Determination of upper atmospheric properties on Mars and other bodies using satellite drag/aerobraking measurements

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If I fly a spacecraft through an atmosphere, what can I learn about that atmosphere?

- Three techniques to measure density
  - orbit decay, torques, forces
- Focus on Aerobraking
- Results from Mars
- Connections to the Solar Wind
- Conclusions

Physics

- Conservation of energy
  - Temperature of spacecraft changes
  - Orbit of spacecraft changes
- Conservation of angular momentum
  - Either angular velocity of spacecraft changes
  - Or reaction wheels within spacecraft must spin slower/faster
- Conservation of momentum
  - Velocity of spacecraft changes
  - Acceleration of spacecraft is related to atmospheric density

Orbit decay

- Density at z_0 + $H/2$ is proportional to $\frac{\Delta T}{\sqrt{H}} \times \frac{m}{C_D A}$

  ΔT = change in period

  H = scale height

  m = spacecraft mass

  C_D = spacecraft drag coefficient (~2)

  A = spacecraft area
- King-Hele, 1964

Problems with orbital decay

- Only one density measurement per orbit
- Based on spherical symmetry of atmosphere
- Need multiple orbits at different periapsis altitudes to resolve scale height ambiguity

Density in Earth's upper atmosphere

be about 10 per cent (s.d.) except near the end of the life, when it could be as high as 2

