SOLAR INFLUENCES ON THE STRUCTURE AND DYNAMICS OF THE VENUS, EARTH, AND MARS UPPER ATMOSPHERES: IMPLICATIONS FOR NEUTRAL ATMOSPHERIC LOSS PROCESSES. 
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Introduction: The thermosphere-ionosphere regions of the Venus, Earth, and Mars upper atmospheres can change dramatically over time, since they are controlled by highly variable components of the Sun’s energy output composed of both solar radiation (~0.1-200 nm) and solar wind particles and fields [1]. In this presentation, available Earth (as statistically represented in MSISE-90) plus Venus and Mars upper atmosphere datasets (e.g. Pioneer Venus, Mars Global Surveyor, Mars Odyssey, MRO, Venus and Mars Express) and modern 3-D thermosphere-ionosphere models are being combined to address the variable solar radiation influences upon these upper atmospheres. The underlying chemistry, energetics, and dynamics giving rise to these observed variabilities are being addressed for each planet. Detailed Venus, Earth and Mars comparisons are valuable for investigating how common “terrestrial-like” upper atmosphere processes are manifested differently in these unique planetary environments [2].

Processes: Several processes are currently estimated to regulate the thermospheric temperatures of Venus and Mars and their distinct climatological variabilities [2, 3, 4, 5]. These processes include (a) solar EUV-UV fluxes producing heating, and its changes with solar cycle, solar rotation, heliocentric distance, and season (solar declination), (2) molecular thermal conduction, (3) CO2 15-µm cooling, (4) hydrodynamic advection, and (5) adiabatic heating and cooling associated with global dynamics. Episodic heating also likely occurs at these planets from particle precipitation associated with CMEs, SEP events, and solar flares.

Recent studies [2, 5] suggest that the primary dayside temperature balance in the Martian upper thermosphere occurs between EUV heating and molecular thermal conduction, with CO2 cooling becoming important just below the peak of EUV heating. In addition, adiabatic cooling due to rising motions on the dayside from the global thermospheric circulation, is expected to play a progressively more important role as solar fluxes increase (e.g. with the advance of the solar cycle). Both non-linearly temperature dependent CO2 cooling and global dynamics serve as “thermostats” to regulate the variation of dayside temperatures (e.g. over the solar cycle, throughout Mars seasons). Since Mars has a highly eccentric orbit, for which the heliocentric distance varies significantly over the course of Martian year, seasonal variations must be accommodated when addressing climatological variations of dayside temperatures. Also, lower atmospheric dynamical forcing, especially during dust storm events, may impact the upper atmosphere temperatures (see Figure 1).

Venus is closer to the sun than Mars, giving rise to enhanced CO2 photolysis and Venusian atomic O abundances, ~10-times larger at the dayside ionospheric peak than Mars [3]. This has important implications for enhanced CO2 cooling, which serves to largely balance EUV heating in the Venus upper atmosphere [3, 6]. The role of molecular thermal conduction, and the global thermospheric circulation, is estimated to be minor in the control of dayside temperatures. However, nightside temperatures are entirely regulated by the strength of the subsolar-to-antisolar circulation and the corresponding downwelling winds near the anti-solar point [6, 7, 8].

Conversely, terrestrial EUV heating efficiencies are calculated to be much larger for Earth than either Venus or Mars [9, 10]. In addition, CO2 15 µm cooling is estimated to be important below 130 km, well removed from the peak EUV heating at higher altitudes [3, 9]. Thus, molecular thermal conduction is thought to generally control cooling above ~150-180 km. This conduction serves as a “weak thermostat”, yielding a large exospheric temperature variation over the solar cycle (i.e. much larger than that for Venus and Mars). The contribution of CO2 cooling below 130 km implies that the Earth lower thermosphere does not require significant eddy diffusion or heat conduction. NO (5.3 µm) cooling also becomes important during auroral heating events. Furthermore, CO2 15 µm cooling is estimated to be relatively weak in regulating Earth upper thermosphere temperatures throughout the solar cycle [3, 9]. Finally, the advance of the solar cycle brings larger thermospheric pressure gradients for Earth that are offset by enhanced ion-drag, owing in part to elevated electron densities. Thus, Earth thermospheric winds at low to mid-latitudes do not change greatly with the solar cycle, and are therefore not important as a thermostat in regulating temperatures.

Model Results: NCAR Thermosphere General Circulation Model (TGCM) simulations have been conducted for the Venus, Earth, and Mars upper atmospheres over the solar cycle, and throughout the seasons (for Earth and Mars). Recent simulations from...
these three TGCMs are able to reproduce the climatological exospheric temperature variations observed at these planets. Mars Thermospheric General Circulation Model (MTGCM) simulations, combining CO$_2$ cooling and dynamical thermostats, provide variations of dayside exospheric temperatures ranging from ~185-300ºK (Equinox) to ~170-315ºK (Solstices), a ~115-145ºK variation over the solar cycle [11]. These temperatures are consistent with limited measurements at Mars over the solar cycle [5, 12, 13, 14, 15]. By contrast, the Venus Thermospheric General Circulation Model (VTGCM) captures very strong CO$_2$:15-micron cooling that largely balances EUV heating, providing an efficient radiative thermostat that regulates thermospheric temperature variations (~240-310ºK). The ~70ºK variation over the solar cycle matches Pioneer Venus measurements [3, 6, 16], and is about half that simulated for Mars. Finally, for quiet auroral conditions, when solar radiation influences are dominant, the simulated Earth solar cycle exospheric temperature variation on the daysides ranges from ~800-900 to ~1500ºK (about ~600-700ºK), the largest of the three terrestrial planets [3, 4].

**Implications for Neutral Atmospheric Loss:**

Losses of neutral species from the upper atmospheres of Venus and Mars are estimated to result from both thermal and non-thermal escape processes [17]. For instance, dissociative recombination (DR) of O$_3$ ions creates energetic (hot) O atoms at Mars available for populating the hot O corona and providing a significant escaping component [11]. Present day ion escape rates are much smaller. The same DR process at Venus populates a hot O corona only, with little hot O escape. Instead, present day ion escape rates are dominant. Jeans escape is sufficient to provide most of the hot H corona and its escape at Mars. However, non-thermal processes are required at Venus to create the bound hot H corona and escaping hot H atoms. Each of these mechanisms is regulated to some extent by the changing solar EUV fluxes and the variable thermosphere-ionosphere structure that is changing with the solar cycle and seasons (Mars).

Selected 3-D MTGCM and Direct Simulation Monte Carlo (DSMC) simulations are presented that illustrate the Mars coupled thermosphere-ionosphere-exosphere system leading to predictions of the oxygen corona and hot O escape, and its variations over the solar cycle and Martian seasons [11]. Calculations are performed for three characteristic seasons (aphelion, equinox, perihelion), while solar activity is either fixed at low or high conditions. Atmospheric loss of hot O is found to vary by a factor of about three between solar minimum and maximum equinox cases, while “extreme” aphelion/solar minimum and perihelion/solar maximum cases reveal a factor of about six variation in hot O escape rates. These “extreme” variations provide clues as to the evolution of hot O escape rates over the history of Mars.

Future applications of the VTGCM and DSMC models to Venus are planned to address escape processes.

![Figure 1. Atmospheric regions for Mars.](image)

**Figure 1.** Atmospheric regions for Mars. The upper atmosphere is impacted by solar forcing (above) and dynamical forcing (below).

**References:**