Winds in the martian upper atmosphere from MGS aerobraking density profiles

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(* = Postdoc job wanted)

The Importance of Winds

Wind, pressure, and temperature fields define an atmosphere’s general circulation and climate. Pressure and temperature can be measured easily by remote sensing from orbiters, such as MGS/TES. Winds cannot.

Winds on Mars have been constrained by cloud tracking, which cannot cover all altitudes or times of day; by Viking meteorology sensors, which only existed at two locations; by aeolian geomorphology, which has poor temporal resolution and only covers surface winds; by Viking descent data, which only provides two vertical profiles and is challenging data to process; by orbiting IR spectrometers; which have poor spatial resolution and can only view the times of day and locations allowed by their orbits; and by earth-based high-spectral resolution measurements of doppler-shifted emissions, which is a challenging technique with poor spatial resolution.

There have been no wind measurements in the upper atmosphere of Mars at all.

Abstract: We have used a novel technique to measure the zonal wind in the martian upper atmosphere using MGS Accelerometer aerobraking density profiles. Typical results for the northern hemisphere (NH) at about Ls=40, 115 km altitude and midafternoon local solar times (LSTs) show a westward speed of 50 to 100 m/s; those for the southern hemisphere (SH) at about Ls=80, 110 km altitude show an eastward speed of 0 to 50 m/s. Solar activity is moderate for both periods with an F10.7 index of about 140 units. In the NH, wind speed shows no dependence on longitude, decreases as latitude increases poleward, and increases as altitude increases. In the SH, repeated measurements of wind speed at fixed latitude, altitude, LST, and longitude during the 8:1 resonance between MGS's orbit and Mars' rotation show a significant dependence of wind speed on longitude. At 20E longitude the typical wind speed is 50 m/s westward, whereas at 335E it is 120 m/s eastward. The dependence of wind speed on latitude and altitude is difficult to examine, because periapsis altitude steadily decreased as periapsis precessed poleward. The two variables are strongly correlated. In some longitude regions, eastward wind speeds increase as periapsis moves poleward and downward, but in others the eastward wind speeds stay constant. At 60S latitude and nighttime LSTs, wind speeds differ from their daytime values. Nighttime wind speeds at a given longitude show much less variability than their daytime counterparts. These results will be compared to MTGCM simulations. Other applications of this technique will be suggested.