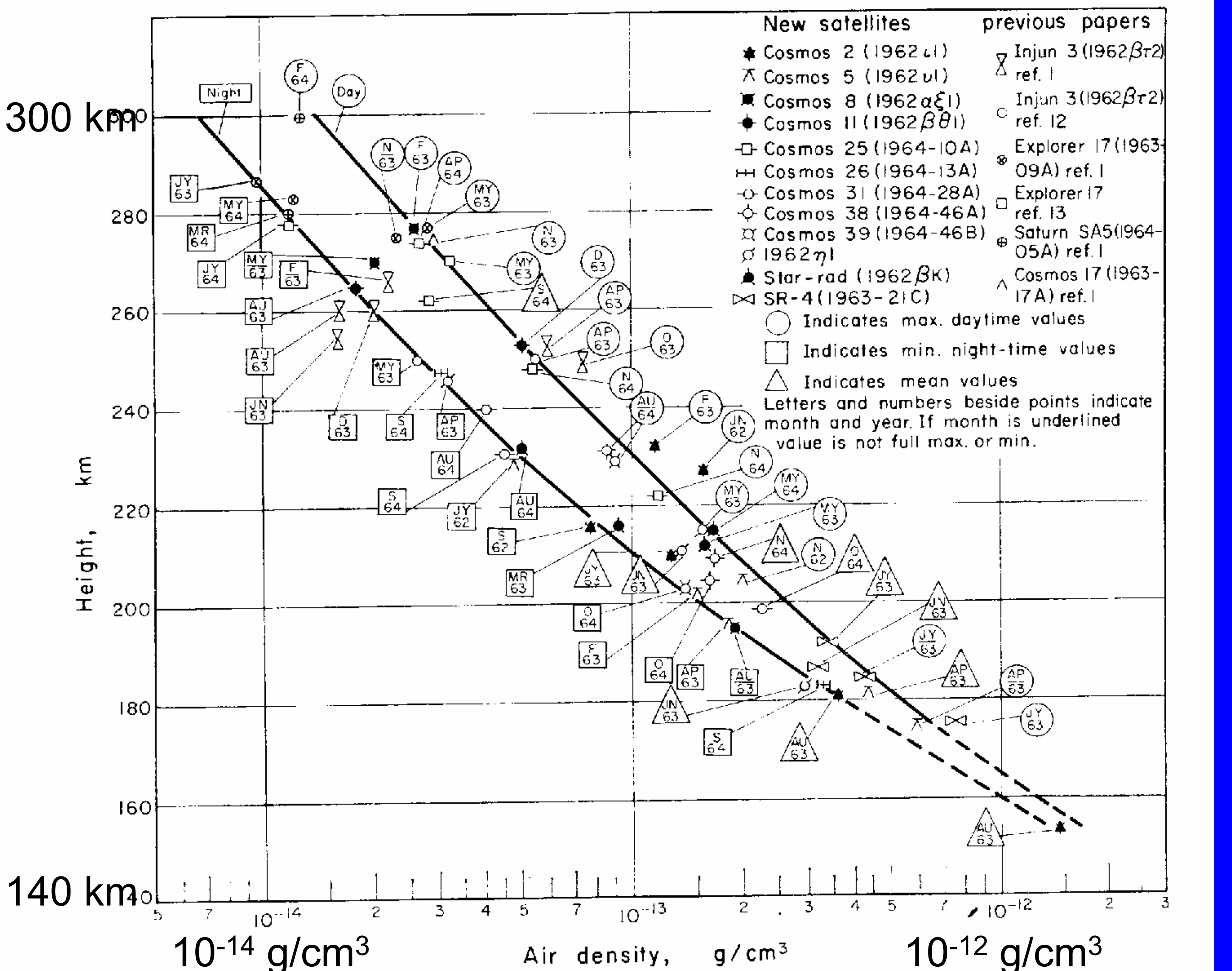


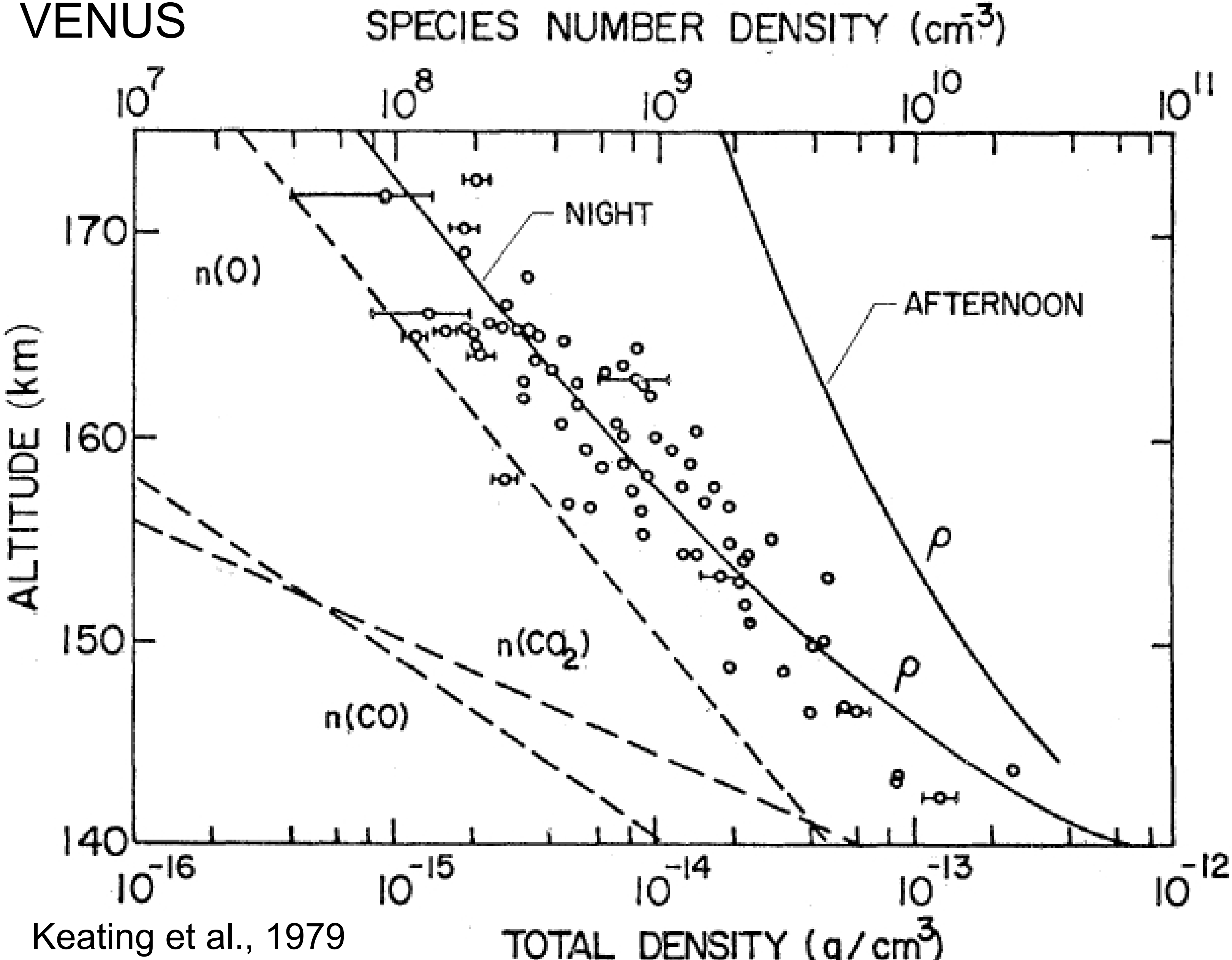
Fig. 8. Maximum daytime and minimum night-time density in 1962–1964. Curves show average day and night density in 1963.

