme ultraviolet wavelength channel (0.1-7, 17-22, and 121.6 nm, respectively), and when used together, they are able to measure a broad range of incident solar flux. This allows one to investigate processes such as solar flux variability, molecular ionization and dissociation, along with processes heating the upper atmosphere.

The measurement technique employed by the EUVM to acquire these data is known as solar occultation (SO). This technique allows the instrument to make vertical profiles of atmospheric optical depth using the sun as a light source (Figure 4). The region where this technique is most effective for our research is along the terminators - the variable lines separating the day and night sides of the planet. As MAVEN crosses the dawn terminator (night to day) and the dusk terminator (day to night), it points the EUVM towards the sun, and measures which wavelengths of light are transmitted through the atmosphere. Doing this allows one to infer the composition of Mars' atmosphere.

It was recently shown that the EUVM 17-22 nm photometer can be used to accurately measure the density of carbon dioxide (CO2) at altitudes between 100 km and 200 km using the SO technique (Thiemann et al., 2018). Since these measurements are constrained to the terminator regions, the resultant data is useful in studying the effects of external forcings (e.g. solar EUV radiation) typically most evident in these regions. The datasets compiled through this technique contain (among other information) CO2 density as a function of altitude as well as MAVEN trajectory parameters - time, latitude, longitude, and altitude. With this information, one can construct profiles of CO_2 density as it varies with time and space (Figure 5), and this is useful in tasks such as comparing real-world (measured) data to climate model predictions.

2.3 Climate Modeling and MGITM

Climate models are virtual environments, designed to simulate the real world in order for scientists to project future climate scenarios. It is important to note, these are long-term simulations with scenarios occurring over months and years rather than hours and days - this is the key difference between climate and weather, respectively. The various parameters of these models (e.g. atmosphere, land surface, oceans) are based on known physical laws which are represented mathematically in the model and then solved by sophisticated computers (sometimes referred to as supercomputers). The virtual environment consists of an outward-propagating grid (or mesh) of bins surrounding the planet of interest (Figure 6). For each bin, the equations are solved using the given inputs defined by the user, and the results provide spatial and temporal information for the environment contained within that bin. When all of the bins are combined and resolved mathematically, the environment as a whole can then be virtually represented. In practice, this process is extraordinarily complex, but the fundamental process is as I've explained here.

One such climate model is called the Mars Global Ionosphere-Thermosphere Model (MGITM) (Bougher, Pawlowski, et al, 2015). Using the known physics of the Martian environment as inputs, this model works to simulate conditions in the Martian ionosphere and thermosphere using a bin resolution of 5-by-5 degrees (in latitude and longitude). In practice, the model is so complex that it takes several days to perform a single simulation, and the output data files are often very large. As such, we utilize the trajectory information from the EUVM datasets to virtually *fly through* the resulting simulated environment. This not only serves to simulate MAVEN's flight path for each orbit in the model's output, but it also greatly reduces the working data needed to compare the measured and simulated profiles. One of the model's outputs is CO_2 density as a function of altitude, and with this data we are able to develop profiles (Figure 7) much the same as the measured CO_2 values from the EUVM SO.

3. Data and Results

3.1 Comparing Measured and Simulated Data

The overarching goal for this work is to develop the means to accurately simulate (and predict) the average trends of Mars' CO_2 density as a function of altitude. In order to do so, we need to compare what has been measured to what has been simulated. Doing so allows us to understand the level of reliability in using the MGITM to simulate real-world conditions. In the cases where it does not do well, we adjust the model inputs in an effort to improve its predictions.

This translates to an effort to better understand the physics underlying this model as well as the real Martian environment, and ideally, this work will lead to accurate predictive abilities for CO_2 density in the upper atmosphere via the utilization of MGITM.

