Thermal Structure of the Martian Upper Atmosphere from MAVEN NGIMS

Shane W. Stone,[1] Roger V. Yelle,[1] Mehdi Benna,[2] Meredith K. Elrod,[2] Paul R. Mahaffy[2]

[1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ

[2]NASA Goddard Space Flight Center, Greenbelt, MD

Introduction

- We calculate neutral temperatures from NGIMS Ar densities.
  - We do this by assuming hydrostatic equilibrium and using the ideal gas law.
  - This work was submitted to the *Mars Aeronomy* special issue in *JGR: Planets*.

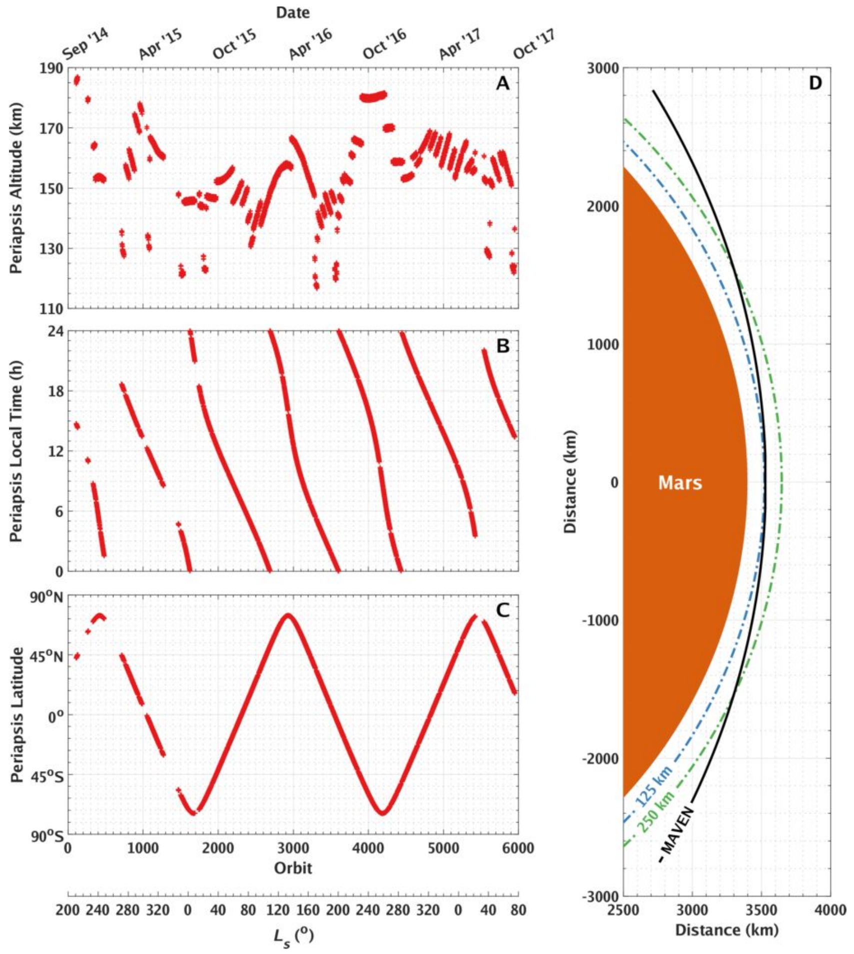
- In the interest of time, I will not cover…
  - … the finest details of the calculation of NGIMS densities.
  - … in-depth comparisons of NGIMS neutral temperatures with other *in situ* and remote measurements.

- Prior to MAVEN NGIMS, *in situ* measurements of upper atmospheric neutral temperature were quite sparse.
  - Single temperature profiles from some entry probes, landers, and rovers
  - More extensive measurements from MGS, ODY, and MRO accelerometers
  - The MENCA mass spectrometer on MOM has obtained some neutral temperatures

Coverage of Mars

- NGIMS greatly extends coverage of the Martian exosphere and thermosphere.
  - Measurements extend to the mesopause during DDs.
  - 4231 orbits of inbound data in this manuscript.
  - The data ends with DD8.

- The MAVEN orbit provides excellent coverage in local time and good coverage in latitude.

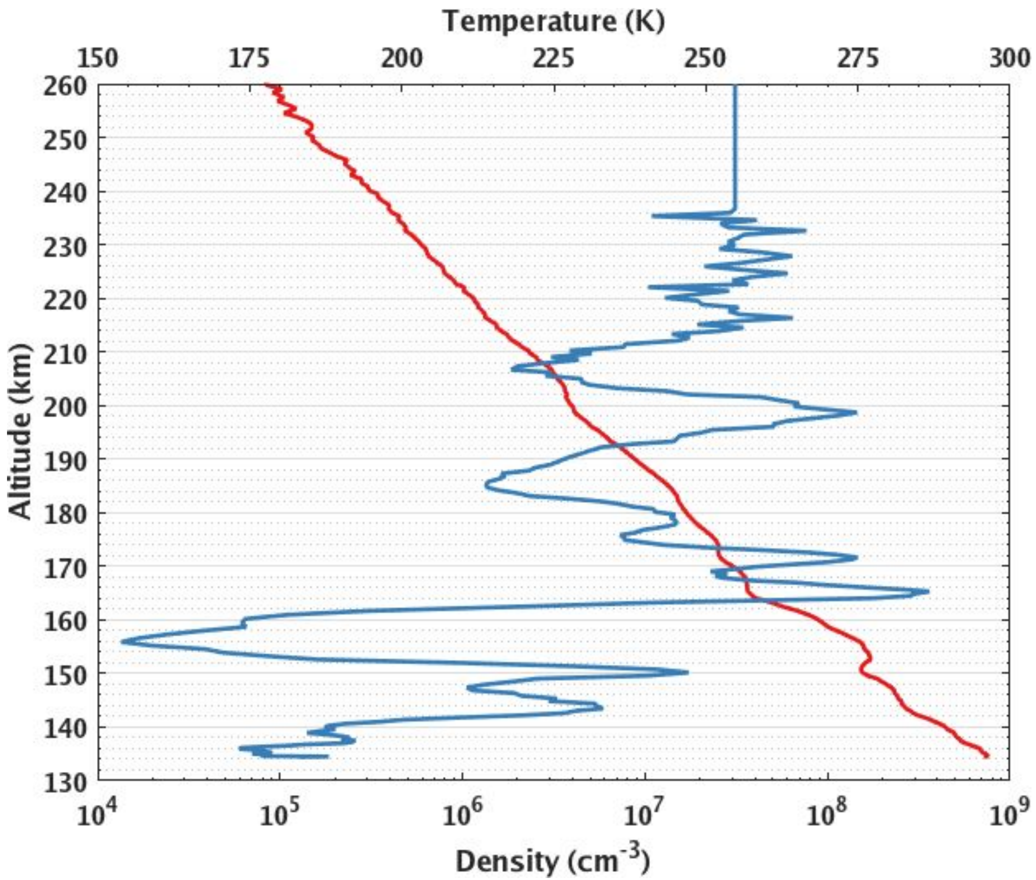


DENSITIES AND TEMPERATURES

- We calculate Ar, CO_2, and N_2 densities. O densities are discussed briefly.

- Background signal is removed and corrections are made for instrumental and spacecraft effects.

- We calculate the neutral temperature from Ar, CO_2, and N_2, but Ar provides the most reliable neutral temperatures since Ar is exceptionally inert.



