Comets with ALMA

I. The comets and their chemistry
II. Cometary observations

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Summary

- Comets are remnants of the planet formation era
  - Their study should bring insight into the physical and chemical conditions in the early Solar System
- The nucleus is a dirty, sublimating snowball
  - Water ice, volatiles, organic grains, refractories
- Direct study difficult
  - Detailed study of the coma to constrain nucleus properties
- Complex chemistry
  - Chemical diversity
  - Extended sources
  - Minor species
  - Isotopes

Open questions about comet chemistry

- Solar Nebula and protoplanetary disk chemistry
  - Detailed composition
    - Most complex molecules, organic grains
    - What could have been brought to the Earth ?
  - Chemical diversity
  - Origin of cometary material
    - What has been preserved from ISM ?
- Formation of km sized bodies in the protoplanetary disk
  - Material in the nucleus ?
    - Ices, homogeneity ?
  - Processes inside the nucleus ?
    - Jets, comet splits, outbursts
- Evolution of cometary material
    - Are the comet still primordial ?

Part II: Cometary observations

  - Space missions
  - Remote observations of the nucleus
  - Remote observations of the dust coma
  - Remote observations of the gas coma
    - UV/Vis
    - IR
- Radio mm observations
  - Single Dish
  - Interferometry
  - Comets with ALMA

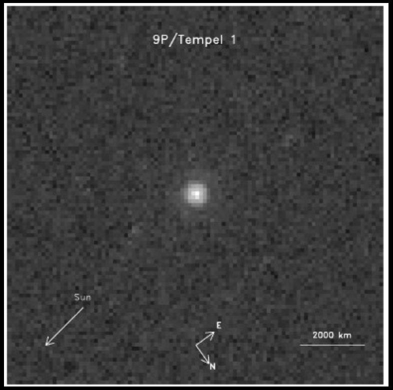
Space missions

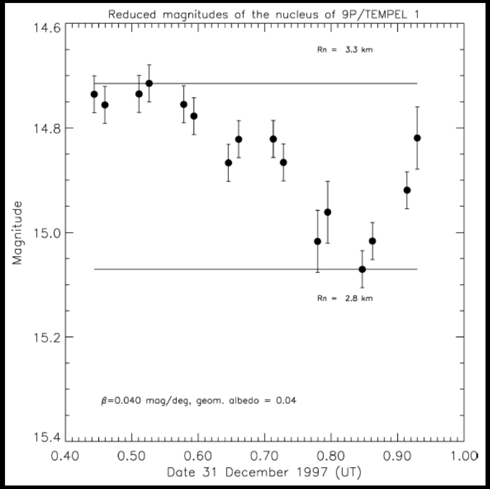
- Past and future studies:
  - Mass spectroscopy, nucleus imaging, surface resolved spectroscopy
    - 1986: Giotto, Vega in Halley atmosphere
    - 2001: Deep Space toward Borelly
    - 2005-2010: Deep Impact towards Tempel 1(+Impactor) and Hartley 2
  - Sample return, microscopic mineralogy
    - 2005: Stardust brought back cometary dust grains
  - Landing and in situ studies
    - 2014: Rosetta
- Limitations:
  - Few comets while we observe a high diversity among comets
  - Mainly ecliptic comets

Remote observations: Nucleus

- Different wavelength ranges complement one another
  - Optical: reflected light
    - Nucleus shape and rotation
  - IR, mm: thermal emission
    - Nucleus size and albedo
  - Radar experiments
    - Nucleus size and rotation
  - Combined studies:
    - Surface properties
    - Albedo, thermal conductivity,...
- Global physical properties
- Few about composition and nucleus structure

Tempel 1 HST image and lightcurve (Lamy et al. 2007)



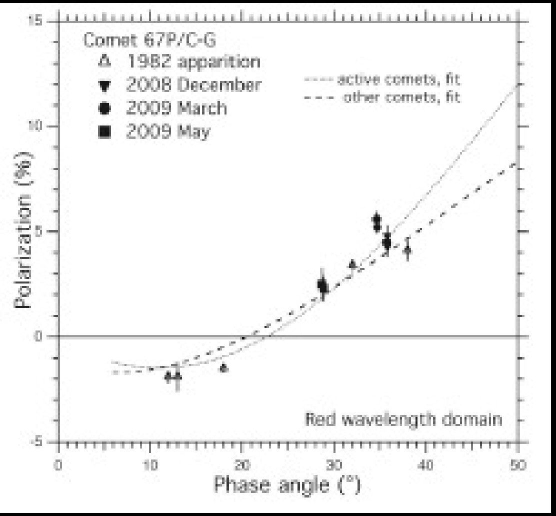


Tuttle shape model deduced from HST light curves (Lamy et al. in prep.)

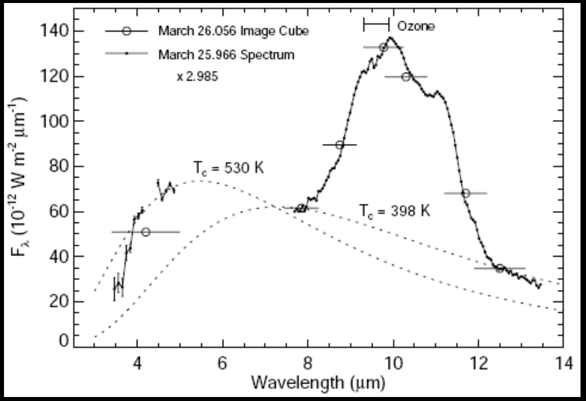
Remote observations: Dust coma

- Optical:
  - Reflected light on small grains
  - Coma structure
    - Jets, nucleus rotation
  - Polarimetry
    - Grain properties (size, shape)
- IR, mm:
  - Thermal emission of µm-mm sized grains
    - Size distribution (up to mm sizes)
  - IR Spectroscopy to study their nature
    - Presence of silicates
- Radar:
  - Echo from large grain coma

Polarization of comet 67P/C-G
(Hadamick et al. 2010)



IR spectrum in Hale-Bopp with
silicate band (Hayward et al. 2000)



