Upper Atmospheric Density Profiles

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Atmospheres Lunch
Presentation
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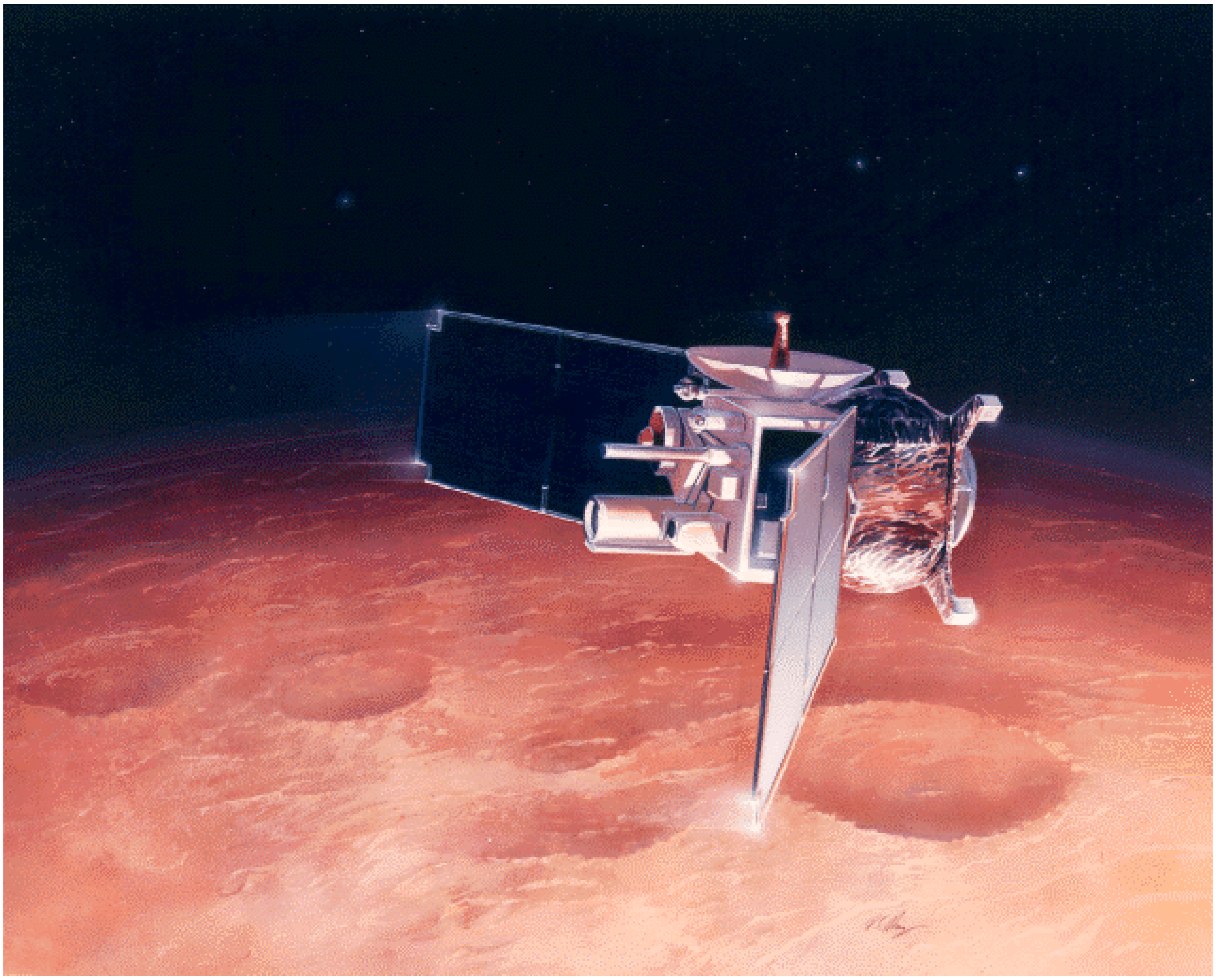
Layout of Talk

- Relevant datasets, MGS and others
- Deriving p, T profiles from vertical density profiles
- Problems due to non-vertical profiles
- Balanced Arch Technique to fix problems
- Testing Balanced Arch Technique on MGS
- Other Uses of Density Profiles



