The Mars Ionosphere: More than a Chapman Layer

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Images

- www.solarviews.com
- The Cosmic Perspective, Bennett et al. (book)
Aim: Present unusual or unexpected observations of the Mars ionosphere. Show that it is scientifically important to understand and explain them.

- Describe how properties of Mars relate to properties of Venus and Earth
- Describe the typical Mars atmosphere and ionosphere
- Discuss unusual ionospheric observations and their implications
Atmospheric Compositions

• Venus: 100 bar pressure
  – Mostly CO$_2$, some N$_2$
• Earth: 1 bar pressure
  – N$_2$ and O$_2$ mixture
• Mars: 0.006 bar pressure
  – Mostly CO$_2$, some N$_2$
Present-Day Venus

- Zero obliquity and eccentricity mean no seasons
- Thick atmosphere, slow rotation mean that weather at surface is same everywhere
- 740 K at surface, slow winds, no storms, no rain
- H$_2$SO$_4$ clouds at 50 km, where pressures and temperatures are similar to Earth’s surface

http://as.e.tufts.edu/cosmos/pictures/Explore_figs_8/Chapter7/Fig7_3copy.jpg

http://rst.gsfc.nasa.gov/Sect19/Ven-atmos-profile-CM.jpg
Venus upper atmosphere

- Reformation of photolysed CO$_2$ catalysed by Cl, terrestrial implications
- Lots of solar heating, but little day-night transport of energy
- Nightside upper atmosphere is very cold, 100 K, whereas dayside is 300 K
- O / CO$_2$ ratio plays a major role, more O than CO$_2$ above 150 km
- Only H is escaping today
Venus ionosphere and plasma

- Ionosphere formed by EUV photoionization of CO$_2$, but CO$_2^+$ + O $\rightarrow$ O$_2^+$ + CO
- O$_2^+$ is dominant at Chapman peak (140 km), O$^+$ dominant 40 km higher up

http://www3.imperial.ac.uk/spat/research/space_magnetometer_laboratory/spacemissionpages/venusexpresshomepage/science

- Transport important near O$_2^+$/O$^+$ transition and above
- Magnetic fields due to draping of solar wind around planet
- Nightside ionosphere and magnetic fields are complex and variable, affected by plasma transport across terminator
Earth Upper Atmosphere

• O is more abundant than O$_2$ above 100 km and more abundant than N$_2$ above 200 km
• T > 800 K above 200 km, much hotter than Venus or Mars. These atmospheres are cooler because CO$_2$ is very effective at radiating heat, whereas Earth needs higher temperature gradients to conduct heat downwards
• Heating at poles due to magnetic fields guiding solar wind
• Only H is escaping today

[Graph of Concentration of Atomic Oxygen in the Thermosphere (45° N, Equinox)]

http://www.meted.ucar.edu/hao/aurora/images/o_concentration.jpg
• $O_2^+$ and $NO^+$ dominant at 100 km, where EUV absorption peaks
• $O^+$ dominant at 300 km (overall peak), where transport plays major role
• Changes from $O_2^+/NO^+$ to $O^+$ and from $N_2$ to $O$ make things complex
• Magnetic fields affect plasma transport, especially at equator and near poles
Present-Day Mars

- 1/3 of atmosphere freezes onto winter polar cap
- Global dust storms
- Large day/night temperature differences
- Surface pressure too low for liquid water to be stable, but ongoing gully formation may require liquid water
- Saturated with H$_2$O, both H$_2$O and CO$_2$ clouds are common
Mars Upper Atmosphere

- Species like OH catalyse reformation of photolysed CO$_2$
- Rapid rotation keeps night/day temperature difference smaller than for Venus
- O / CO$_2$ ratio is again important, more O than CO$_2$ above 200 km
- H, H$_2$, N, and O are escaping today

Bougher et al., 2002

http://data.engin.umich.edu/tgcm_planets_archive/mseasons/equinox/gif/eqtequmax.gif
Mars Ionosphere

- Ionosphere formed by EUV photoionization of CO$_2$
- CO$_2^+$ + O $\rightarrow$ O$_2^+$ + CO

- Transport only important above 180 km, 50 km above peak, so profile is very Chapman-like
- O$_2^+$ dominant at all altitudes?
- Transport not well-understood
- Effects of magnetic fields not well-understood

