Radio observations of Solar System objects

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+ inputs from R. Moreno and E. Lellouch

IRAM Summer school 2015
I Introduction

Which targets, what science

II Physical processes:

II.1 Molecular lines: excitation processes,
II.2 Radiative transfer, line shapes
II.3 Continuum emission

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Tracking moving targets, observation modes, when to observe
Planets as continuum calibrators

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   Giant planets, Venus, Mars -> composition, winds
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   Pluto, Io,...: composition
IV.3 Cometary atmospheres
   Physical studies
   Molecular taxonomy, survey, Isotopic ratios
I. Introduction

Observing solar system targets in the mm to submm range

Which targets can be observed?

Why observing them at this wavelength?
Telluric planets

MERCURY

- $r_h = 0.4$ AU
- $\phi = 5-12''$
- No atmosphere
- Phase effect
- $T_{surf} = 150-600$ K

VENUS

- $r_h = 0.7$ AU
- $\phi = 10-62''$
- Thick atmosphere: 95 bars
- $CO_2$ (95%)
- $CO$, $SO$, $SO_2$, $H_2O$, $H_2SO_4$
- $T_{surf} = 730$ K

EARTH

- $r_h = 1$ AU
- $\phi = 15-60''$
- Atmosphere: 1 bar
- $O_2$ (21%), $N_2$ (78%), $CO_2$, $H_2O$, $O_3$
- $T_{surf} = 280$ K

MARS

- $r_h = 1.5$ AU
- $\phi = 4-25''$
- Atmosphere: 0.006 bar
- $CO_2$ (95%), $CO$, $H_2O$
- +seasonal variations
- $T_{surf} = 230$ K

HPBW=10''
(240 GHz at the 30m)
### Giant (gaseous) planets

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_h = )</td>
<td>5 AU</td>
<td>10 AU</td>
<td>20 AU</td>
<td>30 AU</td>
</tr>
<tr>
<td>( \varnothing = )</td>
<td>30-48”</td>
<td>15-19”</td>
<td>3.5”</td>
<td>2.4”</td>
</tr>
</tbody>
</table>

**Composition:** 

- \( H_2 / He / CH_4 : \)
  - Jupiter: 86:13:0.2 + \( H_2 O, \text{HCN, NH}_3 \) + \( \text{CO,..} \)
  - Saturn: 96:4:0.4 + \( H_2 O, \text{NH}_3, \text{PH}_3 .. \)
  - Uranus: 87:11:2
  - Neptune: 80:18:2 + \( \text{HCN, CO} \)
Asteroids, Main Belt of Asteroids:

Irregular shapes, most of them between Mars and Jupiter

Earth Crossing (Aten/Appolo) | Main Belt | Troyans
---|---|---
Size: | << 1 - 10 km | <1 - 952 km | <1 - 200 km
$r_h =$ | < 1 - 2 AU | 1.7 - 4 AU | 5.2 AU
$\Omega$ | << 0.5" | <0.1 - 0.8" | < 0.1"
Giant Planets Moons

Solar System Major Moons

The Solar System contains 18 or 19 natural satellites of planets that are large enough for self-gravity to make them round. (Why the uncertain number? Neptune’s moon Proteus is on the edge.) Two of them are larger than Mercury; seven are larger than Pluto and Eris. If they were not orbiting planets, many of these worlds would be called “planets,” and scientists who study them are called “planetary scientists.”

Images from Galileo (Jupiter’s moons), Cassini (Saturn’s moons), Voyager 2 (Uranus and Neptune’s moons). Data from NASA/JPL, processed by Ted Stryk, Gordán Ujarkovic, Emily Lakdawalla, and Jason Perry. Earth’s Moon photo by Gari Aarrilla. Montage by Emily Lakdawalla. The Planetary Society, blog@planetary.org.

Io, Europa, Ganymede, Callisto: 1.0-1.8”: Titan: 0.8” Triton 0.1”
Pluto and TNOs: dwarf and minor planets:
distance \( r_h = 30-90 \) AU

Largest known trans-Neptunian objects (TNOs):

- Eris
- Pluto
- Makemake
- Haumea
- Sedna
- Orcus
- Quaoar
- Varuna

Kuiper belt objects

ERIS ~ 2300 km
\[ = 0.03'' \]

PLUTO (2300km)
\[ = 0.1'' \]

(HST)
Comets

Distance to the Sun: 0.001 to 100,000 AU
(Two reservoirs: Kuiper disk (30-50 AU), Oort Cloud: 20,000-100,000 AU)

Gaseous coma observed between 0.1 and 15 AU:

Nucleus: 1 to 100 km
Coma (gas+dust): 10 to 100,000 km
Tail: 1 to 200 million km
Nucleus: 1 to 100 km
Planetary science: Atmospheres

Spectral resolved measurement of molecular line allow:

- **Chemical Composition**: Spatial and Vertical distribution of molecular species
  Search for new molecules

- **Thermal sounding**: Pressure/thermal vertical profile \((P(T), \text{ planets})\), gas temperature \((\text{comets})\)

- **Dynamics sounding**: Winds velocities from Doppler lineshift measurements, gas velocity and outgassing pattern \((\text{comets})\)
3 parameters are intimately coupled:

- Temperature field $\rightarrow$ Wind field

- Wind field $\rightarrow$ horizontal/vertical distribution of minors species

- Minor species $\rightarrow$ Temperature field through atmospheric heat budget (heating/cooling)

3D mapping and monitoring: seasonal variations

To Constraints on the origin and evolution of planets and the formation of the solar system
Detailed Thermal Structure $P(T)$ from Space Missions (e.g. Voyager, Cassini, Mars missions)

Atmospheres: thermal profile

THERMAL PROFILES OF GIANT PLANETS

mm/submm Continuum

TROPOSPHERE

STRATOSPHERE

Titan by Huygens

Pressure [hPa]

