Observations of tides and temperatures in the martian atmosphere by Mars Express SPICAM stellar occultations

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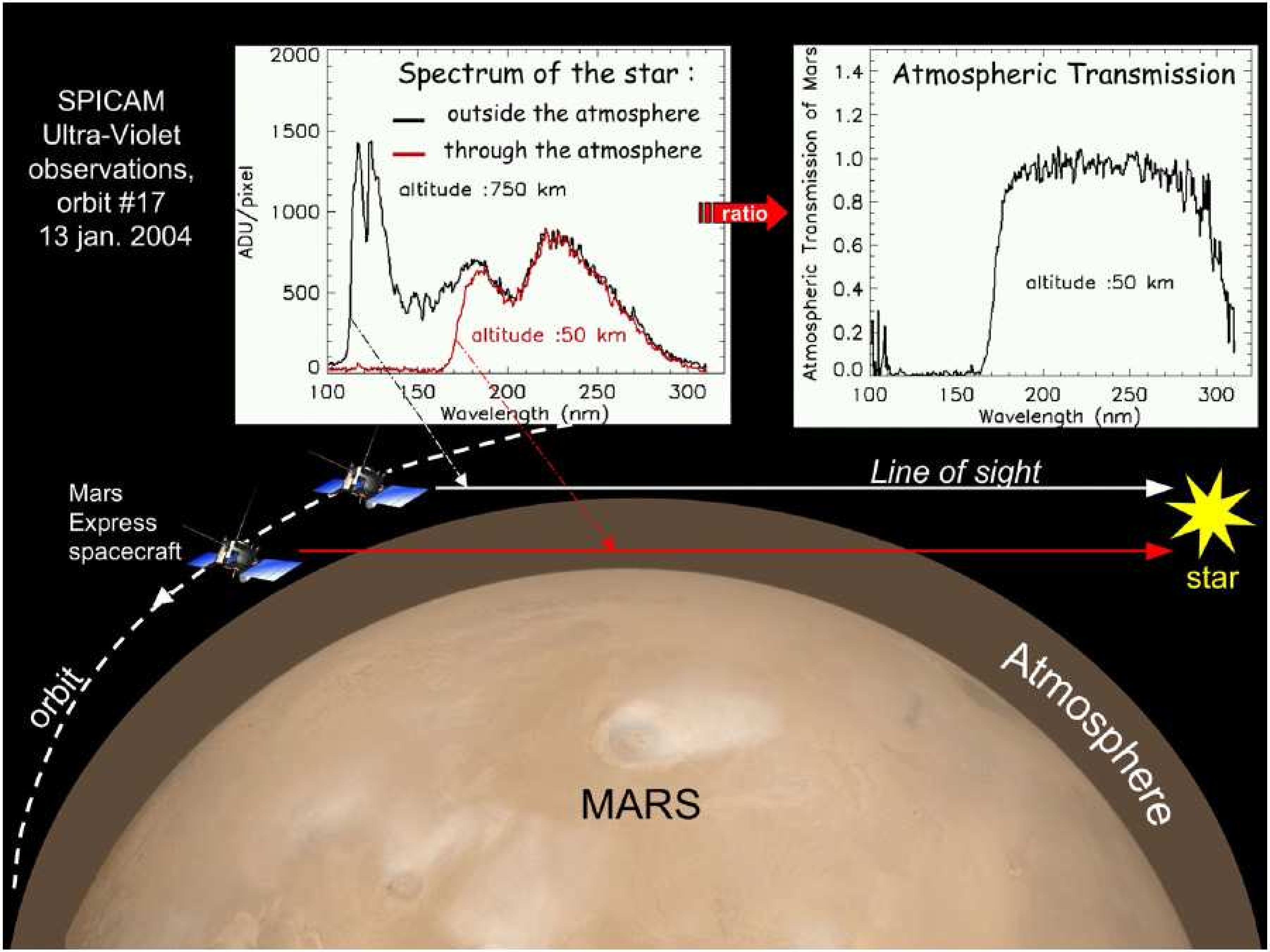
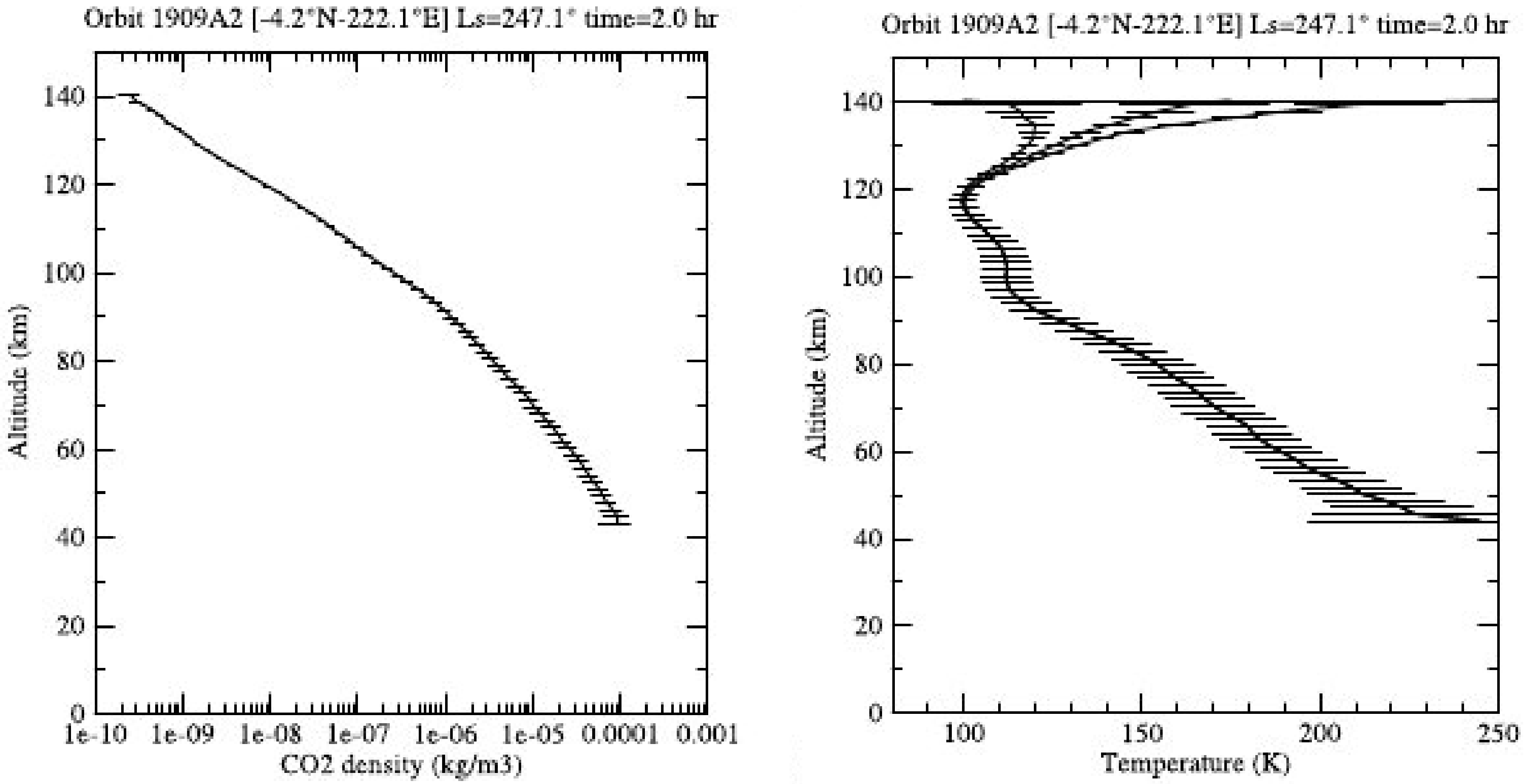


SPICAM
Ultra-Violet
observations,
orbit #17
13 jan. 2004
Spectrum of the star :
outside the atmosphere
through the atmosphere
altitude :750 km
altitude :50 km
ADU/pixel
Wavelength (nm)
ratio
Atmospheric Transmission
Atmospheric Transmission of Mars
altitude :50 km
Wavelength (nm)
Line of sight
Mars
Express
spacecraft
star
orbit
Atmosphere
MARS

Typical density and temperature profiles



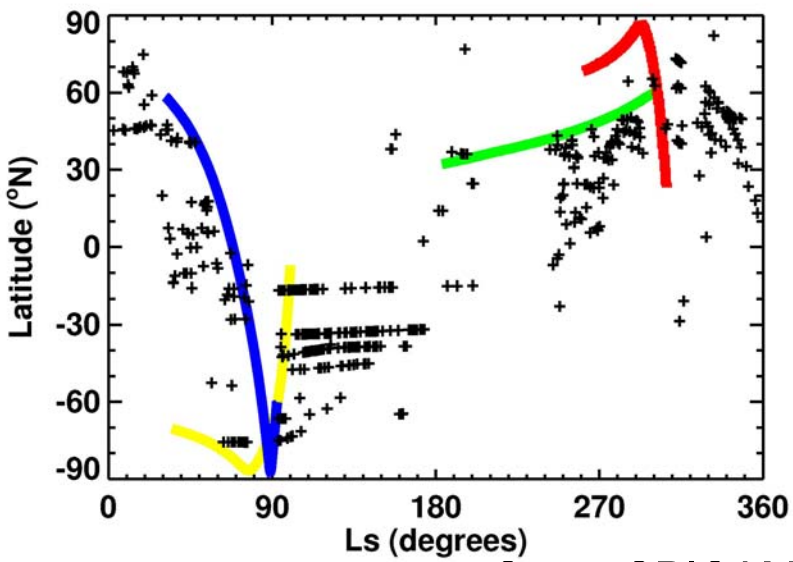
From Forget et al. (2009)