Poster Layout

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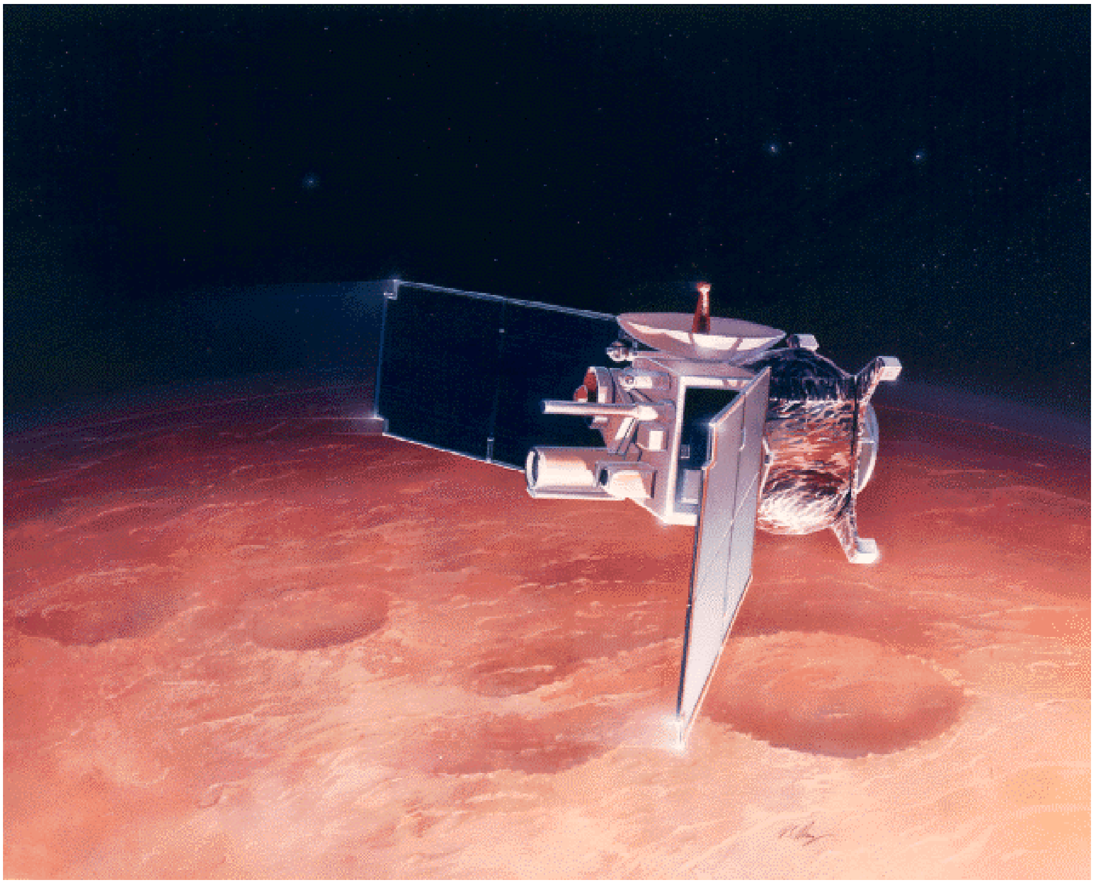
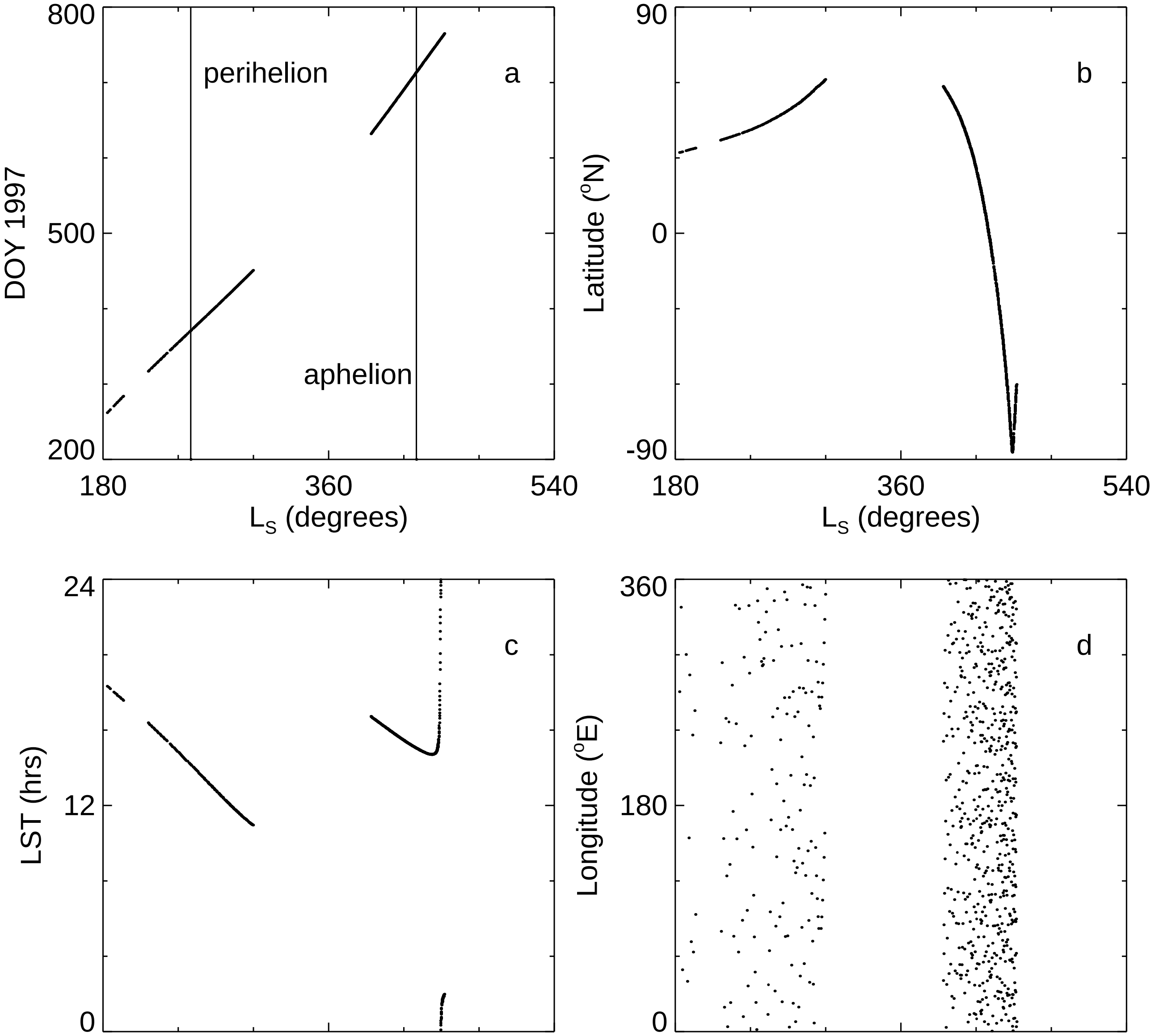
MGS Aerobraking

Aerobraking is a cheap orbital insertion technique that permits the in situ measurement of atmospheric properties. An orbit's energy is steadily decreased by repeated aerobraking passes (and subsequent drag) through the atmosphere. MGS made about 800 aerobraking passes between 1997 and 1999. During each pass, an accelerometer measured **atmospheric densities along the non-vertical flight path** into and out of atmosphere. Due to the sunsynchronous, polar orbit, there was no change in longitude during a typical pass. On each aerobraking pass, the spacecraft detected the atmosphere at about 150 km altitude, descended to periapsis at about 110 altitude, then rose up out of the atmosphere again. A typical pass spanned ~ 30^o of latitude.