Temperature [K]

Altitude [km]
Clouds on Giant Planets

Cloud Chemistry: \( \text{NH}_3(g) + \text{H}_2\text{S}(g) \leftrightarrow \text{NH}_4\text{SH}(s) \)
Example of Vertical Structure: Neptune

Interior (lower atm.) or exterior (upper atm.) source of the minor species. Depend also of vertical mixing.
Cometary « atmospheres »: ~steady state outflow of sublimating ices (gas + dust) (production rate 'Q')

Radicals, atoms, ions

Photodissociation at 1000-10,000 km

Photoionisation

Parent molecules
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II Physical processes

II.1.1 Millimeter to submm spectra: molecular rotation lines

Rotational lines of molecules:
Quantified: $[J]$ (linear molecules),
$[J,Ka,Kc]$ (complex ones),... + hyperfine structure (e.g. HCN: $[J,F]$),...

Energy levels: 4 to $>200$ K:
Typical of cometary and planetary atmosphere temperatures

Einstein coefficient (lifetime)$^{-1}$:
$A_{J+1,J} = 10^{-7} - 10^{-2}$ s$^{-1}$
II.1.2 Molecular excitation processes in solar system atmospheres:

[1] Thermal excitation by collisions (LTE)

Collision rate \( t_c = \sigma_c n v_r(T) \) >> radiative decay \( \sim 10^{-2} \text{ s}^{-1} \)

for density \( n > 10^8 \text{ cm}^{-3} \) or \( P > 0.001 \text{ nb} \) (at \( \sim 100 \text{ K} \))


- self absorption / auto-excitation by emission from surrounding molecules (optically thick lines)

- Pumping of rotational levels via vibration bands in the solar or local **infrared** radiation environment
II.1.2 Molecular excitation processes in solar system atmospheres:

Local Thermodynamical Equilibrium (T):

\[ p_i = g_i e^{-(E_i/kT)} / Q(T) \]

- \( p_i \) = relative population of level i (fraction of molecules in this rotational state)
- \( g_i \) = degeneracy of the level (number of sublevels), \((2J+1)\)
- \( E_i \) = energy of the level

\[ Q(T) = \sum g_i e^{-(E_i/kT)} \] partition function at \( T \)

**Planetary atmospheres => always LTE**

**Exospheres, Cometary atmosphere => Both:** Transition from collision dominated to radiation dominated regimes when moving away from the nucleus
II.1.2 Molecular excitation processes: Comet atmospheres

"Atmosphere" = Radial (r) adiabatic expansion in vacuum:

=> Gas density profile (Haser model) <--> sublimation (production) rate: Q

\[ n(r) = \frac{Q_{\text{molec.}} e^{-r/l_{\text{molec.}}}}{(4\pi v_{\text{exp}} r^2)} \]

=> Expansion velocity: \[ v_{\text{exp}} = 0.4 \text{--} 2.0 \text{ km/s} \sim 0.9 r_h^{-0.45} \ (r_h = 10 \text{--} 0.1 \text{ AU}) \]

=> Gas Temperature: \[ T(r) \]
Rapid cooling from \( \sim 250 \text{ K} \) at the nucleus surface down to \( 5 \text{--} 20 \text{ K} \), followed by photolytic heating up to over \( \sim 300 \text{ K} \) (close to the Sun):

\[ T_{\text{obs}} = 4 \text{--} 150 \text{ K} \ (\text{at } r \sim 10^3 \text{--} 10^5 \text{ km}) \sim 80/r_h \ (\text{K.AU}^{-1}) \]

Excitation mechanisms:

- collisions with neutrals (T): molec.-H\(_2\)O: cross sections poorly known
- collisions with electrons: electron density and temperature uncertain
- radiative pumping by the Sun: dominant far from the nucleus

Other issues: molecular photodissociation lifetimes (\( l_{\text{molec.}}/v_{\text{exp}} \)), opacity of water lines and modelling of the excitation radiative pumping by the dust?
Example:

HCN rotational (J=0-6) population levels as a result of the 3 regimes:

Neutral collision (LTE) dominated ($r < 10^3$ km) (1)

Electron collision dominated ($r = 2-5 \times 10^3$ km) (2)

Fluorescence equilibrium ($r > 10^5$ km) (3)
II.2 Millimeter to submm spectra: radiative transfer and line shapes

Radiative transfer equation:

\[ J_{\text{tot}}(\nu) = J_{bg}(\nu) e^{-\tau m} + \int_0^{\tau m} S(\nu) e^{-\tau} d\tau \]

Spherical geometry (planets, first approximation for comets, too)
II.2.1 Radiative transfer: in planetary atmospheres:

- **Weighting function** $W(z)$:

\[
J_{\text{tot}}(\nu) = \int_0^T S(\nu) \exp^{-\tau} d\tau = \int_0^\infty S(\nu) W(\nu, z) dz
\]

\[
W(\nu, z) = \exp^{-\tau} \frac{d\tau}{dz}
\]

Gives information of the altitude probed

\[
d\tau(\nu, z)/dz = N(z) \alpha(\nu, z)
\]

$N(z)$: density of absorbing species

$\alpha(\nu, z)$: absorption coefficient
Absorption by other components:

\[ \alpha_{\text{tot}} = \alpha_{X-X} + \sum_i \alpha_i + \alpha_{\text{cloud}} \]

- \( \alpha_{X-X} \) Collision Induced Absorption (CIA)
- \( \alpha_i \) Molecular Absorption
- \( \alpha_{\text{cloud}} \) Cloud Absorption

\[ \alpha_{\text{CO}_2-\text{CO}_2} = 1.7 \times 10^{-10} \, \nu^2 \, n^2_{\text{CO}_2} \]
\[ \alpha_{\text{H}_2-\text{H}_2} = 1.0 \times 10^{-10} \, \nu^2 \, n^2_{\text{H}_2} \]