Temperature Derivation

- At the top of the atmosphere, we assume an isothermal temperature,

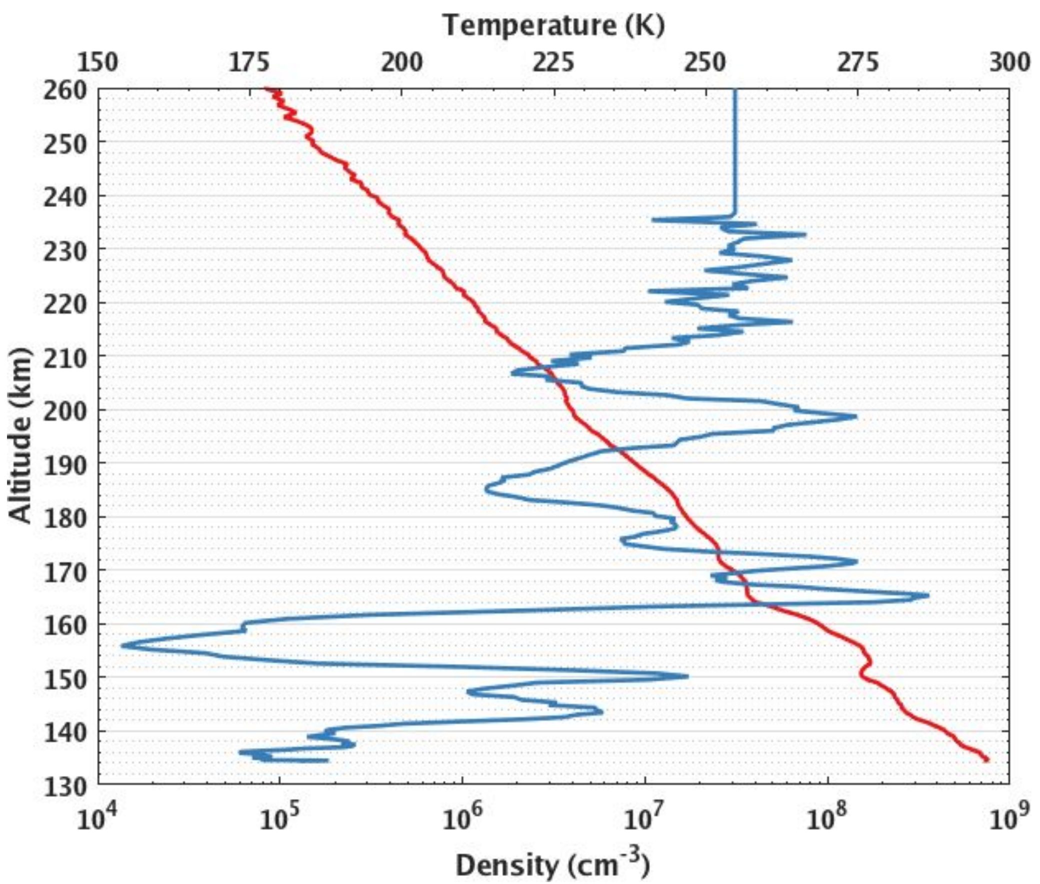
$$N_i = N_{o,i} \cdot \exp\left[\frac{GMm_i}{kT_i}\left(\frac{1}{r} - \frac{1}{r_o}\right)\right]$$

- Then, we integrate downward,

$$P_i = P_{u,i} + \int_{r_u}^{r} N_i \frac{GMm_i}{r'^2} dr'$$

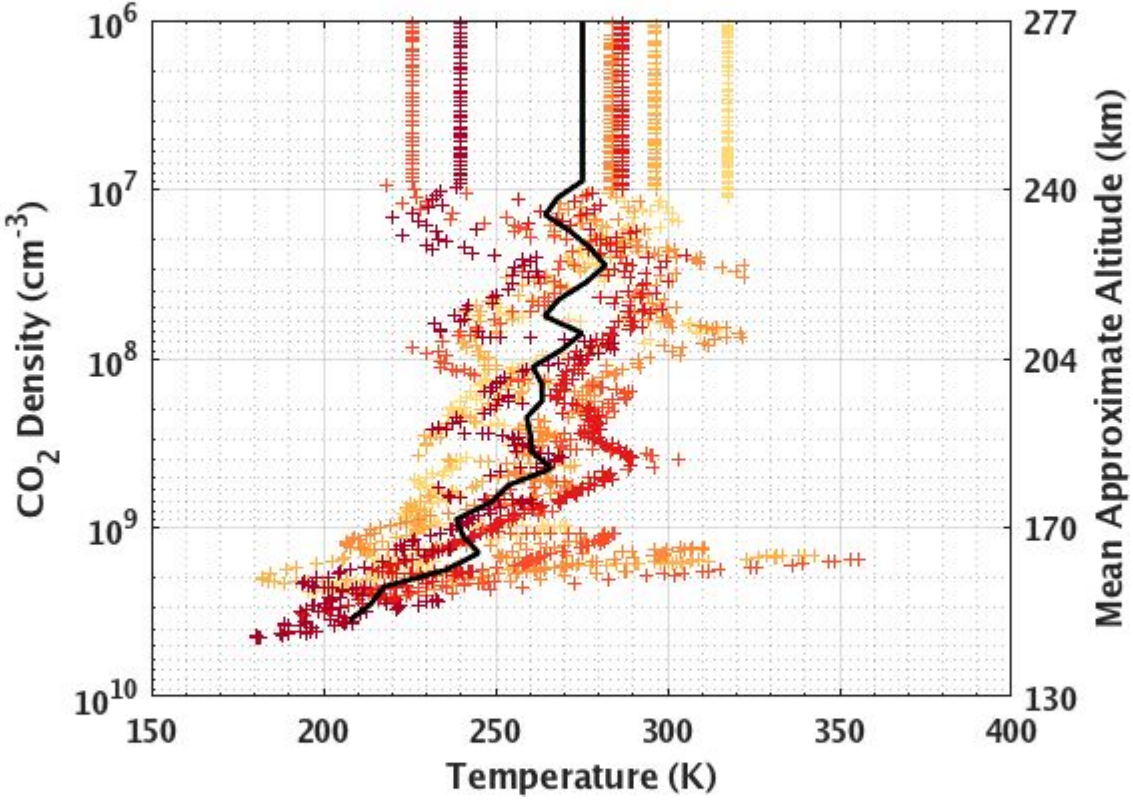
- and calculate temperature using the ideal gas law,

