I came to LPL because everyone I met during my first visit here seemed friendly. Now that I'm ready to leave, I'm sure of it. The welcoming and relaxed environment pervading the department is something that's made my time here a happy one. The faculty, postdocs, and staff are always willing to spend their time, and everyone is willing to spend the faculty's money, encouraging the graduate students. Hawthorne House has been my home for the past five years. I can't imagine LPL without it. As the host of Bratfests, Science Diet concerts, parties, Thanksgiving Dinners and innumerable gatherings of all sorts, it has been the centre of my social scene. I've shared it with many friends, including Kim Cyr, Joe Spitale, Rachel Mastrapa, Dave O'Brien, Laz Keszthelyi, Gareth Collins, Celinda Kelsey, Matt Chamberlain, Abby Wasserman/Sheffer, Jonathan Fortney, Eric Mamajek, and their lovers. Bratfest and its T-shirt industry have introduced me to absolutely everyone ever associated with LPL, trained me for my backup career in door-to-door sales, and thrown some damn fine fests. The Narcolepsy football team has kept me exercised and entertained. Christmas Skits and April Fools Pranks have cost me many hours of sleep and coincided with my worst day at LPL, but given me much laughter and a list of unprintable LPL pseudonyms. If the editing ever finishes before 6am, then I will know that the end is nigh. My officemates, Ross Beyer, Jen Grier, Ingrid Daubar, and Sally House, have given me office supplies and food. Many friends from other universities and the LPL alumni have made conferences less productive, but much more entertaining. Trading gossip with them has made the idea of leaving LPL less foreboding that it otherwise would be. Fieldtrips have shown me and most of the Southwest's scenic gems and the true nature of many LPLers. Who can forget Day 4, Kring Narrows, Ralph ralphing, Pete covering himself in glory, Ross stranding us in Death Valley, Pete's stratigraphic monologue, Dave's glaciation speculation, spheroidal weathering, Alfred's vocabulary, or Jay's giant cracks? I am grateful to staff like Noreen Conarro, Marianne Hamilton, Linda Hickox, and Maria Schuchardt for showing me who really runs any institution; to postdocslike Paul Geissler, Ralph Lorenz, Kevin Righter, Bashar Rizk, and Aileen Yingst for showing me what I have to look forward to after graduation; to my predecessors Betty Pierazzo, Zibi Turtle, Andy Rivkin, David Trilling, Nancy Chabot, Jen Grier, Barb Cohen, Cynthia Phillips, Joe Spitale, Josh Emery, Pete Lanagan, Windy Jaeger, and Rachel Mastrapa for passing their accumulated decades of graduate student lore and wisdom down to me and thus saving me from many mistakes; to my fellow protodoctors Jason Barnes, Ross Beyer, Fred Ciesla, Terry Hurford, and Dave O'Brien for their friendship during every day of my graduate studies; and to the graduate students who follow us, Gwen Bart, Ingrid Daubar, Jonathan Fortney, Celinda Kelsey, Jani Radebaugh, and Matt Tiscareno, Matt Chamberlain, Curtis Cooper, Jim Richardson, and Abby Wasserman/Sheffer, Oleg Abramov, John Keller, and Moses Milazzo for replacing departed old friends with new ones. Section~\ref{intro_support} contains some professional acknowledgements. My tongue doesn't have the words to give the most important thanks to those who are always in my heart.