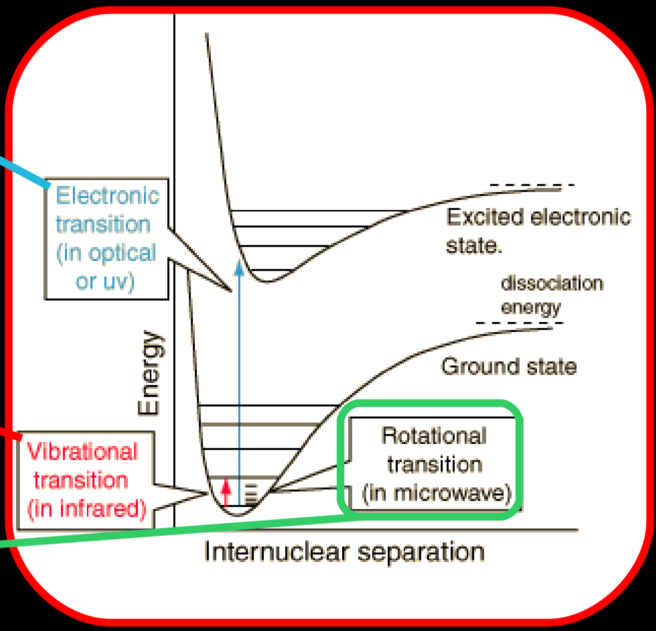
Remote observations: Gas coma

Outer coma

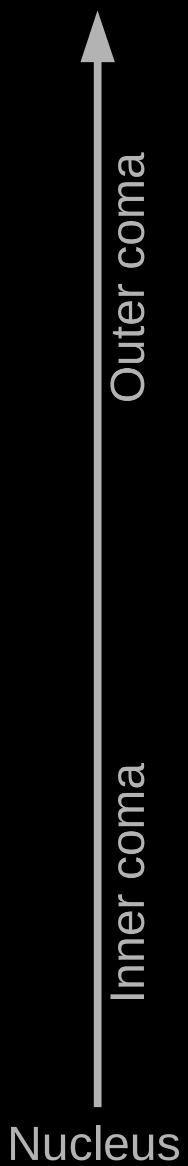
- UV/Optical
  - UV Fluorescence of diatomic parent species
    - S_2, CO
    - More complex molecules dissociated
  - Optical electronic bands of fragment species
    - CN, C2, C3, OH, CS
    - Daughter products
- IR spectroscopy
  - Vibration bands of parent species
  - H_2O, CO, CO_2, symmetric hydrocarbons
  - Difficult from the ground
- Radio (millimetre) spectroscopy
  - Rotational transitions
  - Parent species with dipole moment
  - CHON, S bearing molecules, complex species
  - ***Well suited for detailed study of the chemistry***

Inner coma

Nucleus



Remote observations: Gas coma



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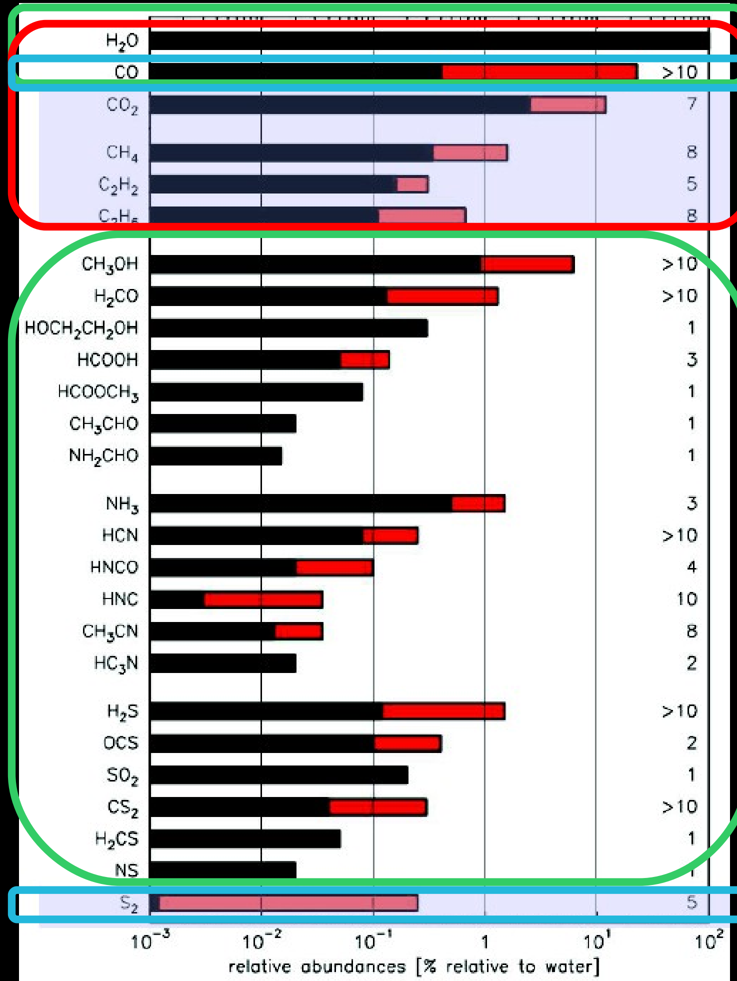
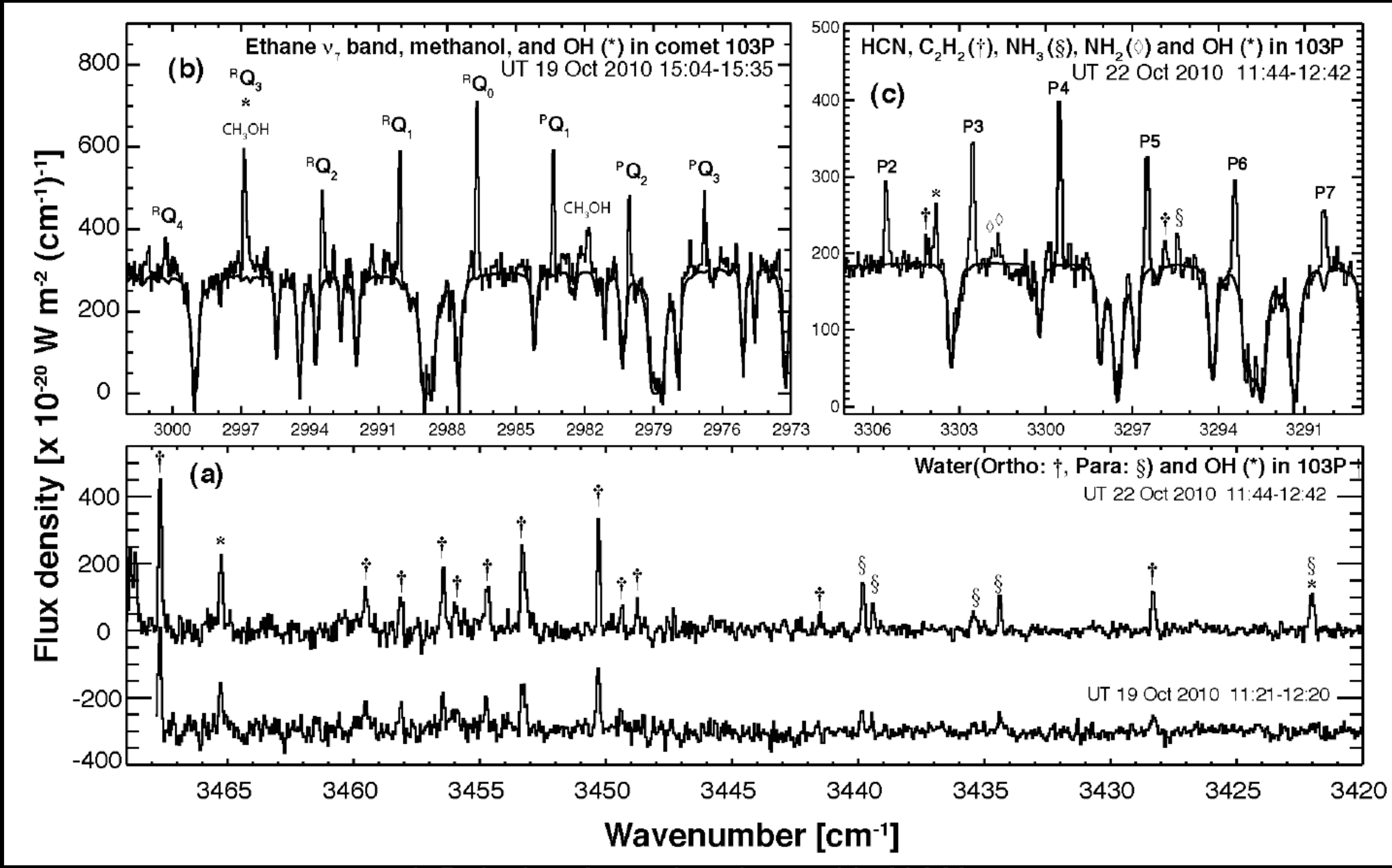


