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

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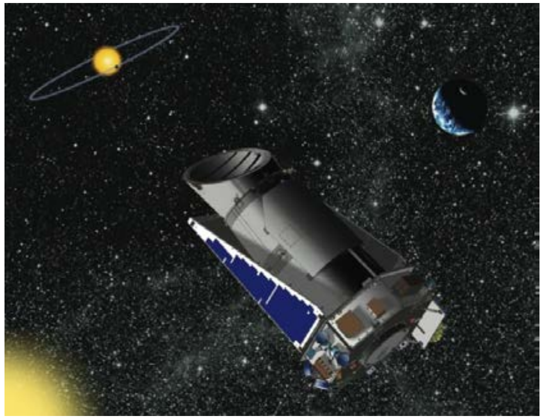
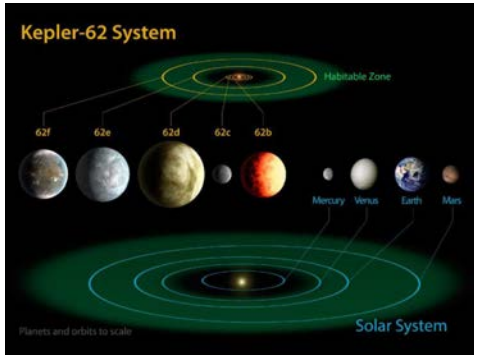
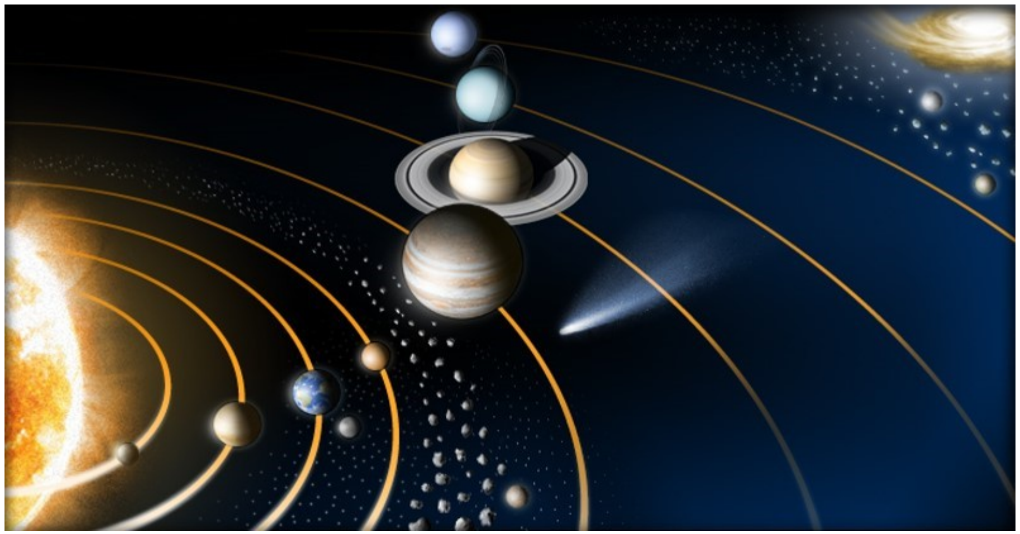
« The Universe explored by Herschel », Noordwijk, 15-18 october 2013

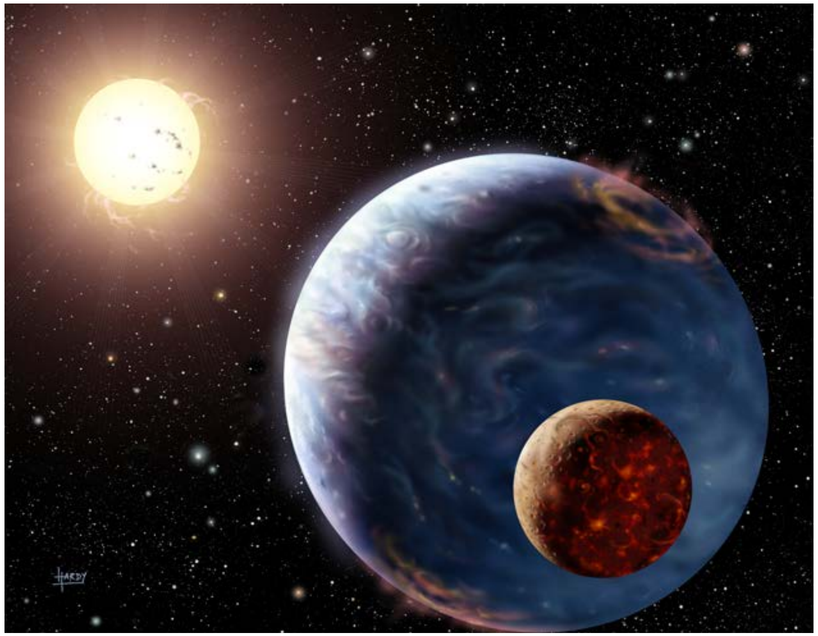


A revolution in Astronomy



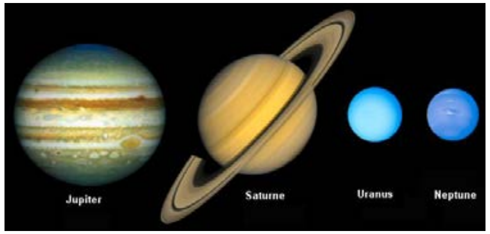
- We know about a thousand exoplanets today
- Each star in the Galaxy might host at least a planet
- **We are surrounded by billions of planetary systems, but the Solar system is the only one we can explore at depth**





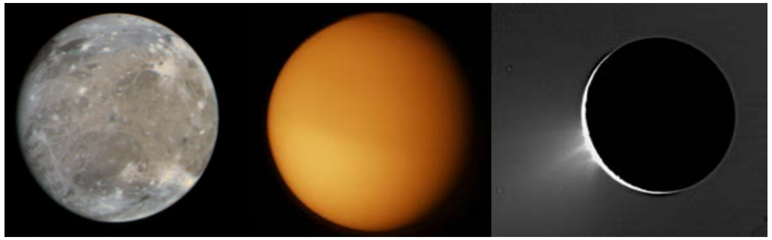
Key questions about the Solar system formation and evolution (1)

- **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, PH_3)
  - > internal structure
- Minor species and isotopes on Mars (O_2 and oxygen isotopes in CO on Mars)
- Search for tiny atmospheres on Galilean satellites (H_2O on Ganymede & Callisto)
- Elemental & isotopic abundances in Titan ($^{18}O/^{16}O$)
- Origin of water in Saturn's system (H_2O torus around Enceladus, H_2O on Titan)

Key questions about the Solar system formation and evolution (2)

- **What can we learn from the diversity of comets?**

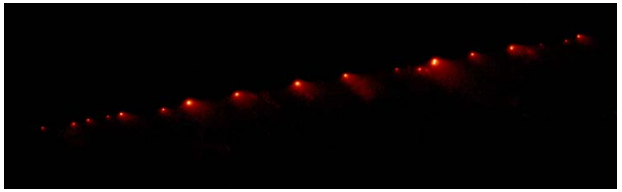


- Characterize the Oort and Kuiper Belt families
  - > H_2O, NH_3 in comets, D/H in Kuiper belt comets

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

- Albedos and sizes of TNOs
- Surface characterization of brightest TNOs

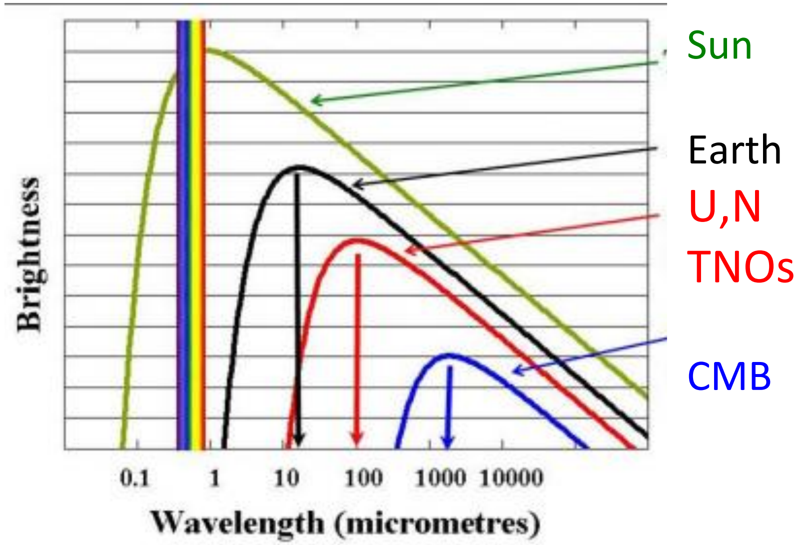
- **Can we characterize the oxygen flux in the outer solar system?**



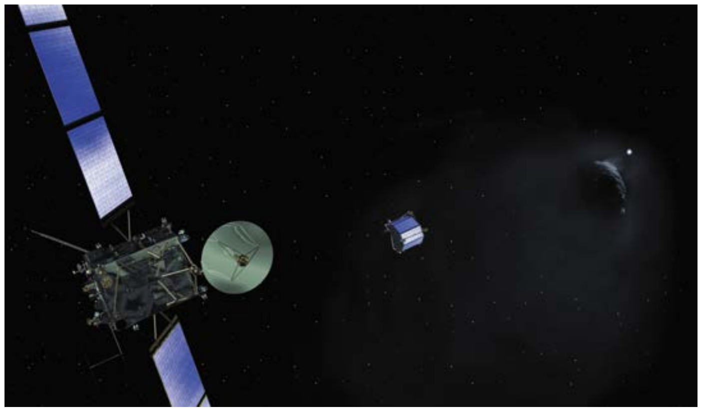
- Stratospheric water in giant planets and Titan

