The Solar System in the IR/Submm range
From IRAS to Herschel and beyond

Thérèse Encrenaz
With inputs from Emmanuel Lellouch and Dominique Bockelée-Morvan

LESIA, Observatoire de Paris, CNRS

« The Universe explored by Herschel », Noordwijk, 15-18 october 2013
A revolution in Astronomy

- We know about a thousand exoplanets today
- Each star in the Galaxy might host at least a planet
- We are surrounded by billions of planetary systems, but the Solar system is the only one we can explore at depth
Key questions about the Solar system formation and evolution (1)

- How did the giants planets form and can we trace their migration?
- Can we understand the diverging evolution of terrestrial planets?
- What can we learn from the diversity of outer satellites?
- Elemental and isotopic abundances (D/H in HD)
- Disequilibrium species (CO, PH₃) → internal structure
- Minor species and isotopes on Mars (O₂ and oxygen isotopes in CO on Mars)
- Search for tiny atmospheres on Galilean satellites (H₂O on Ganymede & Callisto)
- Elemental & isotopic abundances in Titan (¹⁸O/¹⁶O)
- Origin of water in Saturn’s system (H₂O torus around Enceladus, H₂O on Titan)
Key questions about the Solar system formation and evolution (2)

- What can we learn from the diversity of comets?

- Can we characterize the Kuiper belt and understand its history?

- Can we characterize the oxygen flux in the outer solar system?

- Characterize the Oort and Kuiper Belt families
  - $\text{H}_2\text{O}, \text{NH}_3$ in comets, D/H in Kuiper belt comets

- Albedos and sizes of TNOs

- Surface characterization of brightest TNOs

- Stratospheric water in giant planets and Titan
The outer Solar system is best explored by far IR/submm remote sensing

- **Outer solar-system objects are cold**
  - Giant planets: $\lambda_{\text{max}}$ from 25 $\mu$m (Jupiter) to 60 $\mu$m (U, N)
  - Outer satellites: 30 $\mu$m (Galilean sat.)
    -> 70 $\mu$m (Triton)
  - TNOs: 70 -> 100 $\mu$m

- **In situ exploration is limited to a few targets**
  - Distant comet: 1 mission to come *(Rosetta, 2014)* – including the MIRO submm sounder
  - TNOs: 1 mission to come *(New Horizons,-> Pluto, 2015)*

- **Studies of comets and TNOs require surveys for statistical studies**
  - > 12 comets with Odin
  - > 50 TNOs with Spitzer, > 100 TNOs by Herschel
Evidence for an internal energy source in the giant planets (except Uranus)

**A milestone in infrared planetary science**

**Evidence for an internal energy source in the giant planets**

**TABLE 1. Measurements of the Thermal Emission of Jupiter**

<table>
<thead>
<tr>
<th>Source</th>
<th>Te (K)</th>
<th>Energy Balance Type of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gillett, 1969</td>
<td>125</td>
<td>Thermal Emission</td>
</tr>
<tr>
<td>Hanel et al., 1981</td>
<td>124.4</td>
<td>Radiometric</td>
</tr>
</tbody>
</table>

Jupiter: Evidence for an internal energy source, 1.7 times the absorbed solar energy ($T_{eq} = 110$ K)  
Probable origin: Gravitational contraction
Planetary science: Milestones in the millimeter range (IRAM-30m)

HCN in Comet Halley (1986)
HOCH₂CH₂OH (ethylene glycol) in Comet Hale Bopp (2004)
CO and HCN in Neptune (1992)
-> evidence for disequilibrium processes

First detection of HCN in a comet (P/Halley) Despois et al. 1983

First detection of ethylene glycol in a comet (Hale Bopp) Crovisier et al. 2004

CO in Neptune: 10⁻⁶ (expected: 10⁻⁹)
Rosenqvist et al. 1992
Planetary science: Milestones in the submillimeter range (JCMT, CSO)

- D/H in 2 Oort cloud comets (1998)
- H$_2$O$_2$ on Mars (2004)
- Mesospheric sulfur species and HCl on Venus (2010, 2012a, b)

SO$_2$ & SO in the mesosphere of Venus (Sandor et al. 2012)

SO$_2$, SO$_2$, H$_2$SO$_4$ Spectral Data

HDO in Comet Hale-Bopp (Meier et al. 1998)

H$_2$O$_2$ on Mars (Clancy et al. 2004)
1983
  - Discovery of dust trails
    - Sykes, Science 1986
  - Discovery of new comets
    - IRAS-Araki-Alcock, 1983
  - Pluto-Charon @ 60-100 μm
    - Sykes, Science 1987
Deuterium enriched in icy giants

