Comparative Aspects of ITM Physics of Terrestrial Planets: Including Coupling Above and Below

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Who am I? What do I do?

- ❑ AOSS Collegiate Research Professor (2002-present)
- ❑ NCAR Affiliate Scientist (2003-present)
- ❑ Space Research Focus Areas
  - *Upper atmosphere physics (energetics, chemistry, dynamics). Above ~70 km on Venus, Earth, Mars.*
  - *Mesophere, thermosphere, ionosphere physics*
  - *Comparative planetary upper atmospheres*
- ❑ Recent/Current spacecraft mission participation
  - *Mars Reconnaissance Orbiter (2002-2010): Co-I and Aerobraking team member (Accelerometer Team)*
  - *Venus Express (2006-present): SPICAV Data Analysis*
  - *MAVEN (2013-2016): Co-Investigator/IDS*

Outline (1)

- **Overview of Venus, Earth and Mars ionosphere-thermosphere-mesosphere features, processes and their differences**.
  - *Implications of fundamental planetary parameters.*

- **Review of key datasets reflecting solar flux variations over 2-timescales:**
  - *Solar cycle (~11-years): Venus, Earth, Mars*
  - *Solar flares (minutes to few hours): Earth and Mars*

- **Sampling of key Venus and Mars datasets reflecting LATM wave coupling**
  - *Venus upper atmosphere GWs, planetary waves (at/above cloud tops). Initial steps in modeling.*
  - *Mars upper atmosphere GWs, planetary waves, tides (above ~90-100 km). Initial steps in modeling.*

- **Brief survey of Mars "dust storm" impacts from key datasets:**
  - *Mars dust storm impacts on the upper atmosphere*

Outline (2)

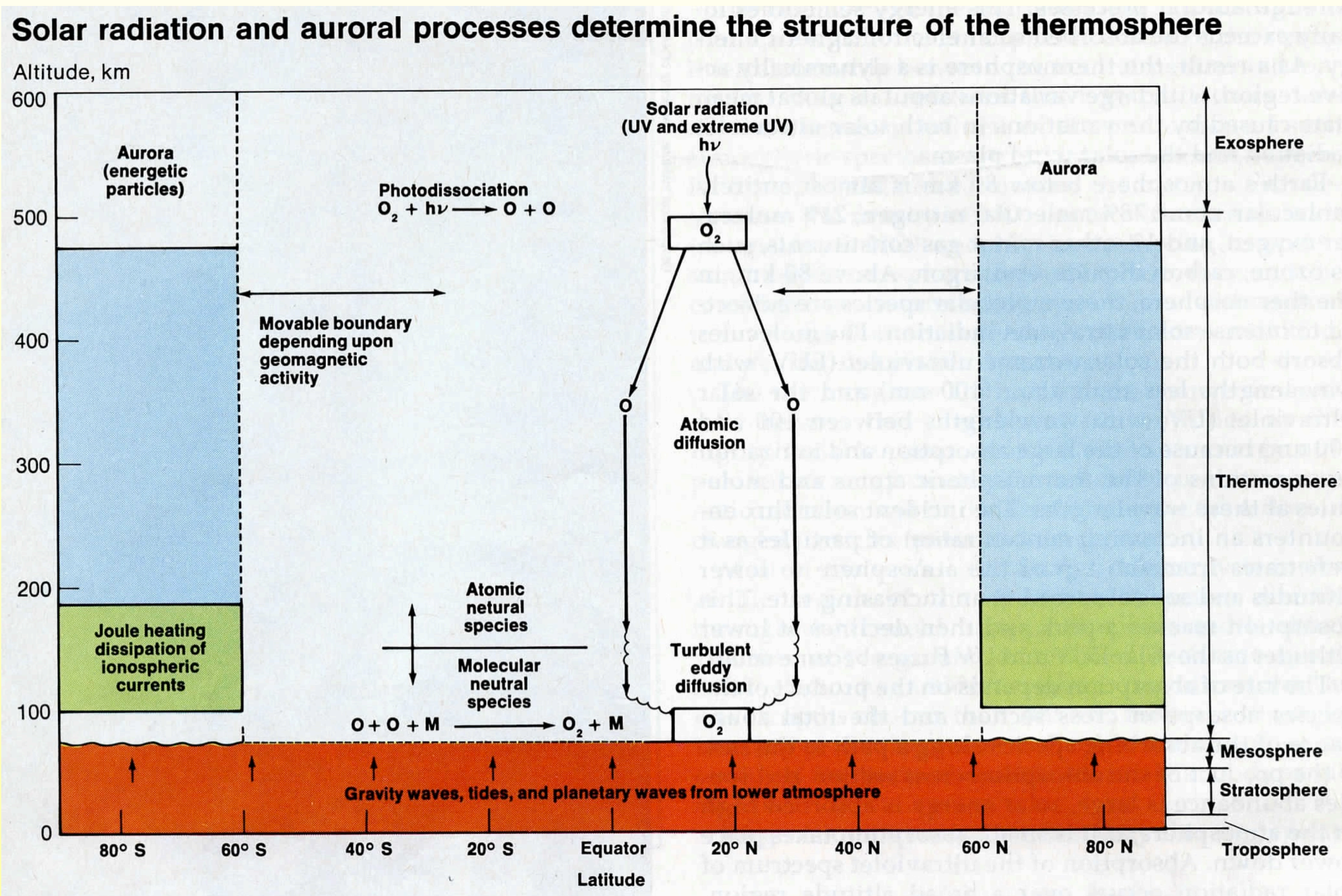
- **Survey of 3-planet upper atmosphere global models (NCAR TGCMs):**
  - *TGCM results illustrating impacts over the solar cycle*
  - *Associated heat balances that likely control these variations.*

- **Examples of Earth (TIE-GCM, GITM) and Mars (M-GITM) solar flare responses:**
  - *3-D model results illustrating impacts from solar flares and comparisons to relevant spacecraft datasets*

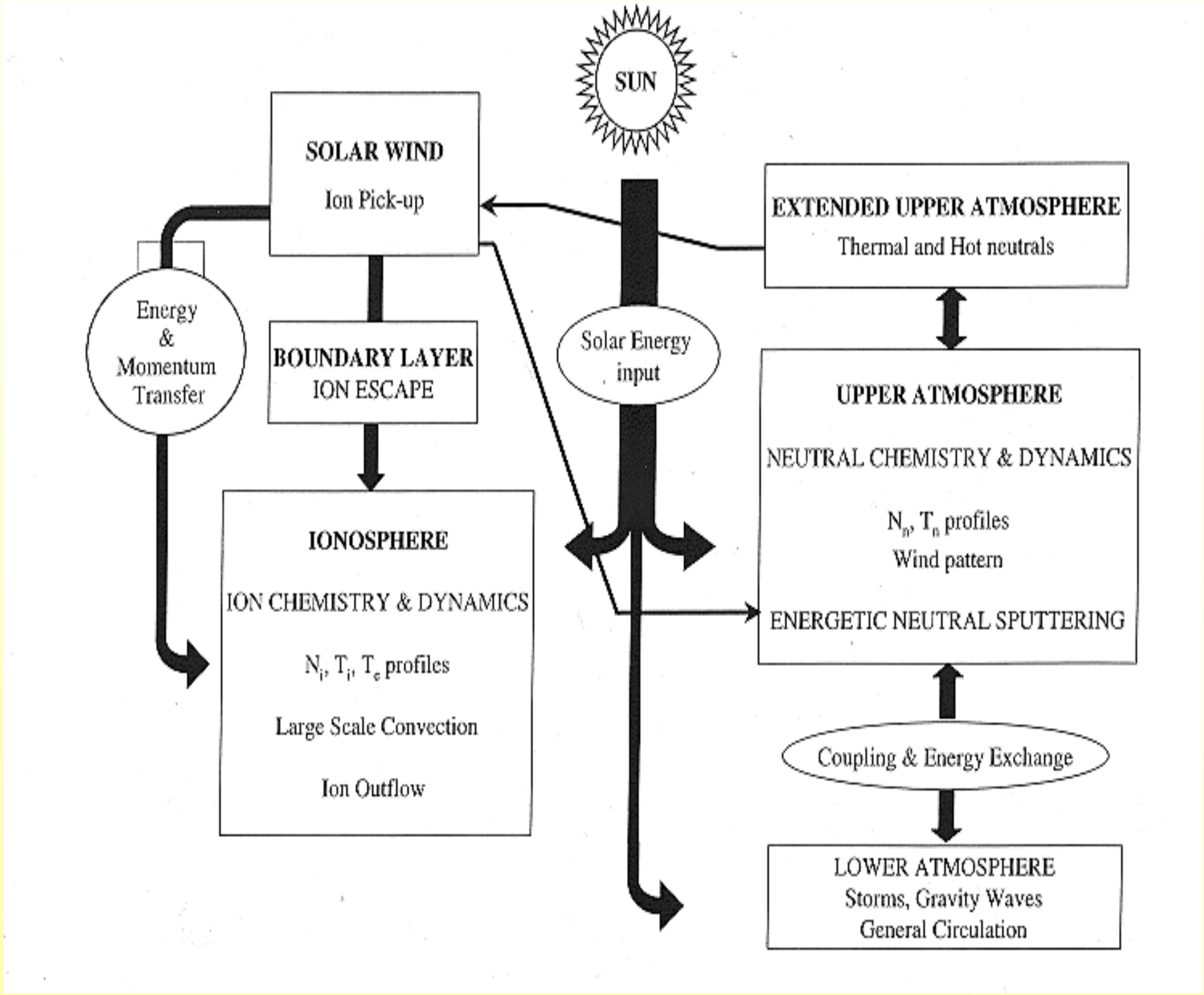
- **Major Take-Aways**

Ionosphere-Thermosphere-Mesosphere (ITM) Features and Processes: Venus, Earth and Mars

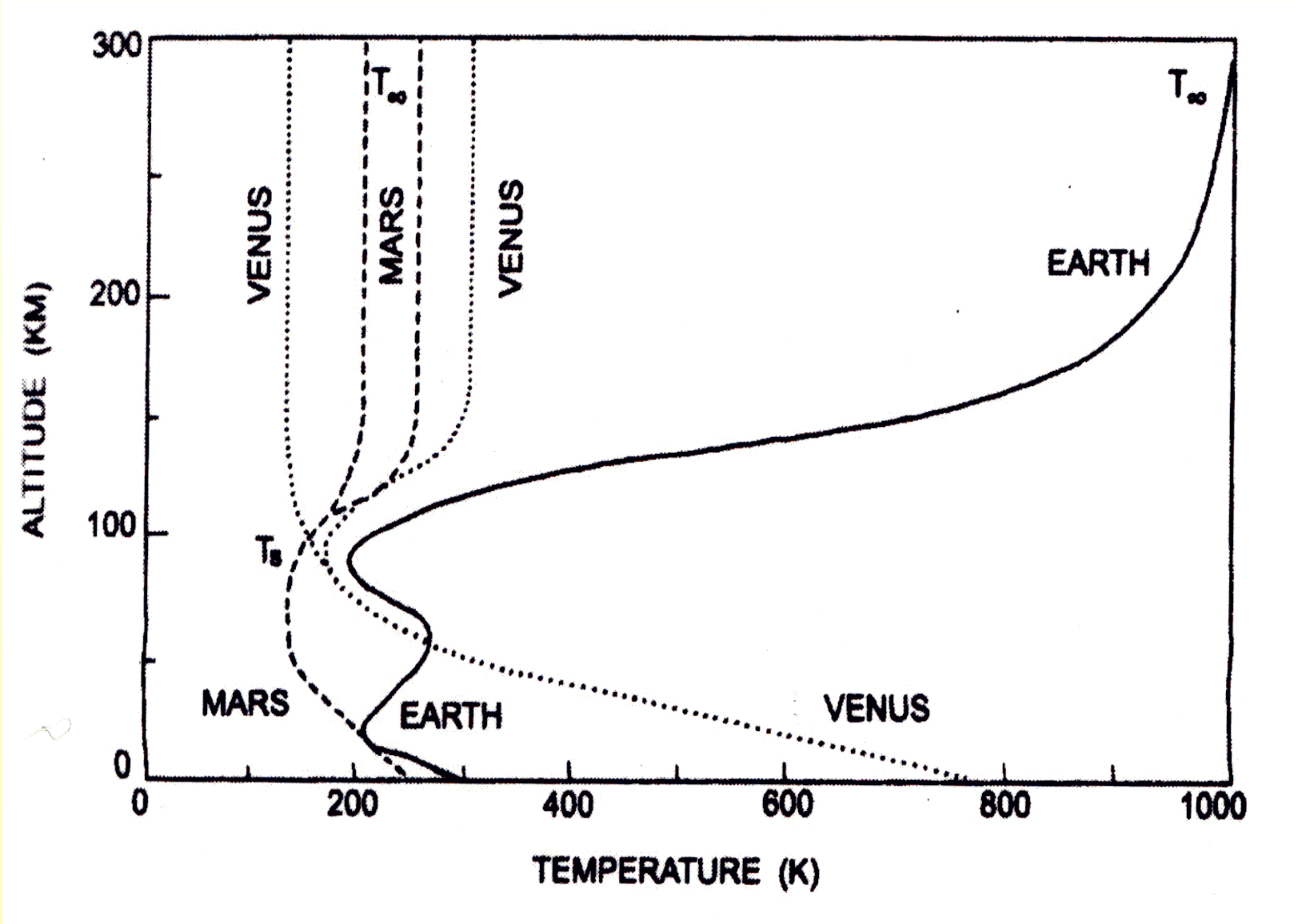
Earth Upper Atmosphere: Regions and Processes (Roble, 1986)



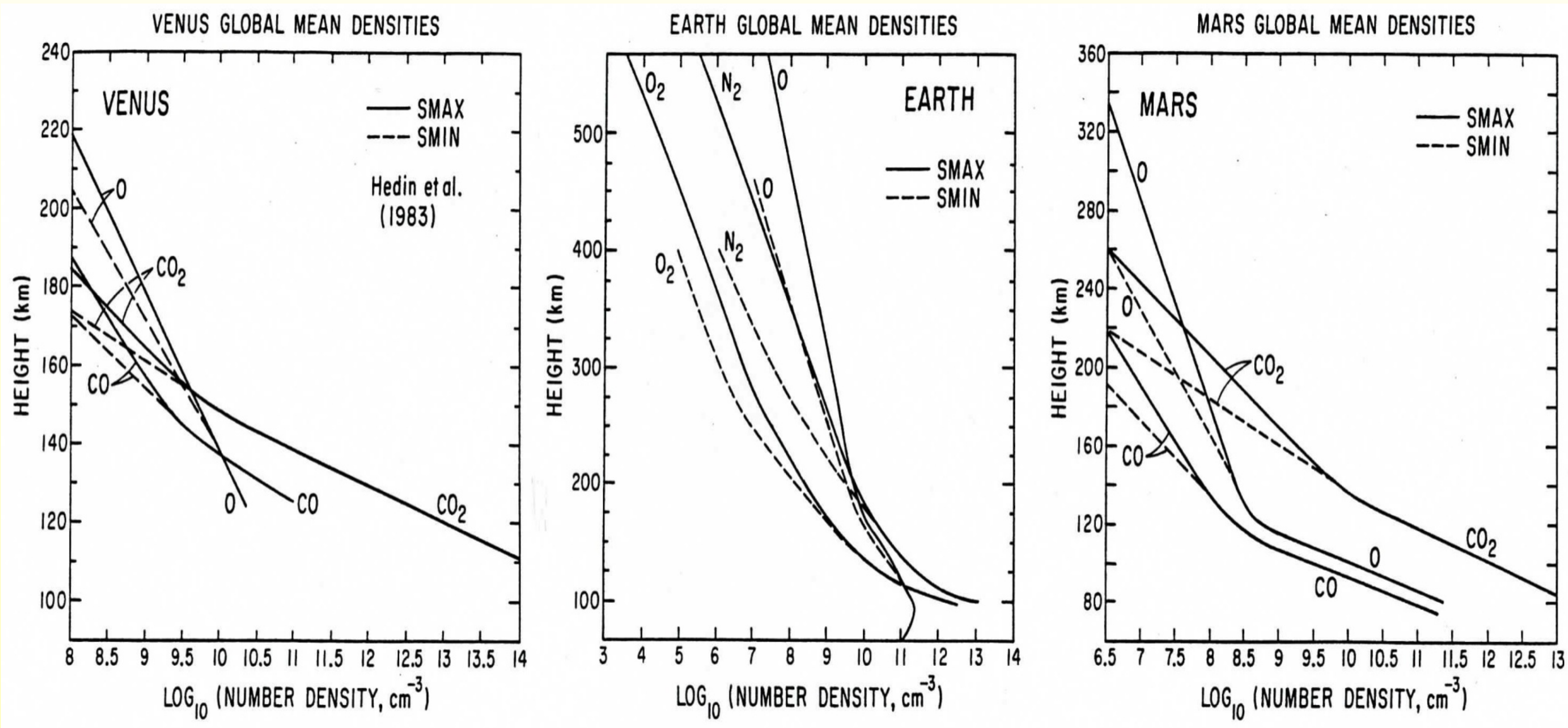
Mars Upper Atmospheric Regions and Processes (Bougher et al., 2002)



Atmosphere Temperature Structure: Venus, Earth, Mars (Bauer and Lammer, 2005)

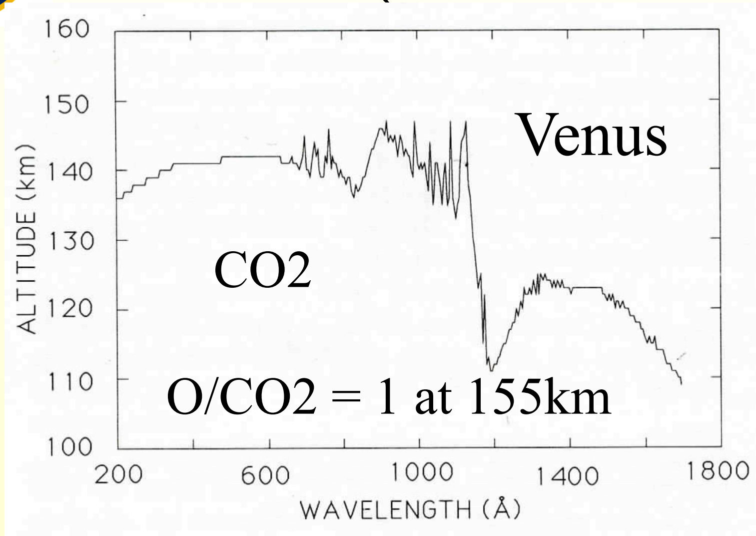


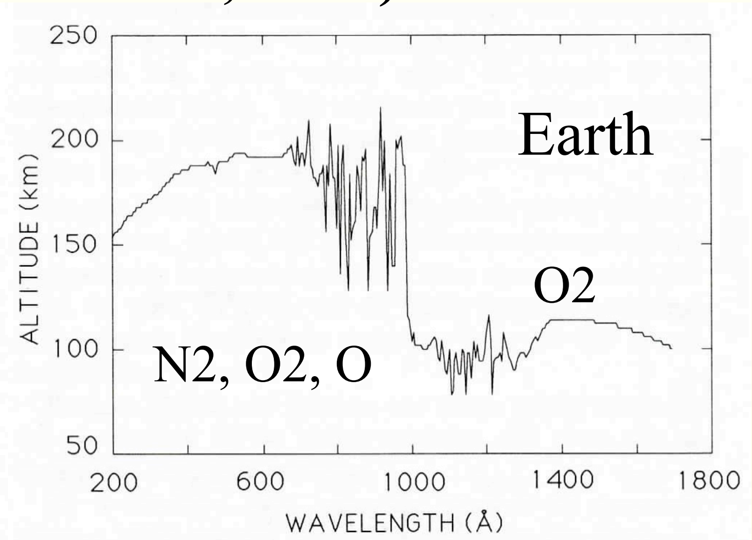
Global Mean Thermospheric Composition: Venus, Earth, Mars (Bougher and Roble, 1991)

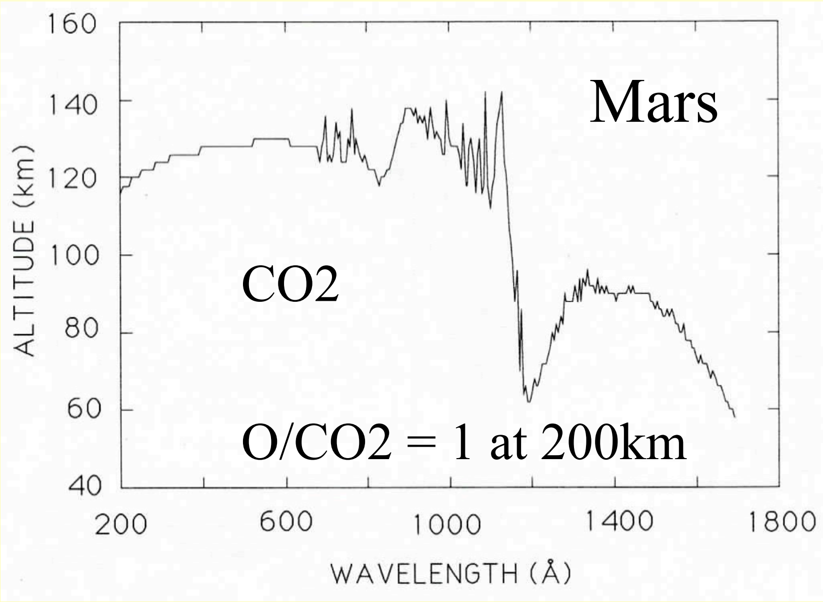


Homopause Altitudes (Venus:~135 km; Earth:~110 km; Mars:~125 km)

τ = 1 Altitudes for Venus, Earth, and Mars (Paxton and Anderson, 1992)

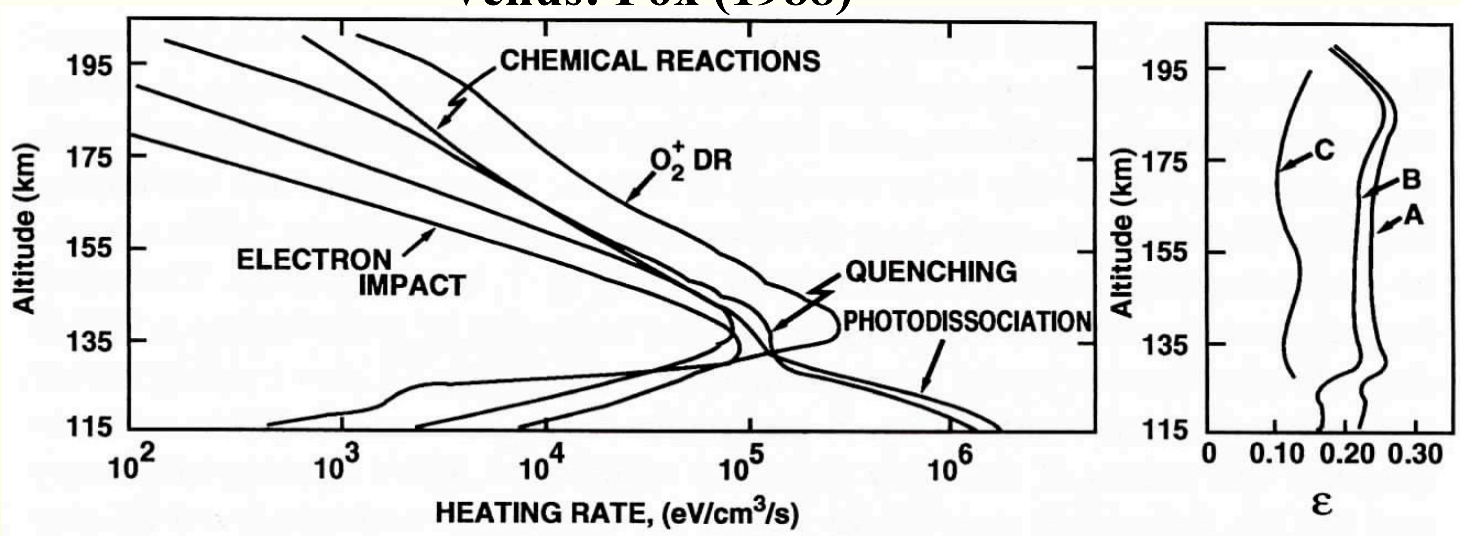


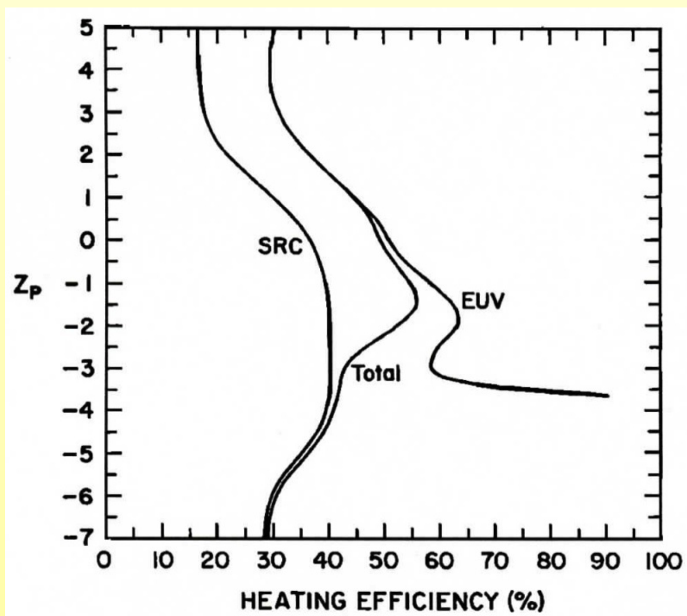




Solar EUV-UV Heating Efficiencies (Venus and Earth)