The outer Solar system is best explored by far IR/submm remote sensing

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



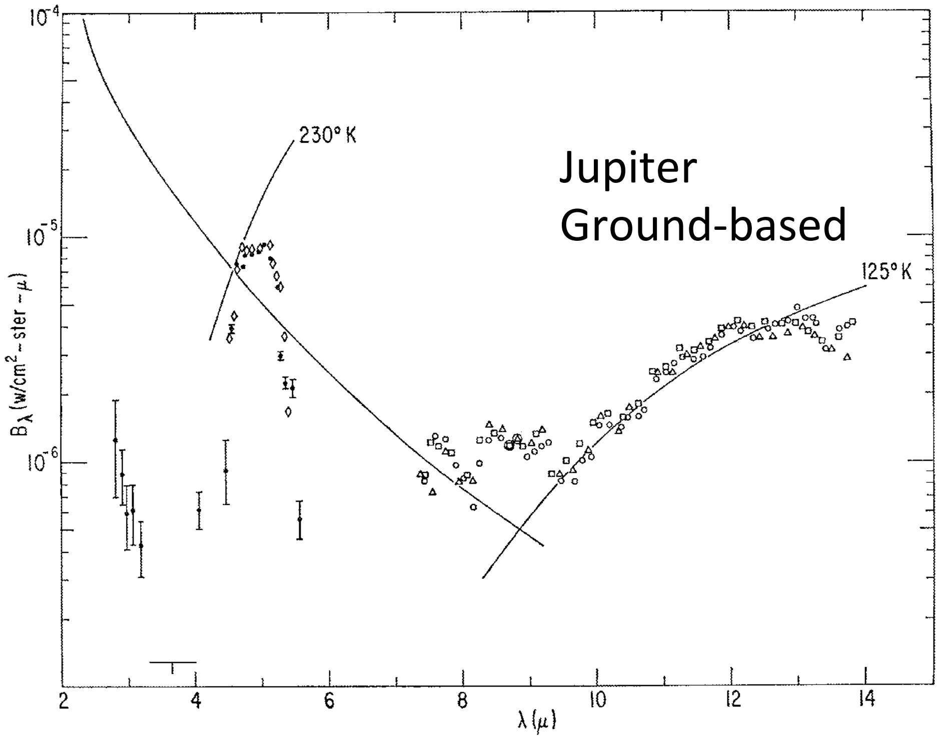
Herschel

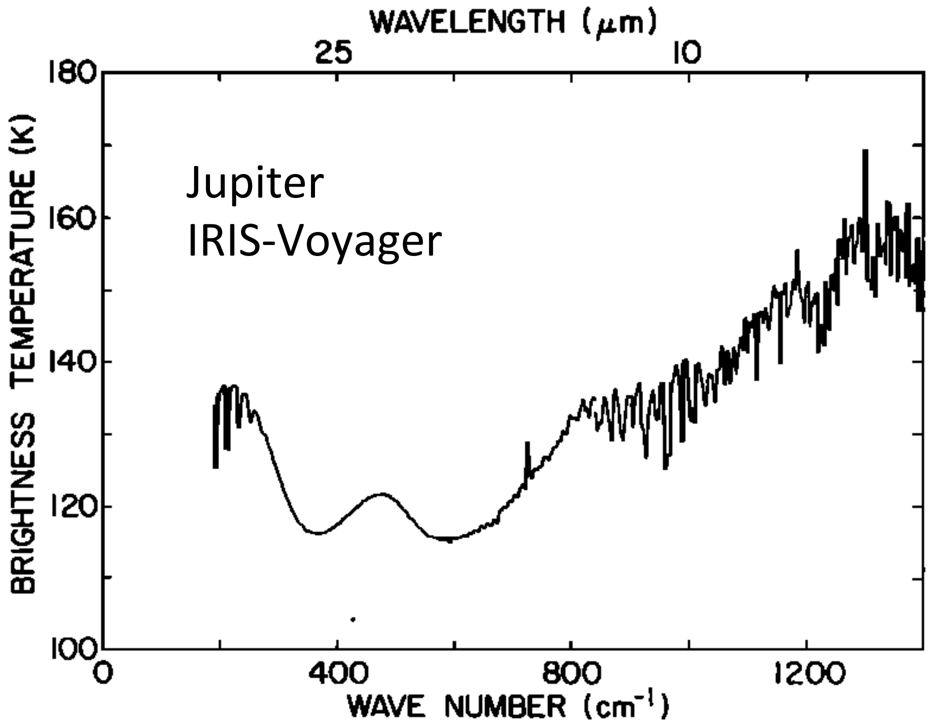


Rosetta

A milestone in infrared planetary science

Evidence for an internal energy source in the giant planets (except Uranus)





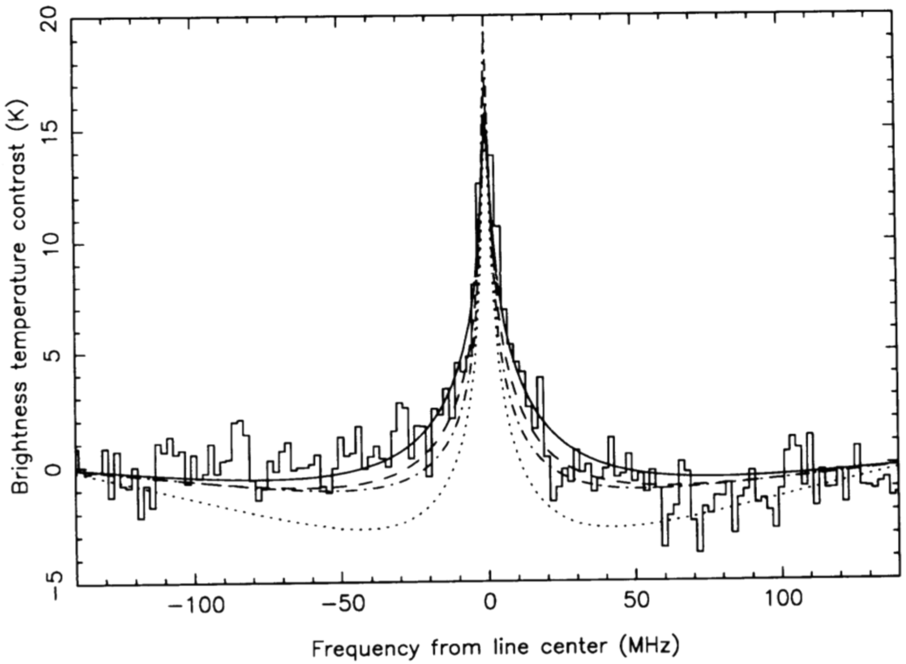
Gillett, 1969
T_B = 125 K

Hanel et al., 1981
T_B = 124.4 K

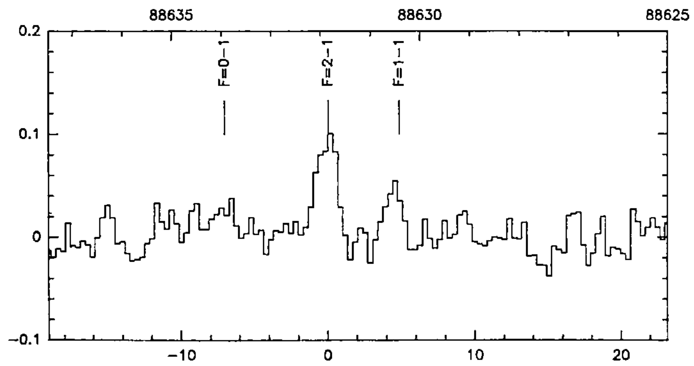
Jupiter: Evidence for an internal energy source, 1.7 times the absorbed solar energy (T_{eq} = 110 K)
Probable origin: Gravitational contraction

Planetary science: Milestones in the millimeter range (IRAM-30m)

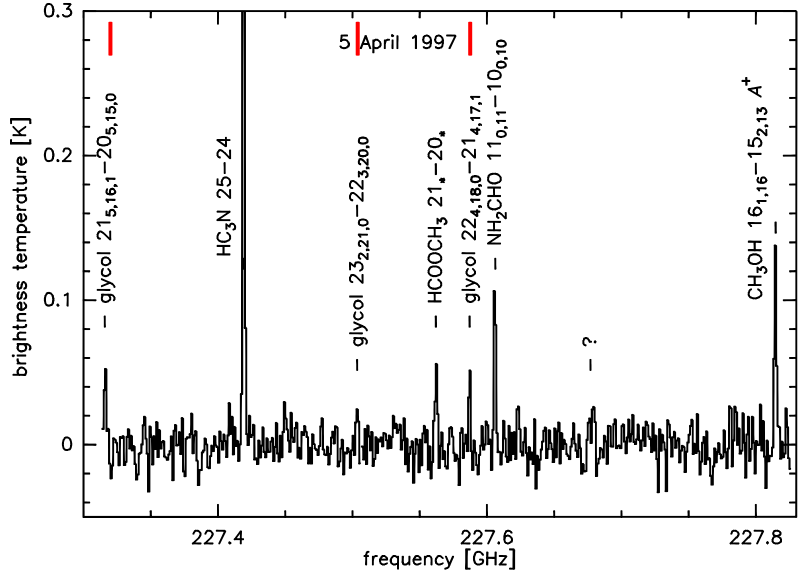
HCN in Comet Halley (1986)
$HOCH_2CH_2OH$ (ethylene glycol) in Comet Hale Bopp (2004)
CO and HCN in Neptune (1992)
-> evidence for disequilibrium processes



CO in Neptune: 10^{-6} (expected: 10^{-9})
Rosenqvist et al. 1992



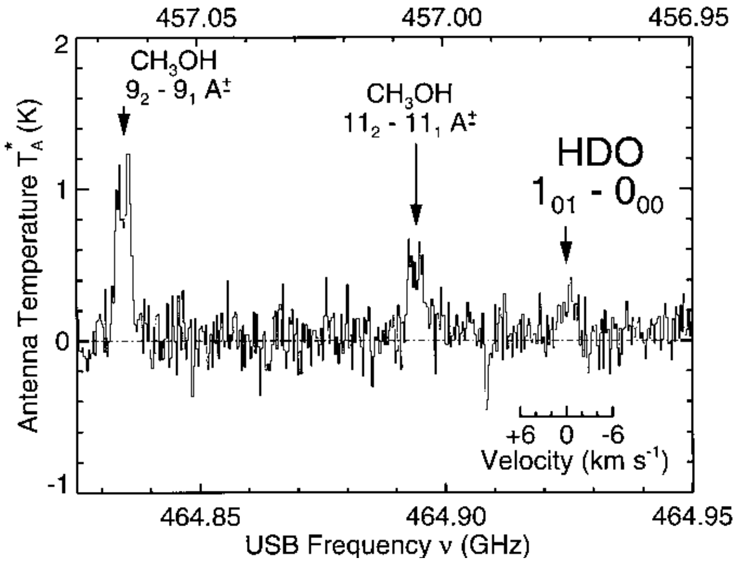
First detection of HCN in a comet (P/Halley) Despois et al. 1983



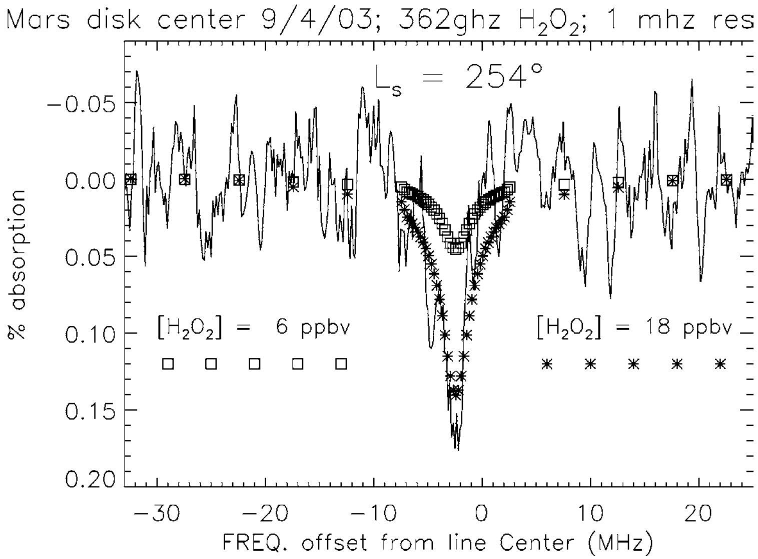
First detection of ethylene glycol in a comet (Hale Bopp) Crovisier et al. 2004

Planetary science: Milestones in the submillimeter range (JCMT, CSO)

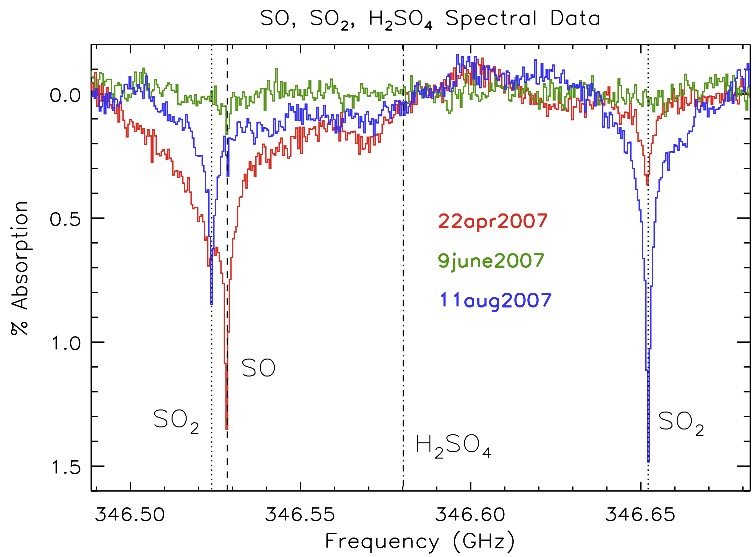
- D/H in 2 Oort cloud comets (1998)
- H_2O_2 on Mars (2004)
- Mesospheric sufur species and HCl on Venus (2010, 2012a, b)



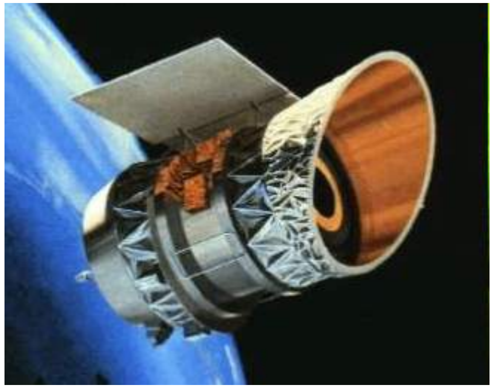
HDO in Comet Hale-Bopp (Meier et al 1998)