$$T_i = \frac{P_i}{N_i k}$$



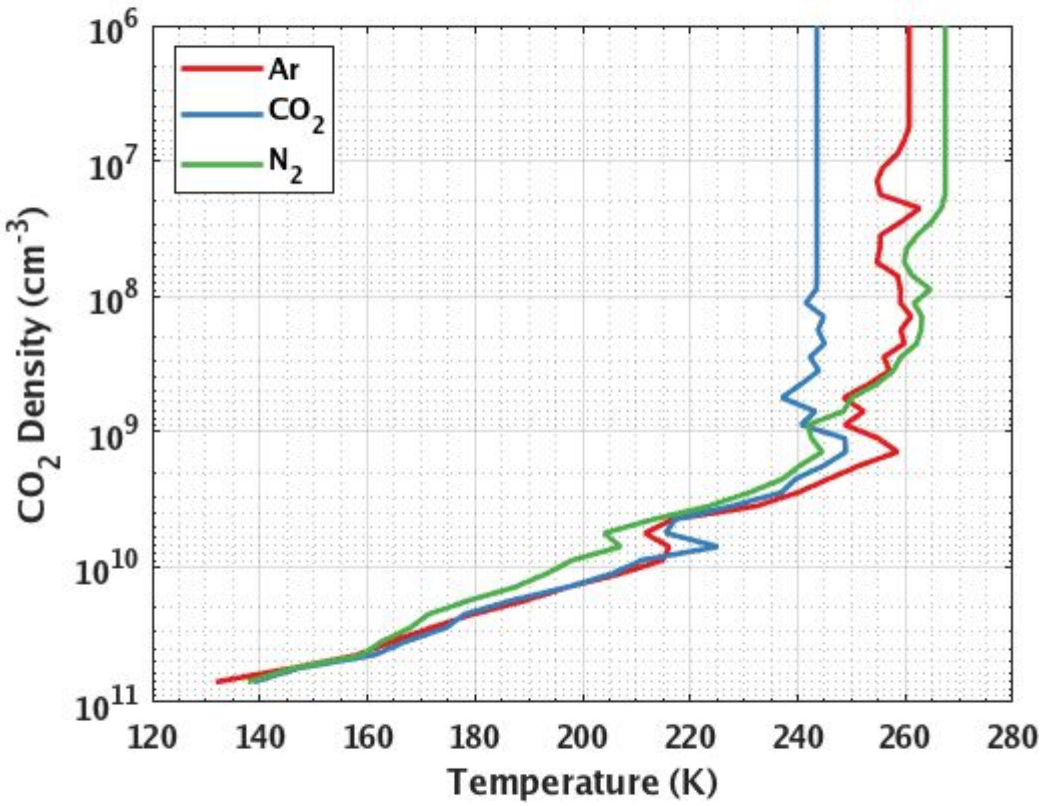
Mean Temperatures

- To produce mean temperatures, we bin on CO_2 density, as it is more physically meaningful than altitude.
- Pervasive wave activity is mostly removed by binning a handful of profiles from consecutive orbits.
- Mean approximate altitudes are derived from the mean temperature profile assuming hydrostatic equilibrium.



Mean Temperatures

- Mean DD2 temperatures derived from Ar, CO_2, and N_2 densities are in excellent agreement at periapsis.
    - Species affected strongly by chemistry (e.g. O on Mars) or rapid escape (e.g. H_2 on Titan) would not be indicative of bulk neutral temperature.
    - Agreement indicates the atmosphere is diffusively separated, even at the lowest altitudes reached by MAVEN.

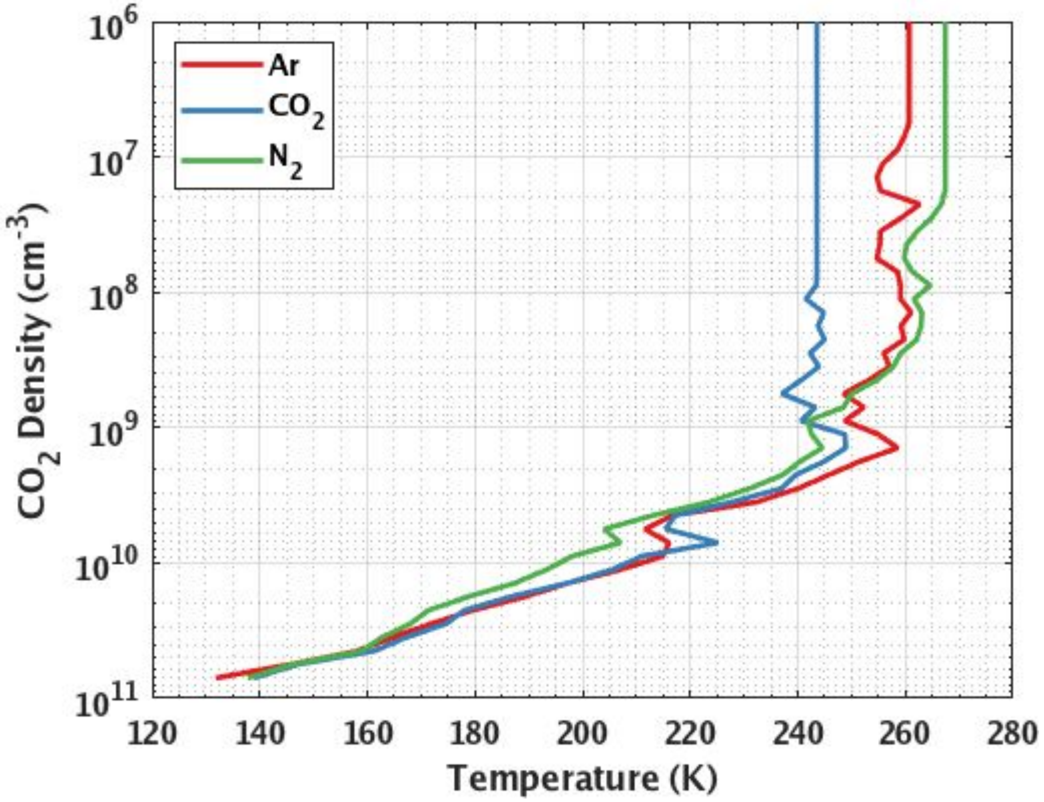


Mean Temperatures

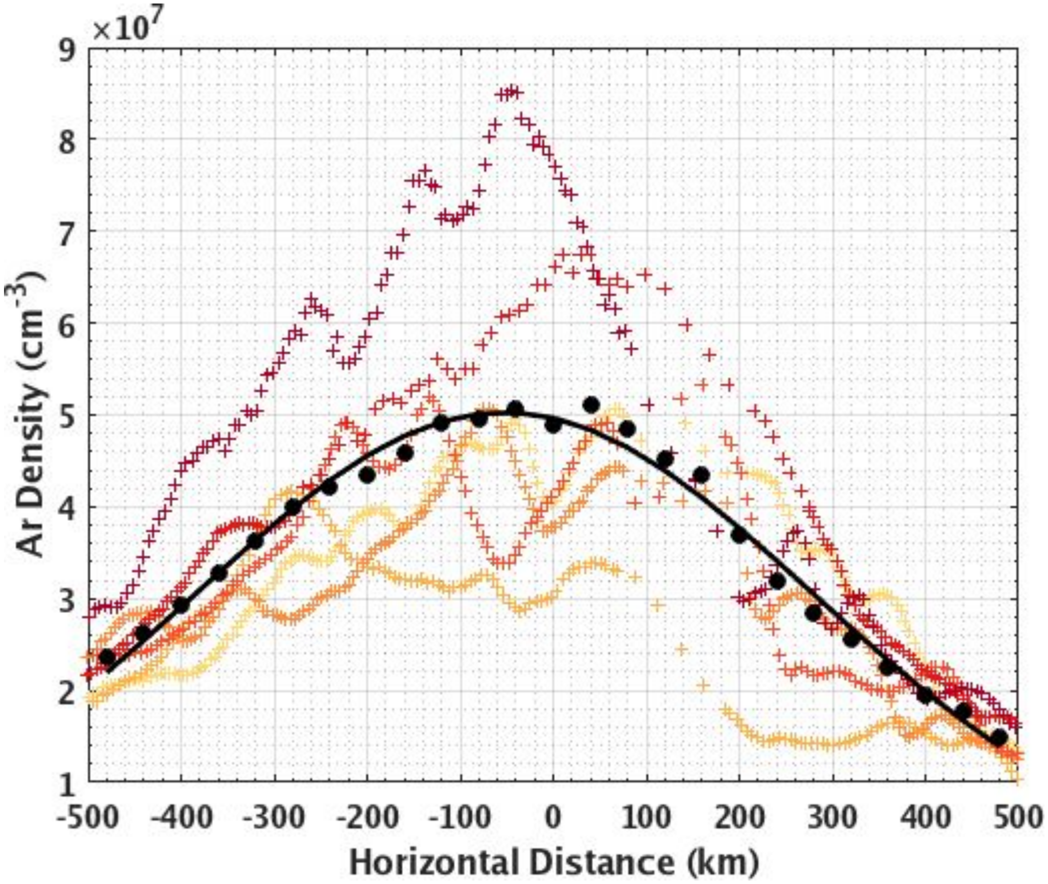
- The disagreement between the Ar and CO_2 temperatures at high altitude is due to adsorption of CO_2 onto the inner walls of the spectrometer.
    - This was also observed by Bougher et al. (2017).