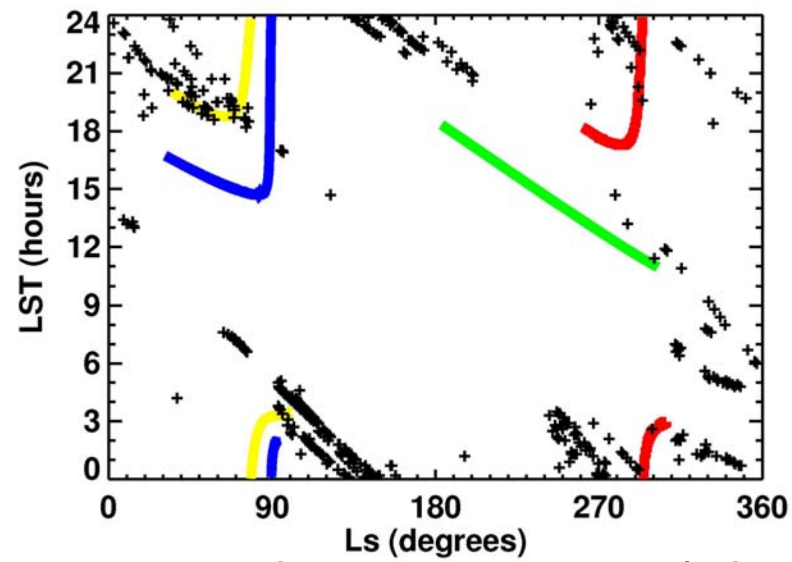
Motivation

- There are extensive observations of the dynamics and thermal structure of the martian atmosphere below 50 km (e.g. IRIS, TES, radio occultations, recently MCS)
- There are limited observations of the dynamics and thermal structure of the martian atmosphere above 100 km (e.g. aerobraking)
- Coupling between these two regions is important, but the dynamics and thermal structure of the intermediate 50-100 km region are poorly constrained
  - What is the ground-to-space thermal structure of the atmosphere?
  - How do thermal tides affect the 50-100 km region?
  - How do dust storms affect the atmosphere above 50 km?

- The SPICAM UV spectrometer instrument on Mars Express has determined hundreds of vertical profiles of density, pressure, and temperature in this region from stellar occultations

Seasons, latitudes, and local times covered by SPICAM and aerobraking accelerometers





MGS Phase 1	GREEN
MGS Phase 2	BLUE
ODY	RED
MRO	YELLOW

Some SPICAM measurements have same season, latitude, and local time as aerobraking measurements (currently different years, occultations from MRO aerobraking period not used in this work)

Subsets of SPICAM measurements made at fixed latitude with slowly changing local time and season, these are good for studying effects of longitude and temporal variations

Comparison of SPICAM and aerobraking measurements to theoretical simulations

- SPICAM = Vertical profiles of density, pressure and temperature
- Aerobraking = Along-track measurements of density, difficult to produce vertical density profiles from which pressure and temperature can be found
- Simulations = Steve Bougher's MTGCM simulations for recent aerobraking missions online at the University of Michigan; density, pressure and temperature

- How well do SPICAM and accelerometer measurements agree?
  - Verify reliability of datasets
  - Quantify interannual variability at range of seasons, latitudes
- If simulations agree well with one dataset, but not the other, are simulated dust conditions most appropriate for the first dataset?
- If two datasets agree well, but simulations do not agree with either, what are most likely causes of errors in simulations?

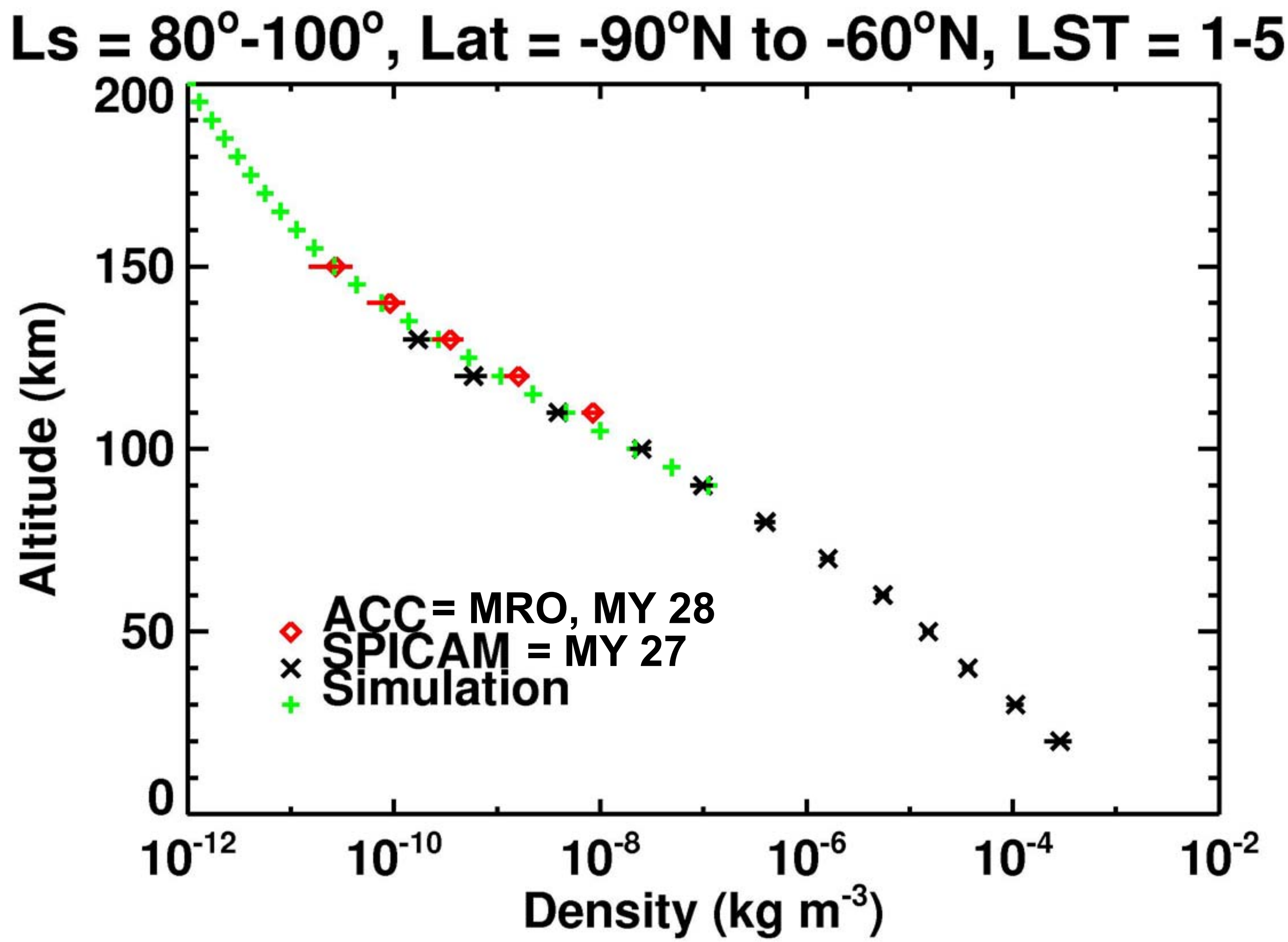
Six cases suitable for comparison of SPICAM data, aerobraking data and simulations

	Ls	Latitude	LST (hr)	N-SPICAM	N-ACC	Spacecraft
1	80^{o} - 100^{o}	90^{o}S - 60^{o}S	01 - 05	8	127	MRO
2	90^{o} - 120^{o}	60^{o}S - 30^{o}S	01 - 05	54	99	MRO
3	90^{o} - 120^{o}	30^{o}S - 0^{o}	02 - 05	35	57	MRO
4	290^{o} - 320^{o}	50^{o}N - 70^{o}N	01 - 03	5	63	ODY
5	90^{o} - 110^{o}	85^{o}S - 65^{o}S	01 - 04	7	49	MGS
6	276^{o} - 316^{o}	40^{o}N - 65^{o}N	10 - 15	7	61	MGS

Table 1. Cases where SPICAM and accelerometer measurements sample the same Ls, latitude, and LST. N-SPICAM is the number of SPICAM profiles that satisfy the Ls, latitude, and LST constraints. N-ACC is the number of accelerometer profiles whose periapsis satisfies the constraints.