The first step of the data handling process is to create an ideal altitude framework (IAF) to which we can interpolate both the measured and simulated CO_2 densities along with the associated MAVEN flight trajectory data described in section 2. To do this, we have developed custom (preliminary) source code using the Matlab development environment. Once the IAF generation and data interpolation is complete, the code then parses the data and calls for the measured and simulated values of CO_2 density at the same location with respect to latitude, longitude, and altitude over a user-defined set of successive orbits. Once these values are captured, we can generate profiles of the measured data versus the simulated data (Figure 8), and we do this for every orbit we want to compare. It should be noted, the model's output values account for all positions at a given time in the simulated environment, not just the position in the virtual flight path of MAVEN. In order to generate a comparable profile to that produced with the EUVM dataset, we must average the model's output for all longitudes at each latitude in the simulated flight path. This results in a single data point for each position in the virtual flight path of a given orbit. The measured-simulated comparison process is limited by the amount of data available from both sources, and since the MGITM simulations can be processed for any amount of time, the real limitation resides in the data available from the MAVEN EUVM SO measurements.

For this work, we have chosen to focus on four orbit intervals (Table 1 and Figure 9), each of which represent a different Mars season and position relative to the Sun (Thiemann et al, 2018). To further constrain our dataset, we only analyze altitudes of 130, 150, 170, and 200 km. These are altitudes where several important physical processes, such as those distinguishing regions of the atmosphere, are typically found. Setting these criteria allow us to test our comparison method in a variety of atmospheric conditions without the need to exhaust the entirety of the EUVM SO measurement data.

In order to determine the best approach for reaching the most accurate results, we have varied the length of time represented in the model output data (that used for comparison to the measured data) over many iterations of the comparison process. Spanning the full range of a single orbit interval (Perihelion #1), we have applied output data in five-day subintervals, single-day subintervals each at the beginning, center, and end (front-, center-, and back-loaded, respectively), and single-day subintervals at the middle of each month of the orbit interval before being combined to present a unified view of the simulated data across the whole of the orbit interval.

3.2 Results and Discussion

Overall, an emerging commonality across the orbit intervals tested so far (Aphelion #2, Perihelion #1, and Perihelion #2) is the success of the MGITM to capture overall trends of the measured CO_2 density data at low latitudes (50S-50N, degrees) and low altitudes (130 km and

150 km) while failing to capture trends at high latitudes (<50S and >50N, degrees) and high altitudes (170 km and 200 km). This considered, individual orbit intervals do showcase significant nuances.

For example, so far the MGITM has been most successful with comparisons made using measurement data for the Aphelion #2 interval. This is a time when Mars is furthest from the Sun meaning it is colder at this time than it is throughout the rest of its orbit. It is also the season when the Mars atmospheric dust load is minimal (and repeatable from year-to-year). During this sampling period (summer season in the Northern hemisphere), temperatures are expected to be warmer that those at equatorial and Southern hemisphere latitudes. Accordingly, we expect to see CO_2 density increase at progressively higher Northern latitudes (because it is warmer), and this effect is detectable in the data from the EUVM SO measurements. When we use the front- or back-loaded simulation data, the model most accurately simulates the measured data (both versions are comparable to one another).

In the other intervals tested so far, the MGITM has not been able to predict the CO_2 densities as well as it has in the Aphelion #2 interval. One hypothesis is that our model may be lacking the necessary input parameters regarding gravity wave propagation throughout the upper atmosphere. These waves can result from winds at various altitudes, and they can go on to interact with the heating and cooling cycles on the local and global scales (Medvedev et al, 2011, 2012, 2015). It seems to indicate we are missing one or more key processes regarding the cooling of the upper atmosphere in our model simulations.

4. Future Work

As of this writing, MAVEN is set to continue taking EUVM SO measurements, and the results of the measured and simulated data comparisons outlined in this paper serve to motivate the continuation of making them. As we continue to garner data spanning increasingly variable seasons and space weather anomalies, we are presented with the opportunity to fine-tune the predictive abilities of the MGITM.