- Small differences between the N_2 and Ar temperatures are not understood.

- Analysis below relies exclusively on Ar temperatures.

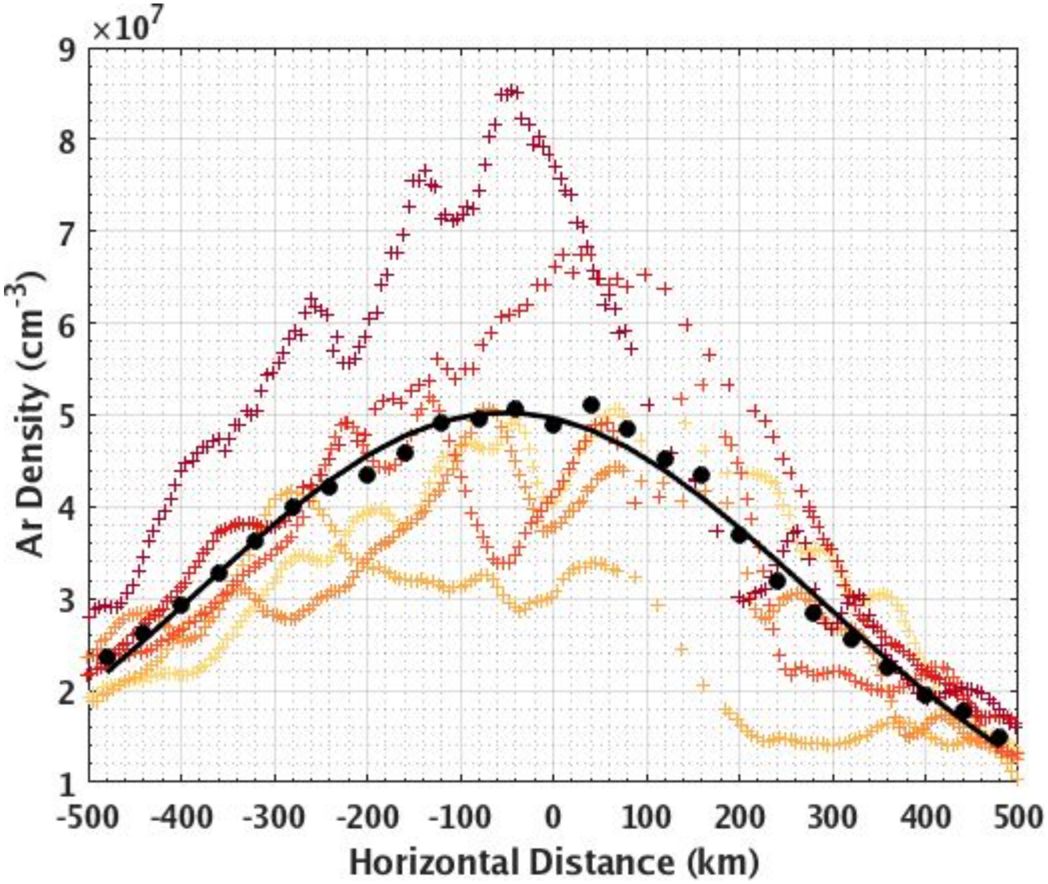


Horizontal Correction



- Temperatures are derived from vertical variations in the density, but MAVEN moves horizontally with respect to Mars as it descends through the atmosphere.
- NGIMS measurements are thus a combination of vertical and horizontal density variations.
- We want to remove the horizontal density variations to obtain vertical temperature profiles.
- Individual orbits have too much wave activity to do this pass-by-pass.

Horizontal Correction



- We first bin sequential orbits by similarity of periapsis altitude, local time, solar zenith angle, and latitude, then fit the densities about periapsis (color) with an equation of the form,

$$N(s, z) = \left(N_o + \frac{dN}{ds}s\right) \exp\left(-\frac{z}{H}\right)$$

to obtain the horizontal density gradient *dN/ds*, then calculate a correction factor, *r*,

