Broadband submillimeter measurements of planetary brightness temperatures

Juan R. Pardo, Departamento de Astrofísica Molecular e Infraroja, CSIC (Spain)
Gene Serabyn, California Institute of Technology (USA)

OUTLINE

- Goals of experiment.
- Instrument setup.
- Calibration procedures.
- Data acquisition and reduction.
- Off line data analysis.
- Main results.
- Recent improvements & results.
- Implications for Herschel.
Goals of the experiment

- Measurement of broadband absolute brightness temperature for the giant planets. Get around the problem of scattered meas.
- Measurement of broad lines from the main constituents of the giant planets.
- Search for key species in Venus.
- Establish data base for calibration purposes.

Science Issues

- Compositional differentes.
- Temperature structure.
- Vertical transport rates.
- Photolysis cycles.
- $\text{NH}_3$ lineshape, collision induced absorption...

Frequency range

- 0.2-1.1 THz; 7-33 cm$^{-1}$/ Resl. up to 5000
- Longward of ISO, overlap with Herschel.

Observational requirements

- Broadband requires FTS.
- Accurate atmospheric correction.
- Accurate beam coupling/efficiency corrections.
- Accurate flux calibration.
Experimental setup

Fourier Transform Spectrometer at the Caltech Submillimeter Observatory

- $^3$He cooled bolometer.
- 46 cm moving arm (200 MHz maximum resolution)
- Mounted on the Cassegrain focus of telescope.
- FOV of Winston Cones: 10", 20" & 30".
- Frequency filters to cover different atmospheric windows.
- Mounted 2-3 times per year for dedicated planetary & atmospheric measurements.
The instrument is simple but currently provides the best broadband (from tens to hundreds of GHz) submillimeter data.

RESULTS OBTAINED IN THE PAST
First detection of PH$_3$ in Saturn

FTS: Available filters

- **CO**: Doble Fabry-Perot designed to explore CO freqs.
- **550 GHz (low pass)**: to explore the low frequencies.
- **650 GHz**: To explore 450 µm window.
- **850 GHz**: To explore 350 µm.
- **750 GHz**: To simultaneously explore the last two.
- **1.1 THz (low pass)**: To explore 300-1100 GHz.
- **1.6 THz (low pass)**: To explore 300-1600 GHz.
Calibration

We have to deal with two problems:

Coupling and efficiency terms

The Atmosphere

These two problems combined make extremely difficult to compare planetary measurements obtained in narrow bands with different instruments at different dates.
Calibration: The atmosphere is our measurement, where:

\[ m(\nu) = \frac{V_{sou} - V_{sky}}{V_{ground} - V_{sky}} \]

- \( V_{sou} = G(\nu) \left[ \eta_{sou}(\nu) P_{sou}(\nu) + (1 - \eta_{sou}(\nu)) P_{bgr}(\nu) \right] e^{-\tau_t(\nu)} + \]
  \[ + \quad G(\nu) \left[ \eta_{sky}(\nu) P_{sky}(\nu) + (1 - \eta_{sky}) P_{hot} \right] \]

- \( V_{sky} = G(\nu) \left\{ \eta_{sky}(\nu) \left[ P_{sky}(\nu) + P_{bgr}(\nu)e^{-\tau_t(\nu)} \right] + (1 - \eta_{sky}) P_{hot} \right\} \]

- \( V_{ground} = G(\nu) \eta_{hot}(\nu) P_{hot}(\nu); \quad \eta_{hot} = 1.0. \]

\( P: \) Spectra emitted by the different sources, \( h: \) Couplings to these sources, \( G: \) Optical-electrical gain factor

\[ m(\nu) = \frac{[\eta_{sou}(\nu) P_{sou}(\nu) + (1 - \eta_{sou}(\nu) - \eta_{sky}(\nu)) P_{bgr}(\nu)] e^{-\tau_t(\nu)}}{\eta_{sky} [P_{hot}(\nu) - P_{sky}(\nu) + P_{bgr}(\nu)e^{-\tau_t(\nu)}]} \]

We want to extract: \( T_{EBB,sou}(\nu) \)
...after rearranging the equation

\[
m(\nu) = \frac{\eta_{\text{sou}}(\nu)}{\eta_{\text{sky}}(\nu)} \frac{e^{-\tau_t} \exp(h\nu/KT_{EBB,sou}) - 1}{1 - \exp(h\nu/KT_{EBB,sou}) - 1}
\]

Two possibilities:

- \(T_e(\tau_t,n) = T_{\text{hot}}\) (standard CSO \(T_A^*\) calibration)

  \[T_{PL,A}^* = m(\nu)(h\nu/k)[\exp(h\nu/kT_{\text{hot}})-1]^{-1} = \]

  \[(\eta_{\text{sou}}/\eta_{\text{sky}}) (h\nu/k)[\exp(h\nu/kT_{\text{hot}})-1]^{-1}\]

  Essentially TEBB,sou except for coupling terms

- \(T_e(\tau_t,n) = T_{\text{hot}} - LH f(\tau_t)\)

\[
L: \text{Tropospheric lapse rate} \quad 5.6 \text{ K(km)}
\]

\[
H: \text{Water vapor scale height} \quad 2.0 \text{ km}
\]

\[
g(\tau_t,\nu) = \left(1 + \frac{LH f(\tau_t)}{T_{\text{hot}}} \left(1 - \exp(-h\nu/KT_{\text{hot}}) \right) (e^{\tau_t} - 1) \right)
\]

\[
T_{PL,A}^{**} = T_{PL,A}^* g(\nu) = (\eta_{\text{sou}}/\eta_{\text{sky}}) (h\nu/k)[\exp(h\nu/kT_{\text{hot}})-1]^{-1} g(\nu)
\]

PRIMARY CALIBRATION
OBJECT: THE MOON

• Coupling and efficiency loses are not an issue on the Moon.

Requirement:
• Full Moon.

Problem:
• Standard calibration scheme not accurate for high $\tau$ due to vertical temperature gradient.

We need:
• $\tau$-dependent correction scheme (it can be derived)
Application: Total Lunar eclipse of July 16th, 2000

Expected behavior: Fastest temperature drop at shortest wavelengths due to less penetration.

Since we deal with a frequency range of $\sim 700$ GHz, the antenna HPBW changes from about 30" to 8".
The error beam, related to the dish rms is responsible for an efficiency drop as ν increases.
Beam pattern + Beam efficiency net effect

![Graph showing the net beam coupling vs. frequency for different disk sizes and dish rms values.]

- **Y-axis**: Net beam coupling
- **X-axis**: Frequency (GHz)
- **Curves**: Different line colors represent different disk sizes (10", 20") and dish rms values (20, 30, 40 μm).

The graph illustrates how the net beam coupling changes with frequency for various disk sizes and dish conditions.
Effect evaluated on Mars

FTS: Main Beam Coupling and Error Pattern Parameters

Best fit:
dish rms = 32.5 μm
HPBW (230 GHz) = 29"

Mars Temperature from Rudy's Model
...then, predictions are made for Jupiter and Saturn for March'01.
March ´01

Raw data (interferograms)

Raw Planetary spectra

With atmospheric correction

With Instrumental correction

FTS: Planetary Calibration

Saturn

Jupiter

Bolometer Output (V)

Sample #

(10 μm)

FT

$T_a$ (K)

$T_B$ (K)

Beam model * 145 K

Beam model * 185 K

Disk rms: 29 μm

Beam$_{360}$: 32.5°

$PH_3$

1–0

2–1

3–2

Correction fails here because model does not reproduce error pattern for Jupiter size correctly

Frequency (GHz)
Final calibration of March '01

![Graph showing temperature vs. frequency with markers for Jupiter, Saturn, Moon, and PH$_3$.](image)
Comparison to a model: NH3 wing detected?
Recent progress: Best Jupiter Spectrum obtained a year ago

Mauna Kea, January 2003
Venus results 450 μm window (January 2003)
The result needs confirmation
Venus: Possible detection of HCl

2003
Conclusions

- Calibration steps understood and implemented.
- Reasonably good results on Jupiter for 330-500 GHz. New data for 300-1080 GHz of very good quality will be analyzed soon.
- Good results for Saturn for 330-920 GHz.
- Preliminary results on Uranus (200-300 GHz)
- Interesting results on HCl in Venus (626 GHz)

Future work

- Analysis of recent results.  Manpower needed
- Comparison with models.
- Solve calibration problems seen in Jupiter at high frequencies.
- Further observations at the higher frequency end (near 1 THz).

Implications for Herschel

- Jupiter and Saturn are potential calibration references in the submillimeter; where calibration sources are scarce.
- Our results have uncertainties around 10-15 % in the ranges specified for Jupiter and Saturn.
- Going down to 5 % will require a tremendous amount of work. May not be feasible.