The success of this work not only enables us to look back in time and address questions about the history of the Martian environment, it also becomes an increasingly valuable tool in the planning of future spacecraft, robotic, and human missions to its atmosphere and surface. In the future, MAVEN's high-gain antenna will allow it to serve as a valuable relay for surface missions. At that time, it will be shifted from the highly-elliptical orbit necessary to perform its current science activities to a more circular orbit appropriate for communication relay objectives. Although this mission will undergo a significant mission-objective shift, it will continue to serve as an invaluable tool for humankind's exploration of Mars.

5. Figures and Tables

Figure 1. Inside the Payload Hazardous Servicing Facility at NASA's Kennedy Space Center in Florida, engineers and technicians test deploy the twin solar arrays on the MAVEN spacecraft. Credit: NASA/Kim Shiflett.

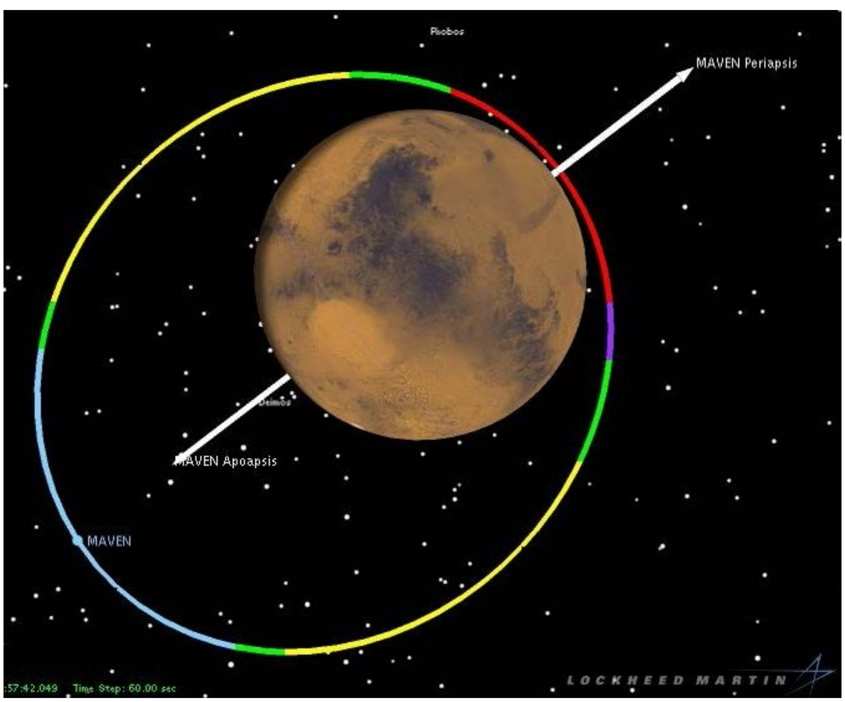

Figure 2. Demonstration of the MAVEN highly-elliptical, science orbit. Credit: NASA/LASP/Lockheed Martin.