-> Support to nucleation model

$^{15}\text{N}/^{14}\text{N}$ in Jupiter

$[^{15}\text{N}/^{14}\text{N}]_J$ is solar

$[^{15}\text{N}/^{14}\text{N}]_J/E = 0.5$

-> Nitrogen came in Jupiter in the form of N$_2$, on Earth from meteorites/comets (HCN, NH$_3$)

ISO (1)

Giant Planets: Origins

D/H from H$_2$

Feuchtgruber et al. 1999; Lellouch et al. 2002

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ISO (2)
Giant Planets: External oxygen flux

Origin?
- Local source (satellites, rings)
- Interplanetary source
  - flux of meteoroids
  - comets (Jupiter: SL9?)

Feuchtgruber et al. 1997

Lellouch et al. 2002
ISO (3)
Comets and small bodies

- Comets
  - H$_2$O in Hale-Bopp and Hartley 2
  - Crystallized silicates in Hale-Bopp
- Asteroids
  - Surface Mineralogy
  - Thermophysical surface studies
- Zodiacal light
  - Temperature structure

![Diagram of zodiacal light and comet spectra](image)
• 1998-2005
• Water mapping on Venus
• H₂O & CO on Mars
• H₂O on Jupiter and Saturn
• 2003-2009
• TNOs and Centaurs
  – Sample of 47 objects
    (24 µm, 70 µm)
  -> albedos & sizes
  Stansberry et al 2008

• Neptune: New hydrocarbons
  (CH₃C₂H, C₄H₂)
  Meadows et al. 2008
• 2001-2012
• Comets
  – 12 comets (2001-05)
  – H$_2$O, H$_2^{18}$O, NH$_3$
  – Evolution with Rh

Biver et al. 2007, 2009
Open questions for Herschel (1)

Planets (KP «HssO » - Water in the solar system + OT programs)

Mars
- What is the vertical distribution of water vapor on Mars?
- What are the abundances of the minor species and their isotopic ratios?
  - -> Photochemistry and dynamics in the Martian atmosphere
  - -> History of the Martian atmosphere

Outer planets
- What is the origin of the external oxygen flux in the outer solar system?
  - -> Local/interplanetary source, role of comets/rings/satellites?
Comets (KP « HssO » + OT Programs)

- What can we learn from water in comets?
  - Thermodynamics of the coma

- What is the D/H in Oort cloud and Kuiper Belt comets?
  - Implication on the origin of water on Earth
  - From D/H in meteorites: Possible origin from asteroids of the main outer belt (Morbidelli et al. 2000)
Open questions for Herschel (3)

- **TNOs (KP « TNOs are cool »)**
  - What are the sizes & albedos of TNOs?
    - -> Measurement of both reflected and thermal components
    - -> Testing predictions from the various formation/evolution scenarios
  - What are the thermal surface properties of TNOs?
    - -> Information on structure/porosity

![Figure 1](image1.png)

**Figure 1**
- Left: STM (standard model) flux predictions for a 1000 km TNO at different distances from the Sun.
  - As input parameters we used the averaged Spitzer values of 1.25 for the beaming parameter $g$ and 0.08 for the geometric albedo $p_V$.
  - For comparison, a 100 km TNO at 20 AU is shown together with a detection limit of 3 mJy.
- Right: Influence of the surface properties on the thermal flux, based on thermophysical model (TPM) calculations. We show here the ratio of the flux to what is expected from a ''default TPM TNO'' model (best fit to all Spitzer TNO results).
  - The thermal inertia causes major uncertainties at wavelengths below the emission peak, while the unknown emissivities affect mainly the sub-mm/mm range.
  - The influence of extreme surface roughness conditions (perfectly smooth, or completely covered by craters) is indicated by the dashed lines.

![Figure 4](image2.png)

**Figure 4**
- Overview of our Herschel sample (squares) in comparison with the currently known Centaurs and TNOs (dots).
  - Top: Inclination vs. semimajor axis.
  - Bottom: Eccentricity vs. semimajor axis. The size of the square-symbols indicates the opposition H-magnitude, the regions of Centaurs, Kuiper Belt und Scattered Disk are indicated together with the semimajor axis of the outer planets.