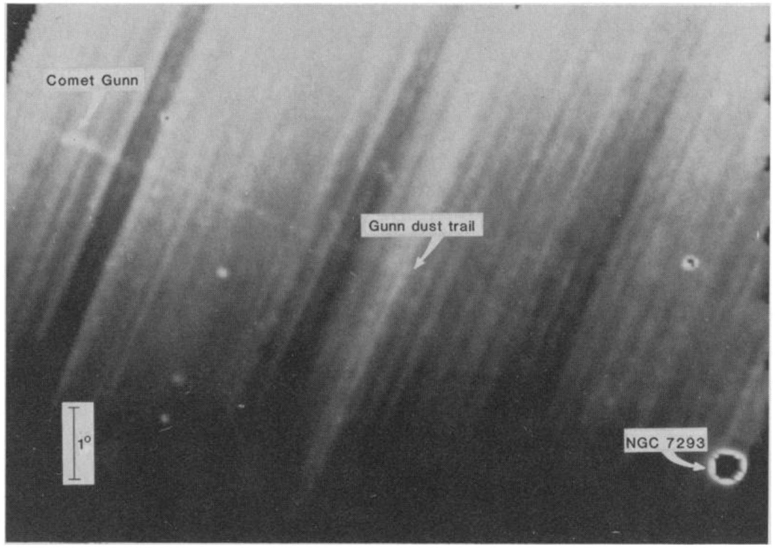
H_2O_2 on Mars (Clancy et al. 2004)



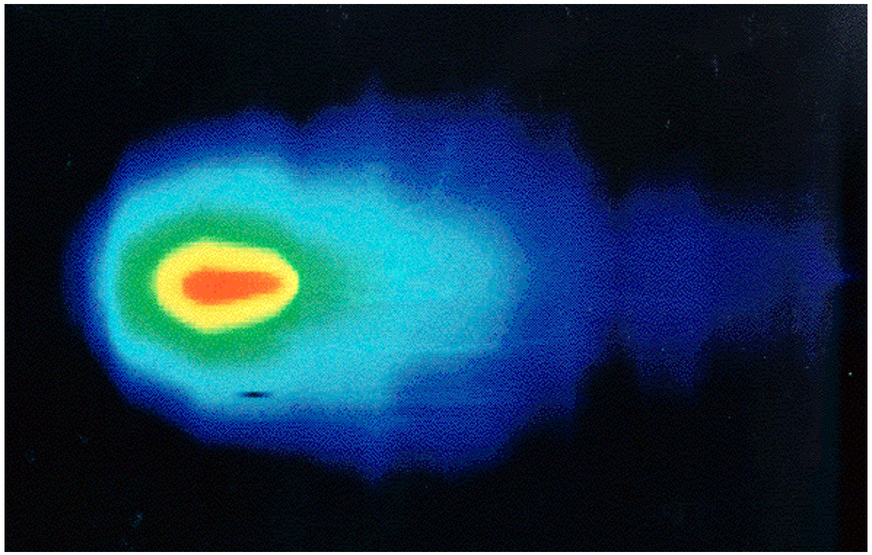
SO_2 & SO in the mesosphere of Venus (Sandor et al. 2012)



IRAS



Sikes et al. 1986
Comet IAA (©IPAC, Caltech)



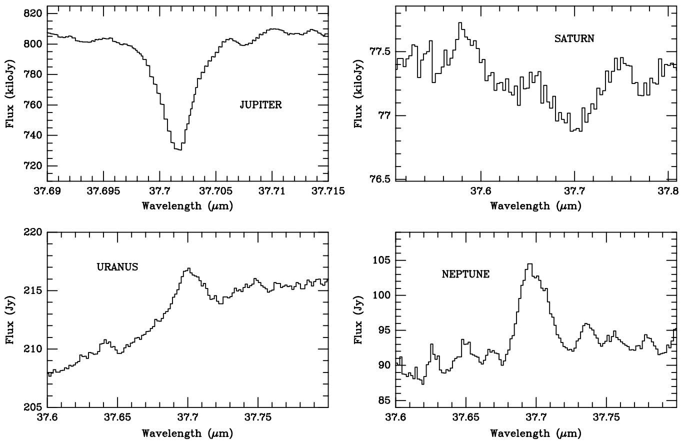
- 1983
- Discovery of dust trails
  - Sykes, Science 1986
- Discovery of new comets
  - IRAS-Araki-Alcock, 1983
- Pluto-Charon @ 60-100 μm
  - Sykes, Science 1987

ISO (1)
Giant Planets: Origins

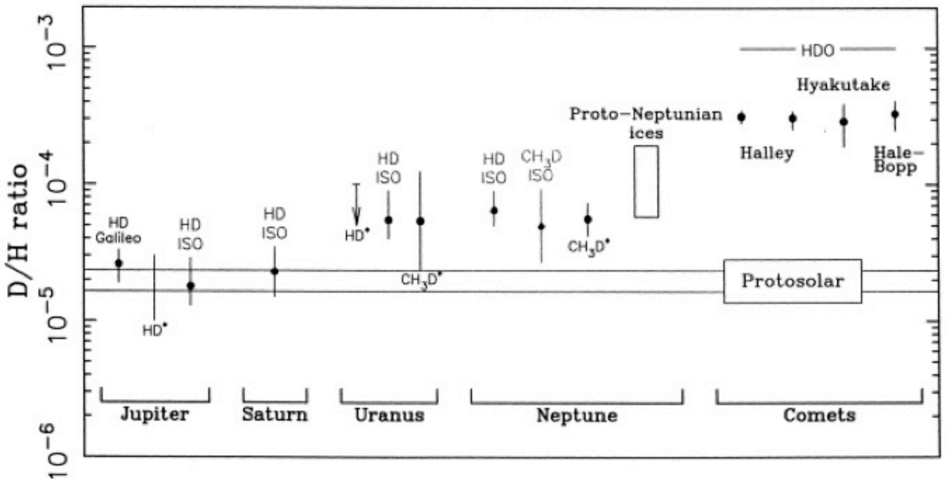
D/H from H_2

Deuterium enriched in icy giants

-> Support to nucleation model



Feuchtgruber et al. 1999; Lellouch et al. 2002



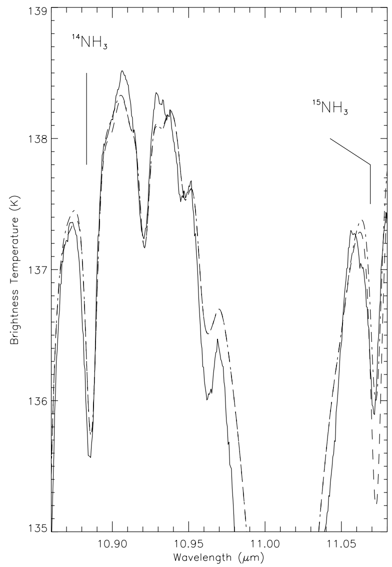
Encrenaz et al. 1999

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

$[^{15}N/^{14}N]J$ is solar

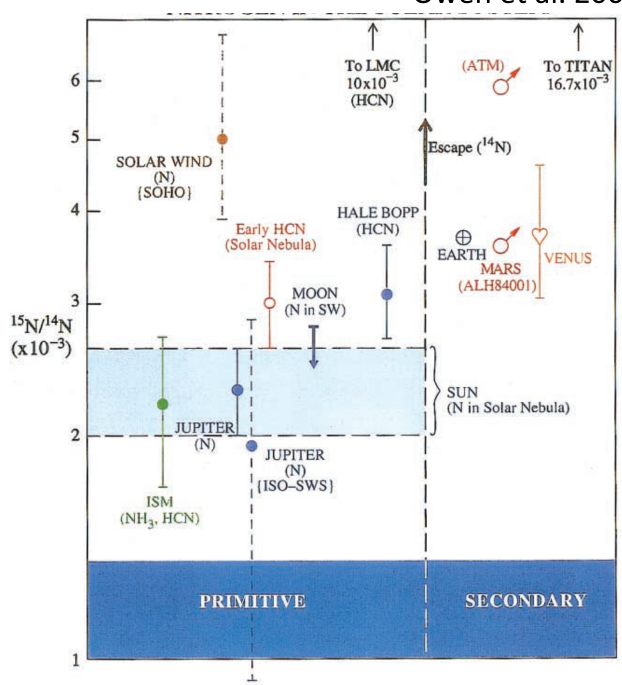
$[^{15}N/^{14}N]J/E = 0.5$

-> Nitrogen came in Jupiter in the form of N_2, on Earth from meteorites/comets (HCN, NH_3)



Fouchet et al. 2000

Owen et al. 2001



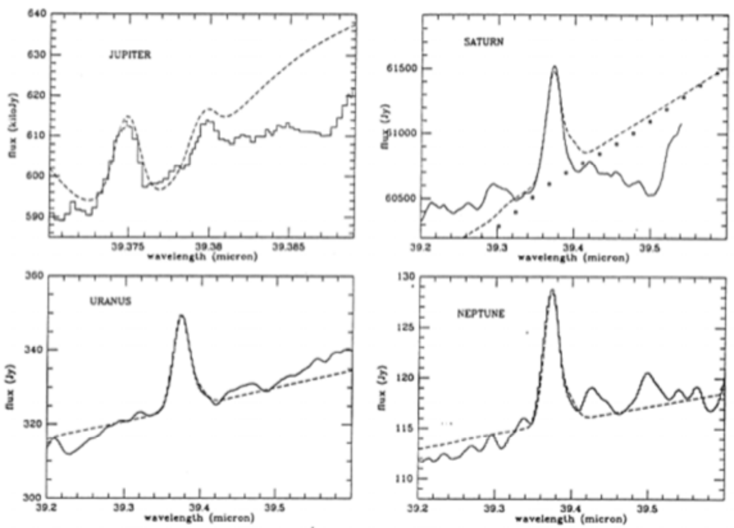
ISO (2)
Giant Planets: External oxygen flux

Origin?

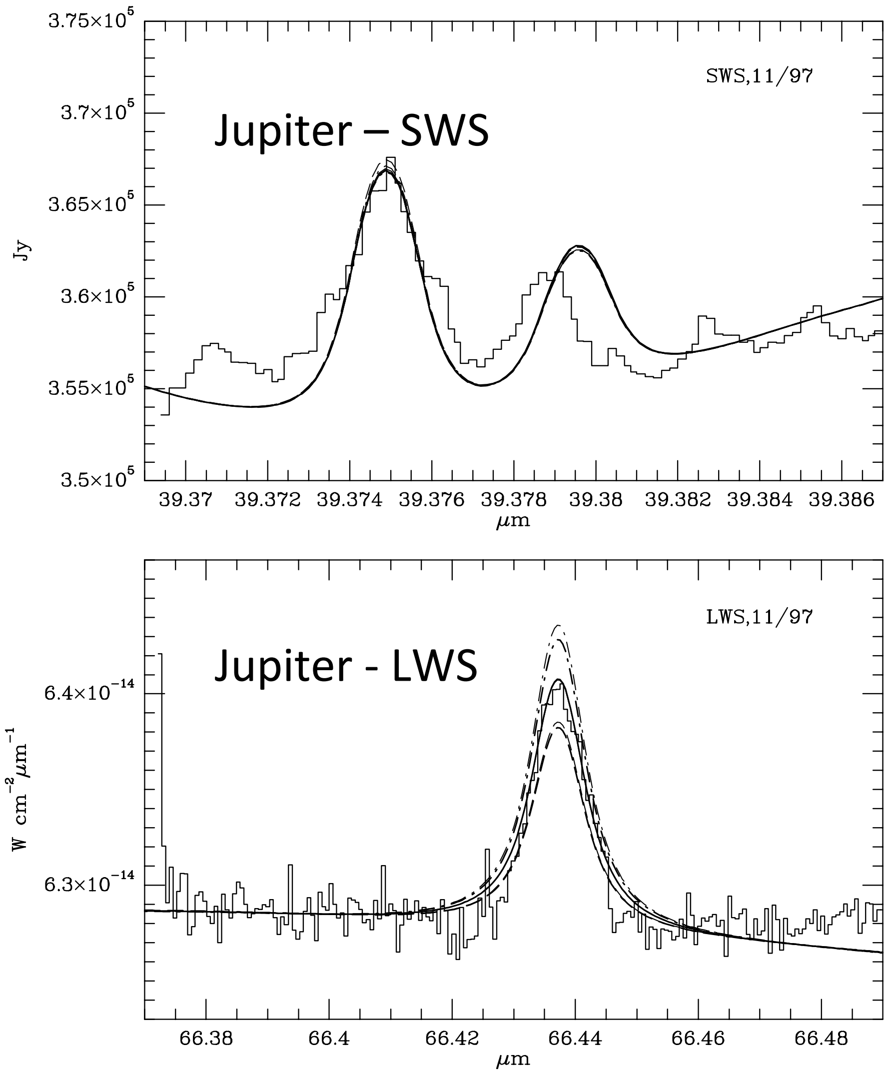
-Local source (satellites, rings)

-Interplanetary source

- flux of meteoroids
- comets (Jupiter: SL9?)