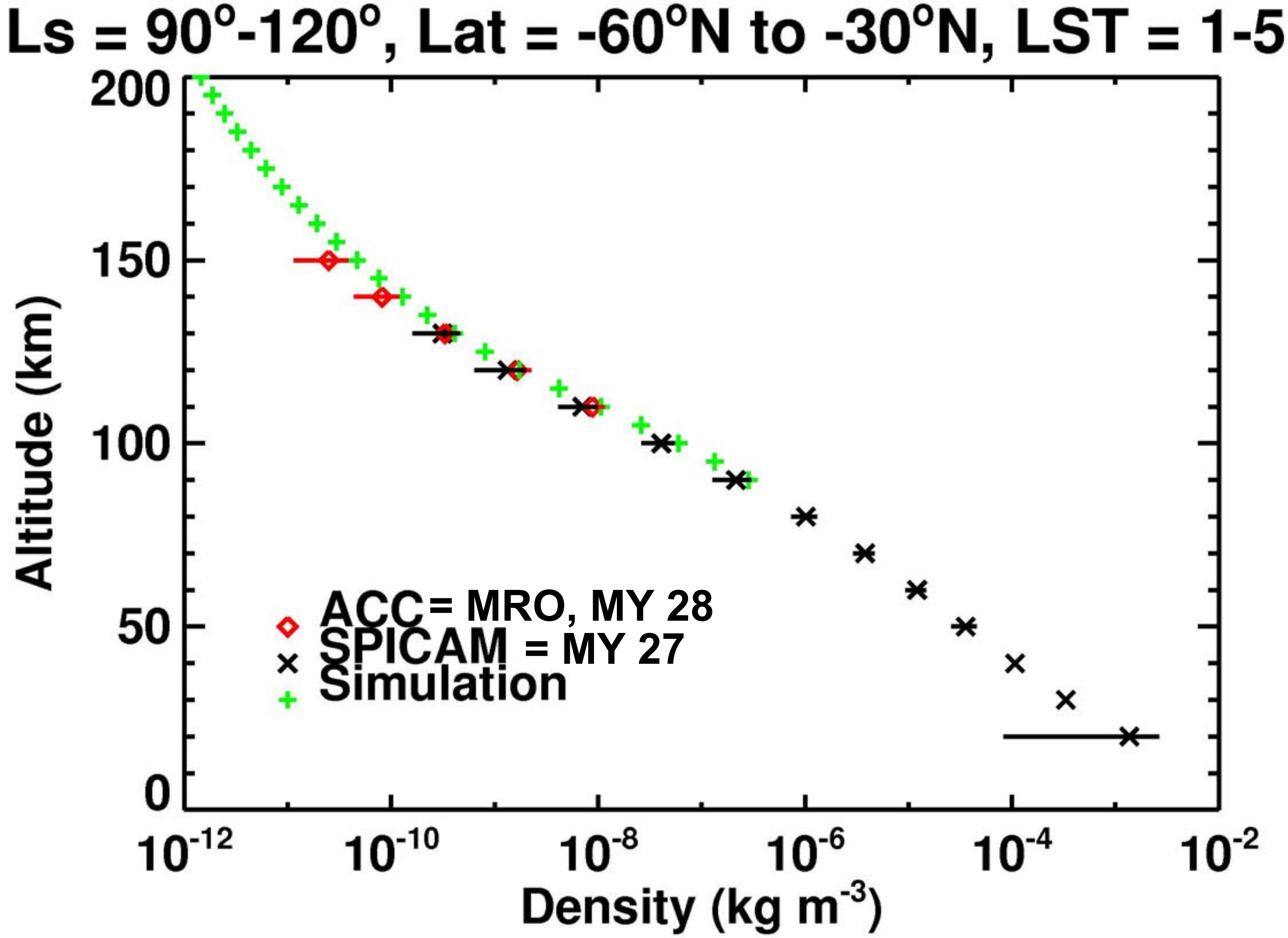
Simulations for ODY and MRO from http://aoss.engin.umich.edu/people/bougher
Simulations for MGS at Ls=90-110 from personal communication (Bougher, 1998)
Simulations for MGS at Ls=276-316 not used in this work

1



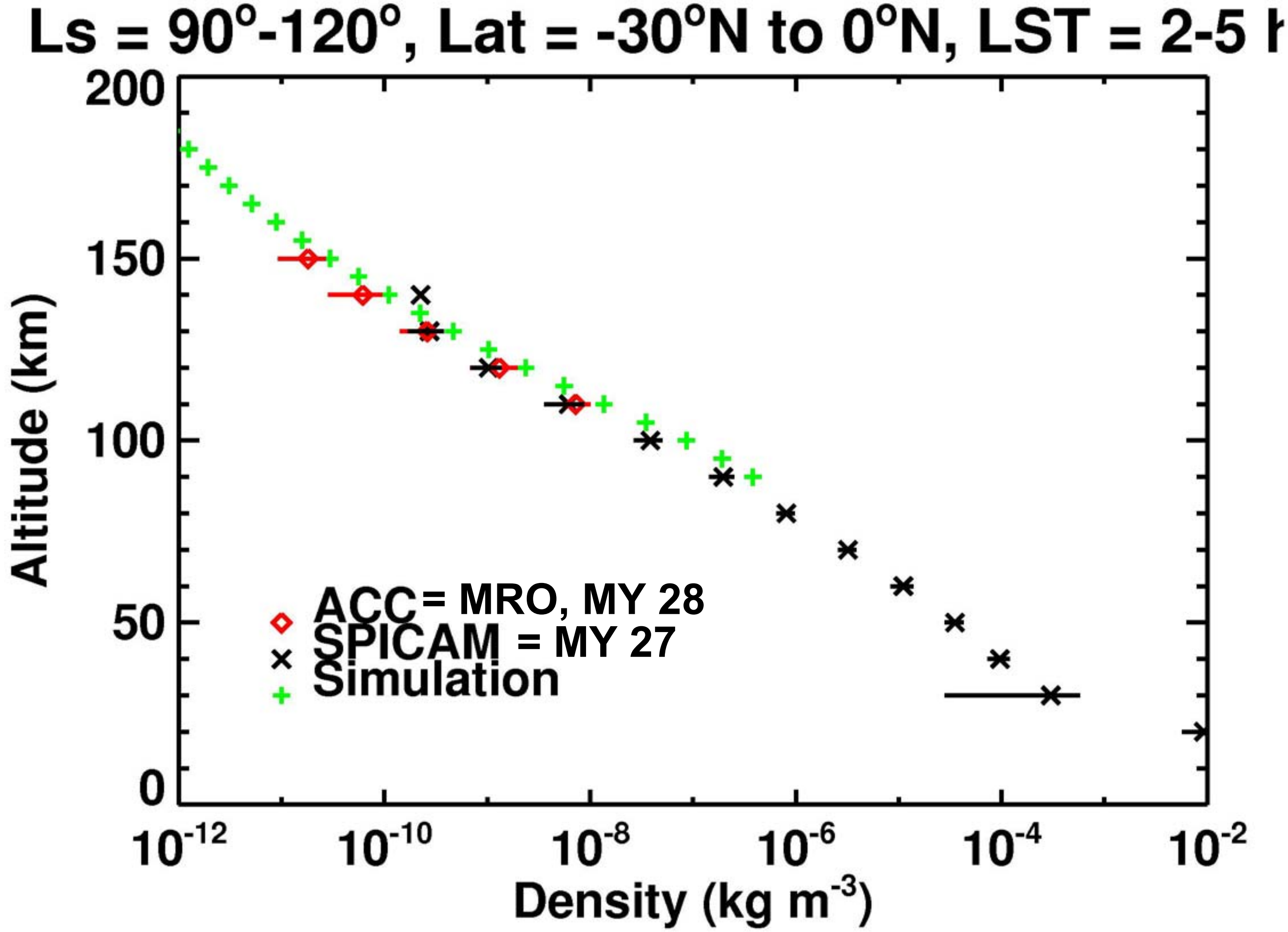
(kg/km^3)	110 km	120 km	130 km
SPICAM	3.92E+00 +/- 8.94E-01	5.92E-01 +/- 2.02E-01	1.72E-01 +/- 4.89E-02
ACC	8.49E+00 +/- 1.92E+00	1.61E+00 +/- 4.33E-01	3.52E-01 +/- 1.17E-01
Simul.	4.68E+00	1.08E+00	2.68E-01

2



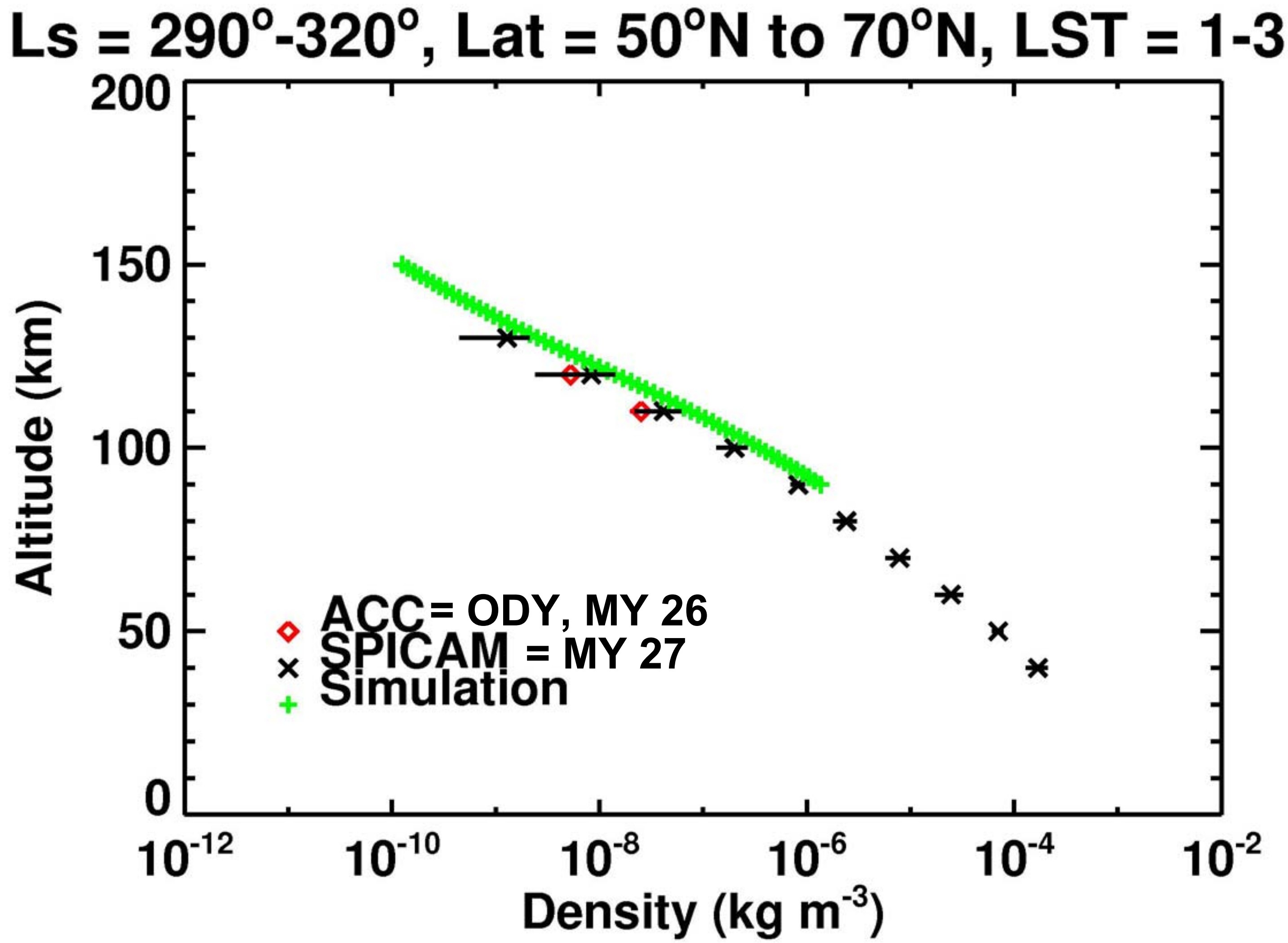
(kg/km3)	110 km	120 km	130 km
SPICAM	7.02E+00 +/- 2.90E+00	1.33E+00 +/- 6.89E-01	3.13E-01 +/- 1.53E-01
ACC	8.84E+00 +/- 2.71E+00	1.65E+00 +/- 6.16E-01	3.30E-01 +/- 1.20E-01
Simul.	1.10E+01	1.73E+00	4.11E-01