Weather in the Martian Atmosphere – And Other Topics

PhD Defence

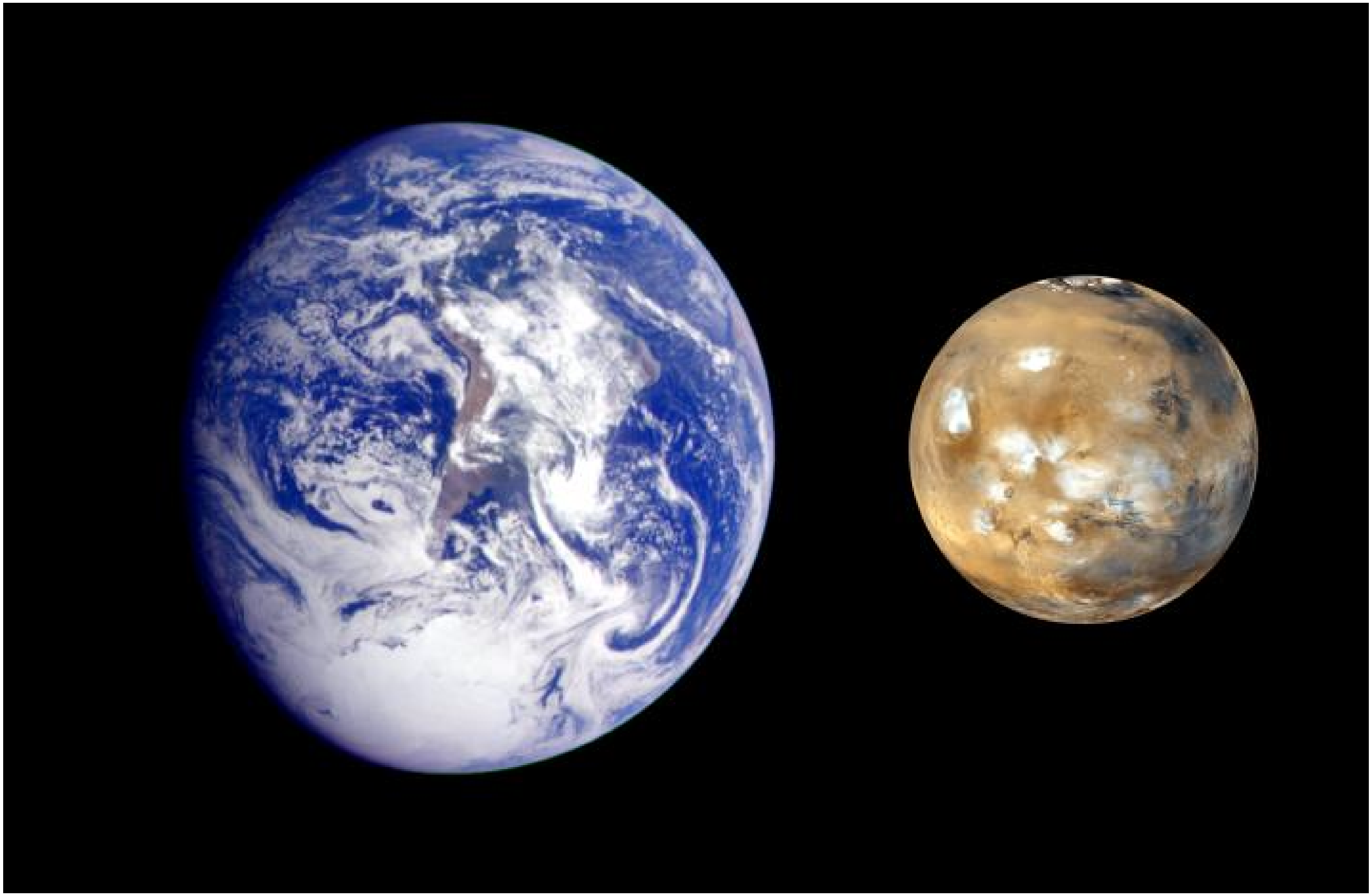
Paul Withers

2003.03.24

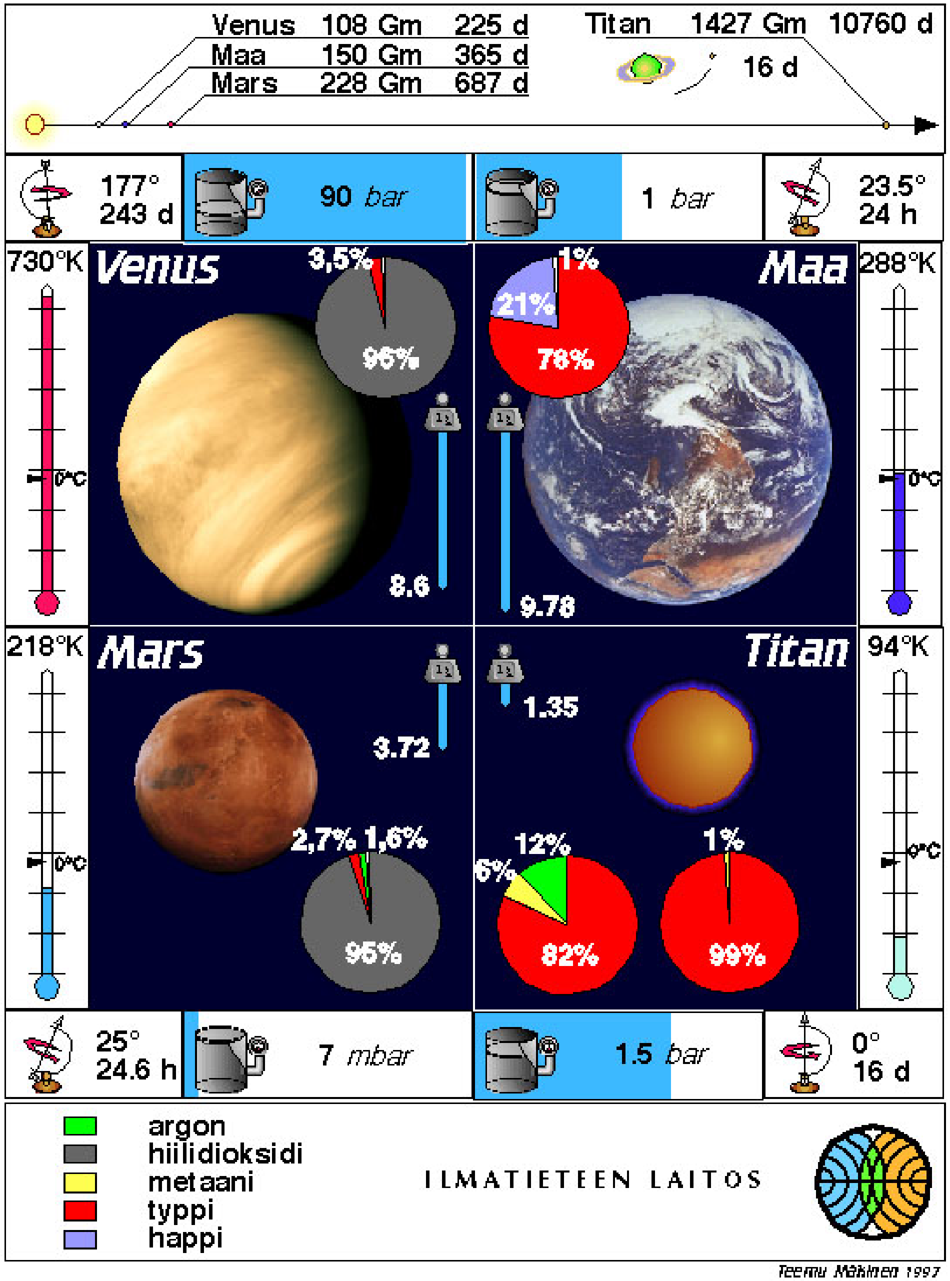
Next job: Boston University

Structure of Talk

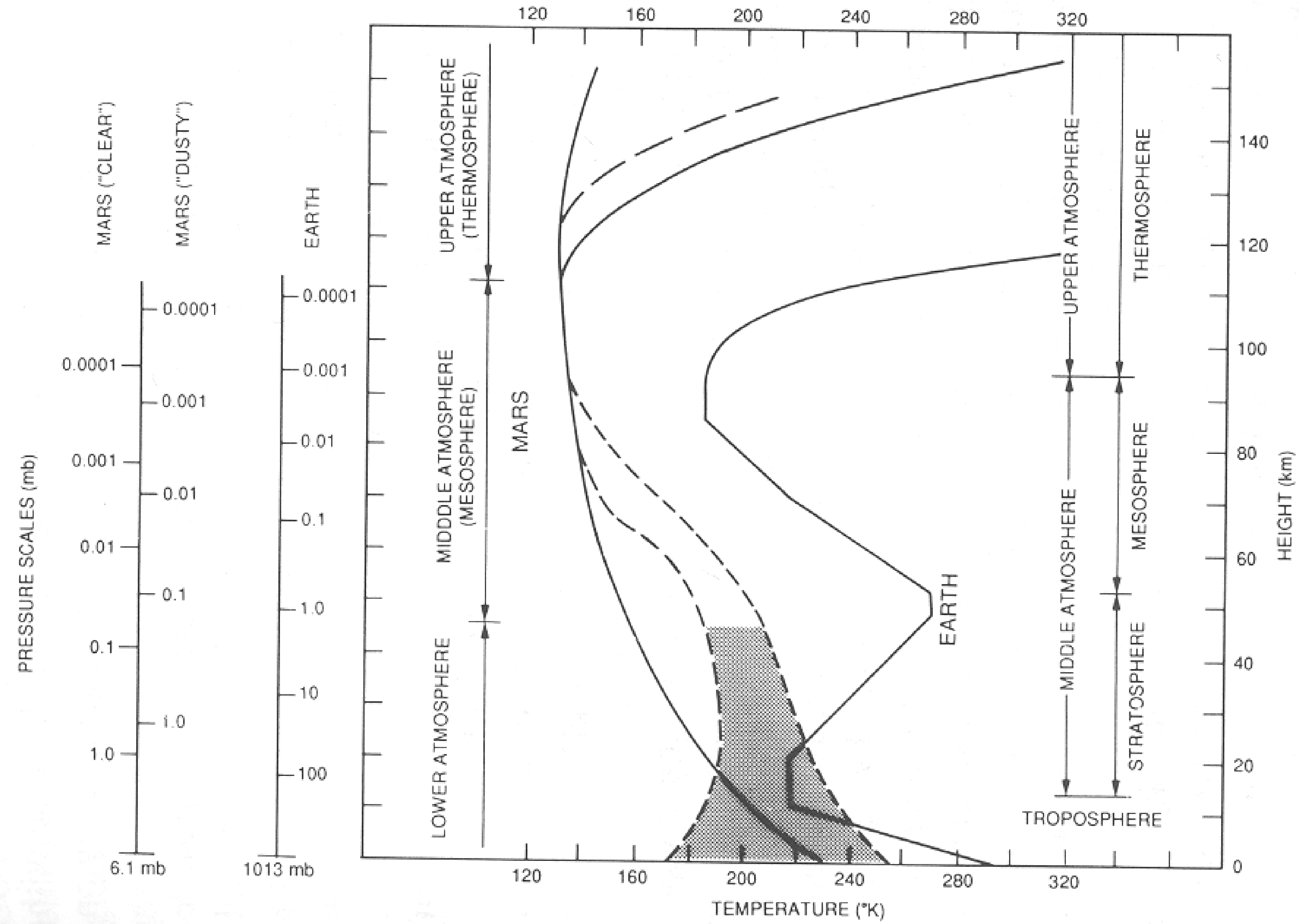
- Introduction to the martian atmosphere
- Topographically-controlled thermal tides in the martian upper atmosphere:
  - Observations
  - Data analysis
  - Modelling
  - Conclusions
- Briefly outline the major results of every other chapter in my dissertation – if time allows