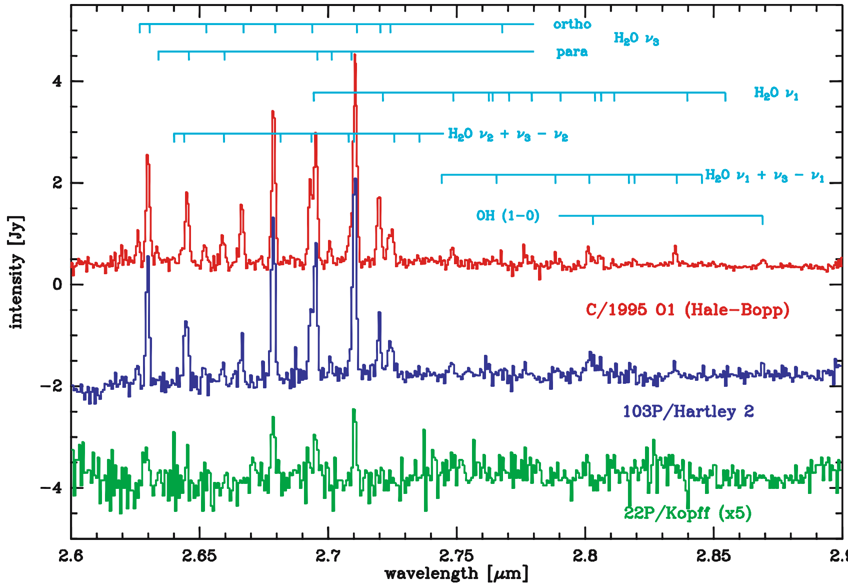
Feuchtgruber et al. 1997



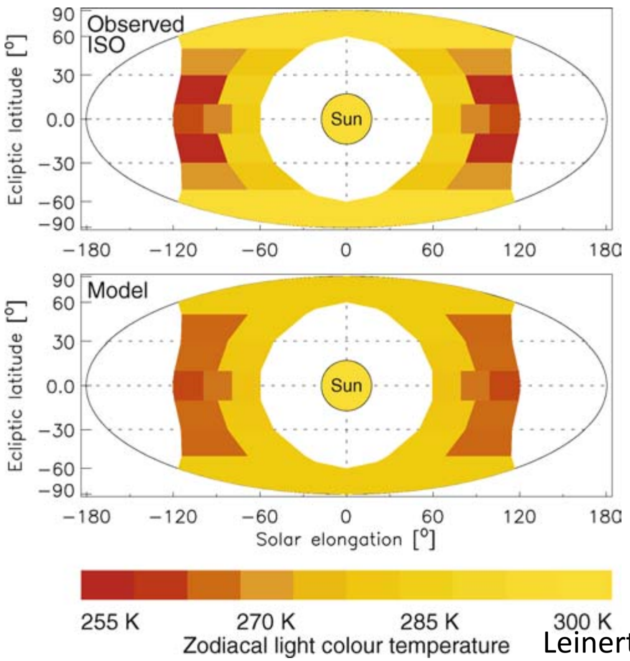
Lellouch et al. 2002

ISO (3)
Comets and small bodies

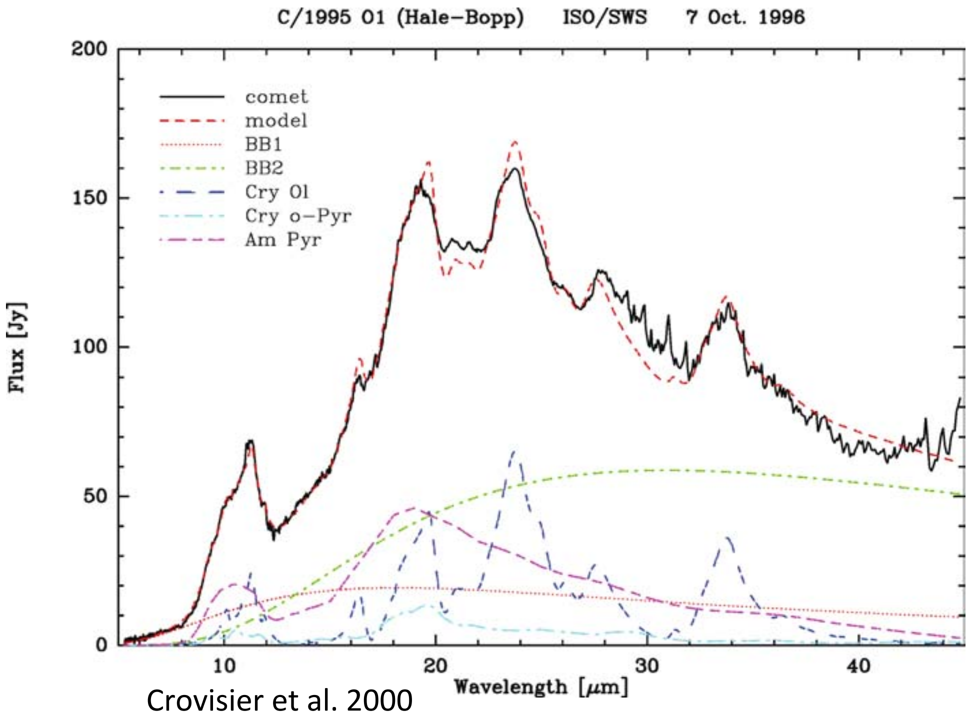
- Comets
  - H_2O in Hale-Bopp and Hartley 2
  - Crystallized silicates in Hale-Bopp
- Asteroids
  - Surface Mineralogy
  - Thermophysical surface studies
- Zodiacal light
  - Temperature structure



Crovisier et al. 1997, 1999



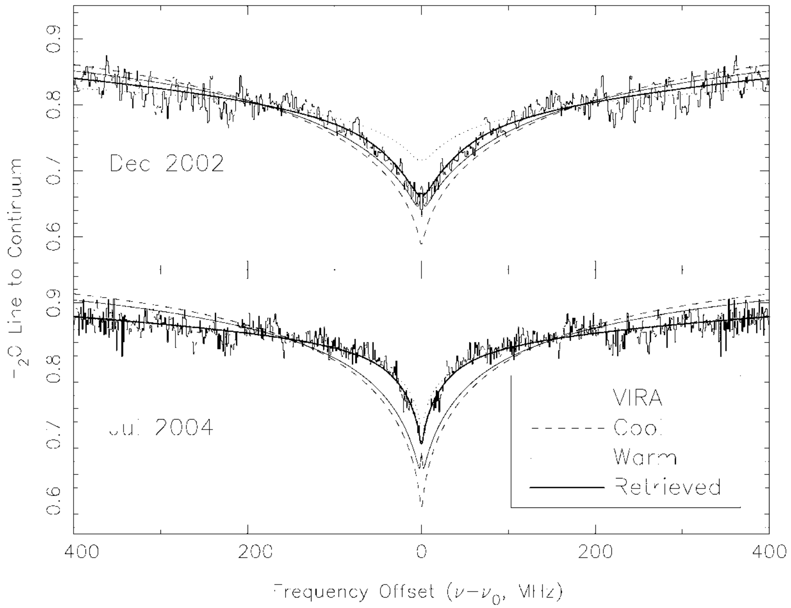
Leinert et al. 2002



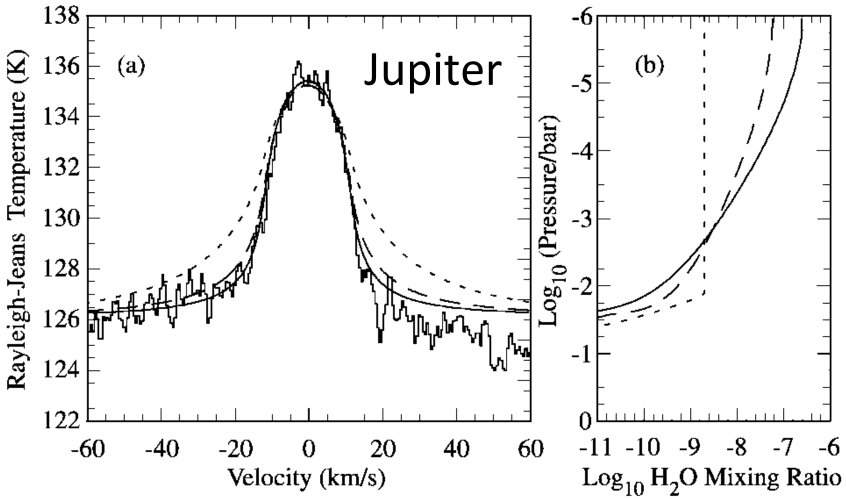
Crovisier et al. 2000

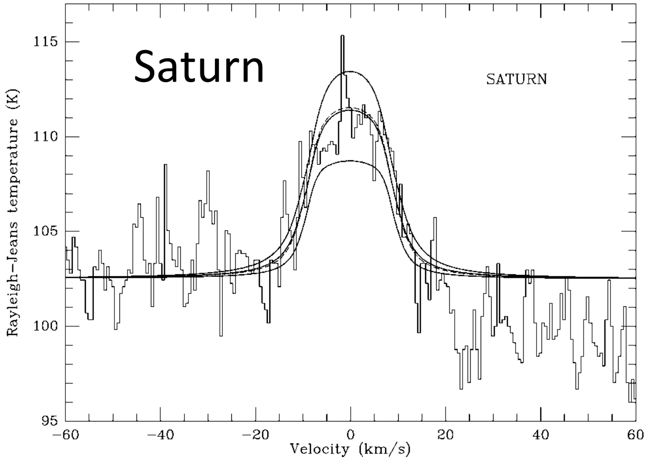
SWAS

- 1998-2005
- Water mapping on Venus
- H_2O & CO on Mars
- H_2O on Jupiter and Saturn

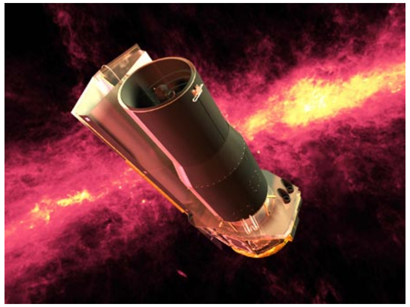


H_2O on Venus (Gurwell et al 2007)