3



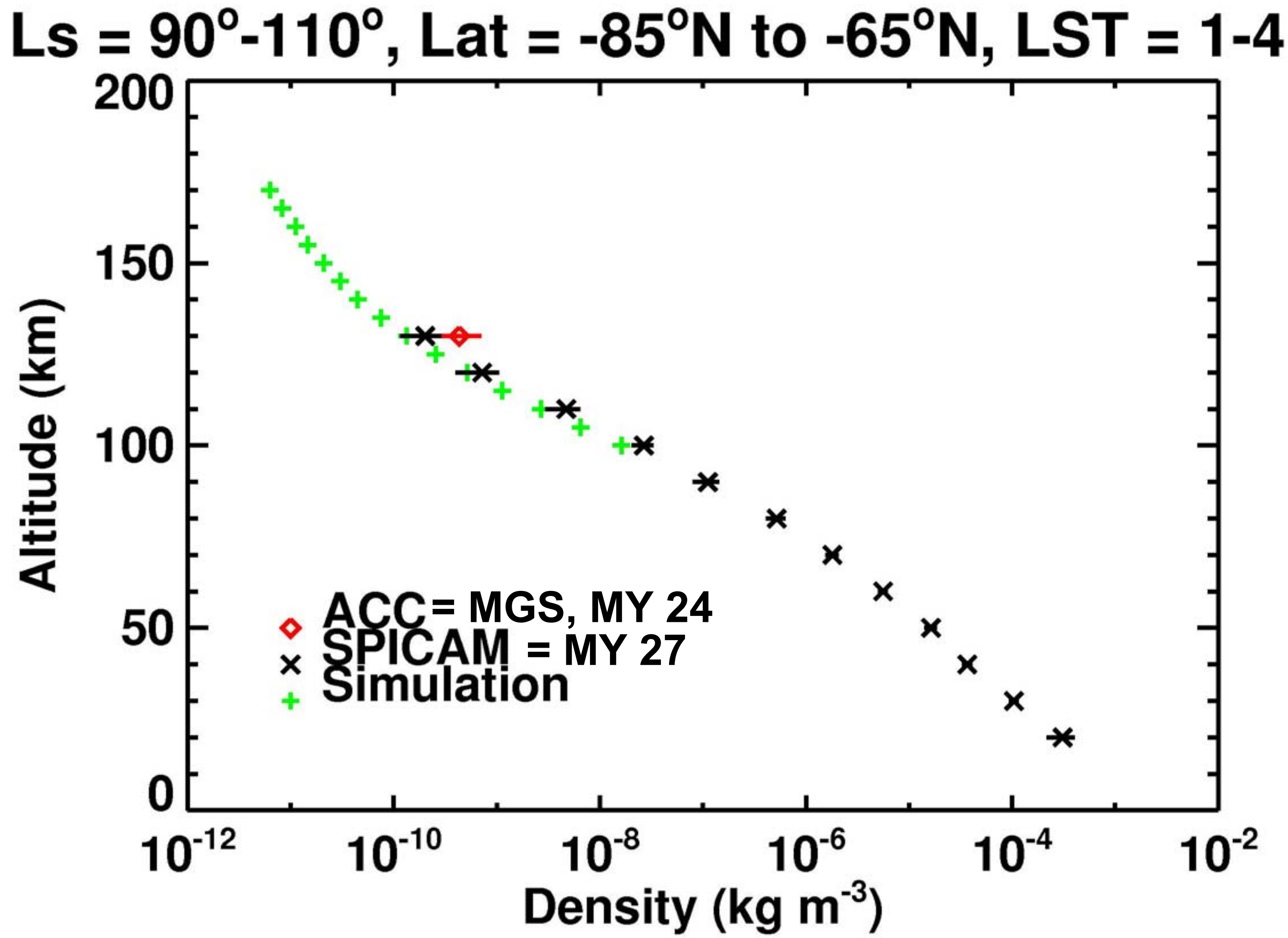
(kg/km3)	110 km	120 km	130 km
SPICAM	6.19E+00 +/- 2.61E+00	1.03E+00 +/- 3.14E-01	2.25E-01 +/- 1.05E-01
ACC	7.23E+00 +/- 2.89E+00	1.32E+00 +/- 6.39E-01	2.61E-01 +/- 1.19E-01
Simul.	1.36E+01	2.36E+00	4.67E-01

4



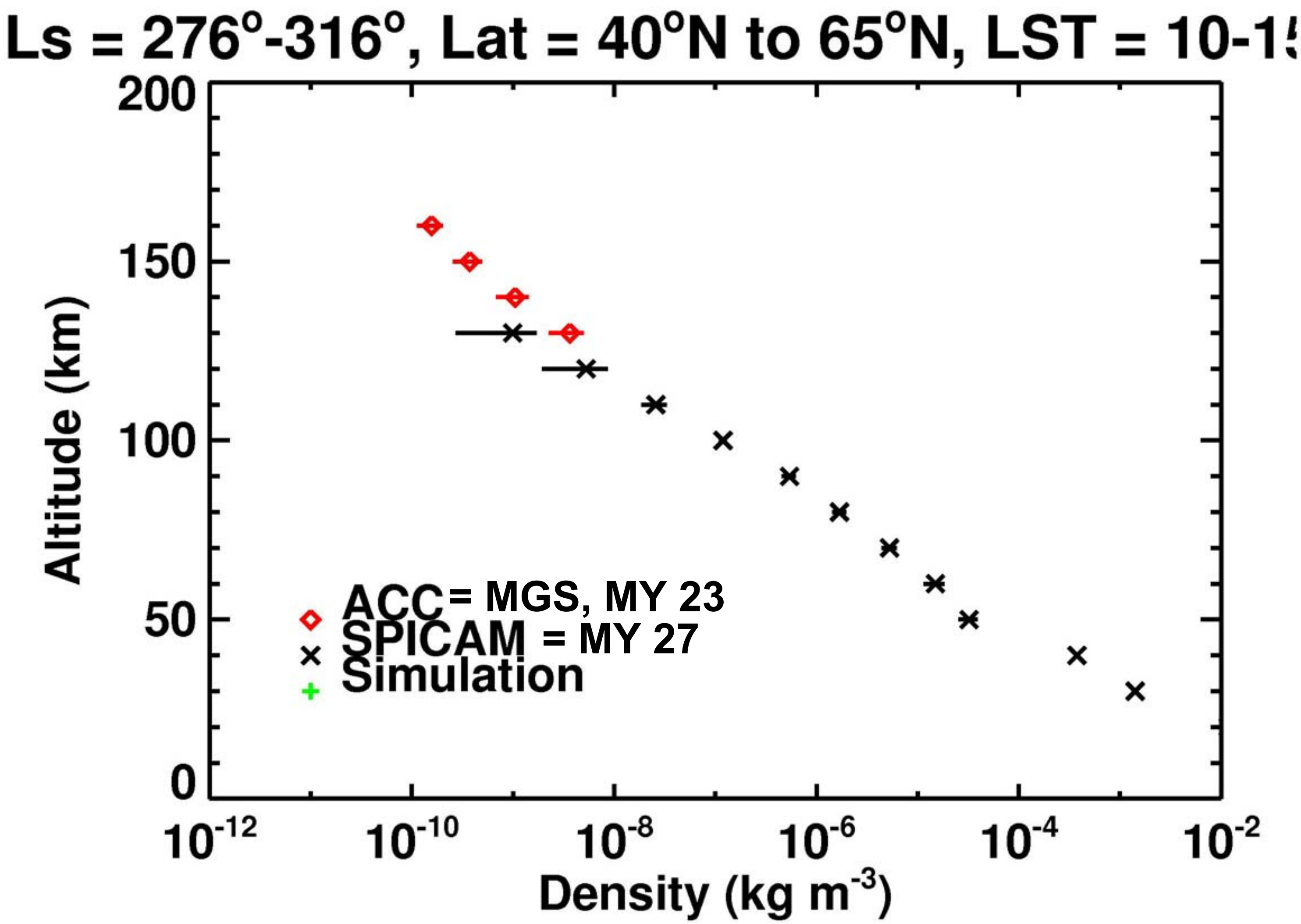
(kg/km3)	110 km	120 km
SPICAM	4.18E+01 +/- 1.98E+01	8.34E+00 +/- 5.93E+00
ACC	2.53E+01 +/- 5.43E+00	5.29E+00 +/- 1.59E+00
Simul.	7.65E+01	1.42E+01

