Exploring Planetary Ionospheres

Paul Withers, Boston University

(withers@bu.edu)

Technical Seminar to Center for Atmospheric Research at University of Massachusetts Lowell

Wednesday 2008.05.27 14:00-15:00

Acknowledgements to collaborators

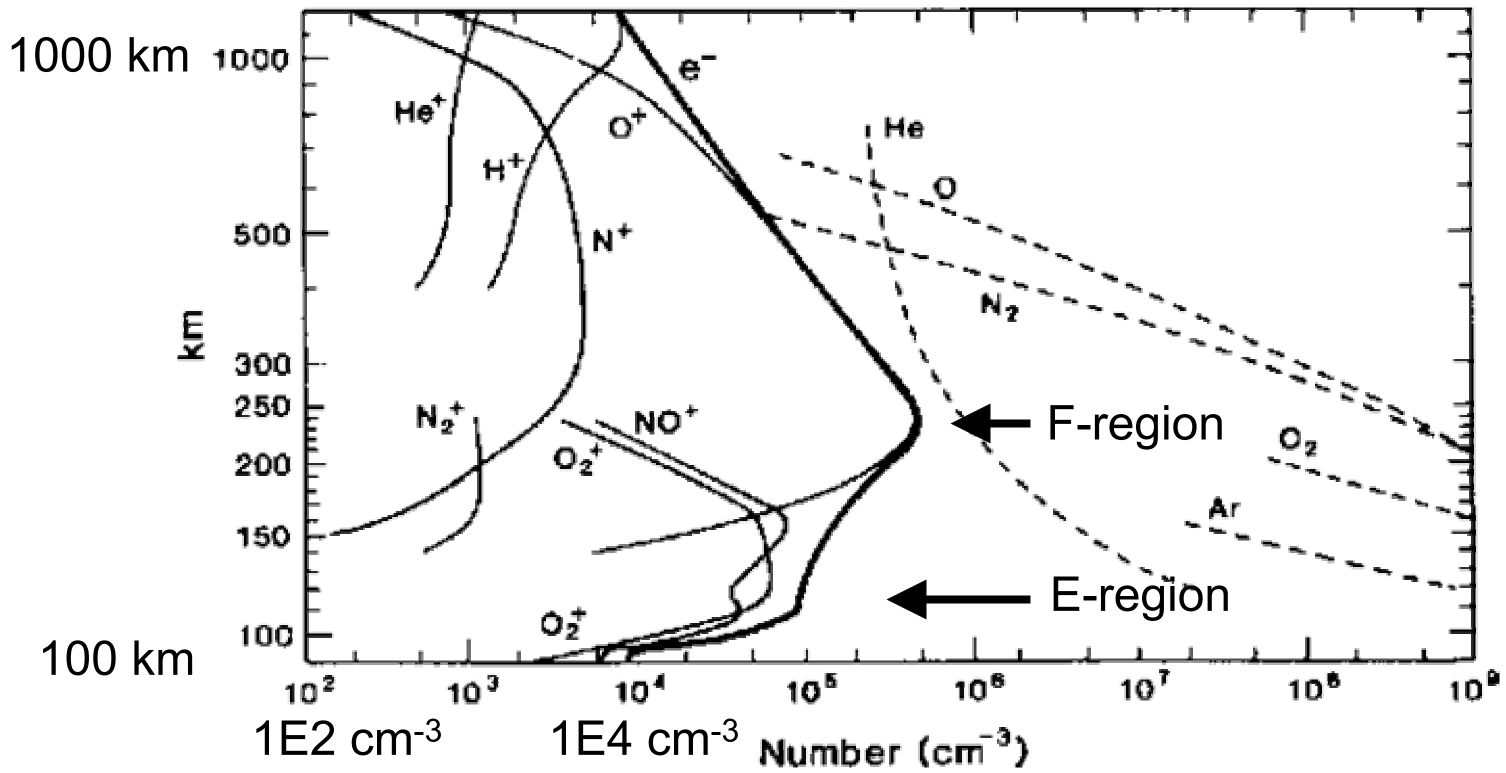
- Michael Mendillo and colleagues at Boston University
- Martin Paetzold and colleagues at University of Cologne, Germany
- Dave Hinson and colleagues at Stanford
- Plus some others, including those involved in studies of neutral atmospheres which I won’t discuss today

Outline

- Diversity of planetary ionospheres
- The ionosphere of Mars
- Selected ongoing research at Mars
- Future research directions

- This is not “Detailed report on my recent work” nor “Summary of my last five papers”
- Instead, this is an overview of extra-terrestrial ionospheres and my research area, with a look ahead to future projects and opportunities

Ionosphere of Earth

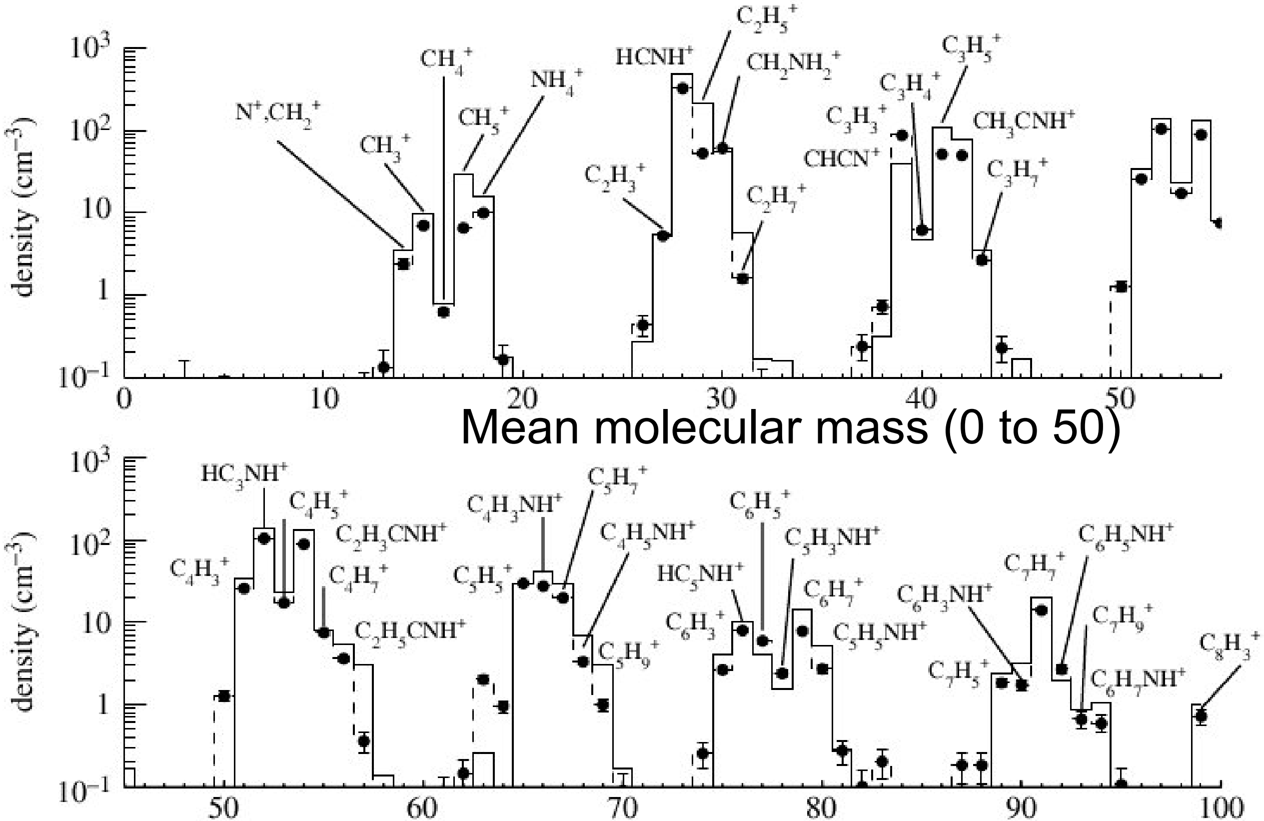


Johnson, 1969

N_2-O_2 atmosphere, with O_2^+, NO^+, O^+ ions abundant
Transport important in F-region, but not in E-region
Strong global magnetic field affects plasma transport

