



Solar System science with ALMA

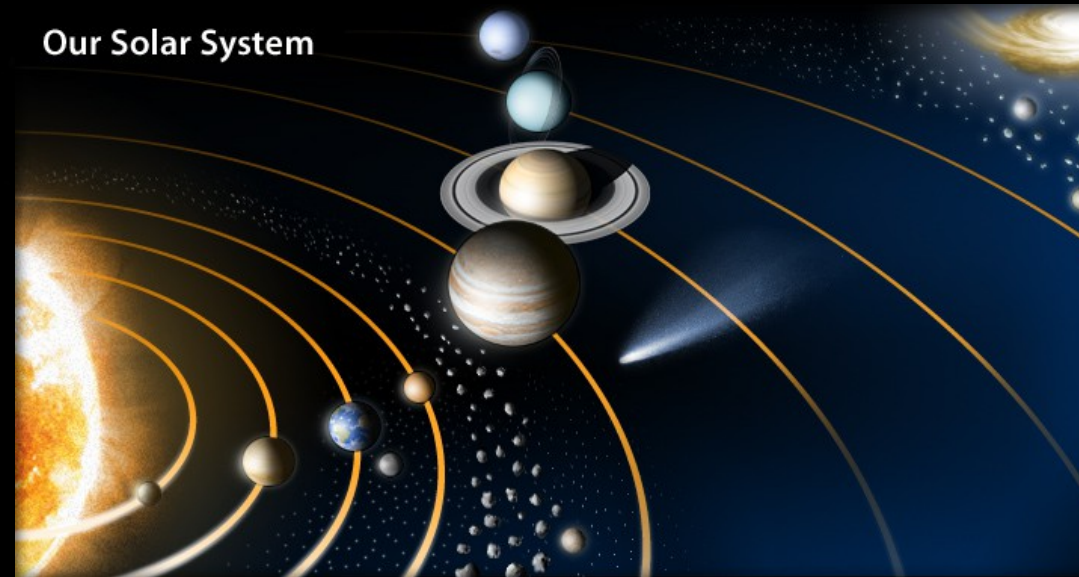
Jeremie Boissier

With inputs from

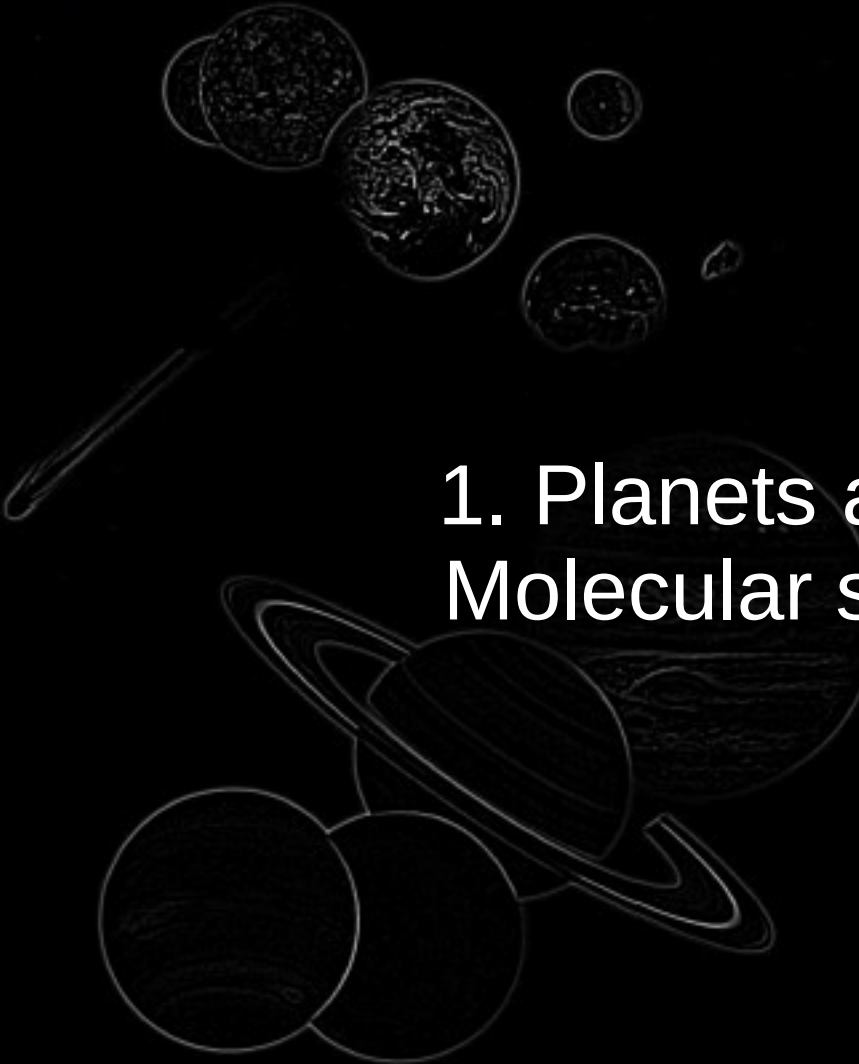
- N. Biver, D. Bockelée-Morvan, J. Crovisier (Observatoire de Paris) about comets
- R. Moreno, E. Lellouch, T. Fouchet (Observatoire de Paris),
T. Cavalié (Obs Bordeaux), A. Moullet (NRAO) about planets

Our Solar System

- Different objects
 - + Planets and satellites
 - + Asteroids
 - + Trans Neptunian objects (TNOs)
 - + Comets
- Radio observations
- Spectral lines
 - + Molecules in gaseous atmospheres
 - Planets
 - Satellites (Io, Titan)
 - Comet atmospheres (coma)
 - Small Bodies (Pluto + ?)



- Continuum
 - + Thermal emission
 - Giant planet atmospheres
 - Telluric planet surfaces
 - Satellite surfaces
 - Small body surfaces
 - Comet nuclei



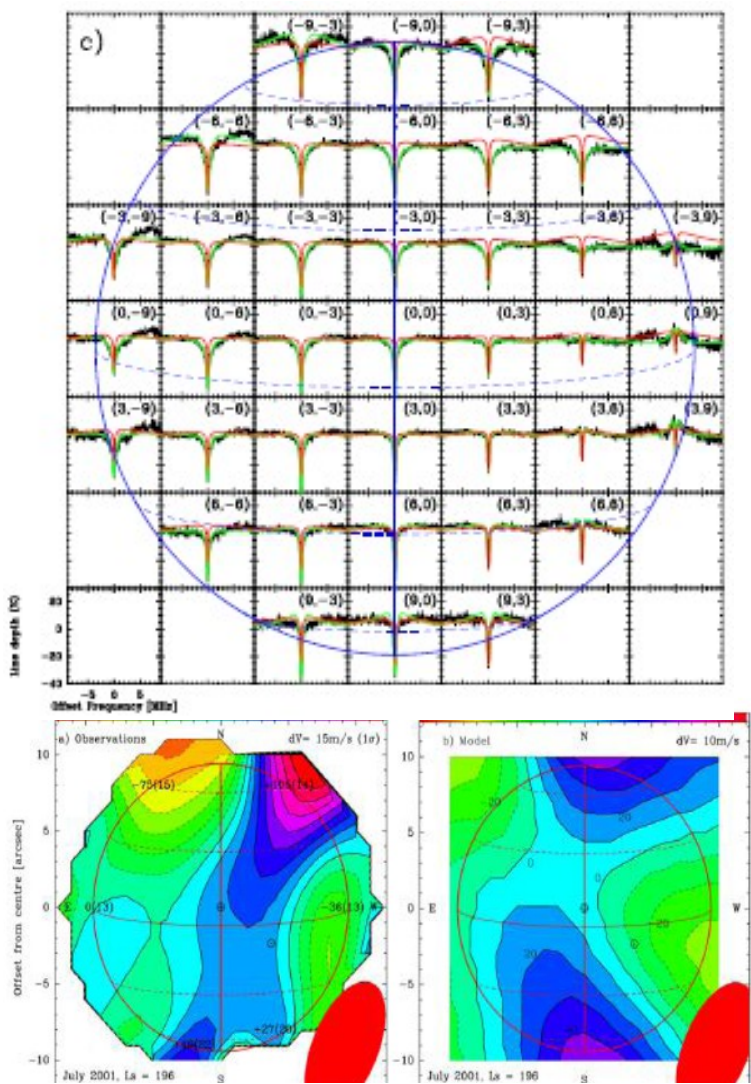
1. Planets and satellites Molecular spectral lines