Venus: Fox (1988)

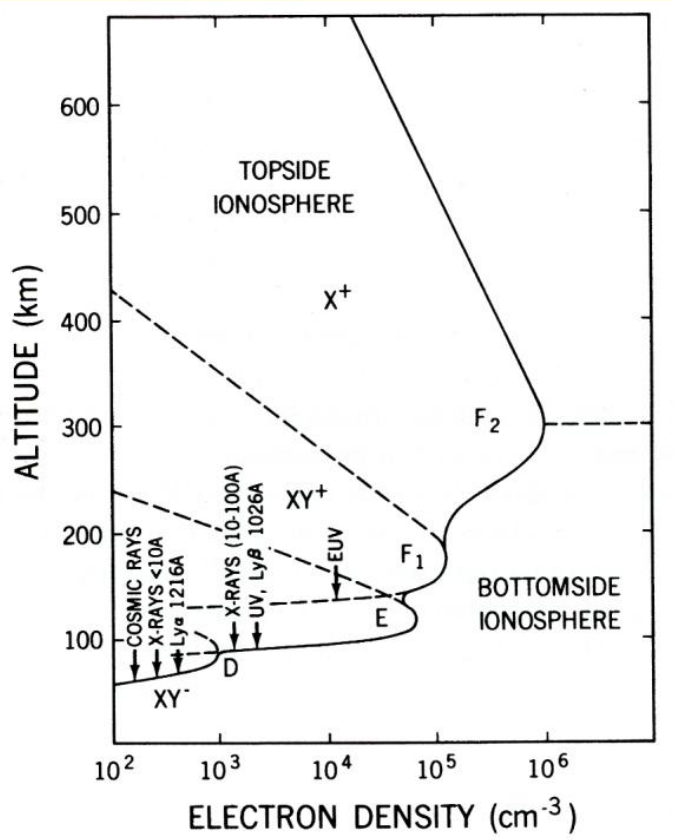




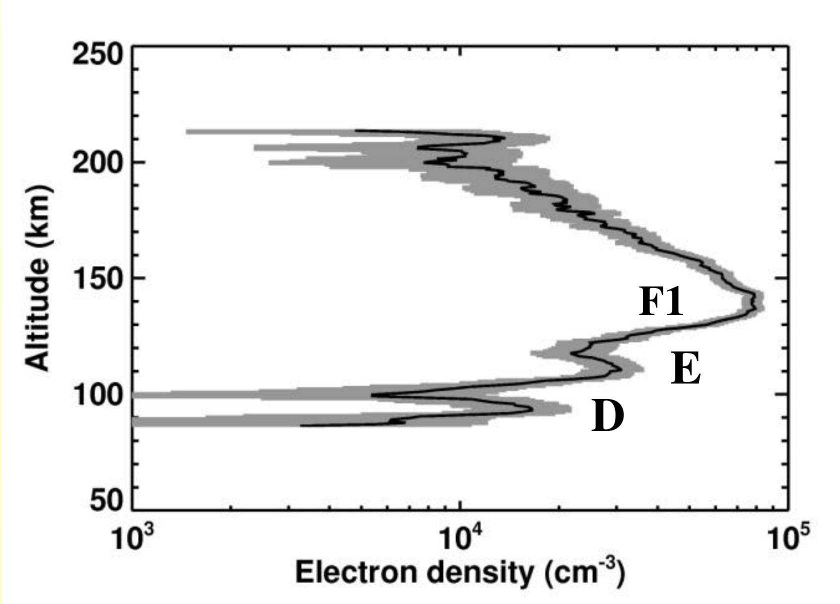
Earth:
Roble et al. (1987)

Comparison of Earth and Mars Ionospheric Regions and Processes

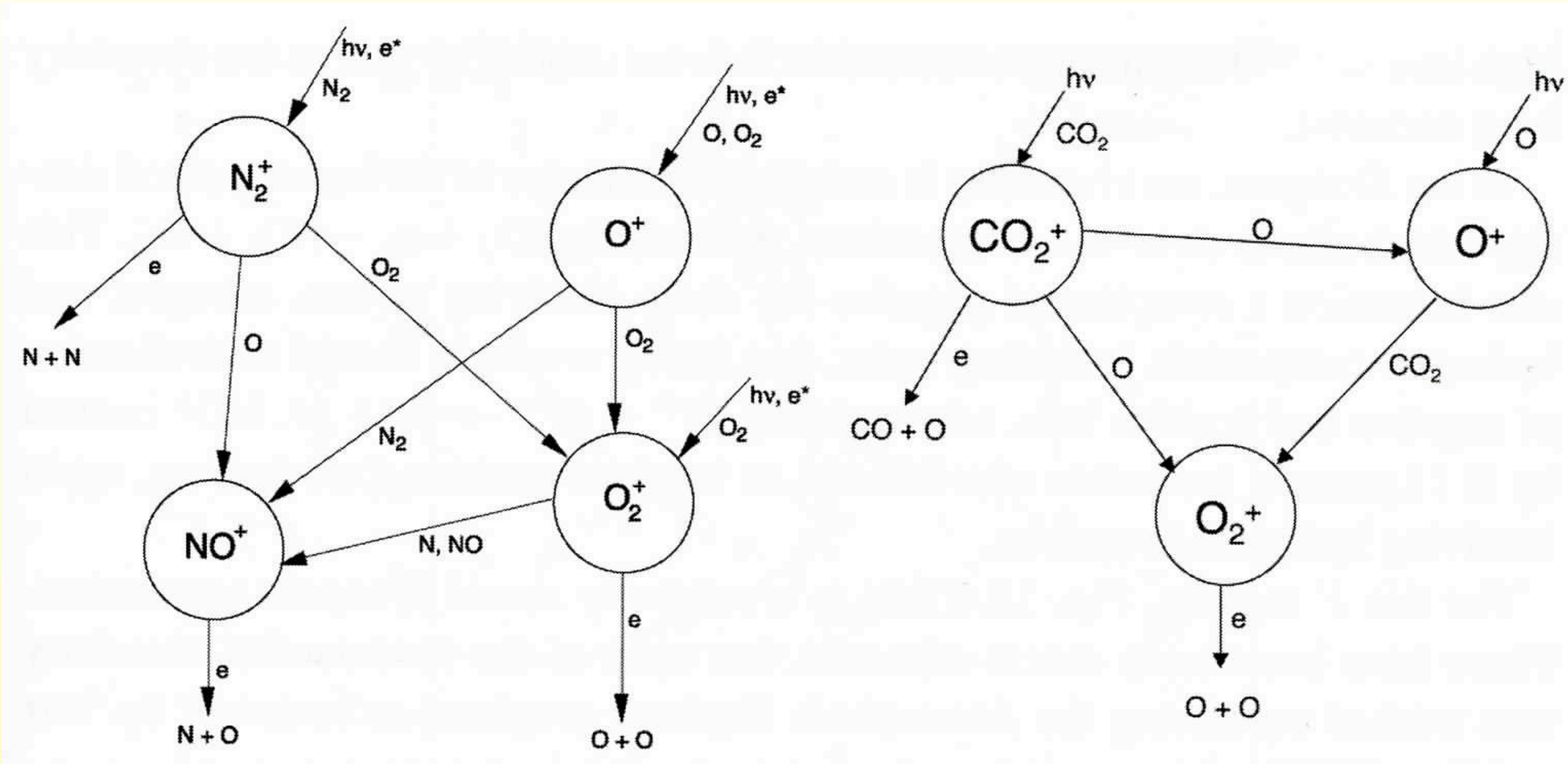
Earth Ionosphere Regions
(Bauer and Lammer, 2004)



Mars Ionosphere Regions
(Withers et al., 2008)

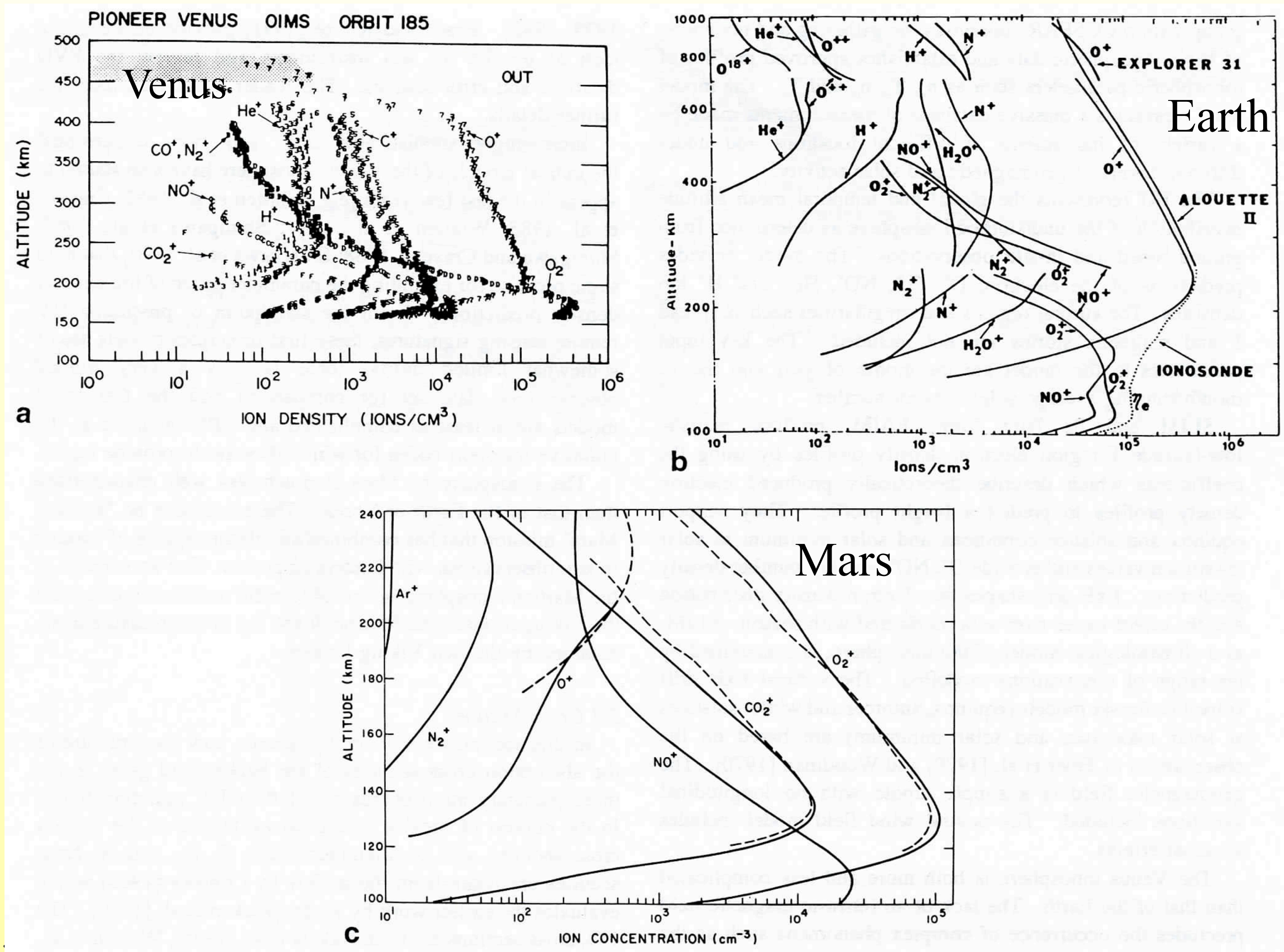


Simplified Ionospheric Chemistry (Solomon, 2010)



Earth **Venus and Mars**

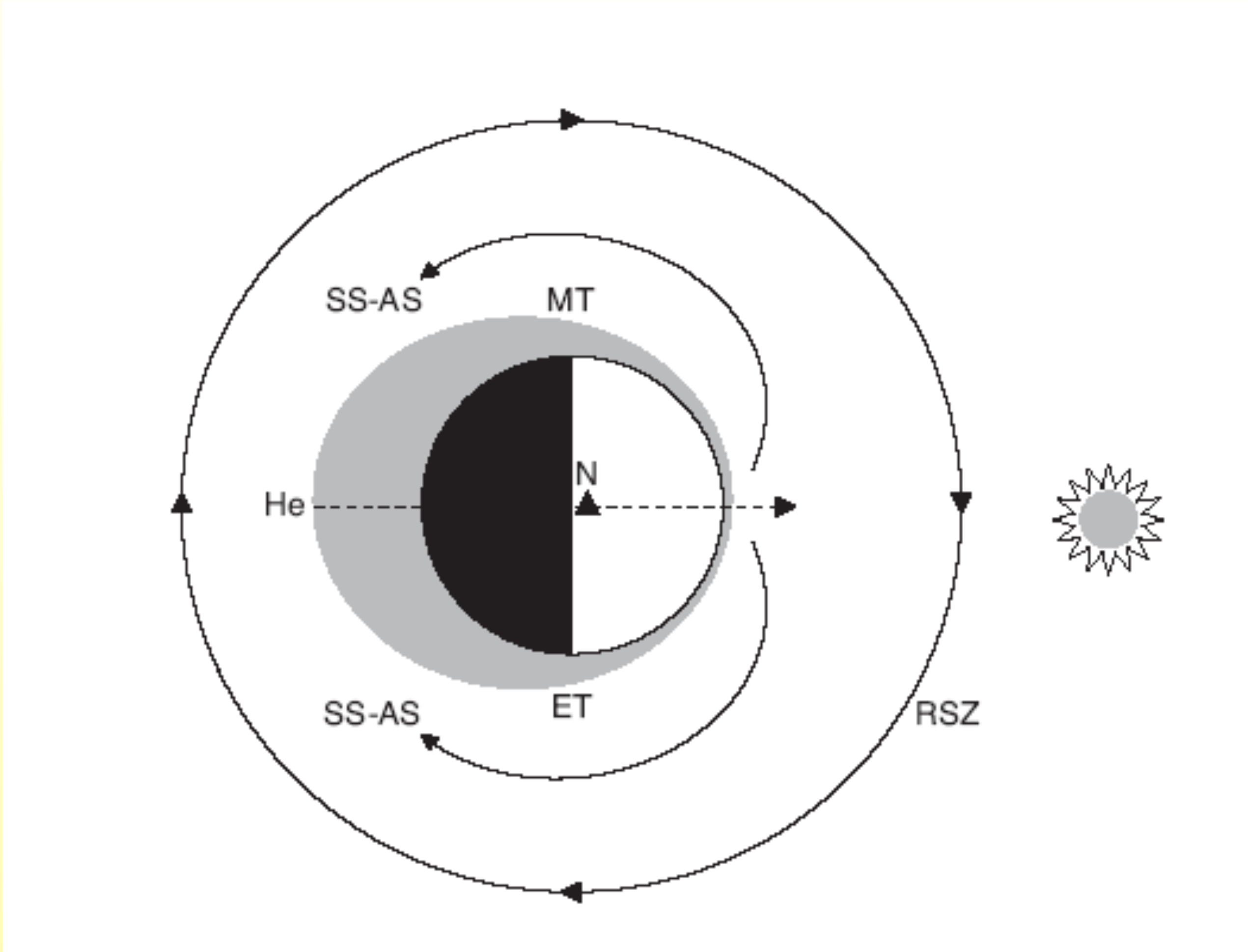
Dayside Ionospheres for Venus, Earth, Mars (Paxton and Anderson, 1992)



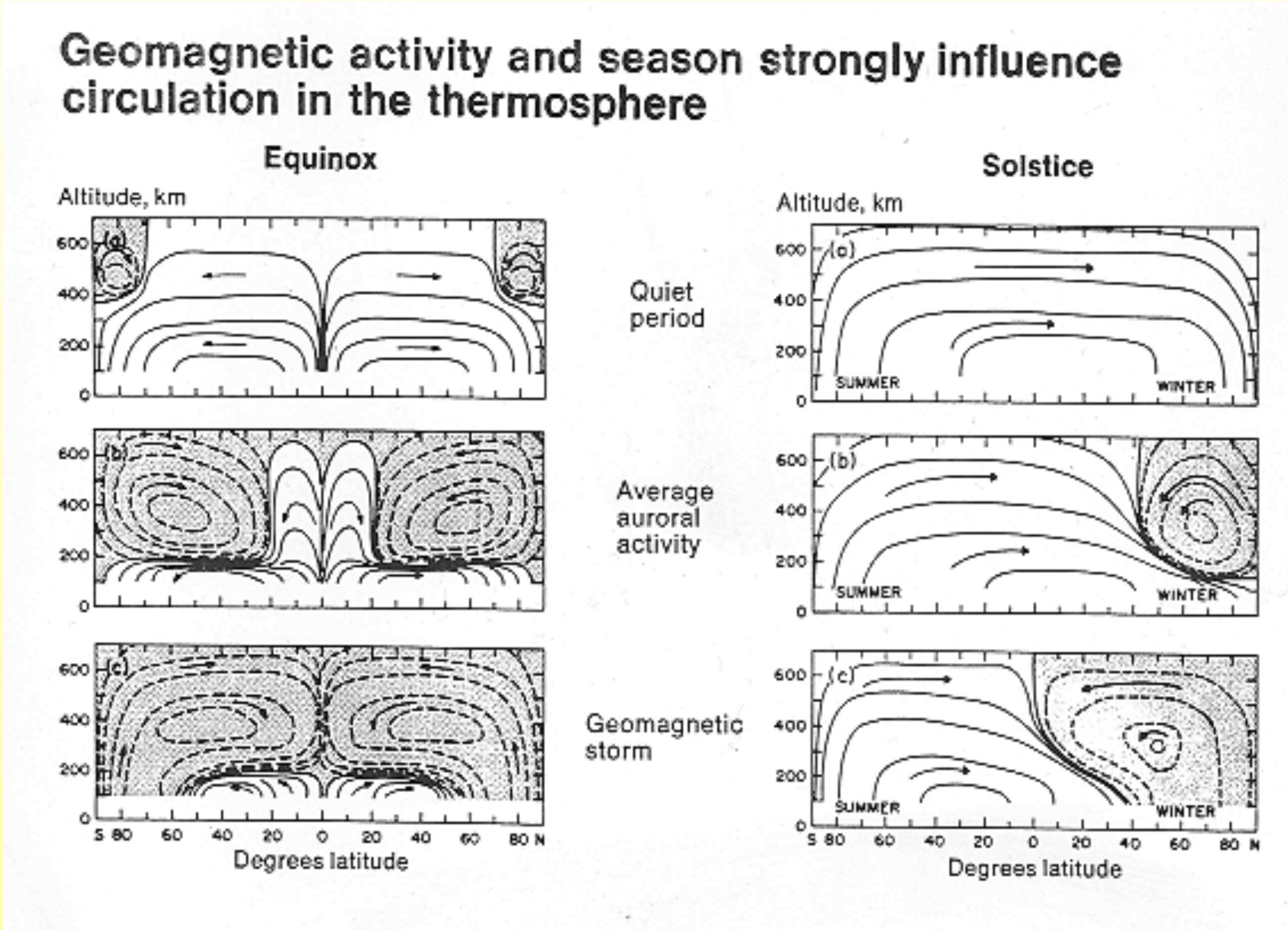
Fundamental Planetary Parameters: Some Implications

Parameter	Venus	Earth	Mars
Gravity (cm2/sec): H(km)	888 [4-12]	982 [10-50]	373 [8-22]
Heliocentric distance (AU)	0.72	1.0	1.38-1-67
Radius (km)	6050	6371	3390
Omega (rad/sec): Coriolis	-3.0(-7) [no]	7.3(-5) [yes]	7.1(-5) [yes]
Obliquity (deg): Seasons	1-3 [no]	23.5 [yes]	25.12 [yes]
B-dipole moment (wrt Earth): Auroral/Joule heat	≤4.0(-5) [no]	1.0 [yes]	≤2.5(-5) [no] Crustal fields
EUV-UV (eff.)	20-22%	30-60%	20-22%

Upper Atmosphere Circulation Venus (Schubert et al. 2007)

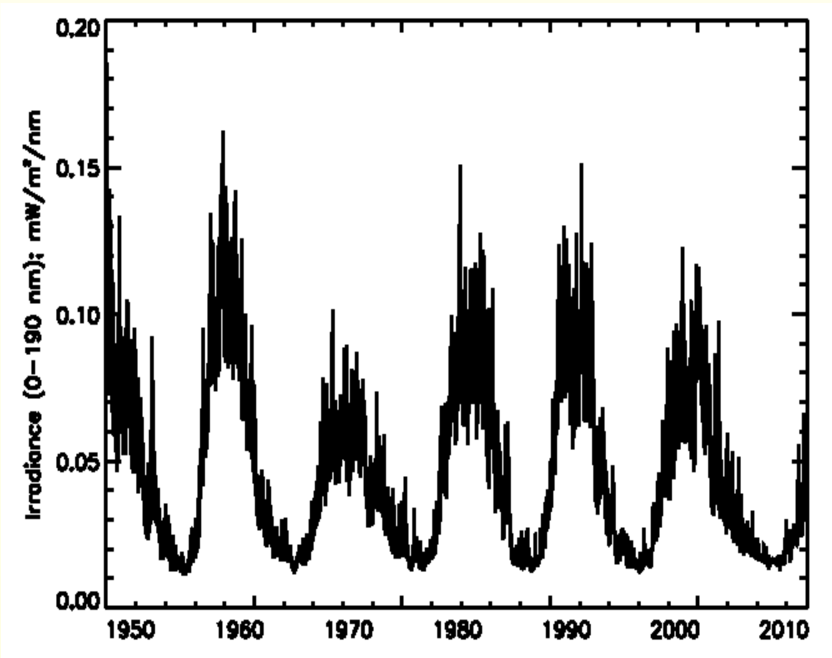


Upper Atmosphere Circulation of Earth (Roble, 1986): Mars Analogue?