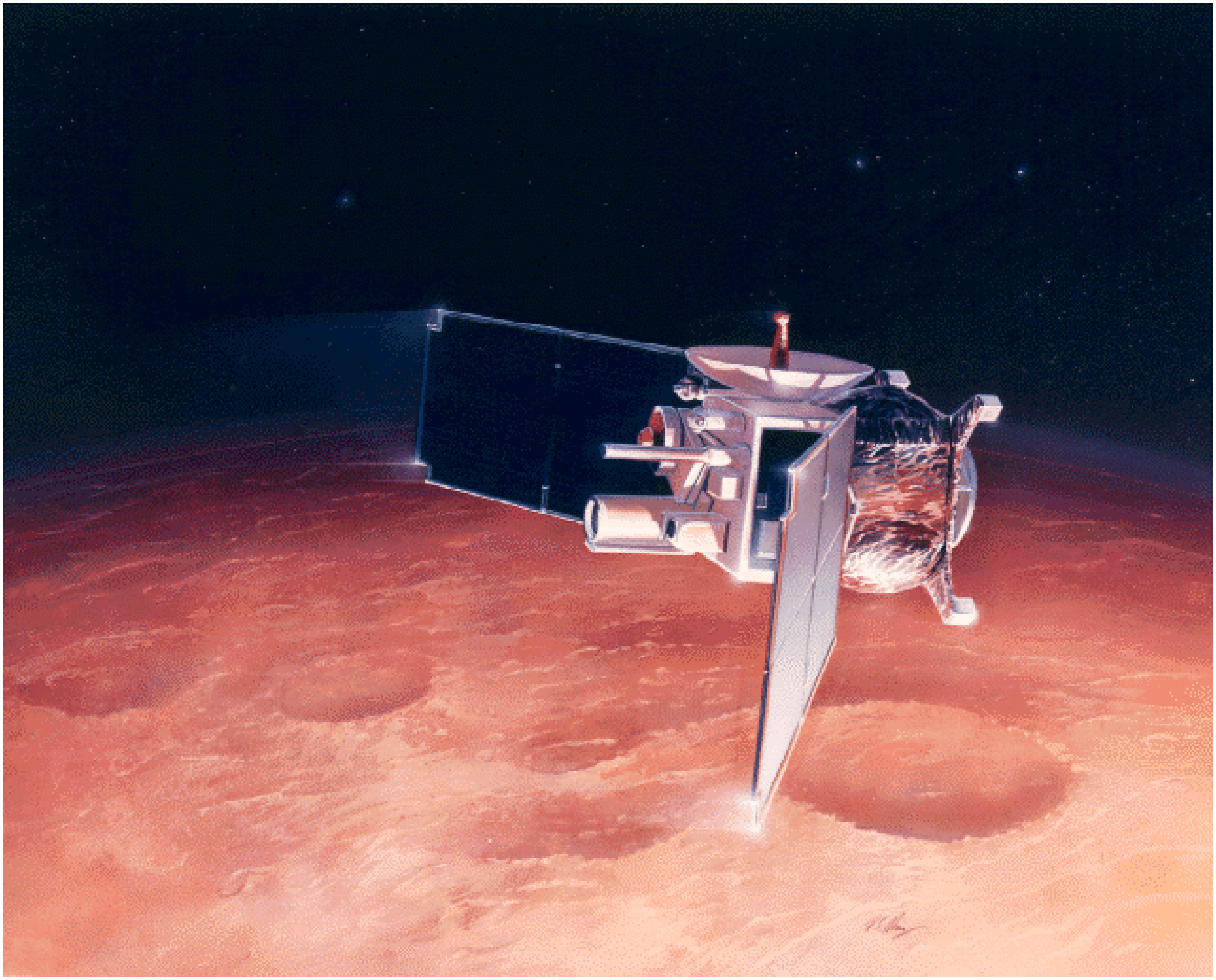
JPL image



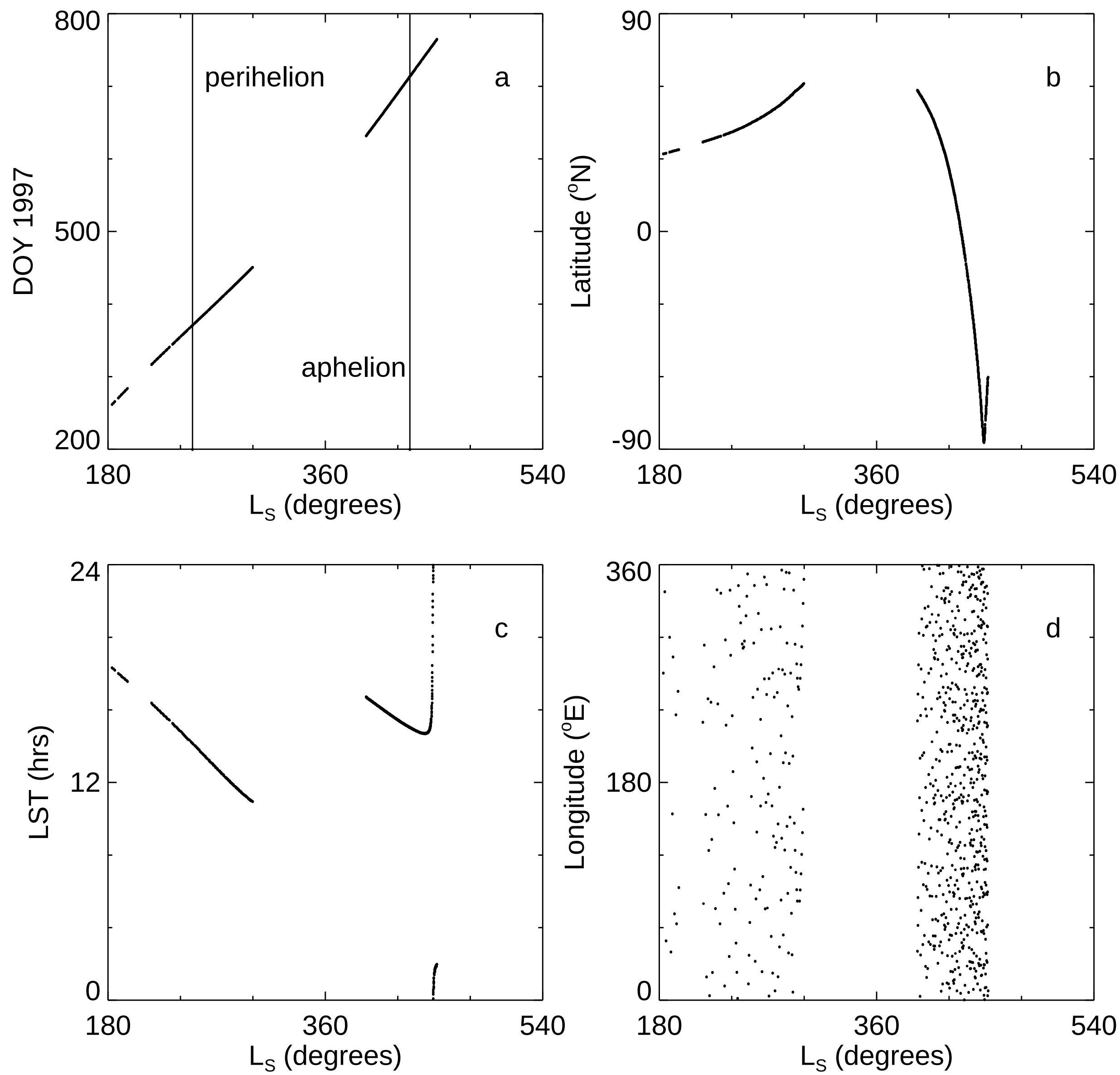
Teemu Makinen,
Finland

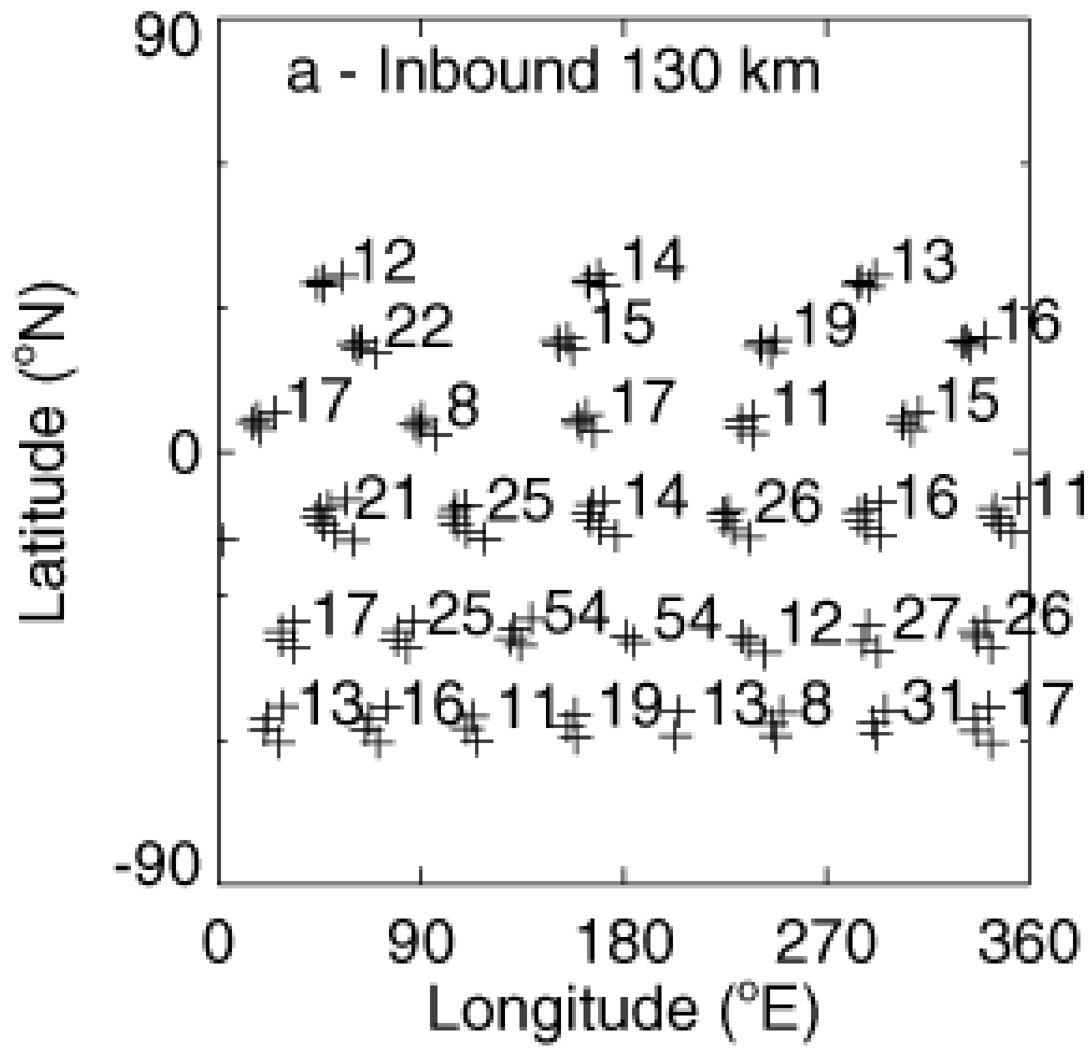


Zurek, Mars Book



JPL Image


800
500
200
DOY 1997
perihelion
aphelion
a
180
360
540
LS (degrees)
90
0
-90
Latitude (oN)
b
180
360
540
LS (degrees)
24
12
0
LST (hrs)
c
180
360
540
LS (degrees)
360
180
0
Longitude (oE)
d
180
360
540
LS (degrees)