Planetary atmospheres

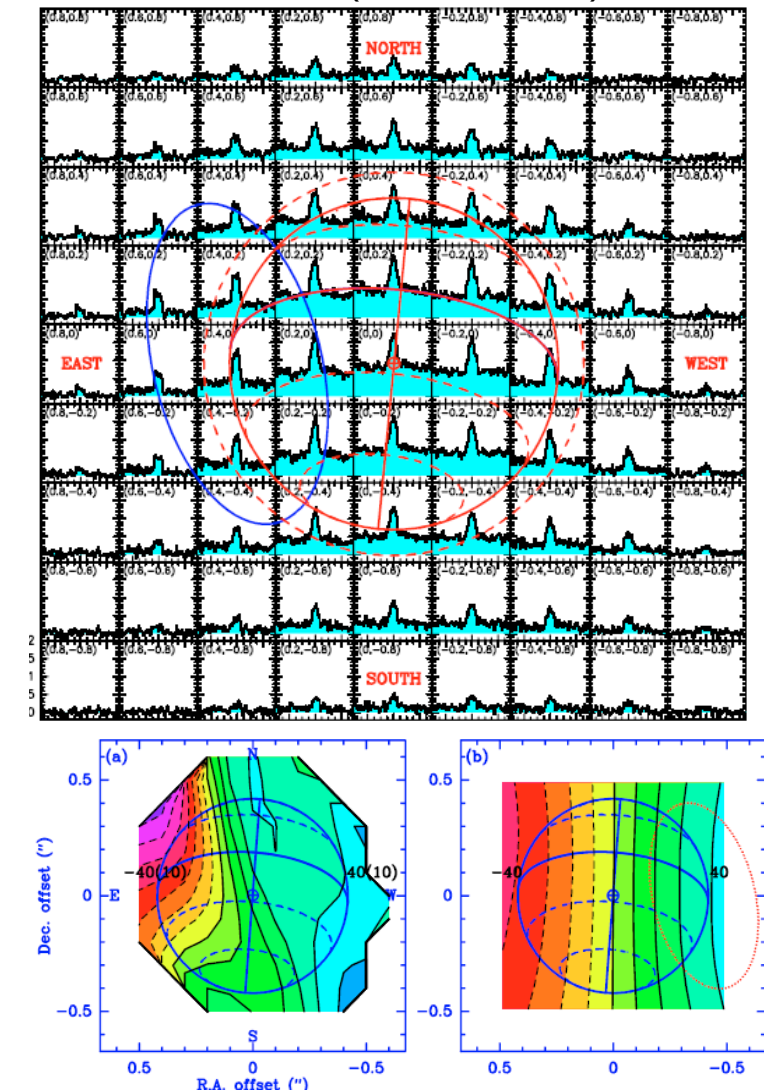
- Observations of molecular lines in atmospheres probe:
 - + Chemistry
 - Composition
 - Distribution of species
 - + Thermal conditions
 - Temperature profiles $T(h)$
 - + Dynamics
 - Time variations
 - Winds (from Doppler shift of the lines)
 - + All of them are coupled and define atmospheric cycles
 - Characterisation of the seasonal variations
 - Comparison to Global Circulation Model
 - ***Study of the origin and evolution of Planets***

Telluric planets and satellites

CO J(1-0) in Mars observed with the Plateau de Bure interferometer (Moreno+2009)

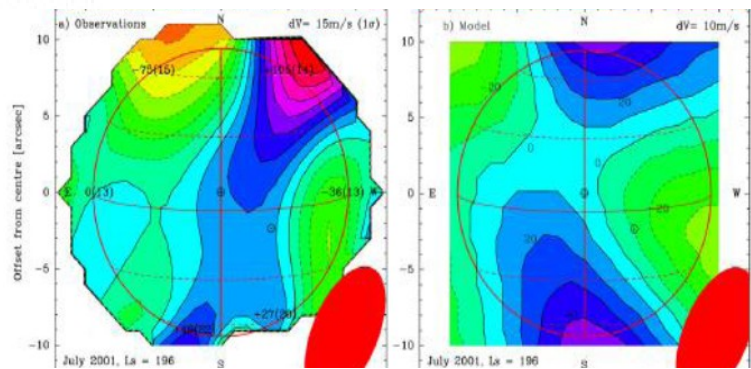
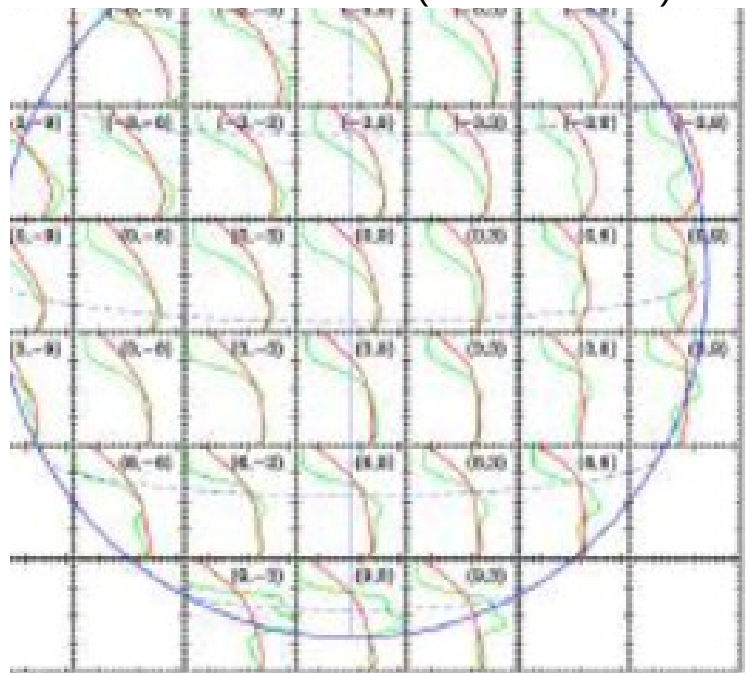


HC₃N in Titan observed with the Plateau de Bure interferometer (Moreno+2005)

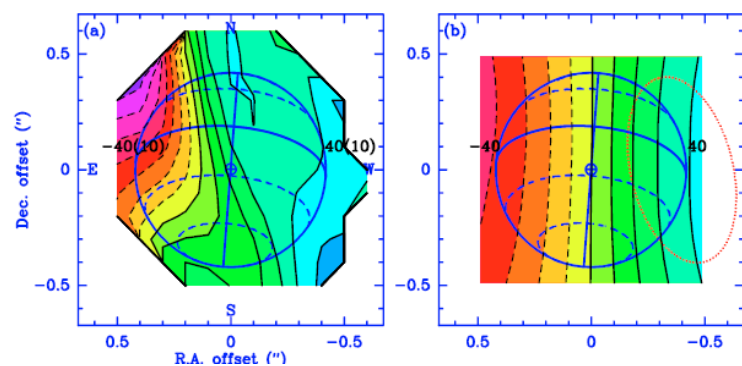
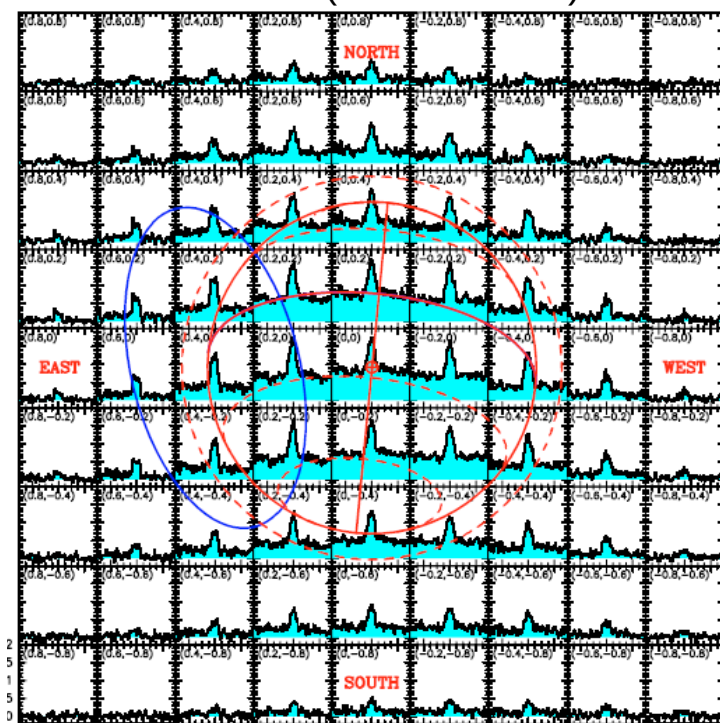