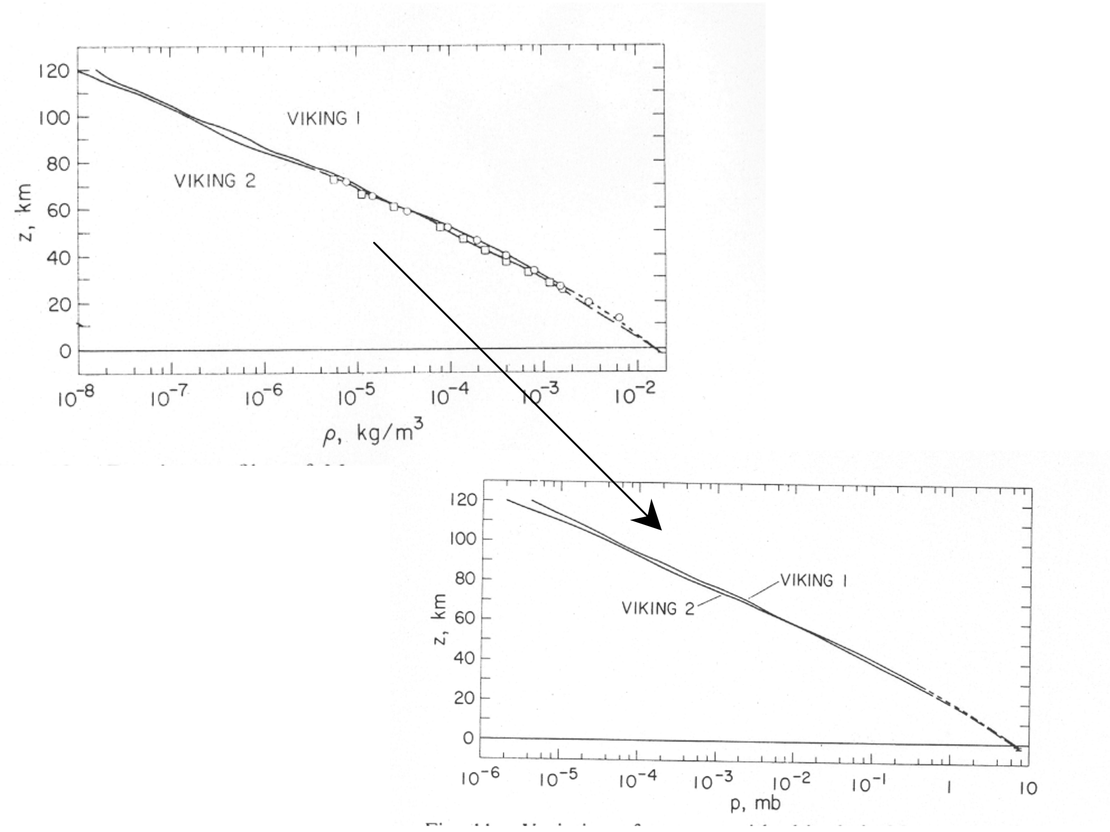
MGS Data Coverage



Aerobraking was broken into two phases, 1 and 2. Phase 2 began on the dayside, then crossed to the nightside close to the end of aerobraking

Uses of Density Profiles

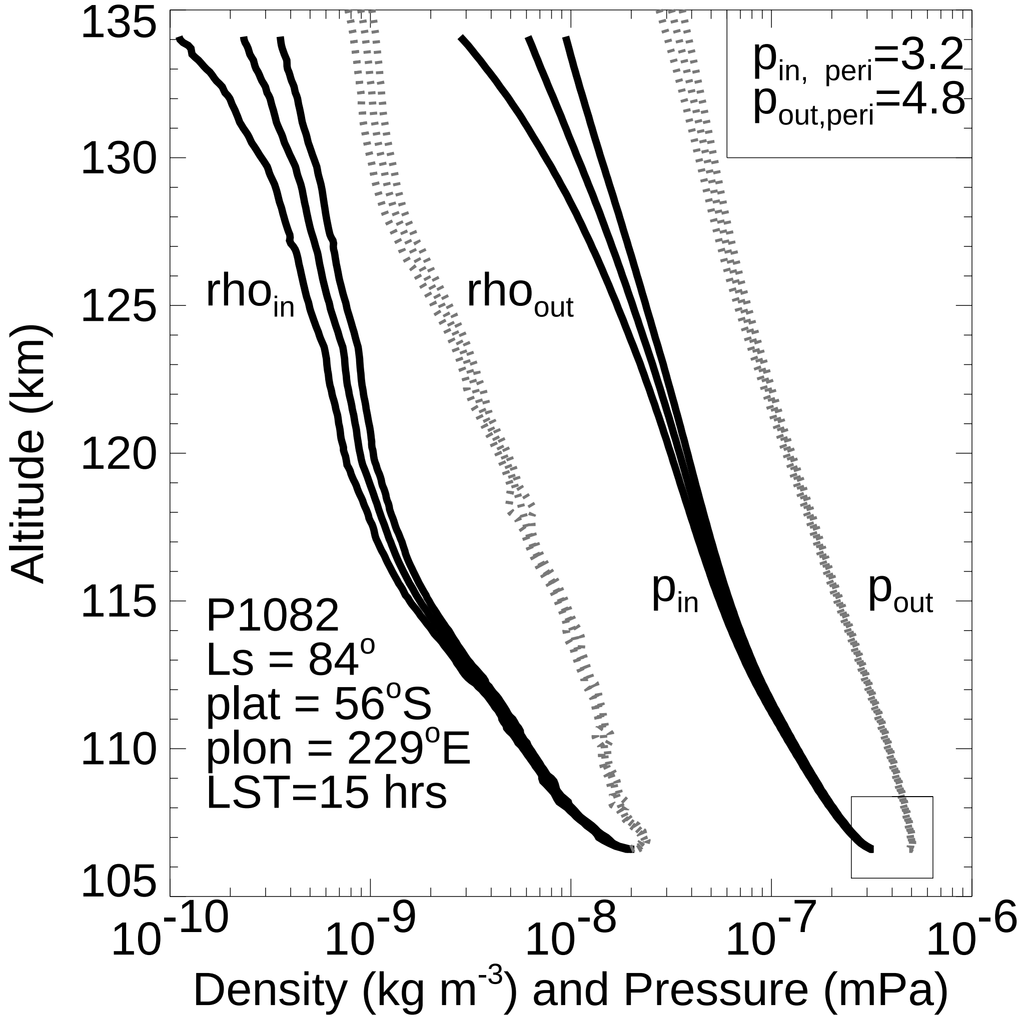
- Density profiles from vertical entry of, eg, Viking landers have been converted into pressure profiles using hydrostatic equilibrium and temperature profiles using an equation of state. These measurements are an important part of the Mars Reference Atmosphere.



