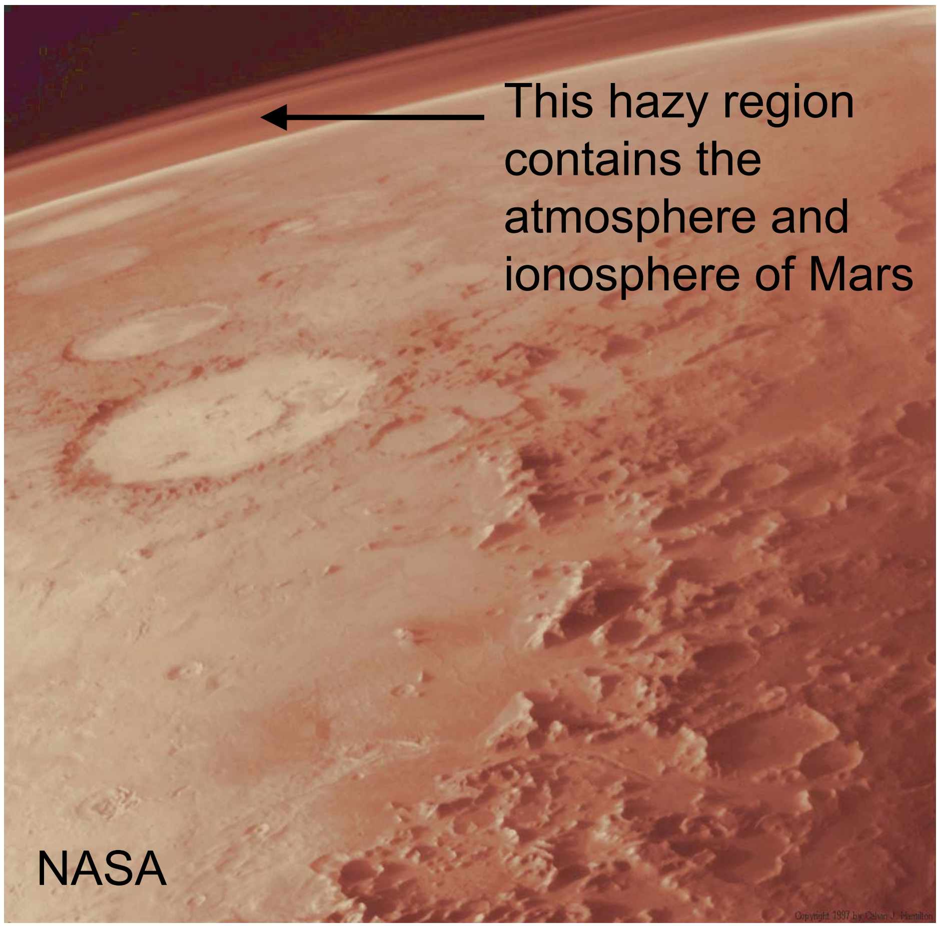
Less studied than Earth, yet more studied than any other planet, Mars is our solar system's best laboratory for testing generalizations of the earth, atmospheric and related sciences beyond Earth. I shall illustrate this using examples from recent studies of its atmosphere and ionosphere.

For the atmosphere, a rich spectrum of tides and waves dominates its dynamics. Changes in the dominant oscillations reveal the influence of the atmosphere's thermal structure and circulation.

For the ionosphere, its basic chemistry is simple enough that ionospheric observations can be valuable diagnostics of atmospheric and solar properties. Yet Mars's incredibly variable and non-Earth-like magnetic environment leads to complex magnetosphere-ionosphere interactions and ionospheric electrodynamics, where the few currently available observations hint that many remarkable phenomena remain to be discovered.

I shall conclude by outlining directions for extending these atmospheric and ionospheric studies to other bodies in the solar system and beyond, including potential instrumentation projects.

Mars: A foundation for exploring planetary atmospheres and ionospheres



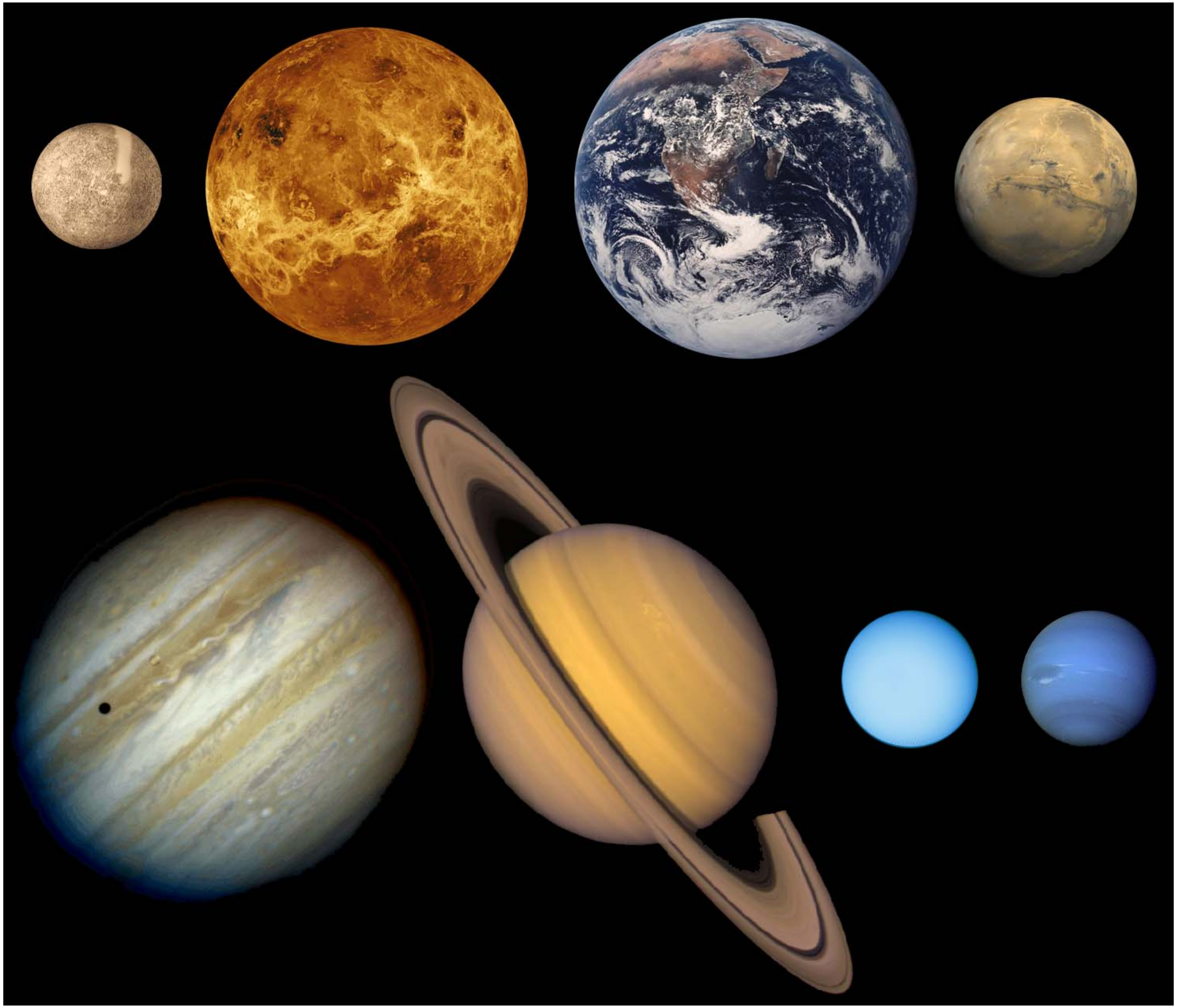
Paul Withers
Boston University
(withers@bu.edu)

Seminar in the Astronomy Department of Boston University

Friday 2010.05.07
16:00-17:00

What I want you to remember

- How I select research topics
- What I've done in my recent research
- Where I want to lead a research group



www.solarviews.com

I like planets

Diversity of environments

"Just enough" data

"Just enough" complexity

Vibrant cycle of hypotheses and tests

Atmospheres and Ionospheres

An ionosphere is a weakly ionized plasma embedded within an upper atmosphere, often produced by photoionization

Principal themes are:

