Comparative meteor science – The effects of meteoroids on planetary atmospheres and ionospheres

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Zia B+C, Santa Fe, NM
2009 CEDAR Meeting
Motivation

• Recent ionospheric observations at Venus and Mars show low-altitude plasma layers that appear analogous to terrestrial metal ion layers produced by meteoroid ablation.

• How can Earth help us understand these extraterrestrial examples?
• How can Venus and Mars challenge and validate Earth-centric theory and models?
Goals of workshop

• To present observations and simulations from Venus and Mars to CEDAR community
• To outline major processes important for terrestrial metal ion layers
• To consider how differences in planetary environment might affect processes that control metal ion layers and hence lead to differences in properties of metal ion layers from planet to planet
• To identify important scientific questions
• To discuss how these questions can be answered
Agenda

- Meers Oppenheim: Introduction (1930-1935)
- Paul Withers: Observations of metal ion layers across the solar system (1935-1950)
- Joe Grebowsky: Simulations of metal ion layers across the solar system (1950-2005)
- John Mathews: Metal ions in sporadic E layers, with some speculation about analogous phenomena on other planets (2020-2035)
- Dave Hysell: The electrodynamics of metal ions in sporadic E layers, with some speculation about analogous phenomena on other planets (2035-2050)
- Michael Mendillo: Summary (2050-2100)
- Margin, time available for general discussion and spontaneous presentations from the audience (2100-2130)
Observations of metal ion layers across the solar system

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Metal ions on Earth

Figure 8.3 of Grebowsky and Aikin (2002)
Sporadic E on Earth

Sporadic E = Dense layers of plasma at E-region altitudes that aren’t related to normal E layer
Plasma persists into night, requires long-lived ions – atomic metal ions
Formed by wind shear in strong, inclined magnetic field

Figure 2a of Mathews et al. (1997)  Ionosonde data from Arecibo
Extraterrestrial observations

• No ion composition data at relevant altitudes
  – No mass spectrometer data
• No surface-based ionosondes or radars making measurements frequently
• Instead, vertical profiles of electron density from radio occultation experiments
  – Thousands at Mars, hundreds at Venus, only a handful at all other planets
Radio occultations

1. Signal is Doppler-shifted due to spacecraft motion
2. Refraction of signal in planetary atmosphere modifies this Doppler shift
3. Measure received frequency as function of time (or tangent height of signal)
4. Subtract all known causes of frequency shift to obtain residual frequency shift
5. Unique solution for refractive index as function of altitude
6. Obtain electron density profile from refractive index
Workhorse of ionospheric studies

- **Venus**
  - Mariner 5, Mariner 10, Pioneer Venus, Magellan, Venera 9, 10, 15, 16
- **Mars**
  - Mariner 4, 6, 7, 9, Mars 2, 4, 5, 6, Viking 1, 2, Mars Global Surveyor, Mars Express
- **Jupiter**
  - Pioneer 10, 11, Voyager 1, 2, Galileo
- **Saturn**
  - Pioneer 11, Voyager 1, 2, Cassini
- **Uranus and Neptune**
  - Voyager 1, 2
- **Pluto**
  - New Horizons (in flight to destination)
- **Comets**
  - Giotto, Rosetta (in flight to destination)
## Characteristics of radio occultations

### Strengths
- Uncertainties \( \sim 10^3 \text{ cm}^{-3} \)
- Span all altitudes
- Vertical resolution \( \sim 1 \text{ km} \)
- Observations not limited to spacecraft position or nadir
- Minimal hardware requirements
- Insensitive to quirks of individual instrument

### Weaknesses
- No composition data
- Spherical symmetry must be assumed
- Restricted by orbit geometry to locations close to dawn/dusk
- Maximum of two profiles per orbit/flyby
Outer Solar System

Narrow plasma layers often seen at low altitudes

Poorly understood

Possibly:
- Metal ion layers from meteoroids
- Heavy ion layers from debris of rings or moons
- “Normal” ions layered by gravity waves
- Unreliable data

Figure 4 of Hinson et al., 1998

Figure 8 of Lindal, 1992

Figure 3 of Nagy et al., 2006

Figure 7 of Lindal et al., 1987
Metal ion layer on Venus

Candidate layers seen in 18 Venus Express profiles from SZA of 60° to 90°

Some double layers seen

Inferred to be metal ions, but not verified by ion composition data
Three more examples from Venus

Figure 2 of Pätzold et al. (2009)
Zoom in on three examples

Figure 2 of Pätzold et al. (2009)
Metal ion layer on Mars

Candidate layers seen in 71 Mars Global Surveyor profiles and 75 Mars Express profiles from SZA of 50° to 90°