- Can these non-vertical density profiles be converted in the same way? Not exactly, because the derived inbound and outbound periapsis pressures from each aerobraking pass are inconsistent.

Typical Aerobraking Density Profile

- Pressure profile is derived from $\nabla p/\rho = \underline{g_{eff}}$ but inbound and outbound periapsis pressures do not agree.



Conservation of Momentum

$$\frac{\partial \underline{v}}{\partial t} + (\underline{v}.\nabla)\underline{v} + 2\underline{\Omega} \times \underline{v} =$$

$$-\nabla p / \rho + \underline{g_{eff}} + visc + MHD$$

- Hydrostatic equilibrium is an approximation to the above conservation of momentum equation.
- $\underline{v}$ = wind velocity
- $\underline{\Omega}$ = planetary rotation vector
- ρ = density
- p = pressure
- $\underline{g_{eff}}$ = gravity + centrifugal acceleration
- visc = small effects of viscosity
- MHD = small effects of magnetohydrodynamics
- Which terms in the momentum equation are important for non-vertical profiles?
- Work in spherical polar coordinates, assume reasonable values for terms in upper atmosphere of Mars, and perform scale analysis

Results of Scale Analysis for Martian Upper Atmosphere

- Between 30^o and 60^o latitudes, geostrophic balance should approximately hold.
- Neglect ϕ (longitude) component of equations, due to polar orbit

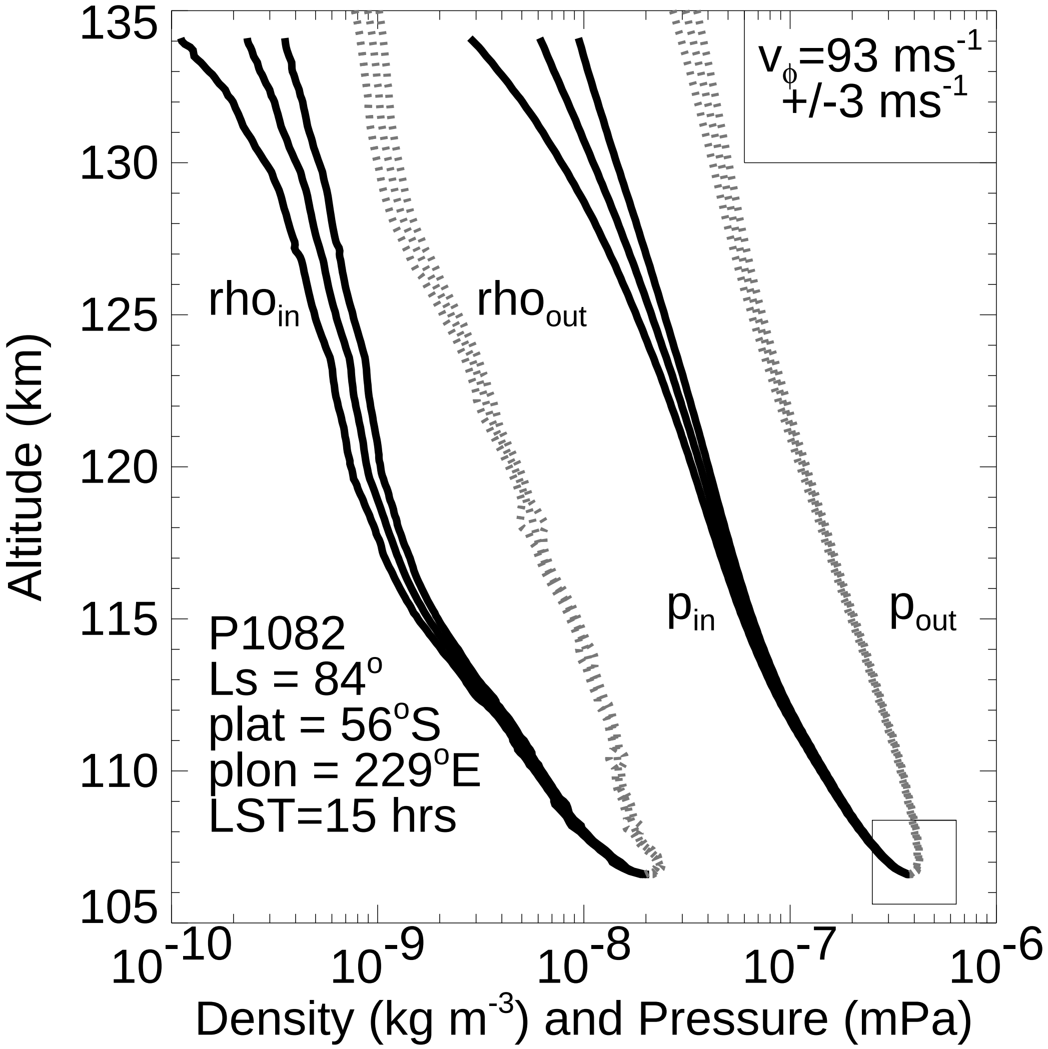
$$\frac{1}{\rho}\frac{\partial p}{\partial r} = g_{eff,r}$$