Chamberlain and Hunten, 1987
Summary

• Venus/Mars have same CO$_2$ compositions, but lots of differences
• Venus/Mars have similar O$_2^+$ photochemical ionospheres, but transport processes will be different
• Effects of Mars magnetic fields potentially important
Mars Ionosphere

- What do we know?
- Neutral composition – Viking
- Ion composition – Viking
- Electron temperatures – Viking
- Neutral temperatures – Aerobraking data
- Neutral dynamics?
- Plasma dynamics?
- Electron density profiles – Many missions

Kliore, 1992
Many photons, no neutrals to absorb them, so no ions produced

Some photons, some neutrals Ions produced

No photons, many neutrals No ions produced

Neutral atmosphere is CO$_2$, with constant scale height

EUV photons create CO$_2^+$ + e (production)

CO$_2^+$ + O -> O$_2^+$ + CO (chemistry, fast)

O$_2^+$ + e -> O + O (loss, slower, minutes)

$P = \alpha N_e^2$
Some Complications

- Typical electron density profile from MGS radio science experiment

- Neutral chemistry – not just CO₂ absorbing photons and CO₂⁺ + O is not only reaction

- X-rays – two competing production functions and multiple ion-electron pairs per photon
Vertical Transport

- Ions move
  - Gravity
  - Pressure gradients
  - E, B fields
  - Drag from winds
- E maintains neutrality
- Topside
  - Large pressure gradients drive plasma upwards
- Bottomside
  - High neutral densities prevent motion of plasma despite pressure gradients

Martinis et al., 2003
Transport is Complicated

- Models depend on ion and neutral composition, but only Ne(z) known
- Neutral winds not known
- Three-dimensional flow at terminator
- Magnetic fields influence plasma flow
- Basic ionosphere photochemistry is understood, but basic transport is not
Unusual Ionospheric Observations

• Unusual -> New science, new discoveries, new interactions
• Unexpected phenomena are powerful tools for testing existing models and developing new models
• A common terrestrial process may behave differently in Mars conditions
• Moving towards more complete understanding
  – Solar flux
  – Meteors
  – Anomalous profiles over magnetic fields
Nielsen et al., 2006

Variation of Nemax with solar rotation period
MARSIS data
Gurnett et al., 2005

Nielsen et al., 2006
Ionospheric profiles during solar flares

Enhanced electron density at low altitudes

Relative increase in density increases as altitude decreases
Solar Flux

- How many ion-electron pairs per X-ray?
- Separate ionosphere/neutral atmosphere responses to solar cycle with flares
- Are current neutral atmosphere models able to reproduce detailed response to flare? Or is response sensitive to neutral composition?
Low Altitude Ionospheric Layer

Patzold et al., 2005
Meteors at Mars

Typical altitude is 80 – 90 km
Same as models

Typical peak electron density is $1 – 2 \times 10^4 \text{ m}^{-3}$
Same as models

Typical thickness is 10 – 20 km
Narrower than models predict
Suggests a large eddy diffusion coefficient
Seasonal Trends

One meteor layer every 200 profiles

Meteor layers are not randomly distributed in Ls

Concentrations at Ls~190 (Asteroid 2102 Tantalus?) and at Ls~210

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Meteors

• Why is meteor layer not always present?
• What comets cause these meteors?
• Why are meteor layer observations not the same in different Mars years?
• Can we model these accurately?

Important processes for meteors have only small role for rest of ionosphere
Some MGS profiles show biteouts or bumps

Very short vertical lengthscale

Caution: Data from spacecraft to Earth radio occultation, not from ionosonde

Only found in regions where the magnetic field is strong
Mars magnetic field is not global dipole. Sources are old crustal rocks.

MGS data to the left
Very restricted latitude range

Shaded regions have $B>100$ nT at 150 km

Mariner 9 data from 1971-2 on right
Same biteouts seen in these data
Unusual MARSIS reflections also seen over strong fields, often vertical fields

Mars magnetism is very complicated
Magnetism

• What plasma instabilities occur on Mars?
• How is plasma transported in non-magnetic regions?
• In strongly-magnetized regions?
• Does the small size of magnetic field regions lead to processes not seen on Earth?
Conclusions

• Mars ionosphere is an important part of the Mars system.
  – It is part of the boundary between the atmosphere and space. Important for escape.
• A natural laboratory to test ideas developed in Earth-centred studies
• Many poorly-understood phenomena are observed
  – They need to be better interpreted and simulated