5



(kg/km3)	130 km
SPICAM	2.02E-01 +/- 8.77E-02
ACC	4.33E-01 +/- 2.72E-01
Simul.	1.34E-01

6



(kg/km3)	130 km
SPICAM	9.94E-01 +/- 7.24E-01
ACC	3.64E+00 +/- 1.38E+00
Simul.	N/A

Summary of Cross-comparisons (1)

- Cases 1, 2, 3, 5 have very similar seasons (Ls~100) and LSTs (03 hrs)
  - ACC densities are 2x as large as SPICAM densities for cases 1 and 5 (90S to 60S)
  - ACC densities are only 1.2x as large as SPICAM densities for cases 2 and 3 (60S to 0N)
  - Possibly interannual variability is greater in south polar regions than in tropics? Possibly smaller number of SPICAM measurements in south polar regions makes those results less reliable?
  - Ratio of simulated density to observed density increases as latitude moves from pole to equator, which suggests simulated meridional gradients are too large
  - Ratio of simulated density to observed density does not vary greatly with altitude, which suggests temperatures are simulated accurately

Summary of Cross-comparisons (2)

- Cases 4, 6 have very similar seasons (Ls~300) and different LSTs (03, 12)
  - Case 4 = 110 km, 120 km and Case 6 = 130 km, uncertainties make it hard to extrapolate to a common altitude with confidence
  - ACC densities are 4x greater than SPICAM densities in Case 6 due to Noachis dust storm during MGS aerobraking
  - Large differences between SPICAM, ACC and model in Case 4. Possibly due to known interannual variability at this season and problems using correct dust distribution in simulation
- Simulated densities are usually, but not always, larger than observed densities
  - Simulating lower atmospheric “foundation” accurately is a challenge

Thermal Tides

$$A\cos(n\Omega t + s\lambda - \phi_{sn})$$

- A is amplitude, t is universal time, n is …, -2, -1, 0, 1, 2, …, s is 1, 2, 3, and ϕ_{sn} is phase

$$\cos(s\Omega t_{LT} + (s - s)\lambda - \phi_{ss})$$

- Incident solar forcing always has s=n, called migrating modes, and is dominant by s=1 and s=2
- Local time, t_{LT}, is related to universal time, t, by $\Omega t = \Omega t_{LT} - \lambda$

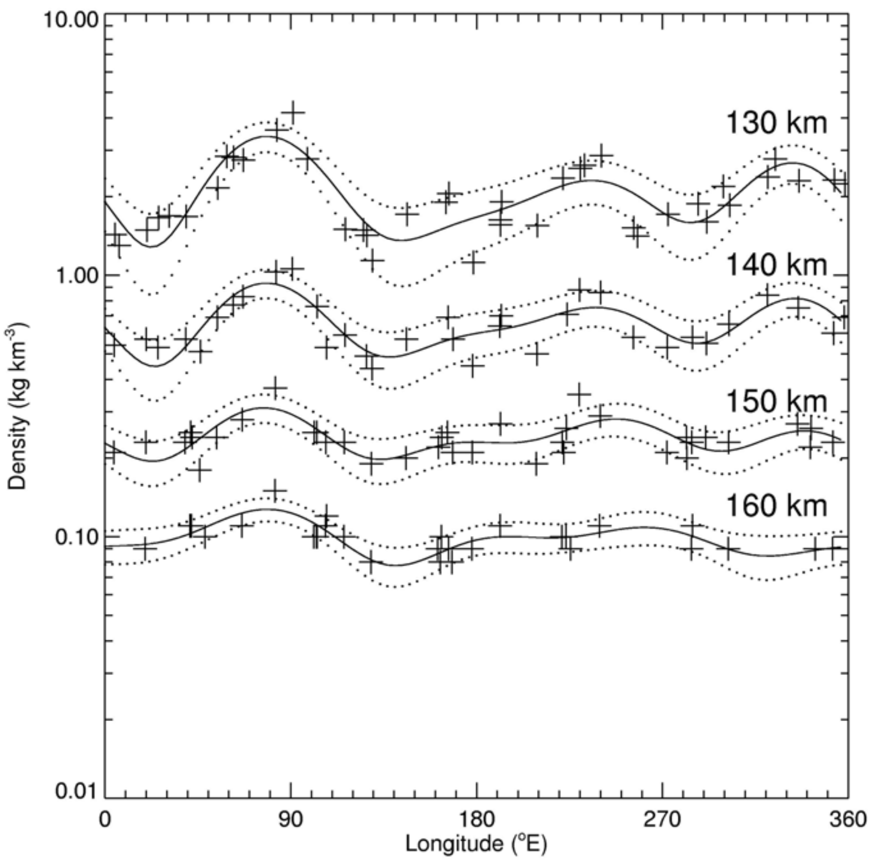
$$\cos(m\lambda - \phi_m)$$

- Let topographic variations have wavenumber m

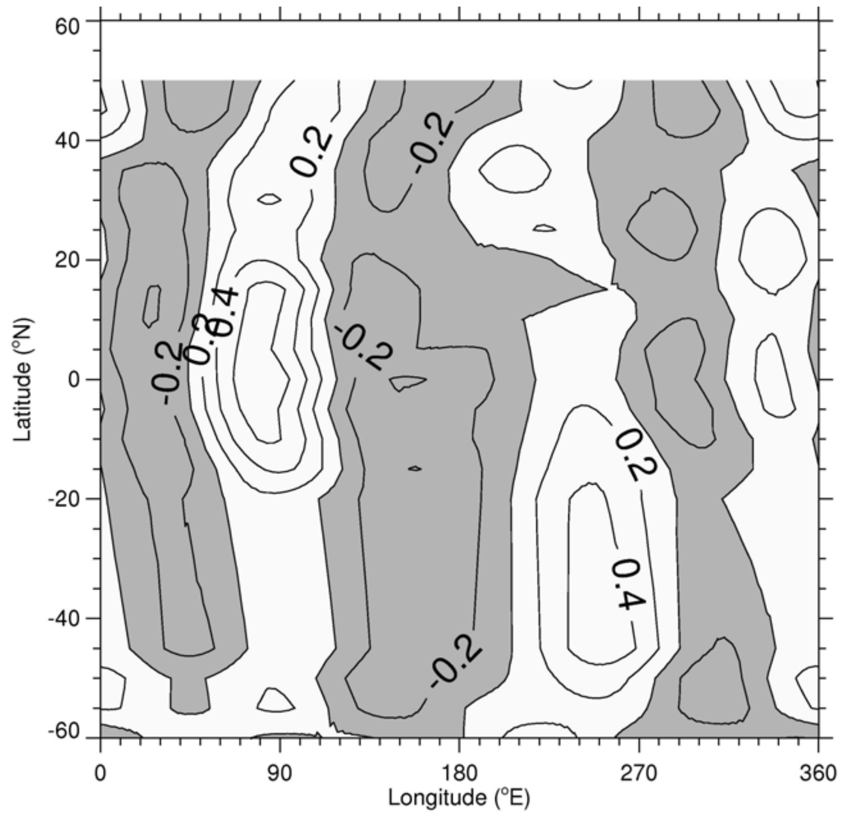
$$\cos(s\Omega t + (s \pm m)\lambda - (\phi_{ss} \pm \phi_m))$$
$$\cos(s\Omega t_{LT} + ((s - s) \pm m)\lambda - (\phi_{ss} \pm \phi_m))$$

- Sum-and-difference modes are produced
- Their propagation depends on s, s+/-m, but their zonal wavenumber in a fixed LT frame is always m