Ionosphere of Titan

Ion mass spectrum
from Cassini
Fig 2 of Cravens et al. (2005)



Ion number density
1E-1 to 1E3 cm^{-3}

Mean molecular mass (0 to 50)

Ion number density
1E-1 to 1E3 cm^{-3}

Mean molecular mass (50 to 100)

N_2 atmosphere like Earth, but with few percent CH_4
Ionosphere is a soup of heavy hydrocarbons, not simple oxygen-bearing ions
Rain of charged particles from Saturn's magnetosphere is important

Diversity of Chemistry, Dynamics and Energetics

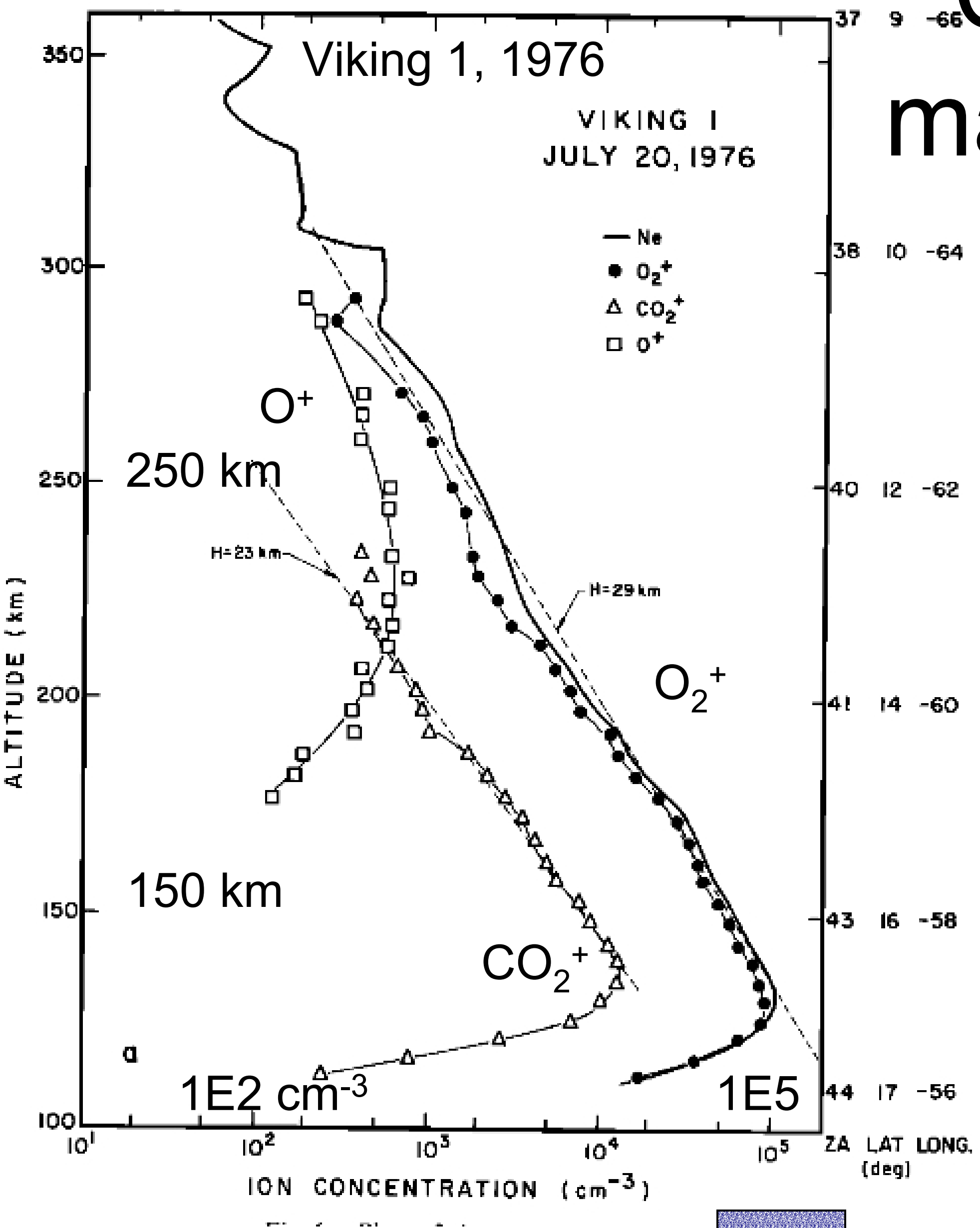
- CO_2 atmospheres: Venus, Mars
- N_2 atmospheres: Earth, Titan, Triton, Pluto
- H_2 atmospheres: Jupiter, Saturn, Uranus, Neptune, extrasolar planets(?)
- Sulphur atmospheres: Io
- H_2O atmospheres: Europa, Ganymede, Callisto, Enceladus, comets, Kuiper belt objects(?)
- Dynamics (little data, much theory)
  - Rotation rate affects dayside to nightside flow
  - Magnetic field affects plasma motion, currents
  - Gravity affects vertical transport and vertical extent
- Energetics (little data, much theory)
  - Distance from Sun affects irradiance
  - Magnetosphere affects charged particle deposition

The Ionosphere of Mars
Why Mars?

- Major discoveries come from new data

- Mars is data rich (volume, quality, diversity) by planetary standards
- Lots of electron density profiles from recent radio occultations and MARSIS topside sounder
- Ongoing missions, and new ones planned
- Venus, Earth and Mars are best group for powerful comparative studies

Chemistry of the martian ionosphere



Viking 1, 1976

O^+

250 km

O_2^+

150 km

CO_2^+

1E2 cm^{-3}

1E5

$CO_2 + h\nu \rightarrow CO_2^+ + e$

$CO_2^+ + O \rightarrow O_2^+ + CO$
(fast)

$O_2^+ + e \rightarrow O + O$
(slow)

Fig 6 of Hanson et al. (1977)
Retarding Potential Analyzers on two Viking Landers

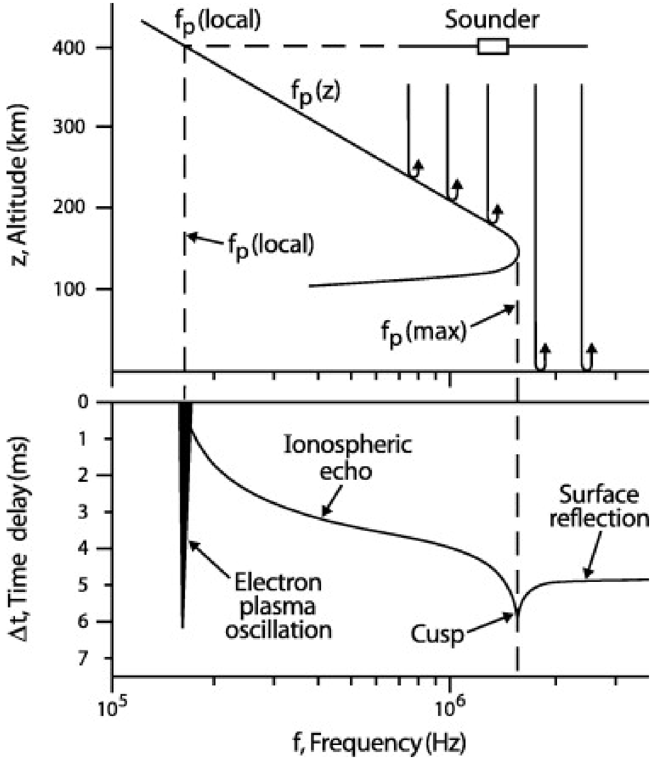
Minimal information on dynamics and energetics