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

- r = radial distance
- θ = colatitude
- v_{ϕ} = zonal wind velocity, postive eastward
- Additional term is due to Coriolis acceleration

Solving for v_ϕ

- Assume geostrophic balance holds and that v_ϕ is constant and uniform
- Find the unique v_ϕ that makes inbound and outbound estimates of periapsis pressure identical when both vertical and horizontal pressure gradients are used in pressure integration
- Uncertainty in v_ϕ corresponds to range from using +/-1σ uncertainties on measured densities in pressure integration



Effect of Horizontal Flight Path on Pressure Profiles

- Calculate pressure profile from inbound leg only, assuming that it is vertical. Let p_{in} = periapsis pressure from inbound leg
- Repeat for outbound leg and let p_{out} = periapsis pressure from outbound leg
- Let $E = 2\,(p_{in} - p_{out}) / (p_{in} + p_{out})$
- Assuming an isothermal atmosphere in geostrophic balance and neglecting a weak latitude dependence, E is roughly:
- $E = 2\,\Omega\, v_\phi\, (2\pi R_o/H)^{1/2}\, g^{-1}$
- This should be used as an order of magnitude guide only
- Ω = planetary rotation rate
- v_ϕ = zonal wind speed
- R_o = radius to periapsis
- H = atmospheric scale height
- g = acceleration due to gravity

Tests on a Toy Atmosphere

- Simulate idealized, isothermal atmosphere forced to be in geostrophic balance with a constant and uniform zonal wind.
- Extract density profile from a synthetic aerobraking pass through this atmosphere.
- Derive zonal wind from this density profile, then compare to actual wind in simulated atmosphere.
- We find that zonal winds are derived correctly.
- If the zonal wind in the simulation is set to one value at high altitude (or latitude) and discontinuously jumps to another value at low altitudes (or latitudes), then the derived zonal wind is intermediate between the two values, as it should be.
- The derived zonal wind is heavily weighted to conditions close to periapsis. If the discontinuity in the simulated wind is only several km above periapsis and the flight path extends vertically for several tens of km, then the derived zonal wind is the mean of the two wind regimes. If the derived zonal wind were an unweighted vertical average, then its value would be much closer to the high altitude wind value that extends over 90% of the vertical range of interest.

Tests on MTGCM Simulations

- MTGCM = Bougher/NCAR Mars Thermospheric General Circulation Model
- We wished to extract synthetic density profiles from the simulations, derive a zonal wind, and compare it to the wind field in the simulation
- However, we found that the baseline simulations do not run for long enough to reach perfect steady state. The departures from steady state, which appear as an imbalance between the two sides of horizontal component of the momentum equation, are larger than the latitudinal pressure gradient term. The baseline MTGCM simulations do not satisfy the equations we are using to derive the zonal wind, so cannot be used to test this technique.
- Additional simulations, set to run longer and reach near-perfect steady state, are in progress and will allow us to test this technique on a detailed and realistic simulated atmosphere.

MGS Results: Hemispheric Averages from Phase 2

- NH, L_S = 30° – 50°,
  Lat = 30° – 60°N,
  LST = 16.7 – 15.6 hrs,
  periapsis altitude = 111 – 118 km,
  good longitudinal coverage
  orbits 574 – 729
- $v_\phi \sim -74 +/- 5\ ms^{-1}$ (westward)
- MTGCM has $v_\phi \sim +20$ to $30\ ms^{-1}$

- SH, L_S = 75° – 85°,
  Lat = 30° – 70°S,
  LST = 14.8 – 14.9 hrs,
  periapsis altitude = 104 – 114 km,
  good longitudinal coverage
  orbits 987 – 1127
- $v_\phi \sim +38 +/- 6\ ms^{-1}$ (eastward)
- MTGCM has $v_\phi \sim +60$ to $100\ ms^{-1}$

MGS Results: NH Phase 1, Dayside

- NH, $L_S = 180^o - 300^o$,
  Lat = $30^o - 60^o$N,
  LST = 18.3 – 11.0 hrs,
  periapsis altitude = 109–134 km,
  good longitudinal coverage
  ~ 160 orbits
- $v_\phi \sim +87$ +/- 8 ms^{-1} (eastward)
- MTGCM simulations not available for comparison
- The significant changes in L_S and LST between orbits and the rise and fall of the Noachis dust storm make it difficult to test for the effects of latitude, altitude, and longitude in this subset of the data.
- Between orbits 180 and 194, MGS sampled 2 different longitudes repeatedly at intervals of one martian day. Periapsis latitude, between 58 – 60^oN, does not change greatly, and nor did periapsis altitude. There are about 6 data points per longitude region. The zonal wind depends on periapsis longitude in this example.