Mueller et al. 2009
Herschel Highlights

**Mars** P 5-5, P 5-6
- H$_2$O, CO, O$_2$, isotopic ratios (HIFI, SPIRE)(Hartogh +10; Swinyard +10)

**Giant planets & satellites** P 5-3, P 5-6, P 5-10
- D/H in Uranus and Neptune (PACS) (Feuchtgruber et al. 2013)
  - E. Lellouch’s talk today
- Stratospheric water in the giant planets and Titan (PACS, HIFI)
  - (Cavalié et al. 2013, Moreno et al. 2013)
- Atmospheric composition of Titan M. Rengel’s talk today
- Water torus of Enceladus (HIFI) (Hartogh et al. 2011)
- H$_2$O atmosphere around Ganymede and Callisto
  - P. Hartogh’s talk on Thursday

**Asteroids** P 5-12, P 5-13
- H$_2$O around Ceres (Kueppers et al. 2013) D. Bockelée-Morvan’s talk on Thursday
- Thermal inertia of Vesta (Leyrat et al. 2012) and Lutetia (O’Rourke et al. 2012)

**Comets:** H$_2$O, NH$_3$, D/H P 5-1, P 5-2, P 5-4, P 5-6, P 5-7, P 5-11, P 5-15
  (Hartogh +11, Bockelée-Morvan +12, Lis +13, Biver +13)

**TNOs** P 5-8, P 5-9, P 5-14
- Sizes/albedos of all classes of TNOs (130 with PACS, 11 with SPIRE)
  (Mueller+10, Lim+10, Lellouch+10, Vilenius+12, Mommert+12, Santos-Sanz+12, ...)
  T. Mueller’s talk on Thursday
- Physical and thermal properties of bright TNOs (PACS, SPIRE)
  (Lellouch et al. 2013, Fornasier et al. 2013, S. Fornasier’s talk on Thursday)
Mars

- A new measurement of O₂ + search for latitudinal variations (HIFI)
  Hartogh et al. 2010a, Poster 5-5
- Isotopic lines of CO (HIFI, SPIRE)
  Hartogh et al. 2010b, Swinyard et al. 2010
- An upper limit on HCl: < 0.2 ppb (HIFI)
  Hartogh et al. 2010a
- On-going studies on isotopic ratios
  D/H, ¹⁸O/¹⁶O, ¹³C/¹²C

![Graph showing signal/continuum vs frequency for CO and H₂O](image1)

![Graph showing signal/continuum vs frequency for C-18-O and 13-CO](image2)

Table 1.

<table>
<thead>
<tr>
<th>J</th>
<th>K</th>
<th>L</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9–8</td>
<td>5</td>
<td>3</td>
<td>1036.91</td>
</tr>
<tr>
<td>6–5</td>
<td>4</td>
<td>3</td>
<td>691.49</td>
</tr>
<tr>
<td>8–7</td>
<td>4</td>
<td>2</td>
<td>936.97</td>
</tr>
<tr>
<td>9–8</td>
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<td>4</td>
<td>1314.22</td>
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<tr>
<td>10–9</td>
<td>5</td>
<td>3</td>
<td>1382.0</td>
</tr>
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<td>11–10</td>
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<td>1228.79</td>
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<td>5</td>
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<td>6</td>
<td>5</td>
<td>1314.22</td>
</tr>
<tr>
<td>11–10</td>
<td>7</td>
<td>4</td>
<td>1562.88</td>
</tr>
</tbody>
</table>

Swinyard et al. 2010
Detection of water vapor around Ceres (HIFI)

557 GHz H₂O line detected with HIFI in October 2012 and March 2013
Kueppers et al., in press (more during D. Bockelée-Morvan’s talk on Thursday)
The origin of water in Jupiter

- \( \text{H}_2\text{O} \) in Jupiter (PACS/HIFI)
  - \( \text{H}_2\text{O} \) is above the 2 mbar level
  - Decreases from south to north latitudes
  - > Origin must be the SL9 collision

Cavalié et al. 2013, Poster 5-3

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**Figure 1**: Line peak intensity \([l/c-1]\) at 65.2 \(\mu\)m.

**Figure 2**: Velocity [km.s\(^{-1}\)] map.

**Figure 3**: Histogram of line ratio (IRTF/TEXES).

**Figure 4**: MIRSI images of Jupiter's stratosphere.

**Figure 5**: IRTF observations of Jupiter.

**Figure 6**: PACS images of Jupiter.

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### HIFI Observations

- **Line Intensity**: \([l/c-1]\) at 65.2 \(\mu\)m.
- **Velocity**: [km.s\(^{-1}\)].
- **Histogram**: Line ratio (IRTF/TEXES).
- **Images**: MIRSI, IRTF/TEXES, PACS.