Mars Global Surveyor Mission

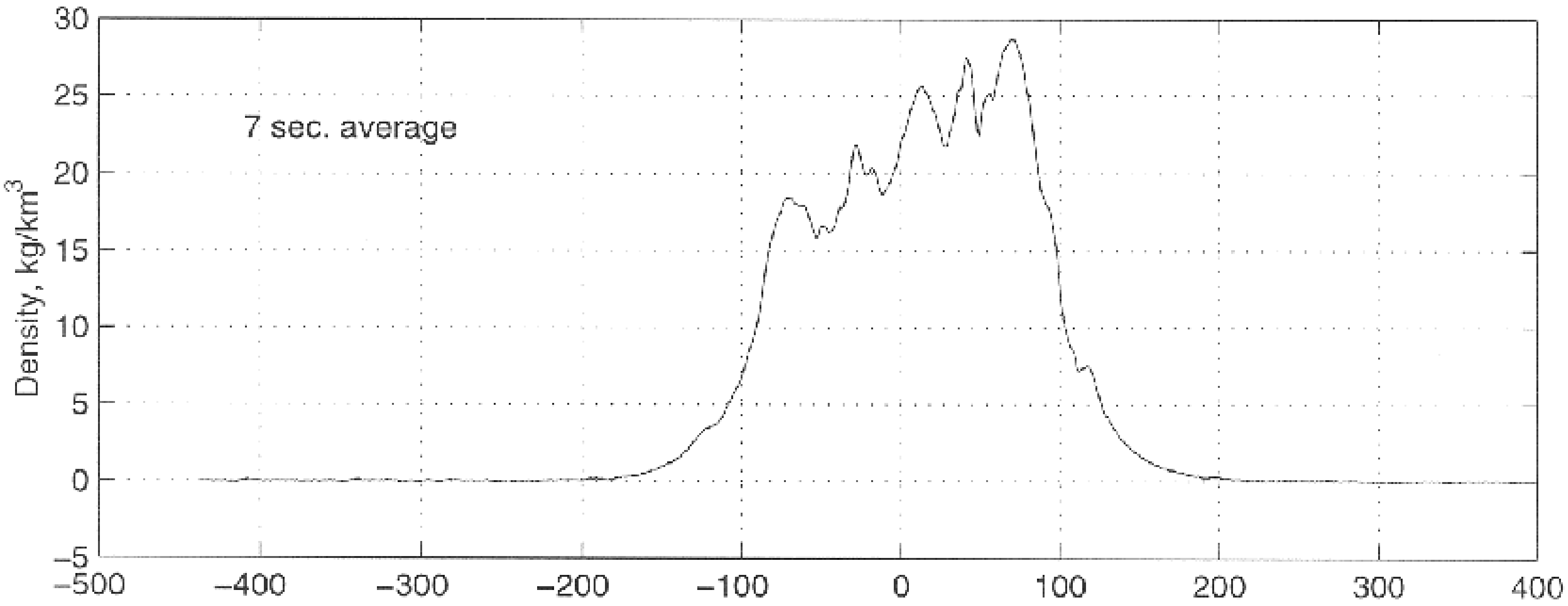
- Carries 5 of 7 Mars Observer instruments, but launched on $50M Delta 2 instead of $350M Titan
- Orbit insertion without needing huge gas tanks – aerobraking
- First operational use of aerobraking in planetary exploration
- About 800 passes through upper atmosphere to reduce orbit energy and semi-major axis
- September 1997 to February 1999
- Survived a broken wing and a dust storm
- Babysitting by engineers and scientists in daily teleconferences required

Measuring Densities

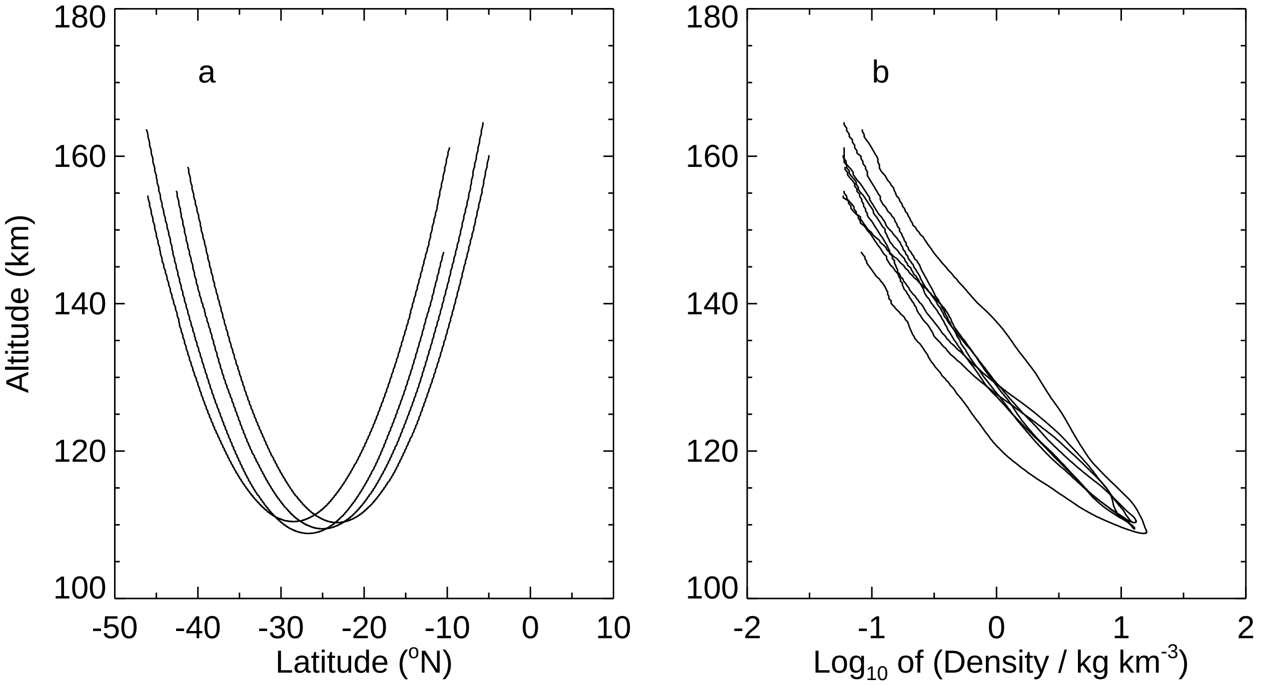
- If spacecraft's attitude, velocity, and aerodynamics are known, then measured aerodynamic acceleration can be used to derive atmospheric density