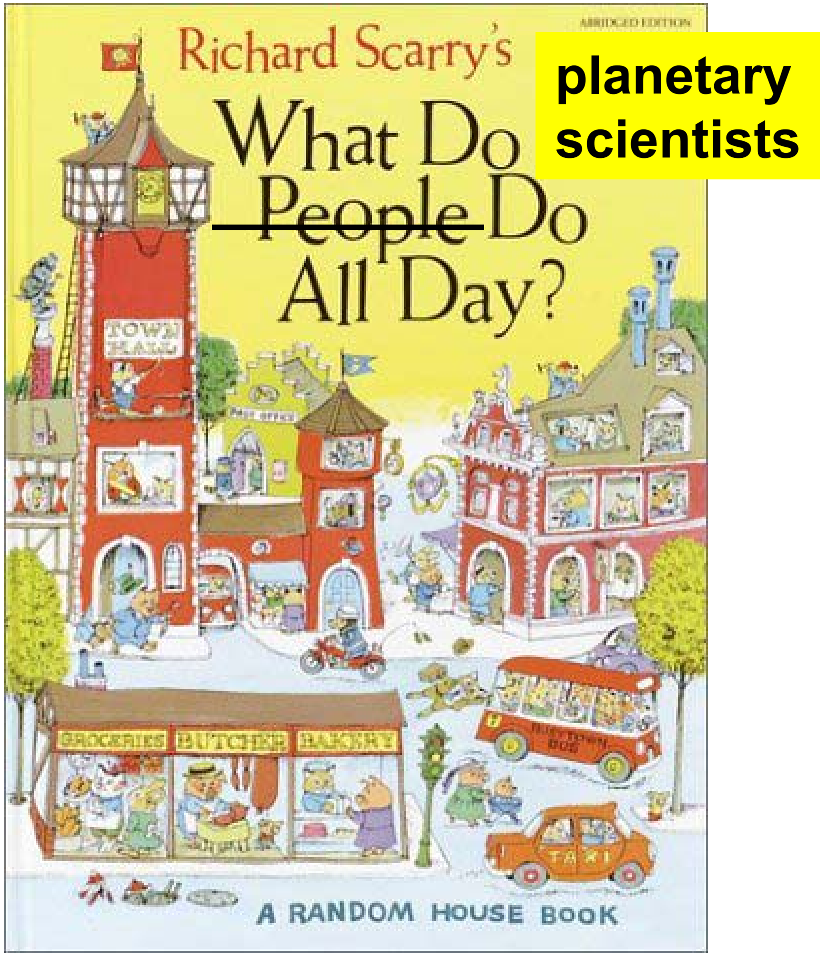
- Chemistry (conservation of mass)
- Energetics (conservation of energy)
- Dynamics (conservation of momentum)
- Coupling to below (deep interior, solid surface, liquid surface, lower atmosphere)
- Coupling to above (magnetosphere and solar wind)

These are planetary science topics that can be studied by "physics without history"

- Unlike geophysics, geochemistry, solar system evolution

"Same processes in different places" lead to wide variety of outcomes

Approaches to planetary science

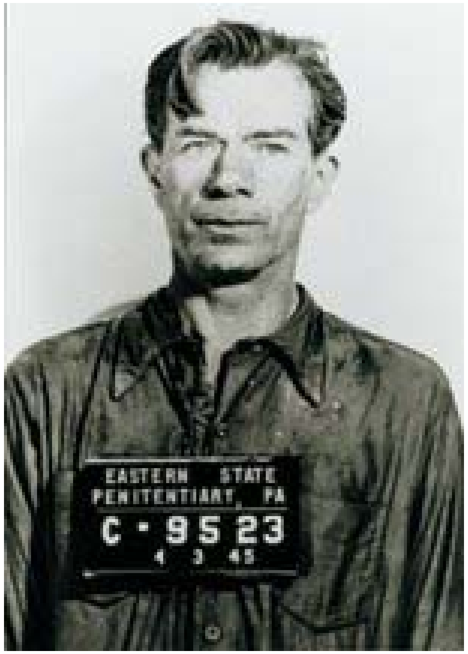


- Instrumentation
- Telescopic observations
- Data analysis
- Laboratory studies
- Fieldwork
- Theory

- I focus on data analysis, supported by theoretical work
- I plan to build upon history of involvement with spacecraft instrument teams

Why Data? Why Mars?

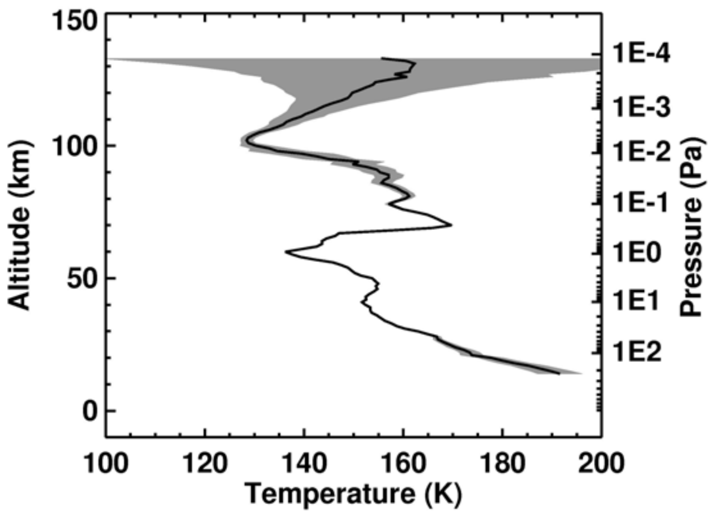
- Why rob banks?
- Because that's where the **money** is
  - Willie Sutton (1901-1980)



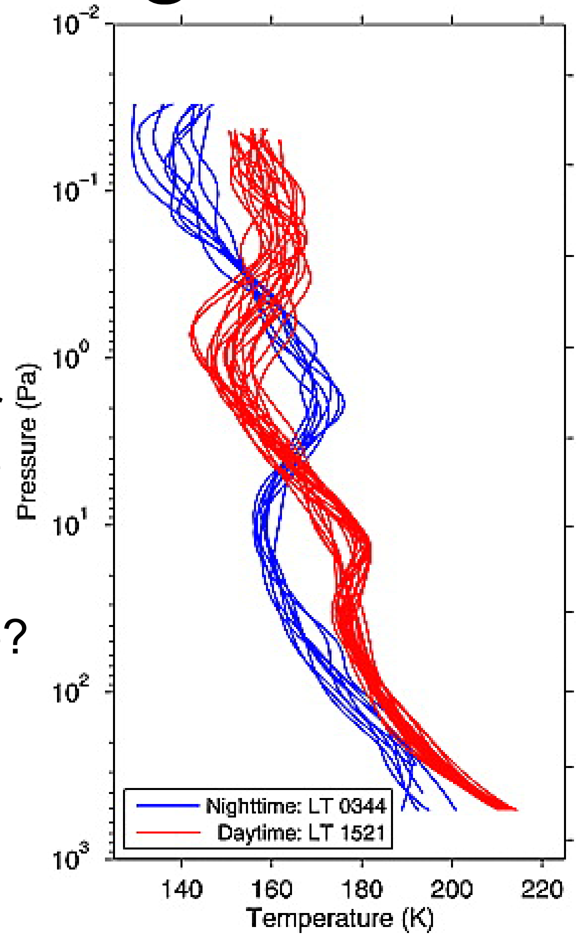
Wikipedia

- Discoveries come from **data**
  - Going where the most rewarding challenges are is common in planetary science
  - Not simply following $, jumping on bandwagon, or inertia of existing projects
- Mars and Saturn are currently data-rich
- Mars is well-suited to comparative studies with Venus and Earth
- Much of my past research has extended beyond Mars and so will my future research

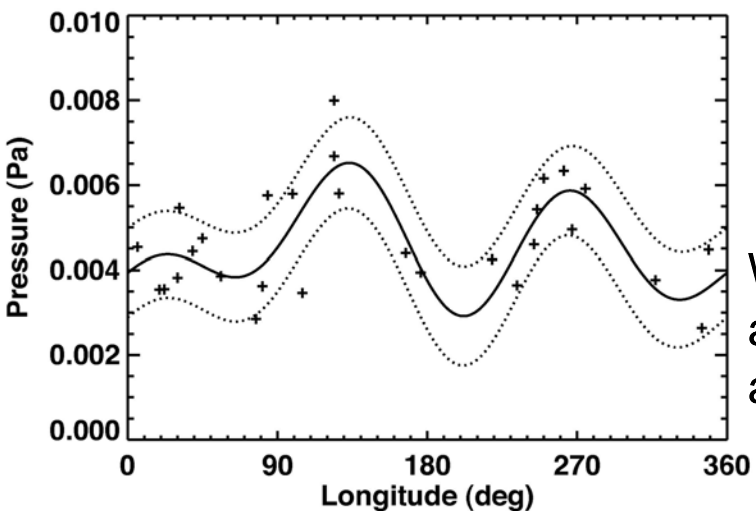
What dynamical behaviours occur in a spherical shell of rotating fluid?



What are the most important dynamical and radiative processes that control thermal structure?

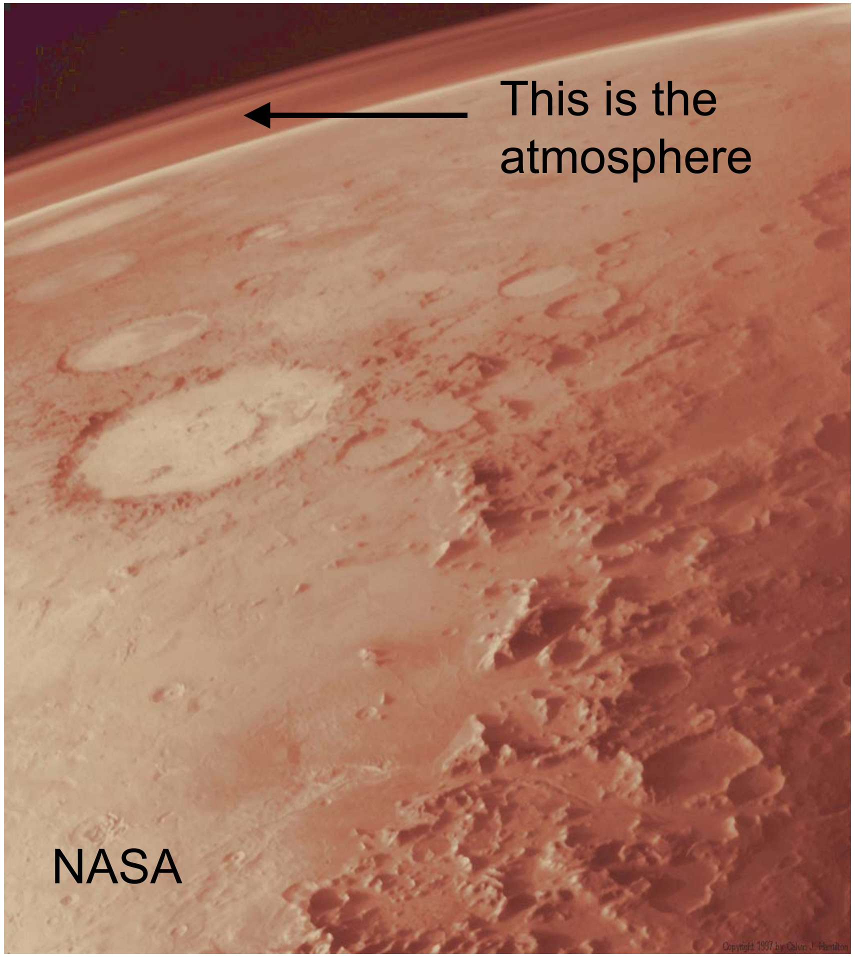


Is the upper atmosphere coupled to the lower atmosphere?