Parent molecules in cometary atmospheres

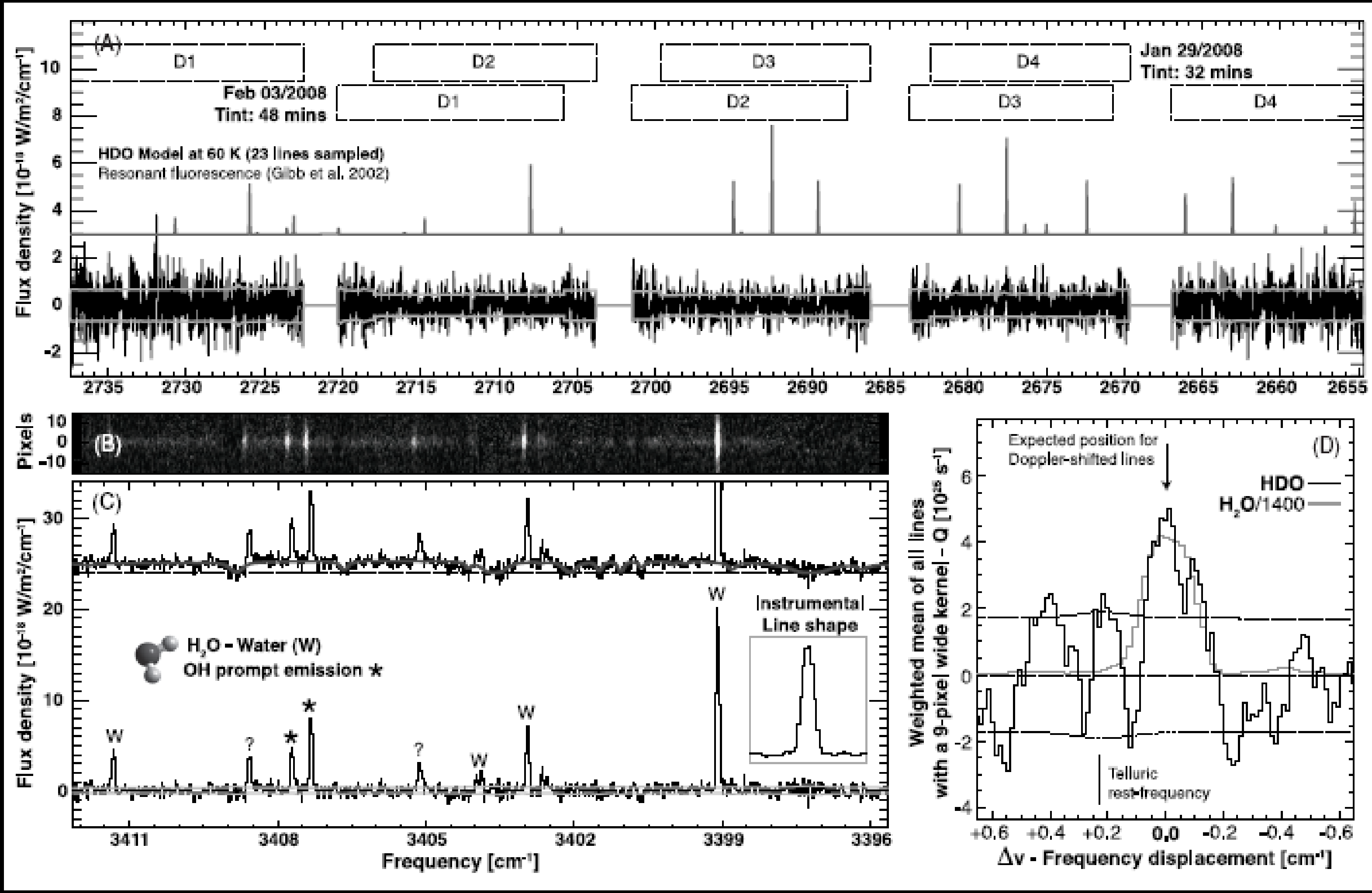
IR spectroscopy

- VLT-NIRSPEC spectra of Hartley 2
  - Water, Ortho-to-Para ratio, rotation temperature, hydrocarbons
  - Mumma et al. 2011



IR spectroscopy

- VLT: HDO in Tuttle
  - Villanueva et al. 2009



IR spectroscopy

- Parent species have bands in the IR
- Symmetric hydrocarbon only detectable in the IR
- Coma morphology:
  - Distribution along the slit of the spectrometer (resolution ~1")

- Low flux at large heliocentric distances
- Dust contribution to be removed
- Atmosphere does not help