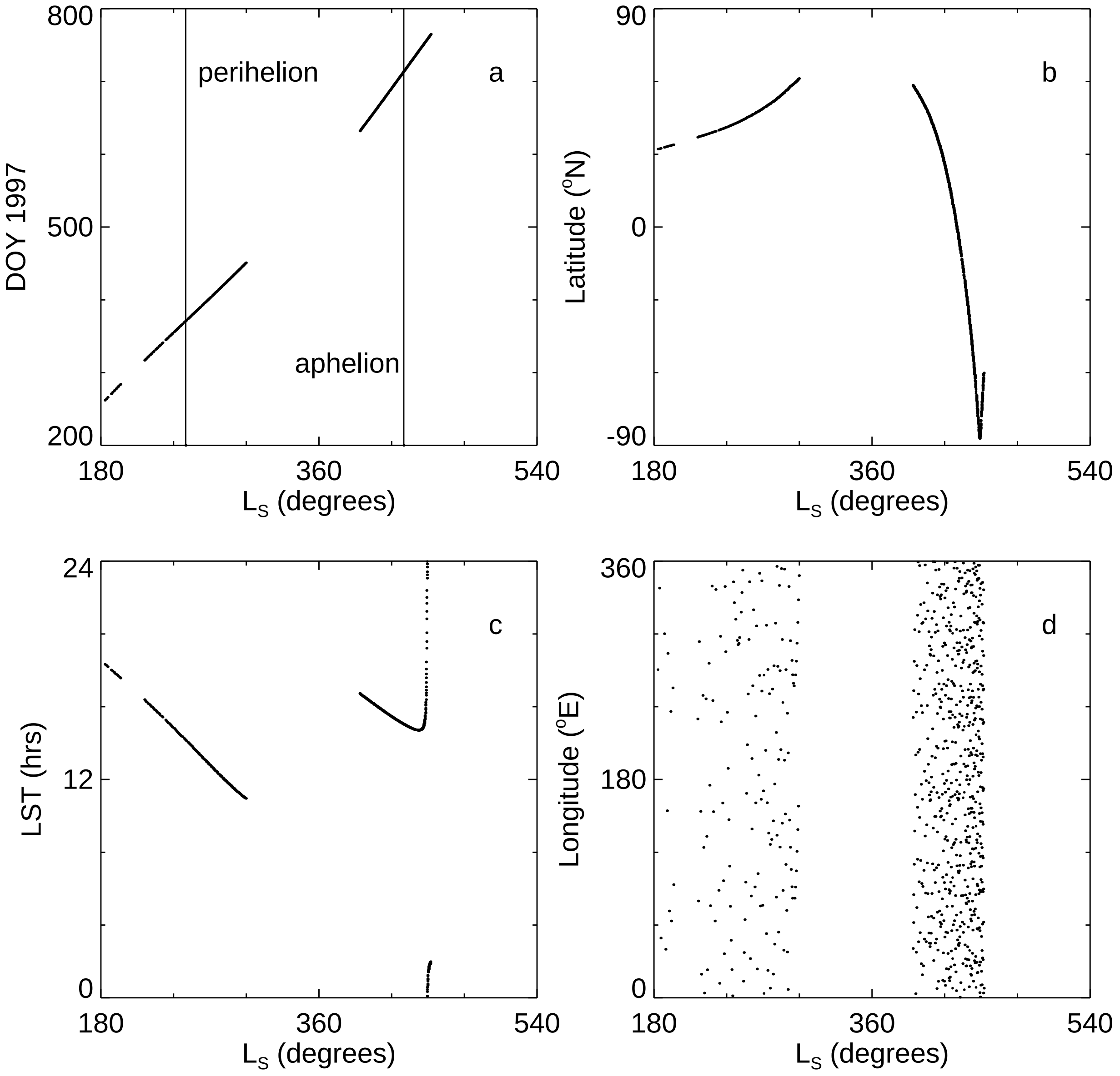
$$a = \frac{\rho V^2 C_D A}{2m}$$

- Uncertainties in aerodynamics, problems with signals from shaking solar panel, rotation of instrument about centre-of-mass, and sporadic firing of attitude control thrusters
- Lots of processing that I haven't been involved in, then archive data at PDS


7 sec. average
Density, kg/km^3
30
25
20
15
10
5
0
−5
−500
−400
−300
−200
−100
0
100
200
300
400

A Typical Density Profile




a
perihelion
aphelion
DOY 1997
800
500
200
180
360
540
L_S (degrees)
b
Latitude (°N)
90
0
-90
180
360
540
L_S (degrees)
c
LST (hrs)
24
12
0
180
360
540
L_S (degrees)
d
Longitude (°E)
360
180
0
180
360
540
L_S (degrees)

MGS Data Coverage

- Periapsis altitude, latitude, longitude, LST, L_S
- Variation along density profile of altitude, latitude, longitude, LST – few minutes flight time
- Changes in altitude, latitude, longitude, LST, L_S (time interval of 24 – 2 hrs) between periapses

- Horizontal/vertical shape of profile basically parabolic, width set by periapsis altitude
- Change in latitude per unit change in longitude along profile set by orbit inclination and latitude, larger for near-polar orbits, smaller for periapses near pole
- Change in LST along profile similar to longitude