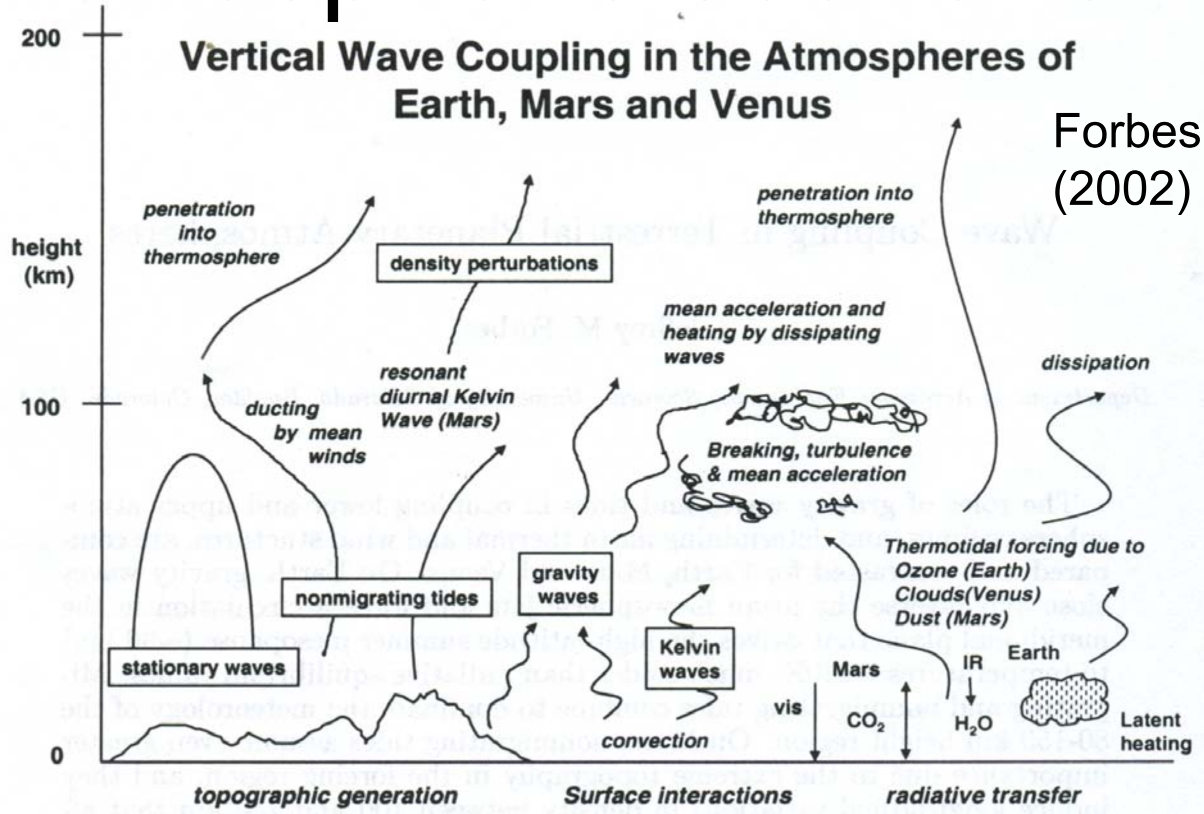
What modes of atmospheric motions are present?

The atmosphere of Mars



- Predominantly CO_2, with O important at high altitudes
- 6 mbar surface pressure
- Atmosphere freezes on winter pole
- Airborne dust affects heating, winds
- Rich spectrum of tides and waves is important for atmospheric dynamics

Atmospheric oscillations



Forbes (2002)

$$A \cos\left(n\Omega t + s\lambda - \phi\right)$$

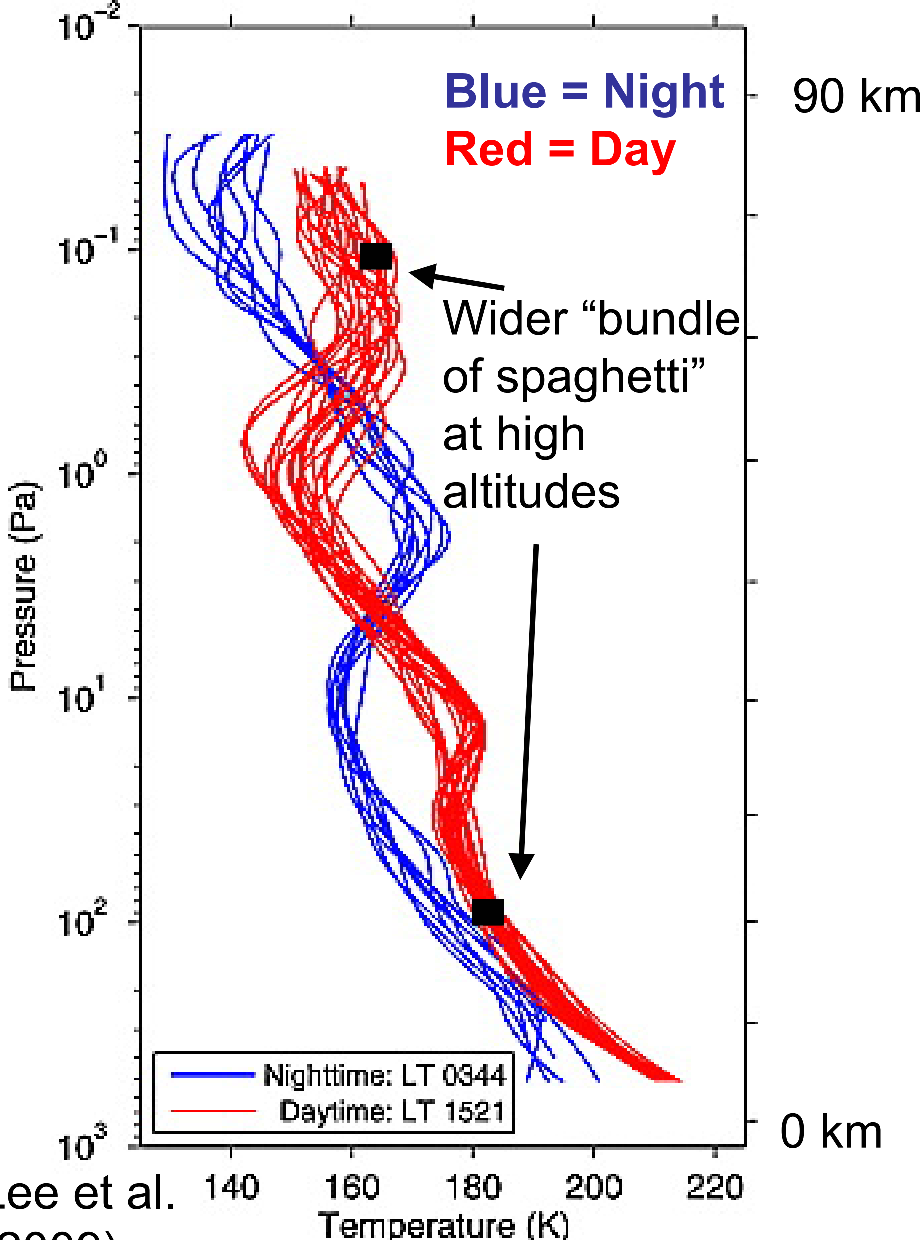
$$A \cos\left(n\Omega t_{LT} + \left(s-n\right)\lambda - \phi\right)$$

Thermal tides are global-scale disturbances with periods related to the martian day