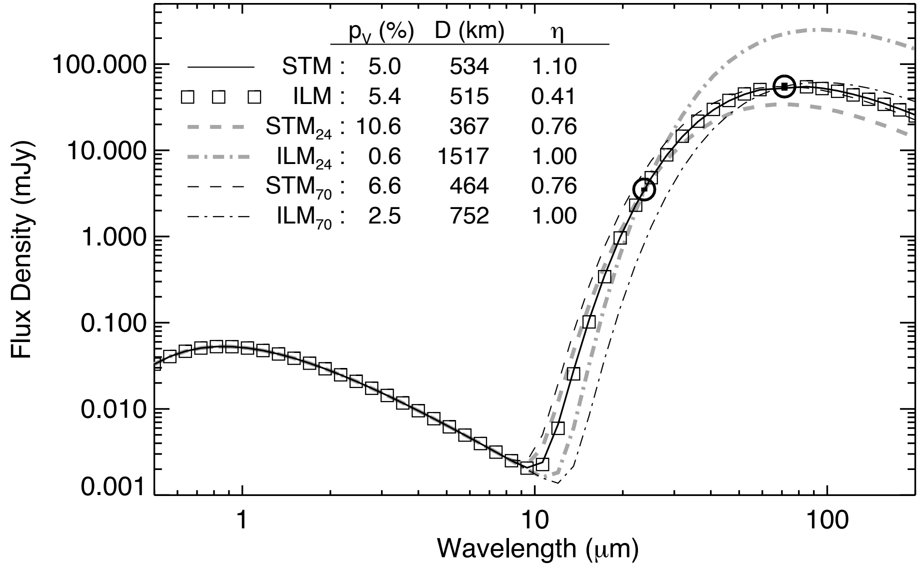


H_2O in Jupiter and Saturn (Bergin et al 2000)



Spitzer

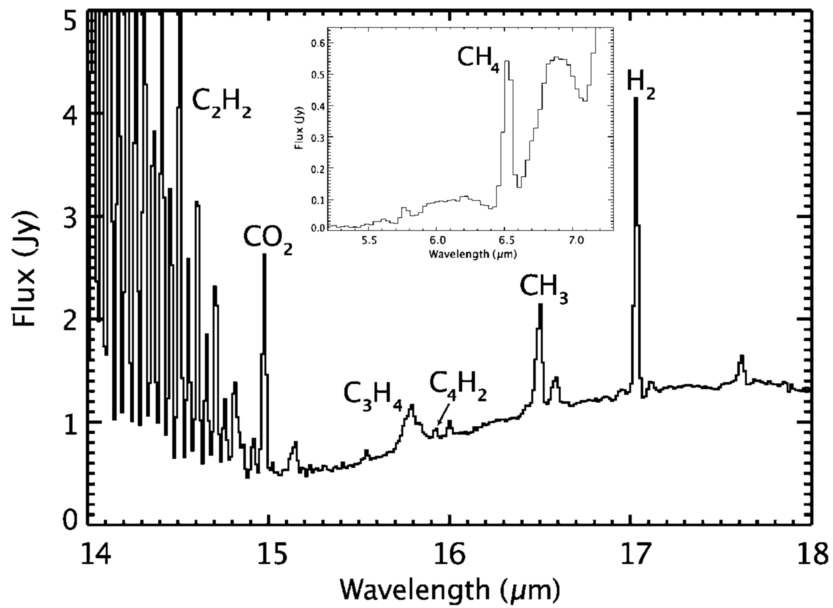
- 2003-2009
- TNOs and Centaurs
  - Sample of 47 objects (24 μm, 70 μm) -> albedos & sizes

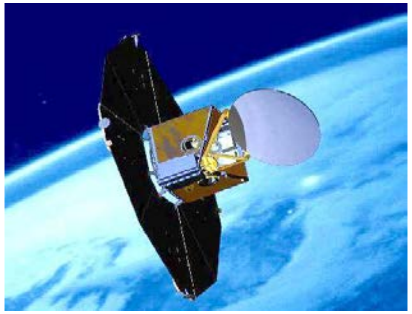


Stansberry et al 2008

- Neptune: New hydrocarbons (CH_3C_2H, C_4H_2)

Meadows et al. 2008

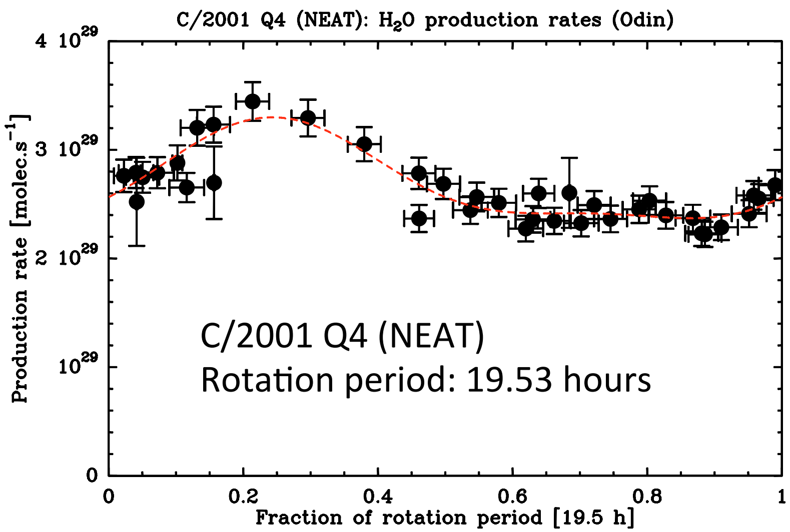


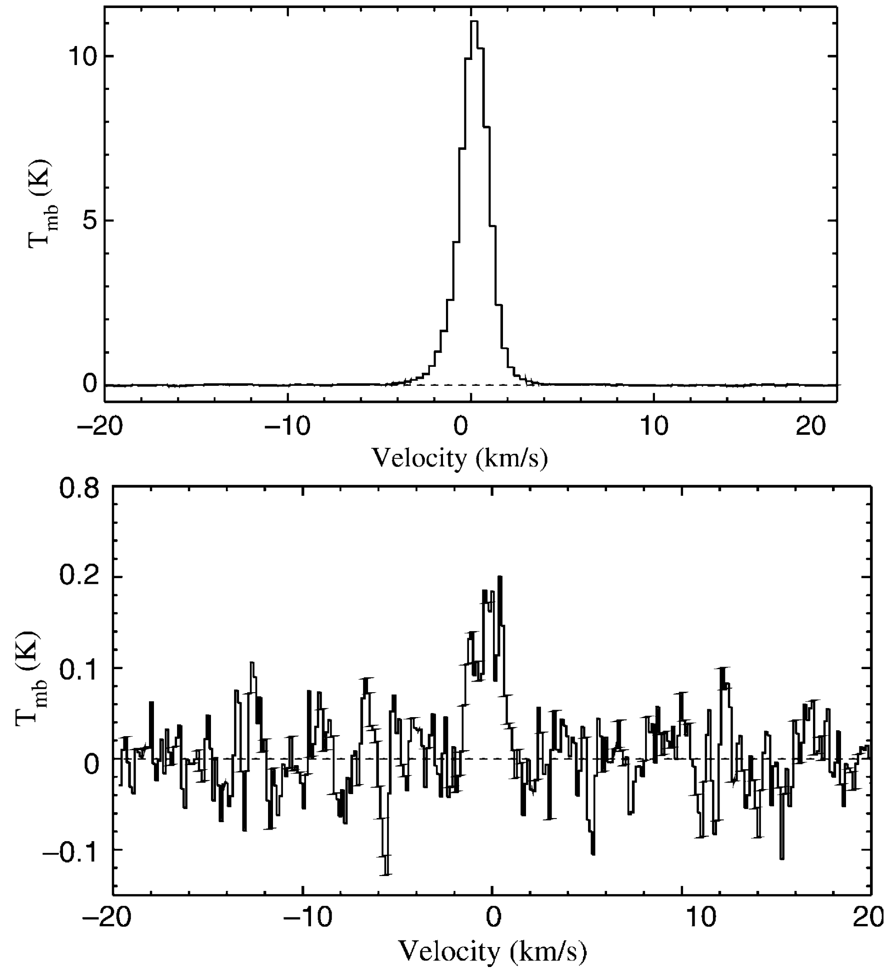


Odin

- 2001-2012
- Comets
  - 12 comets (2001-05)
  - H_2O, $H_2{}^{18}O$, NH_3
  - Evolution with Rh

Biver et al. 2007, 2009





H_2O and $H_2{}^{18}O$ in Comet C/2001 Q4 (NEAT)

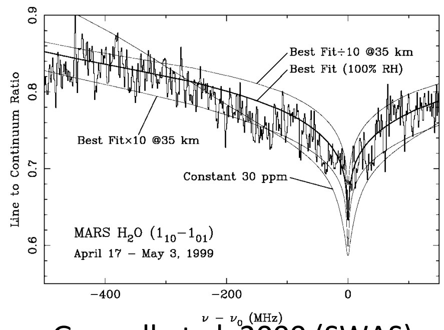
Hjalmarson et al. 2005

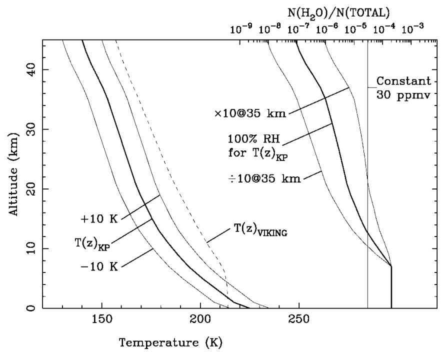
Open questions for Herschel (1)

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

Mars

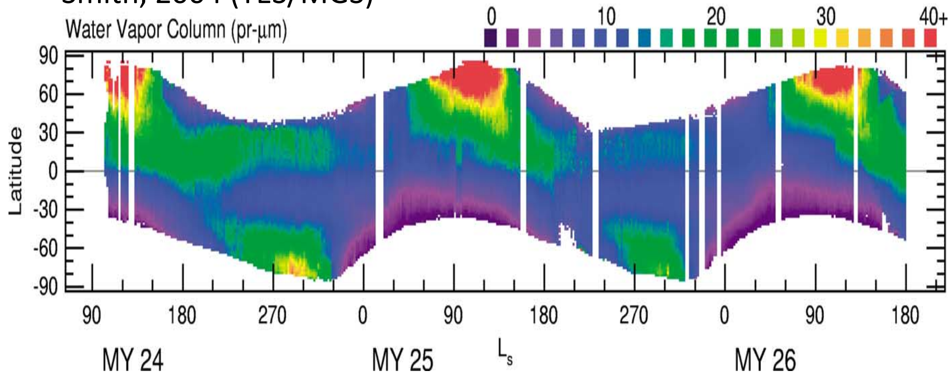
- What is the vertical distribution of water vapor on Mars?
- What are the abundances of the minor species and their isotopic ratios?
  - -> Photochemistry and dynamics in the Martian atmosphere
  - -> History of the Martian atmosphere





Gurwell et al. 2000 (SWAS)

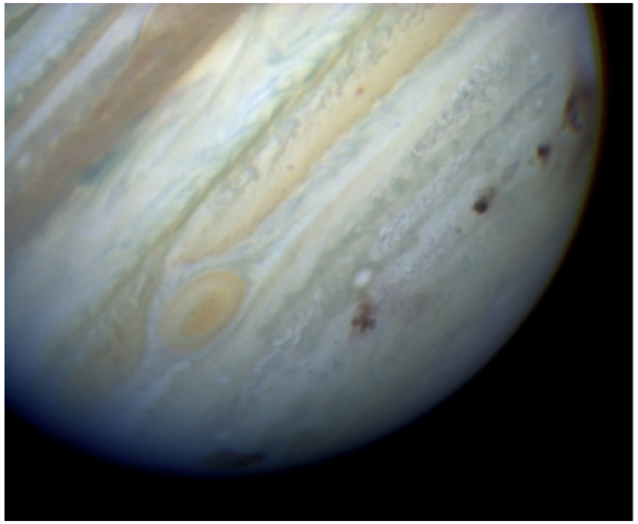
Smith, 2004 (TES/MGS)



Outer planets

- What is the origin of the external oxygen flux in the outer solar system?
  - -> Local/interplanetary source, role of comets/ rings/satellites?