- Change between consecutive periapsis altitudes due to manoeuvres and gravity perturbations
- Change between latitudes due to orbital precession
- Change between longitudes due to planetary rotation and (slightly) precession
- Change between LSTs due to planet orbiting Sun and orbital plane precessing
- Change between L_S's due to orbital period

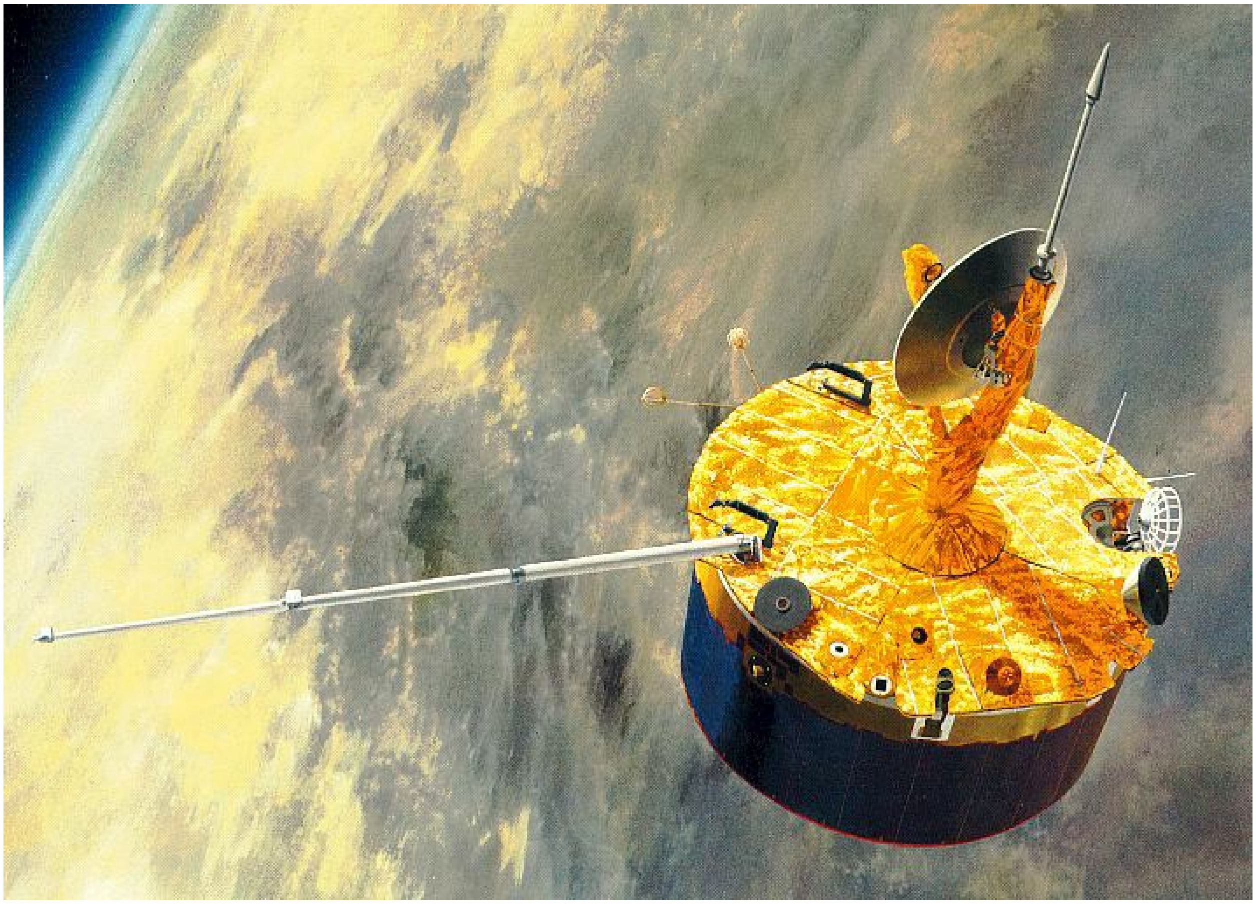
Previous Work with MGS Accelerometer Data

- Keating et al. (1998) Phase 1 data only, discovered variations in density with longitude, saw changes due to a dust storm, compared temperatures to models
- Bougher et al. (1999) Phase 1 data only, compared models to effect of dust storm and latitudinal variations
- Wilson (2002) GCM studies of zonal structure
- Withers et al. (2003) Analysis of zonal structure, changes with altitude, latitude, LST, simple model used to identify causes