a - Inbound 130 km
Latitude (°N)
Longitude (°E)
90
0
-90
0
90
180
270
360
12
14
13
22
15
19
16
17
8
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21
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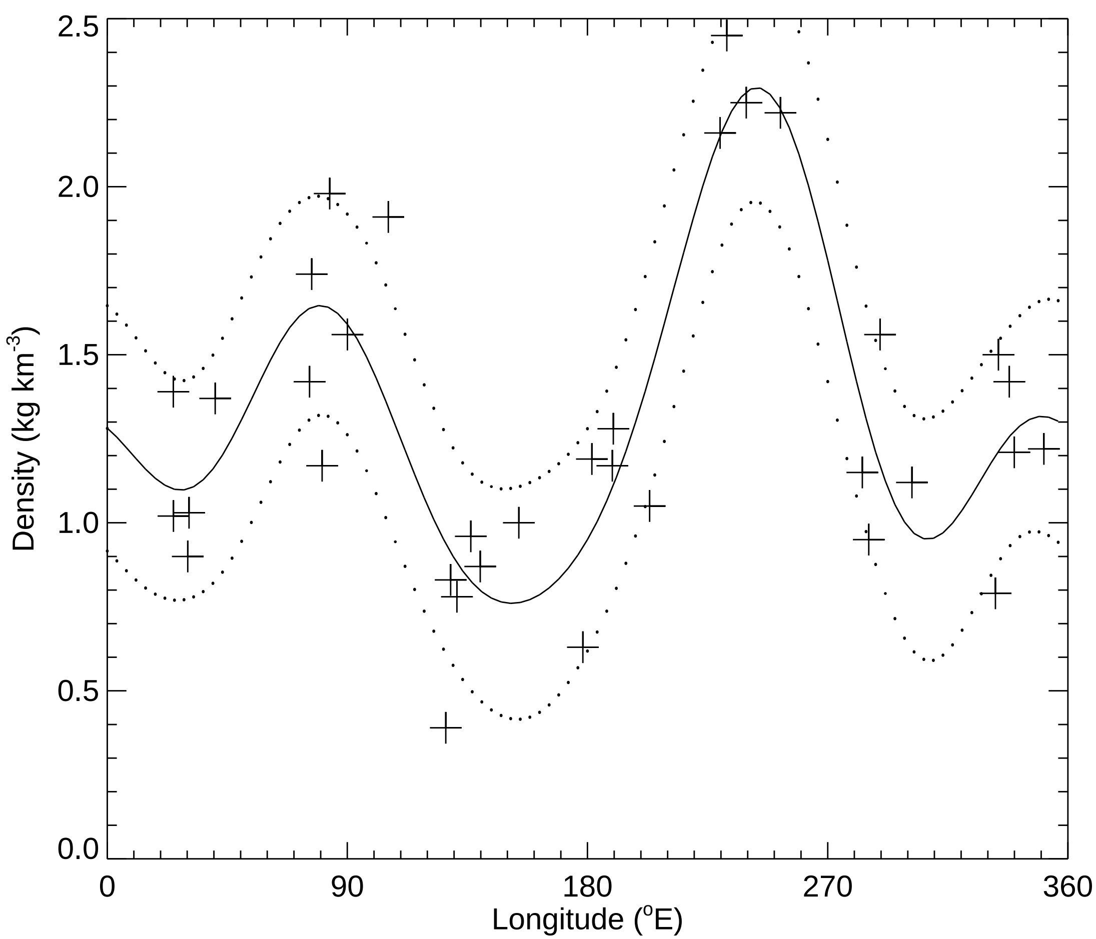
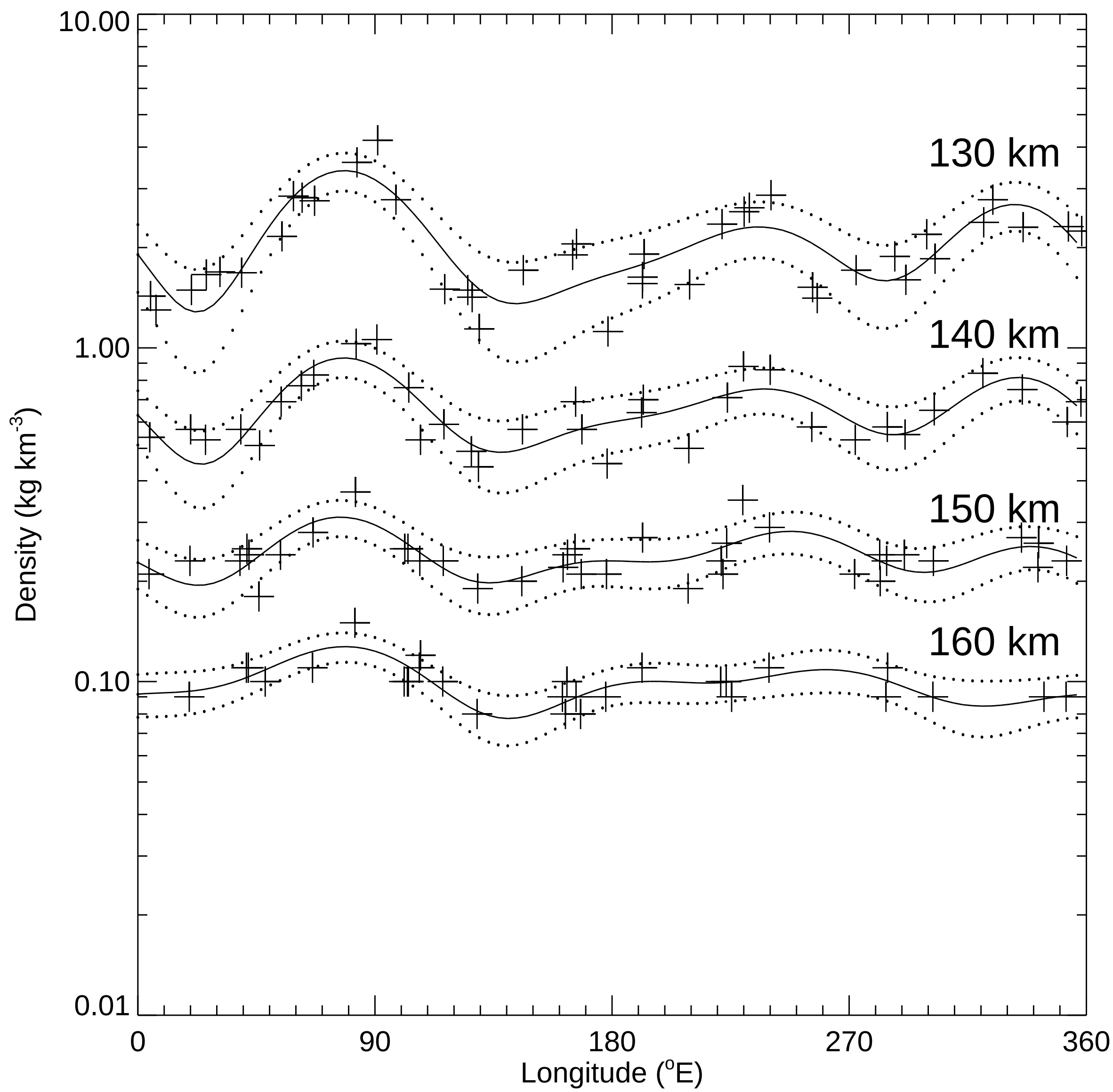
19
13
8
31
17



130 km
10^oS-20^oS
~1 week of data
15hr LST

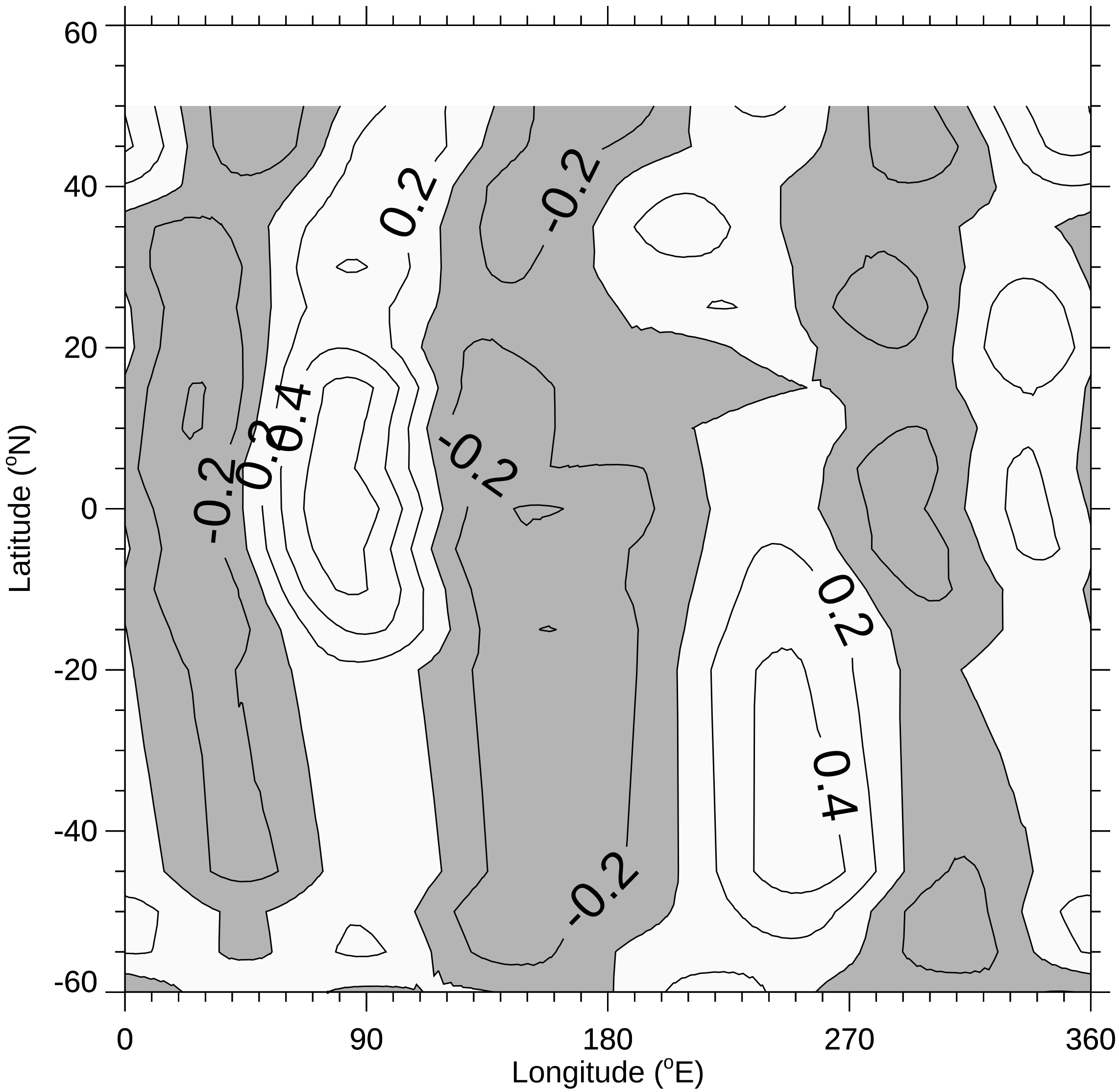
Crosses = data
Solid line = fit
Dotted line = uncertainty