King-Hele and Quinn, 1965

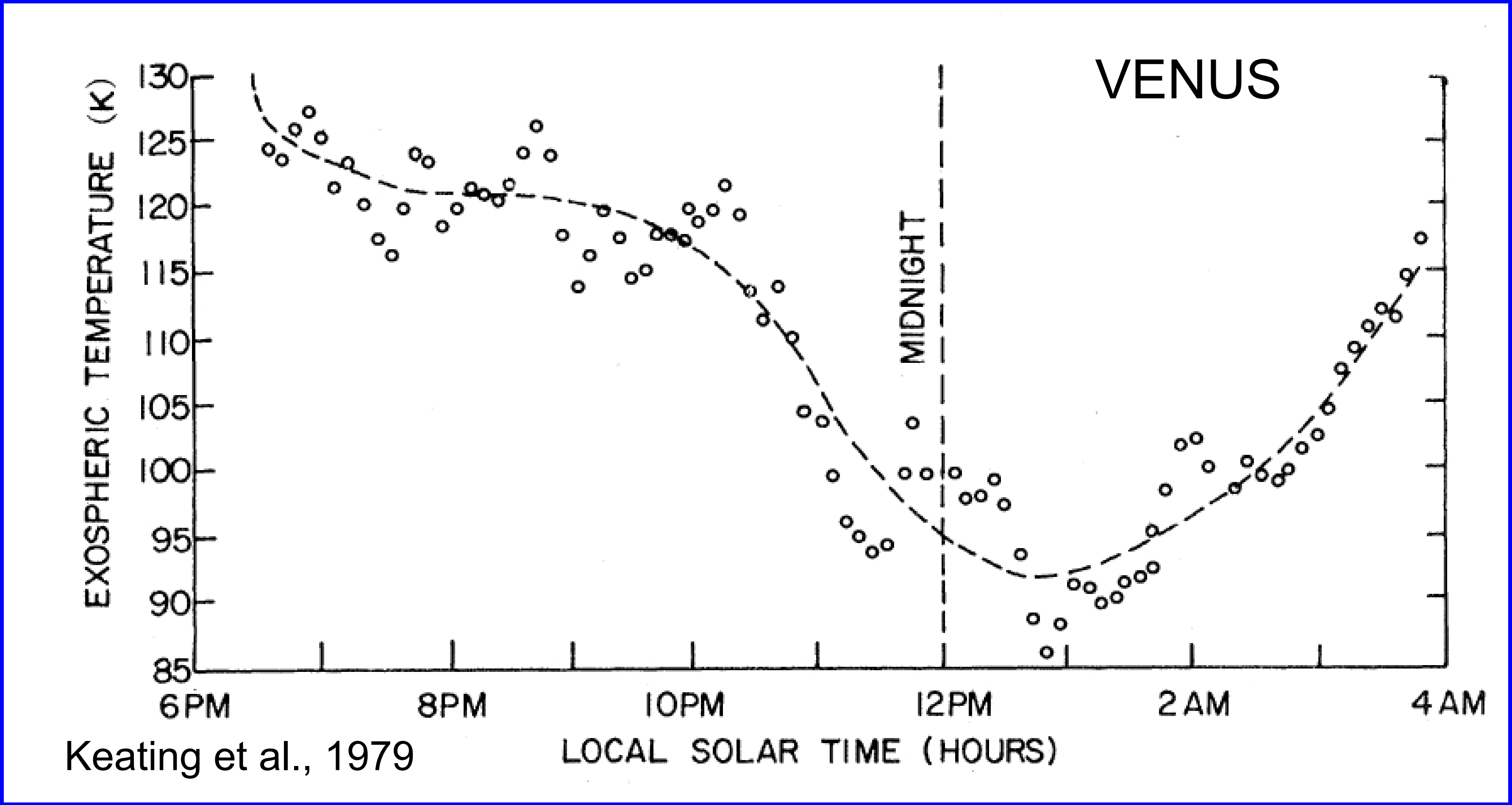
Applications of orbital decay

- First measurements of density and scale height of Earth's upper atmosphere in 1950s-1960s
- Also used to show that upper atmospheric winds blew from west to east at 100 m/s
- Indirectly helped to show that Earth's geoid is more complex than an ellipsoid of revolution (pear-shaped)

VENUS



Keating et al., 1979



King-Hele and others determined upper atmospheric zonal winds from orbital elements of satellites in Earth orbit.