Telluric planets and satellites

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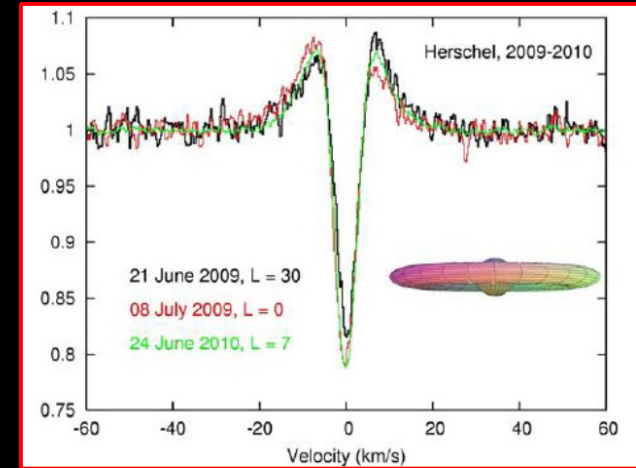


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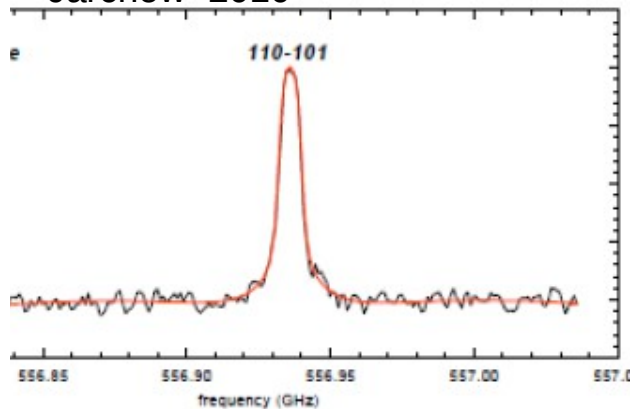


Giant planets chemistry

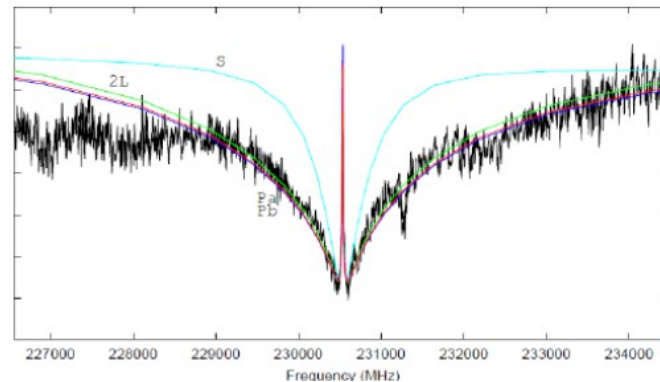
- Atmosphere composition and origin of the molecules
 - Interplanetary dust (IDP), comets ?
 - + Water on Saturn
 - Comes from Enceladus water torus
 - Detection by Herschel HIFI (Hartogh+11)
 - + The case of Neptune
 - H₂O: external flux and vertical diffusion
 - CO: dual internal/external origins
 - HCN



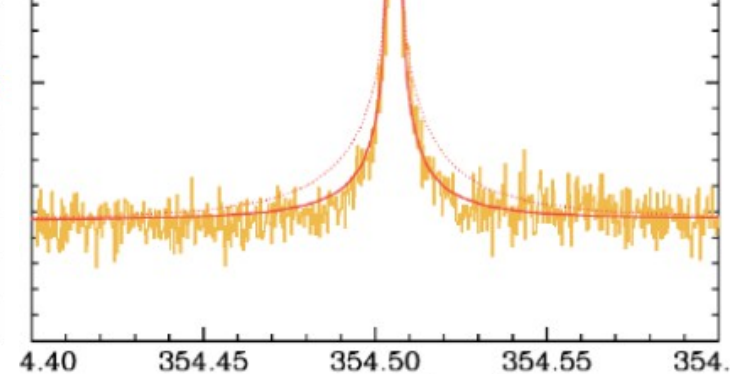
Neptune
Water with Herschel HIFI
Jarchow+2010



COJ(2-1) with IRAM 30m
Lellouch+2005



HCNJ(4-3) with JCMT
Marten+2005



Planetary atmospheres

- ALMA proposals

- + Cycle 0

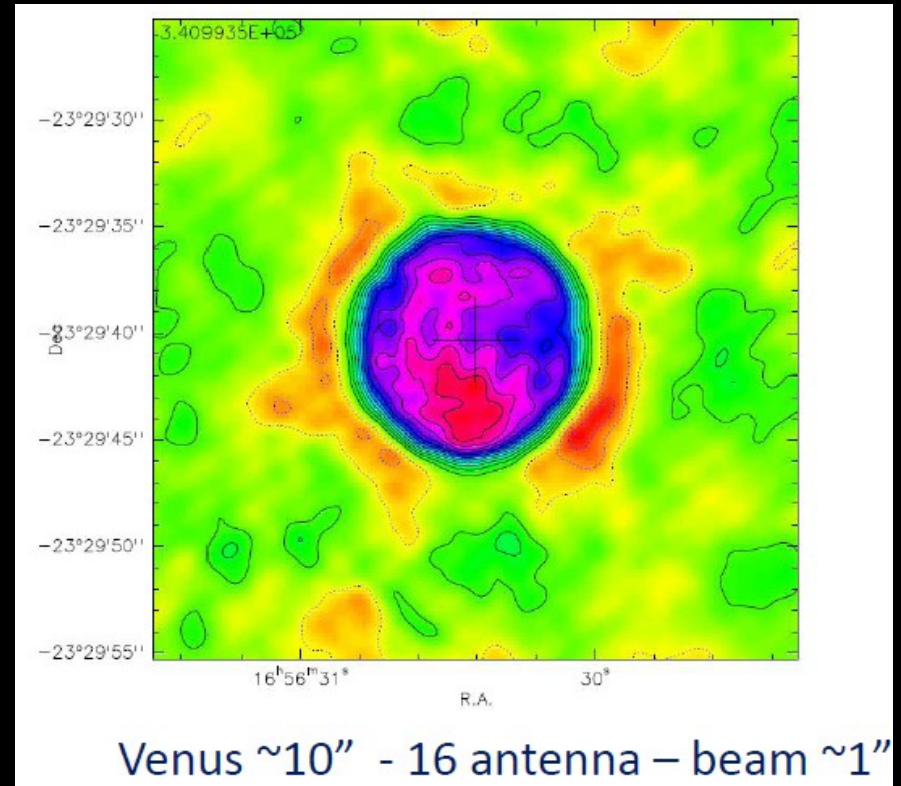
- Sulfur and water mapping in the mesosphere of Venus (T. Encrenaz)
- Mapping the nitrile chemistry and dynamics of Titan's thermosphere (R. Moreno)
- Characterizing Io's atmospheric composition and circulation (A. Moullet)
- Probing the vertical structure of Saturn's storm with ALMA (T. Cavalié)

- + Cycle 1

- Exploring the nitrile and oxygen chemistry in Titan's middle atmosphere (S. Vinatier)
- Isotopic ratios in Neptune atmosphere and the origin of CO and HCN (R. Moreno)
- Characterizing the volcanic contribution in Io's atmosphere (A. Moullet)
- Atmospheric chemistry on Venus: diurnal variation of chlorine species (H. Sagawa)