$A_0 + A_1\cos\lambda + B_1\sin\lambda + A_2\cos2\lambda + B_2\sin2\lambda + \ldots$



130 km
10^{o}N – 20^{o}N
~1-2 weeks data
15hr LST

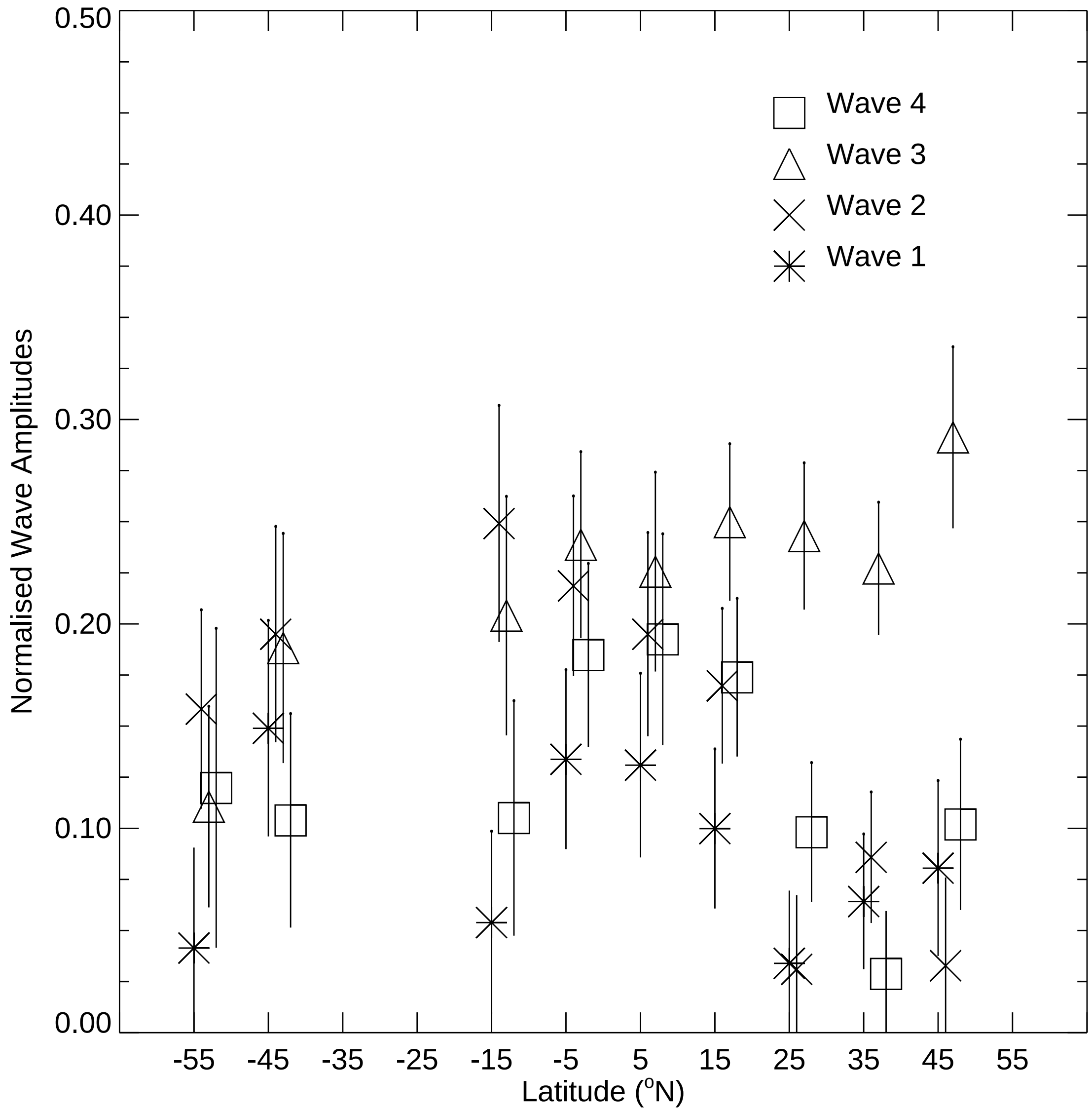
Peaks, troughs are fixed in longitude



130 km
17 - 15hr LST
>few weeks data
$L_S = 30^o – 80^o$

(Fit-Zonal Mean) /
(Zonal Mean)