Sun-synchronous tides have s=n

Non-Sun-synchronous tides do not have s=n

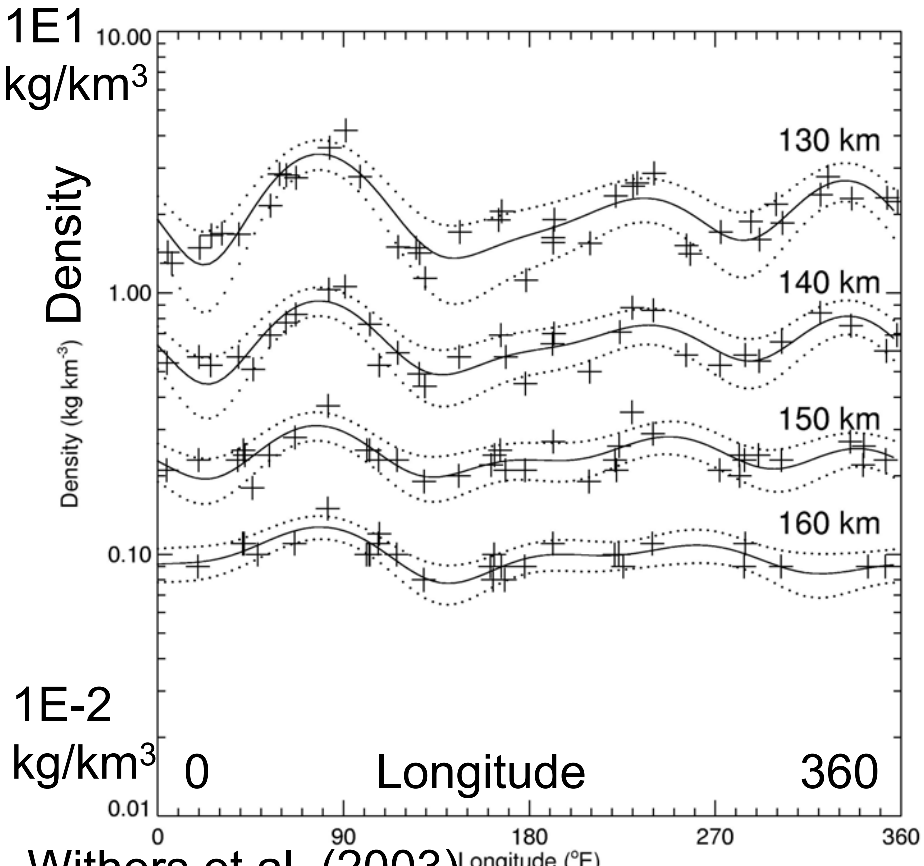
Vertical temperature profile

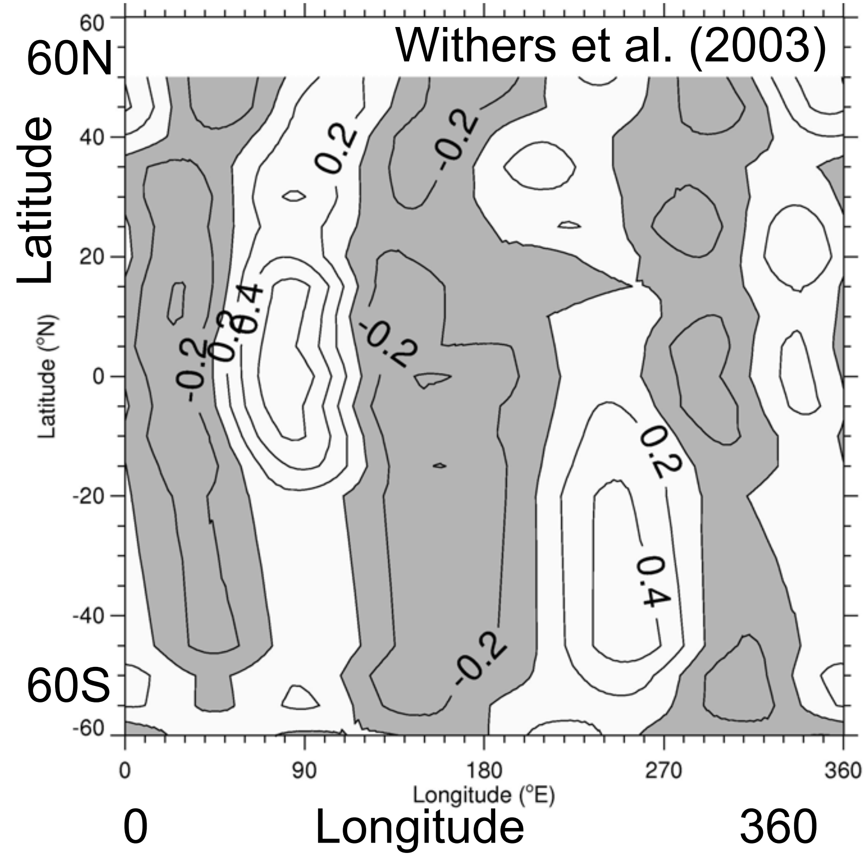


Lee et al. (2009)

- Mars Climate Sounder instrument
- 45-50N, summer
- All longitudes shown
- Strong signature of diurnal, sun-synchronous thermal tide
- Wavelength and amplitude of temperature oscillations are useful
- Many potential graduate student projects in this vast dataset

Effects of the surface extend high



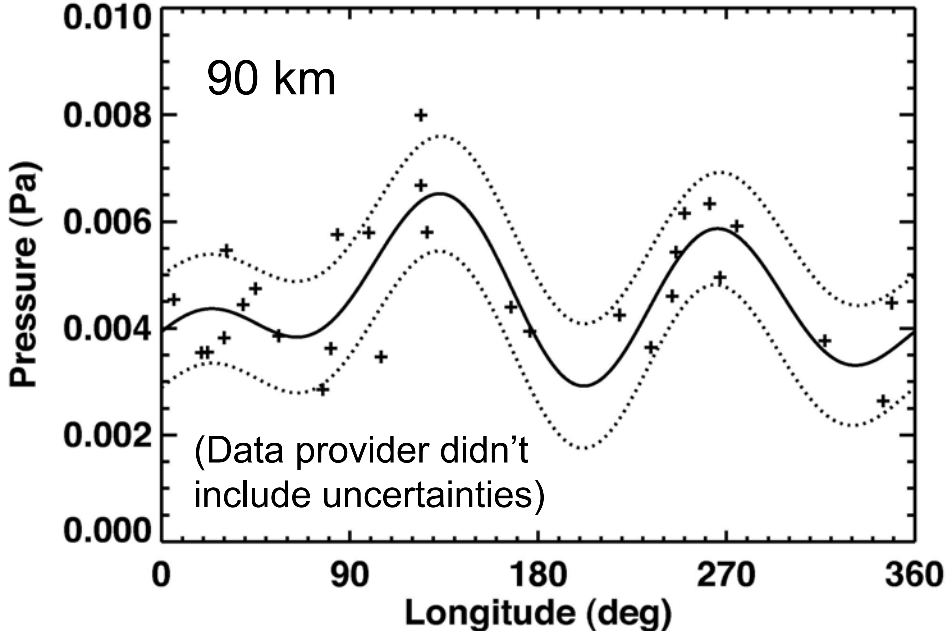


Densities at fixed local time (130-160 km)
Mars Global Surveyor aerobraking
10N to 20N, spring and LST=15 hours

Normalized fitted densities at 130 km and range of latitudes

Spring and LST~15 hours

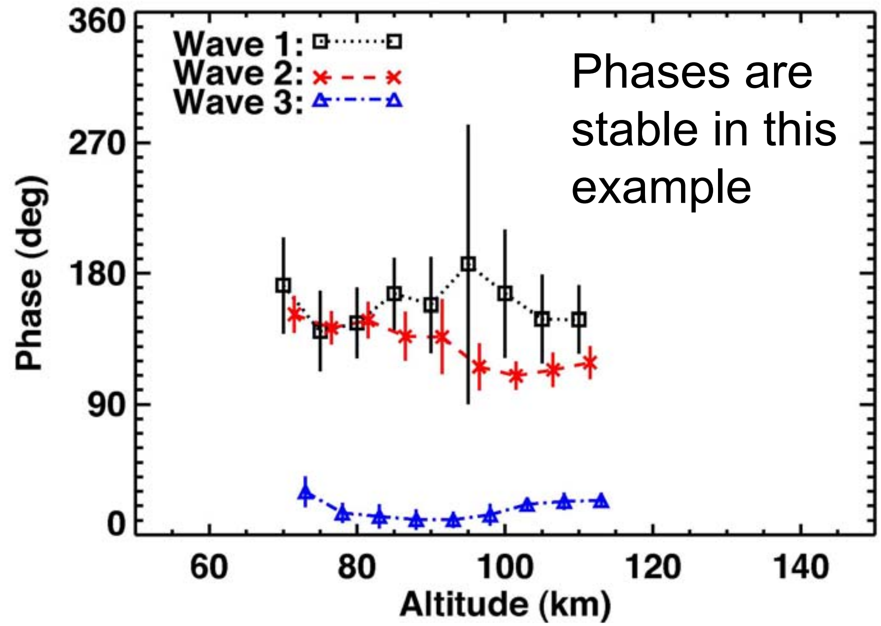
Middle atmosphere tides



SPICAM pressures at 15-45N, autumn, and LST=1-4 hours

Very similar structures to those seen at 130 km by aerobraking accelerometers

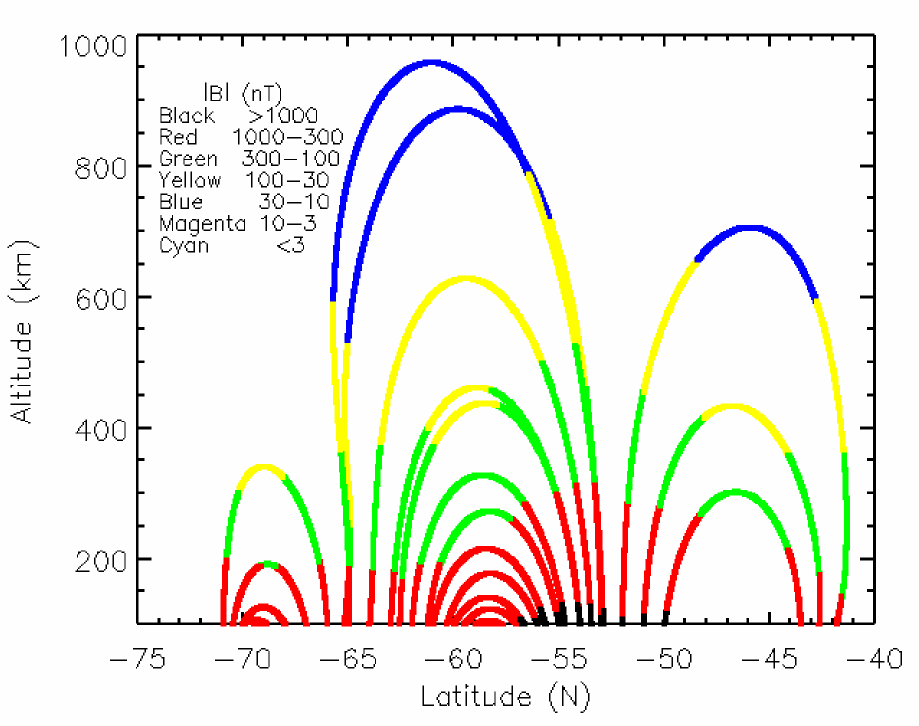
AS major Robert Pratt is studying tides in this dataset and AS major Jeff Russo is comparing data to predictions