Longitude (^{o}E)	Mean v_ϕ (ms^{-1})	σ of Distribution (ms^{-1})	σ of Mean (ms^{-1})
80	**160**	89	**40**
260	**67**	66	**25**

MGS Results:
NH Phase 2, Dayside

- How does the derived zonal wind depend on altitude, latitude, and longitude?
- Sampling in longitude, latitude, and altitude is not well-distributed, so it is difficult to test for dependence on just one of these three variables. There is a great deal of scatter about the tentative trends that are identified and these results do not have great statistical significance

Altitude (km)	Mean v_ϕ (ms^{-1})	σ of Distribution (ms^{-1})	σ of Mean (ms^{-1})	Number of data points
111 – 112	**-40**	52	**14**	13
112 – 115	-76	65	7	78
115 – 116	**-96**	56	**17**	11

- v_ϕ become more negative (faster and still westward) as periapsis altitude increases, but the predicted wind shear is unrealistically large
- Periapsis latitude = 30° – 50°N, periapsis longitude is unconstrained

MGS Results: NH Phase 2, Dayside

- There is no evidence for longitudinal variation in v_ϕ
- Periapsis latitude = 30° – 45°N, periapsis altitude = 113 – 114 km

Longitude (°E)	Mean v_ϕ (ms^{-1})	σ of Distribution (ms^{-1})	σ of Mean (ms^{-1})	Number of data points
0 – 90	-84	71	29	6
90 – 180	-104	61	22	8
180 – 270	-72	43	16	7
270 – 360	-90	93	31	9

- v_ϕ becomes less negative (slower but still westward) as periapsis latitude increases to the north
- Periapsis altitude = 113 – 114 km, periapsis longitude is unconstrained

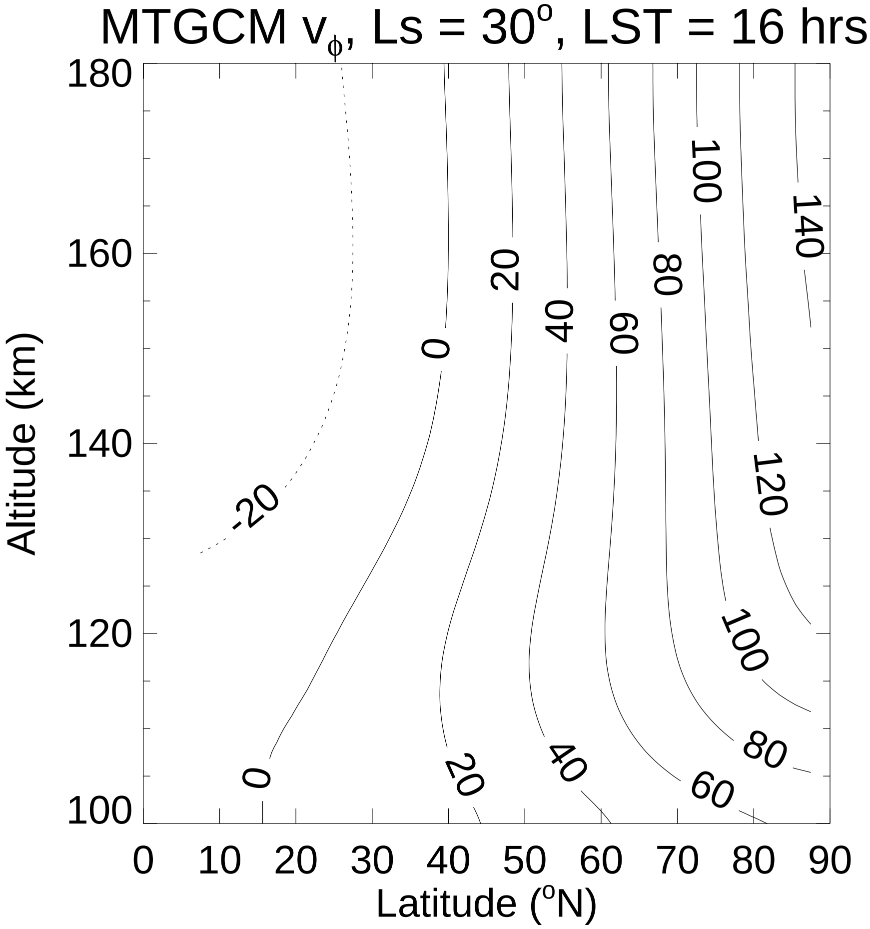
Latitude (°N)	Mean v_ϕ (ms^{-1})	σ of Distribution (ms^{-1})	σ of Mean (ms^{-1})	Number of data points
30 – 35	-78	66	20	11
35 – 40	-106	69	23	9
40 – 45	-85	75	24	10
45 – 50	-43	45	18	6
30 – 43	**-95**	70	**14**	26
43 – 50	**-43**	39	**12**	10