© HST, 1994



Open questions for Herschel (2)

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)

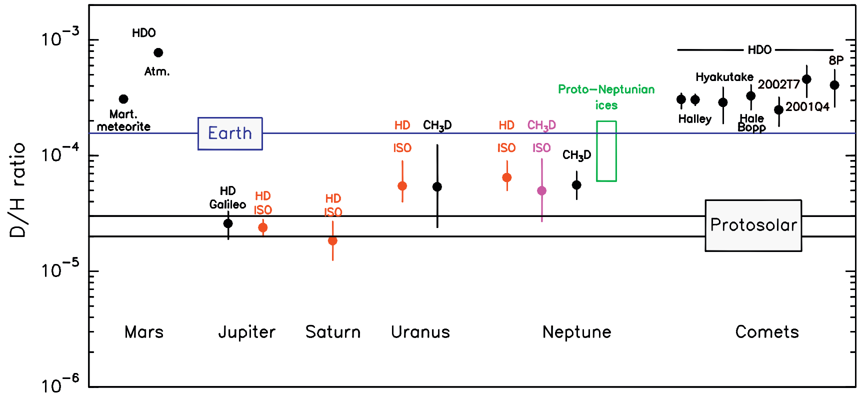
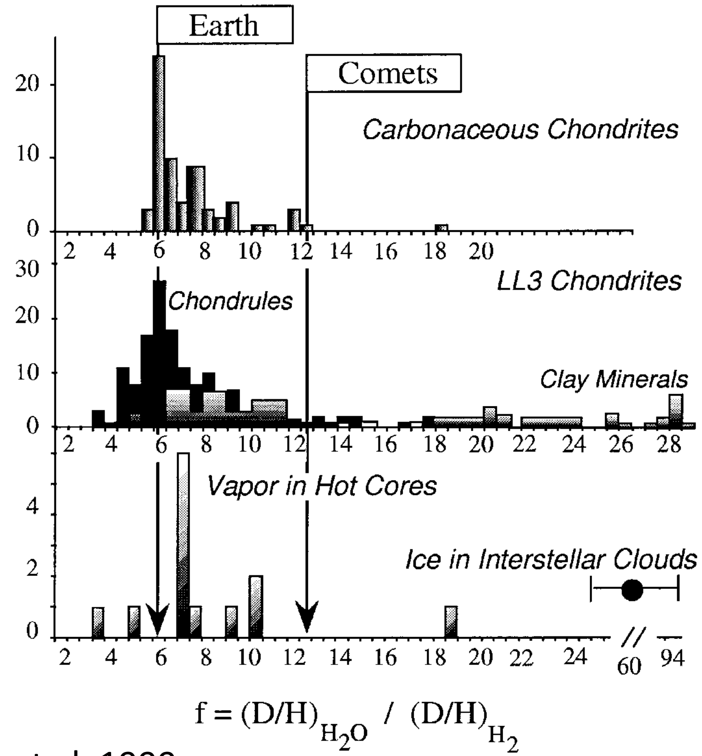


Fig. 1. D/H ratios in the Solar System.

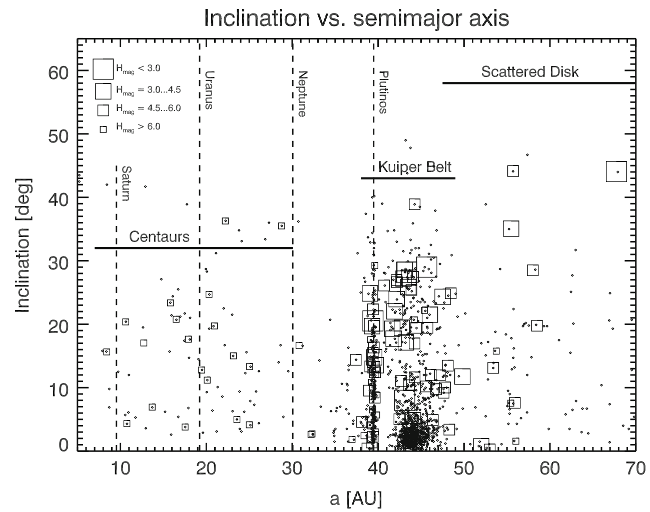
Hartogh et al. 2009

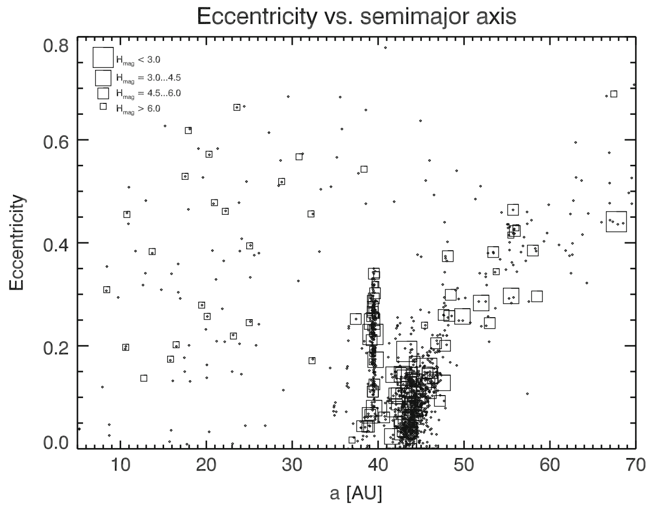


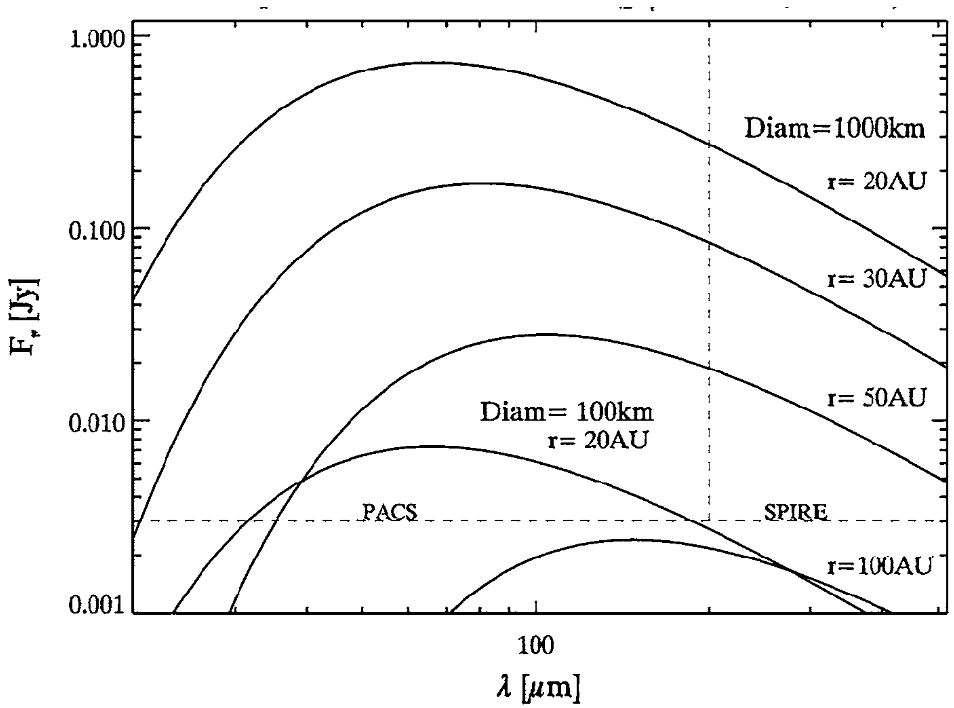
Robert et al. 1999

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







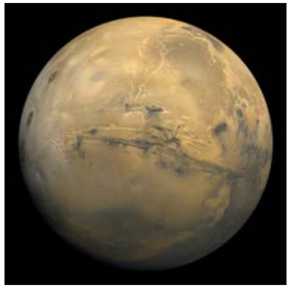
Mueller et al. 2009

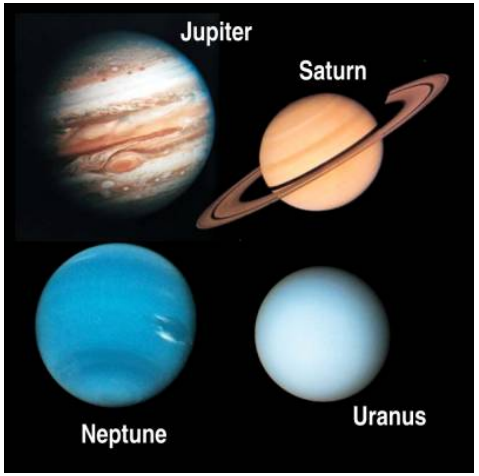
Herschel Highlights

Mars P 5-5, P 5-6

- H_2O, 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_2O atmosphere around Ganymede and Callisto
    - **P. Hartogh's talk on Thursday**

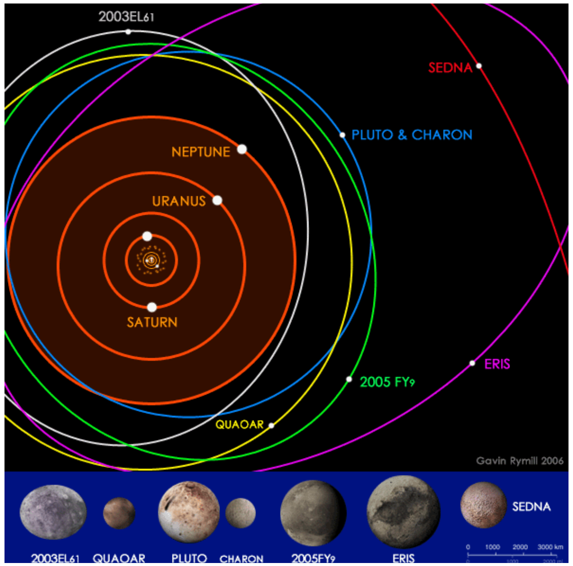
Asteroids P 5-12, P 5-13

- H_2O 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_2O, 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 O_2 + search for latitudinal variations (HIFI)

  Hartogh et al. 2010a, Poster 5-5

- Isotopic lines of CO (HIFI, SPIRE)

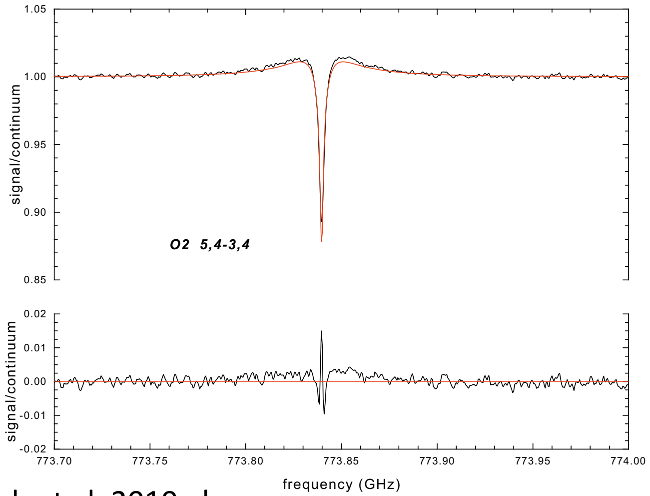
  Hartogh et al. 2010b, Swinyard et al. 2010

- An upper limit on HCl: < 0.2 ppb (HIFI)