Thermal tides above 130 km

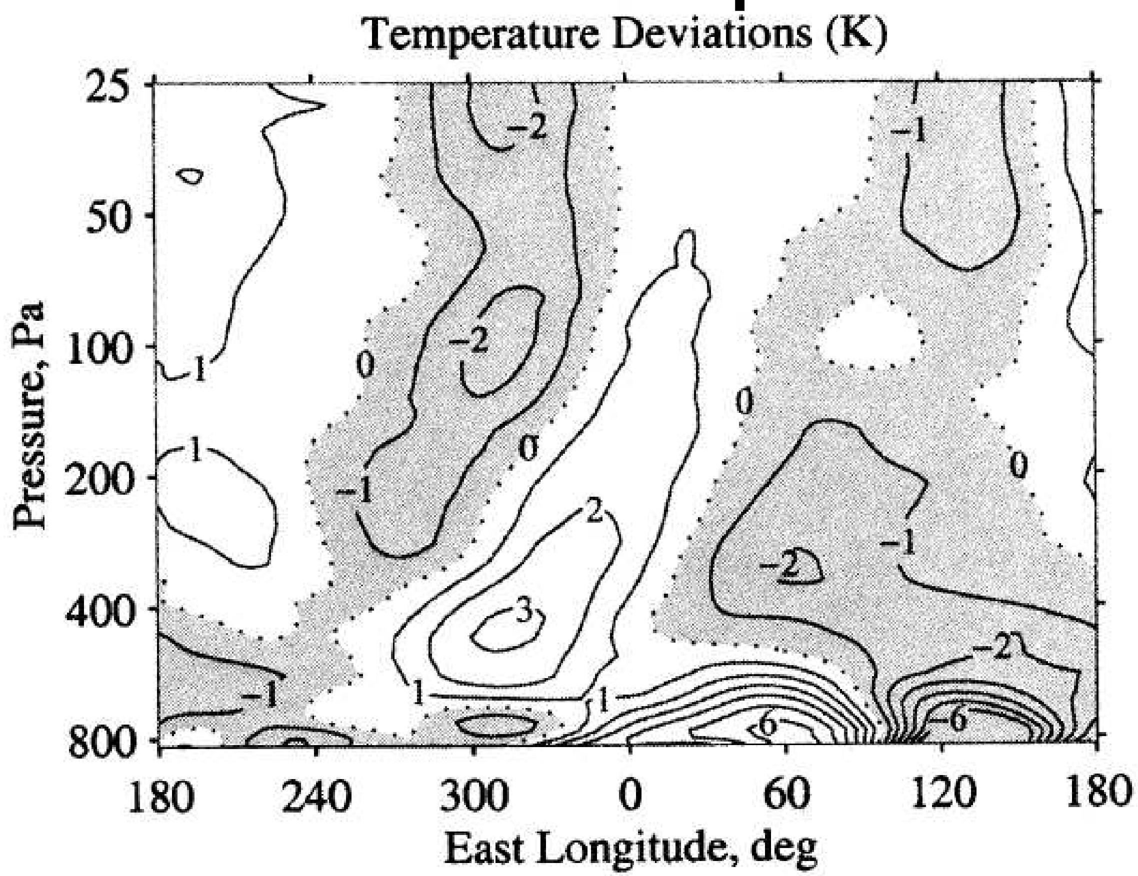


MGS aerobraking densities from 130 km to 160 km between 10N and 20N, Ls~60 and LST=15 hours



MGS normalized fitted densities at 130 km, Ls~60 and LST~15 hours

Zonal variations in the lower atmosphere



From Hinson et al. (2001)

A mixture of waves and tides causes zonal variations in the lower atmosphere. Most of these modes, including the strongest, dissipate before reaching the upper atmosphere. The non-migrating thermal tides that are significant in the upper atmosphere have very small amplitudes in the lower atmosphere, but amplify as they propagate upwards

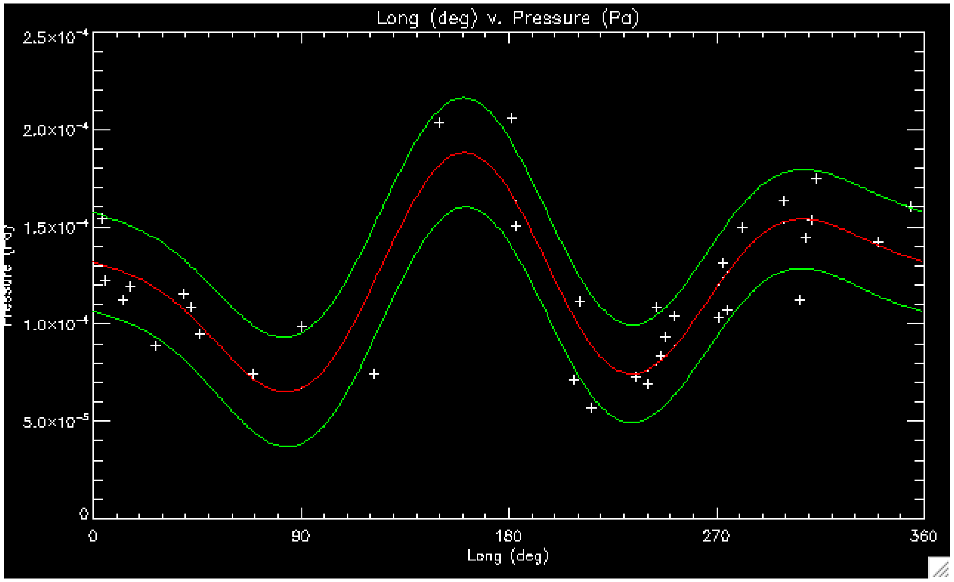
Ten cases in which SPICAM data can be used to study thermal tides

	Ls	Latitude	LST (hrs)	N-SPICAM
A	0° - 50°	40°N - 50°N	19.8 - 23.6	21
B	30° - 80°	30°S - 20°N	18 - 22	38
C	90° - 120°	20°S - 10°S	2.6 - 4.8	35
D	90° - 120°	50°S - 30°S	1.2 - 4.3	52
E	120° - 150°	50°S - 30°S	22.9 - 2.3	60
F	150° - 180°	40°S - 30°S	22 - 24	15
G	240° - 270°	15°N - 45°N	0.8 - 3.5	29
H	270° - 300°	32°N - 52°N	22.2 - 2.1	26
I	328° - 348°	38°N - 63°N	4.7 - 5.7	16
J	325° - 350°	46.7°N - 56.7°N	00 - 02	14

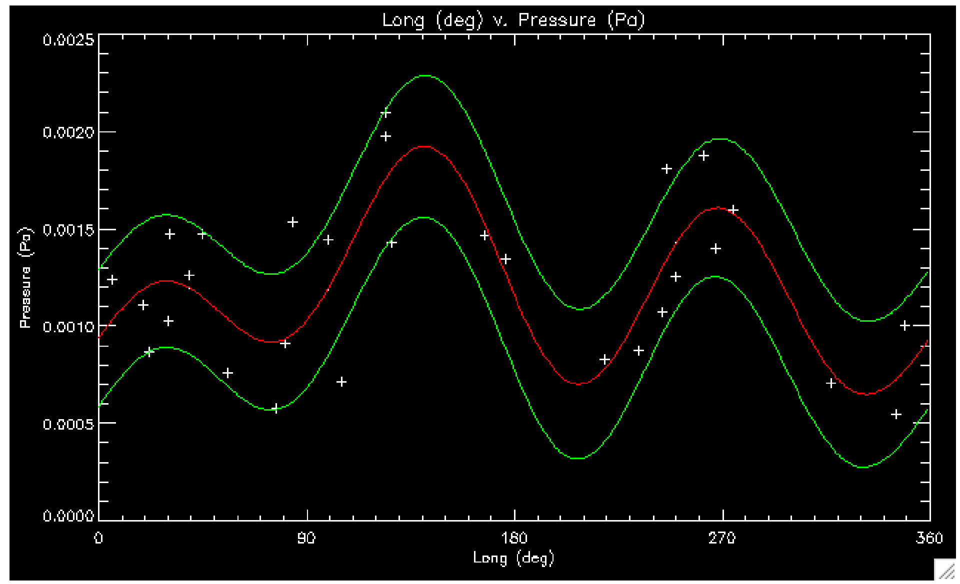
Table 2. Cases where there are many SPICAM profiles in narrow Ls, latitude, and LST ranges that cover all longitudes.

- How significant are thermal tides between 50 and 100 km?
- Which tidal modes are dominant?
- How do tidal amplitudes and phases change with altitude?
- How do these results compare to aerobraking studies above 100 km?
- Studies of aerobraking data have concentrated on zonal variations in density – how are zonal variations in density, pressure and temperature related?

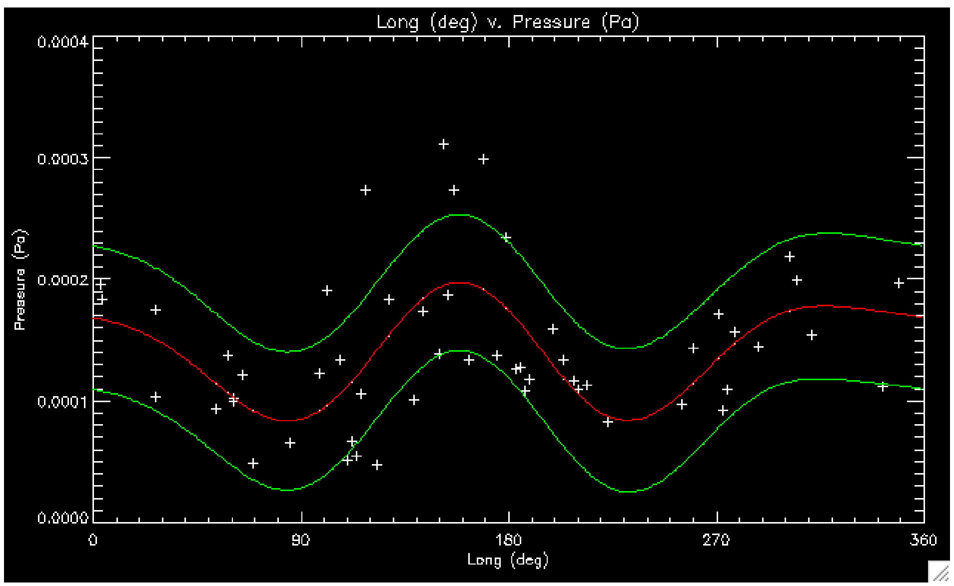
Multiple examples of clear zonal structure can be found in SPICAM pressures at 110 km