(Accurate computation from Borisow and Birnbaum)

\[ \alpha_i = I(T) \text{ from spectroscopic data (JPL, Geisa, Hitran): } \nu, I(T_0), E'' \]

\[ I(T) = I(T_0) \left( \frac{T_0}{T} \right)^\beta \exp \left( -\frac{hE''}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \left( 1 - \exp \frac{h\nu}{kT} \right) \right) \left( 1 - \exp \frac{h\nu}{kT_0} \right) \]

Rotational partition function:

\[ Q_{rs} \approx \left( \frac{kT}{hB} \right)^\beta \]
II.2.2 Radiative transfer: comet atmospheres

Transfert equation has to be integrated along z axis over each ray to the observer (numerical integration in the codes)

\[ J_{\text{tot}}(\nu) = e^{-\tau(\nu)} (J_{\text{bg}}(\nu)) + \int_{z=-\infty}^{+\infty} S(\nu,z) e^{+\tau(\nu,z)} \, dz \]

All lines are clearly separated and treated separately

Local opacity for j->i transition depends on local density \( n(r) \) and relative population of upper (\( p_j \)) and lower (\( p_i \)) level of the considered transition:

\[ \frac{d\tau(\nu,z)}{dz} = \frac{c^2}{8\pi v_{ij}^2} \left[ \frac{g_j}{g_i} p_i - p_j \right] n(\nu) A_{ji} \phi_{ij} \nu S(\nu,z) = \frac{h v_{ij}}{4\pi} p_j n(\nu) A_{ji} \phi_{ij} \nu \]
II.2.2 Radiative transfer: comet atmospheres: isolated line

Line integrated intensity $A$ is the result of integration of the signal from each direction in the beam and over the line shape:

$$A = \int T_b(\nu) \frac{c}{\nu} d\nu = \hbar c^3 A_{ij} / 8\pi k \nu_{ij} \left(1 - \frac{T_{bg}}{T_{ex}(\nu_{ij})}\right) \langle N_j \rangle$$

For optically thin lines and spherical symmetry, signal will depend on mean column density on each levels $\langle N_i \rangle$, $\langle N_j \rangle$, defining a mean excitation temperature $T_{ex}$:

$$I_{ex}(\nu_{ij}) = \frac{2\hbar \nu_{ij}^3}{c^2} \frac{\langle N_j \rangle}{\left[ \frac{g_j}{g_i} \langle N_i \rangle - \langle N_j \rangle \right]}$$

$$\langle N_i \rangle = \int p_i(r) 4\pi r^2 n(r) \left[ \frac{1}{4\pi} \int_{\theta=0}^{2\pi} \int_{\varphi=0}^{\pi} \eta(r, \theta, \varphi) \sin(\varphi) d\varphi d\theta \right] dr. \approx a\langle p_i \rangle Q / (4\pi v_{exp} \Delta)$$

$\eta(\theta, \varphi) = \text{Beam shape fonction}$
II.2.3 Line Profiles

Planetary exospheres and cometary atmospheres:

\[ P < 1 \text{ mbar} \rightarrow \text{Doppler profile} \]
\[ \Phi(\nu,T): \text{Gaussian: FWHM} = \nu_0/c \sqrt{2 \ln 2 kT/m_{\text{molec}}} \]

Planetary thick atmospheres:

\[ 1 \text{ mbar} < P < 10 \text{ mbar} \rightarrow \text{Voigt (convolution Lorentz * Doppler)} \]

\[ 10 \text{ mbar} < P < 500 \text{ mbar} \rightarrow \text{Lorentz} \]
\[ \Phi(\nu,T,P) = (\gamma_l/\pi) \frac{1}{((\nu-\nu_0)^2+\gamma_l^2)} \]

\[ 500 \text{ mbar} < P < 5 \text{ bar} \rightarrow \text{Van Vleck & Weisskopf (1945)} \]
\[ \Phi_{VVW}(\nu,T,P) = (\gamma_l/\pi)(\nu/\nu_0) \{ \frac{1}{((\nu+\nu_0)^2+\gamma_l^2)} + \frac{1}{((\nu-\nu_0)^2+\gamma_l^2)} \} \]

\[ 1 \text{ bar} < P \rightarrow \text{Ben-Reuven (1966)} ... \]

Collisional Broadening coefficient:

\[ \gamma_l = \gamma_0 \left( \frac{p}{p_0} \right) \left( \frac{T_0}{T} \right)^\eta \]

\[ \gamma_0 \sim 1-5 \text{ MHz/mbar at 300 K} \]
Absorption and Emission of gas against a background:

Positive thermal gradient => line in emission (1)

Negative thermal gradient => absorption of the background (2)
II.2.3 Line Profiles in planetary atmospheres

- Limb darkening
Spherical geometry: limb emission
(higher column density / no background / extended atmosphere)

II.2.3 Line Profiles in planetary atmospheres
Doppler shift, line shape and beam integration
II.2.4 Line shapes of comets:

pure Doppler broadening $\rightarrow$ gas expansion velocity

$Q_{CO} = 1.8 + 1.8 \times 10^{28} \text{s}^{-1}$

$v_{exp} = 0.5/0.3 \text{ km/s}$

$T = 6 \text{ K}, r_h = 5.75 \text{ AU}$
II.2 Lines shapes: summary

**Planets atmospheres**

- Finite, small disk
- Resolved or not

**Comets "atmosphere"**

- No edge, 1/r column density profile

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**Frequency**

- Broad (GHz) lorentzian lines
- Sharp, very narrow lines
Solve numerically the 1D conductive heat flow equation for each pixel with latitude and longitude.

\[ \rho c \frac{\partial T(x, t)}{\partial t} = \frac{\partial}{\partial x} \left[ \kappa \frac{\partial T(x, t)}{\partial x} \right] \]

- \( \rho \) is the density, \( c \) the specific heat capacity and \( \kappa \) the thermal conductivity.