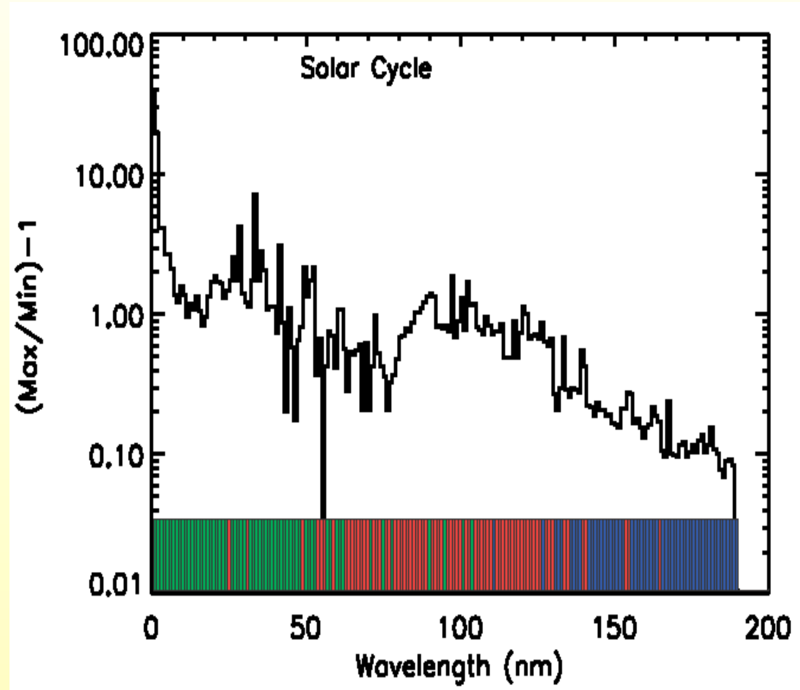


Key Datasets Reflecting Solar Flux Variations over 2-Timescales

Solar Spectral Irradiance Variations over the Solar Cycle (~0.1-190.0 nm)

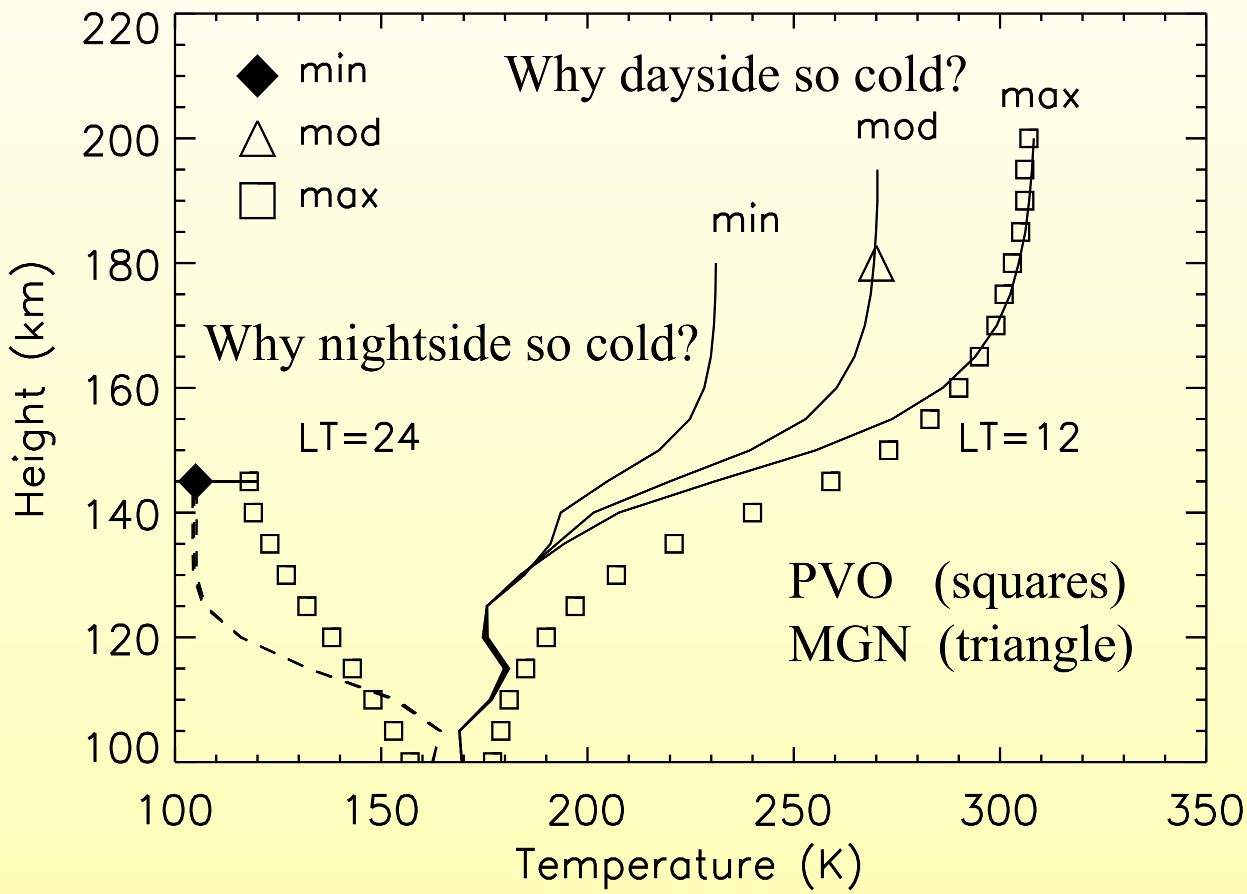


Integrated 0-190 nm FISM irradiance (1947-2011)



Solar maximum to minimum variations over the solar cycle (SC #22-23)

Venus Dayside and Nightside T-Profiles (Bougher et al. 2002)



Venus Dayside-Nightside Exospheric Temperatures (Kasprzak et al. 1997)

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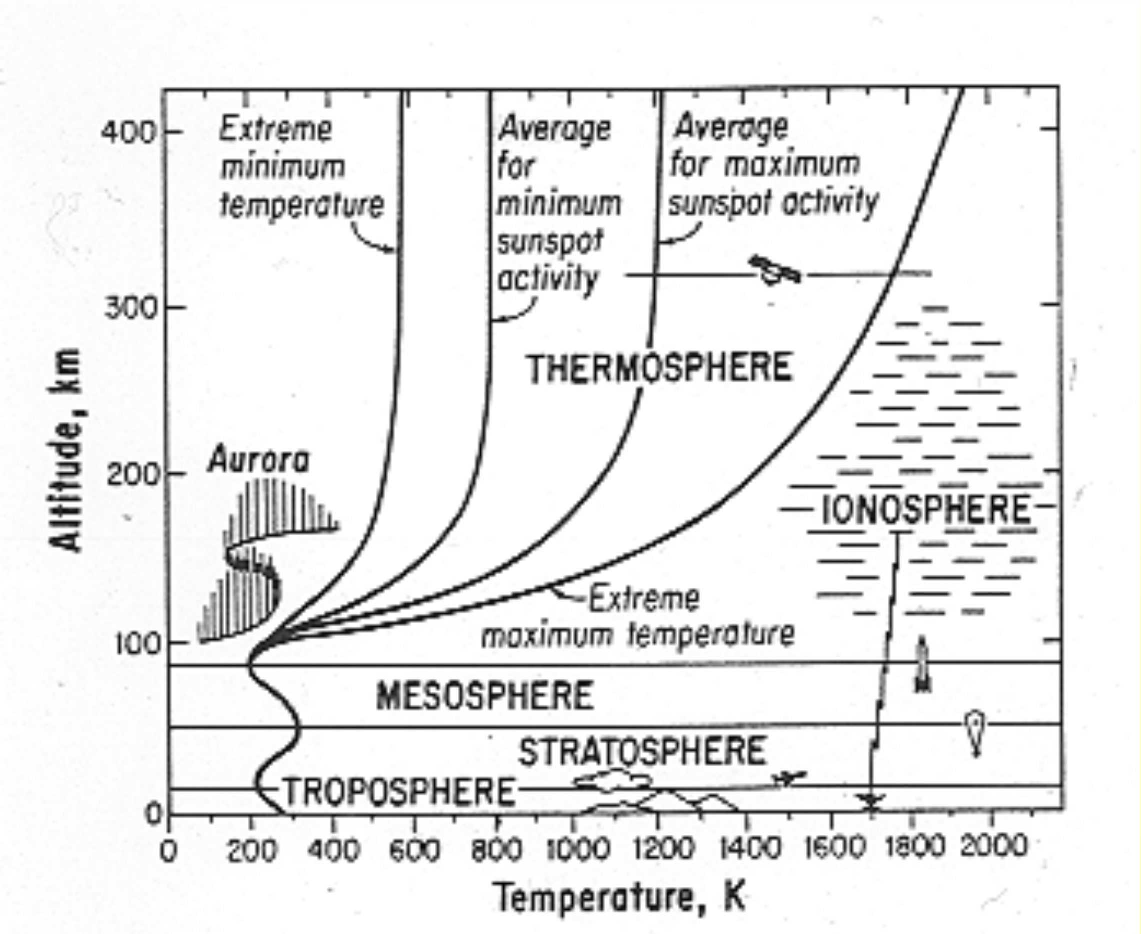
ΔT ~ 70-80 K
ΔT/ΔF10.7 ~ 0.34
(at Venus)

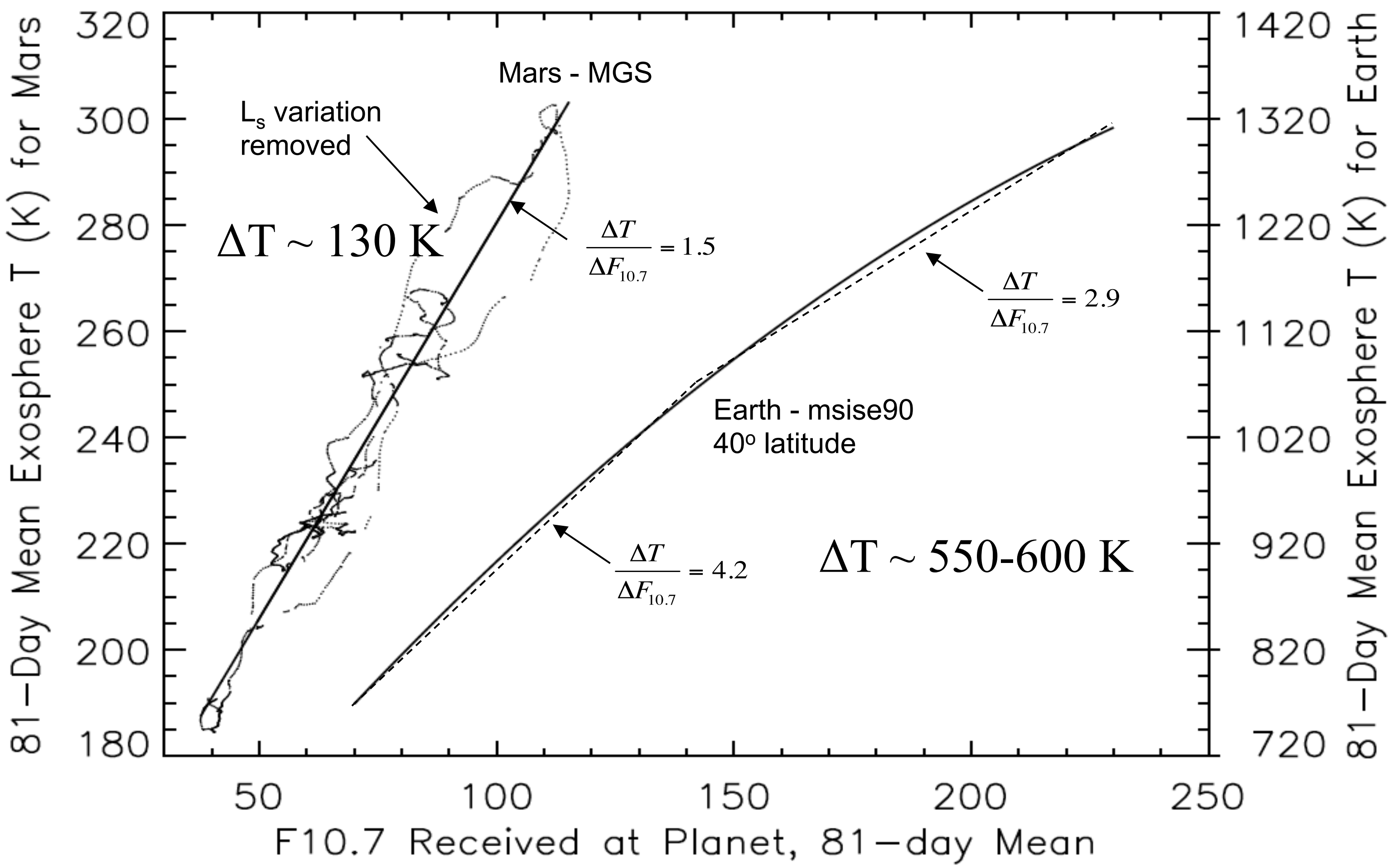
Nearly Constant

Characteristic Earth Dayside T Profiles



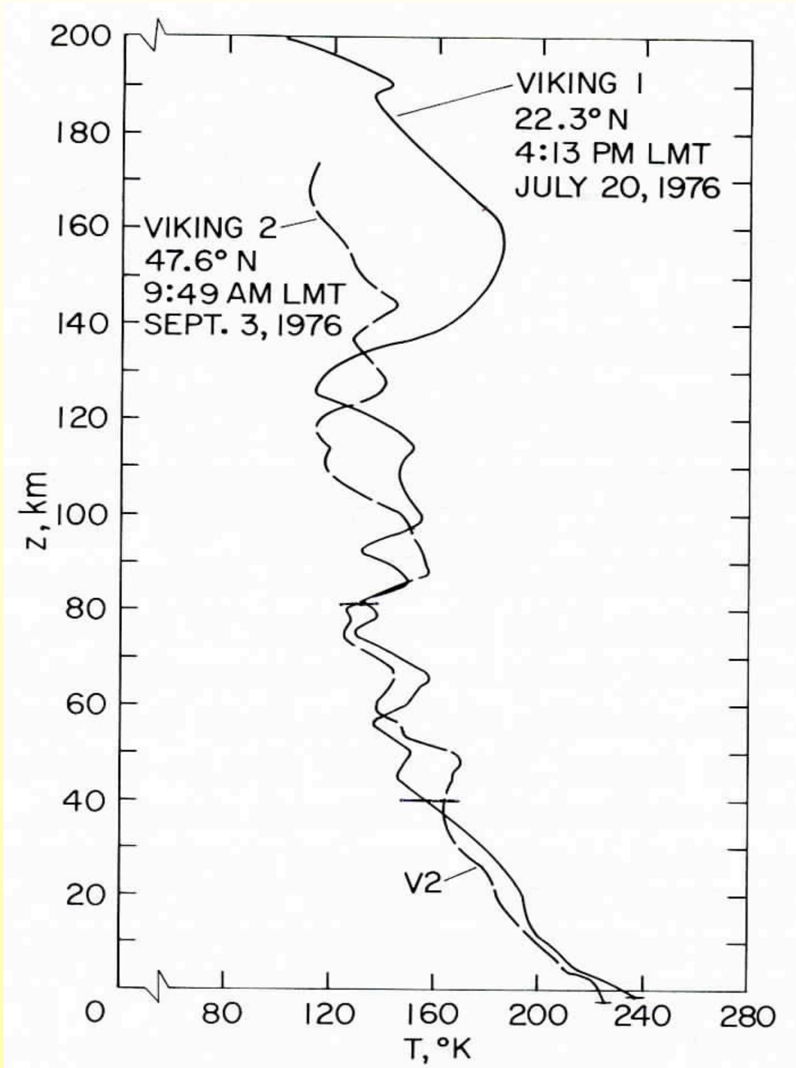
Adapted from Roble (1986)

Earth-Mars Comparative Response to Long-Term Changes in Solar flux (Forbes et al., 2007)

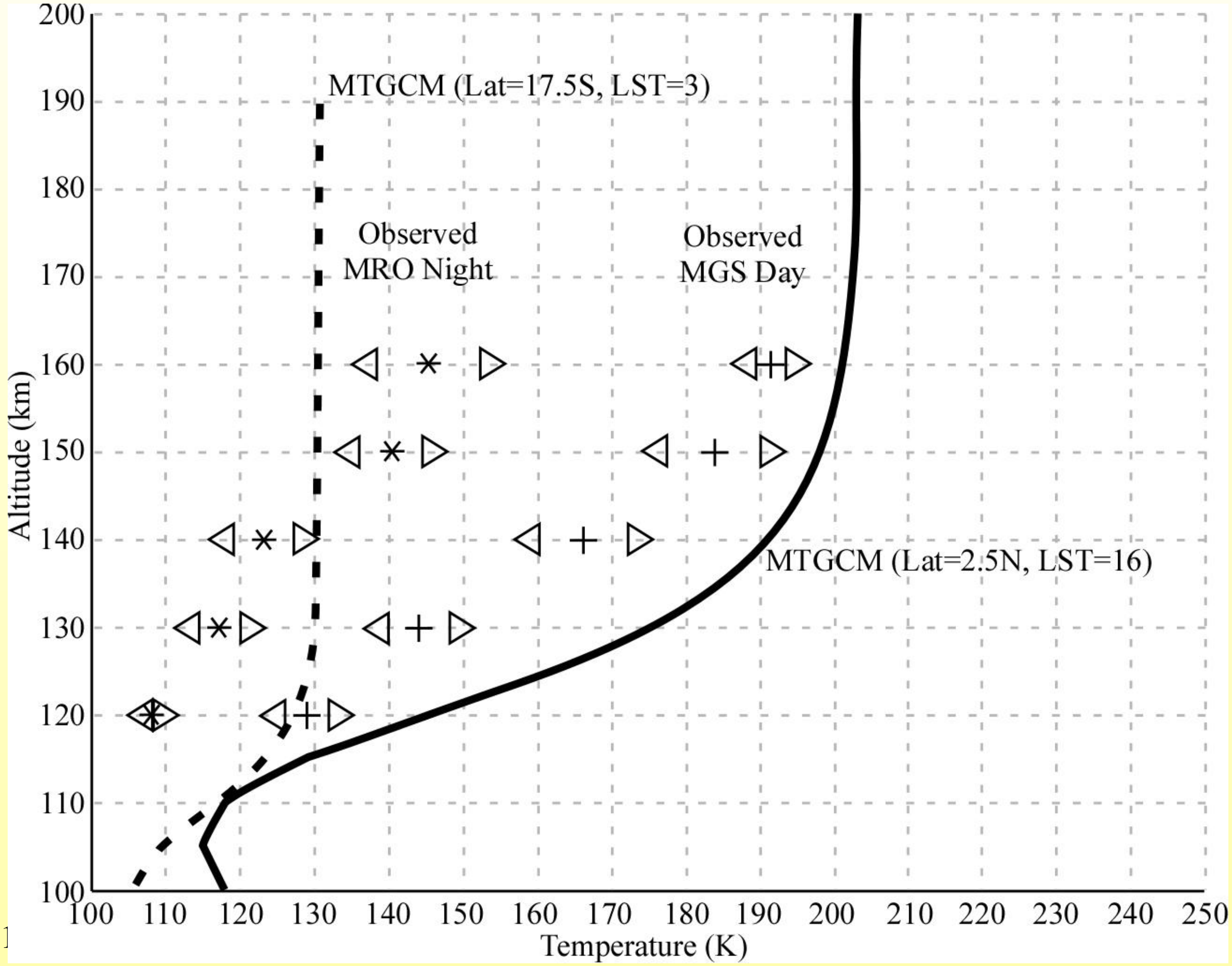


Mars is ~36% - 50% as responsive to solar flux received at the planet, compared to Earth, consistent with Forbes et al. (2006)

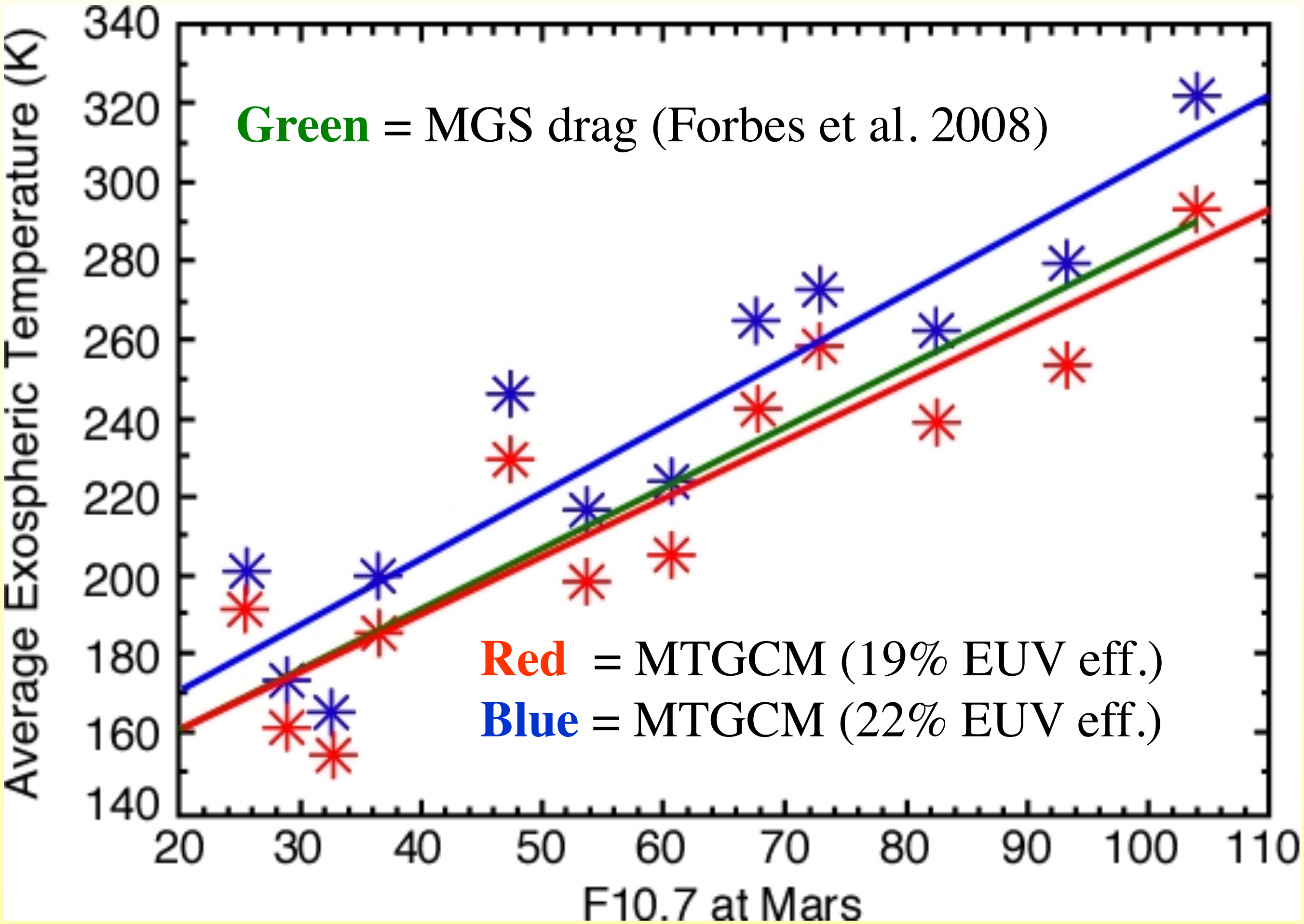
Viking Descent Temperature Profiles: SMIN (Seiff and Kirk, 1977)



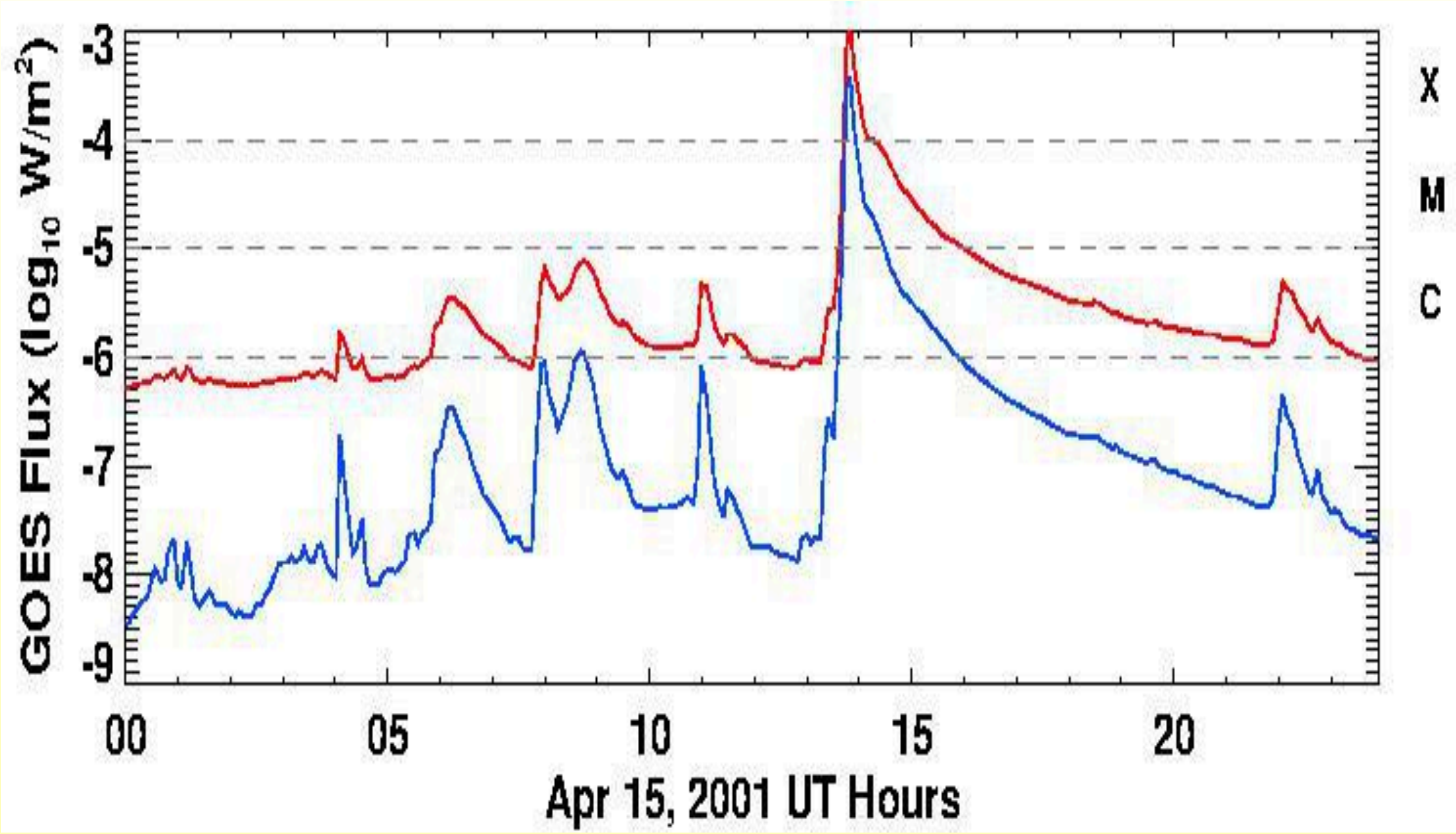
MGS and MRO Accelerometer Derived Profiles of Mars Dayside Temperatures (Bougher et al., 2013)



Measured/Modeled Mars Dayside Exospheric Temperatures (Bougher et al., 2009)