MARSIS Measurements

Plasma frequency

$$f_p^2 = \frac{Ne^2}{4\pi^2\epsilon_0 m_e}$$

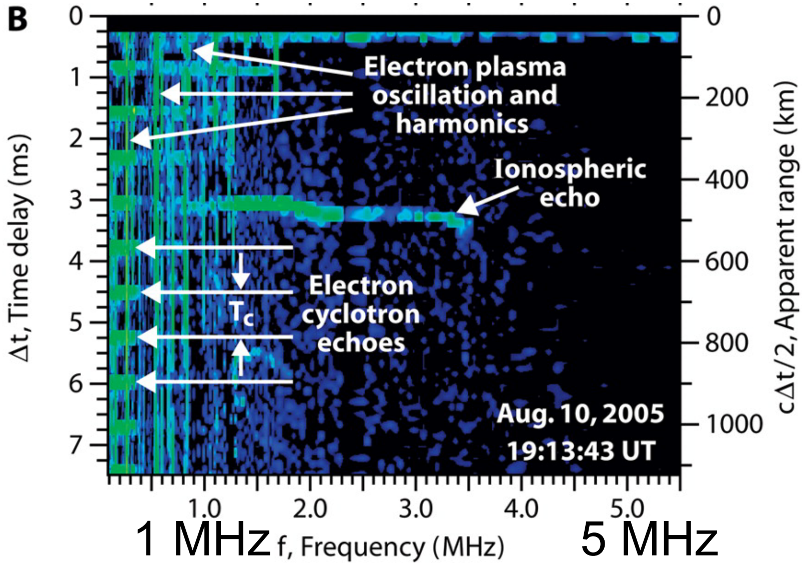
Electron density



2 ms

4 ms

6 ms

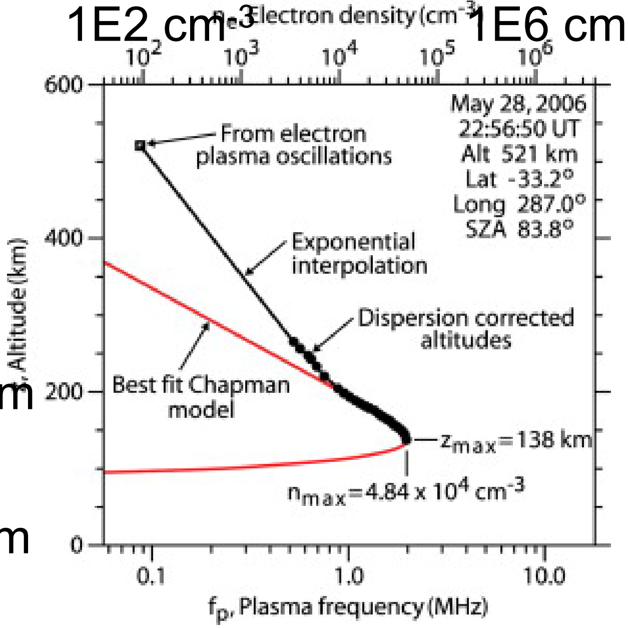


1 MHz

5 MHz

1E2 cm^{-3}

1E6 cm^{-3}

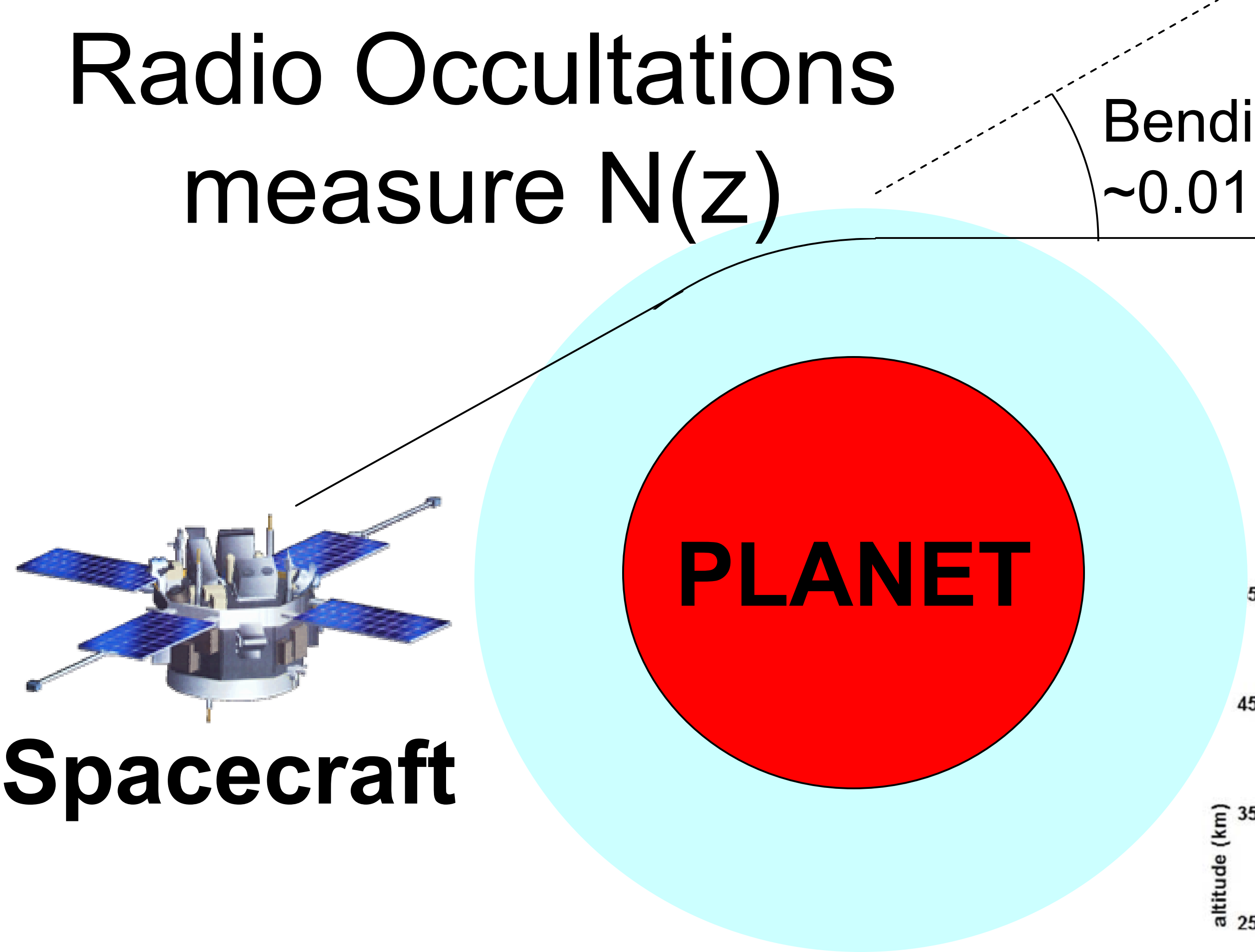


200 km

0 km

Figures from Gurnett et al. (2008)
MARSIS is a topside radar sounder on ESA Mars Express

Radio Occultations measure N(z)

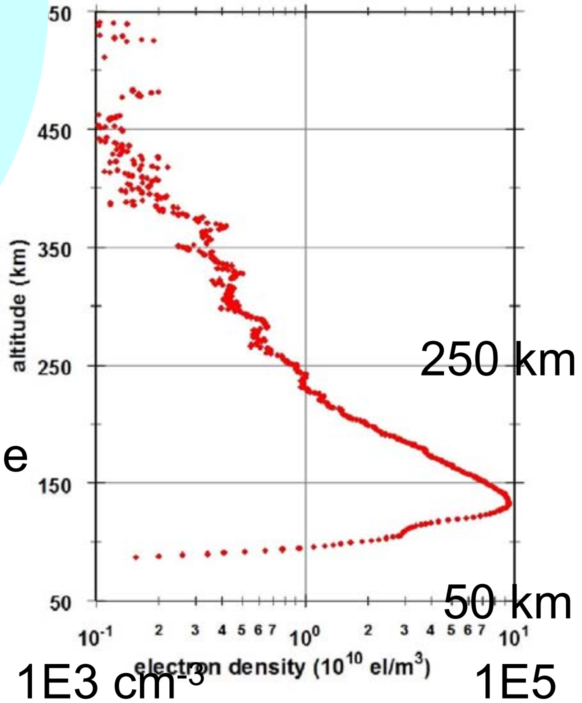


Spacecraft

Antenna on Earth

NASA Mars Global Surveyor:
5600 profiles, σ=3E-3 cm^{-3}, 1998-2005
ESA Mars Express:
~400 profiles, σ=1E-3 cm^{-3}, 2004-present