- All use data from regularly spaced constant altitudes, not complete profiles

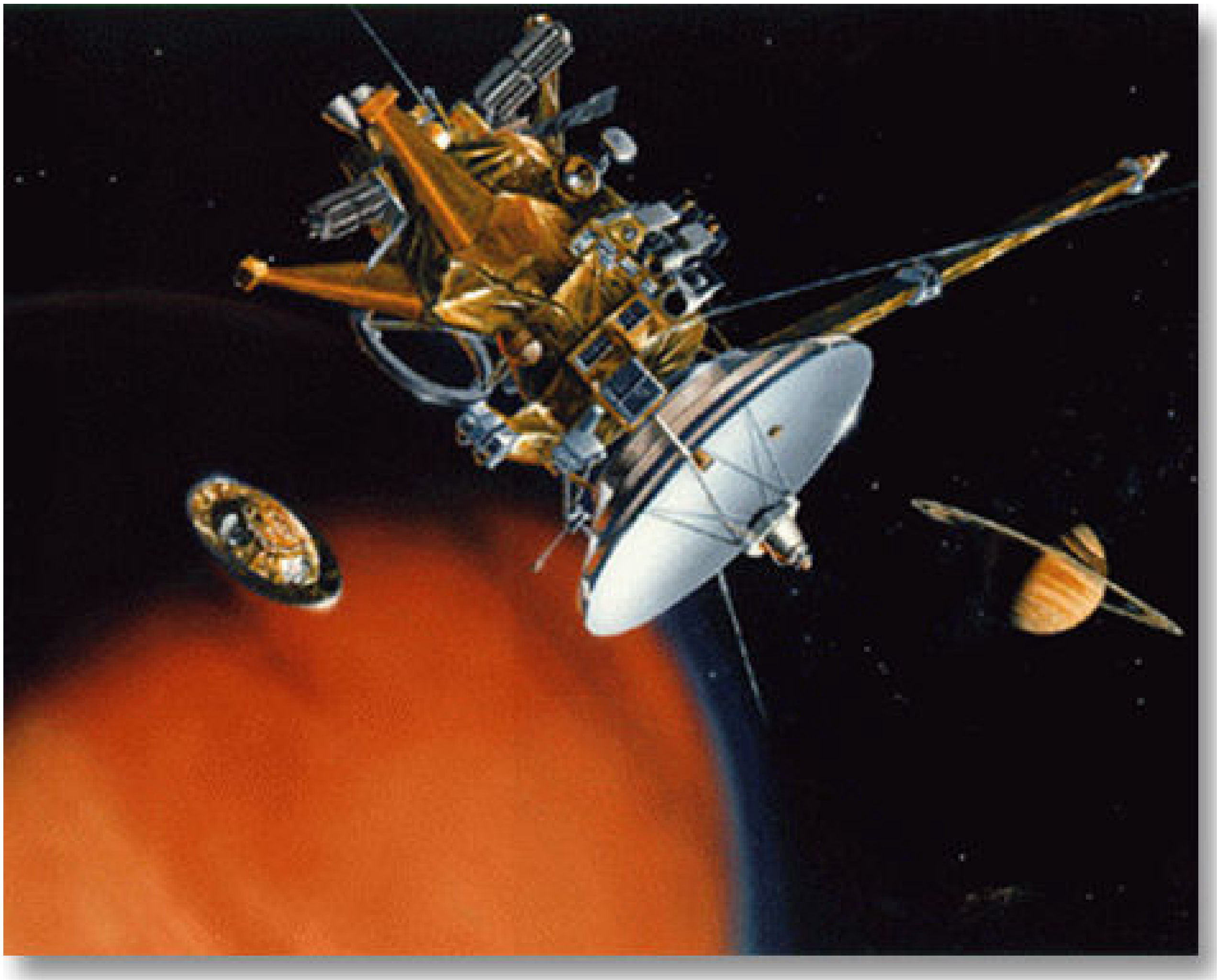
Odyssey and MRO

- Keating has 330 orbits of data from ODY, but is not supported to archive it at PDS. Some low altitude data currently at PDS, rest unlikely to follow…
- Intrinsic data quality better than MGS
- Periapsis crossed over north pole in winter, excellent nighttime data all the way from pole to equator
- Aerobraked shortly after global dust storm
- MRO will launch in 2005, accelerometer is now classified as a science (not engineering) instrument, very high sensitivity, unseen part of 11-yr solar cycle
- Current science team is tiny, just Keating and Bougher



PVO

- Niemann's mass spectrometer onboard the PV orbiter measured densities of major atmospheric species at Venus
- 1978-1980 and 1992
- Periapsis near equator, 15-17N and 10S
- Periapsis altitude 130 – 200 km
- Excellent LST coverage in both mission phases
- No reason for variations with L_S
- Data analyzed by constructing global empirical model and optimizing model wrt data
- Kasprzak et al. (1988) studied wiggles on individual profiles
- Not much study of individual profiles in literature, I haven't seen attempts to derive p, T profiles from measured densities



Cassini

- Niemann’s mass spectrometer onboard the Cassini orbiter will measure densities of major atmospheric species at Titan, facility science team PI is Hunter Waite
- Atmospheric passes will occur as Cassini uses Titan’s gravity to control its tour, so geometry is highly variable
- Expect ~40 atmospheric passes with periapsis about 1000 km above surface
- Some passes will be N-S, some E-W
- Cover many latitudes, longitudes, LSTs
- Will be a very messy dataset to analyze

Deriving p, T

$$\frac{dp}{dr} = -\rho g_{eff}$$

Momentum conservation in the vertical direction only, some terms neglected

g_{eff} known as function of position, includes centrifugal force

ρ measured along flight path, p derived along same flight path

Use measured density scale height to get estimate of pressure at upper boundary, top of atmosphere

Use equation of state (ideal gas law) and independently-known composition to get T along same flight path

Very standard technique with extensive heritage from “near-vertical” entry probes and landers, e.g. Viking, Galileo

Horizontal Gradients

$$\frac{\partial \underline{v}}{\partial t} + (\underline{v}.\underline{\nabla})\underline{v} + 2\underline{\Omega} \times \underline{v} + "ion - drag" +$$

$$"vis\cos ity" = \frac{-1}{\rho}\underline{\nabla} p + \underline{g_{eff}}$$

- Atmosphere is not static, so advection, Coriolis force, curvature terms, and viscosity can cause horizontal gradients in ρ and p
- Typical atmospheric entry has no way of knowing these non-static terms, so neglects them
- How is this neglect incorporated into the uncertainty of published results?
- With two adjacent, simultaneous non-vertical entry profiles, aerobraking offers a way to study effects of horizontal gradients