Has this been attempted for other planets?

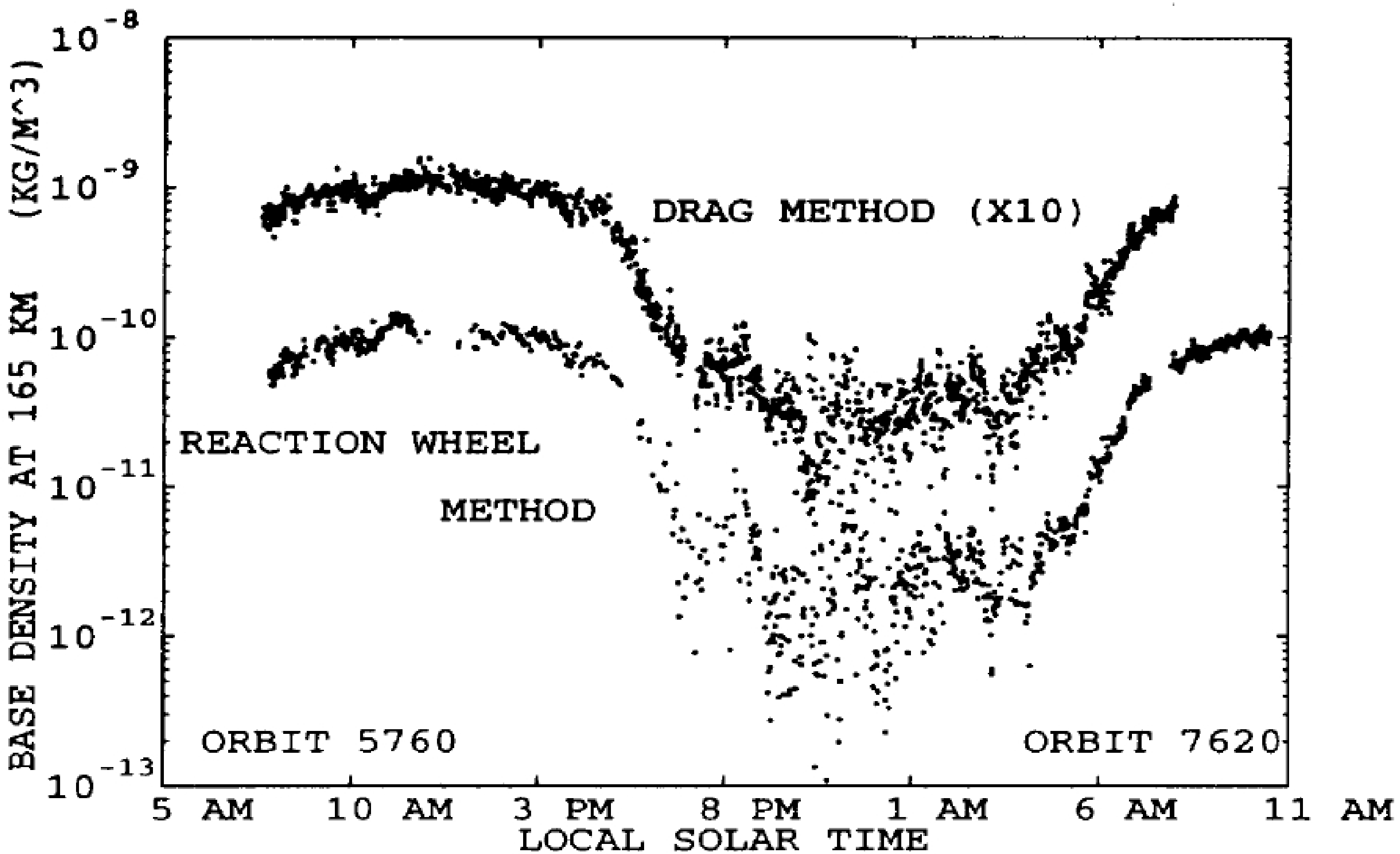
Torques - Theory

- $T = \rho A L v^2 C_m / 2$
- T = torque
- ρ = density
- A = spacecraft area
- L = reference length
- v = atmosphere-relative speed
- C_m = dimensionless coefficient

Practical Issues

- Measure changes in spacecraft's angular velocity and relate to torque
- Or measure changes in speeds of reaction wheels that store angular momentum
- Modelling response to torques is harder than modelling response to forces
- Engineers love this method
- Get density as function of time