Comparison to MTGCM Simulations

- MTGCM simulations are available for dayside Phase 2 conditions. They are not yet available for Phase 1 or nightside Phase 2 conditions.
- The MTGCM simulations match our results better in the SH than in the NH. The simulations are closer to dynamical steady state in the SH than in the NH which may partially explain this. Neglected terms may also be larger in the NH than in the SH, making geostrophic balance an inaccurate approximation and causing the NH results to be suspect. The large vertical wind shear in the NH results is unrealistic.

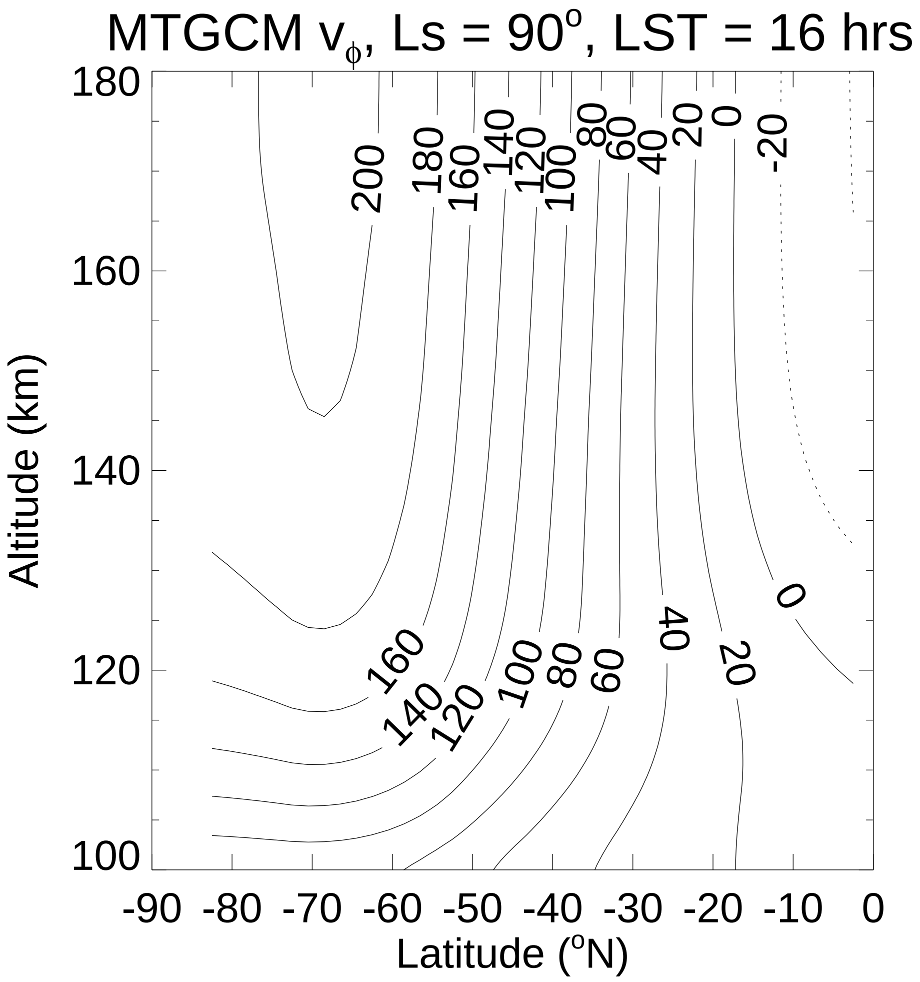
Comparison to MTGCM Simulations

- Our typical NH zonal winds of –74 ms^{-1} are very different to the MTGCM predictions of +20 to 30 ms^{-1}
- MTGCM does not have the drastic increase in westward windspeed with increasing altitude in the NH that is seen in our results
- MTGCM has zonal winds becoming more eastward with increasing latitude in the NH, as do our results
- MTGCM simulations are zonally-averaged, so cannot address longitudinal variability



Comparison to MTGCM Simulations

- Our typical SH zonal winds of +40 ms^{-1} are reasonably similar to the MTGCM predictions of +60 to 100ms^{-1}
- MTGCM has zonal winds becoming more eastward with decreasing altitude/more poleward latitude in the SH, as do our results
- MTGCM simulations are zonally-averaged, so cannot address longitudinal variability



MGS Results: SH Phase 2, Dayside

- Between orbits 1030 and 1057, MGS sampled 8 different longitudes repeatedly at intervals of one martian day. Periapsis latitude, which was between 41 – 49°S, did not change greatly, and nor did periapsis altitude.
- There are three data points per longitude region, except for the 200°E region which only has two.
- Compare 20°E to 335°E or 245°E to 290°E to see significant longitudinal variations in derived zonal wind