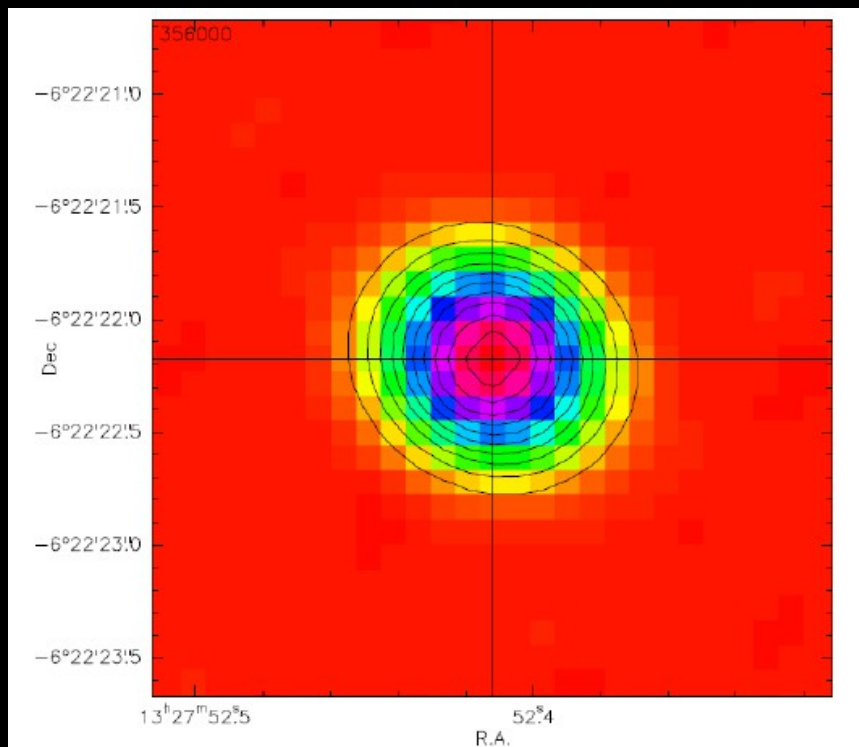
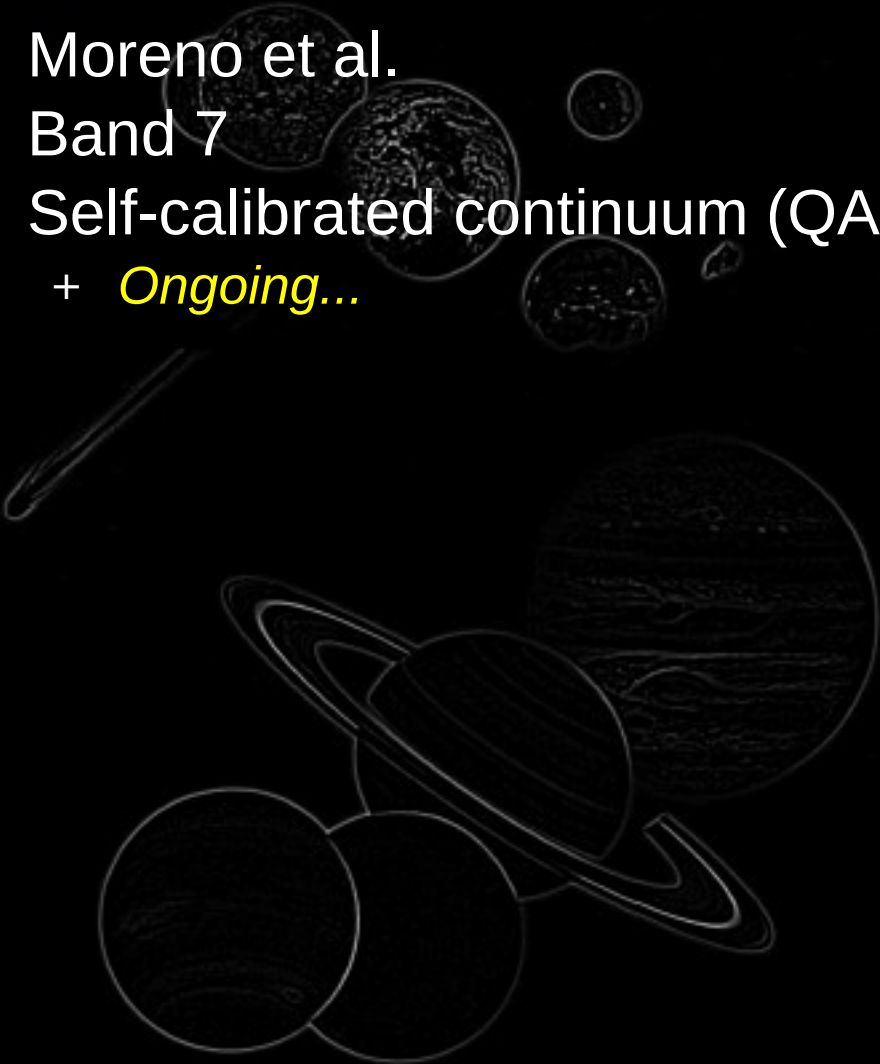
ALMA observations of Venus

- Sulfur and water mapping in the mesosphere of Venus
 - + Band 7
 - + PI: T. Encrenaz
 - + Continuum out of QA2
 - + **See next talk by R. Moreno**



ALMA observations of Titan

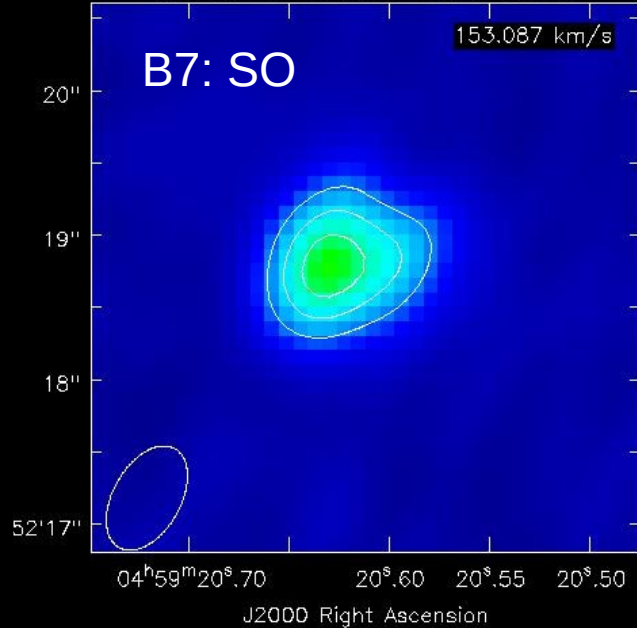
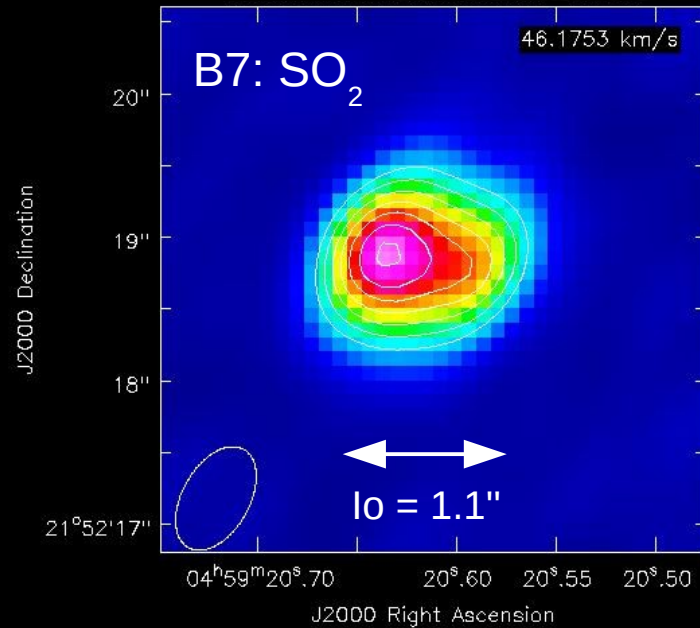
- Moreno et al.
- Band 7
- Self-calibrated continuum (QA2)
+ *Ongoing...*