Results from Venus - Magellan



Croom and Tolson, NASA CR 4619

Also used by Cassini during Titan flybys

Aerobraking Drag - Theory

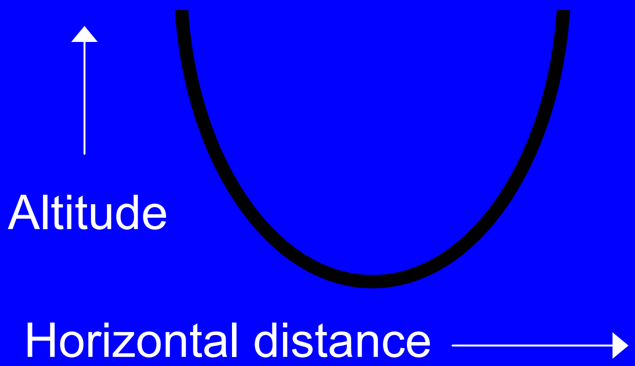
- $ma = \rho A v^2 C_D / 2$
- m, A = spacecraft mass, area
- a = component of acceleration anti-parallel to atmosphere-relative velocity
- ρ = density
- v = atmosphere-relative speed
- C_D = dimensionless drag coefficient ~ 2
  - function of density, attitude, spacecraft shape

Practical Issues

- Don’t try to use all three components of acceleration
- Need to know spacecraft orientation accurately
- Unknown winds may introduce errors in atmosphere-relative speed (v) and in orientation of spacecraft (C_D)
- Need to remove all other measured accelerations, such as $\underline{w} \times (\underline{w} \times \underline{r})$

What You Get

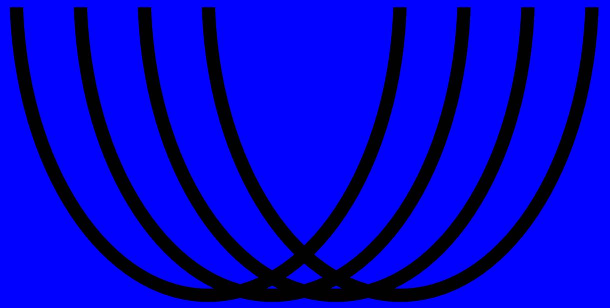
- Density as function of time for ~100s
- Parabolic shape



- Latitude, longitude, LST coverage depend on geometry of orbit

Multiple Orbits

- Precession of periapsis changes latitude
- Rotation of planet changes longitude
- Orbit inclination controls changes in LST
- Interval set by orbital period



- Polar, sunsynchronous orbit leads to an altitude-latitude cross-section of density at fixed LST