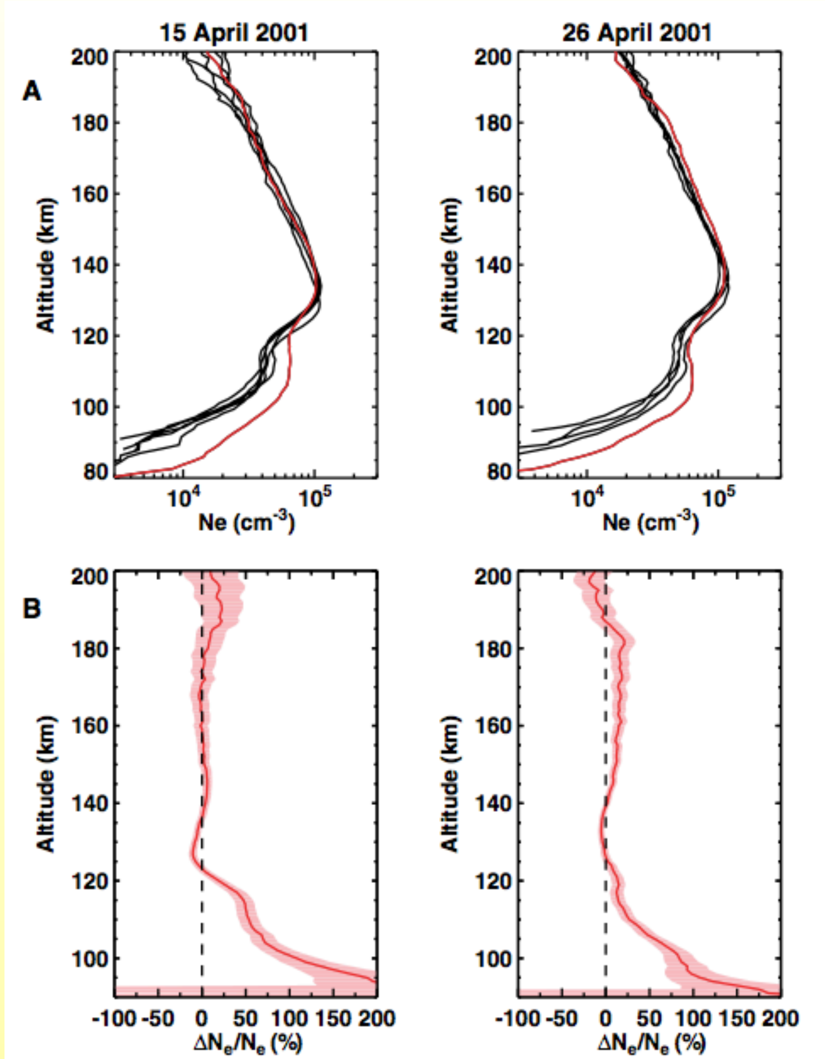


GOES Satellite soft X-ray Solar Fluxes Spanning the April 15, 2001 Solar Flare

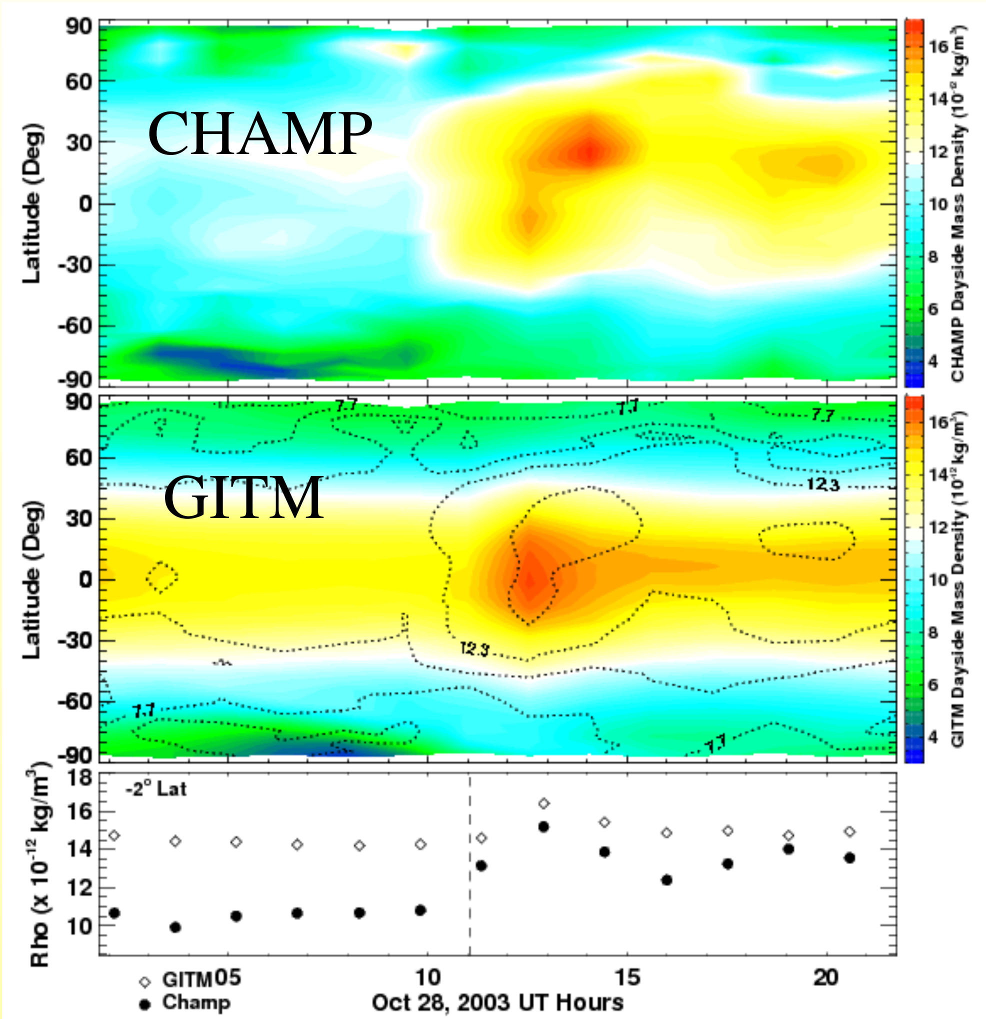


Mars Ionospheric Observations

Mars Global Surveyor (MGS) profiles (Mendillo et al. 2006)

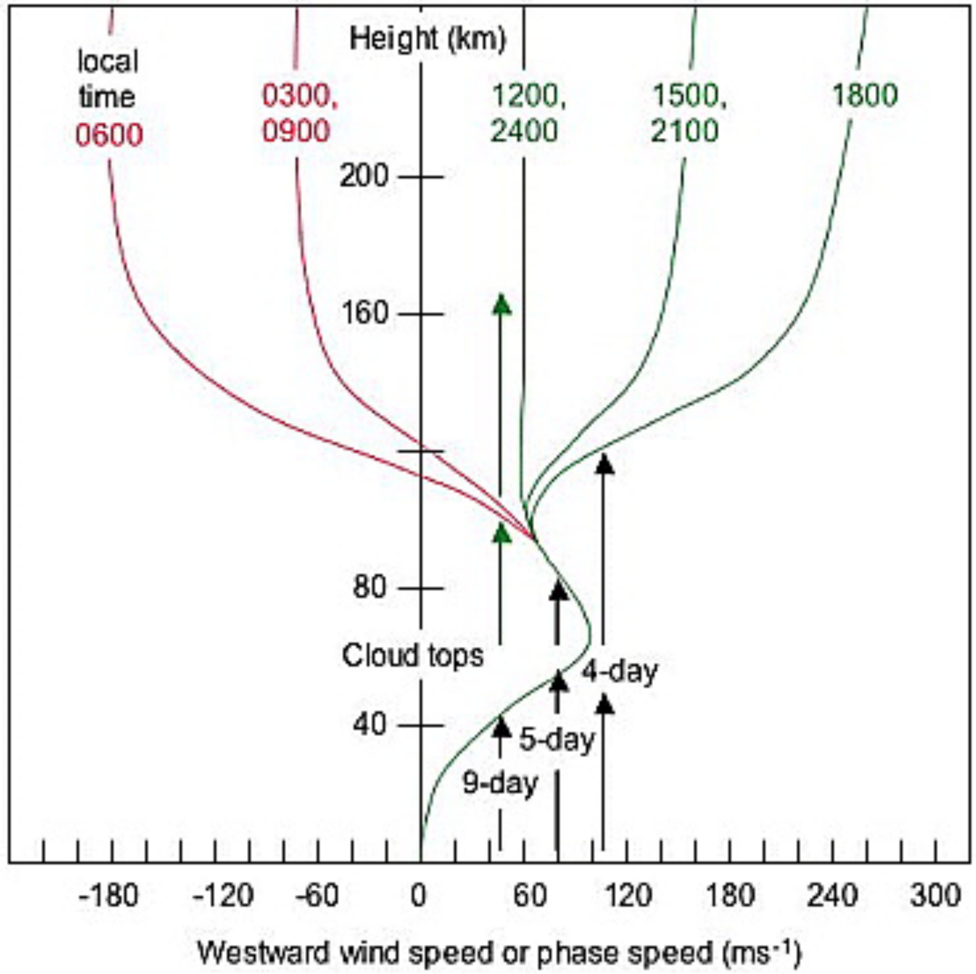


Solar Flare Response by Earth Mass Densities at 400 km (Pawlowski & Ridley, 2008)



Review of key datasets reflecting lower atmosphere wave coupling: Initial Steps in Modeling

Venus Planetary Waves: Cloud Level Evidence and Implications for UATM (Forbes and Konopliv, 2007)



<u>Cloud Top Pl. Waves (~65-70 km)</u>

4-day: Kelvin wave (equatorial)

Cph ~ 100-110 m/s

5-day: Rossby wave (mid-lats)

Cph ~ 85 m/s

(not yet seen in UATM datasets)

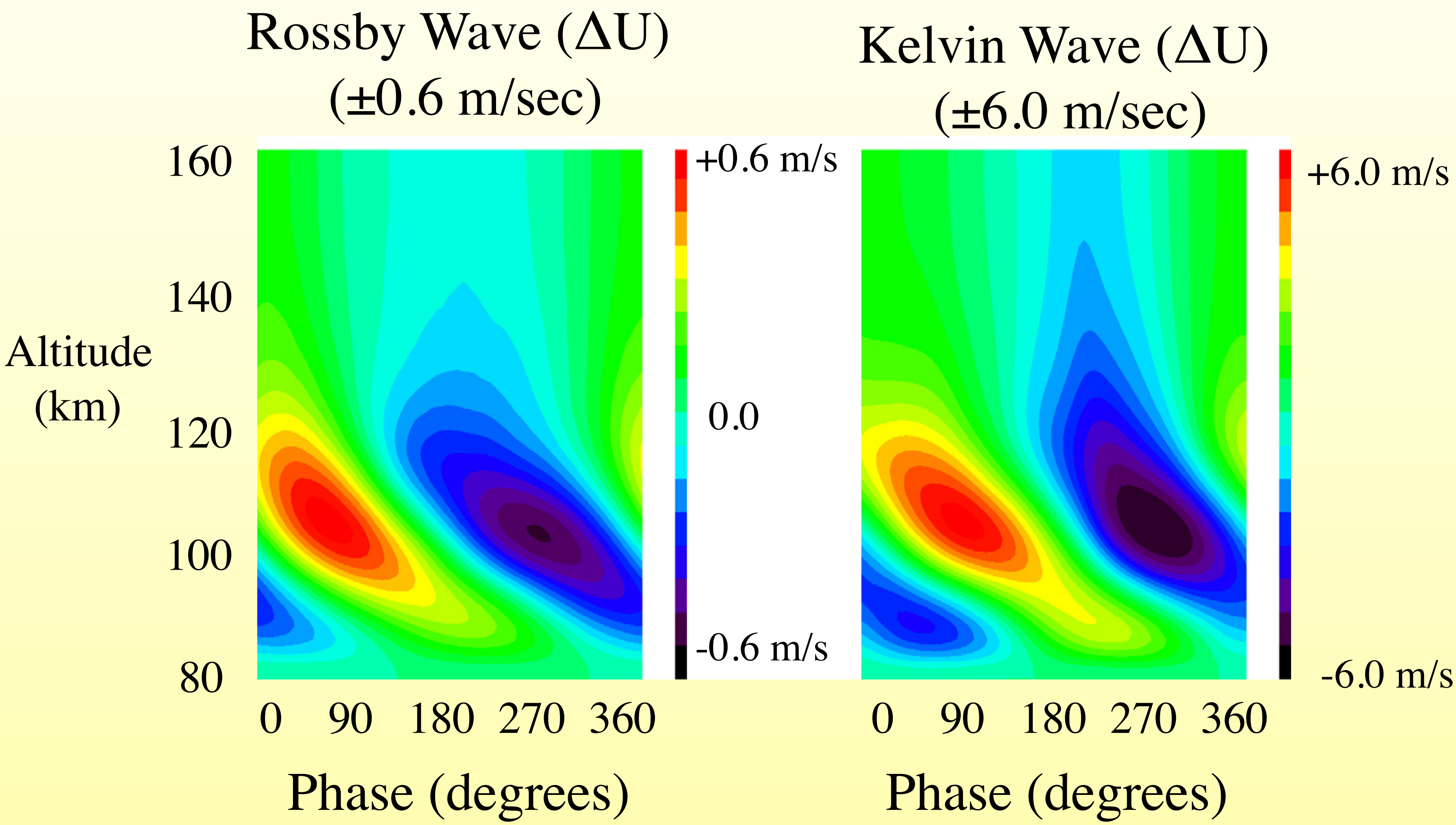
<u>Cloud Base Wave (~40-50 km)</u>

9-day: Wave-wave interaction?

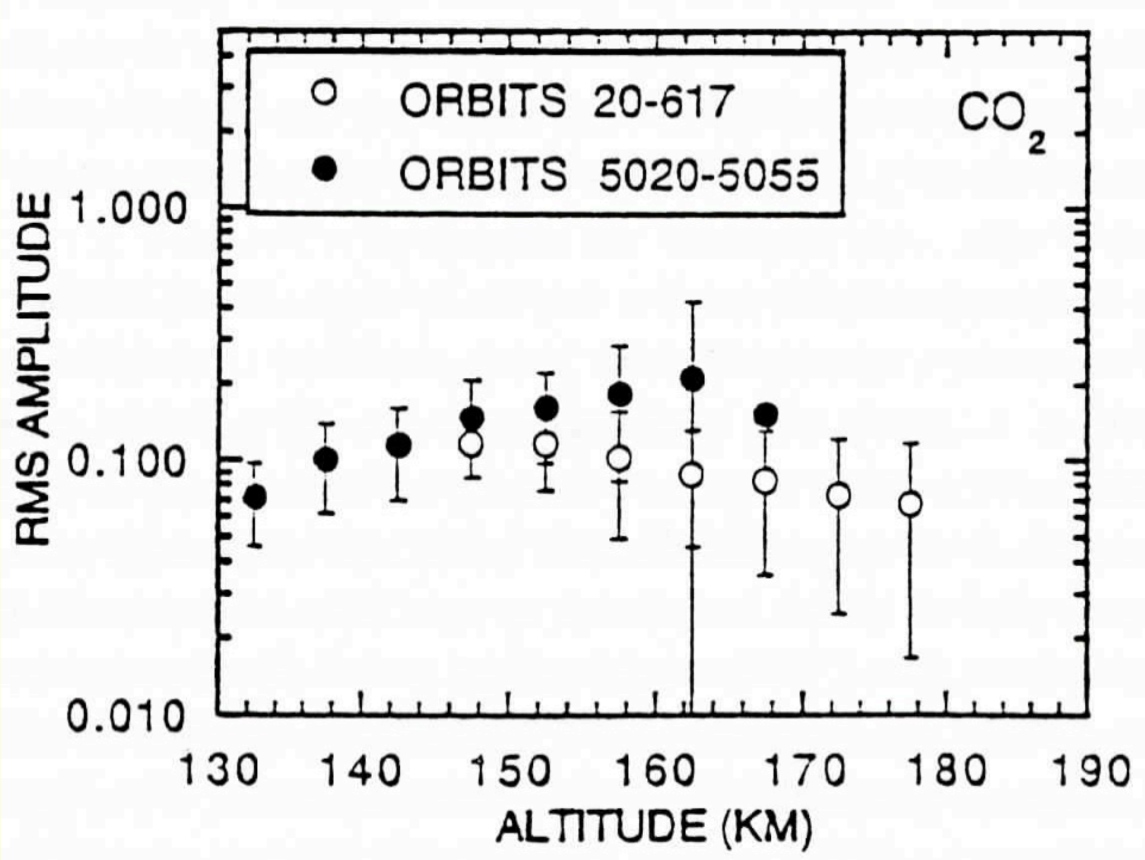
Cph ~ 40-50 m/s

(seen at 164-184 km, with amp. ±30-50% of background)

Initial Planetary Scale Wave Modeling in the Venus UATM (Hoshino et al. 2012)



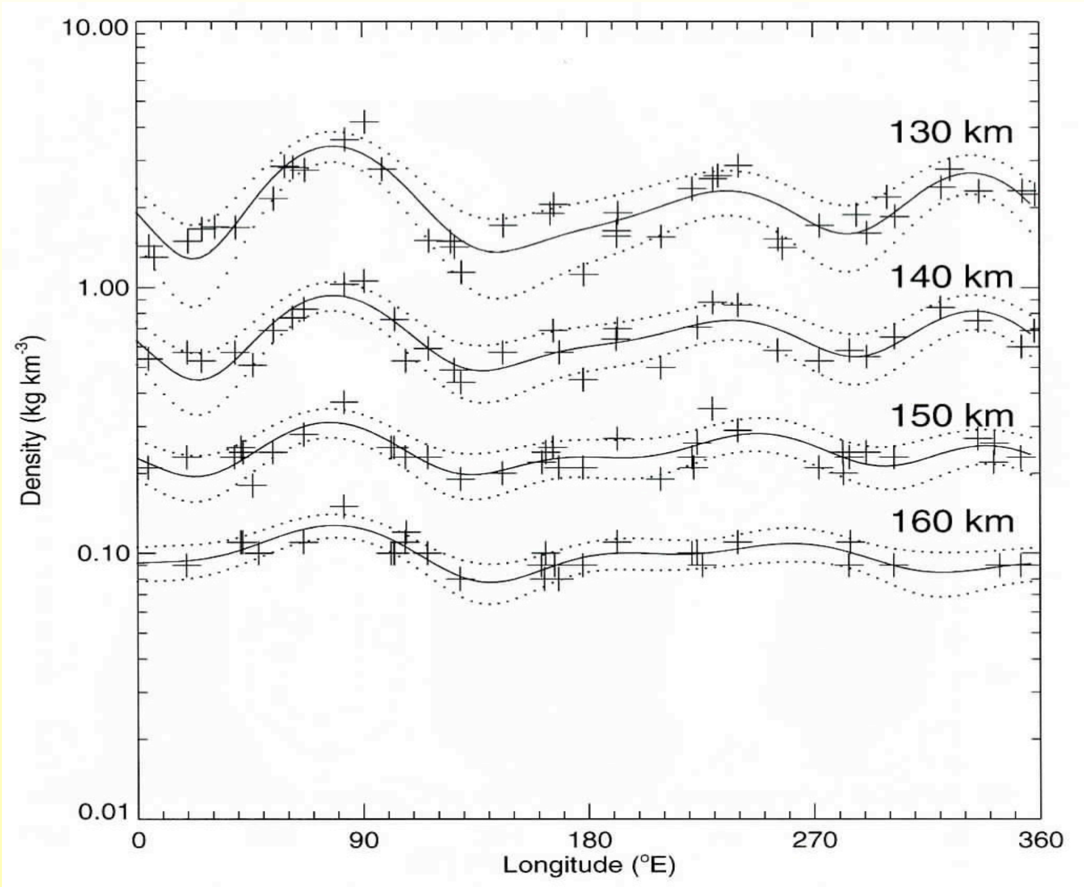
Evidence of Venus Gravity Waves in UATM PV-ONMS Datasets (Kasprzak et al. 1993)



RMS wave amplitude growth

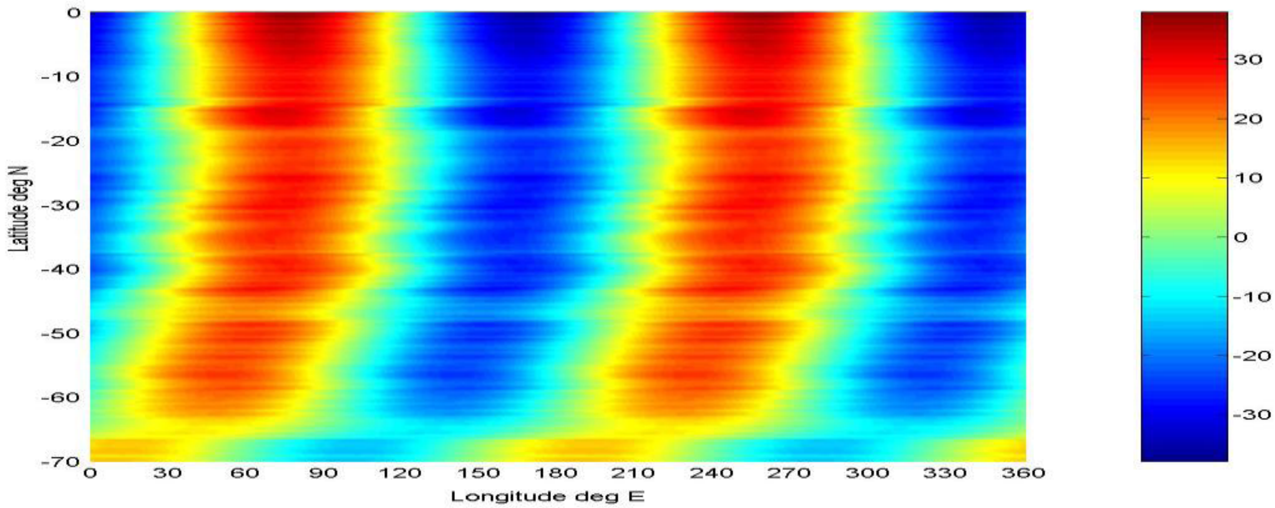
- Over ~130-160 km
- H ~ 30 km
- Limited by saturation or CO_2 radiative damping
- Decrease above 160 km

Lon. Variation of MGS Densities vs Altitude (Lat = 10-20°N; LST = 15)

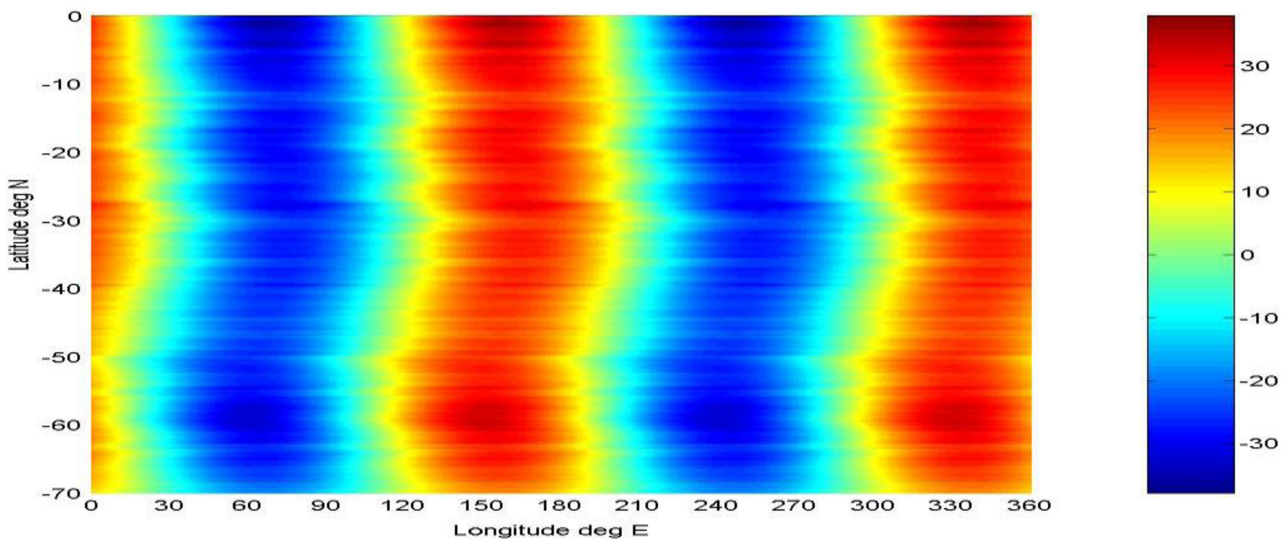


Withers et al (2003)

Mars Accelerometer Mass Density Wave-2 Components (130 km) taken from MGS and MRO