- Thermal inertia \( \Gamma = (\kappa \rho c)^{1/2} \) (2 layers values from Spencer 1987)

- Thermal parameter \( \theta = \Gamma \omega^{1/2} / (\varepsilon \sigma T^3) \), with \( \omega \) the rotation period

- Compute the subsurface temperature using the thermal inertia derived in the IR.
II.3.1 Millimeter to submm continuum: surfaces, small bodies

Radiative transfer in subsurface:

- Compute the image with 100x100 pixel (Fig 1)
- For each pixel on Planet and each frequency, calculate outgoing radiance and local brightness temperature
- Integrate radiances over disk for 1) total flux 2) and average brightness temperature

Fig. 1 Thermal modelling of Callisto

Fig. 2: Averaged sub-surface Temperature
II.3.2 Millimeter to submm continuum: dust coma of comets
To convert dust continuum emission \(S_{\lambda}\) into dust mass production rate \(Q_{\text{dust}}\) of the comet:

\[
S_{\lambda} = \frac{2k}{\lambda^2 \Delta^2} \int_{a_{\text{min}}}^{a_{\text{max}}} T(a) Q_{\text{abs}} \pi a^2 n(a) da = \frac{2kT M \kappa_{\lambda}}{\lambda^2 \Delta^2} \tag{Boissier et al. (2012)}
\]

\(a = \) grain size, size distribution \(n(a) \propto a^{-q}\): with \(a = a_{\text{min}}\) to \(a_{\text{max}}\) and \(q = \) size distribution index (can vary from 2 to 4)

\(T(a):\) temperature. Fast rotating grain: blackbody temperature: \(T \sim 275 r_h^{-0.5}\)

\(Q_{\text{abs}}:\) given by e.g. Mie theory, depends on real/complex refractive index

\(K_{\lambda}:\) the dust opacity related to the total mass \(M\) in the beam. Depends on grain properties (composition, ice fraction, porosity, size distribution), \(K_{\lambda}\) can vary a lot (0.5-10x10^{-2} \text{ m}^2/\text{kg}) - multi-wavelength observation can help constrain \(q\) (and \(K_{\lambda}\)).

\(M \rightarrow Q_{\text{dust}}:\) the velocity distribution \(v(a)\) is needed and might be constrained by other (time dependent) observations and modelling.

\(\Rightarrow Q_{\text{dust}} (\text{dust production rate})\) not easily measured!
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III.1 Submm observations: tracking solar system targets at IRAM-30m

Major Planets and satellites: e.g.: Pako> SOURCE Venus

(Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto, Io, Europa, Ganymede, Callisto, Enceladus, Titan,... in database)

Asteroids and comets: supply osculating 2-body orbital elements:

Pako> SOURCE BODY -
C_NAME      JJJJJJJJ.jjjjjj  OOO.nnnnn  WWW.ppppp  III.iiiiii  Q.qqqqqqqq E.eeeeee

User supplied Name
Perihelion date JDT
Ascending Node
Argument of perihelion inclination
Perihelion distance (AU) excentricty

+ always check that computed ephemerides on display are ok!
III.1 Submm observations: observations modes

All are relatively small targets:
  Diameter < 1' for planets,
  Cometary signal sharply decreasing (as $1/\rho$) beyond one beam
  => best suited for *Wobbler-switching* (WSW) observations

Objects resolved with strong continuum (Mercury->Saturn):
  Stationnary waves in the quasi-optics = strong ripples
  => avoid *frequency switching* (FSW)
  => *Position-switch* on other side of the disk when possible

Planetary Satellites:
  Observe satellites at widest separation (contamination)
  Doppler tracking of lines: minimum variation at maximum elongation

Tenuous atmospheres => narrow lines, *frequency switching*
possible (for single lines observations)
Standing waves: strong continuum variation ON versus OFF:
- source continuum
- sky continuum not well cancelled (high tau, PSW)
- frequency switch (variable receiver gain)
Frequency switching example:
(folded) CO(2-1) comet and atmospheric line

III.2 Observations of solar system targets: when?

**Planets:**
- **Venus, Mars:** large variation in distance (x6): resolved when closest to earth
- **Mercury:** varies x2, phase angle effect
- **Saturn, Jupiter:** always resolved, but better at opposition
  - **Satellites** (Io-Titan): less diluted (x2) at opposition
- **Uranus, Neptune, TNOs:** far, small variation
  - + time variation, seasonal variation, phase/inclination variation

**Satellites:** at maximum elongation to avoid planet contamination

**Asteroids:**
- Never resolved but best at perigee

**Comets:**
- **Very time sensitive:** observing windows restricted to a few days, weeks
  - Activity peaks around perihelion, can vary as $\sim 1/r_h^2$
  - Small heliocentric dist. ($r_h<0.7$AU) reduces signal (photodissociation)
  - signal varies as $\sim 1/\Delta$
  - time variation can be >50% in one day, outbursts (up to x10^4 in 1 day!)
III.2 Observations of solar system targets: when?