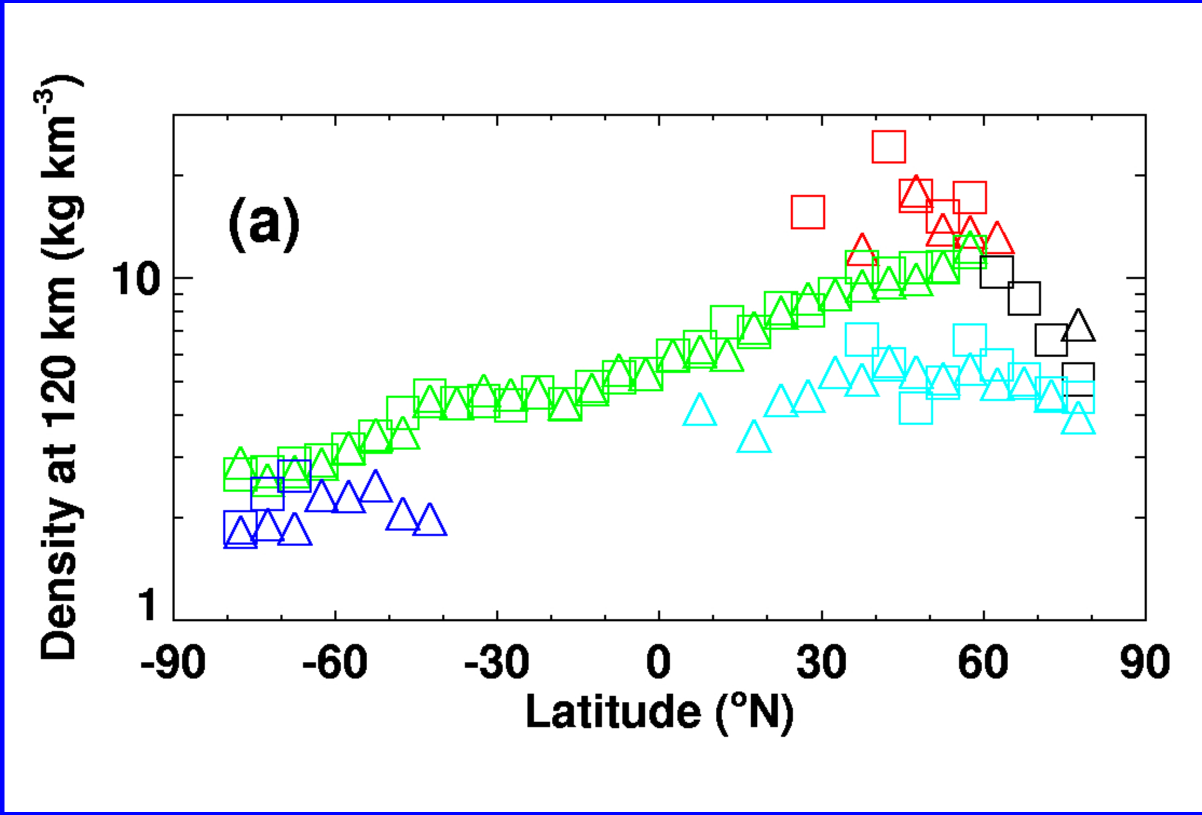
More Than Density

- $dp/dz = - \rho g$
- Hydrostatic equilibrium gives pressure

- $p = \rho k T / \mu$
- Ideal gas law gives temperature

- Horizontal pressure gradients may be related to horizontal winds (cyclostrophic, geostrophic, thermal, gradient wind approximations)
  - But not validated for upper atmospheres

Results from Mars - Density

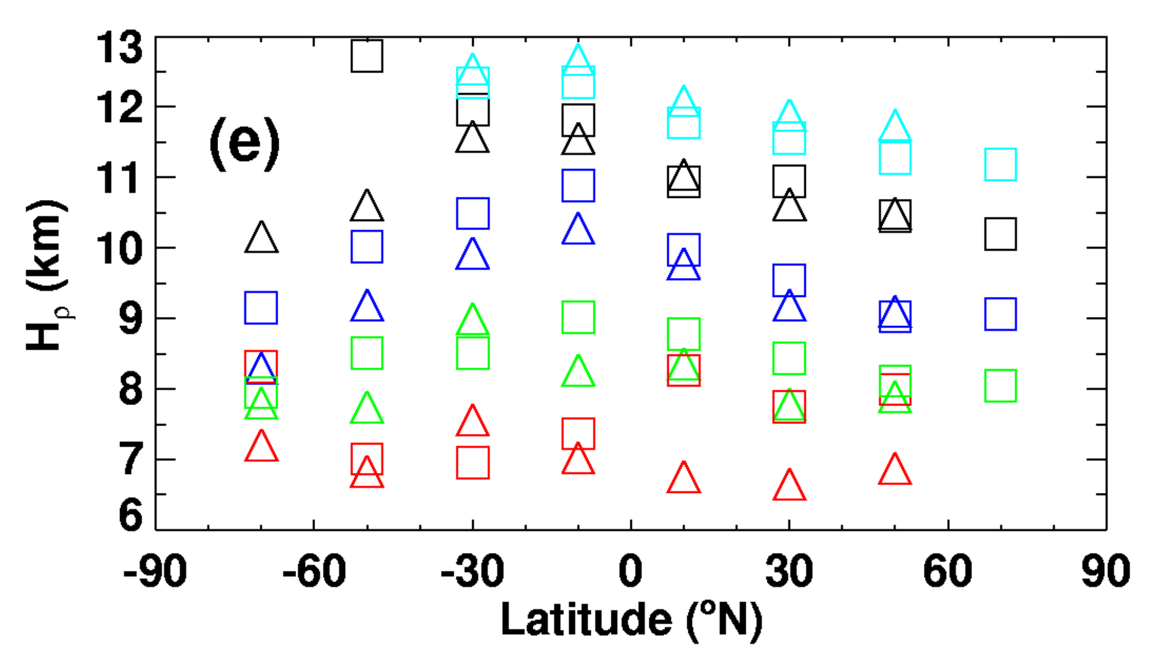


Steeper gradients in density on dayside than on nightside
Meridional flow is strongest on dayside