$$r(s) = 1 + \frac{1}{N_o}\frac{dN}{ds}s$$

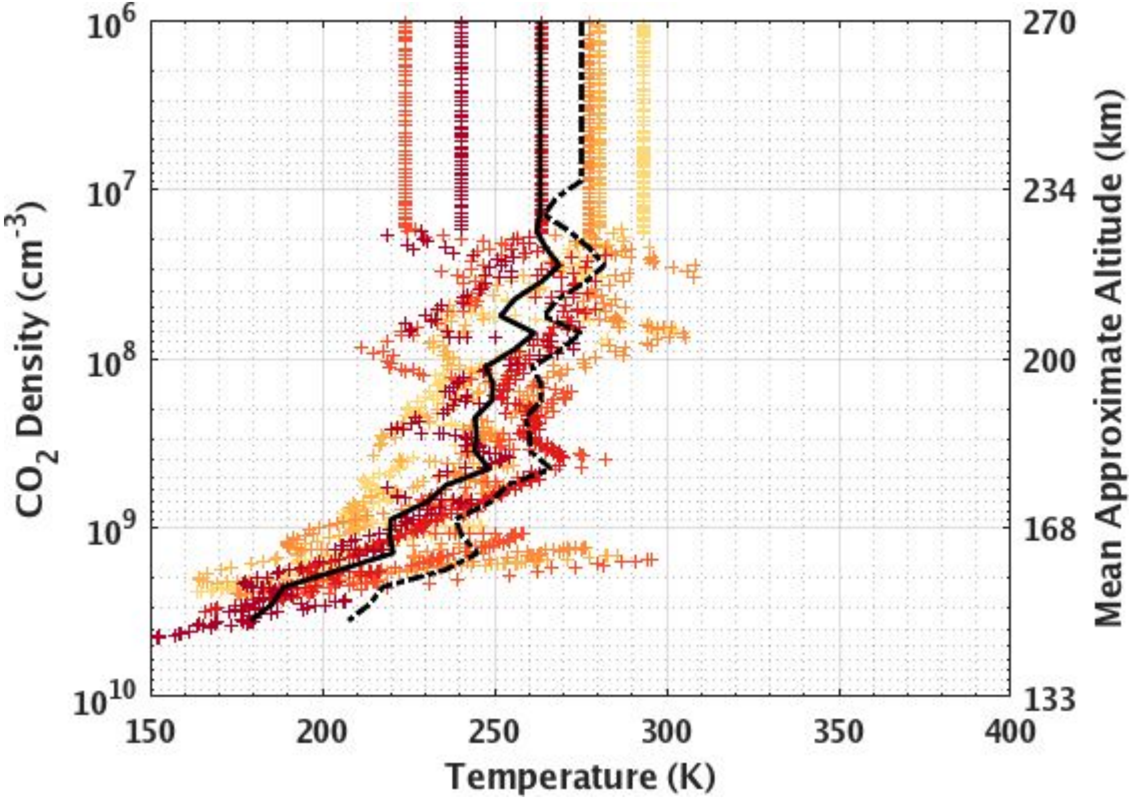
$$N_c(z) = \frac{N(s, z)}{r(s)}$$

Mean Corrected Temperatures

- Corrected temperatures are then calculated from the corrected densities.

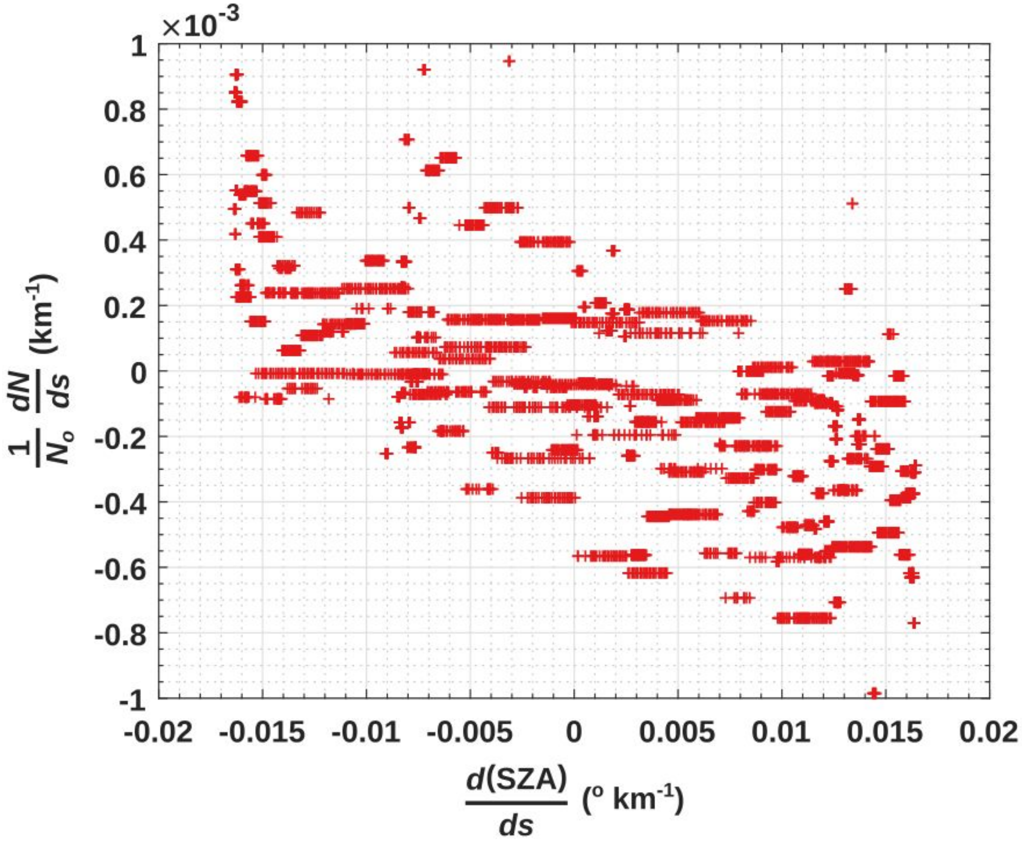
- The effect of the correction is, in general, 10s of K.

- The individual temperature profiles to the right (color) have been corrected. The mean corrected profile is the solid black line. The mean, uncorrected profile is the dashed line.



Horizontal Correction

- The horizontal density gradient, *dN/ds*, is correlated with *d(SZA)/ds*, the change in solar zenith angle with horizontal distance.
- That is, the horizontal density gradient is correlated with the direction the spacecraft is traveling relative to the terminator.
- Therefore, the horizontal density gradients arise generally from the day-night temperature gradient.

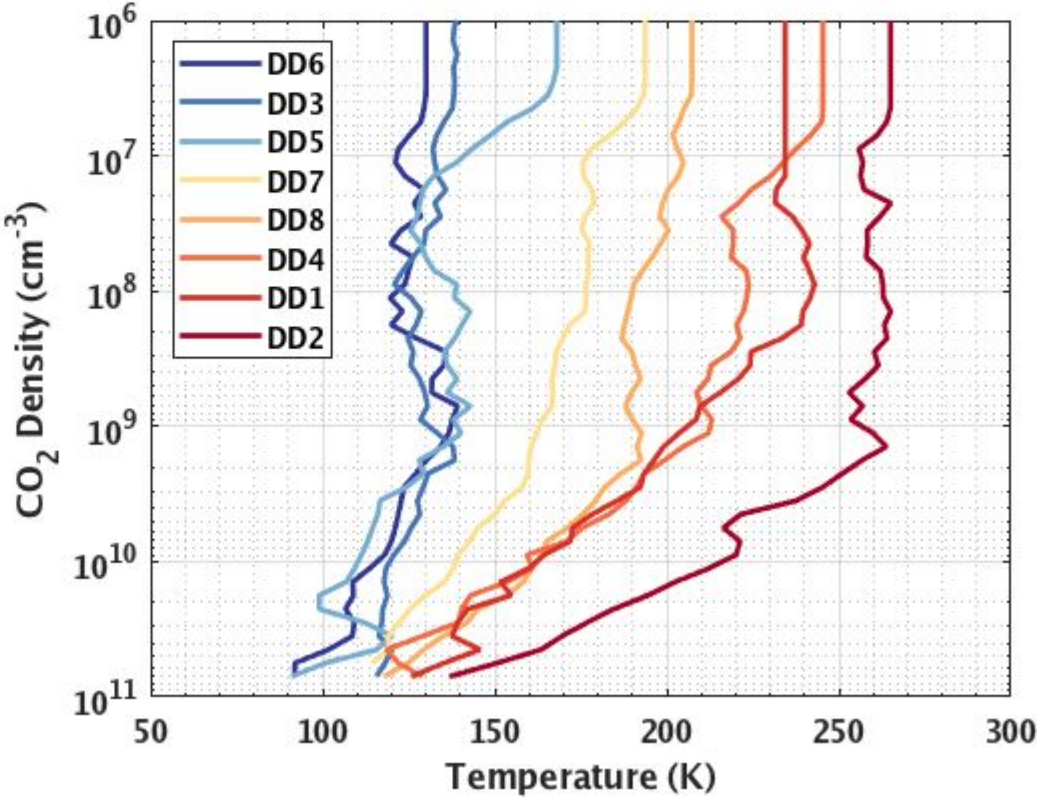


Mean DD Temperatures

- Mean DD temperatures probe down to ~125 km, near the mesopause.
  - DD averages are essentially longitudinal averages.