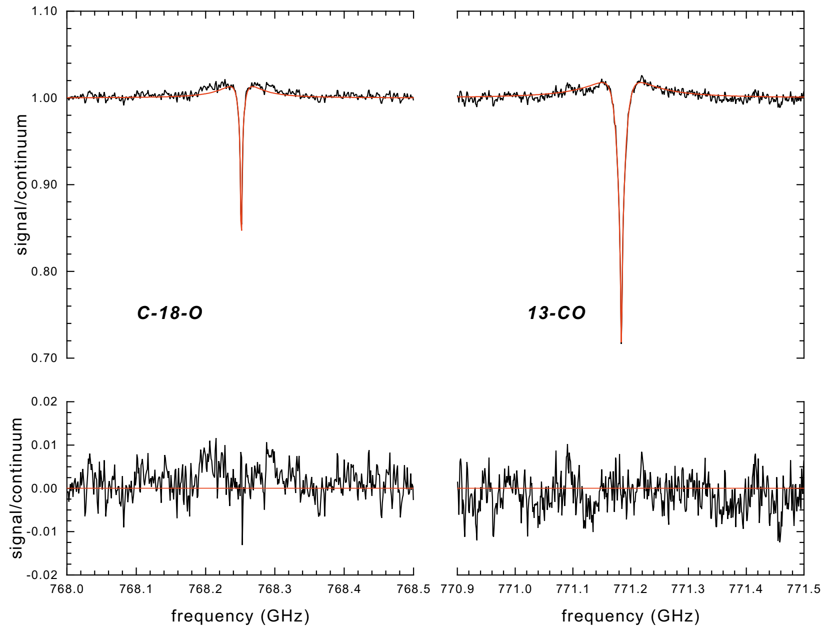
  Hartogh et al. 2010a

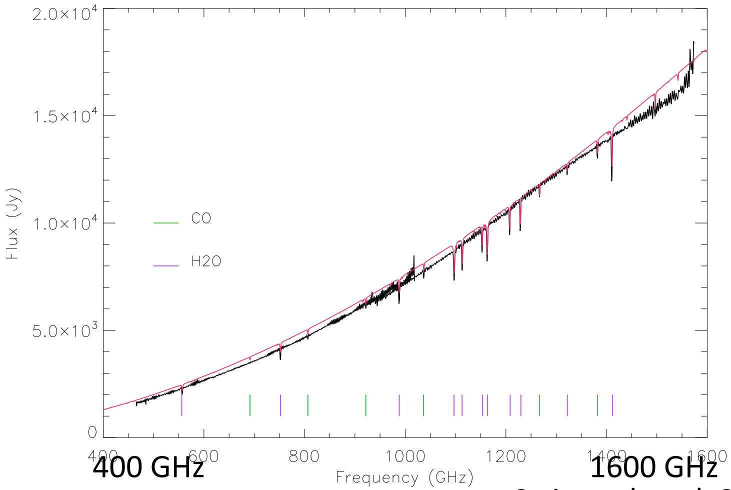
- On-going studies on isotopic ratios

  D/H, $^{18}O/^{16}O$, $^{13}C/^{12}C$



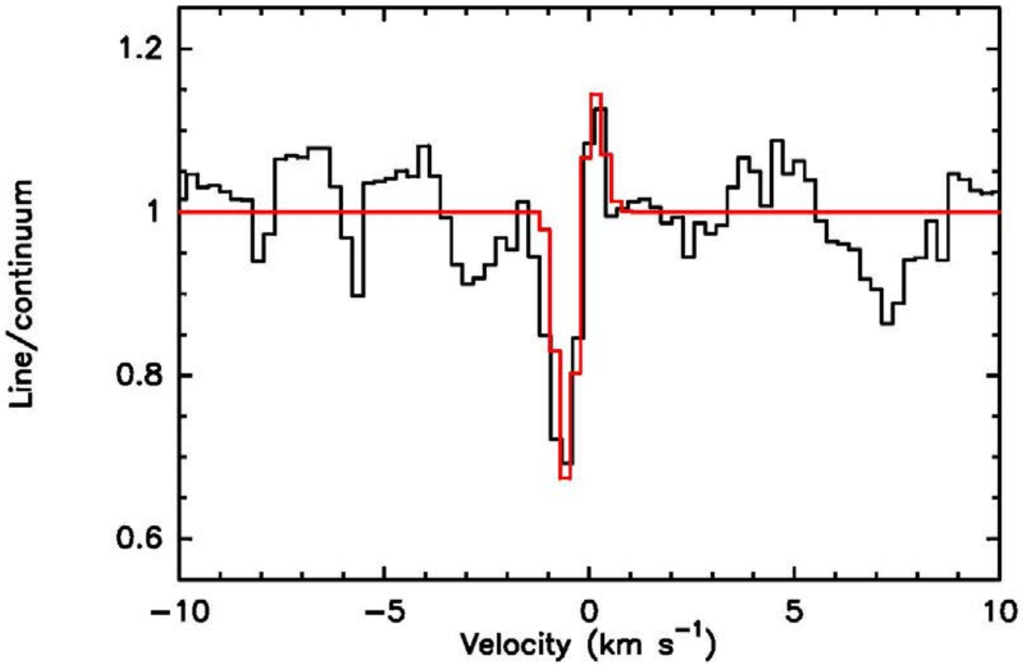
Hartogh et al. 2010a,b

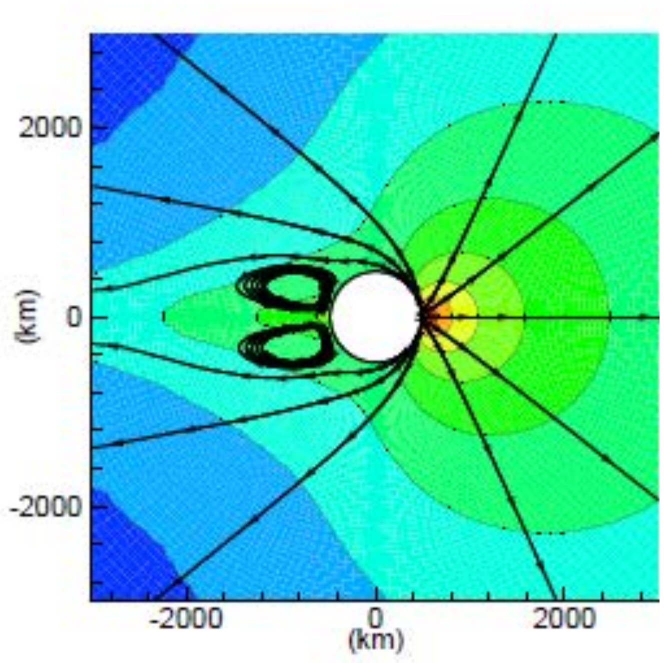




Swinyard et al. 2010

Detection of water vapor around Ceres (HIFI)



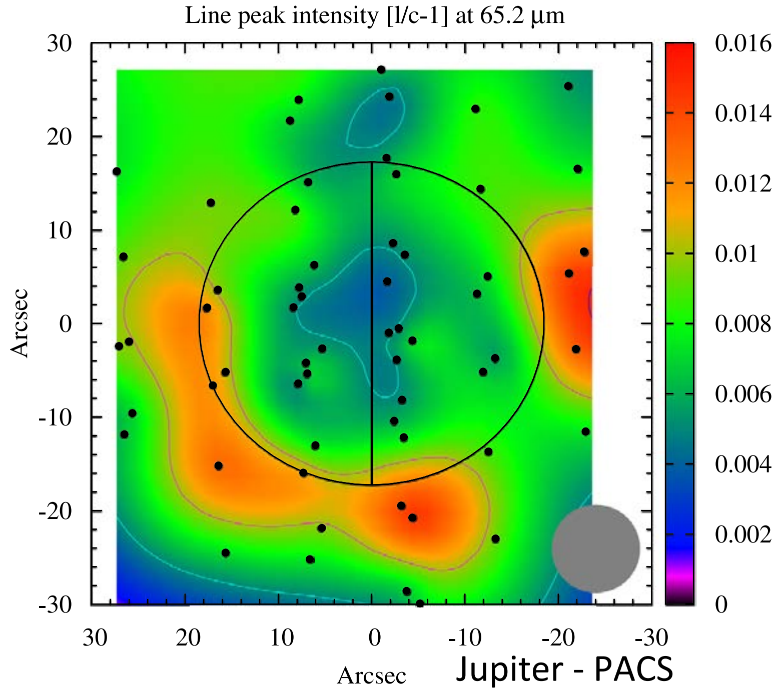


557 GHz H_2O line detected with HIFI in October 2012 and March 2013

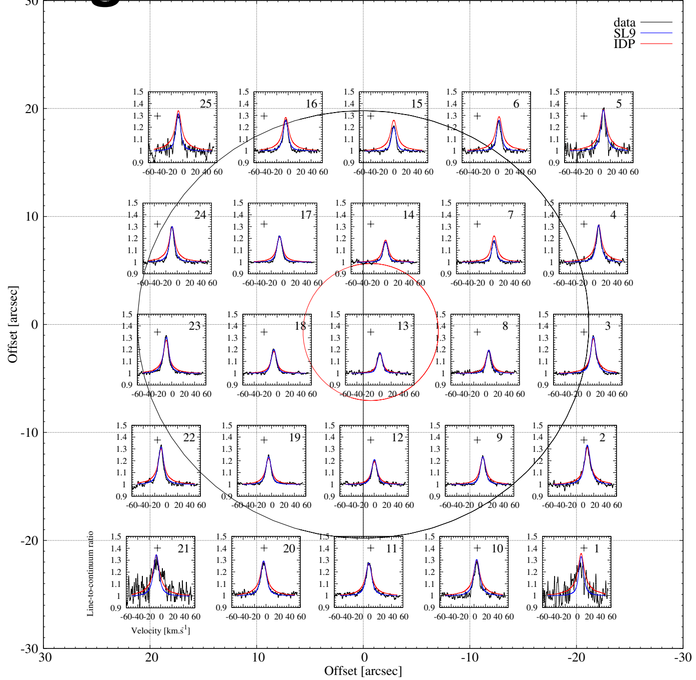
Kueppers et al., in press (more during D. Bockelée-Morvan's talk on Thursday)

The origin of water in Jupiter

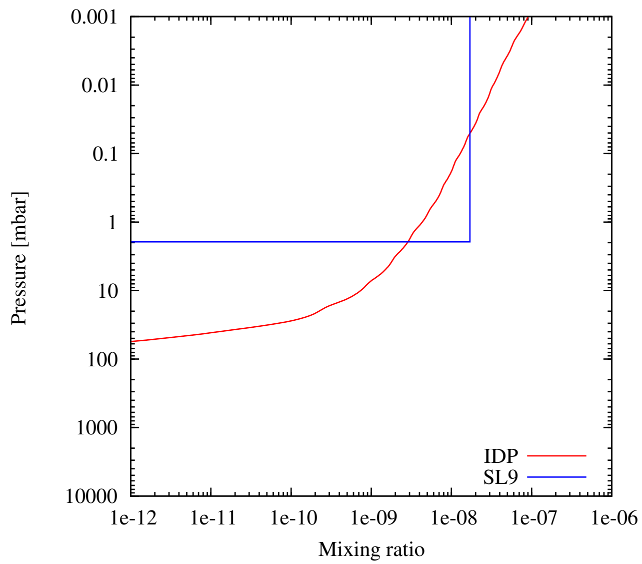
- H_2O in Jupiter (PACS/HIFI)
  Cavalié et al. 2013, Poster 5-3
  – H_2O is above the 2 mbar level
  – Decreases from south to north latitudes
  – **> Origin must be the SL9 collision**

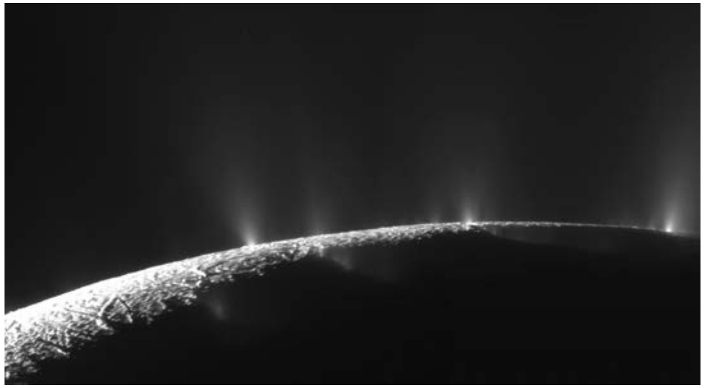


Jupiter - PACS



Jupiter-HIFI



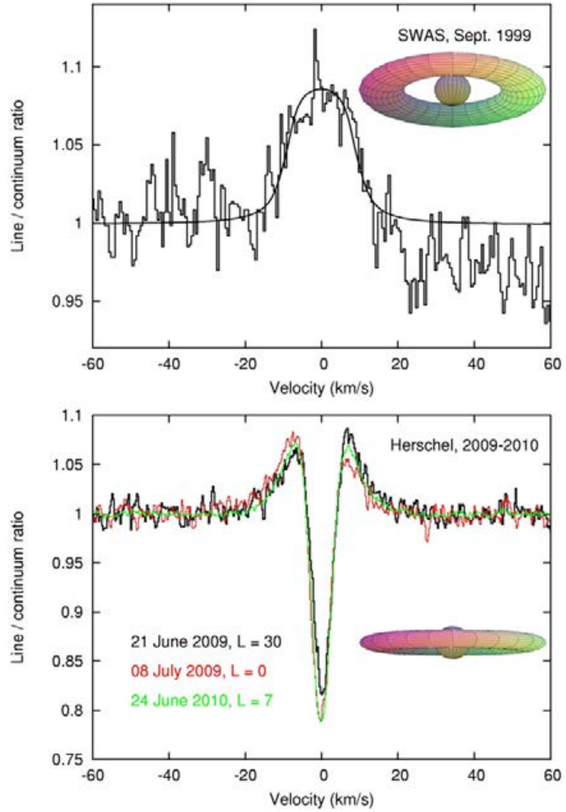


The origin of water in the system of Saturn

- Detection of the water torus generated by Enceladus (HIFI)