Changes in season and LST are small within most of these sets of data

- Red = MGS Phase 1
- Green = MGS Phase 2/pm
- Dark Blue = MGS Phase 2/am
- Black = ODY/pm
- Light Blue = ODY/am

Results from Mars – Scale Heights



Scale heights increase as altitude increases

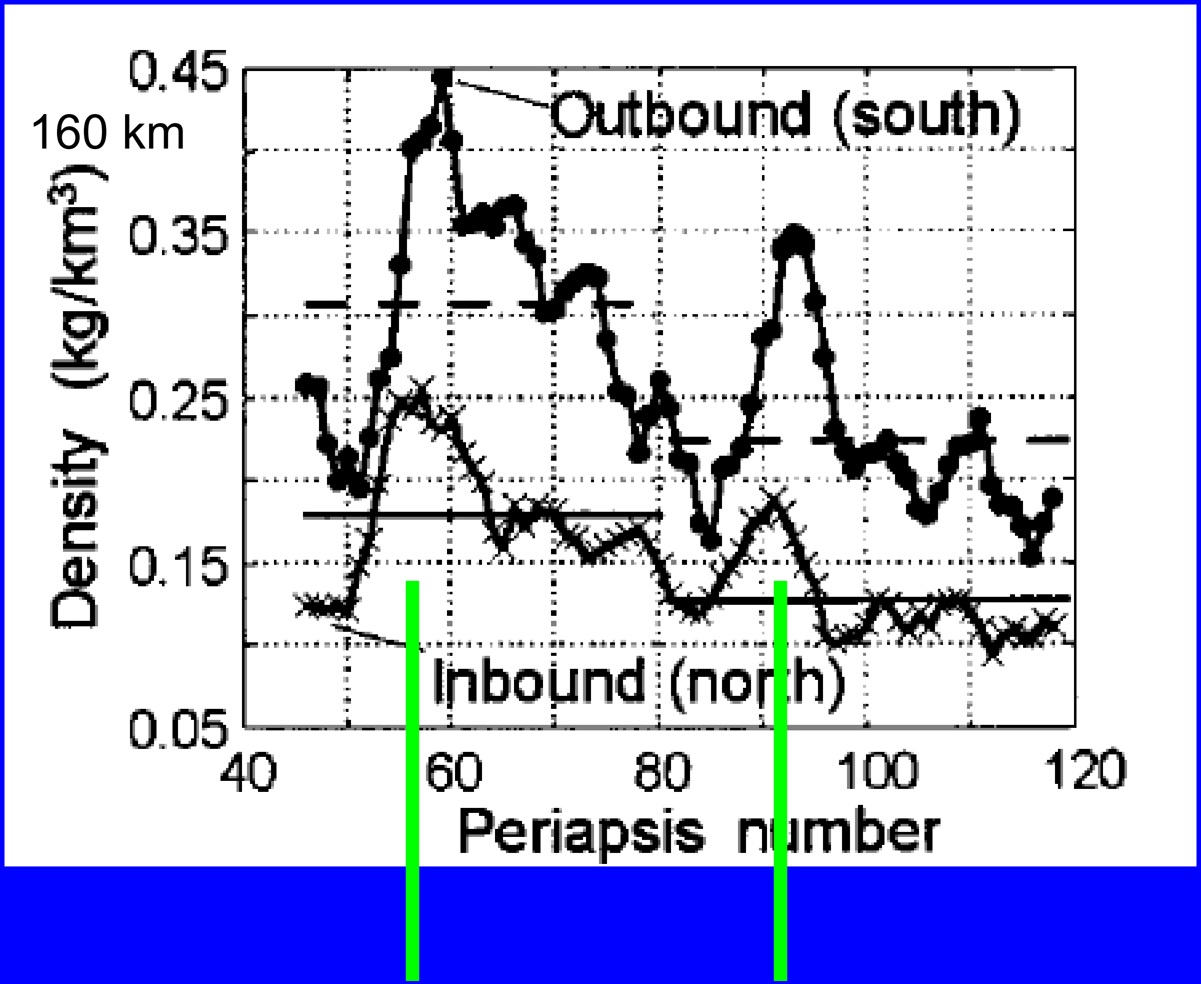
Scale heights change more over 40 km of altitude than over 80° of latitude

Scale heights are greatest in southern tropics, not at sub-solar point in northern tropics

- Red = 120 km
- Green = 130 km
- Dark Blue = 140 km
- Black = 150 km
- Light Blue = 160 km