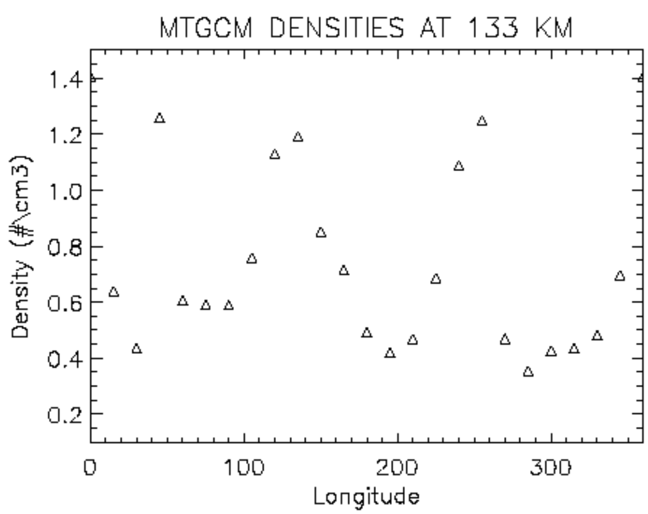


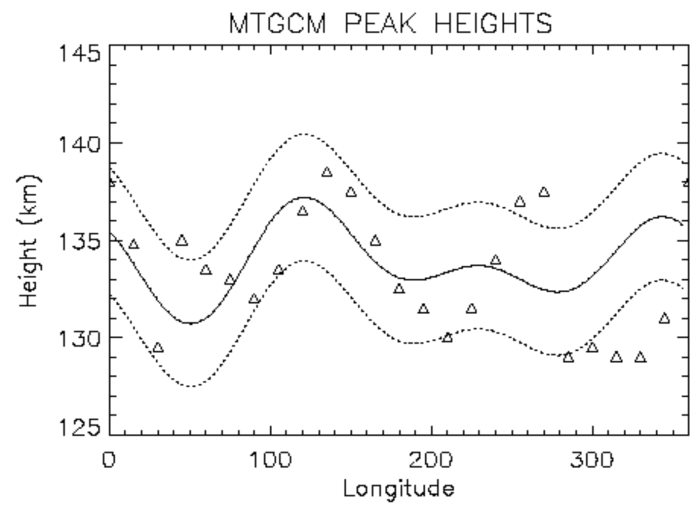
MGS2
Ls = 28-93
LT = 13-17
(Day)



MRO
Ls =36-100
LT = 2-3
(Nite)

MTGCM Longitude Wave Modeling (Mass Densities and F1-Ion Peak Heights)



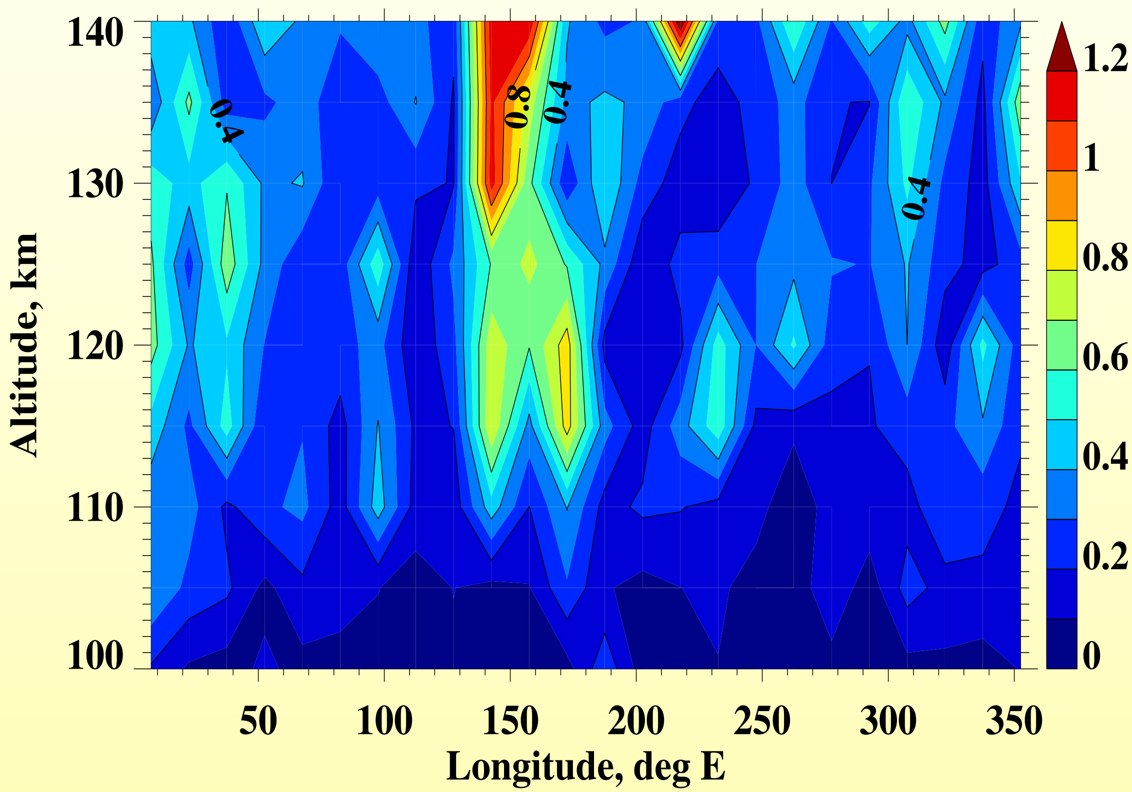


Ls = 90; F10.7 = 130; LAT = 62.5-77.5N

- A wave-3 oscillation appears for both simulated fields, in phase (triangles)
- F1-peak height responds to neutral density oscillations (SW1 migrating tide)
- Observed MGS/RS heights are plotted (solid curve plus 1-sigma errors)

Bougher et al. (2004)

Evidence of Mars Gravity Waves in UATM (Fritts et al. 2006)

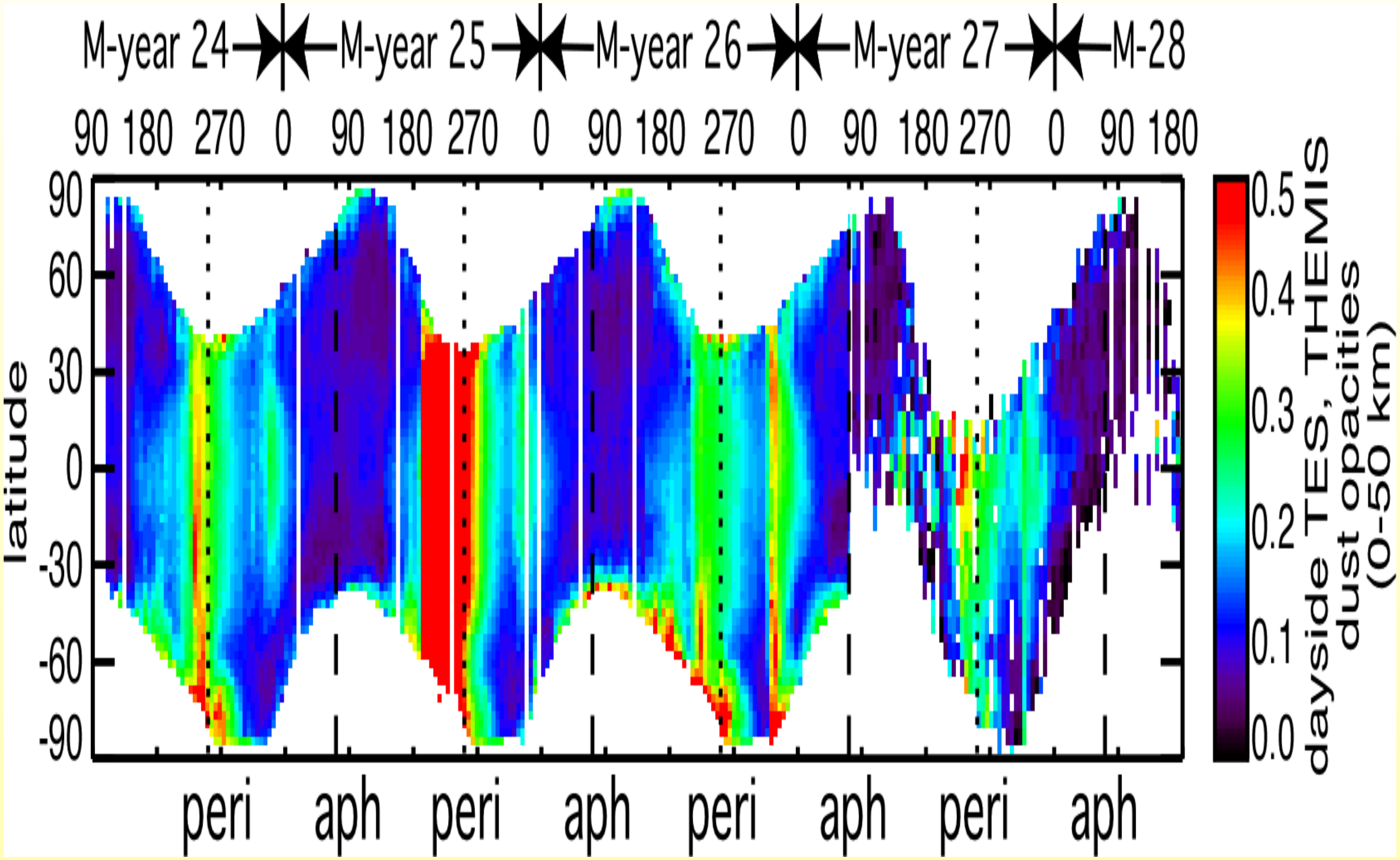


<u>Mars Odyssey Accelerometer</u>

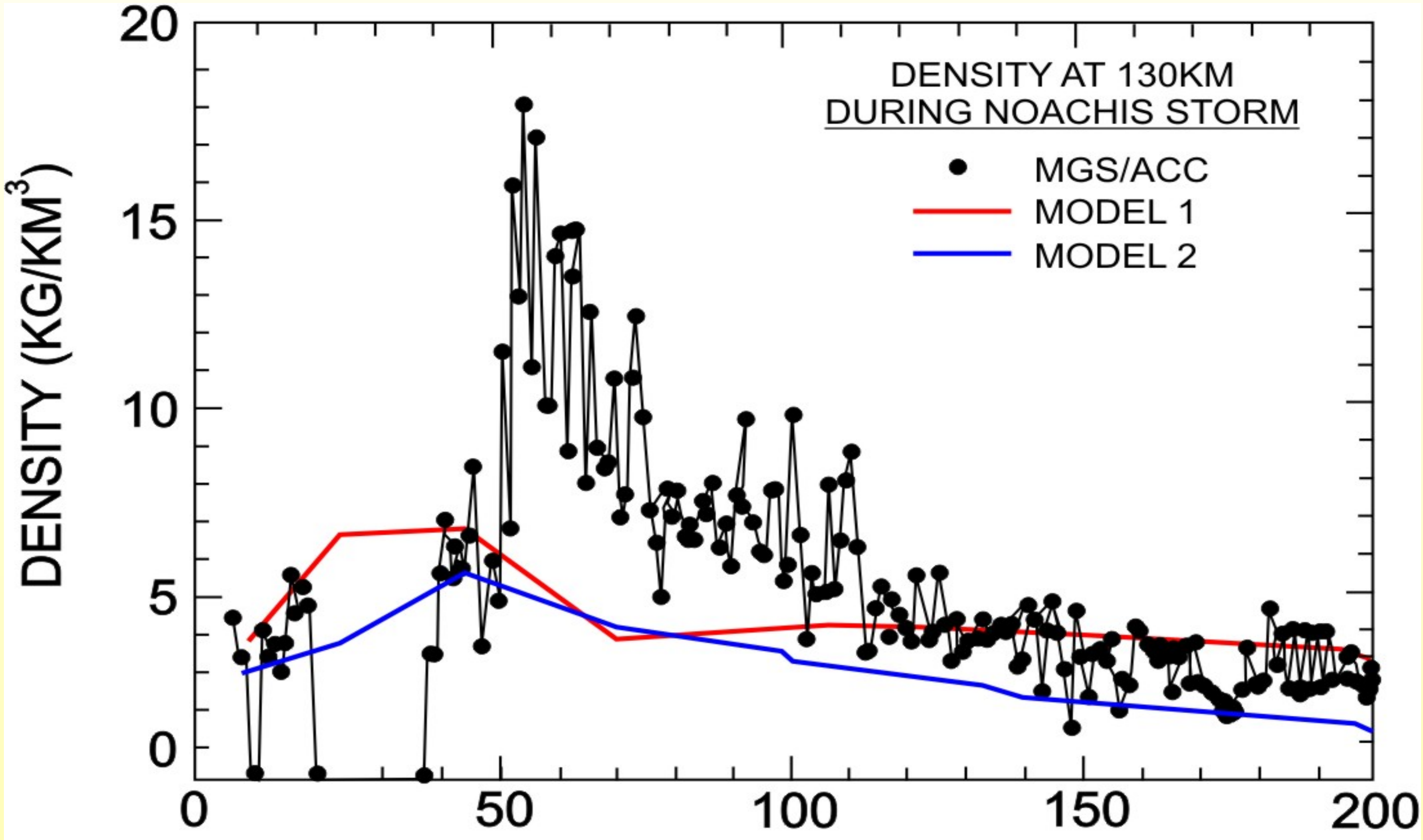
- •High Northern LAT
- •Ls ~ 260-310° (NH Winter)
- •ODY Orbits 7-134
- •λH~20-200 km scales
- •Δϱ/ϱ~ 5-50% typical (100-140 km)
- •130-180°E LON max GW variance, coherence w/ alt.
- •Dissipation, turbulent mixing, & momentum deposition likely
- •Filtering of GW field by non-migrating tides & pl. waves?

Survey of key datasets reflecting impact of Mars dust storms on UATM

Martian LATM Dust Opacities for Four Consecutive Mars Years (Lillis et al. 2010)

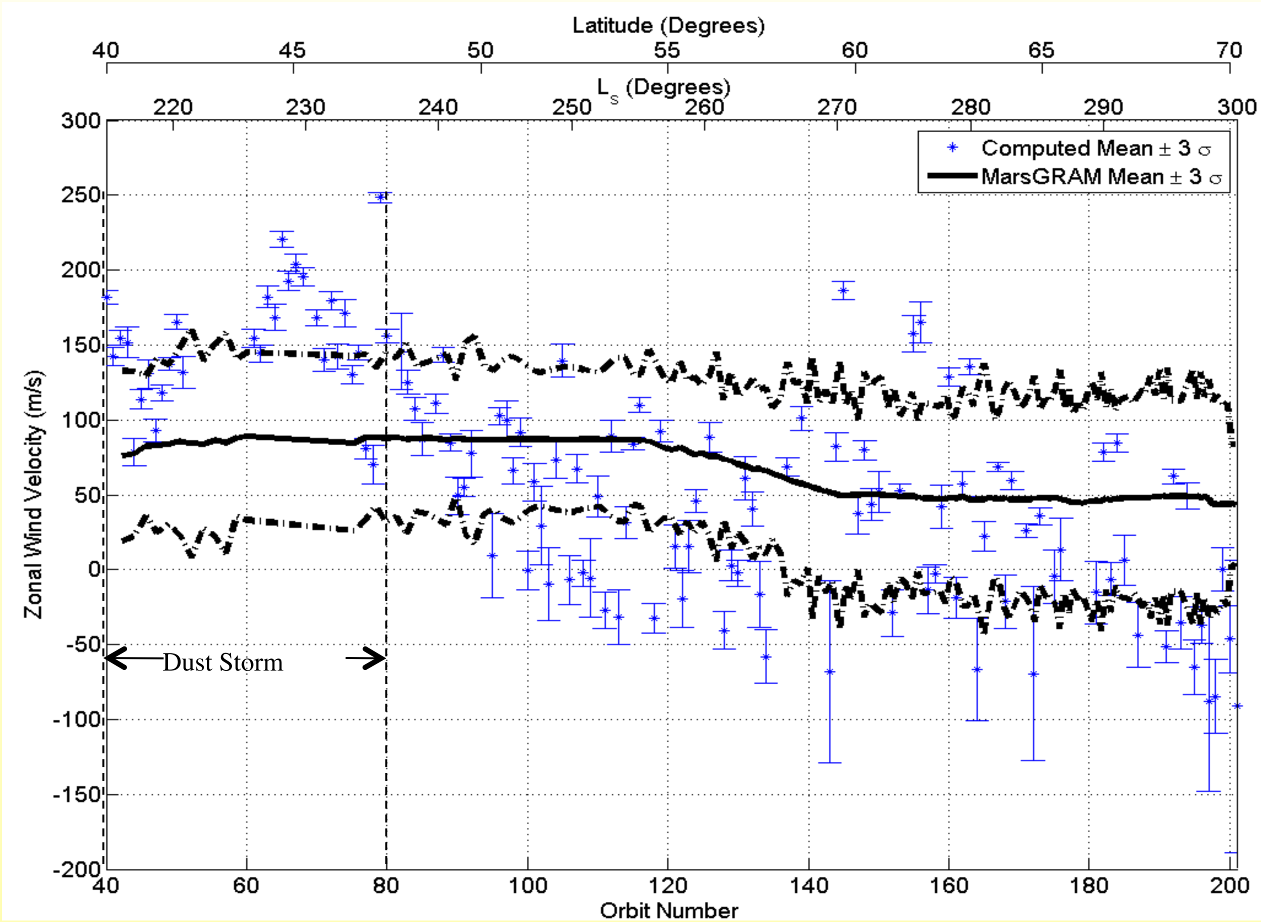


Dust Storm Impacts: Density at 130 km (Bougher et al., 1999)

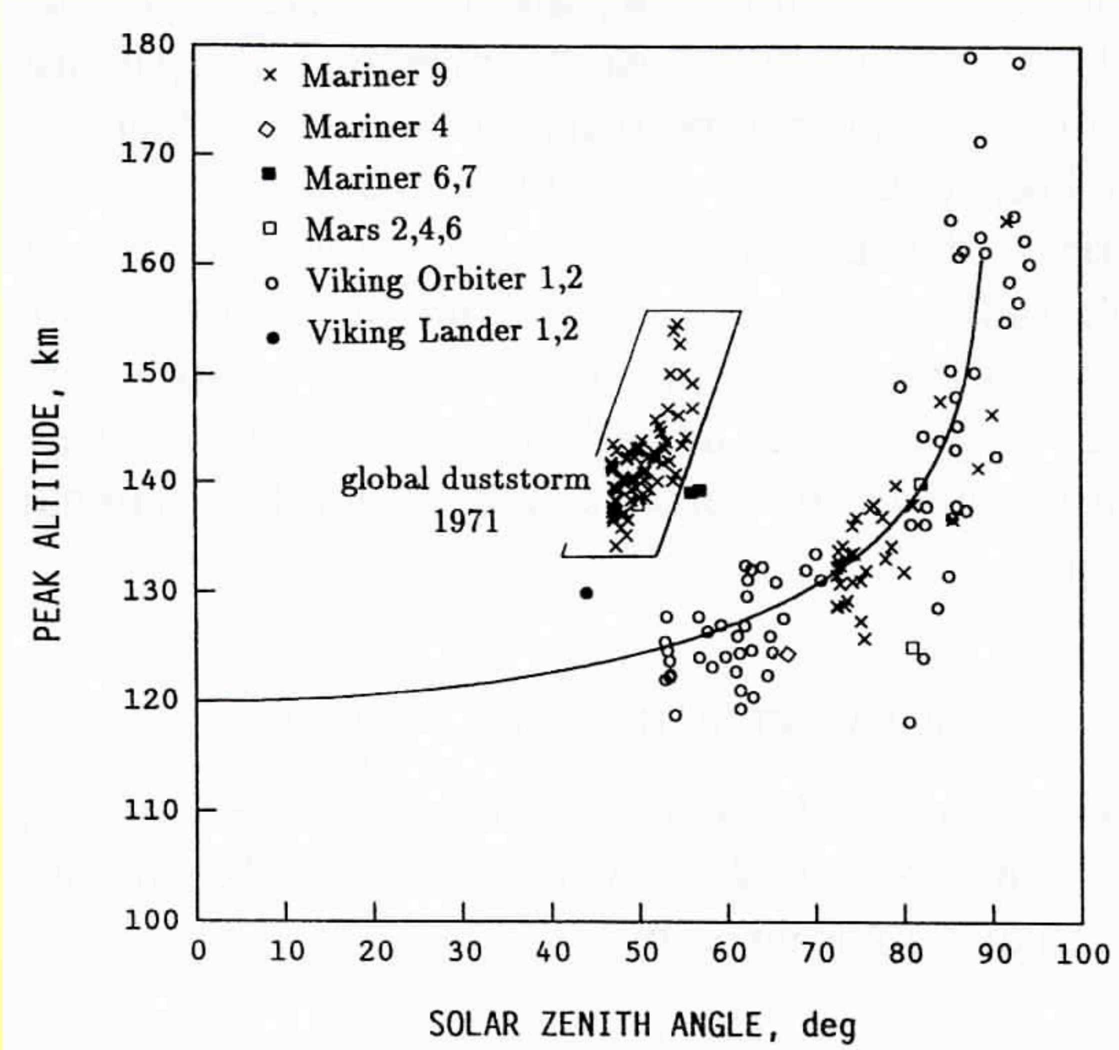


MGS Orbit Number

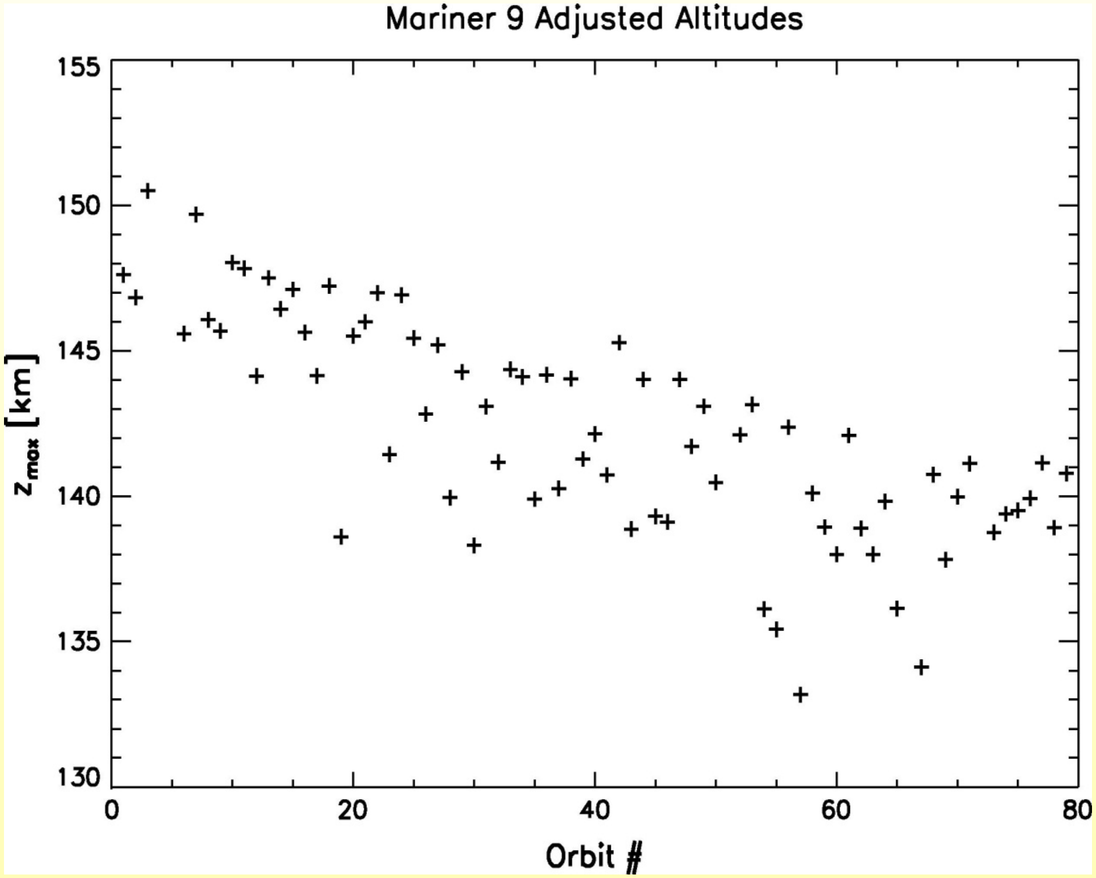
MGS Cross Track Winds (Baird et al. 2007)



F1-peak Altitude vs SZA for various RO pre-MGS Datasets (Hantsch & Bauer, 1990)



M9 Dayside Ion Peak Height During Decay of 1971 Global Dust Storm (Withers & Pratt, 2013)



SZA ~ 47-56°
Ls ~ 292-310°
F10.7 ~ 120
Href ~ 126 km
Duration ~ 30 days
(14-Nov. to 14-Dec. 1971)