Amplitudes and phases of major components for both pressure and temperature can be found

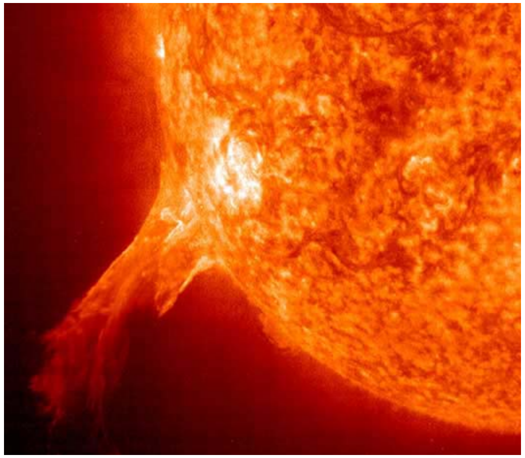
Variations in these properties can be used to constrain underlying tidal modes, background winds and dissipation mechanisms

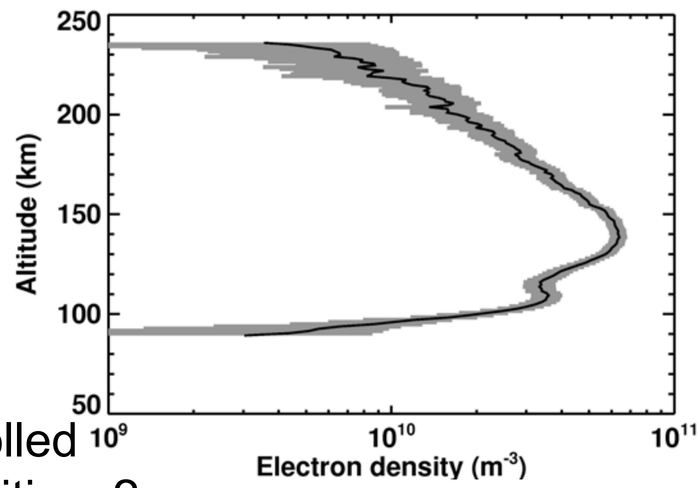
What are terrestrial planet ionospheres like and how do they work?



How do magnetic fields affect ionospheric processes?

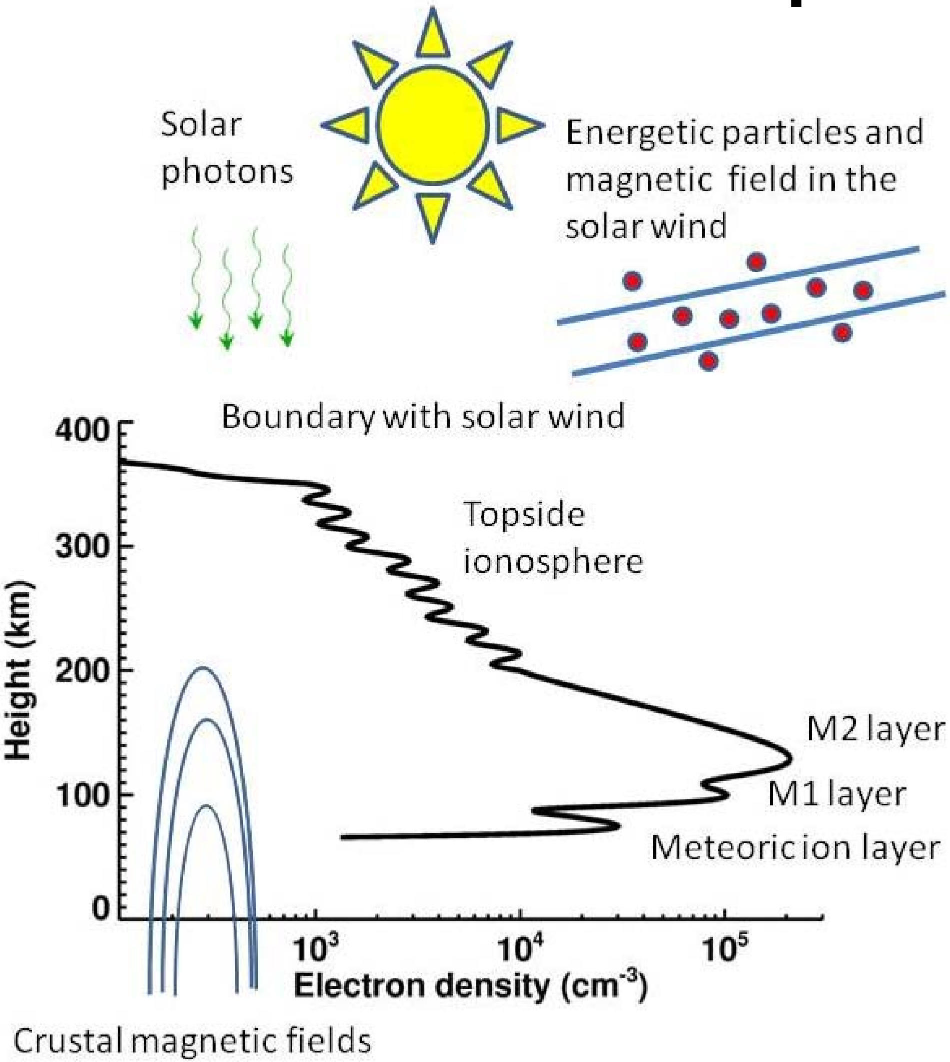
How do atypical forcing conditions affect ionospheres?





What characteristics of ionospheres are controlled by planet-specific conditions?

The ionosphere of Mars



Withers et al. (2009) Decadal Survey white paper

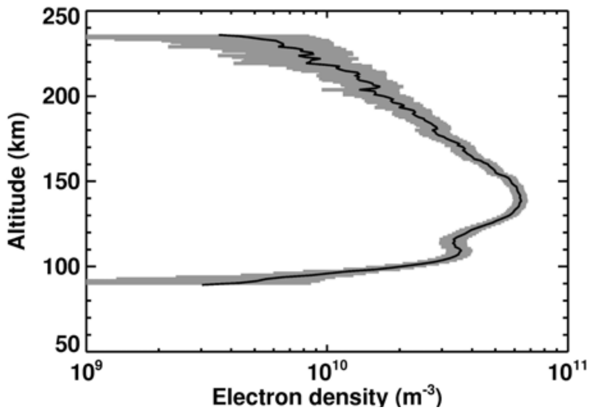
Neutral atmosphere is mainly CO_2, O becomes significant at high altitudes