Data from MGS Phase 2/pm

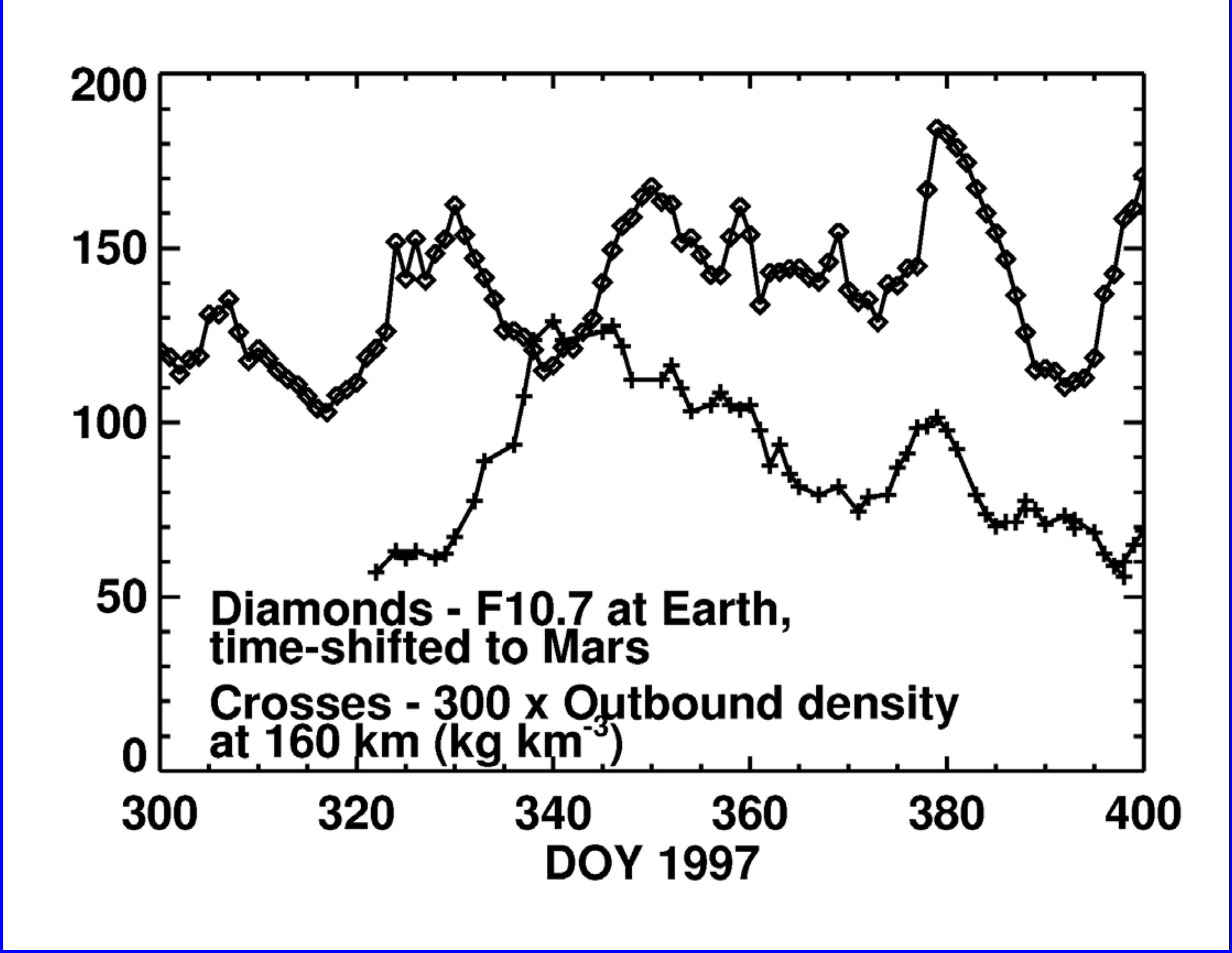
Density Variations on Mars



Dust storm in lower atmosphere. Increased density at all altitudes.

No dust storm. Strong response at high altitudes, weaker response at low altitudes.

Correlation with Solar Activity



Solar Wind Interactions

- Does solar wind affect neutral atmosphere?
- What altitude range?
- What properties of neutral atmosphere?
- Implications of Mars magnetic field?

Conclusions

- Several techniques exist for measuring atmospheric density with an orbiter
- Most effective technique depends on conservation of momentum, balance of forces, measured accelerations
- Pressure, temperature, possibly winds
- Extensive datasets exist for Mars