M9 Global Dust Storm: 22-Sept-1971 to 15-Jan-1972

Survey of 3-planet upper atmosphere global models (TGCMs): Solar Cycle Responses

Key Model Parameters for VTGCM, TIE-GCM, and MTGCM

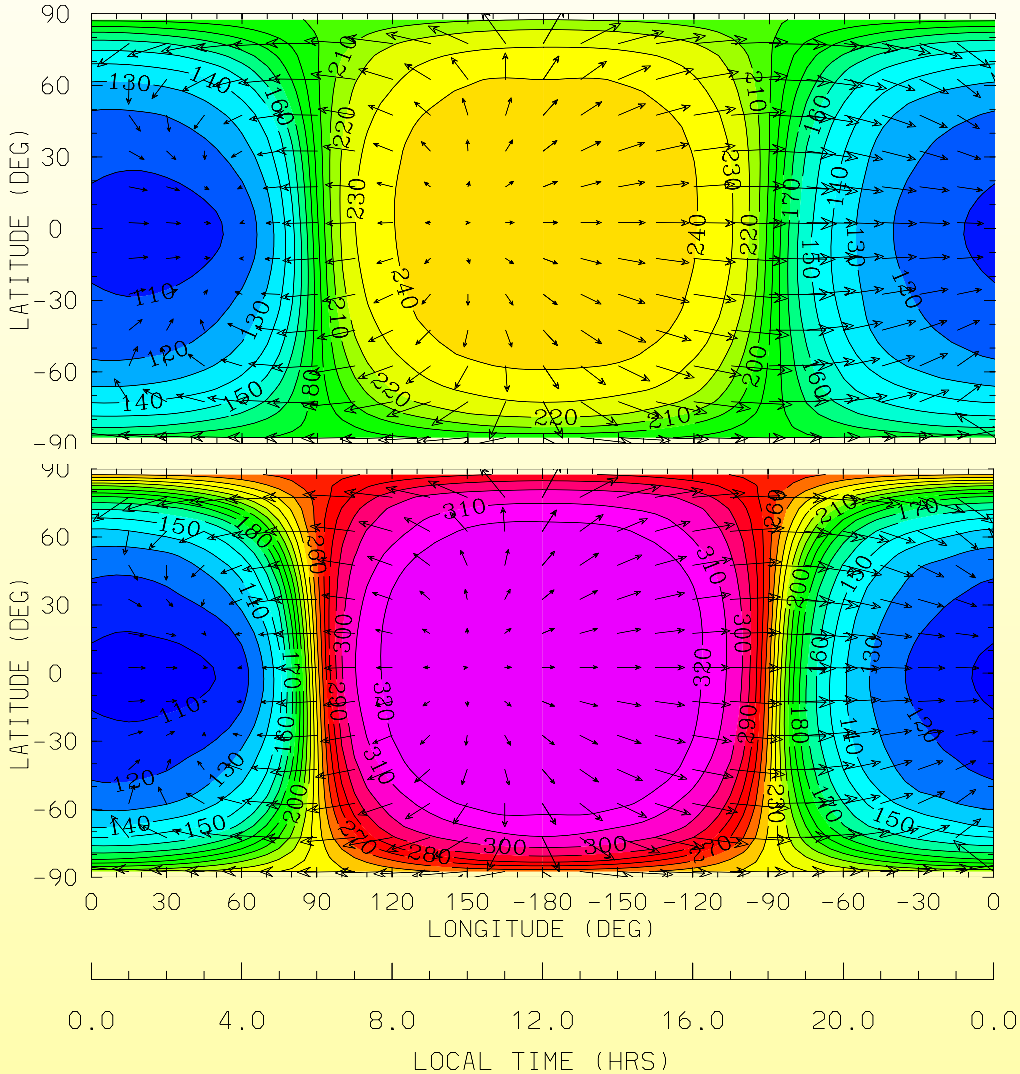
	VTGCM	TIE-GCM	MTGCM
Altitude Range	~70-200 km	~95-800 km	~70-250 km*
Vert. Resolution (pressure coor.)	H/2 or H/4	H/2 or H/4	H/2 thusfar
Horz. Resolution	5x5 or 2.5x2.5°	5x5 or 2.5x2.5°	5.0x5.0° thusfar
Major Neutrals	T, U, V, W, CO_2, CO, N_2,O	T, U, V, W, O, N_2, O_2	T, U, V, W, CO_2, CO, N_2,O
Major Ions	O_2^+, CO_2^+, O^+, N_2^+, NO^+	O_2^+,N_2^+,O^+, NO^+, N^+	O_2^+, CO_2^+, O^+, N_2^+, NO^+, CO^+
Minor Neutrals	N(4S), N(2D), NO, Ar, O_2	N(4S), N(2D), NO	N(4S), Ar, O_2
Rad. Cooling	CO_2 (15-µm)	CO_2 (15-µm) NO (5.3-µm) O (63-µm)	CO_2 15-µm
Time Step	Fixed (30-secs)	Fixed (120-secs)	Fixed (120-secs)

Unique VTGCM Processes

- Fox & Sung (2001) ion-neutral chemical reactions & rates.
- Solomon solar flux models (EUVAC plus UV to 175.0-nm)
- NLTE CO_2 15-micron reference cooling and near IR heating rates adapted from Roldan et al. (2000).
- Wave drag (or Rayleigh friction) used to reduce global winds toward realistic values (PVO and VEx constraints)
- Component of cloud-top RSZ winds present at T-I altitudes. Alternatively, asymmetric ion winds drive RSZ winds?

VTGCM T+UV at 180 km: SMIN/VEx and SMAX/PVO Conditions

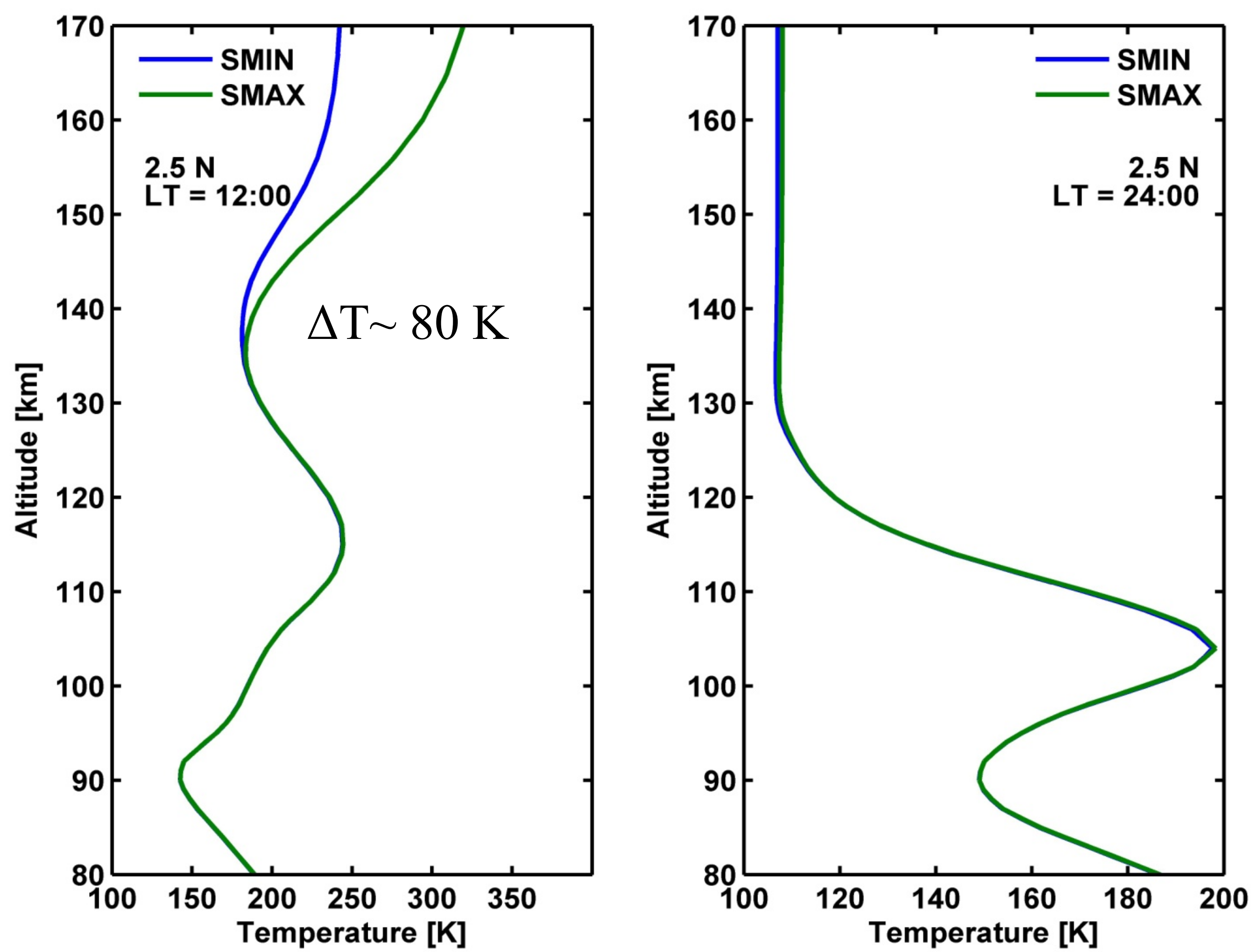
ΔT ~ 80 K
ΔT/ΔF10.7 ~0.34



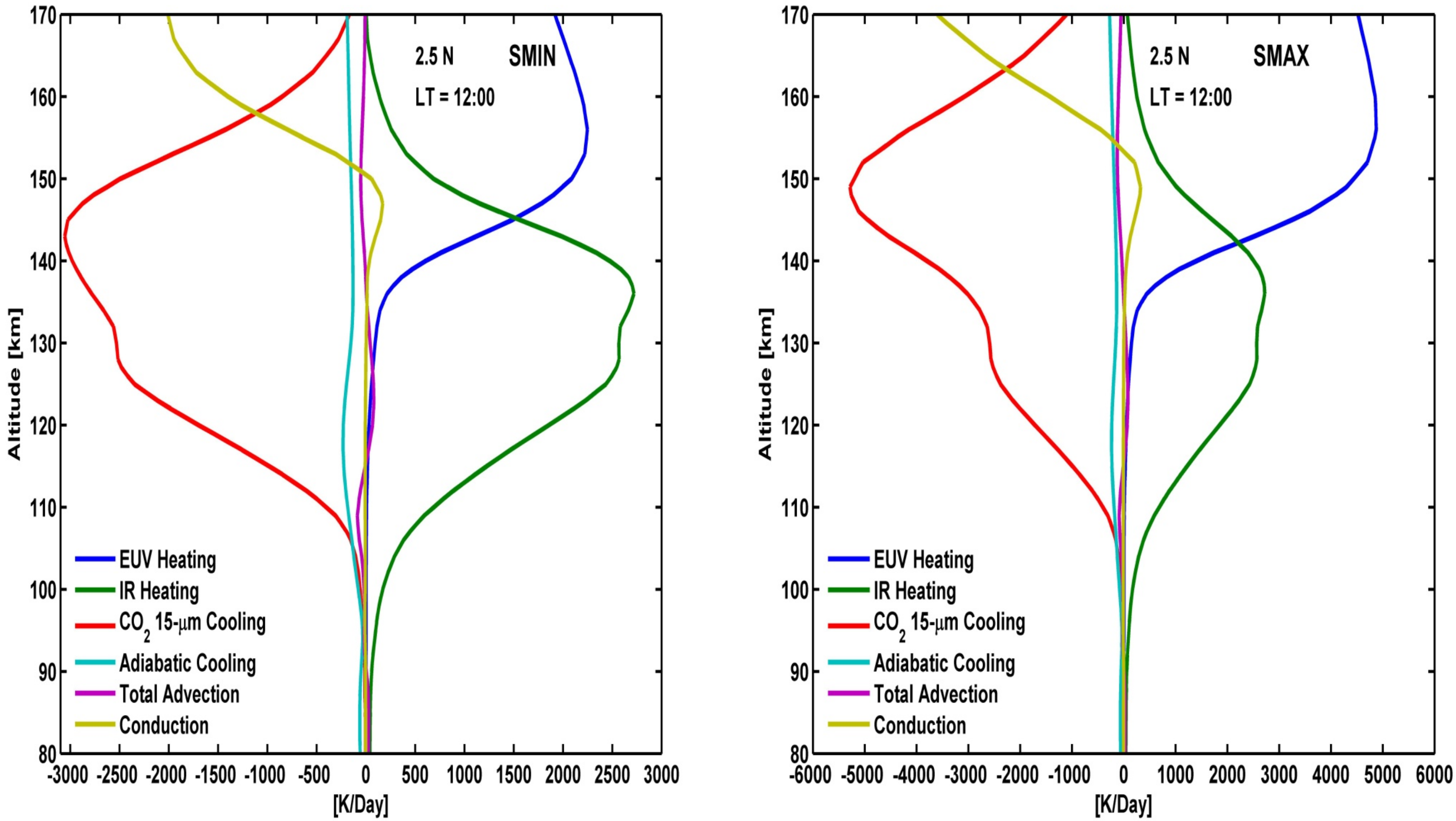
SMIN/VEx
Texo ~ 245 K
Umax ~ 290 m/s

SMAX/PVO
Texo ~ 325 K
Umax ~ 340 m/s

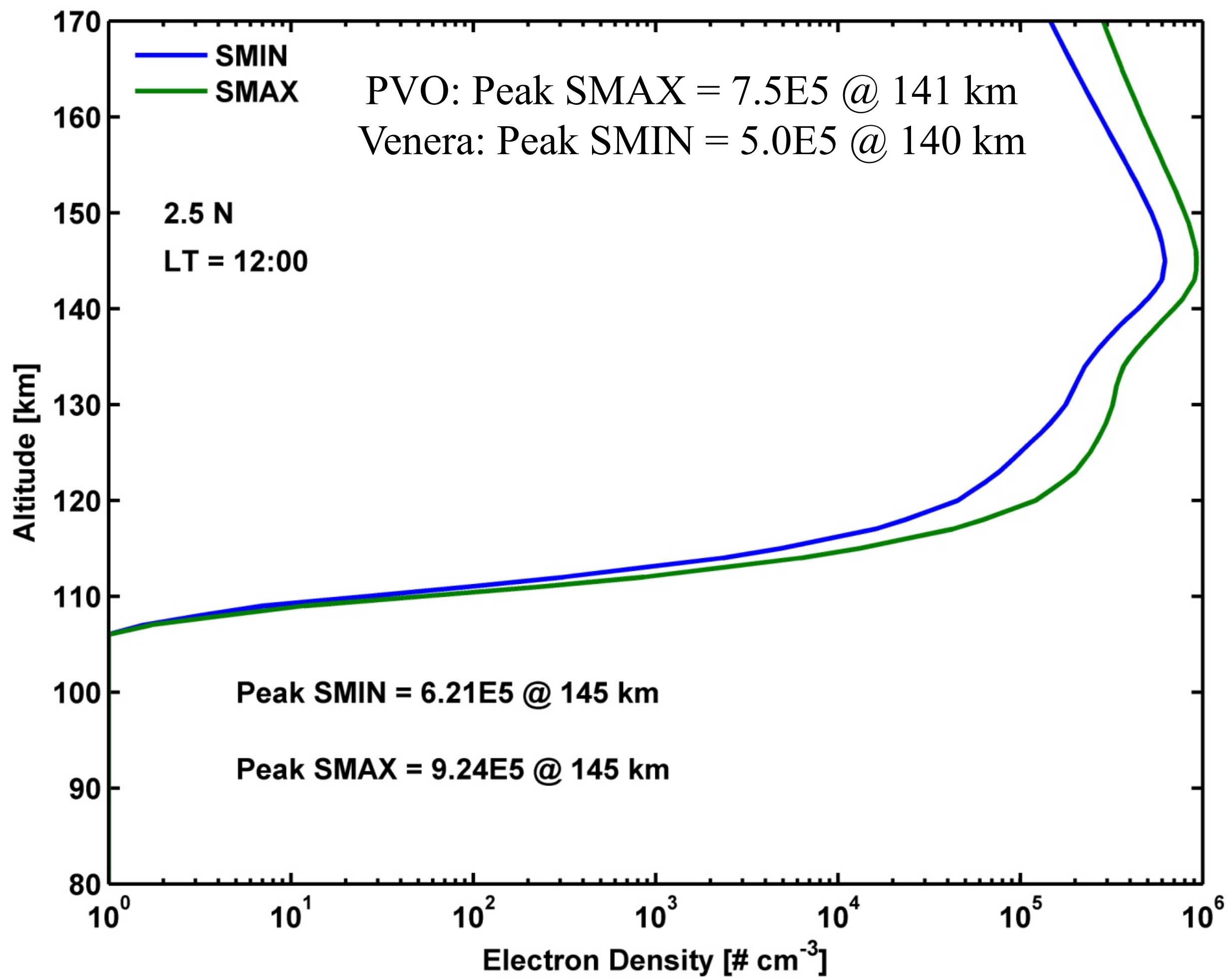
VTGCM T-Profiles: Dayside and Nightside for SMIN and SMAX Conditions



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



VTGCM Electron Density Profiles at SZA = 0: SMIN and SMAX Conditions

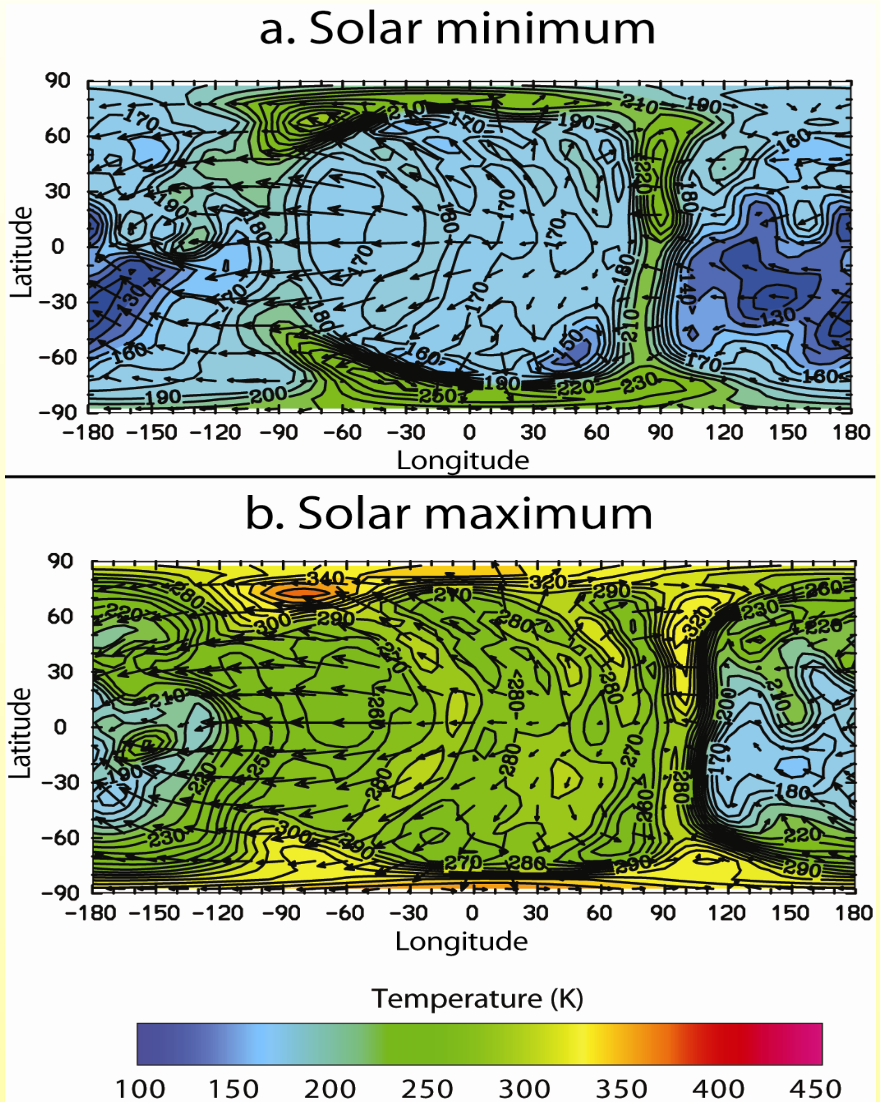


Unique MTGCM Processes

- Fox & Sung (2001) ion-neutral chemical reactions & rates.
- FISM solar flux models (1-190.0-nm) for solar minimum, moderate, maximum conditions (i.e. for low Ap and Kp).
- ±20% variation of fluxes received at planet due to orbital eccentricity.
- NLTE CO_2 15-micron cooling scheme and near IR heating rates adapted from M. Lopez-Valverde (pc. 2000).
- NASA Ames MGCM (0-90 km) and NCAR MTGCM (~70-300 km), coupled across an interface at 1.32-microbars on a regular 5x5º grid. Fields passed upward at interface (T, U, V, Z) on 2-min time-step.

  Coupling captures upward propagating migrating & non-migrating tides (seen in MGS, Odyssey, MRO aerobraking measurements)

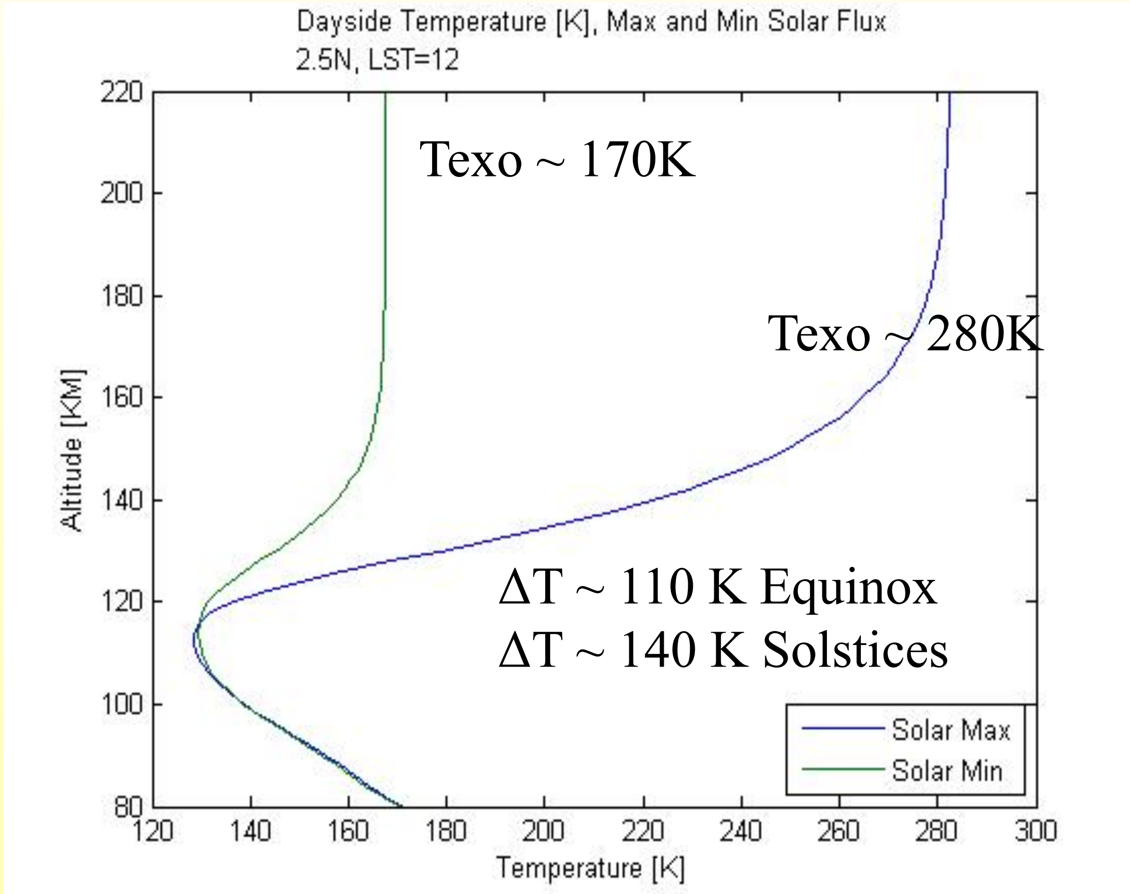
MTGCM Solar Cycle Variations at Equinox: Ls =180 (SMIN, SMAX) . Bougher et al., (2009)