Typical dayside profile from Mars Express



Ongoing research at Mars

- Chemistry
  - Effects of meteors
- Dynamics
  - Effects of magnetic fields
- Energetics
  - Effects of solar flares
- Theme: Unusual conditions or “What happens if you try to break it?”
- Primarily analysis of data, with theoretical interpretation

Chemistry – Effects of meteors

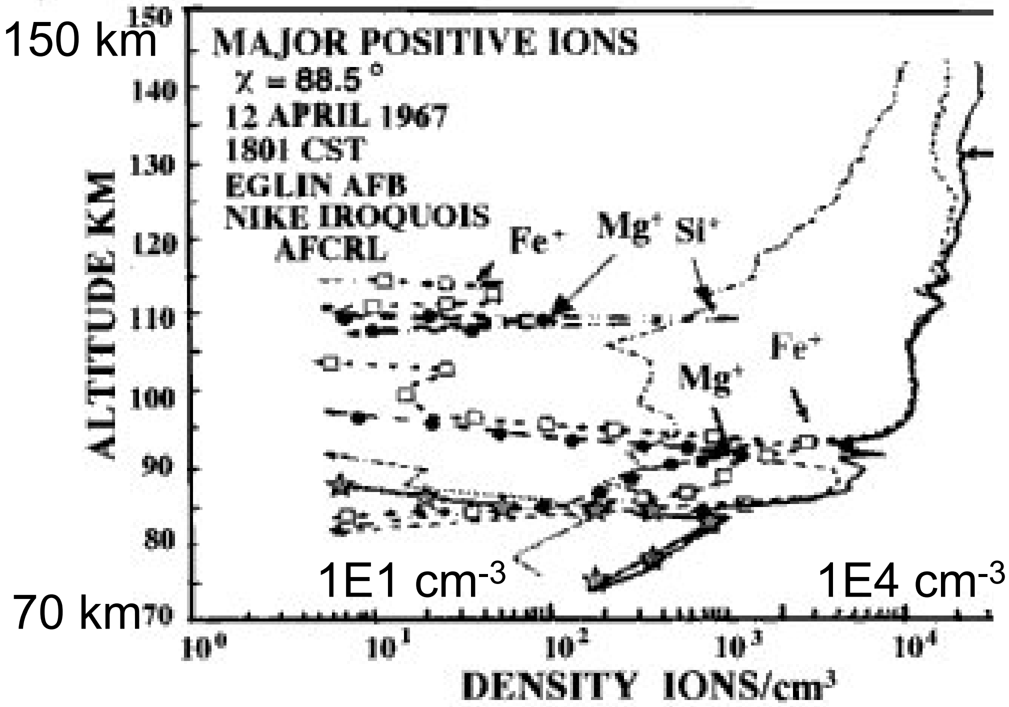
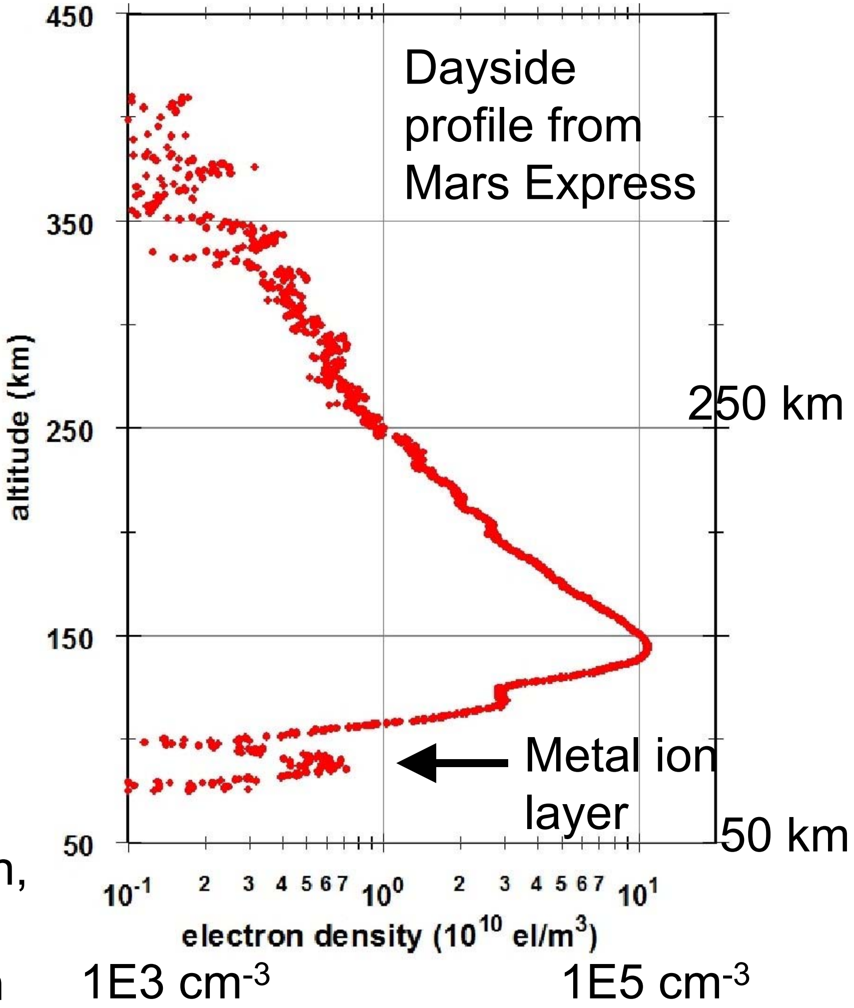


Fig 8.3 of Grebowsky and Aikin (2002)

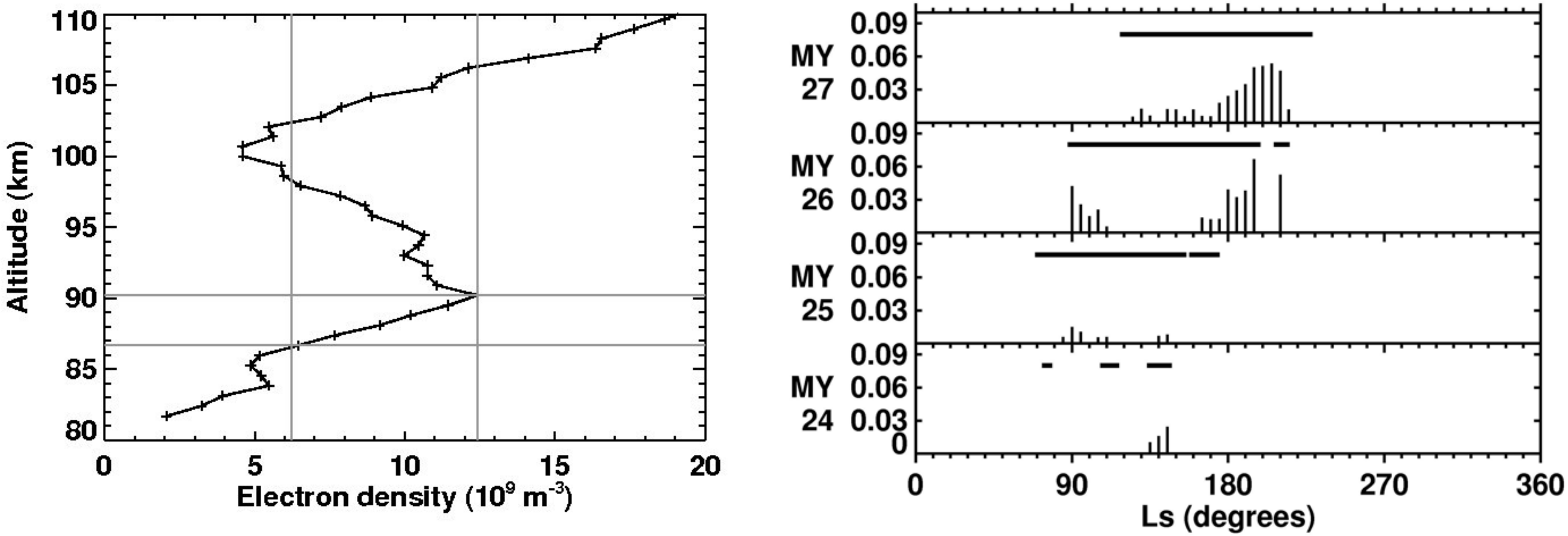


Dayside profile from Mars Express

Metal ion layer

Meteoroids ablate at high altitudes
Fe, Mg, Si ionized by ablation, photoionization, charge-exchange into long-lived atomic ions
Winds and magnetic fields important on Earth