Scale Analysis

- Object is to split terms into simplest form, estimate magnitudes of contributing variables and their lengthscales, then discard negligible terms

$$\frac{\partial}{\partial r} \sim \frac{1}{H}, \quad \frac{1}{r}\frac{\partial}{\partial \theta} \sim \frac{1}{R}, \quad \frac{1}{r}\frac{\partial}{\partial \phi} \sim \frac{1}{R}$$

- Estimate v_r,v_θ, v_ϕ from models or data
- Leave pressure gradient as unknown
- Molecular viscosity (η) only at first, no eddy viscosity
- Magnetic fields affect ion-drag
- Include J_2 component and centrifugal force beyond spherically symmetric gravity

Mars Scale Analysis

- GM/r^2 dominates r-component by two orders of magnitude

  θ-component more complicated

$$\frac{v_\theta \Omega}{2\pi} + \frac{v_r v_\theta}{H} + \frac{v_\theta^2}{R} + \frac{v_\theta v_\phi}{R\sin\theta} +$$

$$2\Omega v_\phi \cos\theta + \frac{v_\theta v_r}{R} + \frac{v_\phi^2}{R\tan\theta} =$$

$$\frac{-1}{\rho r}\frac{\partial p}{\partial \theta} + \sqrt{5}\,\frac{3GM}{R^2}\bar{C}_{20}\sin\theta\cos\theta +$$

$$R\Omega^2 \sin\theta\cos\theta + \frac{\eta v_\theta}{\rho H^2}$$

- Dominant term varies with latitude

Mars Scale Analysis

θ (deg)	Const term	1/sin θ term	cos θ term	1/tan θ term
30	3.6E-3	1.8E-3	1.2E-2	5.1E-3
60	3.6E-3	1.0E-3	7.0E-3	1.7E-3

Units in table are m s^{-2}

$v_\phi^2/R \tan \theta$ dominates at polar latitudes

$v_r v_\theta/H$ dominates at equatorial latitudes

$2\Omega v_\phi \cos \theta$ dominates in mid-latitudes

Dominance of Coriolis term is most useful because it is linearly dependent on one component of *v*, the zonal wind speed

ϕ–component of equation is messy, but since each aerobraking pass occurs at near-constant longitude, this component can be completely neglected

Mars Simplified Equation

$$0 = \frac{-1}{\rho}\frac{\partial p}{\partial r} + \frac{-GM}{r^2}$$

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

- Quasi-geostrophic balance, ϕ-component is not in geostrophic balance
- Only unknown is v_ϕ
- Having two density profiles and hence some knowledge about horizontal gradients provides the additional constraint needed to find v_ϕ and derive consistent pressure and temperature profiles

Balanced Arch Technique

$$\int \rho g_{eff,r} dr + \int \rho r g_{eff,\theta} d\theta$$

$$+ v_{\phi} \int 2\Omega \rho r \cos\theta d\theta$$

- Formula for periapsis pressure valid for both inbound and outbound
- v_{ϕ} assumed constant over large region
- Equate inbound and outbound expressions, solve for v_{ϕ}, then use that to solve for pressure profile and temperature profile
- Can reformulate to solve for $v_{\phi}(z)$ by constraining latitudinal gradients at every altitude, not just once over entire profile
- “Balance” one leg of aerobraking pass against the other
- “Arch” shape of non-vertical flight path
- Latitude restrictions

Venus and Titan

- Venus case is very messy because viscosity is important and PVO periapses were always close to the equator. Terms which depend on one undifferentiated component of the velocity have angular dependences that make them weak at the equator.
- Titan case is only tractable for N-S passes with periapsis more than 20° from equator. In quasi-cyclostrophic balance. Solution for v_ϕ^2 only, so no information on direction of zonal wind.

$$2\Omega v_\phi \cos\theta \rightarrow \frac{v_\phi^2}{r \tan\theta}$$

Quick and Dirty Characterization

- Are horizontal gradients important?
- Estimate both inbound (p_i) and outbound (p_o) periapsis pressures with pressure gradients and gravity as only forces acting.
- Let E =2 (p_i - p_o) / (p_i + p_o)
- Make sweeping assumptions about angular terms being constant and the relative size of certain terms

$$E = \sqrt{\left(\frac{2\pi R}{H}\right)}\ \frac{2\Omega v_\phi \cos\theta}{g} \quad or \quad \sqrt{\frac{2\pi}{RH}}\,\frac{v_\phi^2}{g\tan\theta}$$

- E ~ 0.05 for Titan, E ~ 0.2 for Mars
- From MGS data, E ~ 0.3 – 0.7, which is quite consistent

Simple Test of Balanced Arch Technique

- Fake isothermal atmosphere with constant zonal wind, all other components zero
- Assume polar orbit
- Extract density profile from atmosphere, use Balanced Arch Technique to derive zonal wind, compare to zonal wind specified in model
- Derived zonal wind is correct
- Let zonal wind vary with altitude or latitude in model
- Derived zonal wind is heavily weighted towards value specified near periapsis