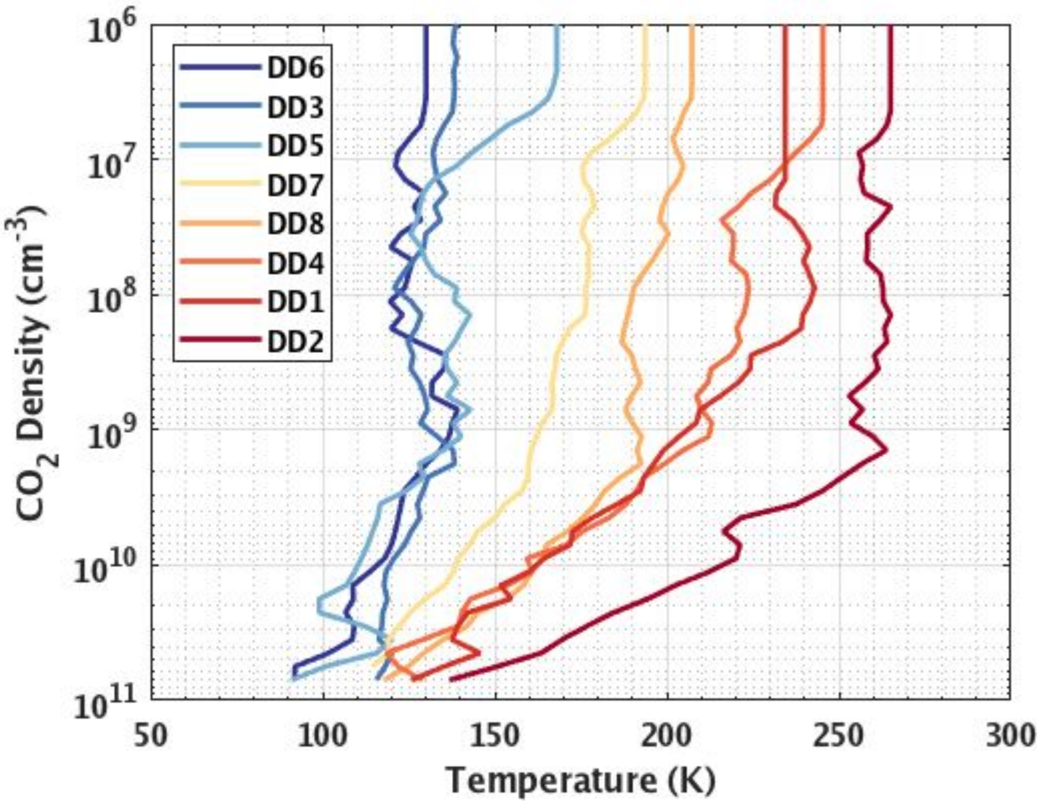
- DDs probe deeply enough to measure the characteristic temperature rise in the thermosphere.

- DD2, near subsolar point is the warmest. DD6, near antisolar point, is the coldest.
  - The difference between the two implies a diurnal variation of ~130 K, a factor of ~2.



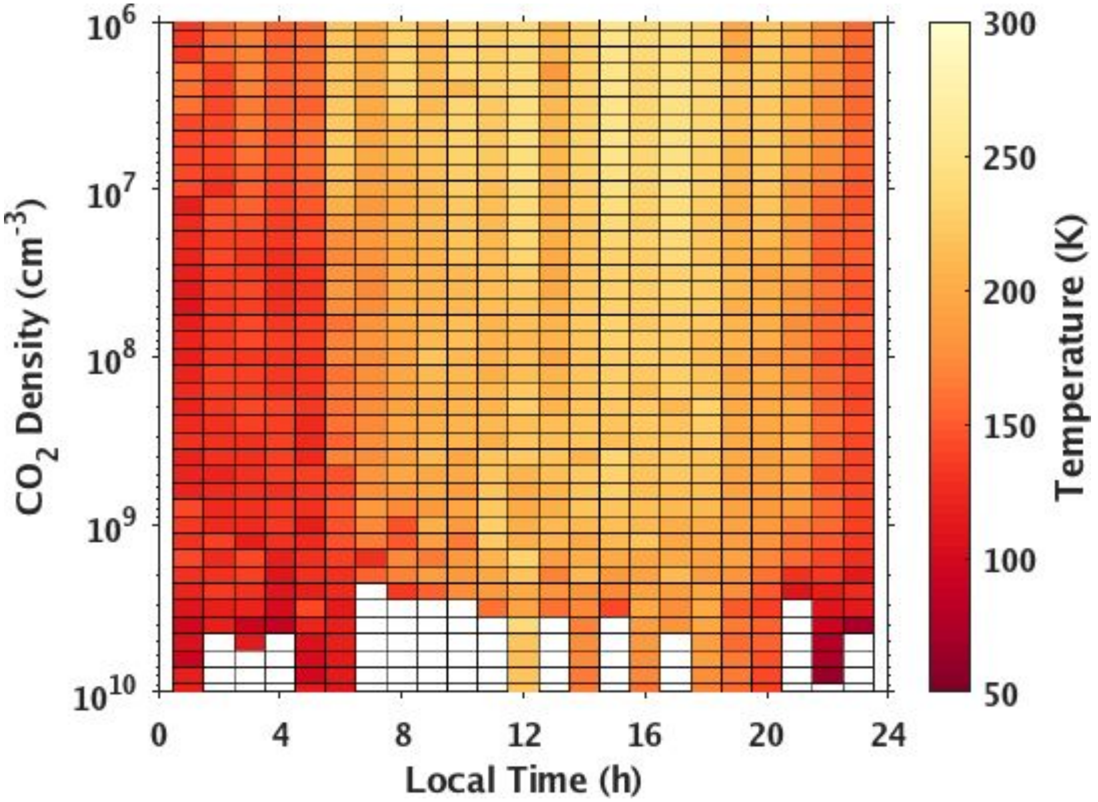
Mean DD Temperatures

- 90 K difference between DDs 3 and 4 provides a rough measure of the diurnal variation at higher latitudes.
- All DDs converge to 90-140 K near the mesopause.
- Thermospheric gradients between 1.57 and 2.31 K km^{-1} for the dayside DDs. Nightside DDs are nearly isothermal.
- More thorough analysis on DD temperatures is available in the manuscript.