Case C, 110 km, wave 2 dominant

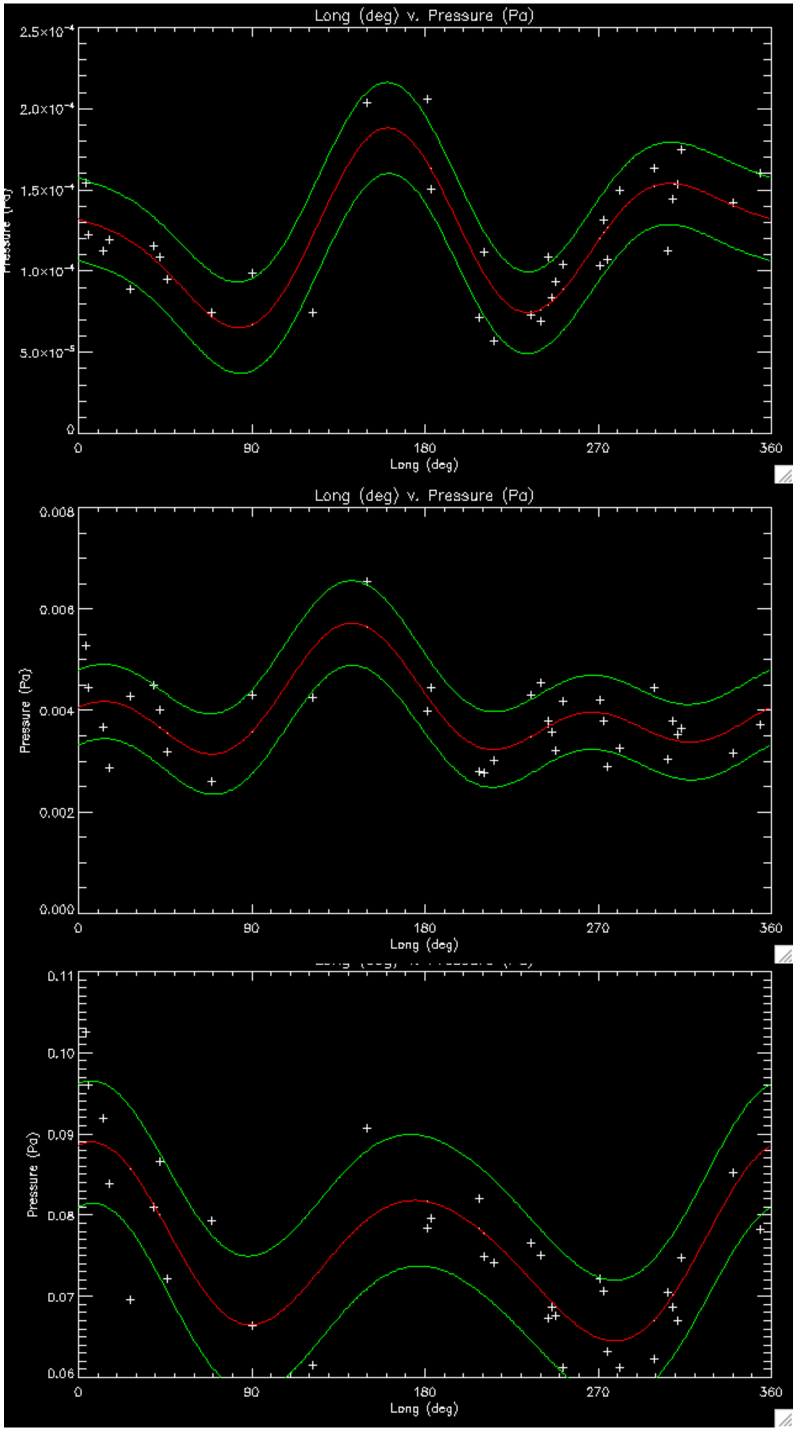


Case G, 110 km, wave 3 dominant



Case D, 110 km, wave 2 dominant

All three cases are equatorial/tropical
Cases C and D at Ls=90-120
Case G at Ls=240-270
Seasonal change between wave-2 dominance and wave-3 dominance?

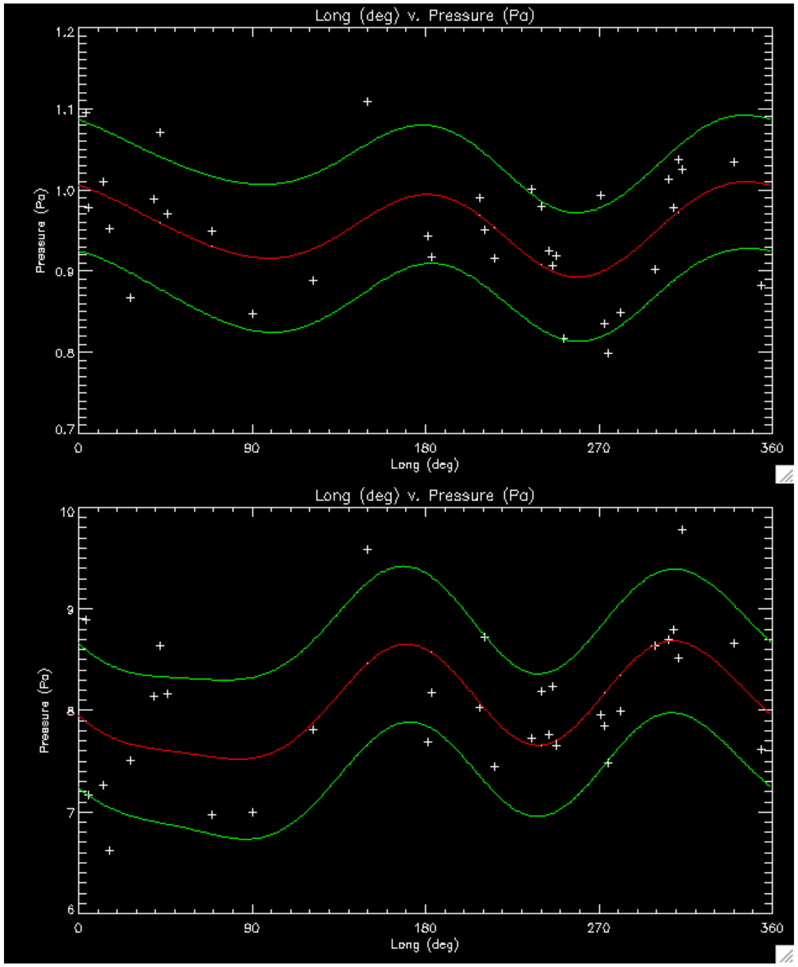


Case C – Changes with altitude
Ls=90-120, 20S to 10S, 2.6 to 4.8 hrs LST

110 km
Wave 1 = 0.084 +/- 0.056, 237.162+/-37.394
Wave 2 = 0.356 +/- 0.056, 155.935+/-4.340
Wave 3 = 0.178 +/- 0.053, 42.344+/-5.431
(Numbers are relative amplitude, dimensionless, and phase, degrees, with errors)

90 km
Wave 1 = 0.138 +/- 0.049, 139.710+/-20.381
Wave 2 = 0.145 +/- 0.048, 145.936+/-9.404
Wave 3 = 0.155 +/- 0.047, 20.931+/-5.421

70 km
Wave 1 = 0.034 +/- 0.026, 43.481+/-45.172
Wave 2 = 0.130 +/- 0.026, 3.612+/-5.708
Wave 3 = 0.024 +/- 0.024, 10.272+/-19.751



50 km
Wave 1 = 0.014 +/- 0.022, 9.788+/-95.065
Wave 2 = 0.049 +/- 0.022, 174.894+/-12.670
Wave 3 = 0.011 +/- 0.021, 75.110+/-35.410

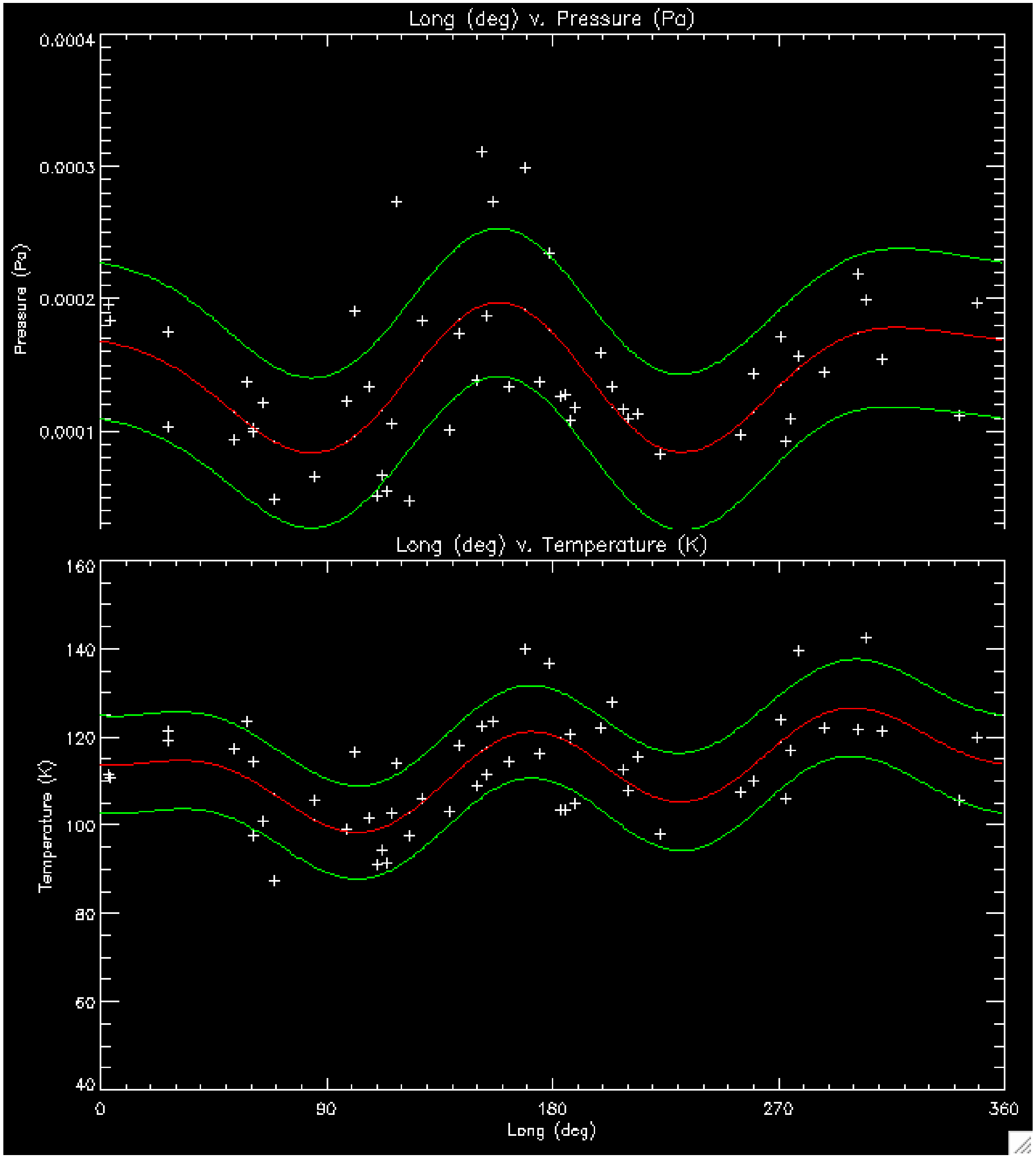
30 km
Wave 1 = 0.034 +/- 0.024, 248.819+/-37.944
Wave 2 = 0.054 +/- 0.023, 151.122+/-12.182
Wave 3 = 0.029 +/- 0.021, 57.725+/-15.245

