ESLAB-52
14-May-2018

Thermospheres of Terrestrial Planets
Including
Coupling with the Lower Atmosphere

S. W. Bougher
(University of Michigan)
Outline of Talk

- Basic Thermospheric Features and P. Parameters

- Three Common Features and Processes to Contrast
  - Venus and Mars NO nightglow distributions as a tracer of UATM winds (proxy view of global circulation patterns).
  - Wind induced diffusion and Helium distributions
  - Day thermal budgets and relative roles of CO$_2$ 15-µm cooling, molecular thermal conduction and global winds

- Lower to Upper Atmosphere Coupling
  - Migrating and non-migrating tides of Mars vs Earth (densities, nightglow)
  - Homopause altitudes and eddy diffusion $K_{zz}$ for Mars vs Earth
  - Dust storms on Mars (regional storm impacts)
  - In-situ Mars thermospheric wind measurements (non-solar forcing)
  - Gravity waves at Venus (see talk by A. Brecht)
Basics Thermospheric Features and Planetary Parameters
**Fundamental Planetary Parameters: Some Implications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity (cm²/sec): H(km)</td>
<td>888 [4-12]</td>
<td>982 [10-50]</td>
<td>373 [8-22]</td>
</tr>
<tr>
<td>Heliocentric distance (AU)</td>
<td>0.72</td>
<td>1.0</td>
<td>1.38-1-67</td>
</tr>
<tr>
<td>Radius (km)</td>
<td>6050</td>
<td>6371</td>
<td>3390</td>
</tr>
<tr>
<td>Omega (rad/sec): Coriolis</td>
<td>3.0(-7) [no]</td>
<td>7.3(-5) [yes]</td>
<td>7.1(-5) [yes]</td>
</tr>
<tr>
<td>B-dipole moment (wrt Earth): Auroral/Joule heat</td>
<td>≤4.0(-5) [no]</td>
<td>1.0 [yes]</td>
<td>≤2.5(-5) [no]</td>
</tr>
<tr>
<td>EUV-UV (eff.)</td>
<td>~20%</td>
<td>30-60%</td>
<td>~20%</td>
</tr>
</tbody>
</table>

6-Jun-18
Mars (and Venus) Upper Atmospheric Regions and Processes (Bougher et al., 2015)
Solar Spectral Irradiance Variations over the Solar Cycle (~0.1-190.0 nm)
Composition Differences:
Venus Upper Atmosphere

Venus

PVO/ONMS
Kasprzak et al (1997)
Venus II book

6-Jun-18
Composition Differences: Mars Upper Atmosphere

Mars

MAVEN/NGIMS
P1064, Ls ~ 256,
LT ~ 12PM, LAT = 4.5S
(Mahaffy et al. 2015. GRL Special Issue)
Thermospheric Temperature Profiles (1): Venus (Pioneer Venus and Magellan)

Why nightside so cold?

Why dayside so cold?

Bougher et al. (2002)
Thermospheric Temperature Profiles (2): Earth

Adapted from Roble (1986)
Thermospheric Temperature Profiles (3): Mars (MAVEN/NGIMS Deep Dips# 1-8)

<table>
<thead>
<tr>
<th>DD</th>
<th>Ls</th>
<th>LT</th>
<th>LAT</th>
<th>SZA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>291</td>
<td>18.3</td>
<td>40-45N</td>
<td>108</td>
</tr>
<tr>
<td>2</td>
<td>328</td>
<td>11.9</td>
<td>2-6S</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>3.4</td>
<td>61-64S</td>
<td>111</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>16.0</td>
<td>62-66S</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>166</td>
<td>5.3</td>
<td>32-36N</td>
<td>96</td>
</tr>
<tr>
<td>6</td>
<td>194</td>
<td>0.6</td>
<td>1-5S</td>
<td>167</td>
</tr>
<tr>
<td>7</td>
<td>49</td>
<td>20-21</td>
<td>62-67N</td>
<td>?</td>
</tr>
<tr>
<td>8</td>
<td>76</td>
<td>13.5</td>
<td>5S-20N</td>
<td>30</td>
</tr>
</tbody>
</table>
Three Common Features and Processes to Contrast
Statistical Maps of VEx O$_2$ and NO Nightglow Distributions: ~100 km & 115 km layers
Soret et al., (2012); Stiepen et al. (2013); Gerard et al. (2018)