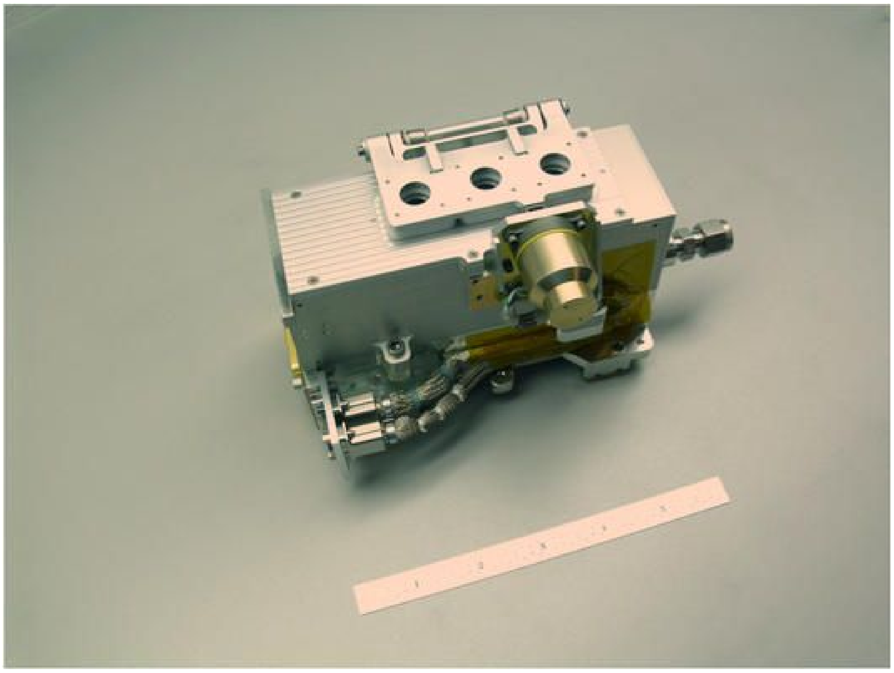

Figure 3. The engineering model of the Extreme Ultraviolet (EUV) sensor that is part of the Langmuir Probe and Waves (LPW)/EUV experiment on MAVEN. Credit: LASP.

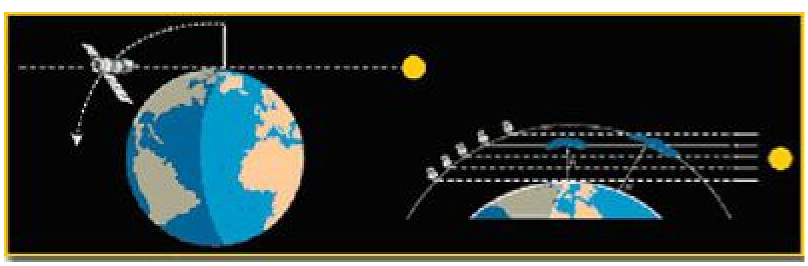

Figure 4. Terrestrial representation of a satellite performing solar occultation measurements allowing for the development of vertical profiles of atmospheric constituents.
Credit: MyNASAData.larc.nasa.gov

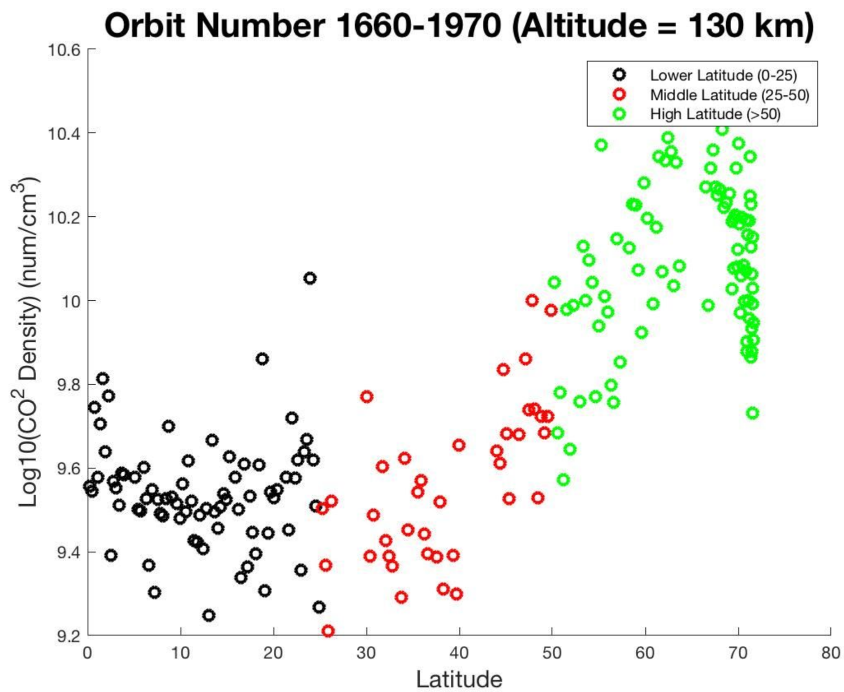

Figure 5. Plot of measured CO2 density (log10 num/cm^3) versus Latitude (degrees) developed by use of the EUVM solar occultation measurement method.