Titan ~1.2", 21 antennas, Beam 0.4"

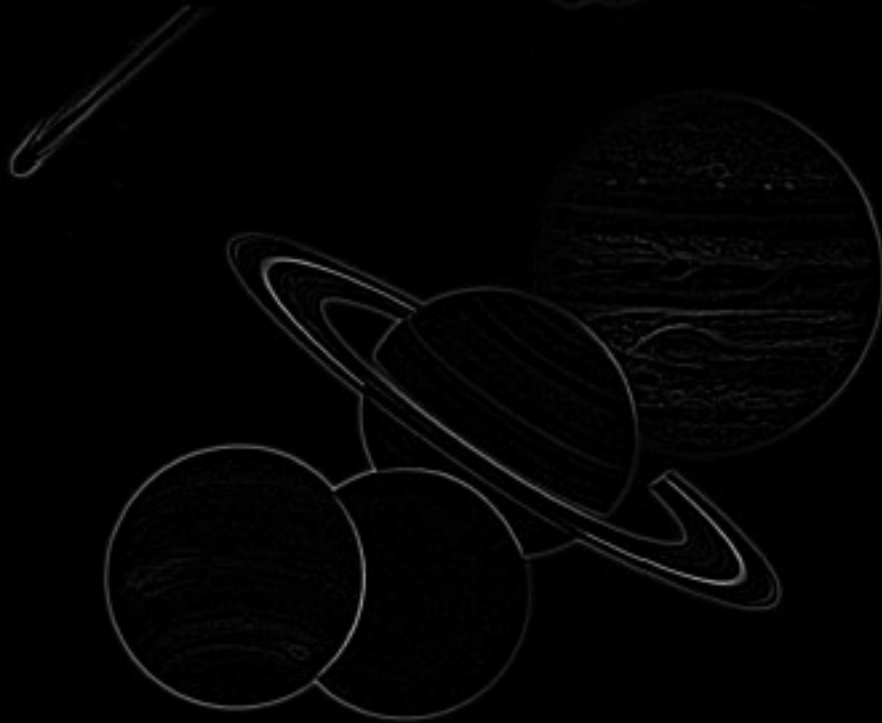
ALMA observations of Io

- Atmosphere of a volcanic moon
 - + Moullet et al.
 - + Location and dynamics
 - Volcanic plumes
 - Photochemistry
 - + *Ongoing...*



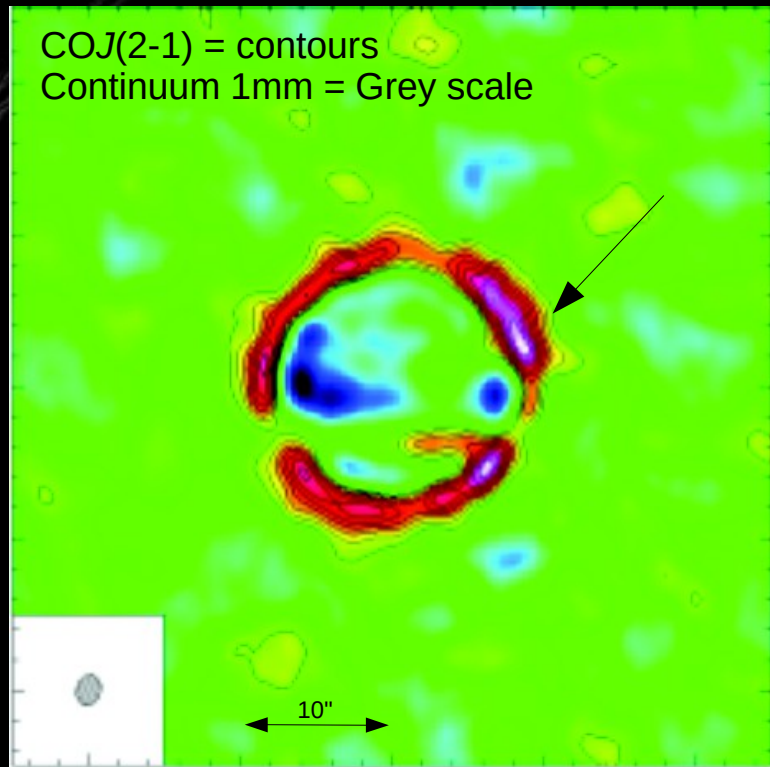
Saturn's storm with ALMA

- Unexpected storm in 2010
 - + Impact on the atmosphere chemistry ?
 - H₂O in the infrared with Herschel
 - CO $J(2-1)$ at 230.5 GHz with ALMA
 - T. Cavalié et al., cycle 0



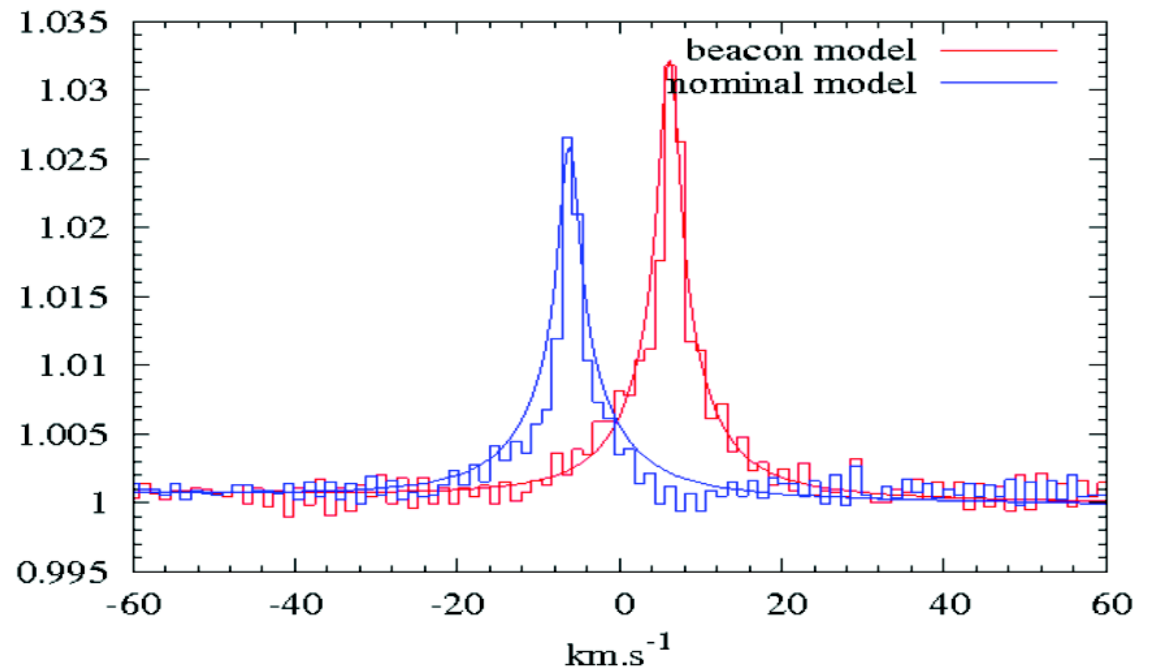
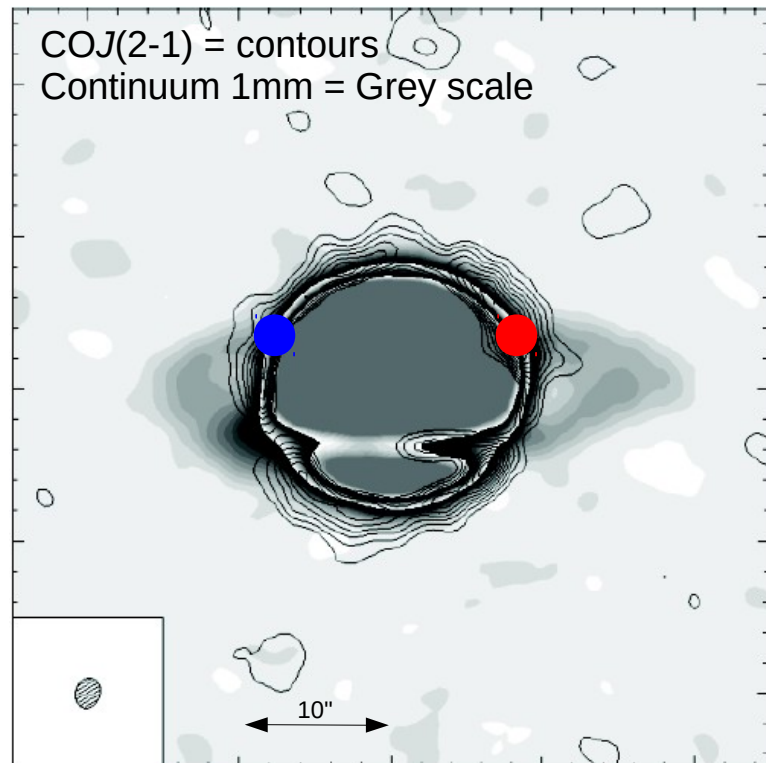
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Saturn's storm with ALMA

- CO spectra **inside** and **outside** the storm
 - + No obvious increase of CO abundance
 - + Effect of temperature variations ?