Diurnal Variation

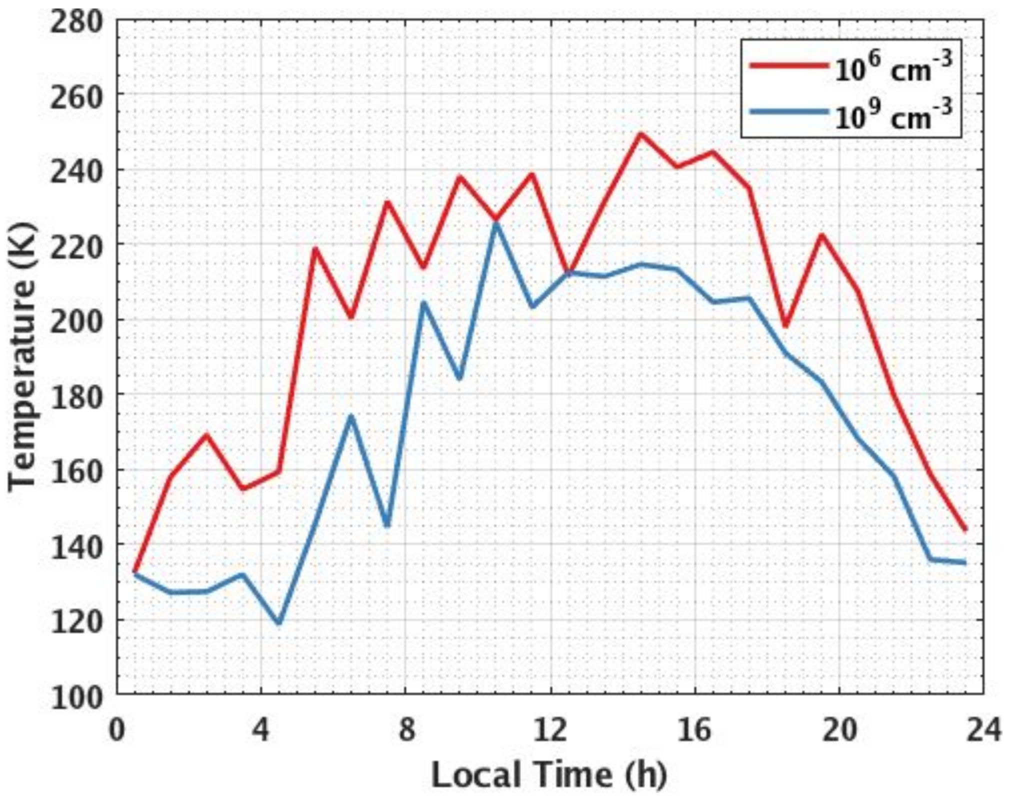
- The diurnal variation of the temperature between 60°N and 60°S is shown.
- Temperature peaks at ~250 K at 3 PM at a CO_2 density of 10^7 cm^{-3}.
- The atmosphere then rapidly cools to ~150 K by 10 PM.



Diurnal Variation

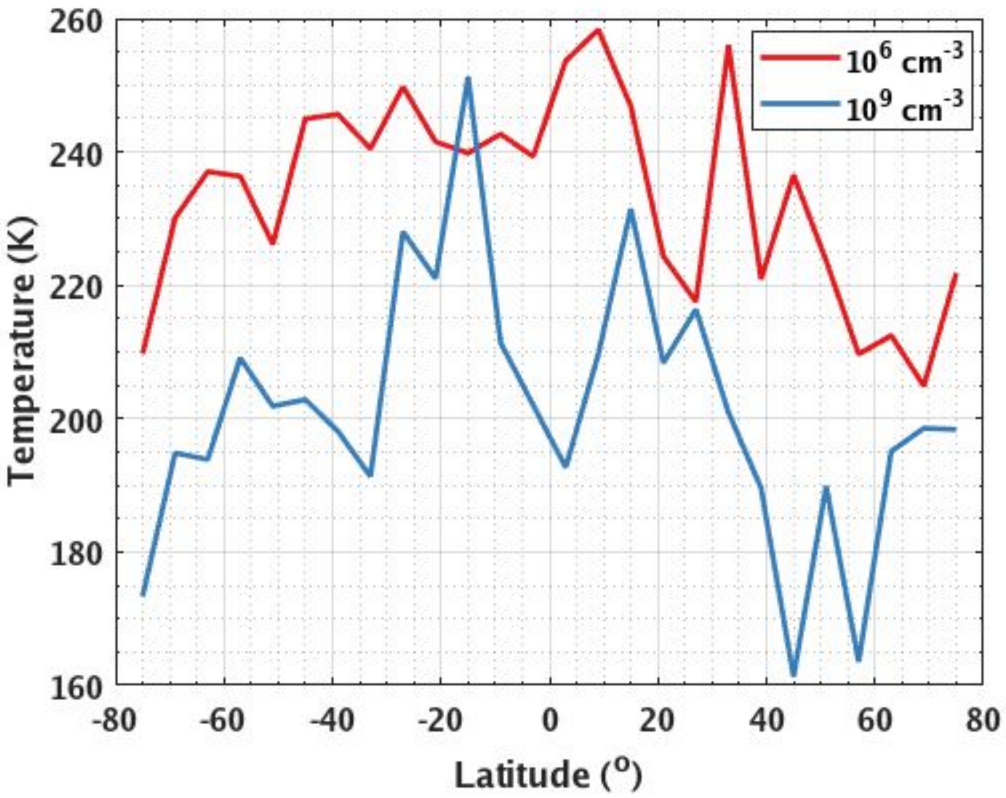
- The plot on the right shows the diurnal variation from the previous slide at two density levels: 10^6 (exosphere) and 10^9 cm^{-3} (near nominal periapsis).

- A ~120 K diurnal variation is observed at 10^6 cm^{-3} and ~85 K diurnal variation is observed at 10^9 cm^{-3}.



Latitudinal Variation

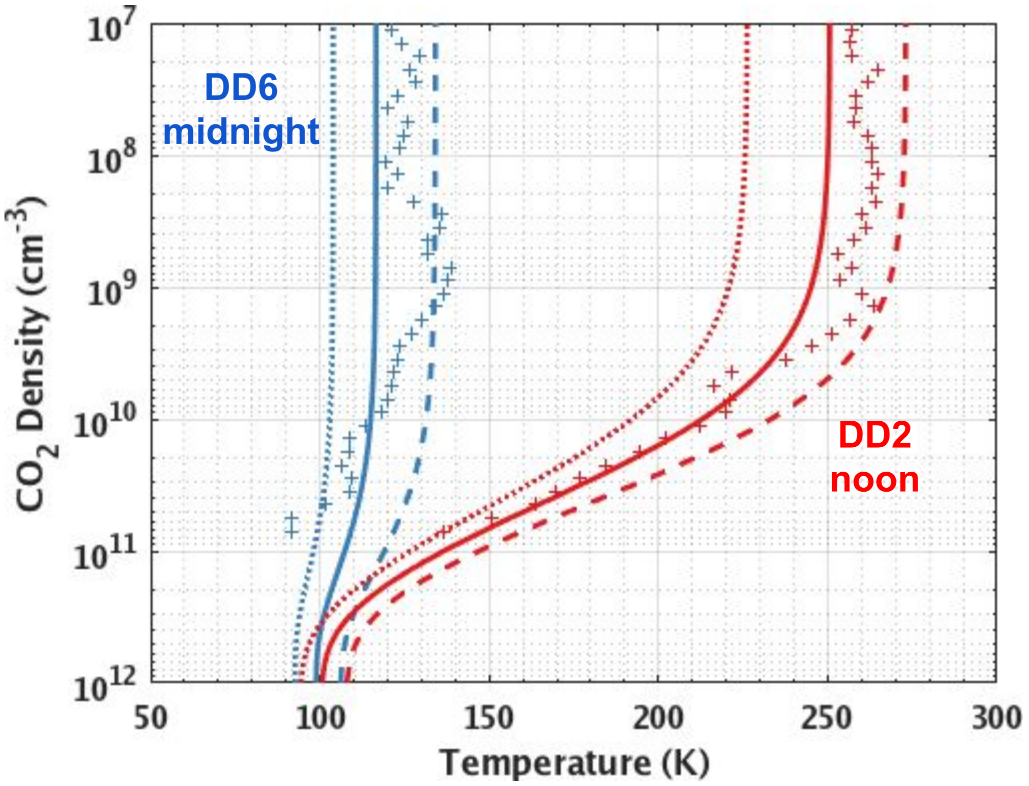
- Latitudinal variation of the temperature on the dayside (9AM-5PM) at the same two density levels is shown to the right.
- There is more noise in this data, as sampling in latitude is not as good as in local time.
- Latitudinal variation appears to be ~40 K at 10^6 cm^{-3} and ~45 K at 10^9 cm^{-3}.