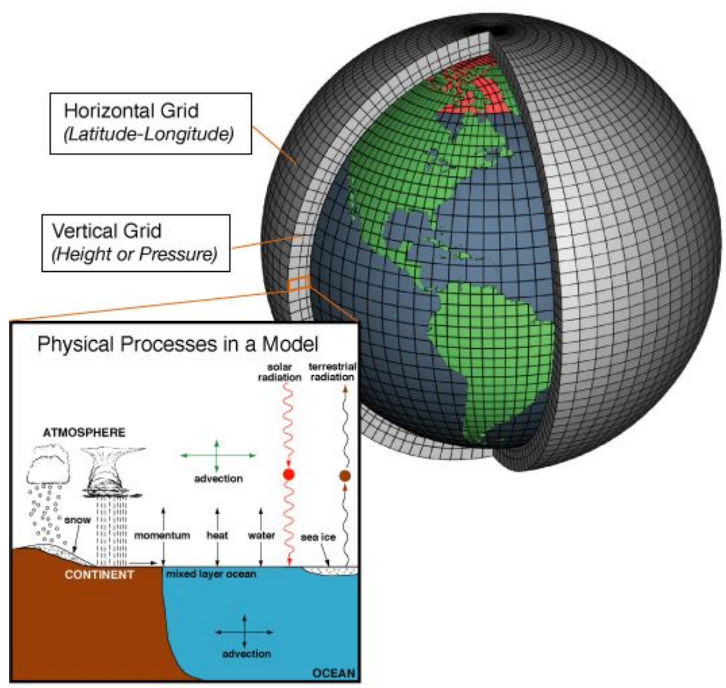

Figure 6: Example of terrestrial 3D outward grid (or mesh) system used in climate modeling software. Source: NOAA.