Radio single dish spectroscopy of comets

- 1973 Nancay radio telescope
  - OH (21 cm) to monitor H_2O
- 1985 IRAM 30m
  - Then other instruments CSO, JCMT, SEST, APEX,...
  - mm observations (ν = 80-460 GHz, λ = 0.06-4 mm)
  - Detailed composition of the coma
- Angular resolution in the mm
  - Antenna primary beam ~10-50''
  - @ 1 mm, 10 m: 24''
  - 2000-10000 km in the coma 1'' ~ 230 km @ 1AU)
- Unequaled spectral resolving power (10^6-10^7)
  - Line profile
  - Low line blending

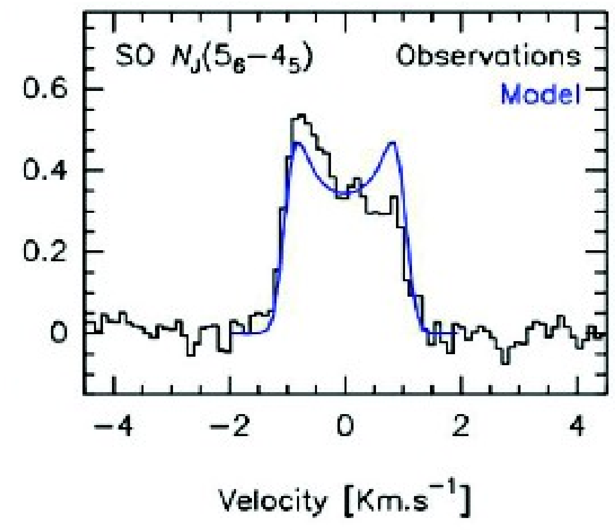
$$\theta \propto \frac{\lambda}{D}$$

Rotational lines

- Emissivity from a cell in the coma
  - $J_{ul} = (1/4\pi)\ h\ \nu_{ul}\ A_{ul}\ n(\mathbf{r})\ p_u(\mathbf{r})\ f(\nu)$
    - h Planck constant
    - Frequency: ν_{ul} [Hz], Einstein coefficient A_{ul} [s^{-1}] for spontaneous emission
    - $n(\mathbf{r})$ density at the position defined by the vector r
    - p_u relative population of the upper level
    - $f(\nu)$ thermal broadening (gaussian) around ν_{ul}
    - $\nu_{ul} \neq \nu^0_{ul}$ due to cell outflow velocity projection on the line of sight
- Line = emission integration over the whole antenna beam

Rotational lines

- Emissivity from a cell in the coma
  - $J_{ul} = (1/4\pi)\, h\, \nu_{ul}\, A_{ul}\, n(\mathbf{r})\, p_u(\mathbf{r})\, f(\nu)$
- Line = emission integration over the whole antenna beam
  - Line integrated intensity ~ Averaged column density ~ Abundances
    - $F_{ul} = \Omega/4\pi\, h\, \nu_{ul}\, A_{ul} <N_u>$
    - $<N_u> = \int_{beam} p_u(r)\, n(r)$
  - Line profile
    - Global line width ~ outflow velocity
    - Line shape ~ coma structure
  - Several rotational lines ~ temperature

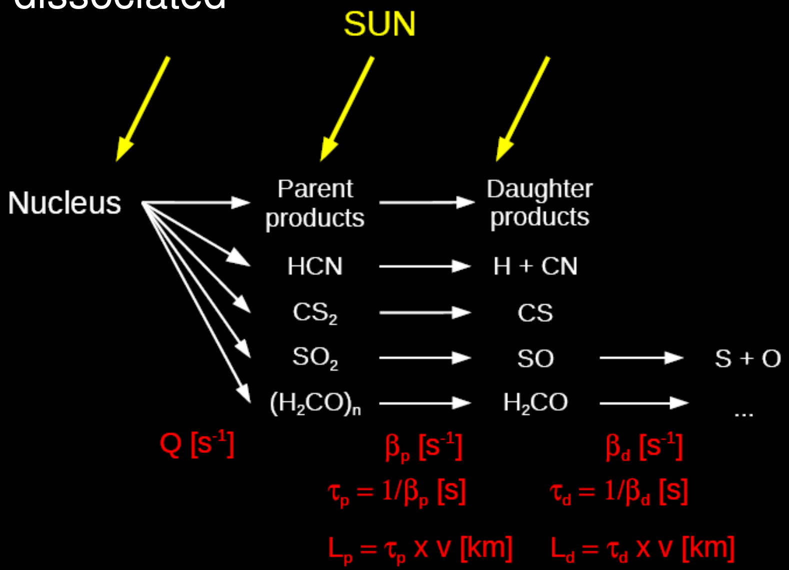


Coma most simple model

- Haser Model $\langle N_u \rangle = \int_{beam} p_u(r)\, n(r)$
  - Density n [km^{-3}] depends on the distance to the nucleus (r [km])
  - Isotropic outflow with constant velocity (v_{exp} [km s^{-1}])
  - 2 cases: parent and daughter products
  - Q = production rate [molecule s^{-1}]
  - L = life scalelength [km]
    - Typical distance beyond which molucules are dissociated

$$n_p(r) = \frac{Q}{4\pi\, r^2\, v_{exp}}\, e^{-\frac{r}{L_p}}$$

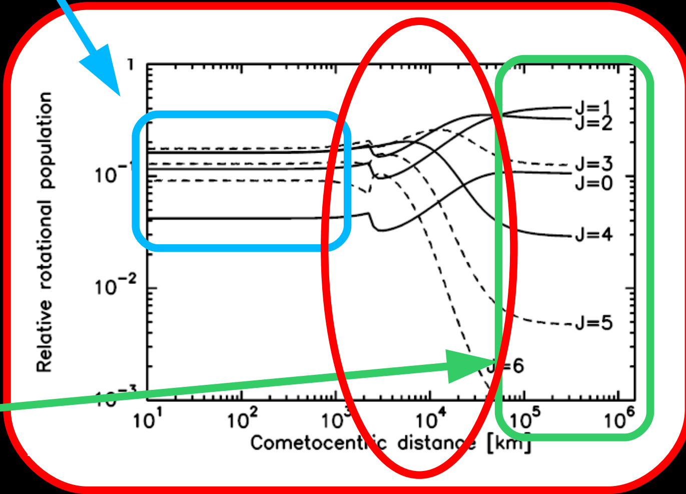
$$n_d(r) = \frac{Q}{4\pi\, r^2\, v_{exp}}\, \frac{L_d}{L_p - L_d} \left(e^{\frac{r}{L_p}} - e^{\frac{r}{L_d}}\right)$$