Chemistrv – Effects of meteors



Figs B1 and 14 of Withers et al. (2008)

Data: ~150 martian N(z) profiles with metal ion layers
Models: Models exist for Earth, preliminary for Mars
Recent work: Discovery, physical characterization, variations in occurrence rate, prediction of meteor showers

(1) Detailed characterization of observations, search for correlations to determine what controls layer characteristics
(2) Forward modelling of patchy narrow layers
(3) Seasonal variations in occurrence rate and layer characteristics

Dynamics – Effects of magnetic fields

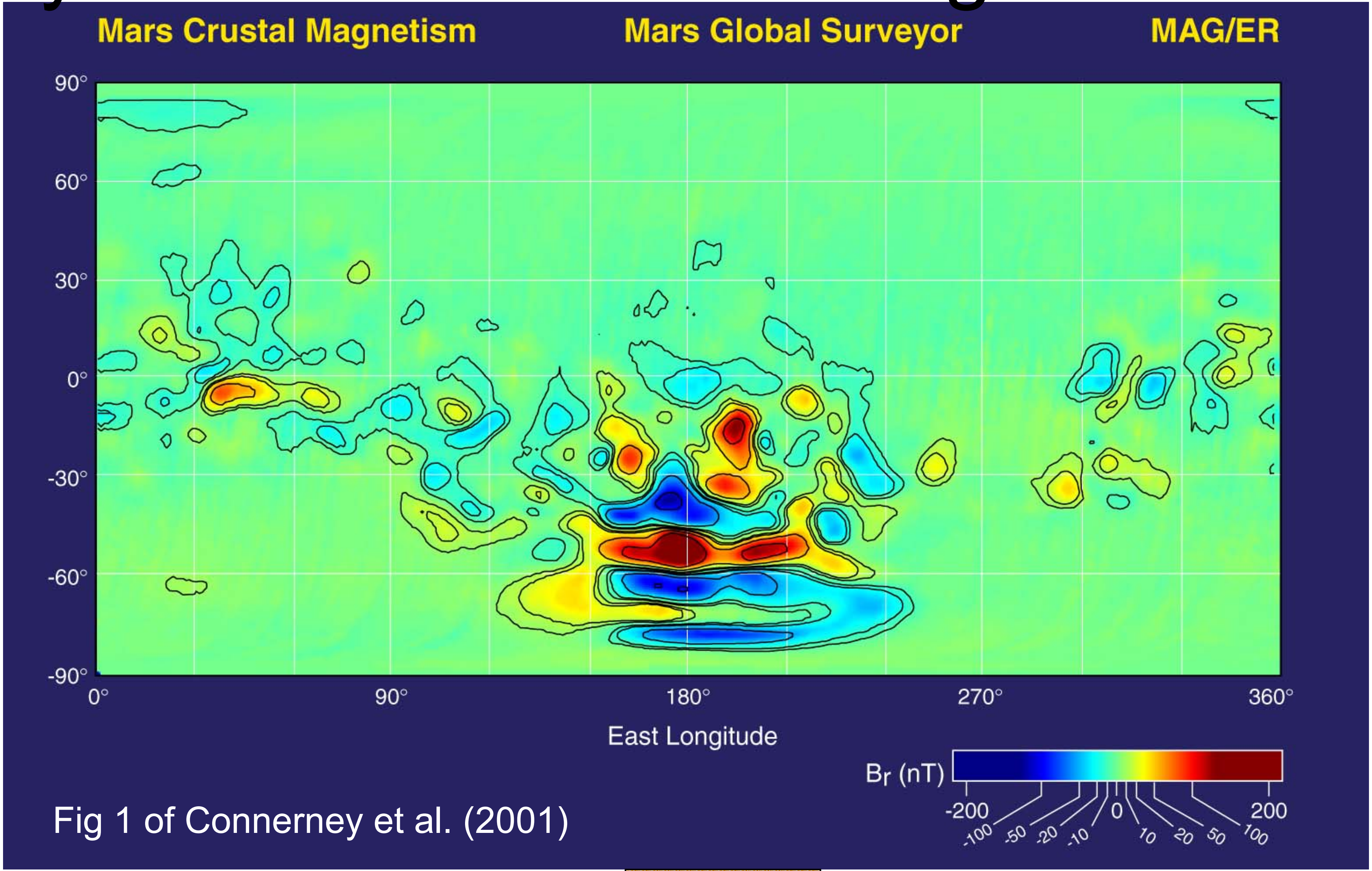
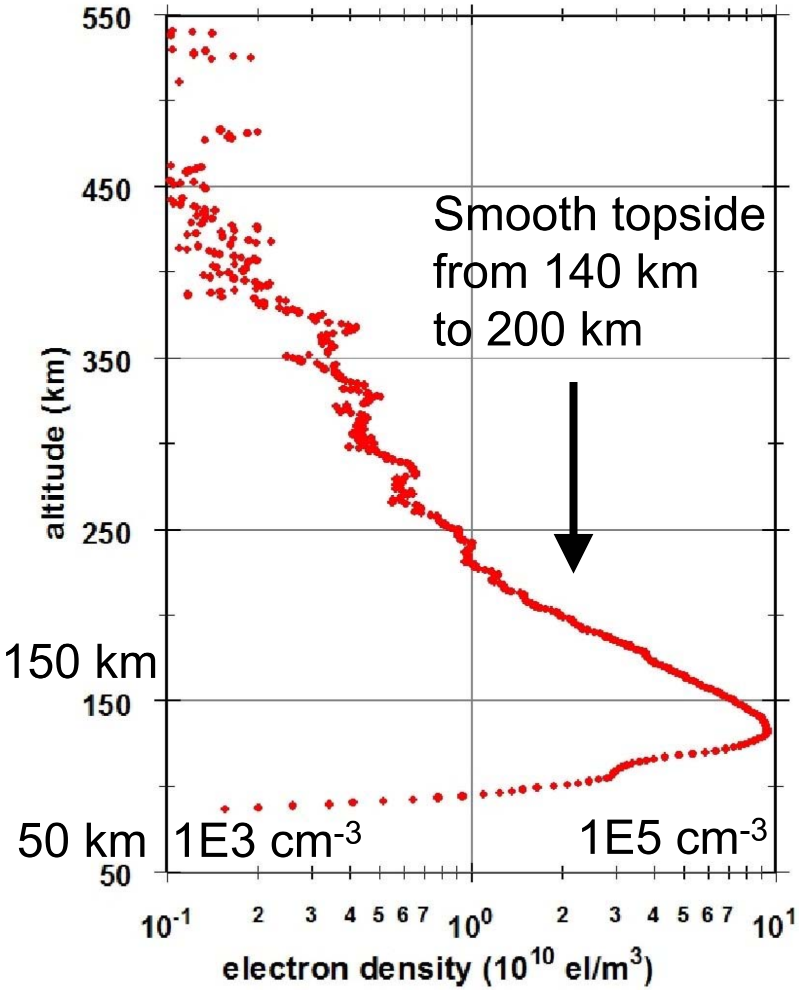


Fig 1 of Connerney et al. (2001)