Phases near
constant with lat,
but amplitudes
change with lat



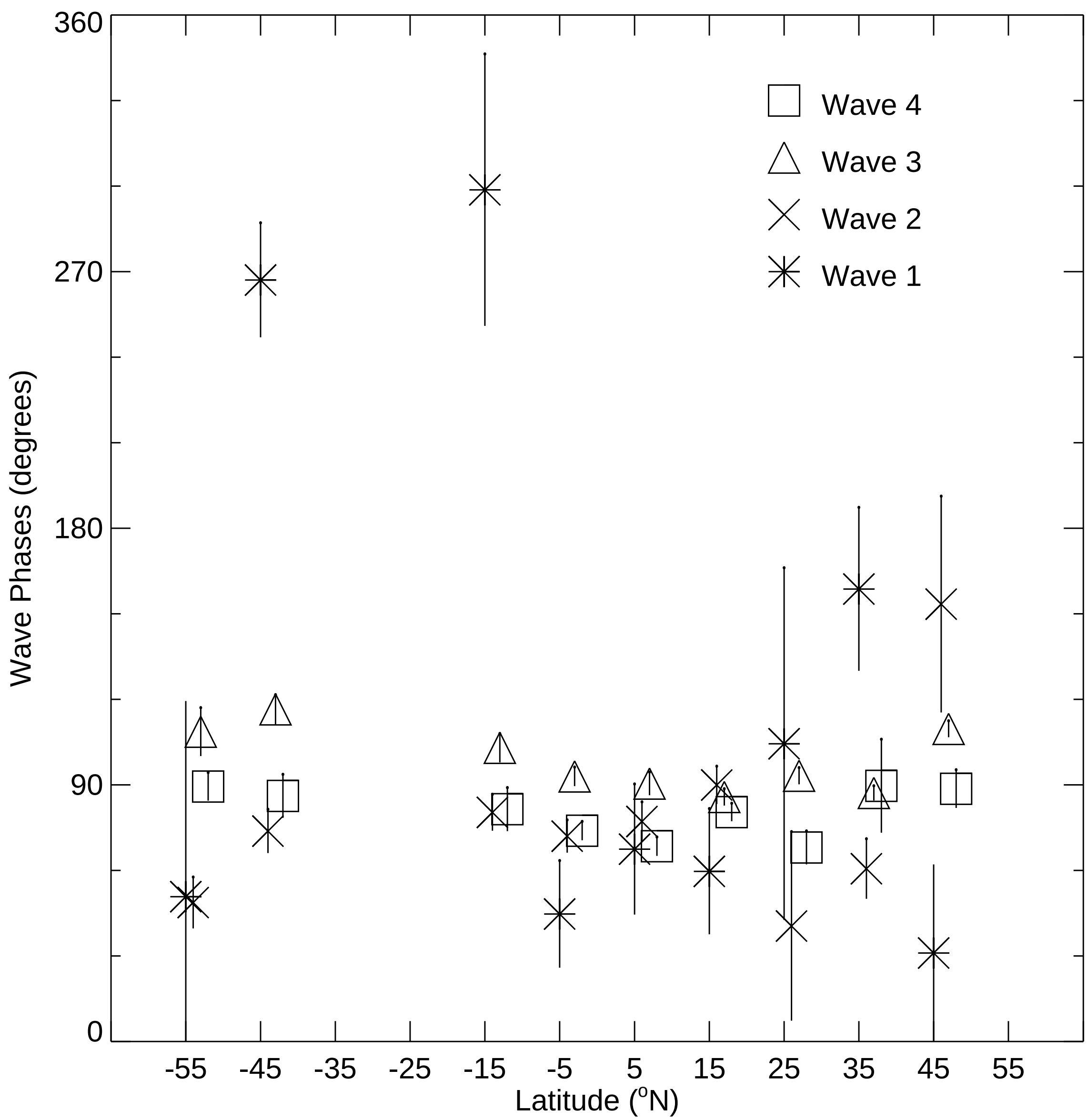
Amplitudes from previous slide

“45N” => 40°N-50°N

Data drops in the south

No one harmonic dominates at all lats

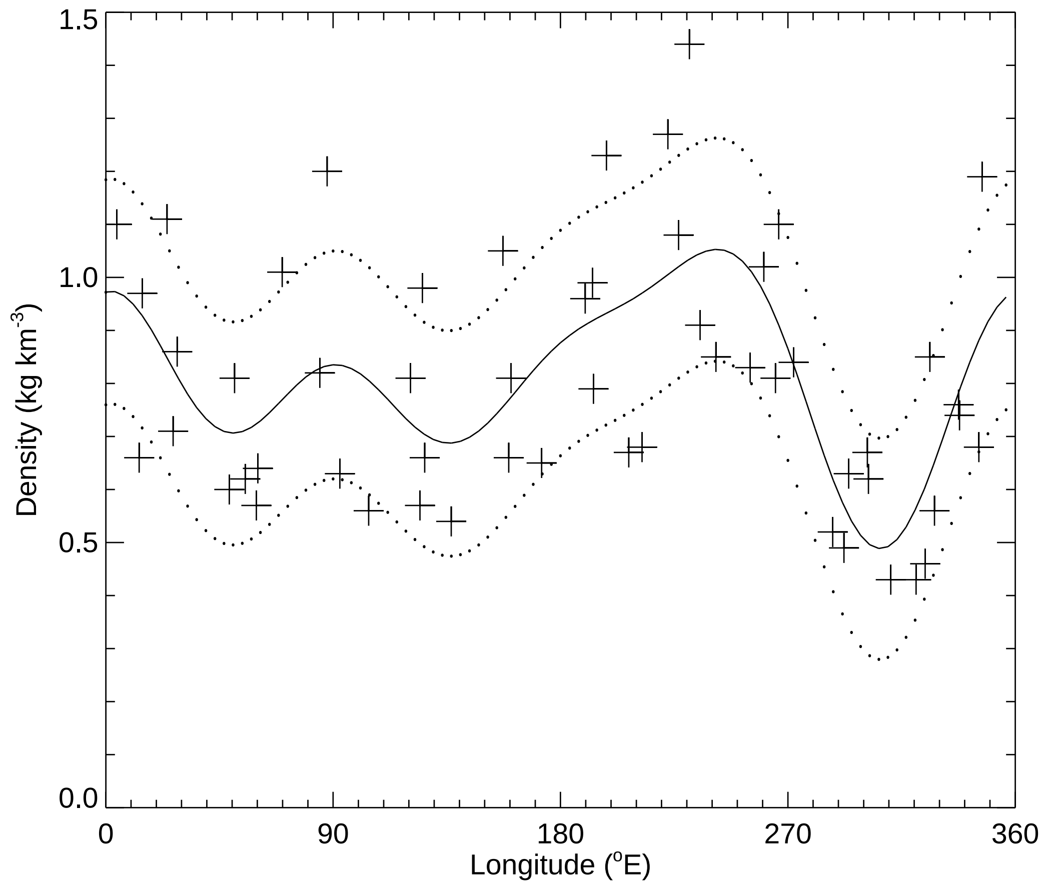
At most lats, more than one harmonic is large



Phases from previous slide

“phase” = longitude of first peak east of 0^oE => phase of wave 4 < 90^oE

Most phases are constant with lat



130 km

50^{o}S – 70^{o}S

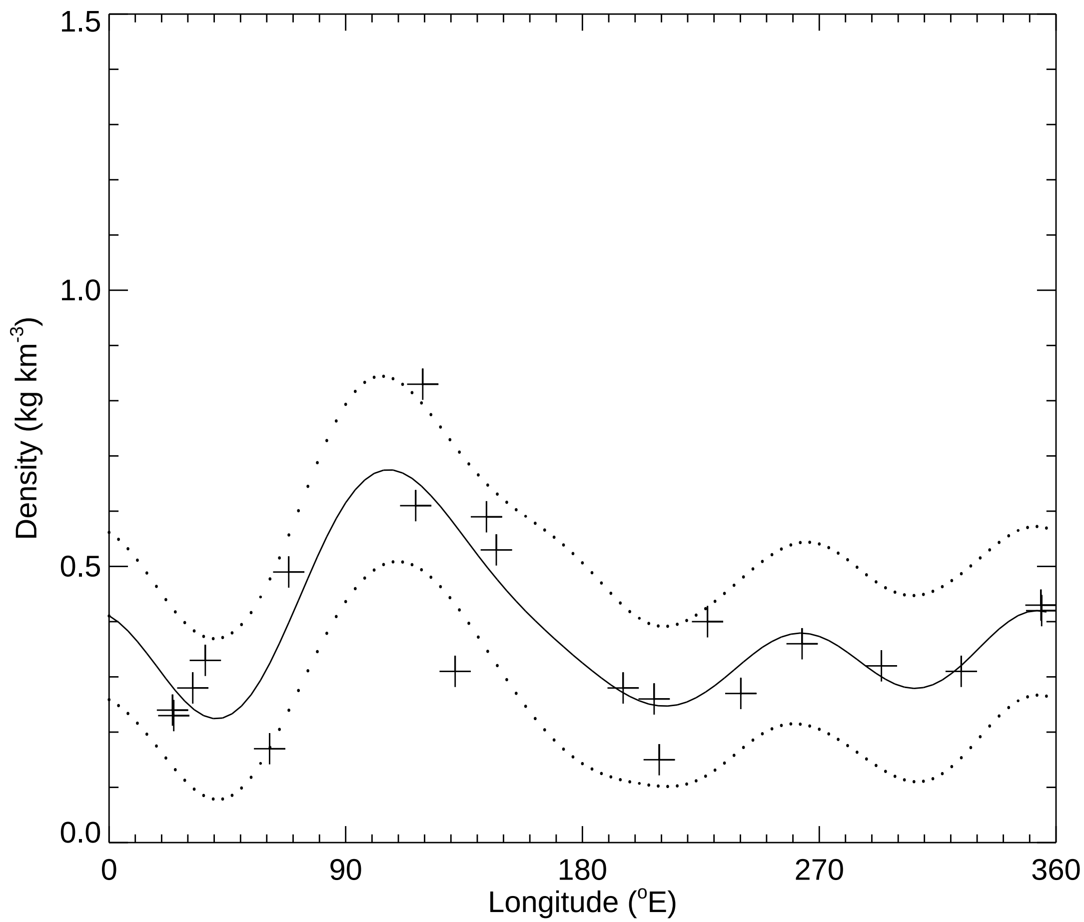
~1 week data

15hr LST

L_S ~ 80^{o}

Mean ρ ~ 0.8

Zonal structure with trough at 300^{o}E



130 km
50^{o}S – 70^{o}S
~1 week data
02hr LST
L_S ~ 80^{o}

Mean ρ ~ 0.4
Zonal structure with peak at 100^{o}E

Zonal structure is not stationary in time

Modelling of the zonal structure (1)

- Solar heating comprises diurnal and semidiurnal components
- Creates **migrating** disturbances which track Sun across sky with form ~ $\cos[\sigma\Omega t_{UT}+\sigma\lambda - \phi]$ and σ=1 or 2 (dimensionless)
- Ω=rotational freq, t_{UT} = Universal time, λ=longitude, ϕ=phase

- Interacts with and is modulated by some zonal asymmetry (such as topography) with true zonal wavenumber *m*.
- Resulting **non-migrating** disturbance ~ $\cos[\sigma\Omega t_{UT}+s\lambda - \phi]$ where $s = (\sigma +/- m)$
- Zonal wavenumber changes, frequency does not
- Change from t_{UT} to t_{LST}: $\cos[\sigma\Omega t_{LST} +/- m\lambda - \phi]$
- This is seen by MGS ACC as wave *m* zonal structure

Modelling of the zonal structure (2)

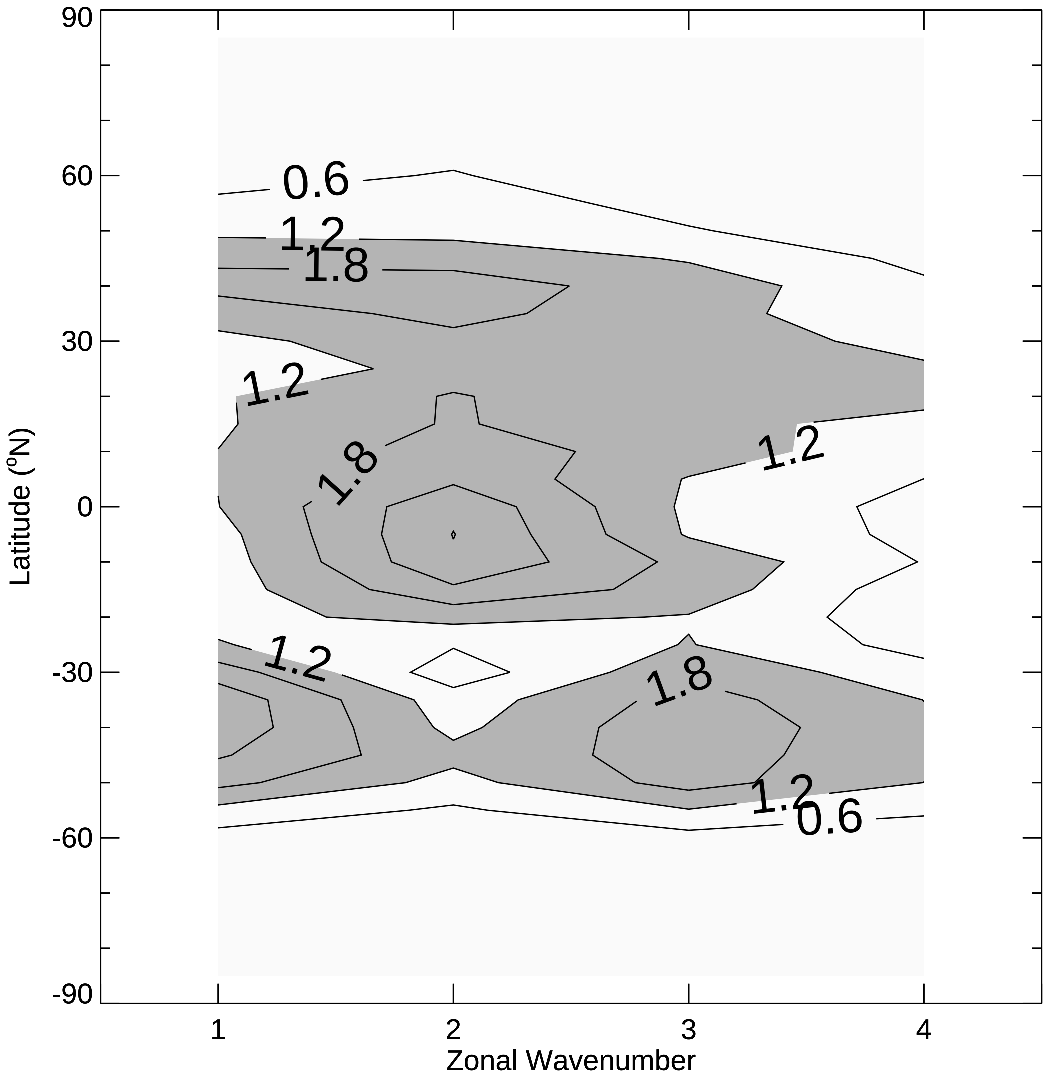
- Given $\cos[m\lambda - \phi]$ in MGS ACC data, what are σ and s of disturbance and what is the cause of m?
- Wave-1 zonal structure could be from **non-migrating** disturbances where $(\sigma,s) = (1,0), (1,2), (2,1)$ or $(2,3)$
- Global-scale disturbances with harmonic relationship to a forcing like solar heating are **tides**, can be studied with Laplace's classical tidal theory