GCM Test of Balanced Arch Technique

- Same idea as before, this time with very detailed General Circulation Model simulation of atmosphere
- Preliminary results showed that technique sometimes worked, sometimes didn't…
- Discovered problems with GCM simulations. Simulation stops iterating when steady state is *almost* reached. This isn't close enough for the θ-component of the momentum balance to be correct.
- The error in this momentum balance is larger than the effect I am looking for, so simulations cannot be used to test idea.
- Steve is trying to work around this for me

First Results from MGS Data

- NH, L_S=30-50^o, LST=15-17 hrs, periapsis altitude=110-120 km, 149 orbits, Phase 2
- v_ϕ = -74 ms^{-1} +/- 5 ms^{-1} (westward)
- MTGCM has +20 to +40 ms^{-1} (eastward)

- SH, L_S=75-85^o, LST=15 hrs, periapsis altitude=105-115 km, 100 orbits, Phase 2
- v_ϕ = +34 ms^{-1} +/- 7 ms^{-1} (eastward)
- MTGCM has +60 to +100 ms^{-1} (eastward)

- SH also has significant variation in v_ϕ with longitude, not seen in NH

- Haven’t examined p, T results at all, what can I do with them?

One or Many?

- Should I use individual density profiles to derive wind information and co-located p, T profiles?
- Or should I merge many density profiles to find $\rho(z, \theta, \phi)$ at fixed LST and L_S – then use synthetic vertical profiles of ρ to find $p(z, \theta, \phi)$ and $T(z, \theta, \phi)$?
- Some wind information will come from these slices
- Merging profiles will lose a lot of small-scale, wave-related structure that might be important
- How realistic will the merged density data be?

Basic Problems

- I have a series of parabolic density profiles from polar orbits with good coverage in periapsis latitude and longitude
- How do I separate vertical from horizontal gradients in density and quantify both?
- Is there anything I can do in equatorial or polar regions where “well-behaved” terms are not the dominant ones?
- When my scale analysis predicts that several competing terms could be important, is there any way the data can reveal if, say, viscosity is dominating over the curvature term?
- How can these techniques be tested?
- How should neglected terms be incorporated into the uncertainty analysis?
- What about non-polar orbits?
- Are results from entry probes affected? If so, can results from Galileo Doppler Wind Experiment fix them?
- What are the results of a scale analysis for Earth?
- Are there any useful Earth datasets to test ideas on?