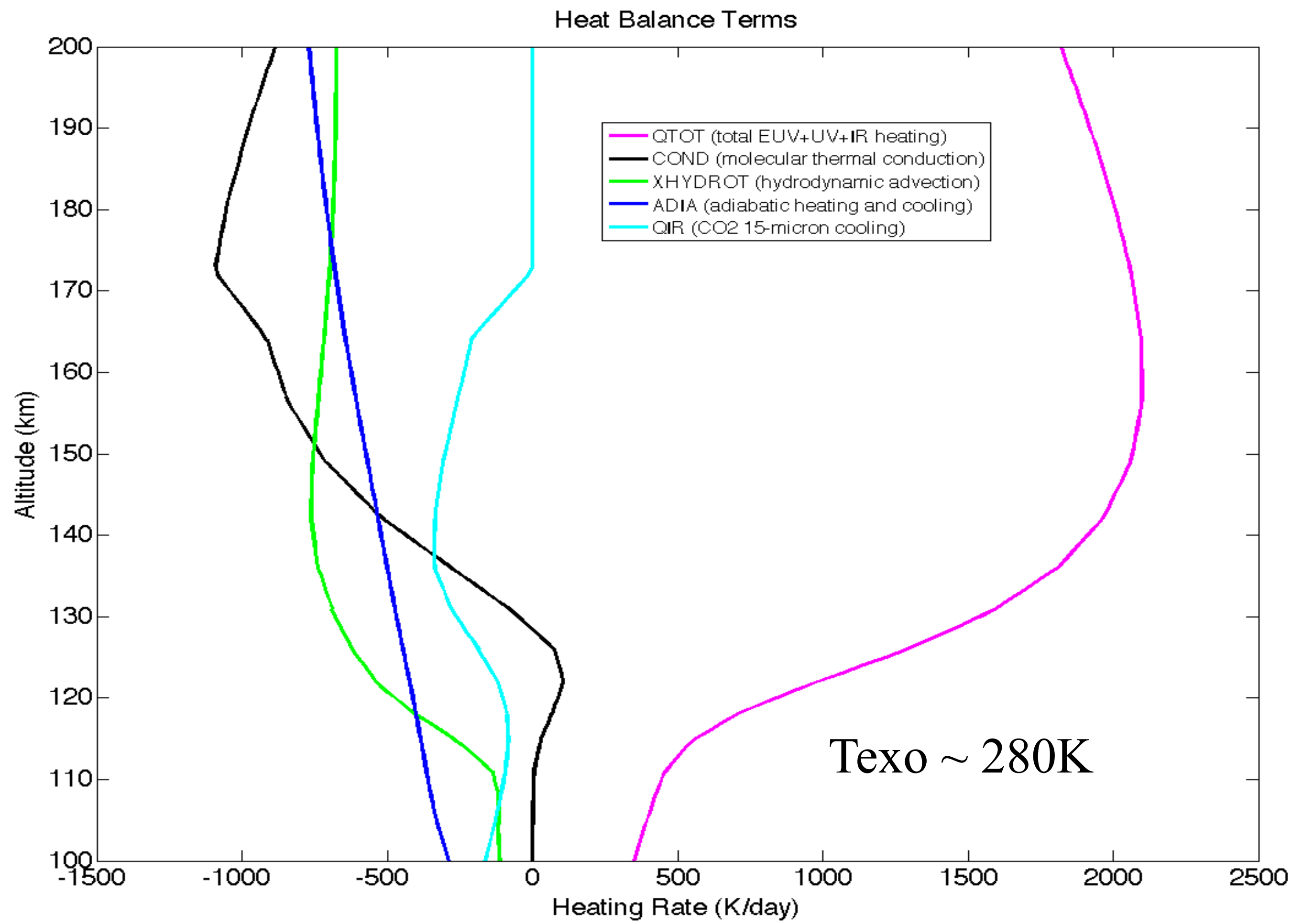
T~ 170K

T ~ 280K

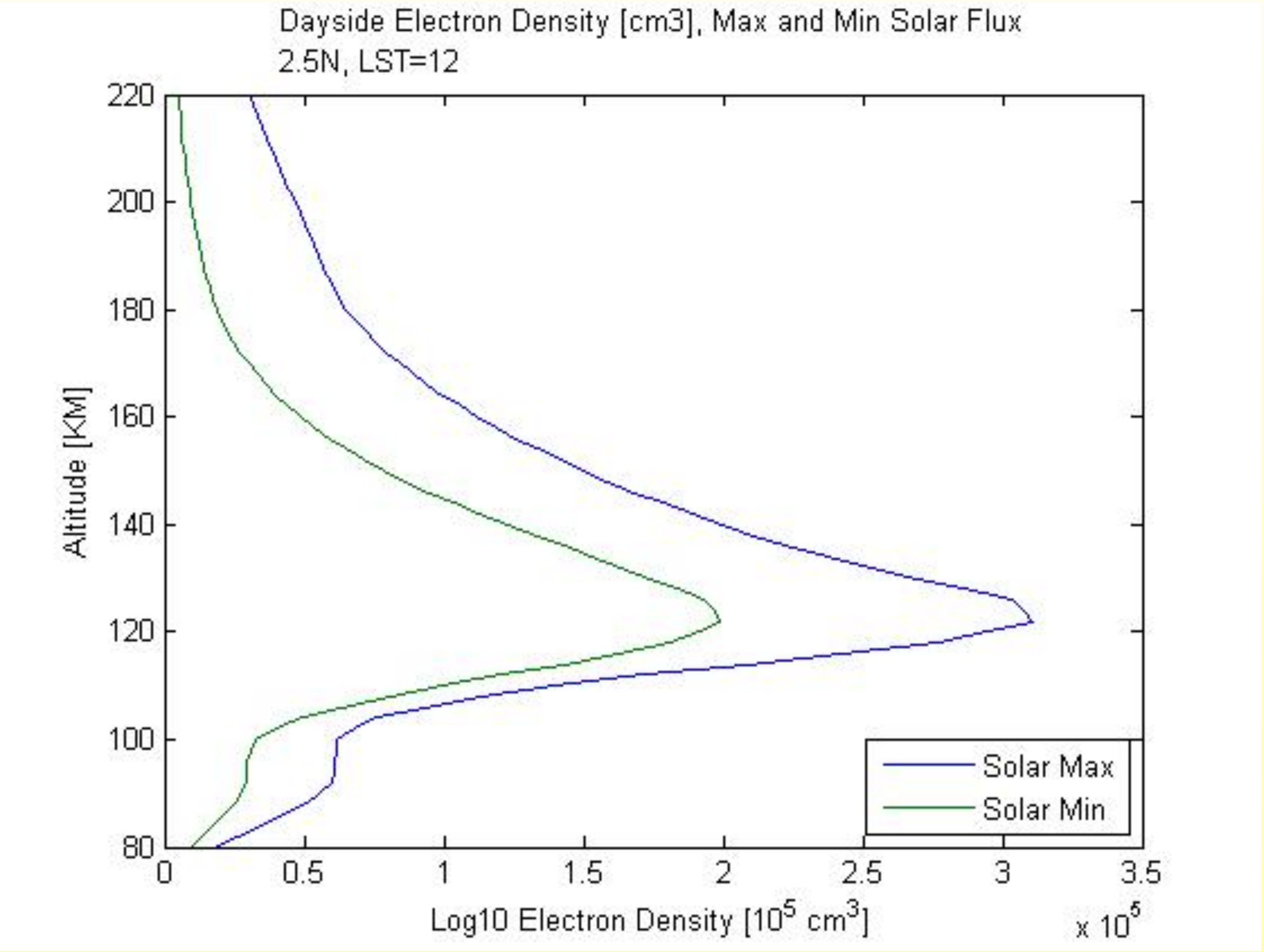
MTGCM T-Profiles: Dayside for SMIN and SMAX Conditions



MTGCM Thermal Balances at SZA = 0: SMAX Conditions (Equinox)



MTGCM Electron Density Profiles at SZA = 0: SMIN and SMAX Conditions

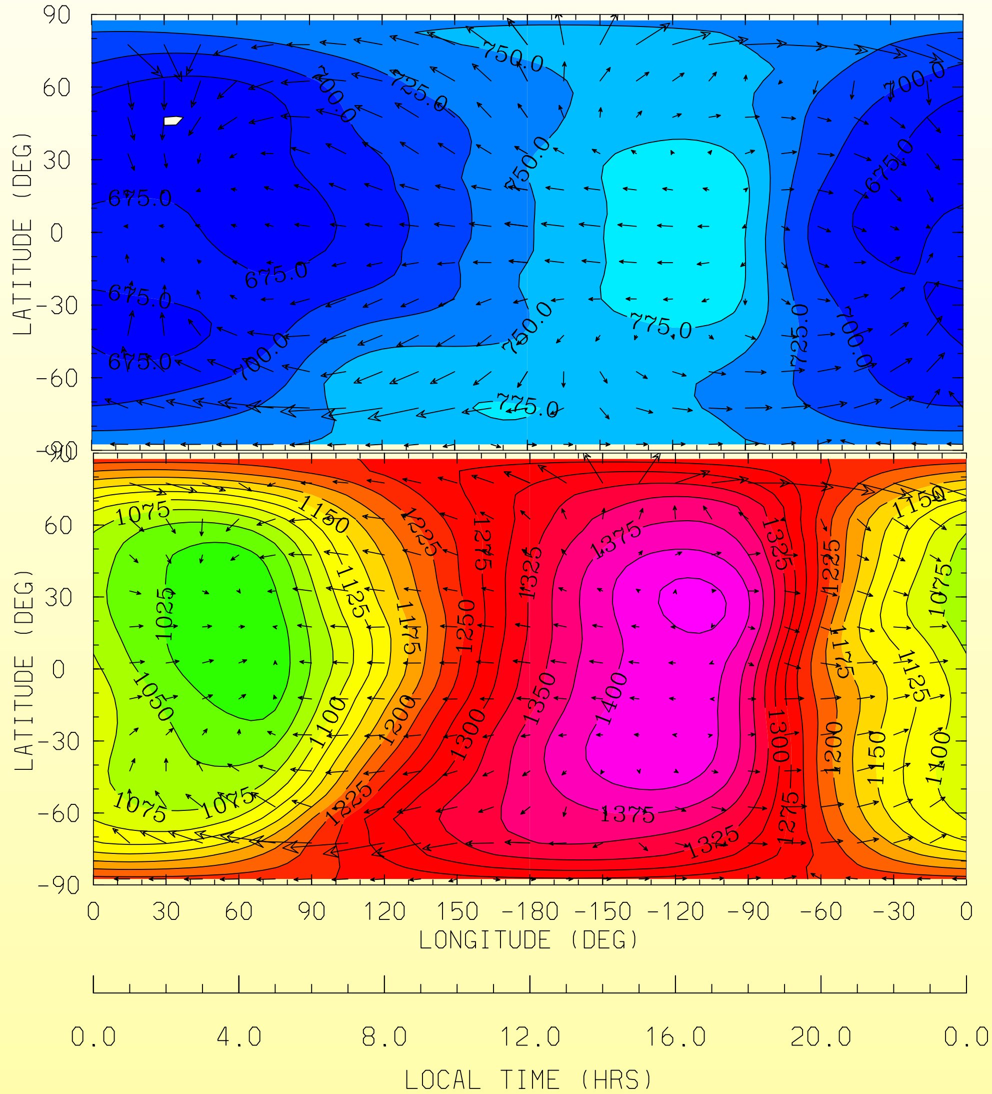


Unique TIE-GCM Processes

- Roble (1987) ion-neutral chemical reactions & rates.
- Solomon solar flux models (EUVAC plus UV to 175.0-nm)
- CO_2 (15-μm) and NO (5.3-μm) cooling parameterizations.
- O (63-μm) cooling parameterization from B&K (1973)
- Dipole magnetic field included
- Kp = 1 (for both Smin and Smax); mostly solar influence.

TIE-GCM T+UV at 400 and 500 km: SMIN and SMAX Conditions

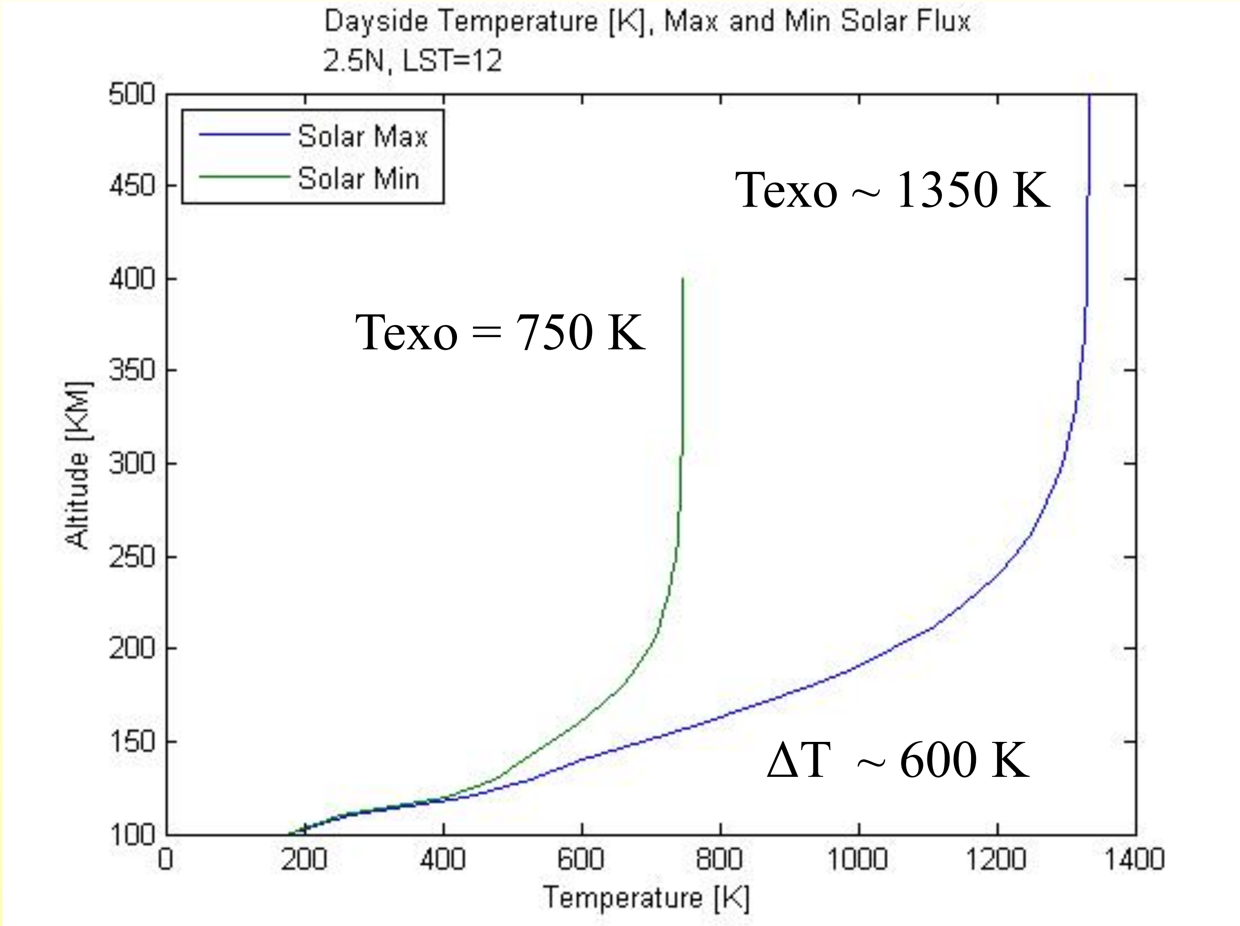
ΔT ~ 640 K



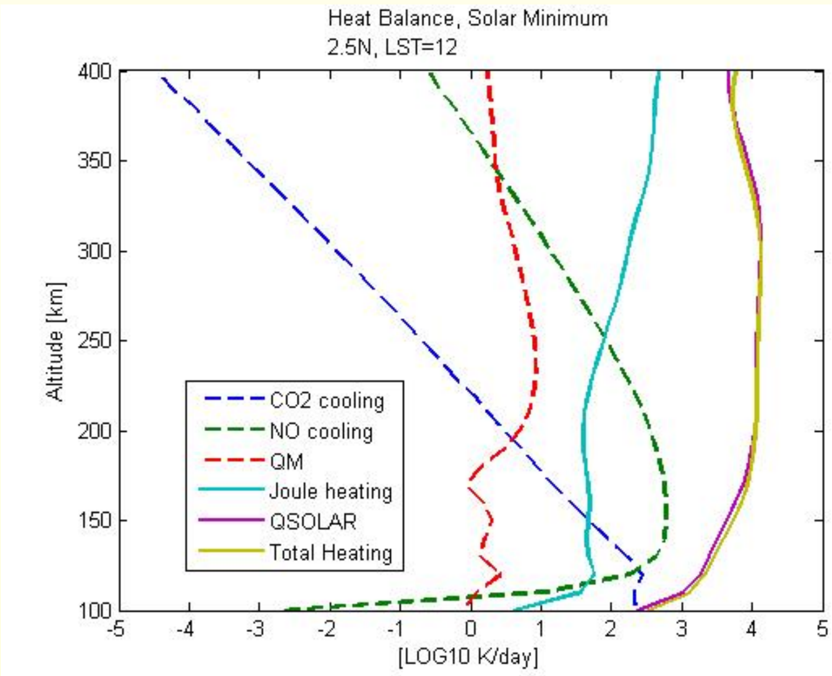
SMIN/EQU
Texo ~ 795 K
Umax ~ 295 m/s
Z = 400 km

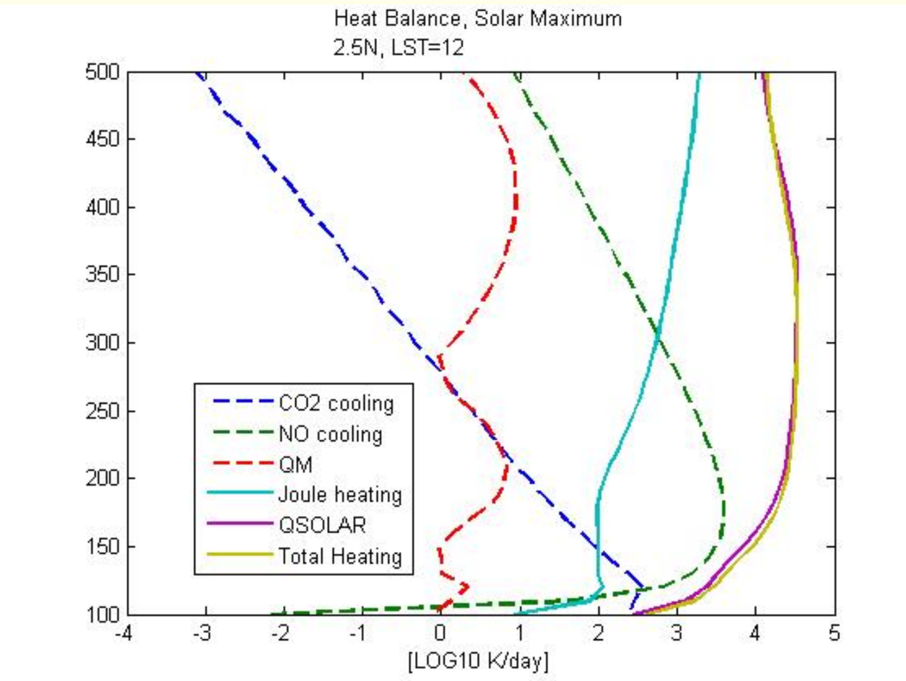
SMAX/EQU
Texo ~ 1434 K
Umax ~ 390 m/s
Z = 500 km

TIE-GCM T-Profiles: Dayside for SMIN and SMAX Conditions (SZA = 0)

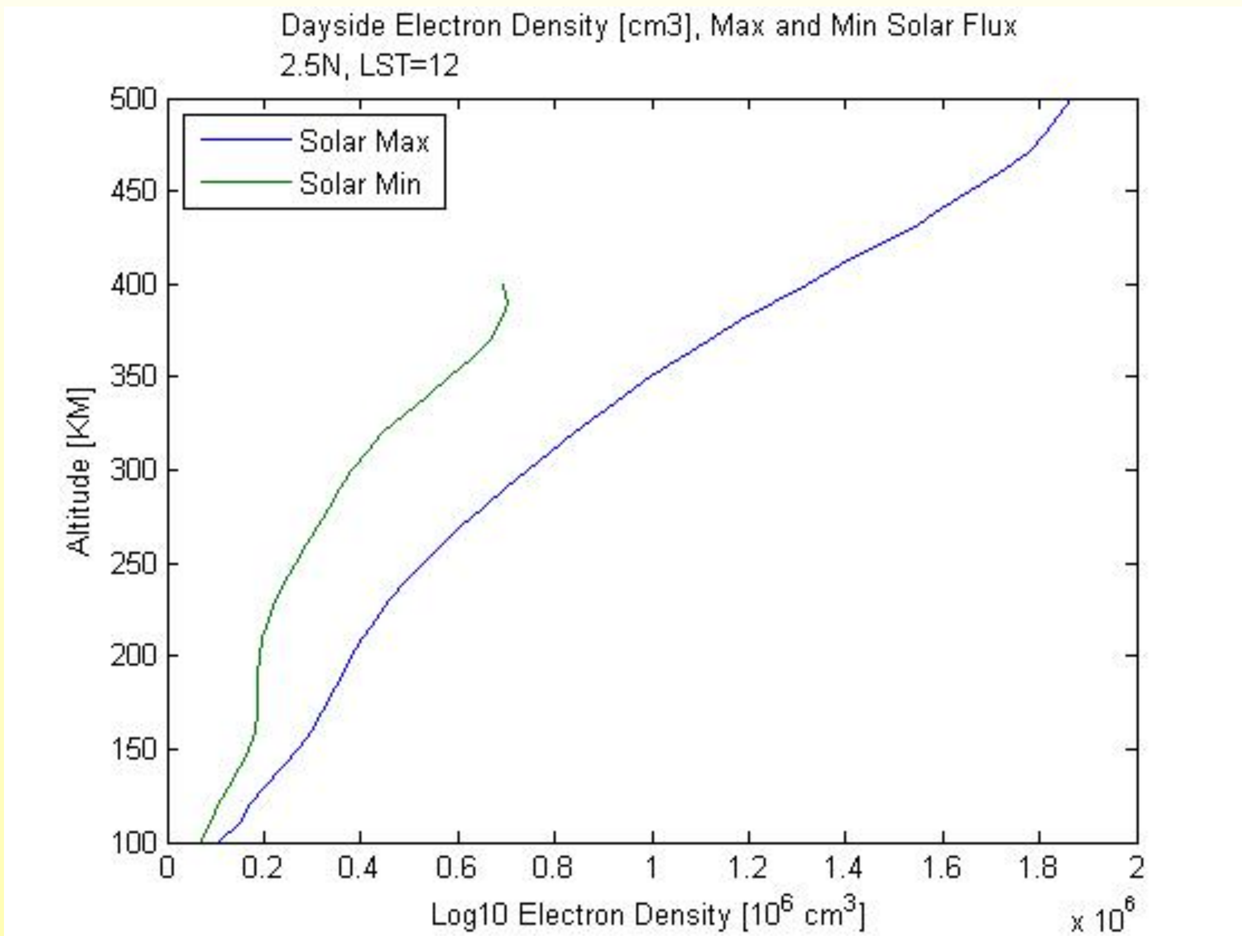


TIE-GCM Thermal Balances at SZA = 0: (SMIN and SMAX Conditions)