LT ~ 0 AM

LT ~ 2 to 4 AM
Venus Helium Bulge at 160 km: Pioneer Venus/ONMS (Mengel et al. 1989)
Venus Thermospheric Circulation Paradigm: Schubert et al. (2007)
VTGCM NO Nightglow VER Map (VEx/SMIN): Bougher et al. (2013); Gerard et al. (2018)

Volume Emission Rate: $\log_{10} \text{(photons/cm}^3\text{s)}$
Seasonal distribution shows brightening at winter poles with strong solstice asymmetries. Data cover full MY, with gaps.
Mars Helium Bulge: MAVEN/NGIMS
Elrod et al. (2017)

![Graphs showing altitude (km) vs. local solar time for different latitude and solar longitude ranges.]

- **All latitudes; all Ls**
- **Northern lat > 45° N; Ls 216-290 & 88-105**
- **Southern Lat < 45° S; Ls 339 - 50**
- **Mid-latitudes 45° N - 45° S; Ls 289-339, 50-88 & 150-189**
M-GITM $T+(U,V)$ and Helium density at $\sim 200$ km: DD2 Conditions ($Ls \sim 328$; SMED)

- Low SZA temperatures peak ($T_{exo} \sim 260-270$ K) along with CO$_2$ densities.
- High SZA (winter polar night) temperatures are a minimum along with CO$_2$ densities.
- Divergence (upwelling, day) and convergence (downwelling, night) of the circulation
- Winter polar night ($LT \sim 2-5$) peak in He densities seen, corresponding to wind transport (horizontal & vertical). He shows opposite behavior of [CO$_2$] distribution.
LMD-MGCM VER Map of NO Nightglow (Gonzalez-Galindo, 2018). In preparation

$\text{Ls} \sim 0-30; \text{LT} = 4$ (Equinox)

$\text{Ls} = 270-300; \text{LT} = 4$ (Perihelion)

Units: $\log_{10} \text{(photons/cm}^3\text{/s)}$

6-Jun-18
# Diagnostic Thermal Balances using GCMs: VTGCM, TIE-GCM, and M-GITM

<table>
<thead>
<tr>
<th></th>
<th>VTGCM</th>
<th>TIE-GCM</th>
<th>M-GITM*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude Range</td>
<td>~70-250 km</td>
<td>~95-800 km</td>
<td>~0-250 km</td>
</tr>
<tr>
<td>Vert. Resolution (pressure coor.)</td>
<td>H/2 or H/4</td>
<td>H/2 or H/4</td>
<td>H/4 typical</td>
</tr>
<tr>
<td>Horz. Resolution</td>
<td>5x5 or 2.5x2.5°</td>
<td>5x5 or 2.5x2.5°</td>
<td>5.0 x 5.0° thusfar</td>
</tr>
<tr>
<td>Major Ions</td>
<td>O₂⁺, CO₂⁺, O⁺, N₂⁺, NO⁺</td>
<td>O₂⁺,N₂⁺,O⁺, NO⁺, N⁺</td>
<td>O₂⁺, CO₂⁺, O⁺, N₂⁺, NO⁺</td>
</tr>
<tr>
<td>Minor Neutrals</td>
<td>N(4S), N(2D), NO, Ar, O₂</td>
<td>N(4S), N(2D), NO</td>
<td>N(4S), Ar, He, O₂</td>
</tr>
<tr>
<td>Rad. Cooling</td>
<td>CO₂ (15-µm)</td>
<td>CO₂ (15-µm)</td>
<td>CO₂ 15-µm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NO (5.3-µm)</td>
<td>O (63-µm)</td>
</tr>
</tbody>
</table>

6-Jun-18

\[ \Delta T \sim 70-80 \text{ K} \]
(at Venus)

Nearly Constant
VTGCM T-Profiles: Dayside and Nightside for SMIN and SMAX Conditions

ΔT ~ 80 K
VTGCM Thermal Balances at SZA = 0: (SMIN/VEX and SMAX/PVO Conditions)

MGS Precise Orbit Determination (POD) data used to extract $T_{\text{exo}}$ over solar cycle and all Mars seasons (Forbes et al. 2008)