Excitation

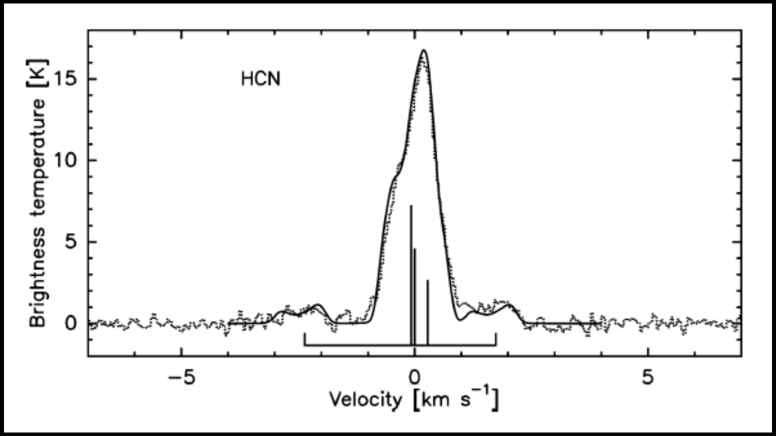
- Thermal equilibrium in the inner coma
  - Collisions with neutrals (H_2O) and electrons
  - Low T: only rotational levels
- Radiative excitation
  - Sun radiation
    - Vibrational excitation
    - Electronic and rotational excitation are negligible
  - Cosmic background (2.7 K)
    - Rotational excitation at large heliocentric distances
  - Self absorption sometimes (thick lines)
  - Fluorescence equilibrium in the outer coma
    - Solar pumping vs decay