O_2^+ is main ion (?) at all altitudes

EUV photons responsible for main M2 layer

Soft X-ray photons and secondary ionization responsible for lower M1 layer

Transport only important in topside ionosphere

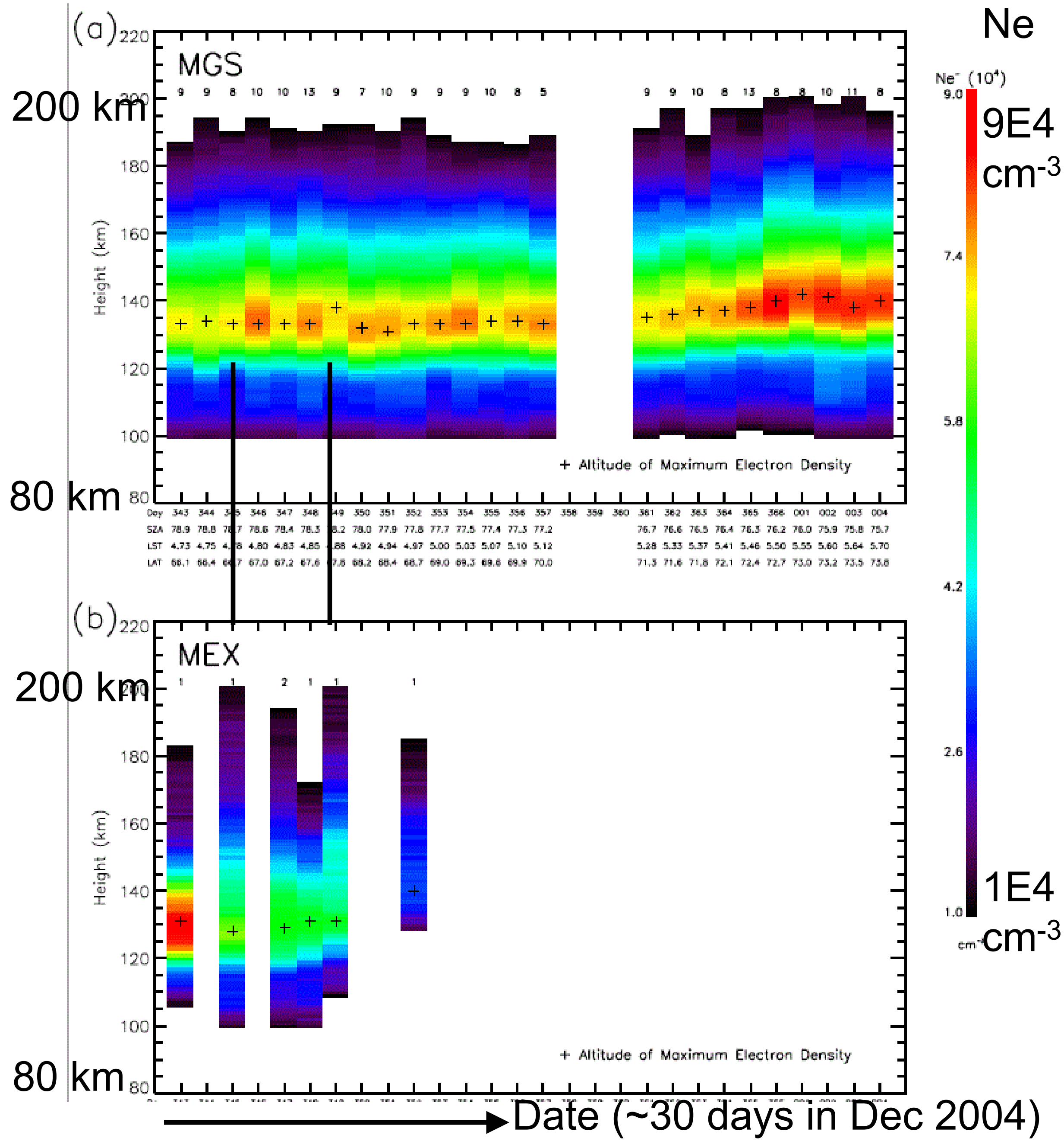


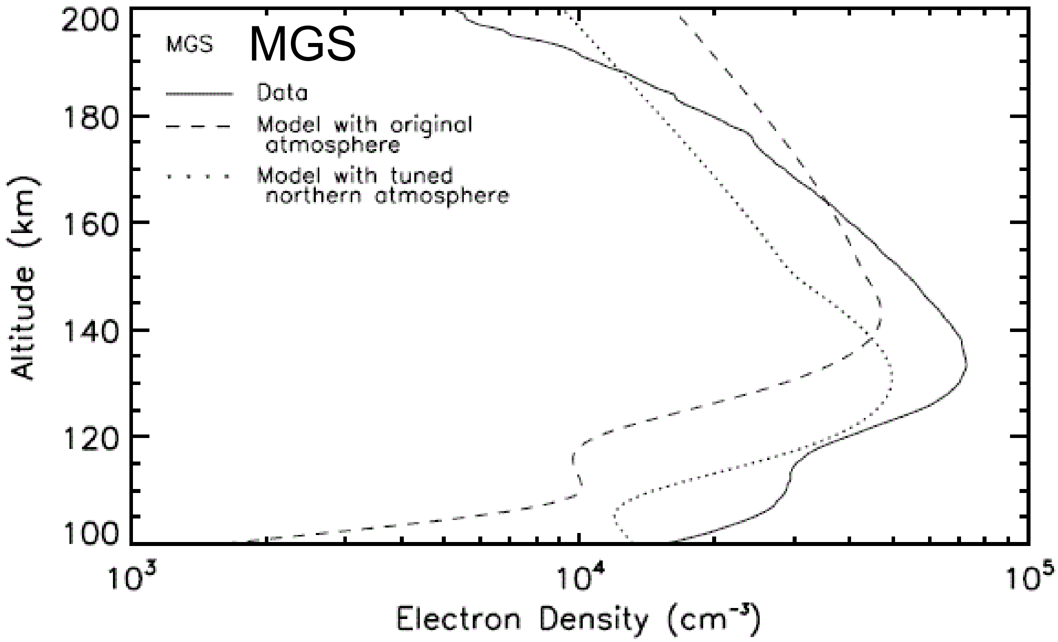
Withers (2009)

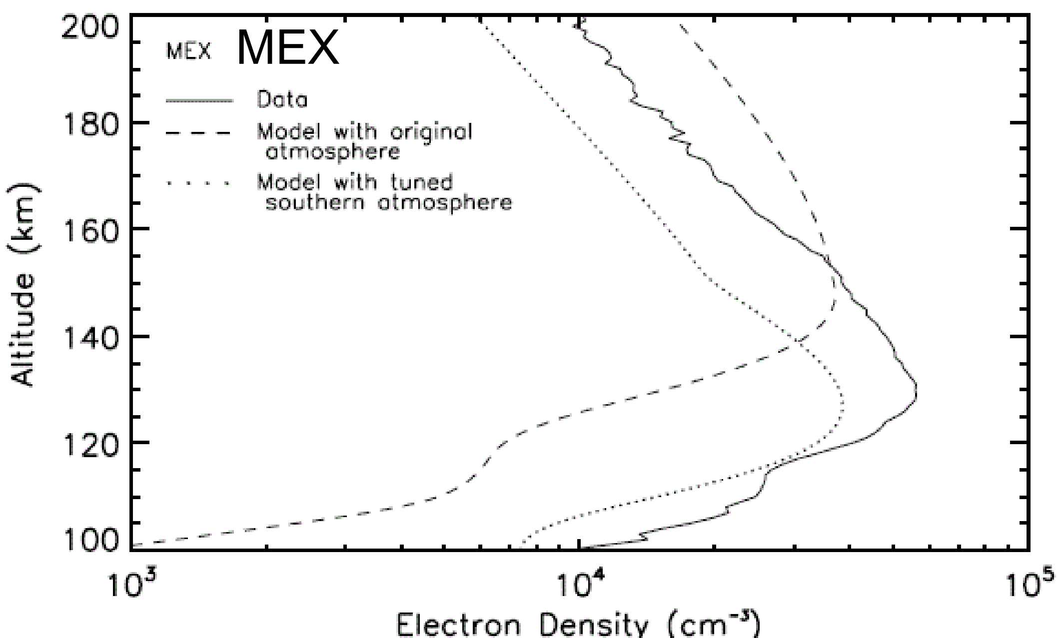
AS major Anthony Lollo is studying simultaneous ionospheric observations in different hemispheres

Goal is to tune model inputs to reproduce observed heights and magnitudes of ionospheric peaks

Model is 1D, run without plasma transport for convenience





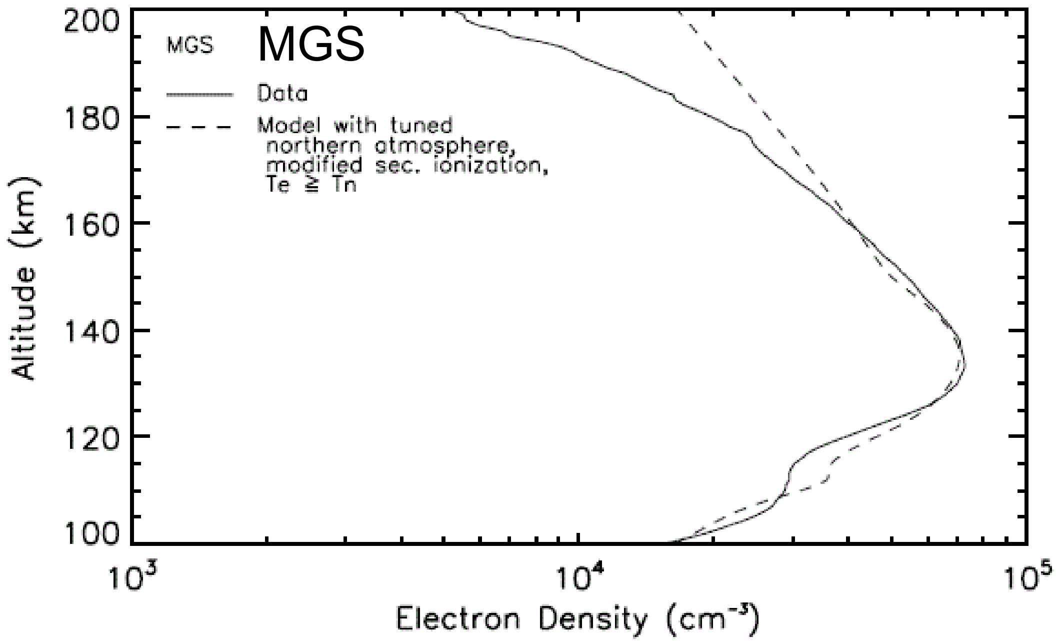


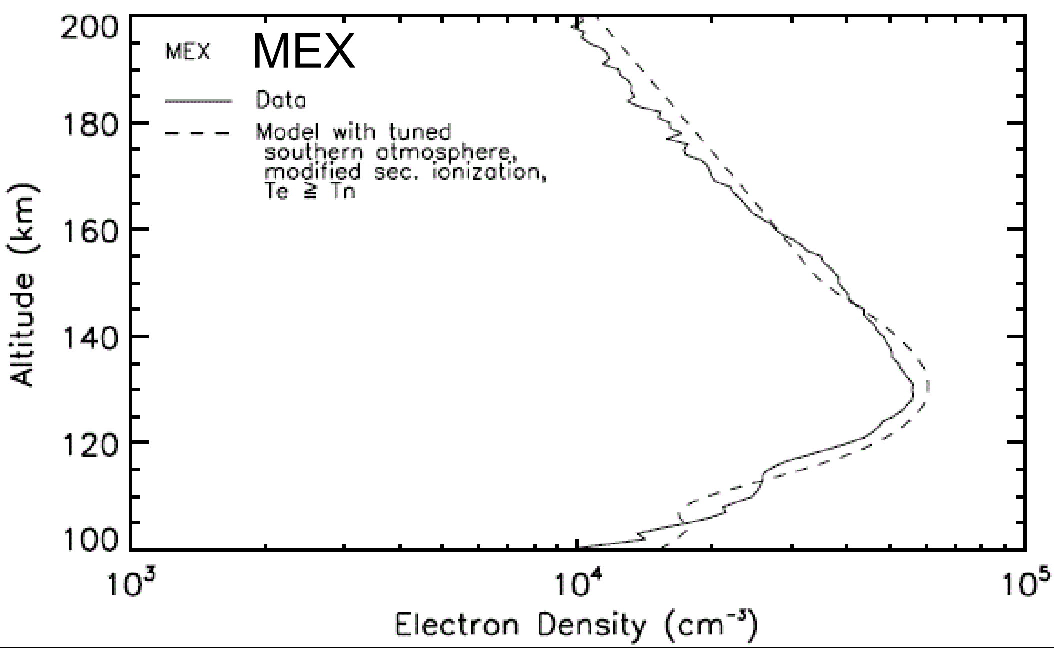
Solid line = Data

Dashed line = Original model atmosphere

Dotted line = Tuned model atmosphere (north and south)