- Cryovolcanism on Enceladus has been reported by Cassini

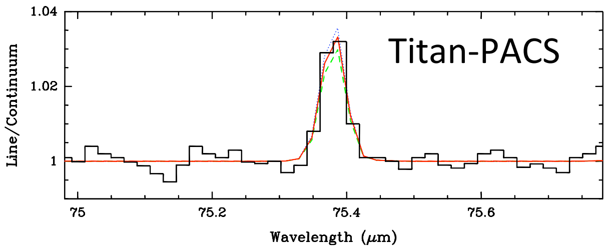
- Using appropriate geometry, HIFI has detected the H_2O torus generated by Enceladus, in absorption in front of the H_2O emission of Saturn

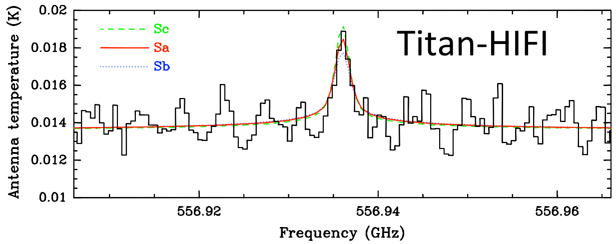


Hartogh et al. 2011

- H_2O in Titan (PACS/HIFI) Moreno +13

- Oxygen flux is weaker than previously inferred from ISO
  - \> **Enceladus cryovolcanim is sufficient to explain Saturn & Titan's external water**





Moreno et al. 2013

D/H in comets

- From previous measurements:

  D/H = 2 [D/H]E in Oort cloud comets

  (Halley, Hyakutake, Hale-Bopp)

Results from Herschel/HIFI:

- Jupiter-family comets
  - Hartley 2: D/H = $[D/H]_E$ (Hartogh et al. 2011)
  - 45 P/Honda-Mrkos-Pajdusakova: D/H < 1.3 $[D/H]_E$

    -> Consistent with Hartley 2 (Lis et al. 2013)
- Oort-cloud comet C/2009 P1(Garradd)

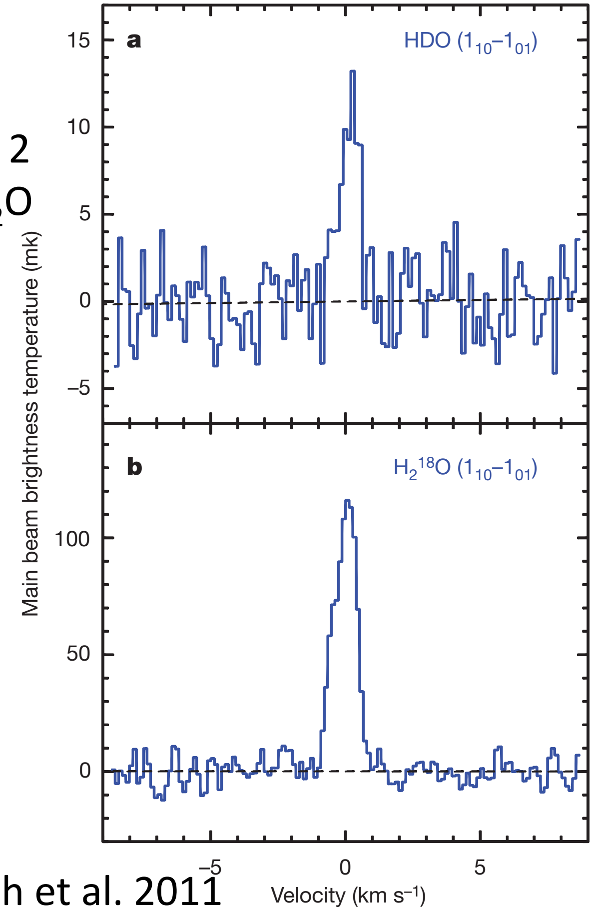
  D/H = 1.32 $[D/H]_E$ (Bockelée-Morvan et al. 2012)

> There is some diversity among the Oort cloud comets

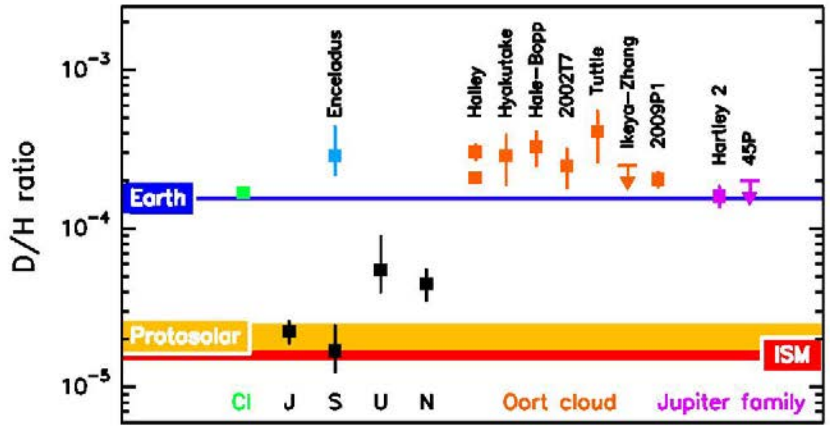
> Their D/H is still enriched wrt the ocean value

P/Hartley 2

HDO & H_2O



Hartogh et al. 2011



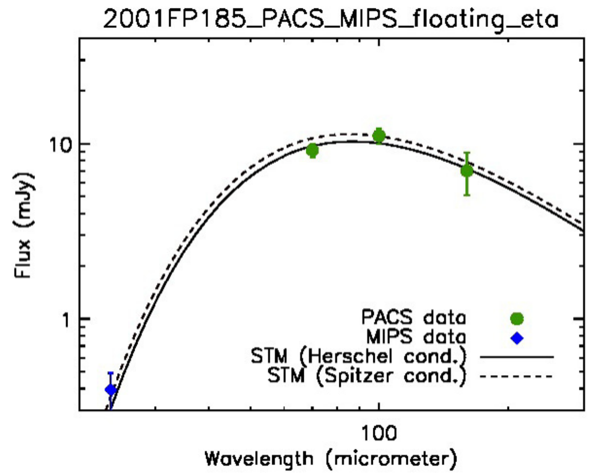
Bockelée-Morvan et al. 2012, Poster 5-2

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



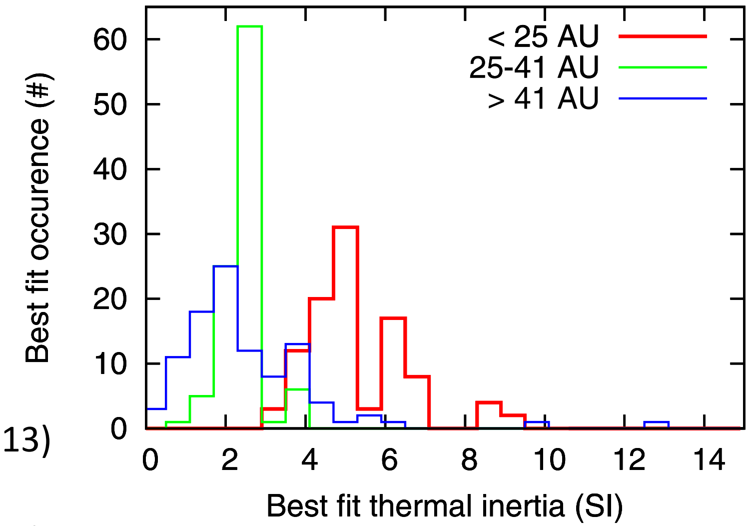
Scattered disk & detached objects (Santos-Sanz +12)
Poster 5-14

Densities of binary systems (Fornasier +13, talk on Thursday)

- Quaoar: 2.2 g/cm^3 -> **high refractory content**
- Orcus: 1.5 g/cm^3 ; Salacia: 1.3 g/cm^3

Thermal properties of TNOs Poster 5-9

- PACS & SPIRE: 9 objects (thermal inertia, surface emissivity)
- Low thermal inertia (Γ = 2.5 Jm^{-2}s$^{-1/2}$ K^{-1}, decreasing as Rh increases)-> **highly porous surfaces** (Lellouch et al. 2013)



Lellouch et al. 2013

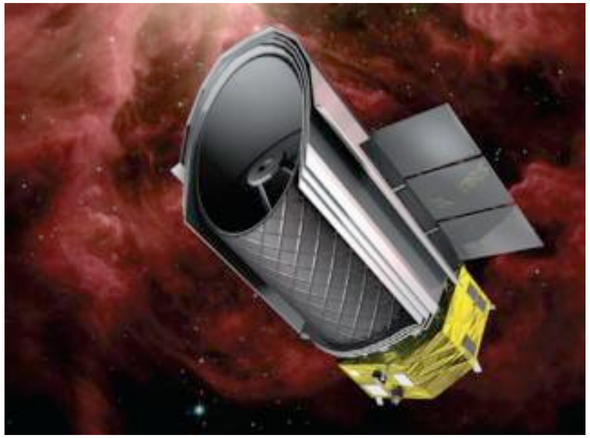
Thermal properties of asteroids

- Vesta: Γ = 20 Jm^{-2}s$^{-1/2}$ K^{-1} > **consistent with fine regolith** (Leyrat +13)
- Lutetia: Γ = 5 Jm^{-2}s$^{-1/2}$ K^{-1} -> **region of small scale roughness** (O'Rourke +13)
- 1999 RQ$_{36}$ (Osiris-Rex target): Physical & thermal properties,
  Γ = 650 Jm^{-2}s$^{-1/2}$ 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 spectrosocpy
- > SPICA-type mission



A higher spatial resolution

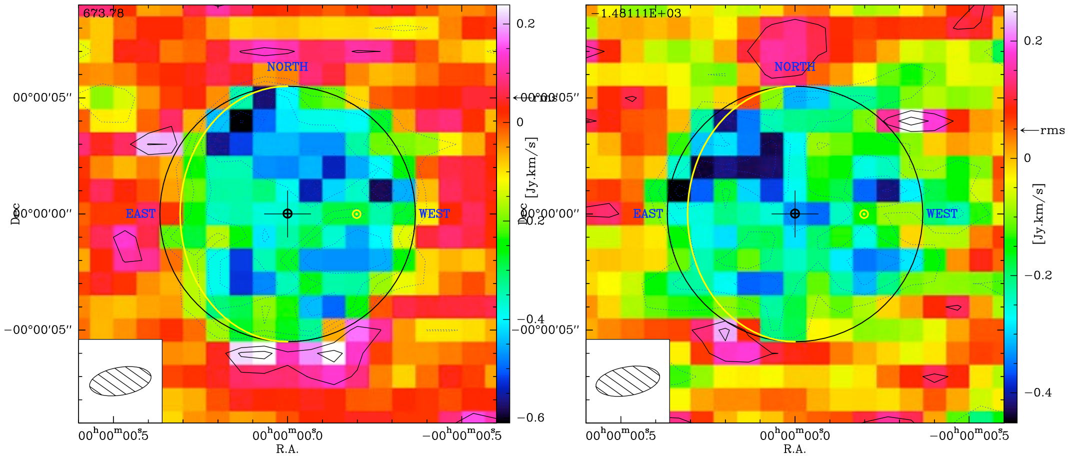
- To identify water jet structures in comets
- To map H_2O in giant planets and Titan
- To study asteroid/TNOs binaries

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

Venus with ALMA – 14 Nov 2011

SO (346.5 GHz) HDO (335.4 GHz)



Venus diameter: 11 arcsec