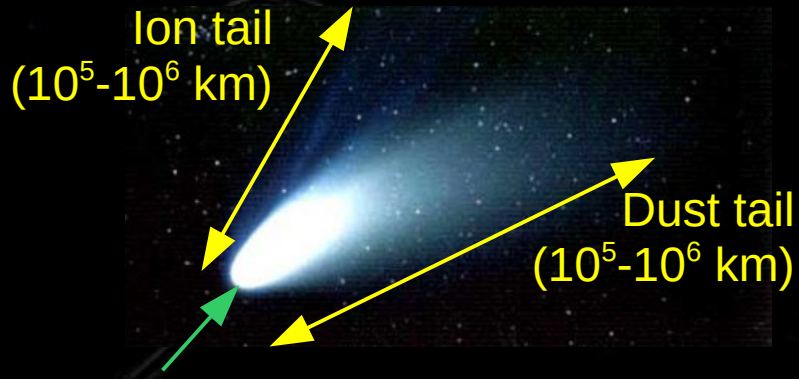




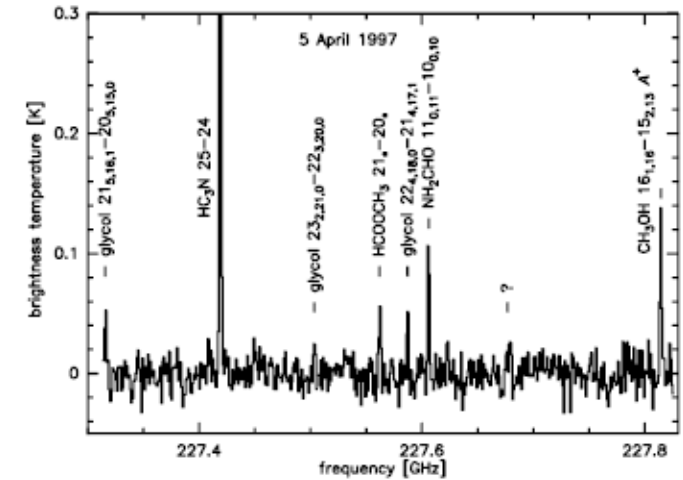
2. Small bodies

2.1 Spectral lines

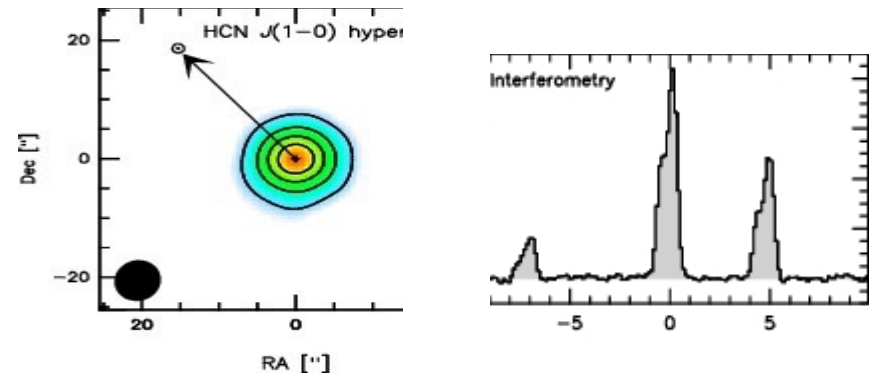
Cometary atmospheres



- Cometary coma
 - + 10^3 - 10^4 km, $\sim 10''$
 - + Extended sources
 - + Narrow lines (~ 1 MHz, 1 km/s)
- Chemistry
 - + Statistics
 - + Complex species, Isotopes
- Structure
 - + Jets
 - + Origin of the molecules



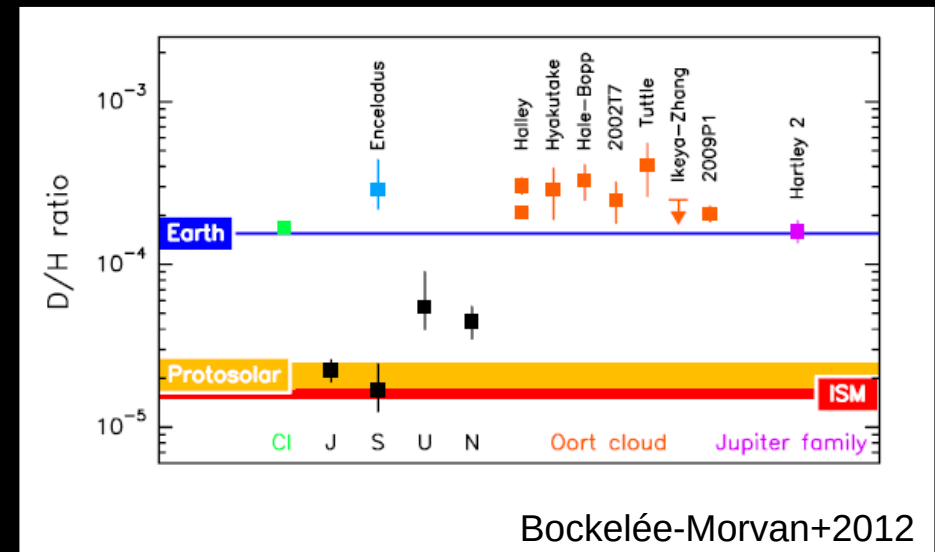
Complex species in Hale-Bopp in IRAM 30m spectrum (Crovisier+2004)



HCN (1-0) in 17P/Holmes with the Plateau de Bure (Boissier+2009)

D/H and origin of water in the Earth's Oceans

- Comet ice as origin of the water on Earth ?
 - + First cometary D/H too high (only strong, Oort cloud comets)
 - + Herschel facts:
 - Ocean like D/H in Hartley 2 (JFC)
 - Stronger value in Garradd (OCC)
 - Hartogh+11, Bockelée-Morvan+12
 - + To be investigated with ALMA
 - More comets
- Similar studies for other species
 - + $^{14}\text{N}/^{15}\text{N}$ ^{15}N enrichment wrt Earth
 - Bockelée-Morvan+08



Cometary atmospheres

- ALMA proposals
 - + Cycle 0
 - A Close-up Look at Comet **Elenin** (M. Drahus)
 - + Cycle 1
 - The origin of cometary matter: **nitriles and isotopes** in comet **PanStarrs** (N. Biver)
 - A Close-up Look at Comet **PanStarrs** (M. Drahus)
 - + Cycle 1 DDT
 - Identifying the origin of molecular species in the coma of comet **Lemmon** (M. Cordiner)
 - Several DDTs on sun grazing comet ISON