**Comets:** What can be observed, when?

« **Classical** » comets: between \( r_h = 0.5 \) and 3 AU from the Sun:
Activity is dominated by the sublimation of water (sublimation rate \( Q_{H_2O} \)):

\[ \Rightarrow (1) \text{ Prediction based on visual brightness: total magnitude } \ll m_1 \ll \text{ (measured by amateurs, or predicted / extrapolated) + correlation law (Jorda et al. 2008):} \]

\[ \log(Q_{H_2O}) \approx 30.7 - 0.25 \ast (m_1 - 5 \ast \log(\Delta)) \quad (\Delta = \text{distance to the Earth}) \]

\[ \Rightarrow (2) Q_{H_2O} \text{ comes from other observations, measurements (IR, OH in the radio (18cm) or visible (near-UV),...)} \]

\[ \Rightarrow m_1 \approx 9-11 \quad \Rightarrow Q_{H_2O}/\Delta \approx 10^{28} \text{ molec./s/AU} \rightarrow \text{About 5 molecules detectable} \]

\[ \Rightarrow m_1 \approx 5-7 \quad \Rightarrow Q_{H_2O}/\Delta \approx 10^{29} \text{ molec./s/AU} \rightarrow \text{About 10 molecules detectable} \]

\[ \Rightarrow m_1 < 4 \quad \Rightarrow Q_{H_2O}/\Delta > 10^{30} \text{ molec./s/AU} \rightarrow >15 \text{ molecules + isotopes,...} \]

**Special cases:** Sungrazing comets \((r_h < 0.1 \text{ AU})\) or comet dominated by sublimation of other molecules \((CO \text{ beyond 3 AU})\)
III.3 Millimeter to submm observations:  
Continuum signal from planets $\rightarrow$ calibrators

Giant planets:

Continuum emission from the deep atmosphere (1-5 bars)

Actual frequency dependence comes from broad lines of NH$_3$, PH$_3$, H$_2$S… layers

$\Rightarrow$ Lower opacity in the wings $\Rightarrow$ probing deeper, at higher Temperature ($\Rightarrow$ higher $T_B$)
III.3 Using planets as continuum (efficiency) calibrators

JUPITER submm spectrum

![Graph showing the brightness temperature (K) vs frequency (GHz) for JUPITER with markers for PH3 and NH3.]
SATURN submm spectrum

But: + ring effects

Saturn from OVRO-BIMA
(Dunn et al. 2005)

de Pater (1989)
URANUS submm spectrum

Modeled spectra at Freq. < 200 GHz depend of the exact lineshape (H$_2$S)
Uranus - Model comparison < 1%

Red: measurements between 2004-2007,
Black: between 1990-1996

Best calibrator: uncertainty (variability, model,...) < 8%
Neptune submm spectrum: summary

- Model uncertainties 1-2%
- Comparison with Orton’s Model within 1%

- Current Absolute uncertainties limited by our knowledge of the thermal structure (5%) at freq. > 200 GHz, and ~3 % at 3mm

- Neptune is also a good calibrator at mm wavelength, but avoid to calibrate within the CO and HCN lines
MARS: continuum model

- Sub-surface temperatures obtained from LMD-GCM model
- Radiative transfer modelling of the sub-surface
- Viewing geometry (Sub-earth and Sub-solar Lat. and long.)
- Absolute uncertainty < 5%

http://www.lesia.obspm.fr/perso/emmanuel-lellouch/mars/
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IV.1 Planetary atmospheres
Venus, Mars, Titan: telluric atmospheres

Images © NASA /ESA
Venus and Mars

- Thermal and wind sounding from CO lines
- Temperature profile Venus 70-120 km, Mars 0-80 km
- Wind measurements from doppler shifts, near 95-105 km for Venus, and 40-70 km on Mars
Venus: wind measurements with CO line

Lellouch, 1991
Venus: winds measurement in support of Venus Express

Doppler wind map, May-Sep. 2007

Lellouch et al. 2008
3-point map of Venus Beam size ~Venus size

Measured Doppler shift =

zonal flow \((-60\pm20\text{m/s})\)

+ sub-solar -> antisolar flow \((100\pm15\text{m/s})\)
Winds on Mars

Example: PdB, CO(1-0) map at perihelic opposition (diameter 25")

R. Moreno et al.
CO(2-1), $^{13}$CO(2-1) 1MHz and 100 kHz, Lellouch et al 1991b
Solstice

Near Equinox

Retrograde

Retrograde + jets + asym

Equinox + dust storm

Direct + jets + asymmetries

Mars seasonnal winds
(PdB, Moreno et al.)
Huge variability of H$_2$O above Venus clouds

First submm detection of SO$_2$ on Venus

First detection of H$_2$O$_2$ on Mars

Planetary Atmospheres: Chemistry and Trace Species Detection

226 GHz Venus HDO Spectra, June 1999 & Dec 2002

HDO 226 GHz

H$_2$O$_2$ 362 GHz

Mars disk center 9/4/03; 362ghz H$_2$O$_2$; 1 mhz res

$\text{H}_2\text{O}_2$, $\text{SO}_2$

(JCMT, T. Clancy and B. Sandor)
Mars Water Cycle

VLA 22 GHz Water Map

OVRO 226 GHz HDO Map

Mars Opposition - March 1997

HST WFPC2-Color composite
Surface features

HST WFPC2-Blue filter (410 nm)
Cloud structure

OVRO - Integrated HDO
Emission (1.3 mm)
Water vapor distribution

1 P. James (U. Toledo), T. Clancy (SSI), S. Lee (U. Colorado), and NASA

2 M. Gerwell (CIA), D. Muhleman (Caltech)

MARS: Odin H$_2$O 2–9 Nov. 2003

MARS: Odin: H$_2^{18}$O 2–9 Nov. 2003

Average disc temperature $T_d$ [K]

Frequency [GHz]
Titan at submm wavelengths

=> HCN vertical distribution
Titan: Other nitriles detected at the IRAM-30m:

**HC$_3$N and CH$_3$CN, Marten et al. 2002**

- (a) HC$_3$N(10–9) Dec. 1999
- (b) HC$_3$N(12–11) July 1997
- (c) HC$_3$N(16–15) July 1997
- (d) HC$_3$N(24–23) July 1997

**CH$_3$CCH and C$_2$H$_5$CN, With ALMA Cordiner et al. 2015**

Titan: results: vertical mixing ratio of nitriles

IRAM 30-m
Marten et al. 2002

\( \text{HC}_3\text{N} \)

\( \text{CH}_3\text{CN} \)