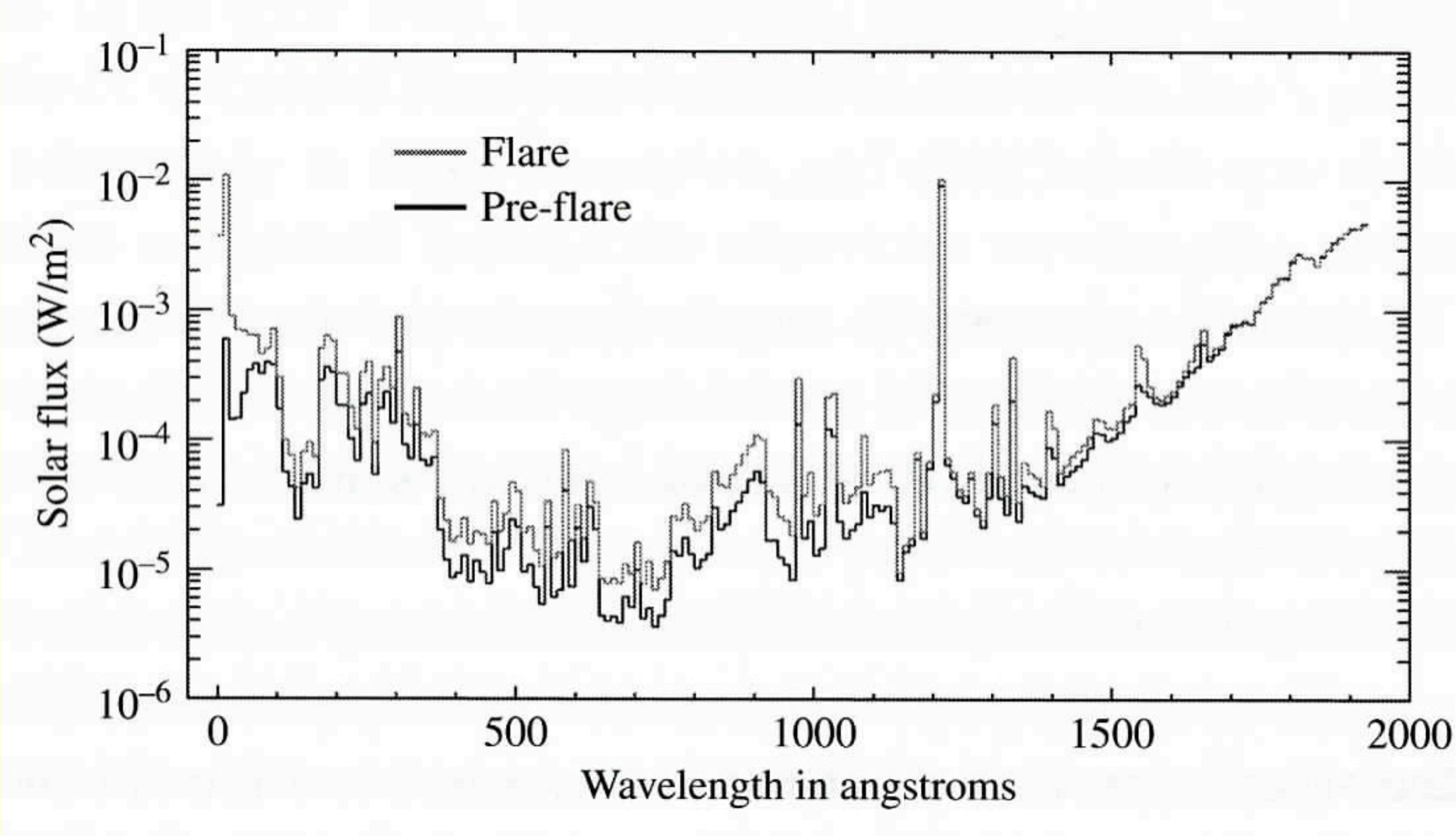


TIE-GCM Electron Density Profiles at SZA = 0: SMIN and SMAX Conditions

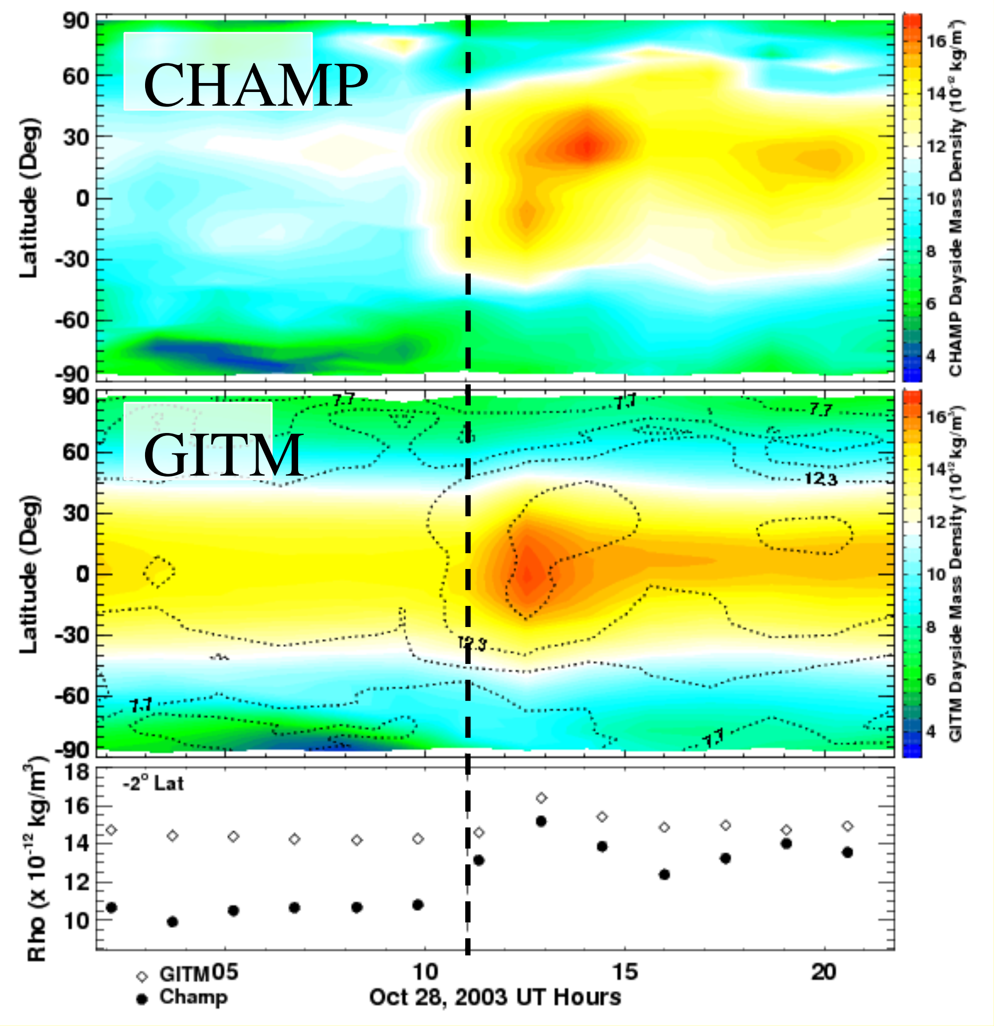


2-planet upper atmosphere global models (GITMs, TIE-GCM): Solar Flare Responses

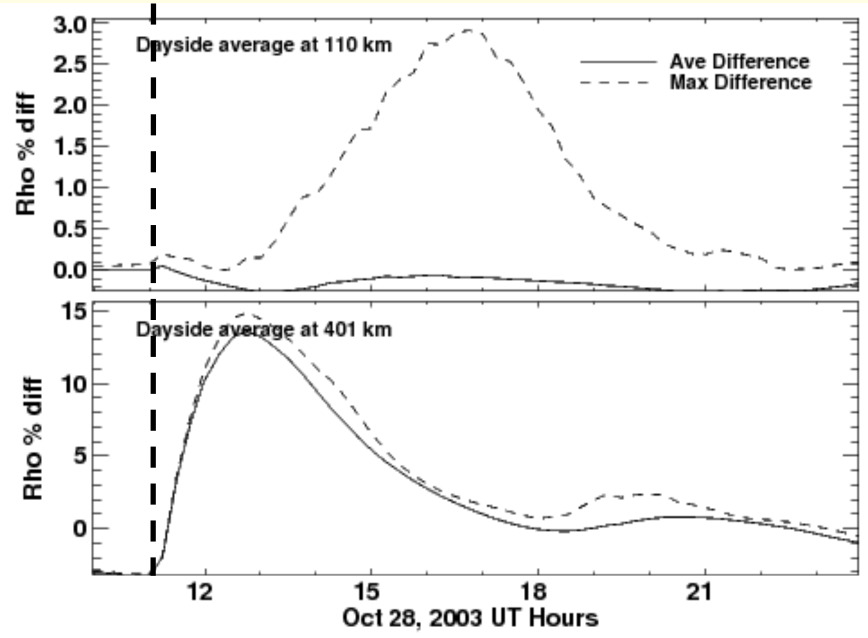
TIMED/SEE Solar Emission Spectrum near Peak of Oct. 28, 2003 Solar Flare (Fuller-Rowell and Solomon, 2010)



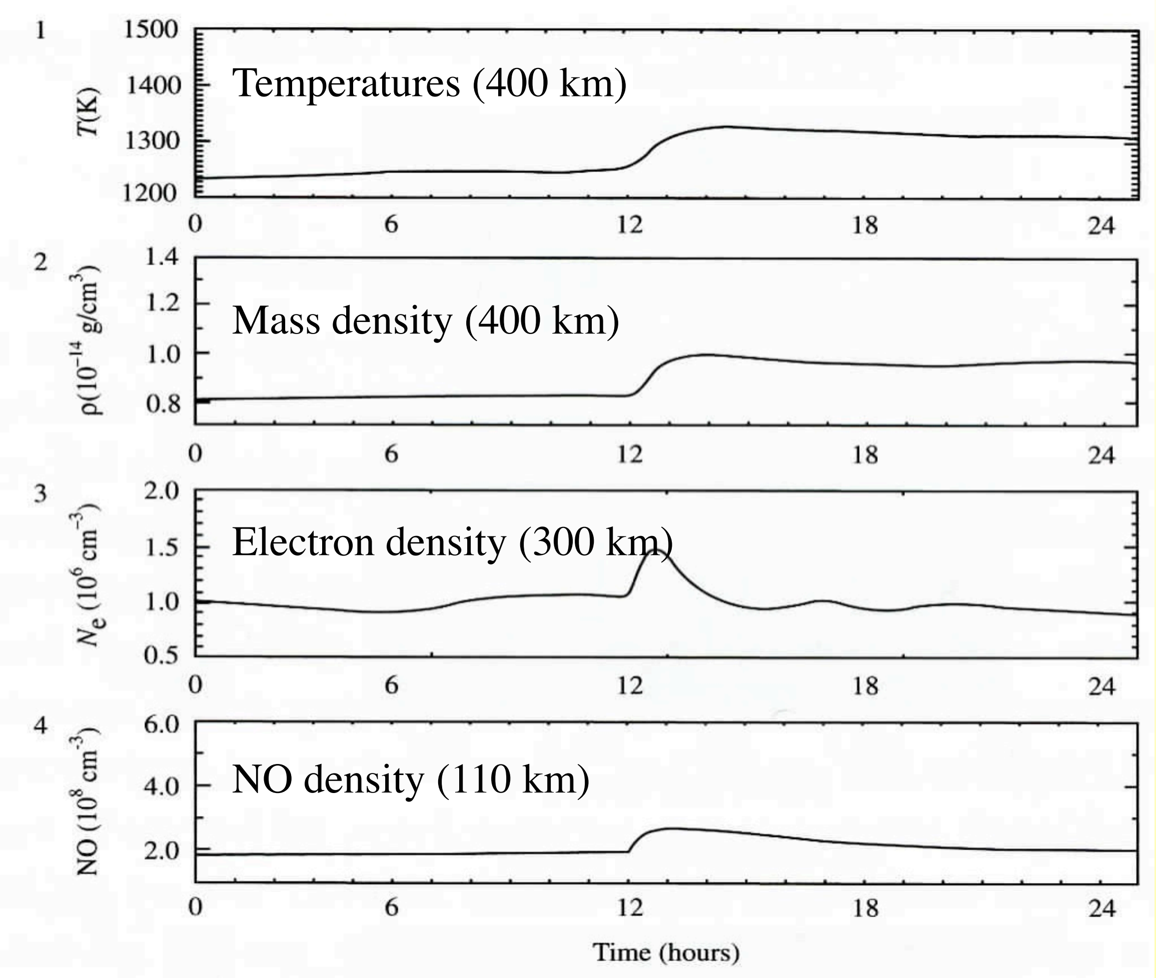
Earth Dayside Density: Data vs GITM



Pawlowski and Ridley, (2008)

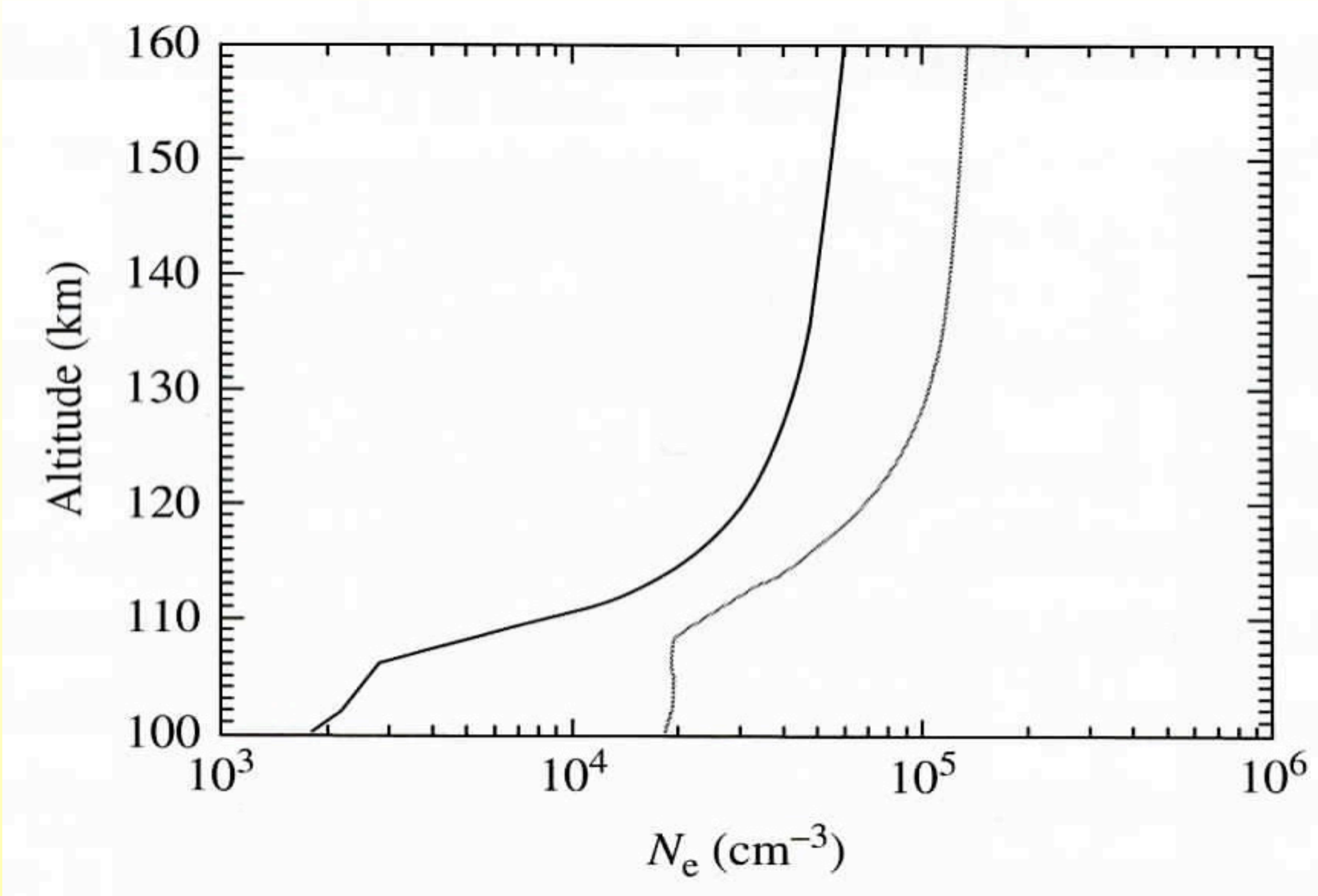


TIE-GCM Responses of Thermospheric Fields during Oct. 28, 2003 Flare (SLT =12; LAT = 0°)



Fuller-Rowell and Solomon (2010)

Model Calculations of Ne Enhancement in E-Region for Oct. 28, 2003 Flare (High SZA, Sondrestrom)



Fuller-Rowell and Solomon (2010)

Tale of Two Mars Models

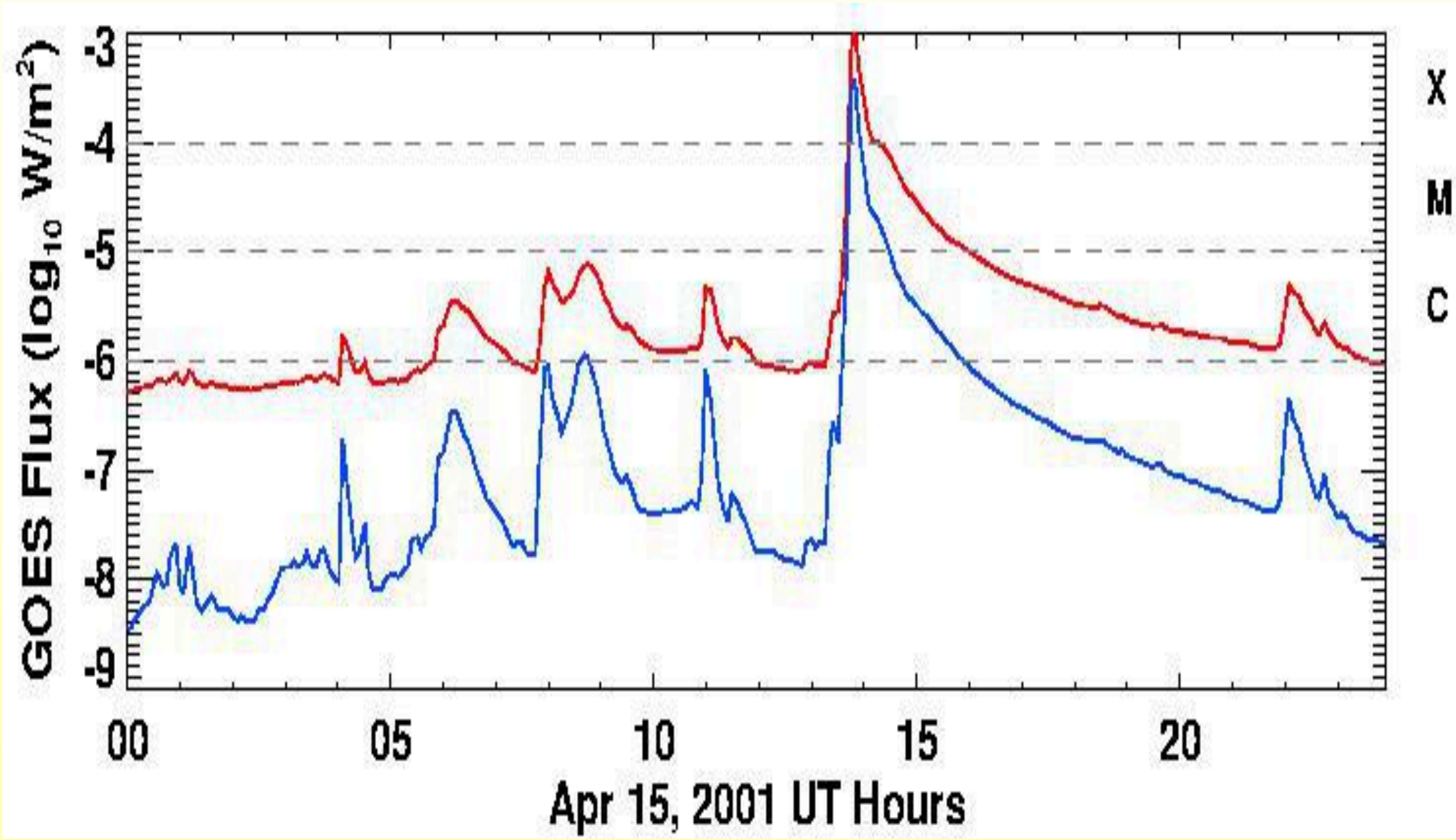
MTGCM

- Altitude range: ~70-300 km (coupled to NASA Ames GCM to 0 km)
- 5x5º or 2.5x2.5º latitude-longitude grid (pole-to-pole)
- Pressure vertical coordinate (1/2 or 1/4-H intervals): 33 to 66 levels
- Major Fields: T, **V**, O, CO, N_2, CO_2
- PCE ions Fields: CO_2+, O_2+, N_2+, NO+, CO+, O+
- Current Minor Fields: O_2 and Ar
- O, CO and O_2 sources and losses explicitly calculated.
- NLTE CO_2 15-micron cooling scheme and near IR heating rates adapted from M. Lopez-Valverde (pc. 2000)
- Topography (in Ames GCM): MOLA

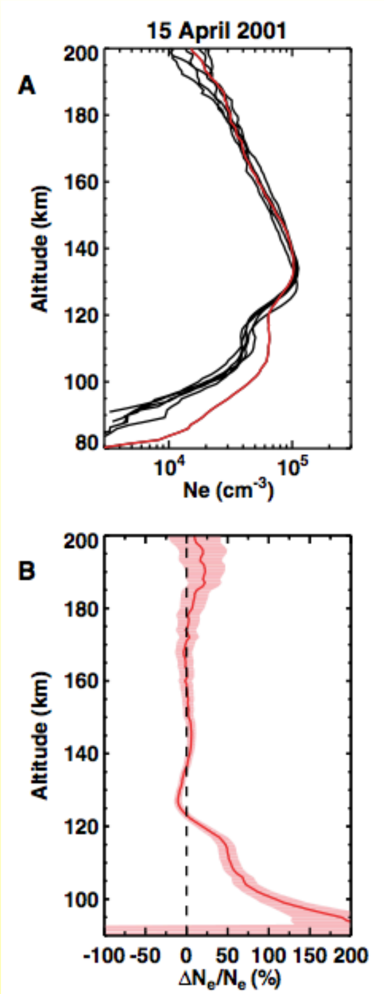
MGITM

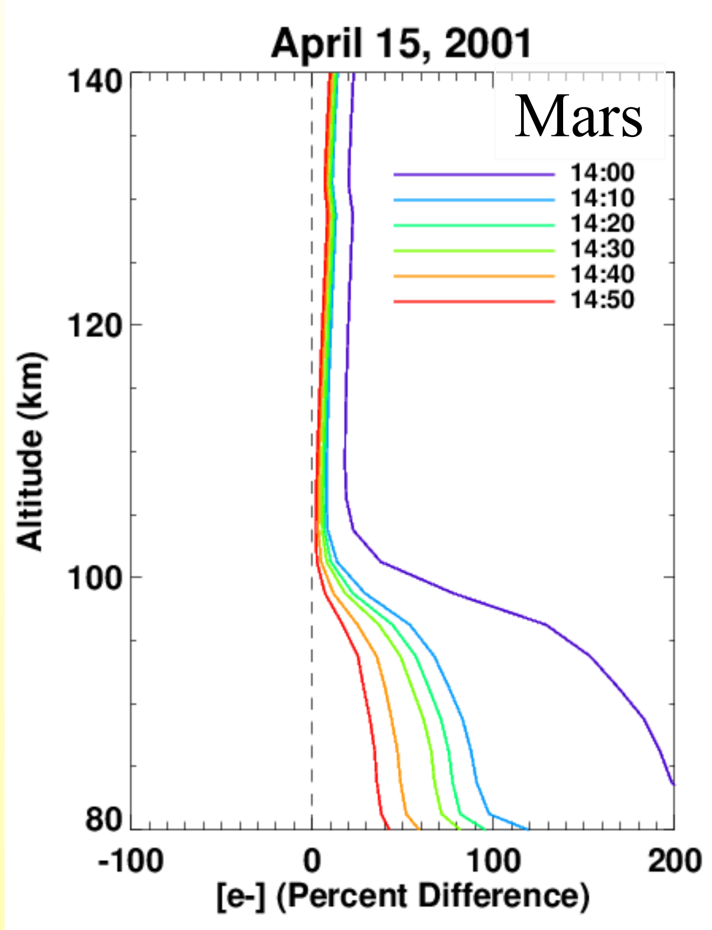
- 0-300 km
- Highly flexible horizontal resolution (pole to pole)
- Altitude vertical coordinate (2.5 km); No hydrostatic assumption
- T, **V**, O, CO_2, CO, N_2, Ar, O_2
- CO_2+, O+, O_2+, N_2+, NO+
- N(4S),N(2D),NO
- All sources and losses explicitly calculated; major species have their own V_{up}
- Same NLTE CO2 scheme
- MOLA Topography added and is currently being validated

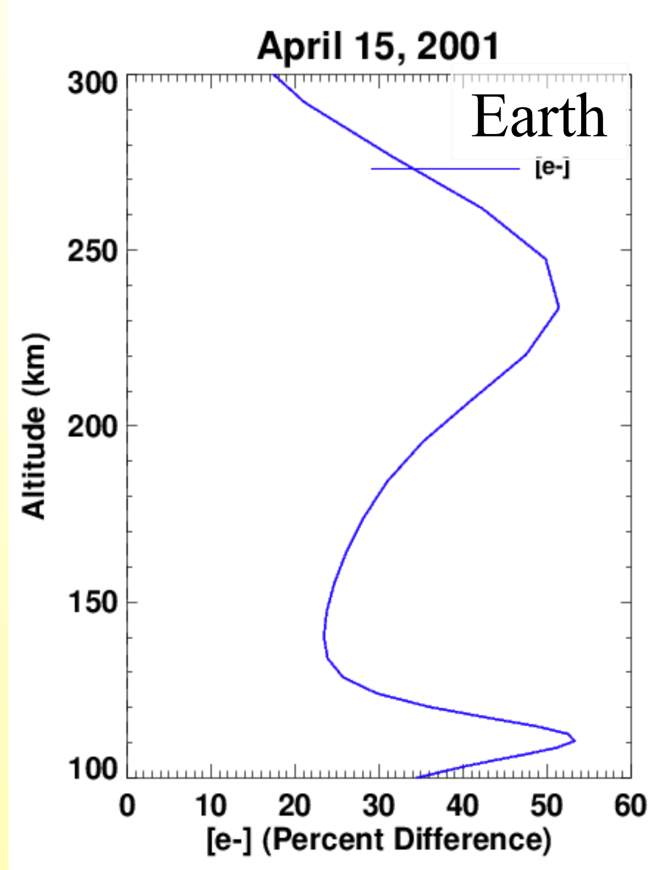
GOES Satellite soft X-ray Solar Fluxes Spanning the April 15, 2001 Solar Flare



Mars vs Earth Ionospheric Responses







Lollo et al. (2012) show photoelectron ionization is necessary to achieve observed E-region Mars electron densities

Major Take Aways (1)

Topside Coupling (SC variations and associate thermal balances):

- Venus has the smallest variation in Ts over the solar cycle due to thermostatic control by CO_2 cooling (cold Ts yet closest to sun).Weak solar cycle response.

- Mars Ts are regulated by large scale dynamics and thermal conduction, yielding variations over solar cycle midway between Venus and Earth.

- Earth Ts are regulated mostly by thermal conduction and NO cooling. Warmest Ts and largest variations over the solar cycle due to largest EUV-UV heating efficiency and "weak" thermostats (above).

- Role of CO_2 15-µm cooling on the thermal budgets of the 3-planet upper atmospheres is profoundly different. Earth: UATM component of CO_2 greenhouse warming of LATM.

Topside Coupling (Solar flare variations):

- Space weather impacts (e.g. solar flares) will depend in part upon these thermostats (especially Earth and Mars). Larger magnitudes of ionospheric and thermospheric responses predicted (thusfar) for Mars compared to Earth.

Major Take Aways (2)

Bottomside Coupling (Tides and planetary waves)

- All 3-terrestrial planet upper atmospheres are significantly alterred by upward propagating planetary waves and tides (winds, densities, temperatures, etc).
  --Aerobraking at Mars has greatly contributed to characterization & analysis.
  --Venus UATM responses still being addressed for the first time. Wave drag?
- The sources for these wave are different for each of the three planets (e.g. Mars variable dust heating and topography; Earth LATM dynamics and thunderstorms; Venus cloud top convection and LATM dynamics).
- Mars dust storms profoundly impact the Martian upper atmosphere (temperatures, densities, winds, etc). No counterpart for Venus or Earth.

Future:

- MAVEN (2013-2016) will fly three solar diodes at Mars, from which the EUV-UV solar spectrum will eventually be reconstructed (using FISM). Model forcing. Detailed comparison of Earth vs Mars solar flare responses.
  MAVEN sampling (all SLT) will characterize tidal amplitudes and phases.
- Venus Express observations of UATM may yet characterize tidal and planetary wave responses (i.e. several year baseline of measurements).