Cometary atmospheres

- ALMA proposals

- + Cycle 0

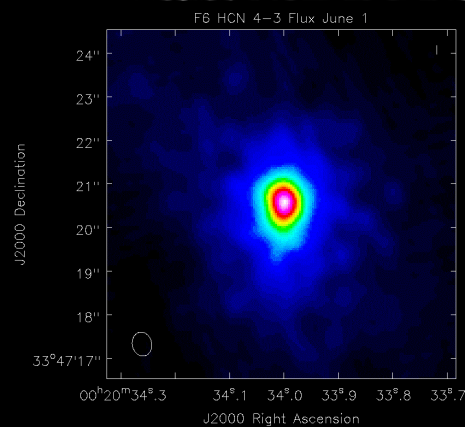
- A Close-up Look at Comet **Elenin** (M. Drahus)

- + Cycle 1

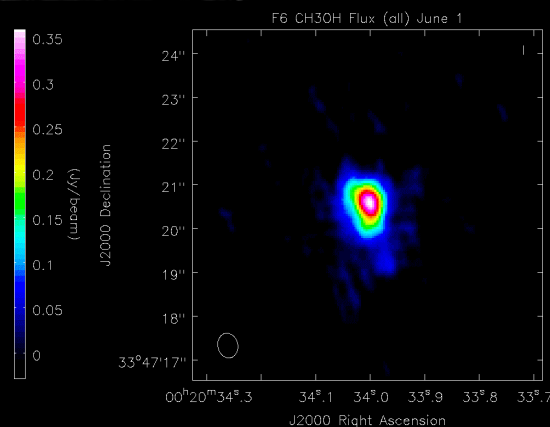
- The origin of cometary matter: **nitriles and isotopes** in comet **PanStarrs** (N. Biver)
- A Close-up Look at Comet **PanStarrs** (M. Drahus)

- + Cycle 1 DDT

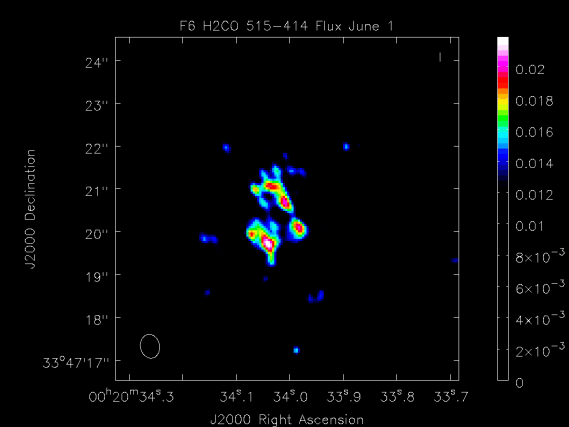
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HCN $J(4-3)$



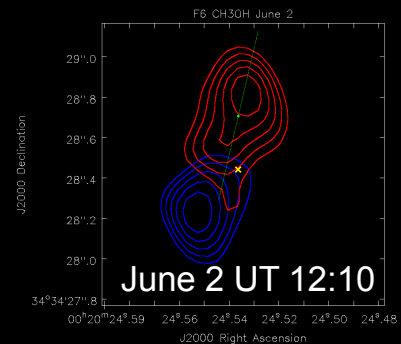
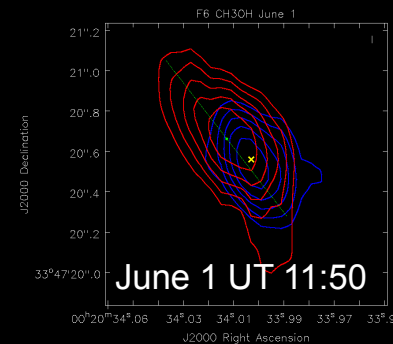
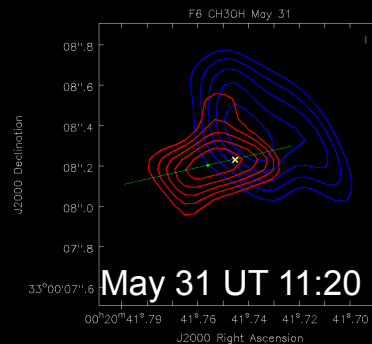
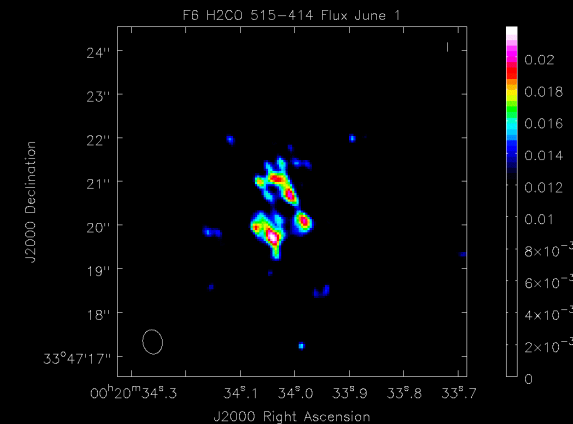
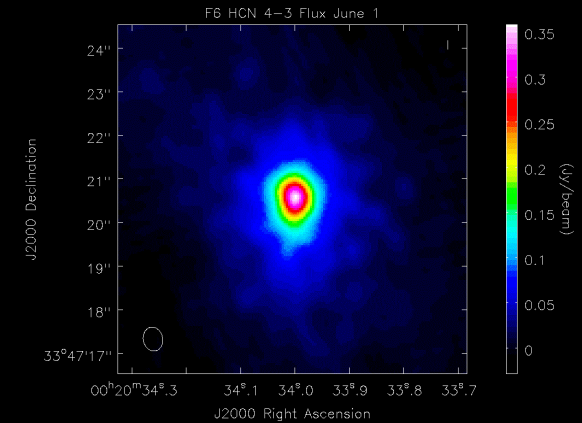
CH₃OH



H₂CO


First cometary observations with ALMA

- Comet C/2012 F6 (Lemmon)
 - + DDT proposal by M. Cordiner et al.
 - + 2 setups in B7, 1.2h of observations
 - HCN, CH₃OH, H₂CO
 - HNC, CH₃OH, H₂CO
- Preliminary results
 - + **H₂CO does not peak at the nucleus position**
 - Not present in the nucleus ice
 - TBD: measure formation scale length, constrain its origin
 - Degradation of PAH (Fray et al. 2006) ?
 - + **CH₃OH time variations**
 - Rotating jet ?



TNOs, Asteroid

- Intermediate case between Planets and Comets
 - + Main topic is detection
 - + Optimum is Band 6-7
- ALMA Cycle 0 :
 - + **Pluto** atmosphere
 - (CO, HCN, several proposals merged and accepted as filler)



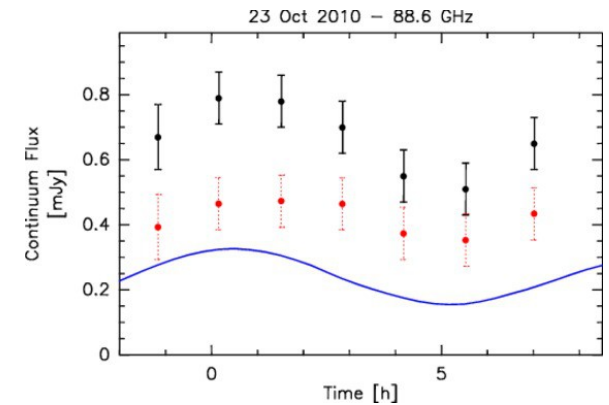
2. Small bodies

2.2 Continuum

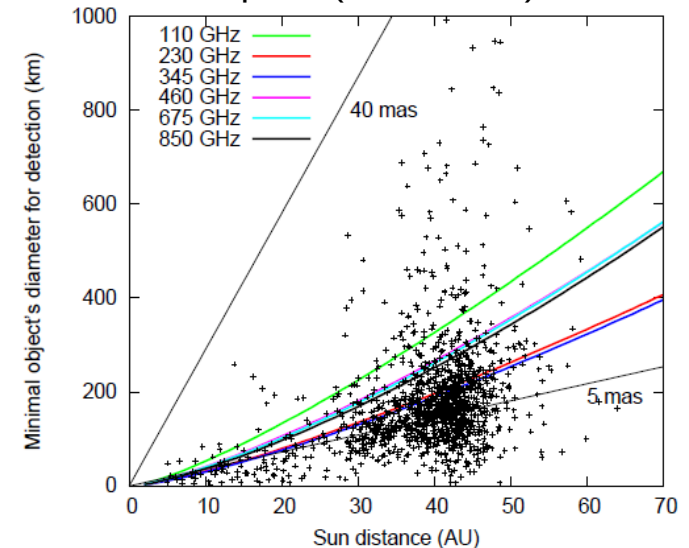
TNOs, Comets

- Mostly point sources
 - + Thermal emission from sub surface ($\sim 10^{\text{km}}$)
 - $T \sim 50\text{-}100\text{ K}$
 - BB emission peaks between 20-100 mm
 - + In the mm, under RJ regime: $S \propto a^{-2}$
 - Detection easier at higher frequency
 - + Detection \propto size from thermal models
 - + Light curve \propto shape
 - + Multi \propto \propto thermal properties
 - Albedo, emissivity, thermal inertia,...
 - + Resolved observations
 - Size from visibilities
 - Surface mapping