Step 1 – Altitude of main peak
Sensitive only to neutral atmosphere





Solid line = Data

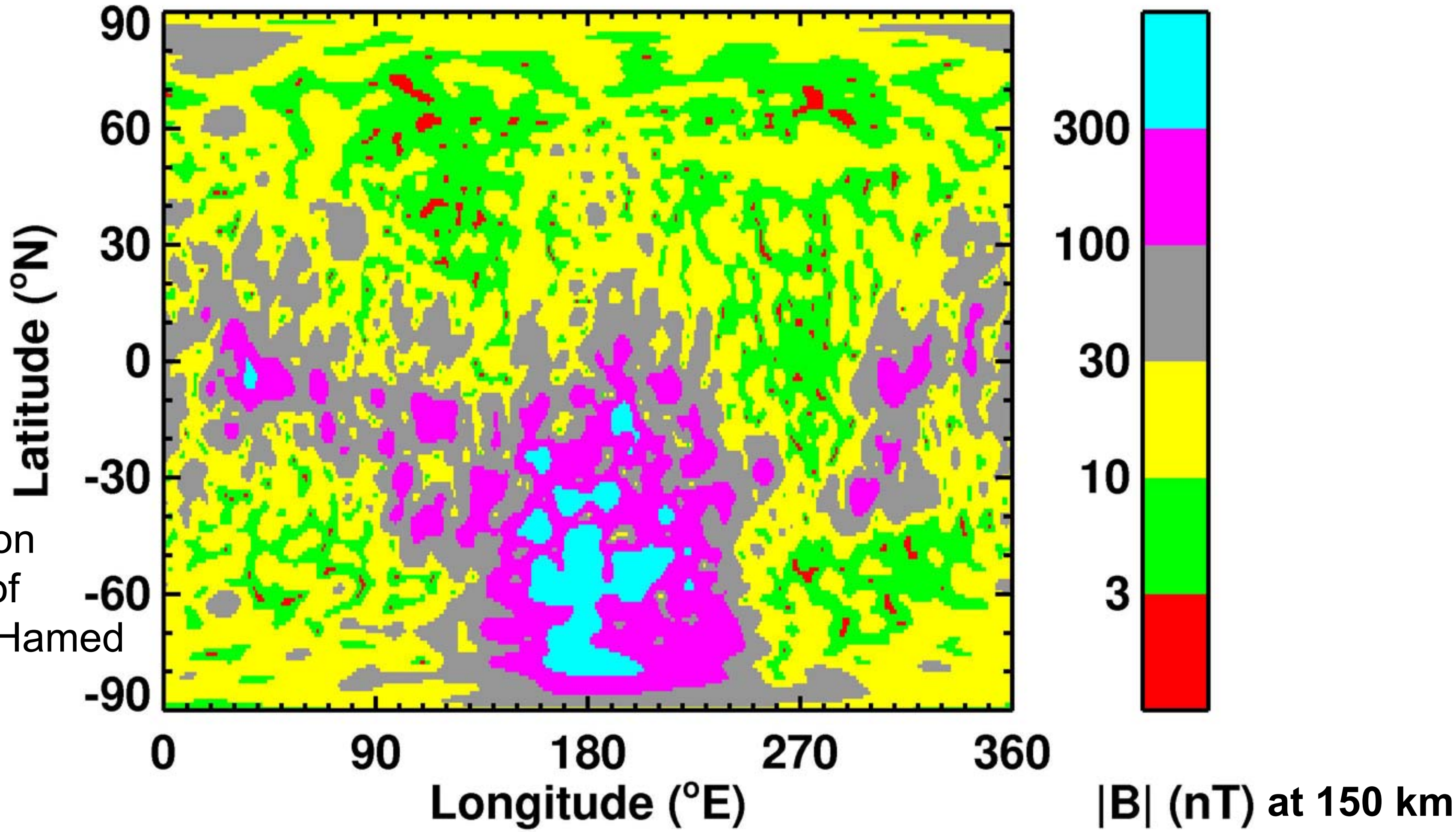
Dashed line:
Tuned model atmosphere,
plus electron temperature,
plus secondary ionization

Step 2 – Magnitude of main peak
Primarily sensitive to electron temperature

Step 3 – Shape, height, and magnitude of secondary peak
Primarily sensitive to secondary ionization

Next step is simulating ionospheric response to solar flares

Magnetic field at Mars



Based on model of Arkani-Hamed (2004)

Magnetic field strength	Strong or weak by comparison to other effects?
Magnetic field direction	Vertical, horizontal, or inclined?
Magnetic field topology	Solar wind field line, open crustal field line, closed crustal field line?

Why does B matter?

- Weak field is easy, plasma moves vertically
  - Ambipolar diffusion

$$v_{ambi,weak} = \frac{-\left(m_i + m_e\right) g}{m_i \nu_{in} + m_e \nu_{en}} \left(1 + \frac{2kT}{\left(m_i + m_e\right) g} \frac{\partial \ln N}{\partial z} \right)$$

- Strong field is easy, plasma moves along fieldlines

$$v_{ambi,strong} = v_{ambi,weak} \times \sin^2 I$$

- What happens in intermediate case?
- What happens in 3-D ionosphere with gradients in field strength and field direction?
- Velocity affects plasma densities, currents, electric field, induced magnetic field (which on Mars can be comparable to crustal field)

Electrodynamics for general $\underline{B}$

Withers (2008)

$$0 = m_j \underline{g} - \frac{1}{N_j} \underline{\nabla} (N_j k T_j) + q_j \underline{E}' + q_j B \underline{\underline{\Lambda}}\, \underline{w_j} - m_j \nu_{jn} \underline{w_j}$$

Gravity — Pressure gradient — Electric field — Magnetic field — Ion-neutral collisions

$$\underline{J} = \sum_j N_j q_j \underline{w_j}$$

Definition of current density, **J**

Algebra leads to:
(generalized Ohm's law)

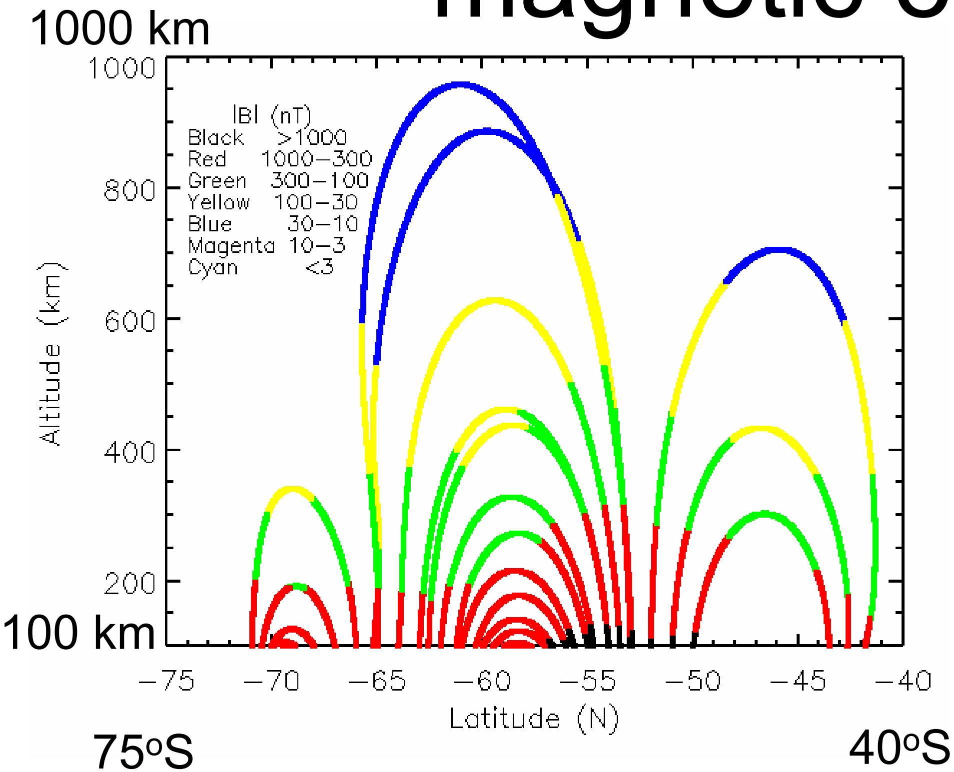
$$\underline{J} = \underline{Q} + \underline{\underline{S}}\,\underline{E}'$$