Dynamics – Effects of magnetic fields



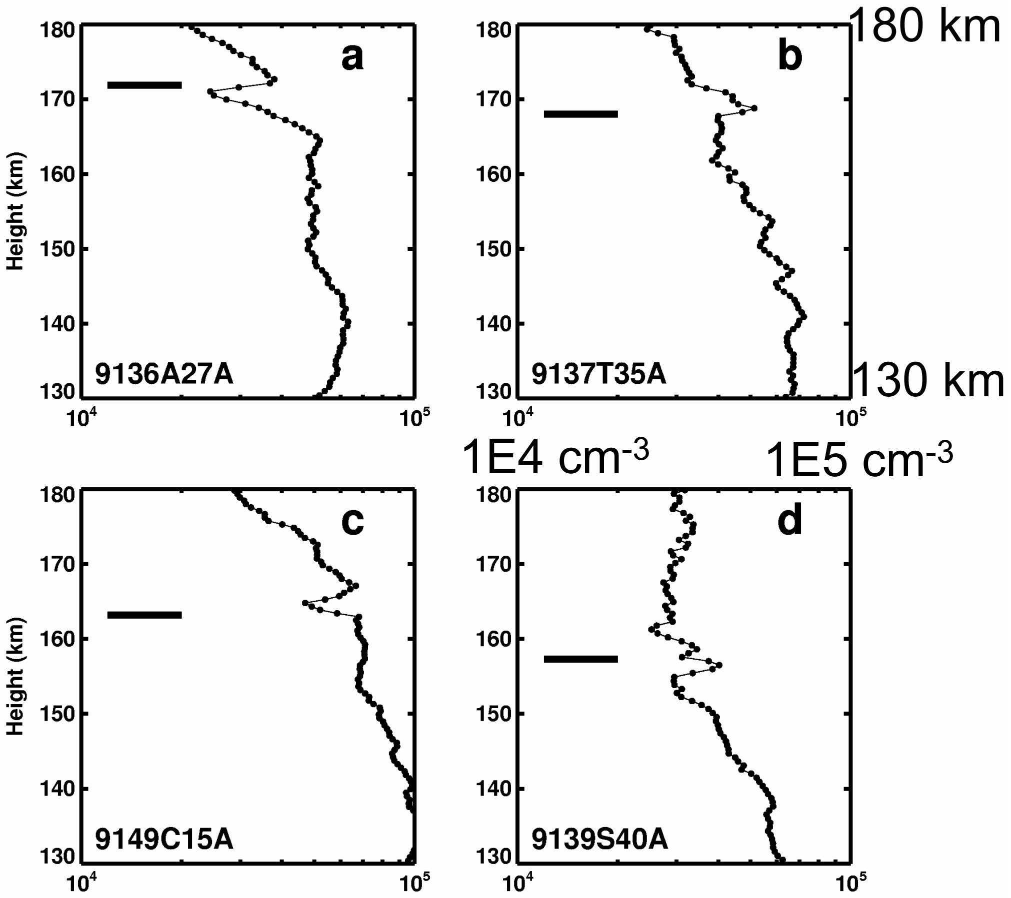
Smooth topside from 140 km to 200 km

150 km

50 km

1E3 cm^{-3}

1E5 cm^{-3}



180 km

130 km

1E4 cm^{-3}

1E5 cm^{-3}

Fig 2 of Withers et al. (2005)

Anomalous bumps or biteouts seen only over strong crustal fields

Caused by fieldlines connected to solar wind or by local plasma dynamics?

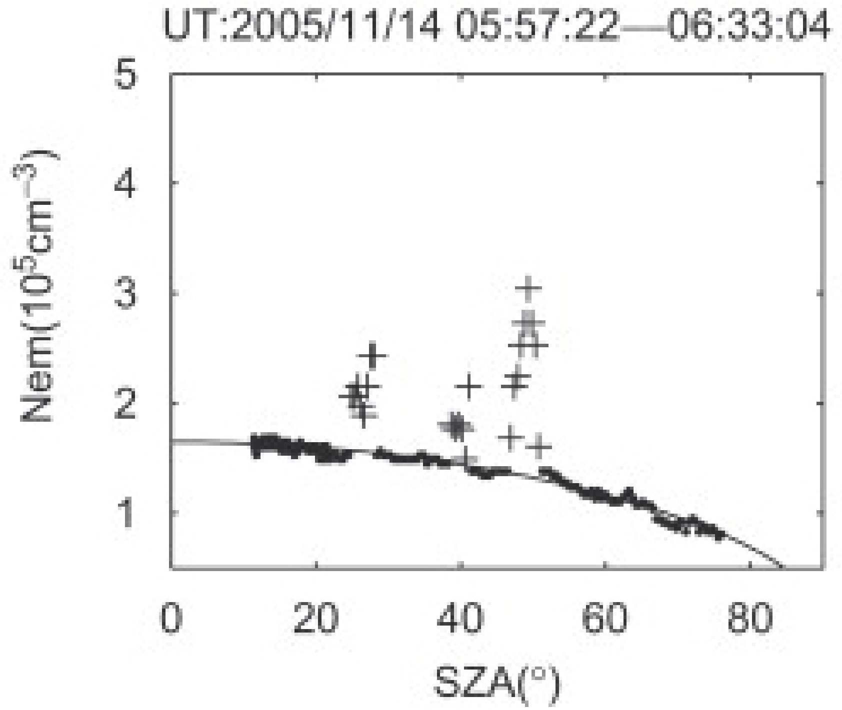


Fig 1 of Nielsen et al. (2007)

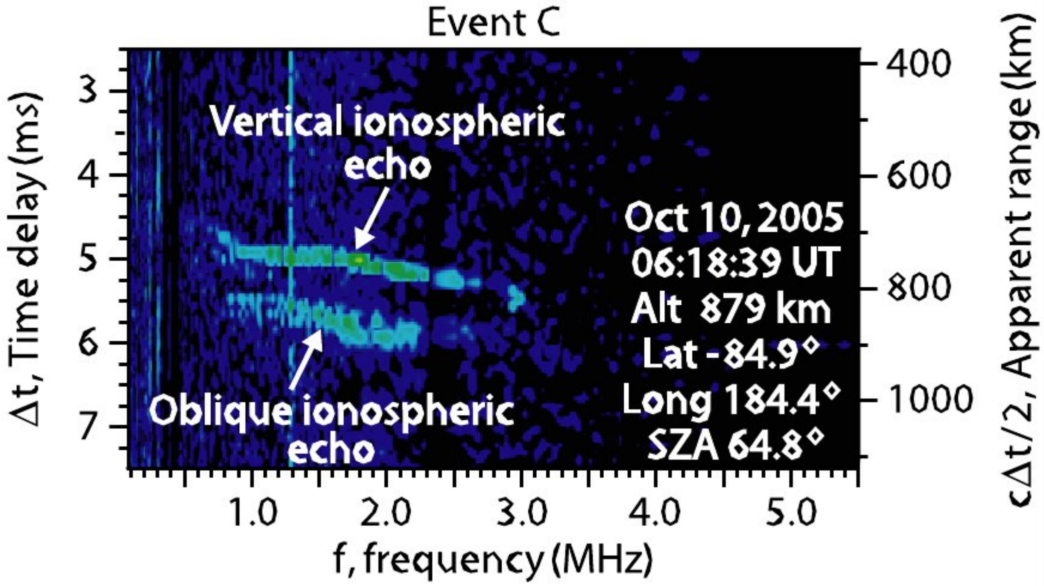
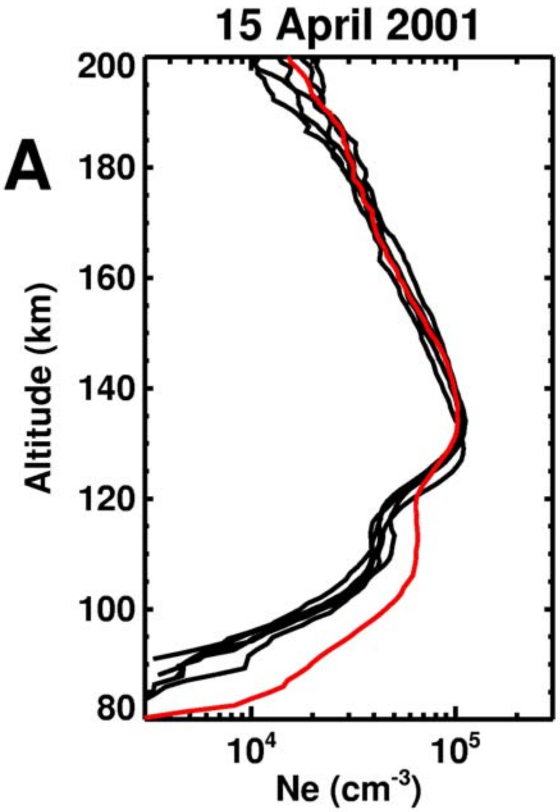