$$\langle N_u \rangle = \int_{beam} p_u(r)\, n(r)$$

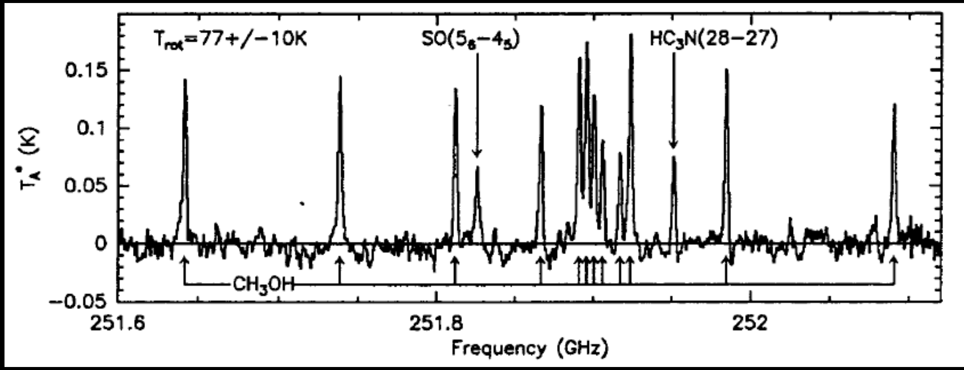


Typical mm spectra

- IRAM 30m spectrum of HCN*J*(3-2) in 17P/Holmes
  - Bockelée-Morvan et al. 2008

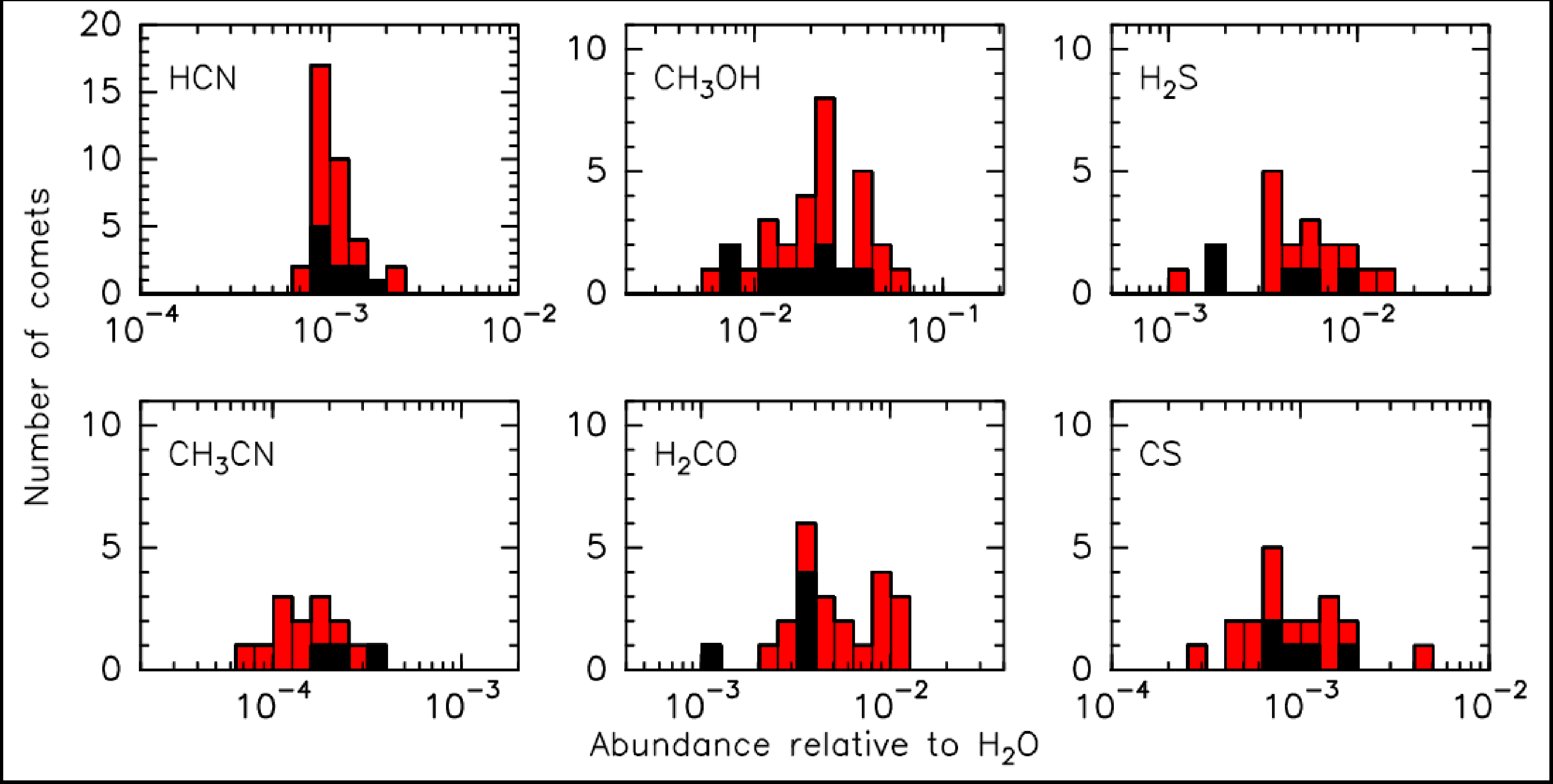


- CSO spectrum of methanol lines
  - Lis et al. 1999



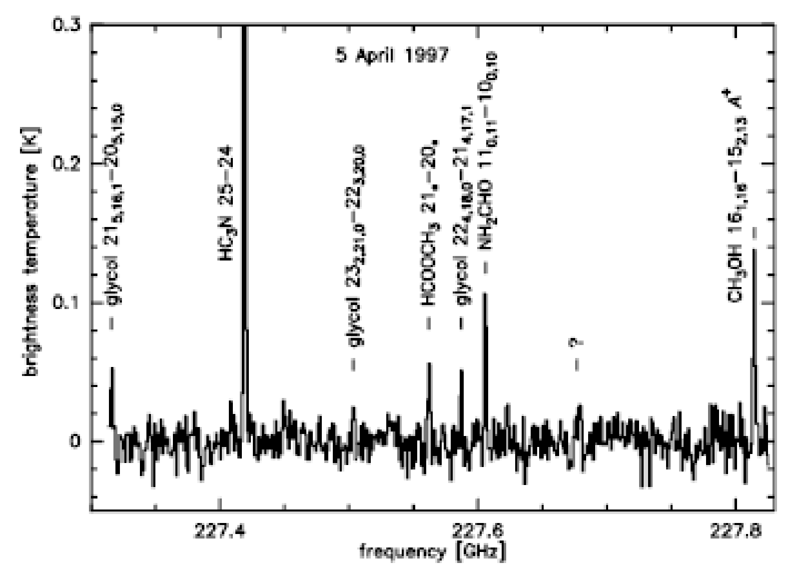
Chemical diversity

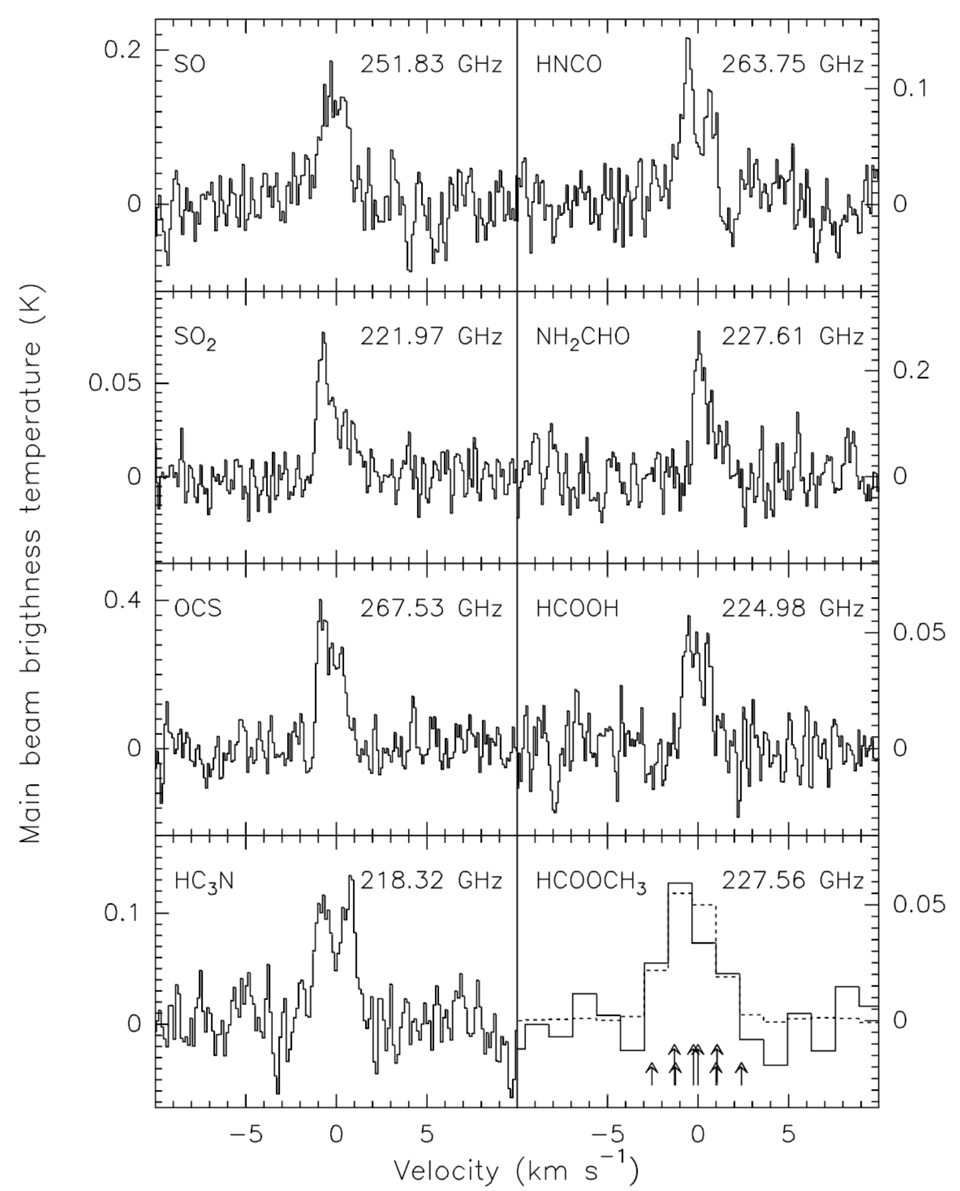
- 10 molecules in more than 10 comets
  - Crovisier et al . 2009



