Current Status of Shock Layer Radiation Studies for Planetary Probes

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Basic Radiation Terminology

• **Radiative Heat Flux** is equal to the:
  - **Irradiance**, which is the integral of the:
    - **Radiance**, which is the integral of the:
      • **Spectral Radiance**, which is the integral of the:
      • **Volumetric Spectral Radiance** kinda
How to validate the radiation model

• Stagnation streamline is a 1-D flow:

\[ h = h_0 + \frac{v_s^2}{2} \]
\[ T = T_s \]
\[ \rho = \rho_s \]

• Shock tube is a 1D flow:

\[ v = v_s \]
\[ \rho = \rho_\infty \]
\[ T = T_\infty \]
\[ h = h_0 \]
Planetary Atmospheres tested in EAST

This Talk

CO₂/N₂/(Ar)
Test 47
Test 50
Test 52
Test 57
Test 59

CO₂/N₂
Test 49

N₂/O₂/(Ar)
Test 47
Test 51
Test 53
Test 54
Test 55
Test 58

H₂/He/(CH₄)
Test 56

Titan
N₂/CH₄
Test 61

Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
Kuiper Belt Objects
Comets
Makemake
Main feature of Titan Radiation is CN
- Comes from $\text{CH}_4 + \text{N}_2$
What is interesting about Titan?

- Until recently, the models were thought to be very conservative
- Newer tests showed models to be close
- Discrepancy was shown to be due partly to contamination (air leaks) in old test data, and some factors still unknown
Main features of Venus Radiation is Atomic Carbon
- Atomic lines
- C⁺ + e⁻ recombination continuum
- At lower velocity, molecular CO and CN radiation contribute
What is interesting about Venus?

- VUV continuum radiation was underpredicted (v13)
- Correcting NEQAIR database (v14) led to overprediction
- An error in the database interpretation routine (corrected v15) eliminated the overprediction
  - Model is not conservative
- Additional database data (Quantum Mechanics Calculation) required
• Most of the data is spectrometer noise floor
  - Radiance nearly insignificant
  - Prediction is small in magnitude, but significantly over measurement
Saturn

EAST Shot 56/22: 11% He (molar) in H$_2$, 27.66 km/s, 6.0 $\times$ 10$^{-5}$ kg/m$^3$ (Prabhu)

- Main feature of Saturn Radiation is atomic H
  - Molecular H in non-equilibrium
What is interesting about Saturn Radiation?

- Ionization in Saturn Entry is very slow
  - Does not come to equilibrium
  - Temperature is elevated
- Boltzmann significantly overpredicts non-equilibrium (conservative)
- Trace amount (0.5%) of CH₄ may change ionization rate?
Summary/Recommendations

- EAST Facility provides a way to test radiative heating models
  - Has been used for building margin policy, revising best practices

- Discussed general features and questions about radiation for Titan, Venus and Saturn probes

- Approximate Heating Magnitude (1m sphere)/Confidence:

<table>
<thead>
<tr>
<th></th>
<th>$q_{\text{Rad}}$ (W/cm$^2$)</th>
<th>Fraction of Total Heating</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titan</td>
<td>10</td>
<td>3%</td>
<td>± 30%</td>
</tr>
<tr>
<td>Venus</td>
<td>5800</td>
<td>40%</td>
<td>± 30%</td>
</tr>
<tr>
<td>Uranus</td>
<td>5</td>
<td>0.5%</td>
<td>Conservative (Boltzmann)</td>
</tr>
<tr>
<td>Saturn</td>
<td>15</td>
<td>0.5%</td>
<td>Conservative (Boltzmann)</td>
</tr>
</tbody>
</table>

*Note: Significant dependence on probe size and velocity*

- This talk has not addressed backshell radiation!
  - Backshell radiation is always (?) less than forebody radiation
  - But it often exceeds convection (e.g. Titan, Mars)
  - May have different mechanisms than forebody heating
Backup
Radiative Heat Flux is equal to the:
- Irradiance is the integral (over solid angle) of the:
  - Radiance is the integral (over wavelength) of the:
    - Spectral Radiance is the integral (over distance) of the:
      - Radiative Transport Equation, which to first order is the
        - Volumetric Spectral Radiance
How we model radiation

• Flowfield solution gets a map of species number densities, temperatures at every grid point
• Extract a “line of sight” (LOS) through the flow field to the body
• Pass the LOS to NEQAIR
• NEQAIR solves
  - Non-Boltzmann Equation (density of excited states)
  - Atomic and Molecular emission and absorption coefficients (Volumetric Radiance)
  - Radiative transport equation (Radiance)
  - Tangent Slab or Full Angular Integration (Irradiance)
  - Integrate over wavelength