Longitude (°E)	Mean v_ϕ ($\mathrm{ms^{-1}}$)	σ of Distribution ($\mathrm{ms^{-1}}$)	σ of Mean ($\mathrm{ms^{-1}}$)	Periapsis Altitude (km)
20	**-55**	63	**36**	109 – 110
65	18	72	42	108 – 109
110	62	50	29	108 – 109
155	86	37	21	109 – 110
200	-49	35	25	109 – 110
245	**70**	41	**24**	108 – 109
290	**7**	36	**21**	108 – 109
335	**122**	38	**22**	109 – 110

MGS Results:
SH Phase 2, Dayside

- Periapsis altitude and latitude are very strongly correlated in this part of aerobraking. To maintain the desired periapsis density, JPL dropped the periapsis altitude lower as periapsis latitude moved towards the south pole and its low densities.
- The derived zonal winds are split into two groups, those which have periapsis altitude below 108 km and periapsis latitude south of 50°S, and those which have periapsis altitude above 108 km and periapsis latitude north of 50°S.
- Mean v_ϕ +/- the standard deviation of the mean are tabulated

Longitude (°E)	High and North Winds (ms^{-1})	Low and South Winds (ms^{-1})
0 – 90	**00 +/- 20**	**60 +/- 20**
90 – 180	**20 +/- 20**	**20 +/- 20**
180 – 270	**00 +/- 20**	**60 +/- 20**
270 – 360	**60 +/- 20**	**60 +/- 20**

- There is longitudinal dependence in the value of the zonal wind in the southern hemisphere *and* in how it changes with latitude/altitude. In some longitude regions, zonal winds become more positive as altitude decrease/latitude tends southward. In some, there are no changes.

MGS Results:
SH Phase 2, Nightside

- Nightside data is acquired towards the end of aerobraking, after periapsis crossed the terminator near the South Pole. These profiles have significant changes in LST within the southernmost, outbound leg due to the proximity of the terminator. They also have significant changes in longitude during the entire aerobraking pass. Preliminary studies show that these effects are not significantly larger than previously neglected terms in the equations of motion, so we will neglect them here. However, the nightside results are less robust than those from the dayside.

MGS Results:
SH Phase 2, Nightside

- SH, $L_S = 91^o - 93^o$,
  Lat = $70^o - 60^o$S,
  LST = 1.8 – 2.0 hrs,
  periapsis altitude = 108 – 118 km,
  orbits 1248 – 1281

Longitude (^{o}E)	Mean v_ϕ (ms^{-1})	σ of Distribution (ms^{-1})	σ of Mean (ms^{-1})	Number of data points
0 – 90	-18	21	7	9
90 – 180	67	38	17	5
180 – 270	-1	34	12	8
270 – 360	40	30	14	5

- Longitude is important on the nightside and the uncertainty of the mean is small. For comparison, here are the dayside results from the same narrow latitude region

Longitude (^{o}E)	Mean v_ϕ (ms^{-1})	σ of Distribution (ms^{-1})	σ of Mean (ms^{-1})	Number of data points
0 – 90	88	20	8	7
90 – 180	-16	80	36	5
180 – 270	42	63	26	6
270 – 360	48	28	10	8

- The most eastward and most westward wind speeds have reversed their longitude bins between dayside and nightside

Future Work on MGS Data

- Verify technique on steady state MTGCM simulations which are closer to conserving momentum than the currently available ones.
- Balance the pressure gradient between the inbound and outbound legs at various altitudes to obtain a profile of v_ϕ that varies with altitude
- Compare pressure profiles to MTGCM predictions
- Derive self-consistent inbound and outbound temperature profiles from the pressure and density profiles and compare them to MTGCM predictions
- Characterize any small-scale tidal variations in the temperature profiles
- Develop technique to characterize horizontal pressure gradients in equatorial regions where geostrophic balance cannot be used.
- Compare longitudinal variations in zonal wind to longitudinal variations in density

Future Work in General

- Apply this technique to existing Mars Odyssey and anticipated Mars Reconnaissance Orbiter aerobraking data
- Develop cyclostrophic balance version of this technique and apply it to Pioneer Venus upper atmospheric data
- Extend this technique beyond polar orbits and apply it to anticipated Cassini data from Titan's upper atmosphere
- Investigate Earth-orbit applications
- Comtinue experimenting with simulations to refine understanding of how neglected terms affect results, what observed scatter in derived zonal winds implies, and develop ways to use observations to test whether assumed balance based on scale analysis is actually true.

One Minute Highlights

- Winds are important, yet difficult to measure
- Horizontal pressure gradients measured from aerobraking density data can measure winds
- Martian northern spring zonal winds at 110 km ~ 70 ms^{-1} westward in the northern hemisphere, ~ 40 ms^{-1} eastward in the southern hemisphere
- Longitudinal variations in zonal winds are seen in the southern hemisphere
- Simulations and observations do not agree well

Conclusions

- We have presented a novel technique to measure upper atmospheric winds
- We have applied this technique to make the first measurements of winds in the upper atmosphere of Mars
- Variations in zonal wind with season, altitude, latitude, longitude, and time of day can be studied as well as the distribution of available data permit
- Relating longitudinal variations in zonal winds and in densities could relate tidally-induced density variations and tidally-induced winds
- Detailed comparisons with simulations are awaiting more runs