Minor species: Detection

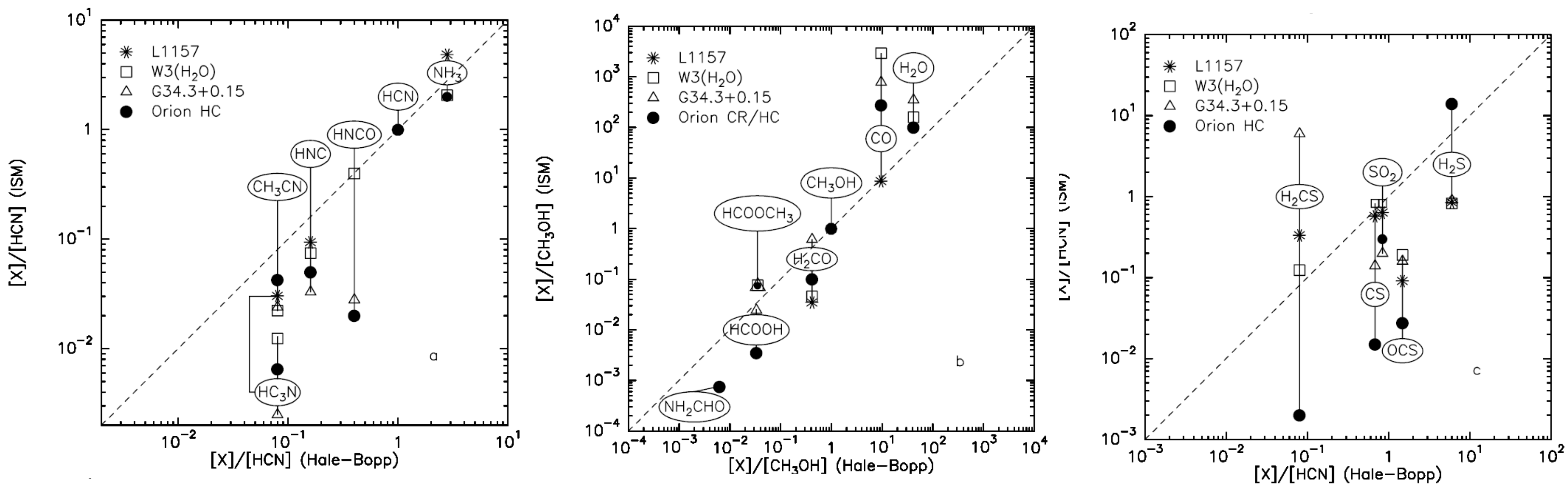
- Complex molecules in Hale-Bopp
  - IRAM Plateau de Bure and 30m
  - Bockelée-Morvan et al. 2000
  - Crovisier et al. 2004





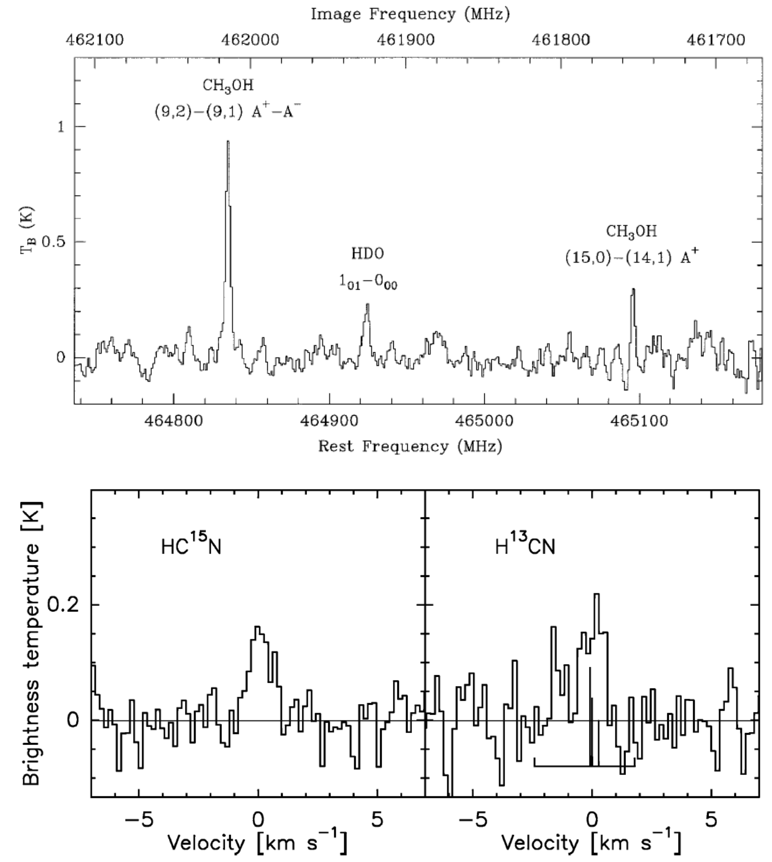
Minor species: Comparison to ISM

- Hale-Bopp vs hot core composition
  - Bockelée-Morvan et al. 2000



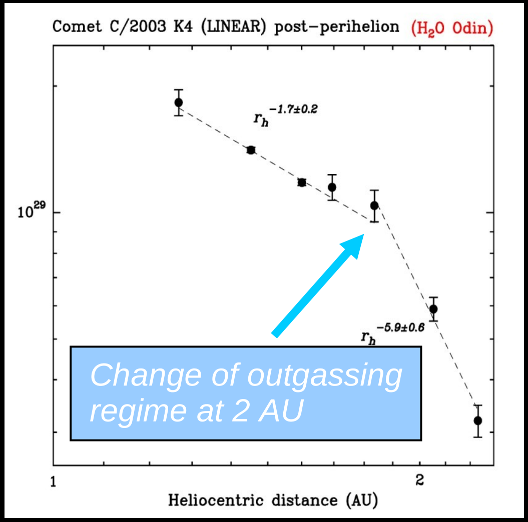
Minor species: Isotopologues

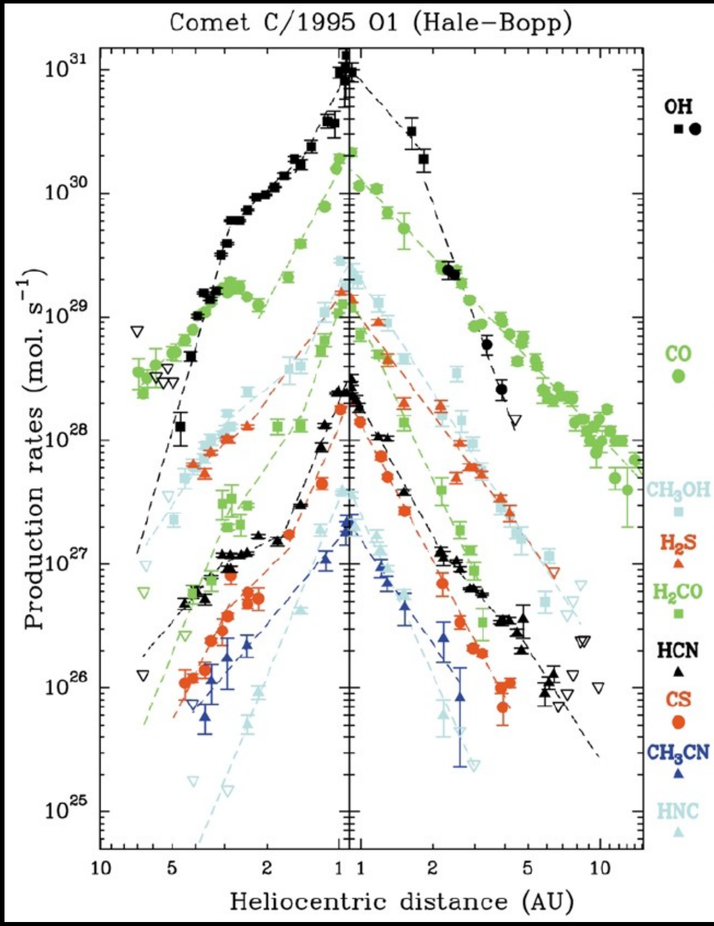
- HDO in Hyakutake
  - Very close to the Earth
    - Bockelée-Morvan et al. 1998
- $HC^{15}N$ and $H^{13}CN$ in 17P/Holmes
  - Comet outburst
    - Bockelée-Morvan et al. 2008