- Arbitrary disturbance with a given (σ,s) can be represented as infinite sum of basis functions labelled with (σ,s,n), use Hough functions instead of Fourier series
- Does latitudinal structure overlap well with solar heating?
- Does vertical structure permit upward propagation?

Modelling of the zonal structure (3)

- Reject the (σ,s,n) Hough functions which cannot affect upper atmosphere, if all (σ,s,n) for a given (σ,s) are rejected then that (σ,s) tidal mode is not present in upper atmosphere
- I conclude that $(\sigma,s) = (1,-1)$; $(\sigma,s) = (2,-1)$; $(\sigma,s) = (1,-2)$ dominate – consistent with Wilson's GCM predictions

- What is the cause of *m*?
- For a wave *m* zonal asymmetry such as topography to interact with migrating disturbances, its latitudinal profile must, like solar heating, be peaked in equatorial regions and decrease monotonically towards the poles
- Examine topography, thermal inertia, and albedo…



Zonal harmonics
Of topography

Waves 1 and 4 are poor overlaps with solar heating, but waves 2 and 3 are good overlaps

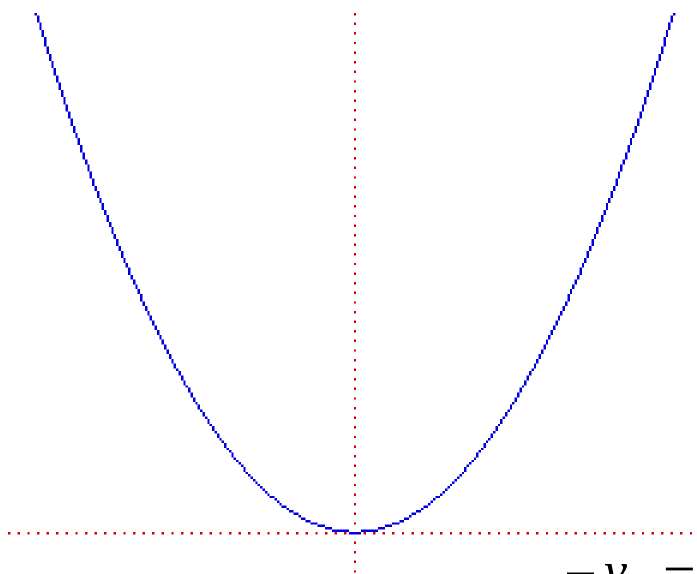
All components of thermal inertia and albedo are poor

Consistent with strong waves 2 and 3 in data

Conclusions

- I have characterized zonal structure in the martian upper atmosphere as a function of altitude, latitude, and LST.
- Its week-to-week stability and broad latitudinal range require a planetary-scale cause – thermal tides.
- Comparison of observations and simple theory has led to the identification of several dominant tidal modes.
- Topography generates these tides.
- Tides have long been known to play a major role in the lower atmosphere of Mars. This work is the first detailed study of their importance in the upper atmosphere.

C3/4: Development of a novel “Balanced Arch” technique for measuring winds



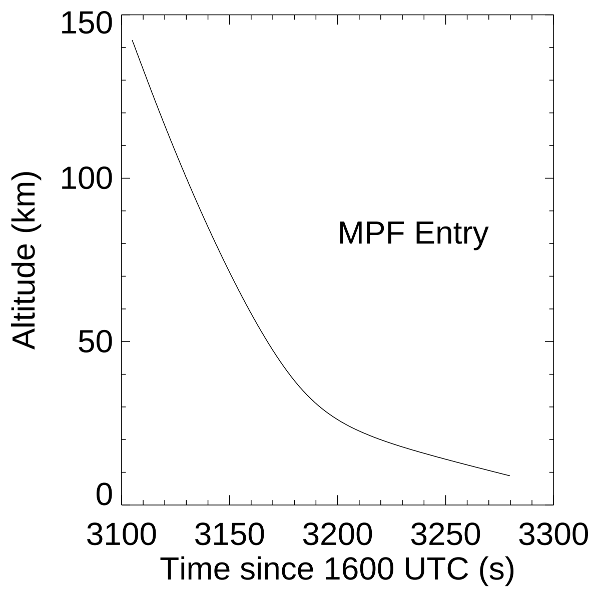
$$\frac{1}{\rho}\frac{\partial p}{\partial r} = \frac{-GM}{r^2} = g_{eff,r}$$

$$\frac{1}{\rho r}\frac{\partial p}{\partial \theta} = 2\Omega v_\phi \cos\theta + g_{eff,\theta}$$

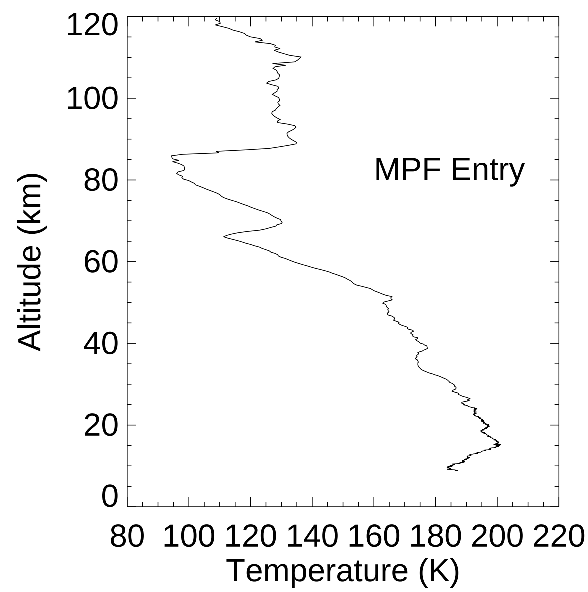
$$-v_\phi = \frac{\left(\int_{entry}^{peri} \rho g_{eff,r}\,dr + \int_{entry}^{peri} \rho r g_{eff,\theta}\,d\theta\right) - \left(same \quad but \quad exit\right)}{\left(\int_{entry}^{peri} 2\Omega \rho r \cos\theta\, d\theta\right) - \left(same \quad but \quad exit\right)}$$

$$\frac{2\left(p_i - p_o\right)}{p_i + p_o} = \sqrt{2\pi R/H}\,\frac{2\Omega v_\phi \cos\theta}{g}$$