Wave-2 phase, which ranges from 0 to 180 degrees is:
156, 146, 4 (=184), 175, 151 degrees at 110 km to 30 km
Are these phases sufficiently similar that same tidal mode is responsible at all altitudes?
Or does tidal mode responsible for wave-2 structure change at ~50-70 km?
Amplitude of wave-2 is significant at all altitudes, increases monotonically from 50 km

No obvious coherence in phases of wave-1 and wave-3

Conclusions

- Substantial interannual variability seen in SPICAM and accelerometer observations
- Simulated densities are usually, but not always, larger than observed densities
- Thermal tides, previously seen in accelerometer data, can be seen in SPICAM observations
- Wave-2 component often strongest
- Tidal characterization can be extended far below 100 km with SPICAM measurements
- Phase of a wave component in a fit to temperature or scale height are related to whether amplitude of corresponding component in a fit to density or pressure increases or decreases as altitude increases



Pressure and Temperature

Case D
Ls=30-80 degrees
Latitude = 30S to 20N
LST = 18-22 hours

(top) Pressure at 110 km

(bottom) Average temperature between 90 km and 110 km

Peaks and troughs in pressure occur at same longitudes as those in temperature

Zonal structure in temperature is controlled by zonal structure in pressure

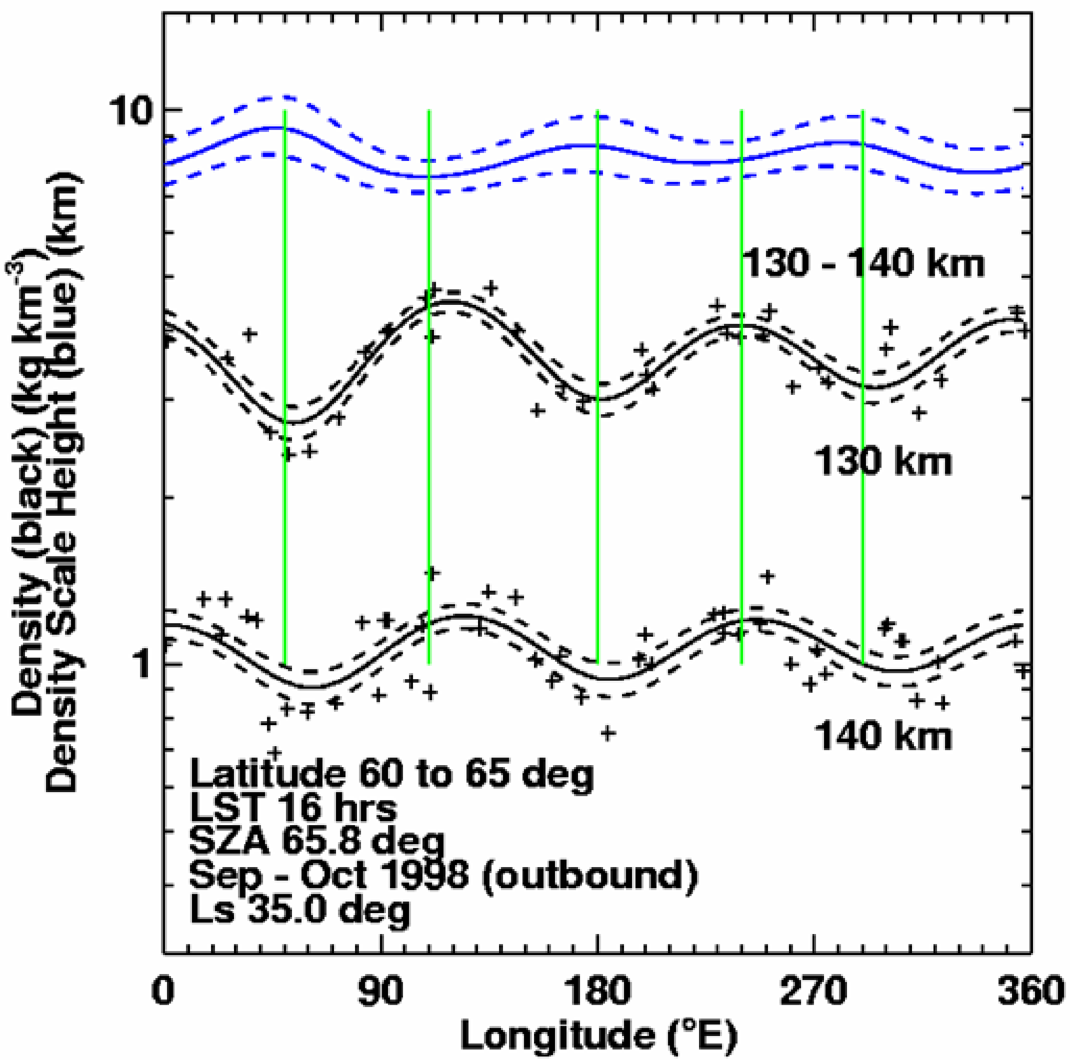
Quantitative Comparison

Wave 1 amplitude (% for p, K for T)	Wave 1 phase (degrees)	Wave 2 amplitude	Wave 2 phase (degrees)	Wave 3 amplitude	Wave 3 phase (degrees)
0.068 +/- 0.081	318.591+/- 67.249	0.326 +/- 0.085	156.420+/- 7.181	0.146 +/- 0.081	40.046 +/- 10.320
6.602 +/- 2.078	293.595+/- 18.917	5.243 +/- 2.144	159.631+/- 11.977	6.744 +/- 2.082	50.503 +/- 6.011

Phases are very similar for fit to 110 km pressure data and for fit to 90-110 km temperature data

Amplitudes are dissimilar

Phasing at Higher Altitudes



In MGS aerobraking data from 130 km to 140 km, opposite trend is visible

Peaks in density match troughs in scale height

Troughs in density match peaks in scale height

Why is situation different?

Expected relationship between tides in pressure and temperature

$$p = p_0(z)\left(1 + w(z) f(\lambda)\right)$$

$$\frac{d \ln p}{dz} = \frac{-1}{H} \qquad \frac{d \ln p_0}{dz} = \frac{-1}{H_0}$$

$$H = H_0 \left(1 + H_0 \frac{dw(z)}{dz} f(\lambda)\right)$$

- Pressure, p(z), has zonal mean value p0(z), and dependence on longitude, l, with relative amplitude set by w(z)

- Scale height is proportional to temperature
- Scale height, H, depends on zonal mean scale height, H0, and gradient in w(z)

- If tides amplify as they propagate upwards, phasing of tides in p and H/T should be identical
  - Expected at lower altitudes
- If tides dissipate as they propagate upwards, phasing of tides in p and H/T should be opposite
  - Expected at higher altitudes

Phasing depends on whether tides are amplifying or dissipating as they propagate upwards

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The SPICAM UV spectrometer instrument on the ESA Mars Express spacecraft has used stellar occultations to measure over 400 vertical profiles of atmospheric density, pressure and temperature between 20 km and 140 km. This extensive dataset is well-suited to studies of the dynamics and thermal state of the middle atmosphere. We shall report on two investigations.

First, comparison of data from SPICAM, data from aerobraking accelerometers, and published predictions from a thermospheric general circulation model. Several restricted regions of parameter space can be defined, typically spanning thirty degrees of Ls, thirty degrees of latitude and three hours of LST, for which SPICAM, accelerometer and model data are all available. We shall discuss the consistency of the SPICAM and accelerometer datasets, and also the results of model-data comparisons.

Second, characterization of non-migrating thermal tides in SPICAM data. Thermal tides are known to cause zonal variations in densities measured between 100 km and 160 km at fixed local solar time by aerobraking accelerometers. We shall characterize thermal tides in density, pressure and temperature data between 20 km and 140 km. There are two primary objectives. (A) To extend the characterization of thermal tides downwards into the middle and lower atmosphere in order to see how the amplitudes and phases of tidal modes change as tides propagate upwards. (B) To compare tidal structures in density, pressure and temperature data in order to test predictions that tidal effects on density and temperature are anti-correlated.