\( \text{HCN} \)
Titan at submm wavelengths: high spatial resolution

SMA, Gurwell 2005

IRAM PdB
Moreno et al. 2005

Winds in HC$_3$N
60 m/s @ 450 km

Winds in CH$_3$CN
160 m/s @ 300 km
Titan chemistry-dynamics coupling

Rannou et al. 2002
Hourdin et al. 2004

Flasar et al 2005
Titan: HCN, CO isotopes

$^{15}\text{N}/^{14}\text{N}$: enriched 4.5 times compared to terrestrial value. => Implication on selective atmospheric escape (sputtering) link to the planet Sun insolation history.
Giant planets atmospheres: Jupiter, Saturn, Uranus, Neptune
Giant planets

Different kind of lines
- Narrow (< 50 MHz), stratospheric emissions. Ex. H$_2$O, HCN
- Broad (> 2 GHz) tropospheric, absorptions. Ex. PH$_3$
- Absorption+emission. Ex. CO on Neptune

Lellouch et al. (2005)
Jupiter’s stratosphere after the collision of comet Shoemaker-Levy 9

July 1994: Impacts of fragments of comet SL9 on Jupiter
Detection of CO, CS and HCN at mm wavelengths (Lellouch et al/1995, Marten et al/1995) with the 30m telescope
Monitoring and mapping of these species: 1995-1998
Dispersion towards northern hemisphere (Moreno et al/2003)
IRAM-30m Telescope observations

CO(2-1)  |  CS(5-4)  |  HCN(3-2)

Antenna Temperature (K)

Velocity (km/s)

Feb 2004

ON  |  Off

HPBW
CO, CS and HCN total mass evolution with time since impacts of comet SL9 on Jupiter. A loss factor is computed from 2006 data compared to averaged 1995-1998 mass measurements.
Stratospheric $\text{H}_2\text{O}$: time evolution - Decrease since SL9? (From space at 557GHz: SWAS and Odin monitoring, Cavalié et al. 2012)

Map of water with Herschel HIFI and PACS: Cavalié et al. (2013): still more water on the hemisphere of impacts
The observations of 2004 and 2006 indicate clearly a decrease of the total masses of CO, CS and HCN compared to the early Jupiter/SL9 amounts.

A possible mechanism to explain their depletions is a downward loss in the polar regions into the deep atmosphere.

The different values of mass loss factors between CO, CS and HCN, may arise from photochemical processes in the high latitude regions, where magnetospheric electrons and ions are focused, which could form other species in the polar regions. This has been observed with CO$_2$ from Cassini/CIRS measurements (Kunde et al 2004).
IV.2 Tenuous atmospheres: Io, Pluto, Triton, TNOs, Icy satellites, Céres
Tenuous atmospheres: Io

Io’s atmosphere

- $p \approx 0.1$-1 nbar, spatially heterogeneous

- $SO_2 \approx 90\%$ (sustained by combination of sublimation + volcanism) + photochemical products ($SO$) and purely volcanic species ($NaCl, S_2$)
Tenuous atmospheres: Pluto, Triton, ...

Pluto: $p \sim 5 \mu\text{bar}$, currently increasing
- Triton: $p \sim 15 \mu\text{bar}$
- $N_2 + \sim 1\%$ of $CH_4$

Pluto: CO and HCN emission detected with ALMA on 12/13 June 2015 (IAUC 9273)

+ Extend studies to other « dwarf planets » (Eris, Makemake, Haumea) and other large trans-neptunian objects and centaurs (search for CO outgassing)

Bockelée-Morvan et al. 2001
Ceres: a minor planet or a comet...?

Detection of water with Herschel at 557 GHz:

- Two localised sources, likely corresponding to bright spots (HST, Dawn)
- Variable activity, mostly close to perihelion

(Küppers et al., 2014, Nature 505)
Tenuous atmospheres: Enceladus Torus

2009-2011: Detection of the torus of water vapor from Enceladus geysers in absorption against Saturn (Herschel/SWAS/Odin) - other species?


Jan. 2011:

Odin: Biver et al. 2011 EPSC
IV.3 Surfaces/Small bodies - thermal emission
Ganymede & Callisto continuum emissions: What do we know?

- Thermal IR - Ground-based observations and Voyager IRIS Spectra (both 1 and 2)
  - Ganymede: 136-147 K
  - Callisto: 147-158 K

- Radio/mm/submm - Single dish and interferometric observations show conflicting results (see Muhleman and Berge 1991)
  - cm: < 70 K ~90 K
  - submm: ~110 K ~130 K

- Extremely low temperatures for Ganymede in radio
  - Very low thermal inertia of the deep interior or
  - Very low emissivities = very high dielectric constant
Voyager IRIS modeling: diurnal variability

1 layer and 2 layer models considered
By Spencer (1987, 1989)

Constrain the subsurface Thermal inertia
Brightness temperature versus wavelength: Callisto

Measurements: IRAM-PdB (red) - SMA (green) - Muhleman and Berge, 1991 and Spencer 1987 (black)
Brightness temperature versus wavelength: Ganymede
Callisto and Ganymede Summary

- Ganymede and Callisto are good alternatives for absolute flux calibration standards

- Callisto being preferred as it is:
  - Warmer
  - Typically far from Jupiter
  - Brightness variation versus Frequency better understood at least at longer wavelengths

- Absolute errors are estimated to be 7% in $T_B$
- Good sources for interferometer flux calibration
- Need some measurements at 7mm (VLA) and 100 micron (Herschel)
Planetary Surfaces: Mapping Mercury and large Asteroids

Mapping temperature in the upper centimeter (~10\(\lambda\)) of the surfaces of terrestrial planets, moons, and minor bodies, provides understanding of surface material characteristics: regolith, thermal conductivity,...
Mercury surface

- Surface properties: Thermal inertia
- Dielectric constant, roughness

(Greve et al. 2009)
Planetary Surfaces: distant icy bodies
Pluto-Charon, Centaurs, TNOs, icy satellites, comet nuclei

- Comparison to visible magnitudes => size and albedo
- Time variation => rotation lightcurves, shapes, rings
- thermal properties

Pluto is 0.10", Charon is 0.05", Triton 0.12", Eris 0.03" at current distance from sun (not resolved)
Centaurs and TNOs: Size and albedo

**Photometry**: size, albedo determination

- Coupling Thermal and Optical measurements, constrains both the diameter and albedo.