Some double layers seen

Inferred to be metal ions, but not verified by ion composition data

Figure 4 of Withers et al. (2008)

Withers et al., in prep
Physical characteristics of metal ion layers from Mars

- Height of 87-97 km
- Width of 5-15 km
- Electron densities of ~$10^4$ cm$^{-3}$
- Height, width, electron density of metal ion layers are positively correlated

- These characteristics are not correlated with solar zenith angle, neutral scale height, solar flux

- This is unlike the rest of the ionosphere
## Comparison of observations for Venus, Earth and Mars

<table>
<thead>
<tr>
<th>Planet</th>
<th>Layering</th>
<th>N (cm(^{-3}))</th>
<th>Height (km)</th>
<th>Width (km)</th>
<th>Pressure (Pa)</th>
<th>Density (kg m(^{-3}))</th>
<th>Scale height (km)</th>
<th>Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>Mostly single, some double (radio occ)</td>
<td>2E4</td>
<td>109 – 117</td>
<td>5 – 10</td>
<td>0.1</td>
<td>4E-6</td>
<td>4</td>
<td>190</td>
</tr>
<tr>
<td>Earth</td>
<td>Many (rockets), single (Sporadic E)</td>
<td>1E3 (XX)</td>
<td>95 – 100</td>
<td>~2 (rockets)</td>
<td>0.03</td>
<td>5E-7</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>Mars</td>
<td>Mostly single, some double (radio occ)</td>
<td>1E4</td>
<td>87 – 97</td>
<td>5 – 15</td>
<td>0.01</td>
<td>5E-7</td>
<td>7</td>
<td>140</td>
</tr>
</tbody>
</table>

Venus – Pioneer Venus Sounder probe data at 112 km from Seiff et al. (1980)

Earth – MSISE-90 model at 100 km for mean solar activities, averaged over local time, season, latitude
Taken from www.spnvis.oma.be/spnvis/ecss/ecss07/ecss07.html

Mars – Viking Lander 1 data at 92 km from Seiff and Kirk (1977)
Planetary properties that may affect metal ion layers

• Chemical composition of atmosphere
  – $O_2/N_2$ for Earth, $CO_2$ for Venus and Mars

• Magnetic field
  – Strong and dipolar at Earth, non-existent at Venus, spatially variable crustal fields at Mars

• Rotation rate (duration of nighttime darkness)
  – 1 day for Earth and Mars, hundreds of days for Venus

• Atmospheric dynamics
  – Tides and waves important at Earth, subsolar to anti-solar flow on Venus, possibly a combination at Mars

• Distance from Sun
  – Meteoroid influx will vary from planet to planet
Conclusions

• Plasma layers that appear to be metal ion layers derived from meteoroids have been seen on Venus, Earth and Mars
• Present in ~10% of dayside observations from Venus and Mars (N>10^3 cm^{-3})
• Wind shear in strong magnetic field, which is critical on Earth, will be less important on Venus and Mars

• Don’t forget about the ultimate source – meteoroids
• The meteoroid environment at Venus or Mars will not be the same as Earth
  – Relative importance of shower and sporadic meteoroids
  – Seasonal variations in shower and sporadic fluxes
Backup
Comets and meteor showers

Composite image of comet Wild 2 taken by Stardust

Comet West (1975, San Diego)


(Left) Stardust, NASA
(Centre) http://www.solarviews.com/browse/comet/west2.jpg
(Right) Figure 1 of Christou et al. (2007)
Effects of meteor showers

• Predicted, but not yet definitively detected, on Earth
  – Too many other causes of variability

• If robust repeatable annual variations seen on Venus or Mars, then must discriminate between possible causes
  – seasonal variations in wind shear in magnetic field
  – seasonal variations in sporadic meteoroids
  – meteor showers (insignificant source of mass on Earth)

• The first possibility should be easy to exclude at Venus, which has no magnetic fields and no seasons
• Discrimination between variations in meteoroid influx at Venus or Mars due to changes in showers or sporadics is harder
  – Timescales for changes should be shorter for showers
  – If enhanced metal ion layers seen during expected meteor shower, meteor shower is most likely cause
Observed distribution of sporadic meteors

Figure 8 of Chau et al. (2007)
Schematic distribution of sporadic meteors
Meteors beyond Earth

• Sporadic meteoroids seen at Earth do not have uniform distribution of radiants
• Wiegert et al. (2009) showed that sporadic meteoroid distribution at Earth is dominated by debris from Encke and Tempel-Tuttle

• Do sporadic meteoroids at other planets have a uniform distribution of radiants?
• Are sporadic meteoroids at other planets predominantly produced by a small number of comets? Which comets?
• How does ratio of sporadic meteoroid mass flux to shower meteoroid mass flux vary from planet to planet?