C5: Analysis of entry accelerometer data



Preparation for Beagle 2 and MER in December/January



$$a = \frac{\rho C_D A V^2}{2m}$$

C6: Scientific uses of crude telemetry during atmospheric entry

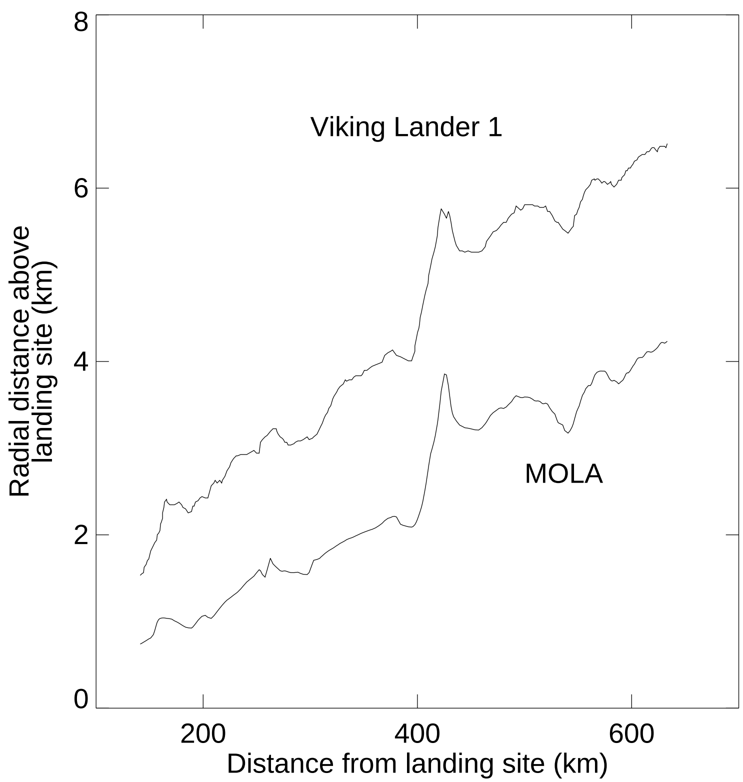
- Use Doppler shift in telemetry from failed lander to derive atmospheric properties
- Works only at peak acceleration:

$$T = \frac{M_{mol} g \Delta t}{k_B} \frac{v_n^2}{v_{n-1} - v_{n+1}}$$

- Assumes constant C_D:

$$p - p_0 = \frac{-mg}{C_D A} \ln\left(\frac{v}{v_0}\right)$$

C7: Comparison of Viking Lander 1 and MOLA Topography

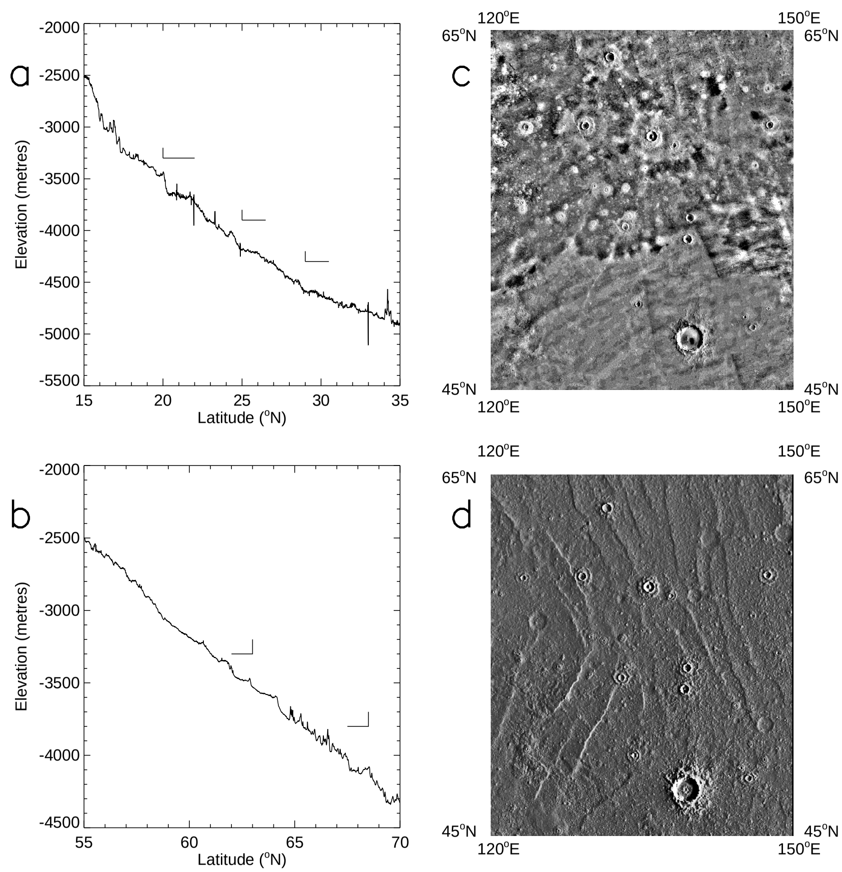


Compare VL1 radar's topographic profile to MOLA topo profile beneath flight path.

Difference is due to misplaced position of VL1 during entry.

Correct VL1's position, hence correct VL1's vertical profiles of atmospheric structure

C8: Enigmatic Northern Plains of Mars

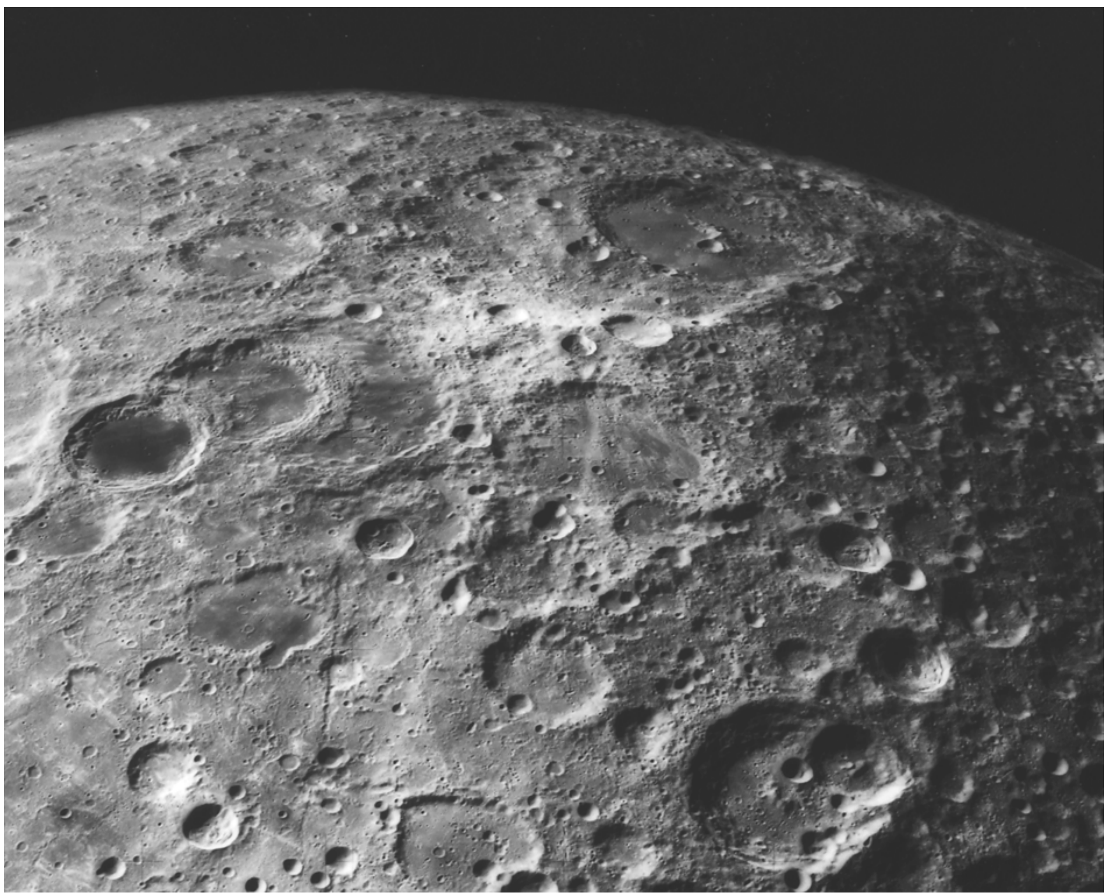


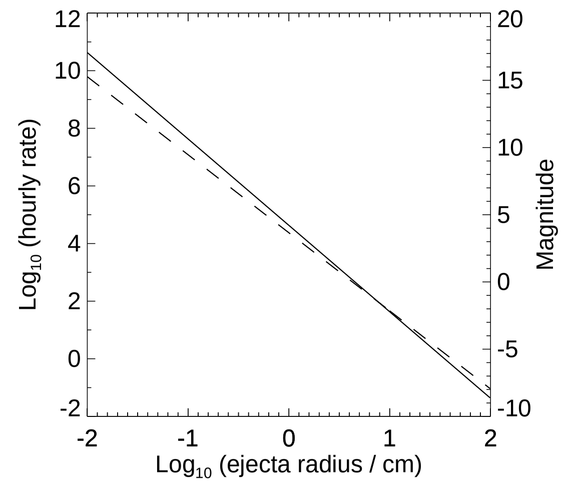
Featureless northern plains are crisscrossed by a network of tectonic ridges.

These ridges are not shorelines; they are related to Tharsis.

By relating these ridges to models, the tectonic evolution of Mars can be better understood.

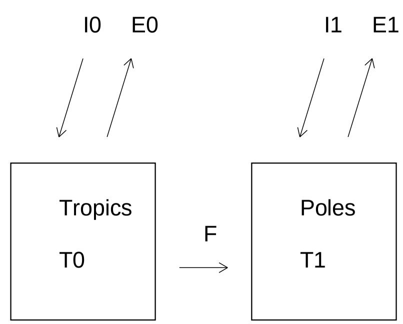
C9: Age of lunar crater Giordano Bruno





“The moon throbbed
like a wounded snake …
spewing out … fire,
hot coals, and sparks”

C10: Simple Climate Models



- $I_o - F - E_0 = 0$ (energy balance)
- $I_1 + F - E_1 = 0$
- $E_i = A + BT_i$
  (linearize outgoing radiation)
- $F = 2\,D\,(T_0 - T_1)$
  (parameterize atmospheric heat transport)
- Extremize entropy production
  => $4D \sim B$

Things I Would Like To Discuss With My Committee

- What are most promising “future work” avenues in MGS and Odyssey data?
- What things do I generally do well and what things do I generally do poorly?
- What new skills should I try to acquire in the next few years?
- What should I aim to do in my first year as a postdoc?
- How should I deal with Beagle 2 and MER entry accelerometer data access without funding?