3mm thermal emission lightcurve of Hartley 2 observed with the IRAM PdBI (Boissier+13)



Detectability of TNOs: 5 s curves in the Distance/size space (Moulet+11)

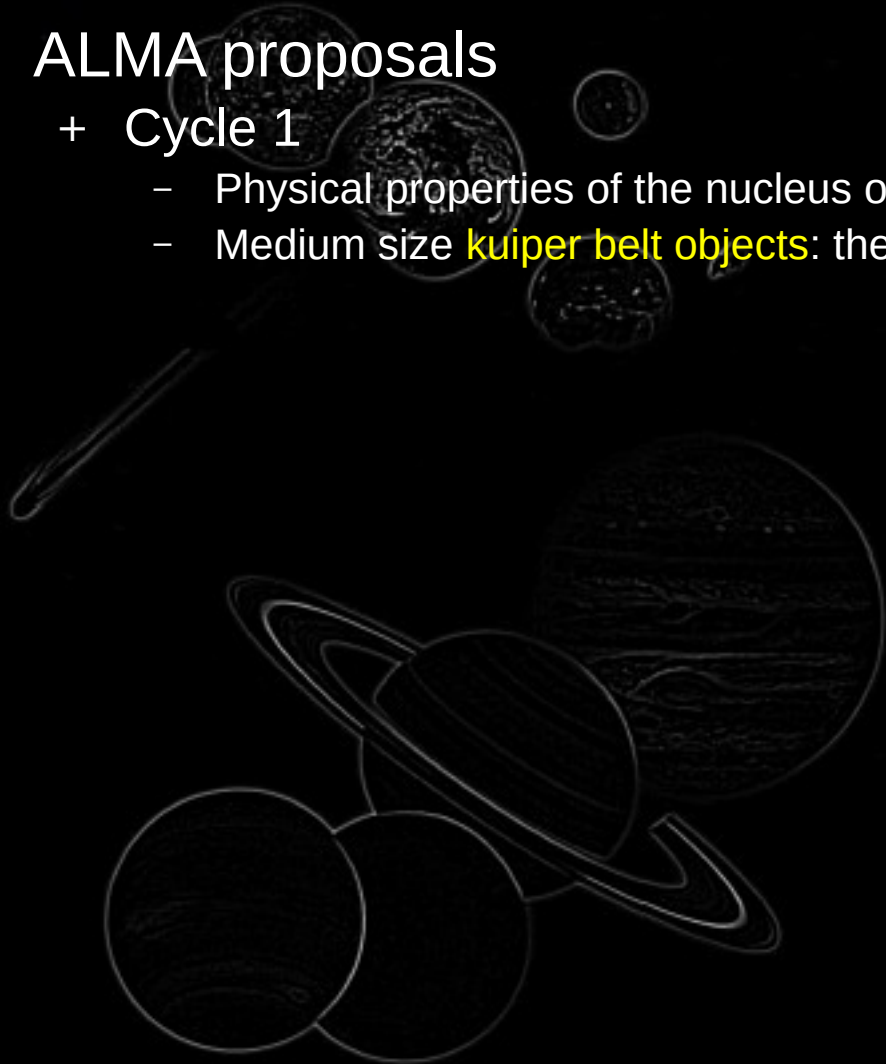


TNOs, Comets

- ALMA proposals

- + Cycle 1

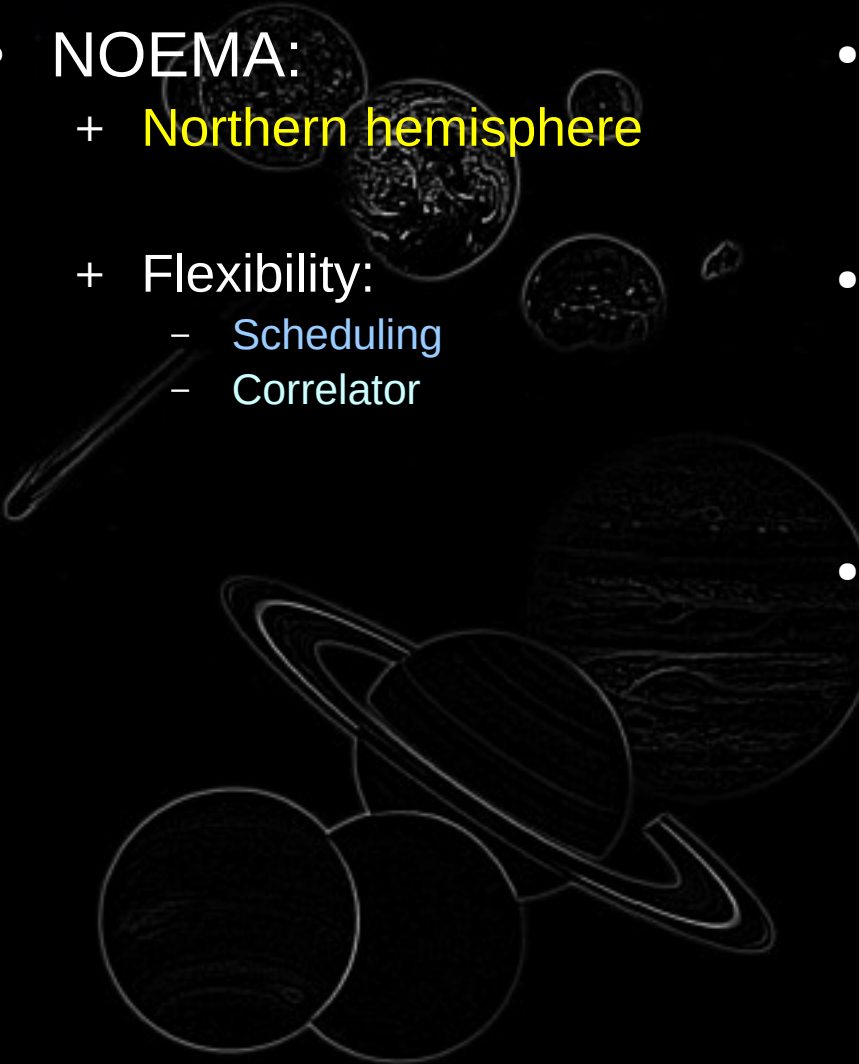
- Physical properties of the nucleus of comet **PanStarrs** (O. Groussin)
- Medium size **kuiper belt objects**: the key to accretion in the Solar System (M. Brown)



Summary

- Solar System proposals successful on ALMA
 - + 15 highest priority projects in cycle 0 and 1
- ALMA sensitivity:
 - + Fainter signals (lines or thermal fluxes)
 - + Time resolution
- ALMA spatial resolution
 - + Image small planets and satellites
 - + Look closer to comet nuclei
- Still some difficulties:
 - + Low flexibility, not easy for variable sources
 - + No velocity tracking at the observatory

PdBI/NOEMA

- 
- NOEMA:
 - + Northern hemisphere
 - + Flexibility:
 - Scheduling
 - Correlator
 - Planets, satellites
 - + Monitoring, tight time constraints
 - Asteroids, TNOs
 - + North targets
 - + Continuum+line
 - Comets
 - + Northern hemisphere targets
 - + Simultaneous Interferometry+On-Off
 - + Simultaneous line+continuum
 - High spectral resolution for lines
 - Wide total bandwidth for continuum

Thanks !