$T_{\text{min}} \sim 165K; \ T_{\text{max}} \sim 315K; \ T_{\text{avg}} \sim 240K$
Temperatures (scale heights) are highly correlated with incoming solar EUV
Scale heights are also highly correlated with Sun-Mars distance
DD2 versus DD8 Averaged Dayside T- Profiles: NGIMS-MGITM Comparisons + Thermal Balances

Texo ~ 270 K (MGITM) and ~265 K (Stone et al. 2018): DD2
Texo ~ 190-200 K (MGITM) and ~190-200 K (Stone et al. 2018): DD8
ΔTexo ~ 65-70 K (DD2: SMED/EQU to DD8: SMIN/APH)
Lower to Upper Atmosphere Coupling with Examples from Mars Spacecraft Observations
Summary of Primary Tidal Forcings for Earth and Mars (Siskind & Bougher, 2016)

<table>
<thead>
<tr>
<th>Tidal Component</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Migrating diurnal</td>
<td>NIR abs. of H₂O</td>
<td>VIS and IR abs of CO₂</td>
</tr>
<tr>
<td>Migrating semi-diurnal</td>
<td>Ozone heating</td>
<td>Dust heating</td>
</tr>
<tr>
<td>Non-migrating</td>
<td>Latent heat release from tropical convection</td>
<td>Topographical and pl. wave modulation of near surface heating</td>
</tr>
</tbody>
</table>

- Similar rotation rates of Earth and Mars imply that the mathematical characteristics of the tidal modes for Earth and Mars are similar.
- In general, due to large topographic variations, the manifestation of these tides in the Martian upper atmosphere is greater on Mars than Earth.
- Overall: Local time sorting is needed to go beyond harmonic analysis to address identification of specific tides.
Harmonic fits to LON variations in CO$_2$ densities as observed by IUVS at 130 km. Wave-2 has largest amplitude (~20-30%) and near constant phase at low LAT.
Harmonic analysis reveals wave-2 is dominant at all LATs and ALTs.
Fixed local time observations.
IUVS NO Nightglow Periapse Data & Disk Images Show Wave-3 Equatorial Structure during Southern Winter (Royer et al. (2017))

Periapse data: 80 < Ls < 120

Disk images: 130 < Ls < 170

~1 Martian Year apart
Same equatorial latitude range

We observe:
- Changes in the longitudes of the peaks,
- Changes in the space between each peak,
- Changes in the ratio between enhanced regions
Homopause varies significantly and does not track a fixed density level.

Lowest homopause altitudes occur between 4 – 6 AM and the highest values near noon when $L_s > 270^\circ$ (near perihelion). Implies $K_{zz} \sim 10$ to 10,000 m$^2$/s.
Dust Storm Impacts on Mars Thermosphere: Regional Storms

MY23 Noachis Storm (Ls ~ 224): Mass Density at 130 km (Bougher et al., 1999)

MY27 Storm (Ls ~ 130): Ion Peak Height (Withers & Pratt, 2013)

**NGIMS sampling during regional storms (Jan-Apr 2017) and impacts over 170-220 km (Liu et al., 2018). ~50-200% density enhancements.**
• Winds were derived below ~200 km using technique of “yawing” NGIMS left/right; monthly 2-day (10-orbit) campaigns since September 2016
• Large, unexpected orbit-to-orbit measured wind variability, as large as ± 100 m/s
• Comparisons with M-GITM model predictions show good agreement much of the time. However, significant differences suggest the importance of processes such as vertically propagating gravity waves and tides. Cite examples above.
Major Take Aways

- **Planetary fundamental parameters** indeed play a significant role in determining UATM structure and dynamics on these terrestrial planets. Exoplanet (HZ) simulations possible using these planets as prototypes.

- **Solar cycle variation of dayside Texo** smallest (~70-80K) for Venus, owing to thermostatic control by CO$_2$ cooling. Mars day Texo are instead regulated by large scale dynamics, CO$_2$ cooling and thermal conduction, yielding larger variations (~70-140K) over the solar cycle.

- **Coupling of 3-terrestrial planet thermospheres** (from below) is very important for determining structure and dynamics (e.g. tides & dust).

- **NO nightglow** is being used effectively at Venus and Mars to serve as a tracer of UATM circulation and a monitor of short term variability. NGIMS wind measurements suggest coupling from below is likely.

- **Mars homopause altitudes** show large variations with season, latitude and local time. Consistent with large K$_{zz}$ (up to $10^8$ cm$^2$/s). 100x Earth.