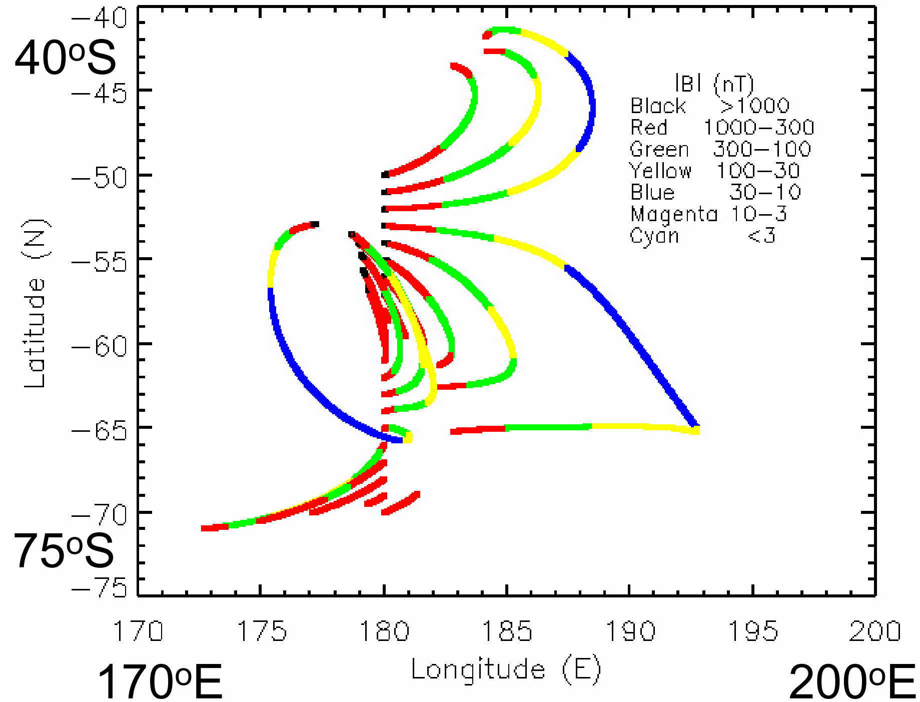
Key ratio is: $\kappa_j = \frac{q_j B}{m_j \nu_{jn}}$

Next, use conservation of charge, Maxwell's equations, and assumed boundary conditions to obtain expression for ion velocity that:

Reduces to the strong field limit for ambipolar diffusion if B strong
Reduces to the weak field limit for ambipolar diffusion if B weak
Provides smooth transition between weak and strong regimes with currents (dynamo region)

Extending 1D model in unusual magnetic environment





Field strength and direction vary tremendously on short spatial scales

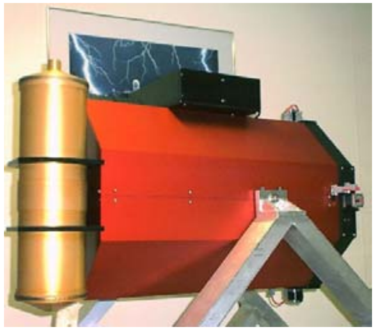
AS grad student Majd Matta is working to simulate 2D plasma motion under martian conditions – code is currently being tested and debugged

Future research

- Atmospheres
  - Long-term atmospheric oscillations at Venus
  - Thermal tides in extensive Mars Climate Sounder dataset
- Ionospheres
  - Explore topside radar sounder data from Mars
  - Comparison of Venus and Mars (summer project for incoming student Zachary Girazian)
- Outer solar system
  - Titan/Venus neutral atmosphere comparisons
  - Cassini drag data at Titan and Saturn
  - Atmospheric oscillations in Huygens entry profile
- Beyond our solar system
  - Explore range of possible ionospheres by adapting existing models

Instrumentation

Mimir



PRISM

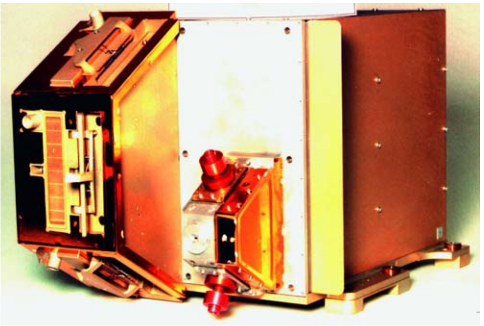
Ground-based astrophysical and aeronomical instrumentation

MANIC

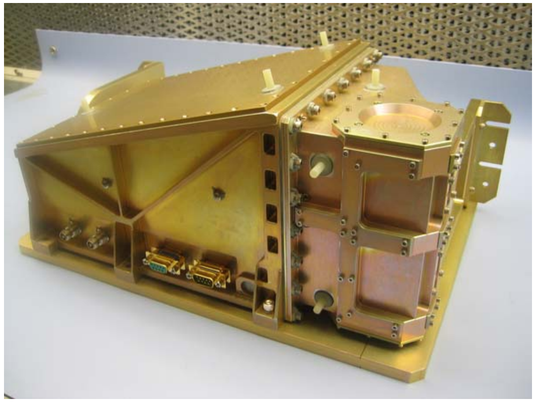
Rocket payloads

A rocket

Spaceflight instrumentation for heliophysics missions



RAPID

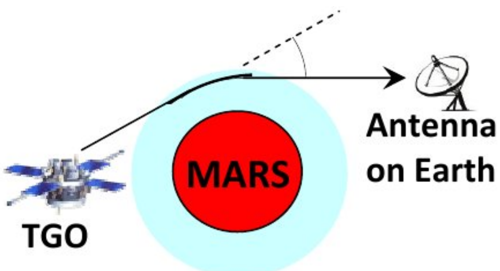


Crater

I want to enhance BU's involvement in spaceflight instrument teams for planetary missions

Experience and Opportunities

- Aerobraking accelerometers
  - Many grazing profiles of atmospheric density
- Radio occultations
  - Many profiles of ionospheric electron density and neutral pressure/temperature
  - Co-I on pending instrument proposal for 2016 Mars orbiter (TGO)

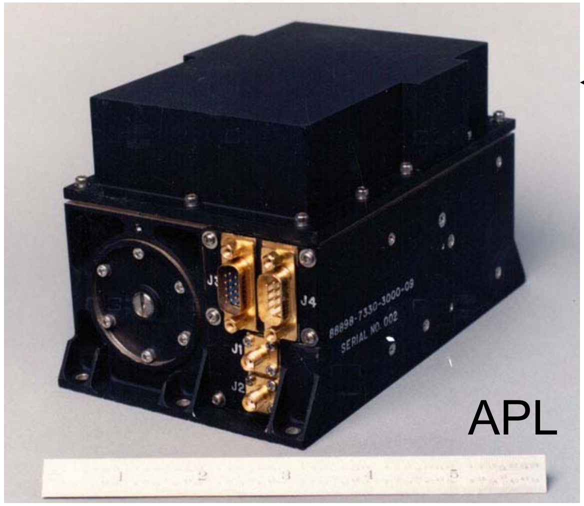


Atmospheric Sounding Through Radio Occultations (ASTRO)

ASTRO's experienced team will explore the atmosphere of Mars using the well-established radio occultation (RO) technique, exploiting the unique observing geometry provided by an orbit that drifts in local time. With its extensive heritage, ASTRO can address central science objectives of the TGO mission.

- Entry accelerometers
  - Single vertical profile of atmospheric density, pressure and temperature
  - Smart strategy is to leverage this focused involvement into collaborations with related instruments
- All
  - Past and current involvement as Co-I and in other roles
  - Hardware is essential for mission operations
  - Established groups have recently disintegrated via retirements

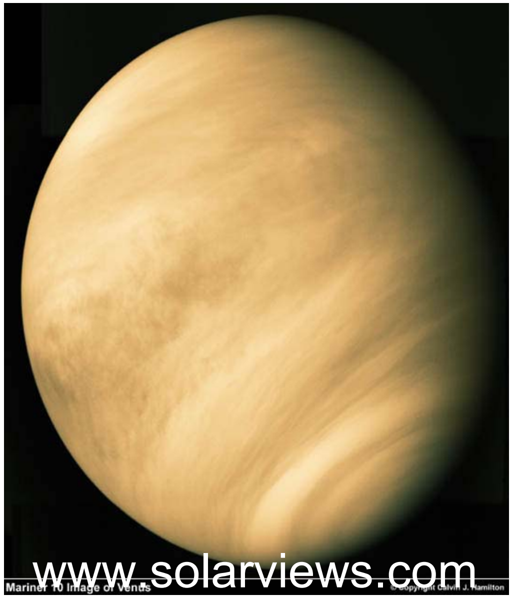
Potential collaborations at BU



New Horizons
Radio Science
Experiment

Instrumentation – Chakrabarti, Clemens, Clarke, Fritz, Janes, ECE

Atmospheres – Clarke, Mendillo, Earth Sciences and other BU departments



Ionospheres – Oppenheim, Mendillo, Semeter, ECE

What I want you to remember

- How I select research topics
  - Go where the big opportunities are
  - Apply “physics without history”
  - Complementary use of data and models

- What I’ve done in my recent research
  - Tides and thermal structure of atmosphere of Mars
  - Variations in the ionosphere of Mars
  - Related work beyond Mars

- Where I want to lead a research group
  - Atmospheres and ionospheres beyond Mars
  - Instrumentation opportunities