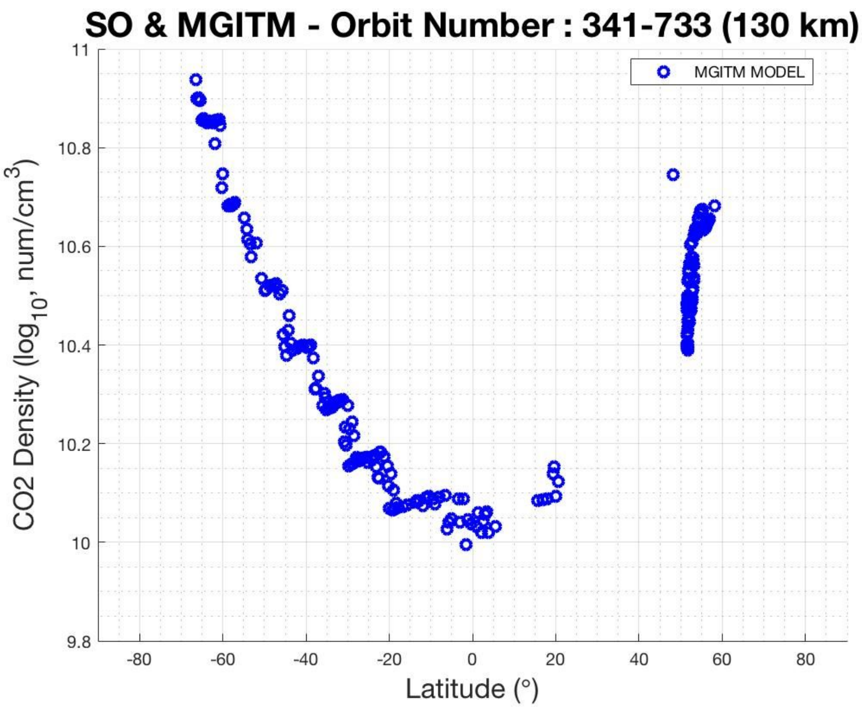

Figure 7. Plot of simulated CO2 density (log10 num/cm^3) versus Latitude (degrees) developed by use of the MAVEN trajectory information and the MGTIM.

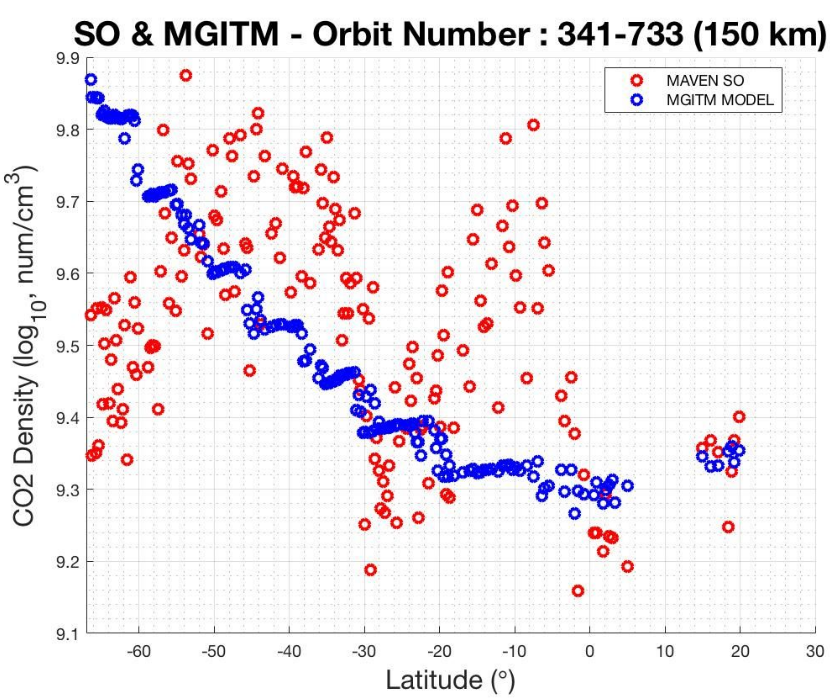

Figure 8. Plot of measured and simulated CO2 density (log10 num/cm^3) versus Latitude (degrees) developed by use of the EUVM solar occultation measurement method and the MGTIM virtual fly through using MAVEN trajectory information.