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**Table**: Radiance vs. emission angle.

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**Equation**: 
\[
\text{Water mixing ratio} = \frac{\text{Number of molecules}}{\text{Total number of molecules}}
\]
The origin of water in the system of Saturn

- Detection of the water torus generated by Enceladus (HIFI)
  - Cryovolcanism on Enceladus has been reported by Cassini
  - Using appropriate geometry, HIFI has detected the H$_2$O torus generated by Enceladus, in absorption in front of the H$_2$O emission of Saturn

- H$_2$O in Titan (PACS/HIFI) Moreno +13
  - Oxygen flux is weaker than previously inferred from ISO
    - Enceladus cryovolcanism is sufficient to explain Saturn & Titan’s external water

Hartogh et al. 2011

Moreno et al. 2013
D/H in comets

- From previous measurements:
  \[ \text{D/H} = 2 \text{[D/H]}_E \text{ in Oort cloud comets} \]
  (Halley, Hyakutake, Hale-Bopp)

**Results from Herschel/HIFI:**

- Jupiter-family comets
  - Hartley 2: \( \text{D/H} = [\text{D/H}]_E \) (Hartogh et al. 2011)
  - 45 P/Honda-Mrkos-Pajdusakova: \( \text{D/H} < 1.3 \text{[D/H]}_E \)
    -> Consistent with Hartley 2 (Lis et al. 2013)

- Oort-cloud comet C/2009 P1(Garradd)
  \( \text{D/H} = 1.32 \text{[D/H]}_E \) (Bockelée-Morvan et al. 2012)

> There is some diversity among the Oort cloud comets

> Their D/H is still enriched wrt the ocean value

Bockelée-Morvan et al. 2012, *Poster 5-2*
Transneptunian objects and asteroids: Sizes, albedos and thermal properties

Albedos and sizes of TNOs
- PACS: 130 objects, SPIRE: 11 objects
- Classical objects (19): \( a = 0.17 \) (cold), 0.11 (hot)
- Plutinos (18): \( a = 0.08 \)
- Scattered disk & detached (15): \( a = 0.07 \) (SDOs), 0.17 (detached)
  T. Mueller’s talk on Thursday

Densities of binary systems (Fornasier +13, talk on Thursday)
- Quaoar: \( 2.2 \text{ g/cm}^3 \) - high refractory content
- Orcus: \( 1.5 \text{ g/cm}^3 \); Salacia: \( 1.3 \text{ g/cm}^3 \)

Thermal properties of TNOs Poster 5-9
- PACS & SPIRE: 9 objects (thermal inertia, surface emissivity)
- Low thermal inertia (\( \Gamma = 2.5 \text{ Jm}^{-2}\text{s}^{-1/2} \text{ K}^{-1} \), decreasing as \( R_h \) increases) - highly porous surfaces (Lellouch et al. 2013)

Thermal properties of asteroids
- Vesta: \( \Gamma = 20 \text{ Jm}^{-2}\text{s}^{-1/2} \text{ K}^{-1} \) - consistent with fine regolith (Leyrat +13)
- Lutetia: \( \Gamma = 5 \text{ Jm}^{-2}\text{s}^{-1/2} \text{ K}^{-1} \) - region of small scale roughness (O’Rourke +13)
- 1999 RQ₃₆ (Osiris-Rex target): Physical & thermal properties, \( \Gamma = 650 \text{ Jm}^{-2}\text{s}^{-1/2} \text{ K}^{-1} \) - rubble pile nature (cf. Itokawa, Mueller et al. 2012)
What is needed after Herschel?

A better sensitivity
- To enlarge the sample of Jupiter-family comets
- To detect more parent molecules in comets (HCl, HF...)
- To enlarge the sample of TNOs toward smaller sizes & PANSTARRS/GAIA targets
- To characterize the surface of bright TNOs by FIR spectroscopy
- > SPICA-type mission

A higher spatial resolution
- To identify water jet structures in comets
- To map H₂O in giant planets and Titan
- To study asteroid/TNOs binaries

Follow-up with ALMA
- HDO in Mars, Venus, giant planets and Titan
- CO on Mars and Venus -> winds
- HDO, HCl & Sulfur species on Venus
- Parent molecules in comets: Detection and mapping; deuterated species
- Activity of distant comets & Centaurs
- TNOs: albedos and sizes of binaries
  - Typical sizes: 0.1 – 1 arcsec