**Size**: Constrains the Distribution

**Albedo**: Improve the VIS./IR spectra interpretation (composition)

Search for correlation between size/albedo/color/TNO family (orbital parameter)

- Origin and evolution of TNO populations

(Herschel Key Program "TNOs are Cool" = 130 targets)

Jewitt et al 2001
Observations of largest TNOs with IRAM bolometers Array:

Pluto, Lellouch et al., 2000

Varuna, Lellouch et al., 2002

Eris: Bertoldi et al., 2006

=> Larger than Pluto!
Cometary nuclei
Need for interferometer resolution

- Measurement of thermal emission:
  - size, albedo, possibly shape (cf asteroids)
- Long baselines required to separate nucleus from dust emission
- Comet nuclei unresolved in most cases (res.> 10 km at 1AU)

<table>
<thead>
<tr>
<th></th>
<th>R (km)</th>
<th>Δ (AU)</th>
<th>S/N -1h 0.8 mm</th>
<th>Nucleus/Dust Contrast 5 km baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hale-Bopp</td>
<td>35</td>
<td>1.4</td>
<td>2500</td>
<td>10</td>
</tr>
<tr>
<td>103P/Hartley 2</td>
<td>1</td>
<td>0.13</td>
<td>320</td>
<td>100</td>
</tr>
<tr>
<td>Typical</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>29P/SW1</td>
<td>30</td>
<td>6</td>
<td>55</td>
<td>2</td>
</tr>
</tbody>
</table>
# Thermal emission of small bodies

<table>
<thead>
<tr>
<th>Category</th>
<th>R (km)</th>
<th>$\Delta$ (AU)</th>
<th>Flux</th>
<th>Number of targets available (ALMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEOs</td>
<td>$&gt; 0.5$</td>
<td>$&lt; 0.1$</td>
<td>$&gt; 1$ mJy</td>
<td>~50(900)</td>
</tr>
<tr>
<td>MBAs</td>
<td>$&gt; 10$</td>
<td>2-3</td>
<td>$&gt; 1$ mJy</td>
<td>~4000(135000)</td>
</tr>
<tr>
<td>Trojans</td>
<td>$&gt; 20$</td>
<td>4-5</td>
<td>$&gt; 1$ mJy</td>
<td>~50(600)</td>
</tr>
<tr>
<td>TNOs</td>
<td>$&gt; 250$</td>
<td>30-50</td>
<td>$&gt; 1$ mJy</td>
<td>~50(900)</td>
</tr>
<tr>
<td>Comets</td>
<td>$&gt; 2.5$</td>
<td>$&lt; 0.5$</td>
<td>$&gt; 1$ mJy</td>
<td>~50</td>
</tr>
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<td>30</td>
<td>6</td>
<td>2 mJy</td>
<td>1</td>
</tr>
</tbody>
</table>

**IRAM Sensitivity:** $3\sigma \sim 1$ mJy in 8h at $\lambda=1$mm

**Continuum flux at 1mm:**

$$F \approx 0.07 \ r_h^{-0.25} \ R^2/\Delta^2 \ [\text{mJy}]$$

$r_h, \Delta$ : helio- and geocentric distances (AU)
IV.4 Cometary atmospheres
Nuclei cannot be resolved in the submm domain, but interferometric observations can separate nucleus from dust continuum and explore jet structure close to the nucleus.

Single dish (IRAM-30m) observation samples the inner coma and can map molecular species, especially daughter molecules produced in the coma.
Comet continuum: dust atmosphere, production

Hale-Bopp, Althenoff et al. (1999)

IRAM-PdB 3.3mm maps of the cloud of dust ejected by comet 17P/Holmes after its outburst on 24.8 Oct. 2007.

Contour levels: $2-\sigma \sim 0.2-0.3$ mJy/beam.

Radio data + visible data + time evolution $\Rightarrow$ dust size distribution and Mass loss $\sim 10^{12}$ kg ($\approx 5\%$ of the nucleus mass).

Nucleus contribution $< 1\%$

17P/Holmes, Boissier et al. (2012)
Cometary atmospheres

- Composition of comets: *Chemical diversity, taxonomy;*

- Molecular survey of bright comets: *New molecules, COMs*

- Evolution of the outgassing and relative abundances with heliocentric distance: *Release mechanisms?*

- Map molecules in the coma: *Distributed sources (e.g. H$_2$CO), ions,..)*

- Explore distant activity (CO): 95P, 29P, centaurs, TNOs,...

- Short term activity: rotation, outbursts -> *heterogeneity?*

- Isotopic ratios: *fractionation mechanisms when comet formed, input to the Earth?*
Gas temperature measurement:

Best = methanol lines observed simultaneously

Model: $T_{rot} = 41.70$ K

$T_{mod} = 50$ K  off = 2.2$"
Molecules and radicals observed in comets

- **H₂O** (100%)
- **CO** (1-25%)
- **CO₂** (5-10%)
- **CH₃OH** 0.5-6%
- **H₂CO** 0.1-1.2%
- **HCOOH** 0.1%
- **CH₃CHO** 0.02%
- **HC₅O₃** 0.08%
- **(CH₂OH)₂** 0.3%
- **CH₄** 0.2-1.4%
- **C₃H₂** 0.1-0.5%
- **C₂H₆** 0.1-0.8%
- **NH₃** 0.3-0.6%
- **NH₂**
- **NH**
- **HCN** 0.01%-0.3%
- **HNC** 0.01%
- **HC₂NCH₃** 0.01%
- **HC₃N** 0.01%
- **NH₂CHO** 0.01%
- **CS** 0.1%
- **CS₂** 0.1%
- **C₃**
- **H₂S** 0.2-1.5%
- **H₂CS** 0.02%
- **OCS** 0.1-0.4%
- **SO₂** 0.1-0.3%
- **H₂SO₃** 0.1-0.3%
- **H₂CO** 0.1-1.2%
- **HCOOH** 0.1%
- **CH₃CHO** 0.02%
- **HC₅O₃** 0.08%
- **(CH₂OH)₂** 0.3%
- **CH₄** 0.2-1.4%
- **C₂H₆** 0.1-0.8%
Comparison of molecular abundances

$73P-B = 73P-C$

but different from Hale-Bopp => Evidence of compositional homogeneity
Abundances relative to HCN in comets

Dynamically New comets
Long Period comets
Halley Family comets
Jupiter Family comets

$\frac{\text{H}_2\text{S}}{\text{CH}_3\text{OH}}$

$\frac{\text{CH}_3\text{OH}}{\text{HCN}}$

17P/Holmes
73P-B/S.W.3
73P-C/S.W.3
9P/Tempel 1
22P/Kopff
C/2006W3 (Christensen)
8P/Tuttle
153P/Ikeya–Zhang
109P/Swift–Tuttle
C/2007 N3 (Lulin)
C/2004 Q2 (Machholz)
C/2001 Q4 (NEAT)
C/2001A2 (LINEAR)
C/2000WM1 (LINEAR)
C/1999T1 (McNoughton)
C/1998B2 (Hyakutake)
C/199501 (Hale–Bopp)
C/1990K1 (Levy)
C/1989X1 (Austin)
Molecular Survey with IRAM-30m + EMIR + FTS

Comet C/2013 R1 (Lovejoy): 9–16 Dec. 2013; IRAM–30m + EMIR 1mm + FTS

Frequency [MHz]
260000
240000
220000

Velocity (km/s)
-20000
0
20000
40000

Tmb [K]
0.2
0.1
0
Molecular survey: identified lines in C/2014 Q2 (Lovejoy)
Ethylene-Glycol \((\text{CH}_2\text{OH})_2\) in comet C/2013 R1 (Lovejoy)

**Frequency survey:**
Detecting complex organic molecules by averaging multiple lines

Averaging several lines of similar expected intensity (set align velocity!)

\[(\text{Biver et al. 2014, A&A 566, L5})\]
Heliocentric variation: Monitoring of comet gaseous activity

Biver et al. 2002, E.M.P. 90, 5
Study of nuclear ices structure, differentiation, and seasonal effects

Biver et al. 2007 PASS 55, 1058

Change of outgassing regime at 2 AU

H$_2$O to CO-dominated activity
Heliocentric variation: the origin of HNC

Detected in 22 comets (3 lines) since 1996
- HNC/HCN ratio varies strongly with $r_h$, for a given comet (e.g. HB, 153P, C/2001 A2)
- HNC/HCN increases with activity (e.g. 17P ?)
- at given $r_h$, especially for JFC, abundance still varies by a factor $\geq 2$
- Not a parent molecule: maps + ALMA shows coma production
Temporal variation: C/2007 N3 (Lulin): Q 2.5 in 42h!
But constant ratio of all molecules $\rightarrow$ homogeneous

C/2007 N3 (Lulin): HCN(3–2) at 265.9GHz: 25.04 Feb.09 $\phi=0.00$

Comet C/2007 N3 (Lulin)


Production rates (molec. s$^{-1}$)

Feb. 20 30
Date [UT days]
Dramatic variation of outgassing: break-ups, outbursts

The Mega-outburst of comet 17P/Holmes on 24.8 October 2007

Comet 17P/Holmes: evolution of outgassing

Brightness: \( \times 400000 \) in 24h

\( Q_{\text{prod}} \times 3000 \)

24.0 --> 30.0 October 2007

Images © J.A. Henriquez-Santana,
E.Guido+S.Sostero,
R.Ligustri, N.Biver,
B.Brinkmann, B. Bayle &
J.C. Dalouzy
Some species are not subliming from nucleus surface:
- photolysis products (e.g., SO from SO₂)
- decomposition of organic grains (e.g., H₂CO) or icy grains
- product of coma chemistry HNC?

Extended sources in the coma

PdB: Hale-Bopp (Boissier et al. 2007)

ALMA: comet Lemmon (Cordiner et al. 2014)
- **H₂CO**: ~ 80% extended: thermo-degradation of polymers?
- **HNC**: extended in Hale-Bopp, Lemmon, Lovejoy,...
- **OCS**: From IR data
- **Origin of NS?**
D/H in short period comets with Herschel


\[ \text{H}_2^{16}\text{O} \]
Isotopic ratios in cometary gases

\[ \frac{^{12}C}{^{13}C} \text{ in HCN (3 comets), CN, C}_2 \text{ (several): } 90-114 \text{ (89)} \]
\[ \frac{^{16}O}{^{18}O} \text{ in H}_2\text{O (>7 comets): } 470-550 \text{ (499)} \]
\[ \frac{^{32}S}{^{34}S} \text{ in CS (4 comets) and H}_2\text{S (1): } 16-27 \text{ (22.5)} \]
\[ \frac{D}{H} \text{ in H}_2\text{O (11 comets): } 1.4-6.0 \times 10^{-4} \text{ (1.56 x10^{-4})} \]
\[ \frac{^{14}N}{^{15}N} \text{ in HCN (3) in CN (several): } 140-200 \text{ (272)} \]
\[ \frac{^{14}N}{^{15}N} \text{ in NH}_2 \text{ (several): } 130-140 \]