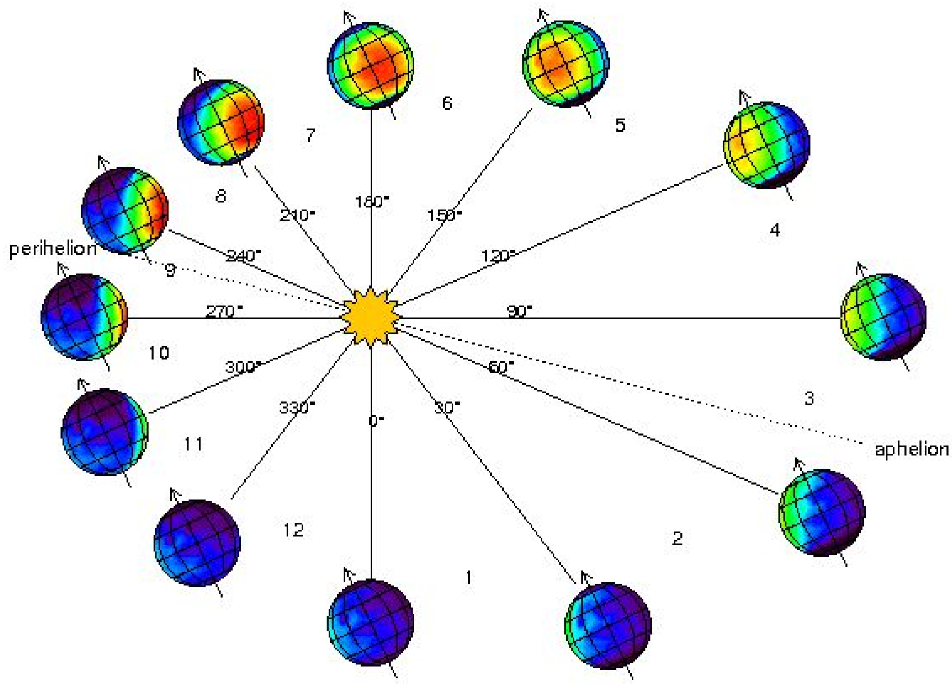

Figure 9. Graphic description of the meaning of aphelion and perihelion as it frames the relative positions of Mars and the Sun. Credit: http://www-mars.lmd.jussieu.fr

Interval	Dates	Orbits	Latitudes (degrees)
Aphelion #1 (Dawn)	08/06/2015 - 10/04/2015	1660-1970	11N to 72N
Aphelion #2 (Dusk)	10/04/2015 - 11/06/2015	1970-2149	72N to 11N
Perihelion #1 (Dusk)	12/02/2014 - 02/14/2015	341-733	67S to 30N
Perihelion #2 (Dusk)	09/15/2016 - 01/15/2017	3827-4461	70N to 30N

Table 1. Table with defining parameters (dates, orbits, latitudes in degrees) for each of four orbit intervals (Aphelion #1, Aphelion #2, Perihelion #1, and Perihelion #2) used in our data comparison of measured and simulated CO2 densities as a function of altitude.

6. References

Bougher, S.W., Cravens, T.E., Grebowsky, J. et al. (2015), The Aeronomy of Mars: Characterization by MAVEN of the Upper Atmosphere Reservoir That Regulates Volatile Escape, *Space Sci Rev*, 195: 423. doi: 10.1007/s11214-014-0053-7

Bougher, S. W., D. Pawlowski, J. M. Bell, S. Nelli, T. McDunn, J. R. Murphy, M. Chizek, and A. Ridley (2015), Mars Global Ionosphere-Thermosphere Model: Solar cycle, seasonal, and diurnal variations of the Mars upper atmosphere. *J. Geophys. Res. Planets*, 120, 311–342. doi: 10.1002/2014JE004715.

Medvedev, A. S., and E. Yiğit (2012), Thermal effects of internal gravity waves in the Martian upper atmosphere, Geophys. Res. Lett., 39, L05201, doi:10.1029/2012GL050852.

Medvedev, A. S., E. Yiğit, P. Hartogh, and E. Becker (2011), Influence of gravity waves on the Martian atmosphere: General circulation modeling, J. Geophys. Res., 116, E10004, doi:10.1029/2011JE003848.

Medvedev, A. S., F. González-Galindo, E. Yiğit, A. G. Feofilov, F. Forget, and P. Hartogh (2015), Cooling of the Martian thermosphere by CO2 radiation and gravity waves: An intercomparison study with two general circulation models, J. Geophys. Res. Planets, 120, 913–927, doi:10.1002/2015JE004802.

Thiemann, E. M. B, F. G. Eparvier, S. W. Bougher, M. Dominique, L. Andersson, Z. Girazian, M. D. Pilinski, B. Templeman, and B. M. Jakosky. Mars thermospheric variability revealed by MAVEN/EUV Solar Occultations: Structure at aphelion and perihelion, and responses to EUV forcing, Journal. Geophys. Res., in press, doi:10.1029/2018JE005550, (2018).