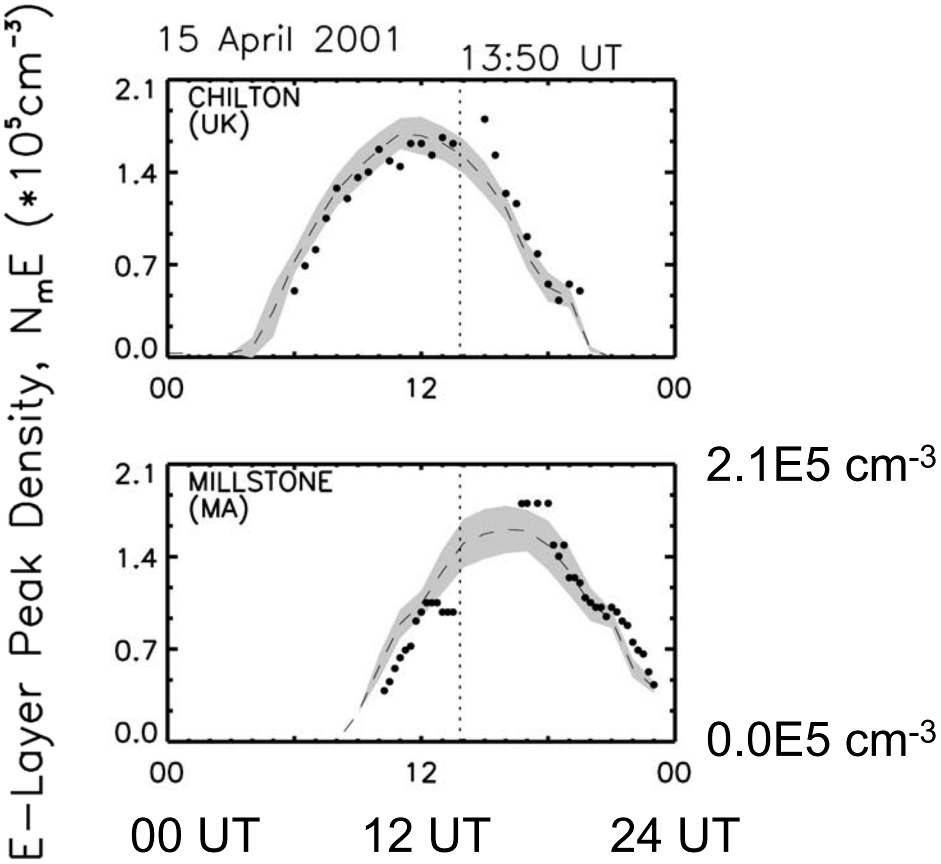
Fig 8 of Gurnett et al. (2008)

Data: Hundreds of occultation N(z) profiles, countless MARSIS ionograms
Models: Solar wind inflow, plasma motion, plasma instabilities, electrodynamics
Recent work: Discovery-mode classification of phenomena

(1) Derive N(z) over crustal fields from MARSIS ionograms
(2) Theoretical simulations of electrodynamics in wild magnetic environment
(3) Determine shapes of plasma bulges from oblique MARSIS echoes

Energetics – Effects of solar flares

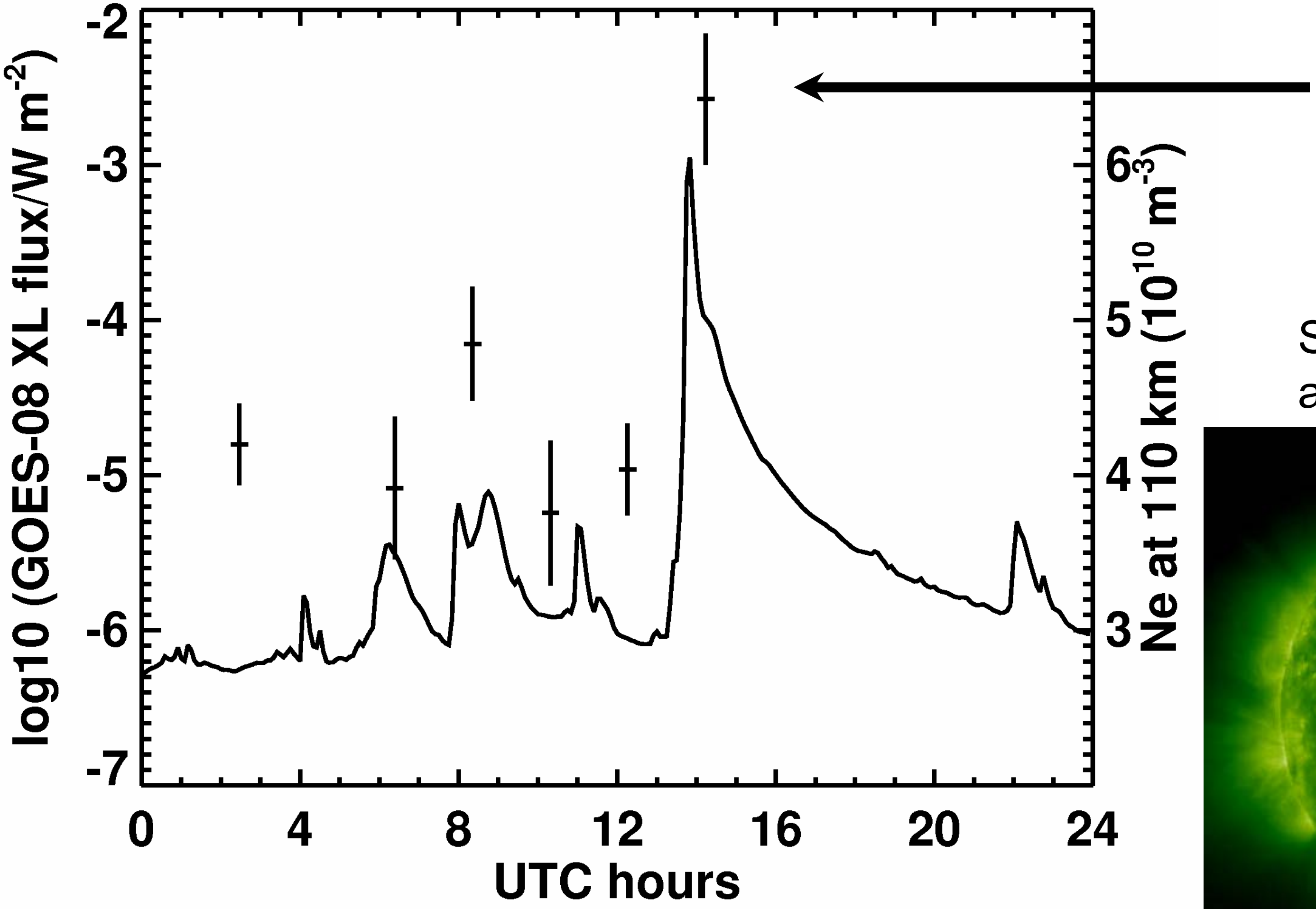




Figs 1 and 3 of Mendillo, Withers, Reinisch et al. (2006)

Simultaneous enhanced electron densities in bottomside of martian ionosphere and E-region of terrestrial ionosphere

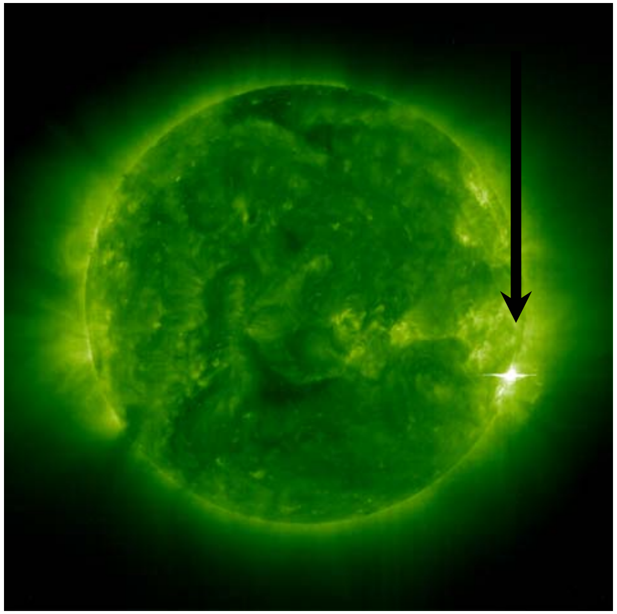
Energetics – Effects of solar flares



Electron density at 110 km for enhanced profile

X-ray flux (0.1 to 0.8 nm) measured in Earth orbit.
Flux increases by 2-3 orders of magnitude