Analysis with 1D Model

- Using a time-dependent 1D thermal structure model, we demonstrate that derived temperatures are broadly consistent with solar UV and NIR heating, thermal conduction, and radiative cooling.

- Equatorial model temperatures (lines) from noon (red) and midnight (blue) compared to DD2 (red crosses) and DD6 (blue crosses) using O-CO_2 collisional de-excitation rates of 1.5 (dashed), 3 (solid), and 6 × 10^{-12} (dotted) $cm^{-3}\ s^{-1}$.

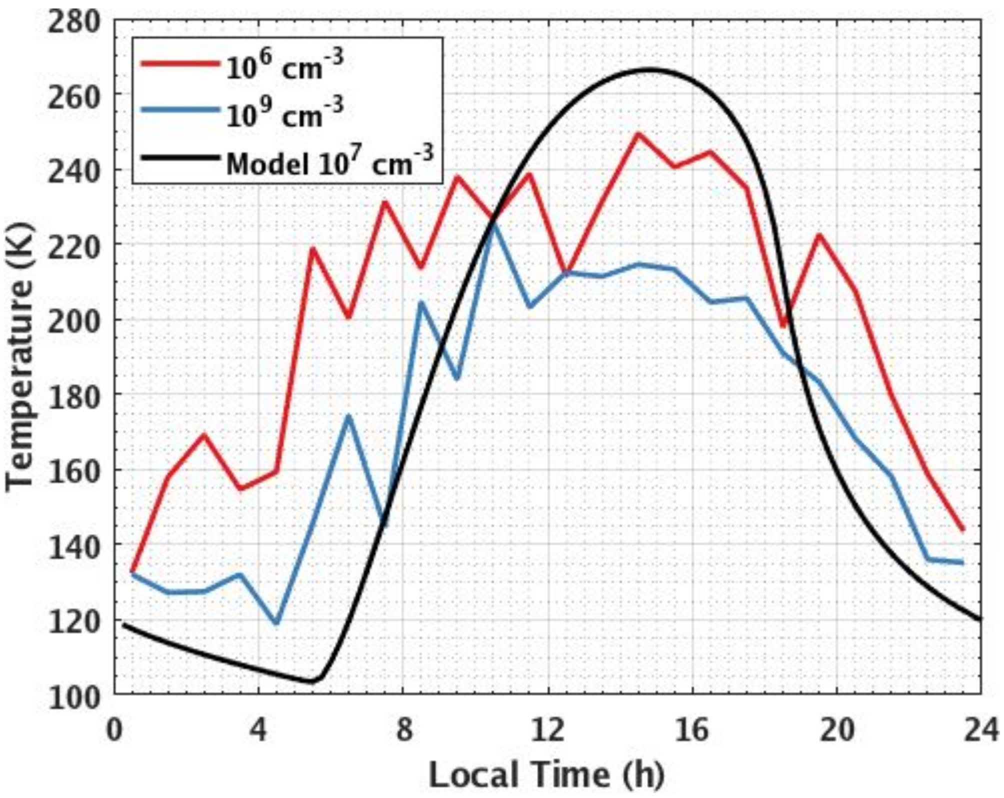


Analysis with 1D Model

- The model replicates well the derived temperature profiles (last slide), as well as the diurnal variation (this slide).

- However, model temperatures are systematically cooler in the early morning hours.
  - This is likely due to the neglect of dynamics in the 1D model.

  - A ~20 K difference between model and data would indicate 10-15% of solar energy deposited on the dayside is transported to the nightside.

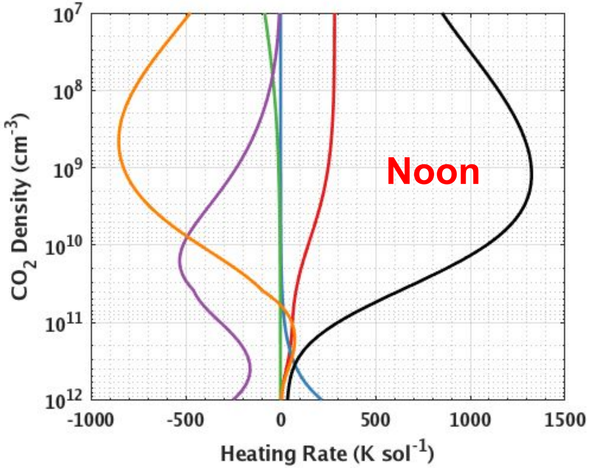


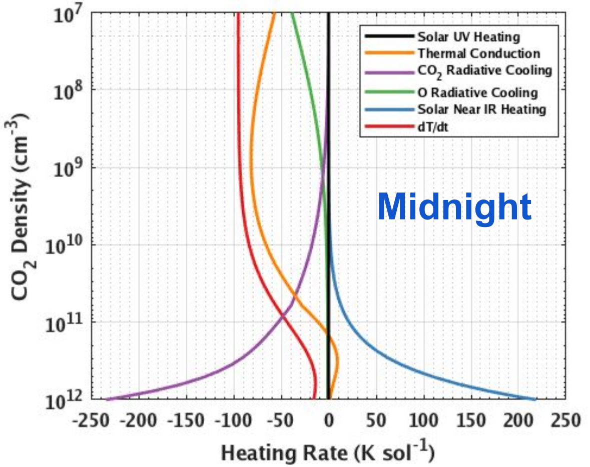
ANALYSIS WITH 1D MODEL

- At noon, solar UV heating is balanced mainly by thermal conduction at high altitudes and CO_2 radiative cooling at low altitudes.

- Model results in accord with observations are obtained using NGIMS O densities, and nominal values of the UV heating efficiency (20%) and O-CO_2 collisional de-excitation rate (slide 18).

- NGIMS measurements of O significantly reduce the uncertainty seen in previous models of the Martian thermosphere.





Summary and Conclusions

- Neutral temperatures are derived from NGIMS Ar, CO_2, and N_2 densities assuming hydrostatic equilibrium and the ideal gas law.

- Densities are corrected for instrumental and spacecraft effects.

- Horizontal density gradients experienced by MAVEN are derived and removed from the NGIMS data to obtain vertical density and temperature profiles.

- Thermospheric gradients of 1.57 to 2.31 K km^{-1} and diurnal variations of up to a factor of 2 are observed.

- NGIMS temperatures are consistent with previous *in situ* and remote sensing measurements and a simple 1D time-dependent thermal structure model.

Future Work

- DD9 temperature profiles can now be derived.
- Aerobraking phase will provide an extended period of deep temperature profiles.
- The current global dust storm may have interesting effects on thermal structure (and composition) of the upper atmosphere.
- If you would like access to NGIMS neutral temperatures, please feel free to email me: *stone@lpl.arizona.edu*.