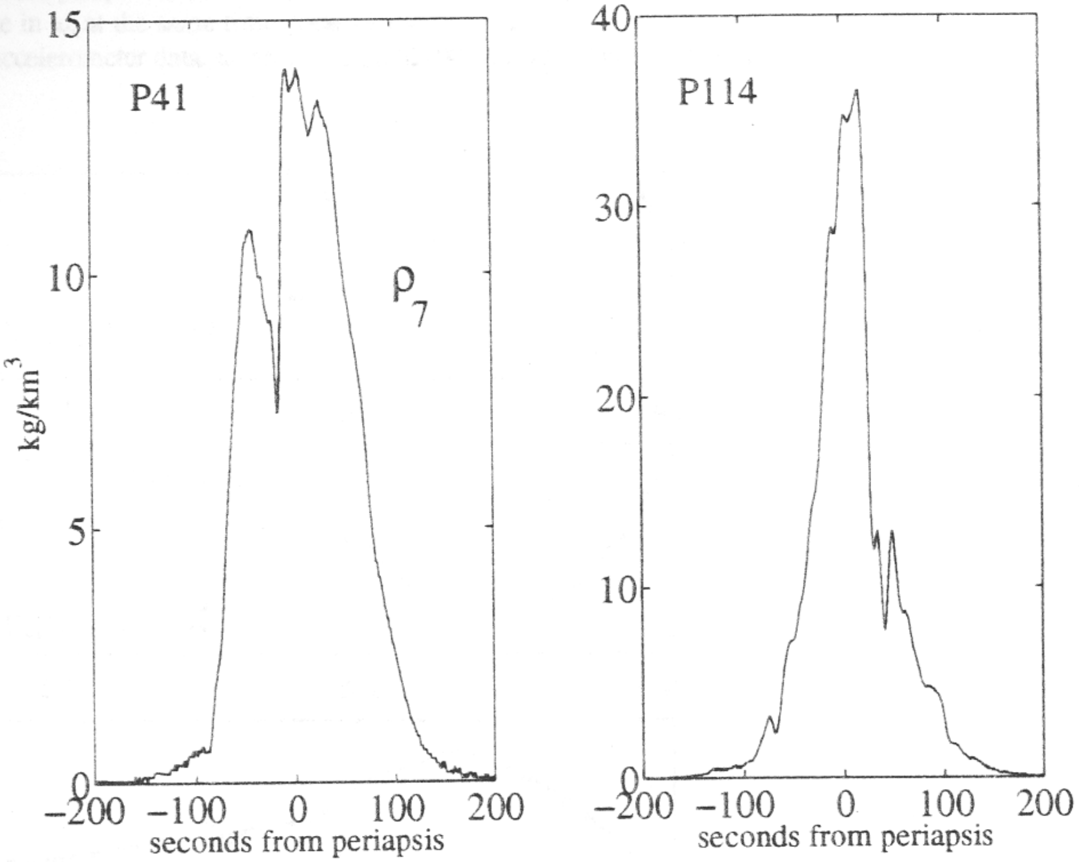
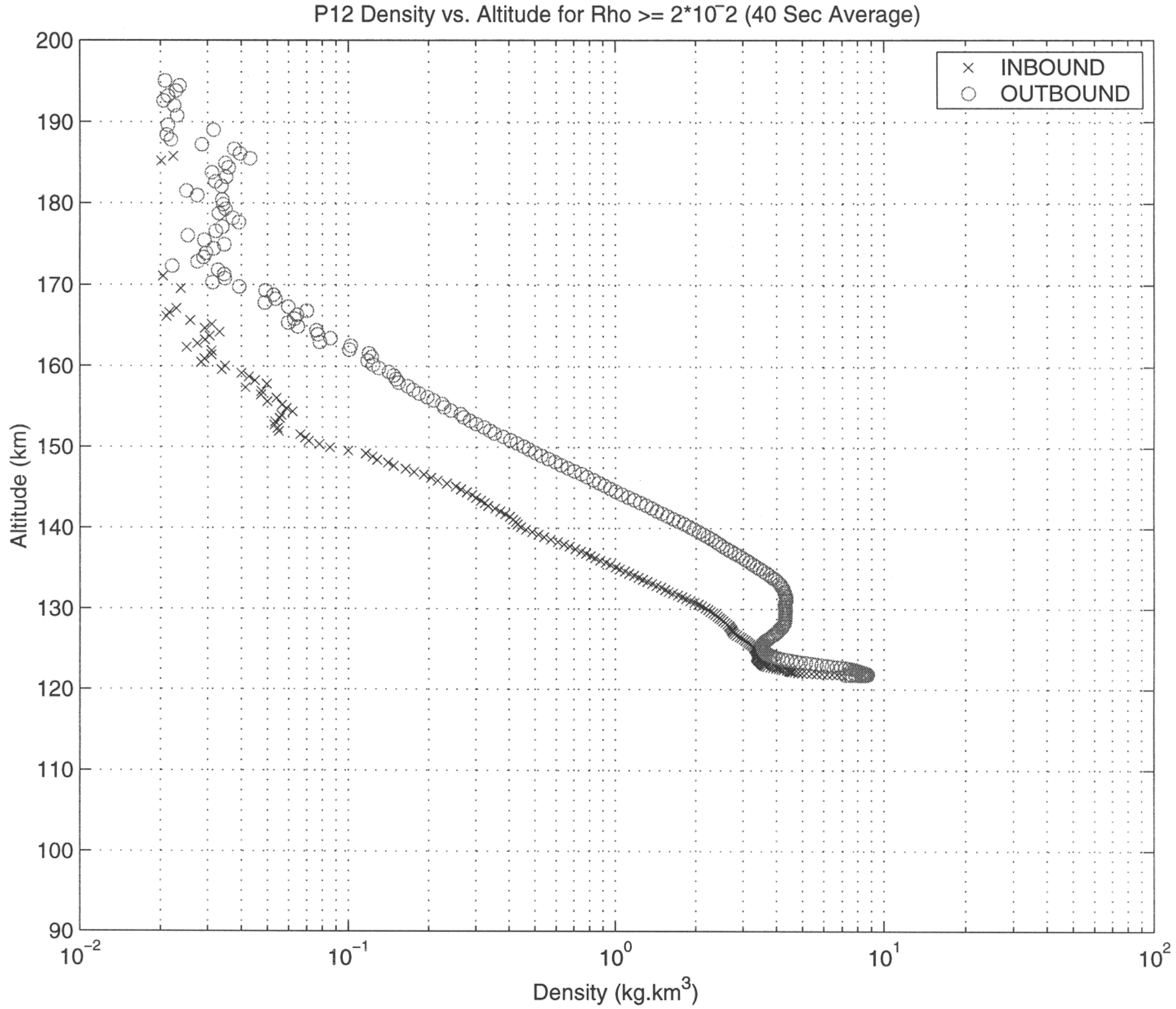


Figure 10. Orbits 41 and 114 density, ρ_7.


P12 Density vs. Altitude for Rho >= 2*10¯2 (40 Sec Average)
× INBOUND
○ OUTBOUND
Altitude (km)
200
190
180
170
160
150
140
130
120
110
100
90
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Density (kg.km^3)

Other Uses of Density Profiles

- Characterize amplitude and wavelength of wiggles on profiles as function of z, θ, ϕ, LST, L_S
- Wiggles in PVO profiles attributed to gravity waves
- What can I learn by doing this? What sort of models are needed to compare against observations?
- Very rapid changes in density – how can they be characterized and what might be happening?
- Other strange structures

Resonances

- When MGS’s orbital period is a simple fraction of martian day, periapsis returns to the same longitude at one sol intervals
- This essentially gives several density profiles at one sol intervals over exactly the same z, θ, ϕ, LST path
- What can be studied with this repeated sampling?
- Sol-to-sol variability in density as function of z, θ, ϕ, LST, L_S
- Repeatability of wiggles on profiles
- What kind of model is useful on this timescale?

PVO and Cassini

- Would it be useful to examine PVO data for signals from solar flares or 28 day solar rotation?
- Would it be useful to directly derive p, T profiles from individual PVO density profiles?
- If so, why wasn’t it done earlier?
- Is there any way to test whether viscosity or curvature or something else controls the horizontal gradients?
- Cassini has wide range of flight paths, how should geometrically challenged orbits be used?