SOHO/EIT image at 19.5 nm at flare onset



Energetics – Effects of solar flares

Radio occultations good for vertical structure, poor for temporal resolution

MARSIS poor for vertical structure, good for temporal resolution

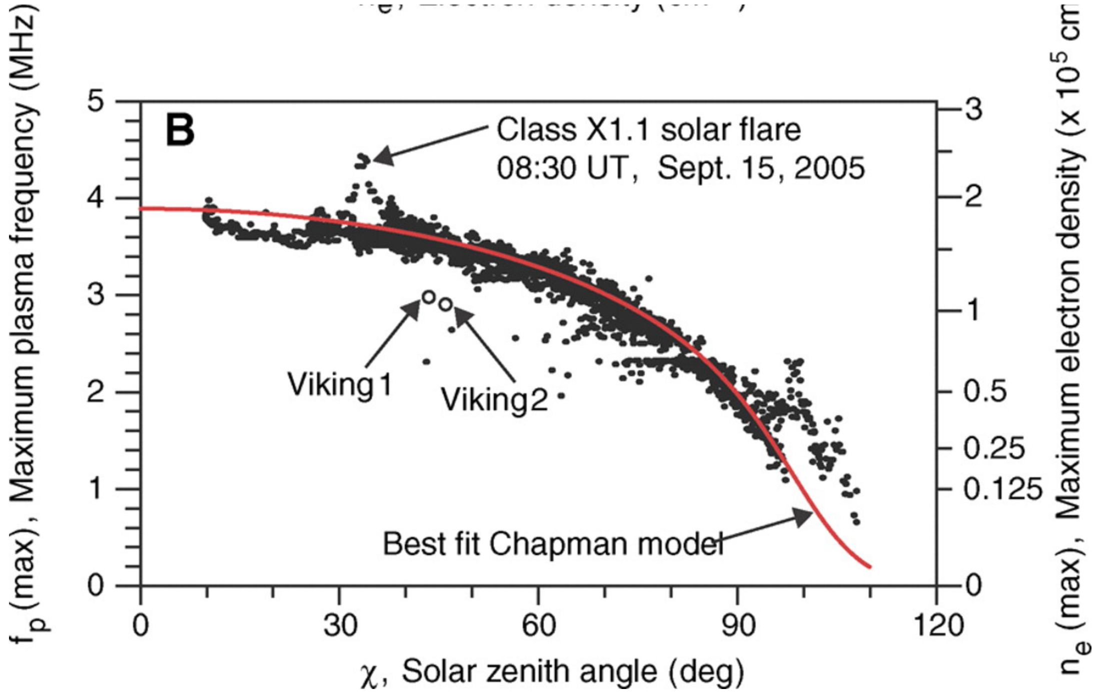


Fig 3 of Gurnett et al. (2005)

Data: Thousands of radio occultation N(z) profiles, at least 10 affected by solar flares, and countless MARSIS ionograms
Theory: Boston Univ. model ready for use with time-varying solar irradiances

(1) Detailed characterization of observations
(2) Comparative analysis of Earth and Mars observations
(3) Compare simulated and observed N(z) to optimize electron impact ionization
(4) Compare variations with time of N_m from MARSIS data and estimated solar spectrum

Future – MARSIS Data

- Vast dataset, not yet used outside instrument team
- Only ionograms archived (signal strength as function of frequency and travel time)
- Very rich dataset that will reward in-depth analysis
- Great potential for multi-instrument projects

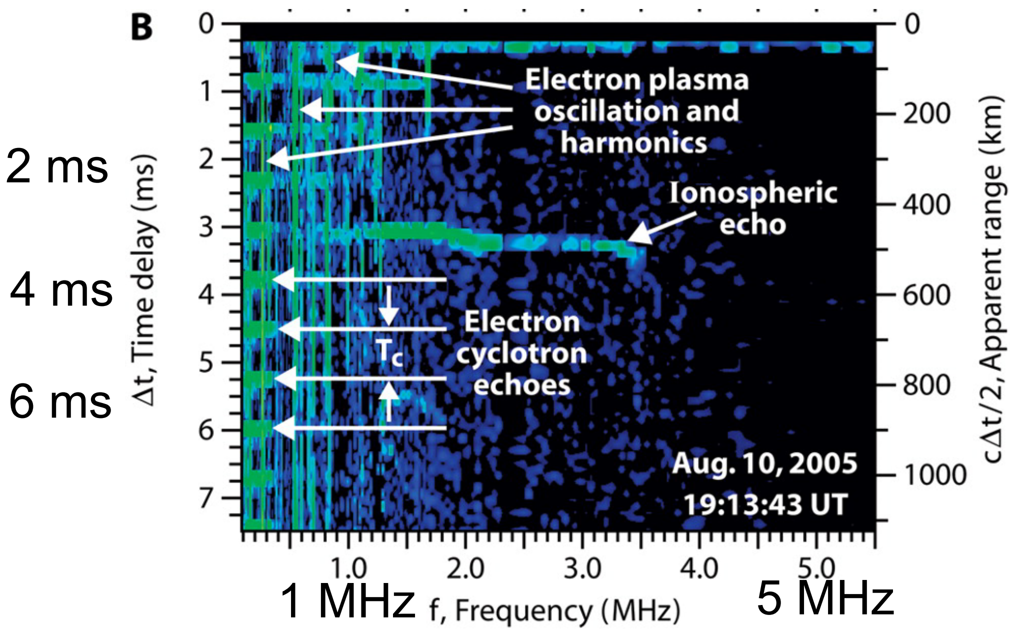


Fig 2 of Gurnett et al. (2005)

- Automatically, not manually, obtain any additional data products, such as local magnetic field, local electron density, peak electron density, attenuation in surface reflection
- Exploit large size, rapid cadence, geographic extent of dataset
- Take advantage of UML's expertise with ionosondes and IMAGE RPI instrument

Future – Beyond Mars

- Venus
  - Venus Express in operation. Carries radio occultation investigation and electron spectrometer that can identify photoelectrons
  - Venus Climate Orbiter (Japan) anticipated in 2010
- Saturn and Titan
  - Cassini in operation, passing through Titan's ionosphere periodically. Large payload, including ion/neutral mass spectrometer, radio occultation investigation, radio and plasma wave instrument (including Langmuir probe), and electron/ion spectrometer
- Comet: Rosetta (in flight, arrive 2014)
- Pluto: New Horizons (in flight, arrive 2015)
- Jupiter
  - Juno (launch 2011, arrive 2016)
  - Jupiter/Europa Orbiter (launch 2020, arrive 2025)
  - Jupiter/Ganymede Orbiter (launch 2020, arrive 2026 – if selected)
- Discovery and New Frontiers mission selections in 2010 (Venus likely)

- Compare radio occultation observations from Venus Express and Mars Express; comparative studies with Venus, Earth and Mars
- Explore relations between neutral atmosphere and ionosphere at Saturn, extend to Jupiter

Future – Instrumentation

- I have worked with data and spaceflight experiments, but not hardware
  - Team member for Venus Express, Mars Express, The Great Escape (Phase A study), Huygens
  - Involvement in Mars Science Laboratory, Mars Odyssey, Spirit, Opportunity, Beagle 2
- UMLCAR has great expertise in radio instrumentation, including spaceflight hardware
- Existing centres of excellence in planetary radio science are Iowa, JPL and Stanford
  - Iowa
    - Plasma waves and magnetospheres
    - Strong scientifically and technically with stable demographics
  - JPL
    - Radar, radio navigation and communication
    - Operational and engineering focus, part of scientific base is aging
  - Stanford
    - Radio occultations
    - About to disintegrate through retirements