Comet monitoring

- Study ice structure, differentiation, seasonal effects
  - Hale-Bopp production rates
    - 1995-2002 observations
    - Different steepness
    - Changes in slopes
    - CO predominance
    - Biver et al. 2002
  - H_2O in Linear
    - Odin mm observations
    - Change in slope
    - Biver et al. 2006

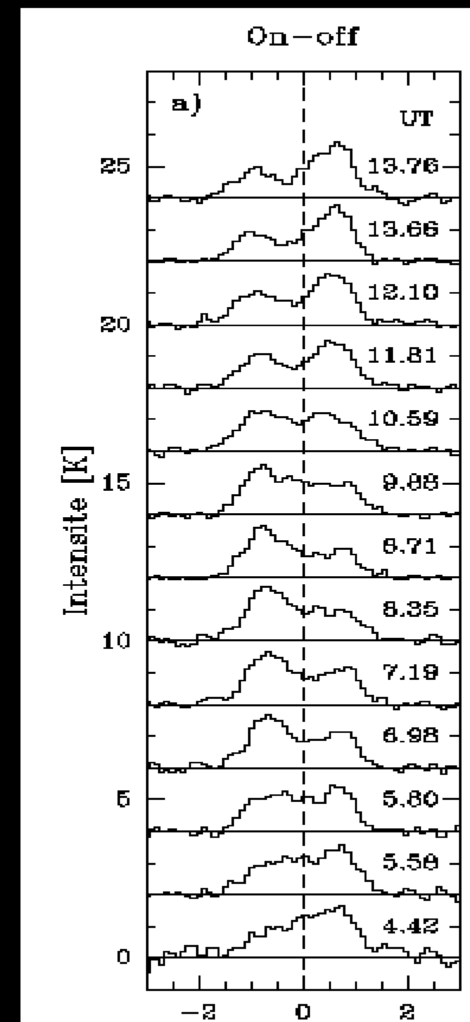




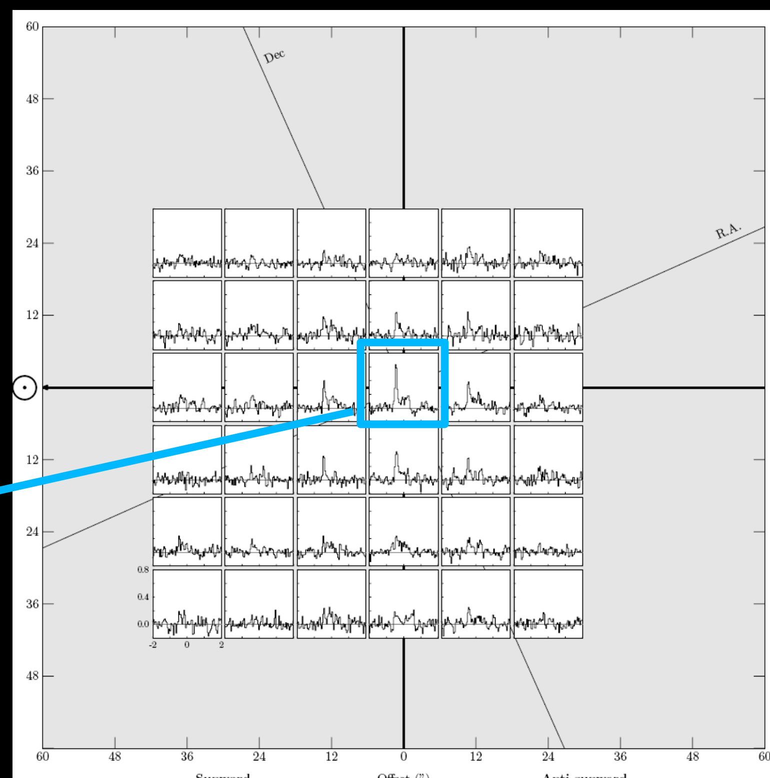
Coma structure

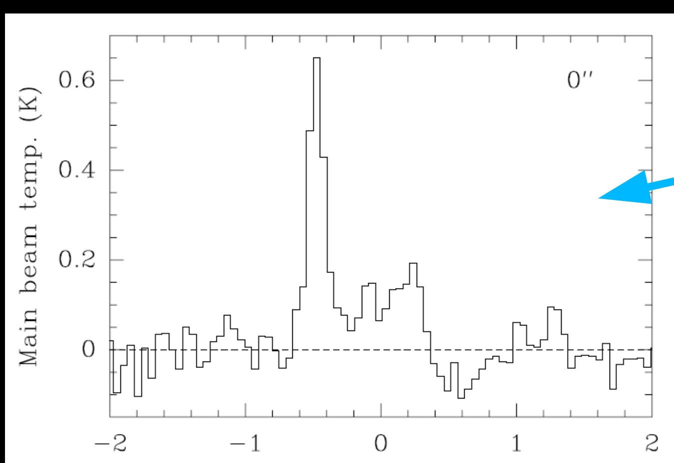
- Line profile studies
  - CO in SW1
  - CO jet in Hale-Bopp
- Large scale maps
  - CO in SW1

Sequence of CO *J*(2-1) spectra observed in Hale-Bopp
Bockelée-Morvan et al. 2009



CO *J*(2-1) emission map in SW1
Gunnarsson et al. 2008





Interferometric observations

- Spectral map rather than spectra:
  - 3D information (x,y,v)
  - Resolution 1-10''
    - Single dish: D up to 30 m
    - Interferometer: B ~ 150 m to 10000 m
      - 1mm, B=150m: 1.6''

$$\theta_{SD} \propto \frac{\lambda}{D}$$

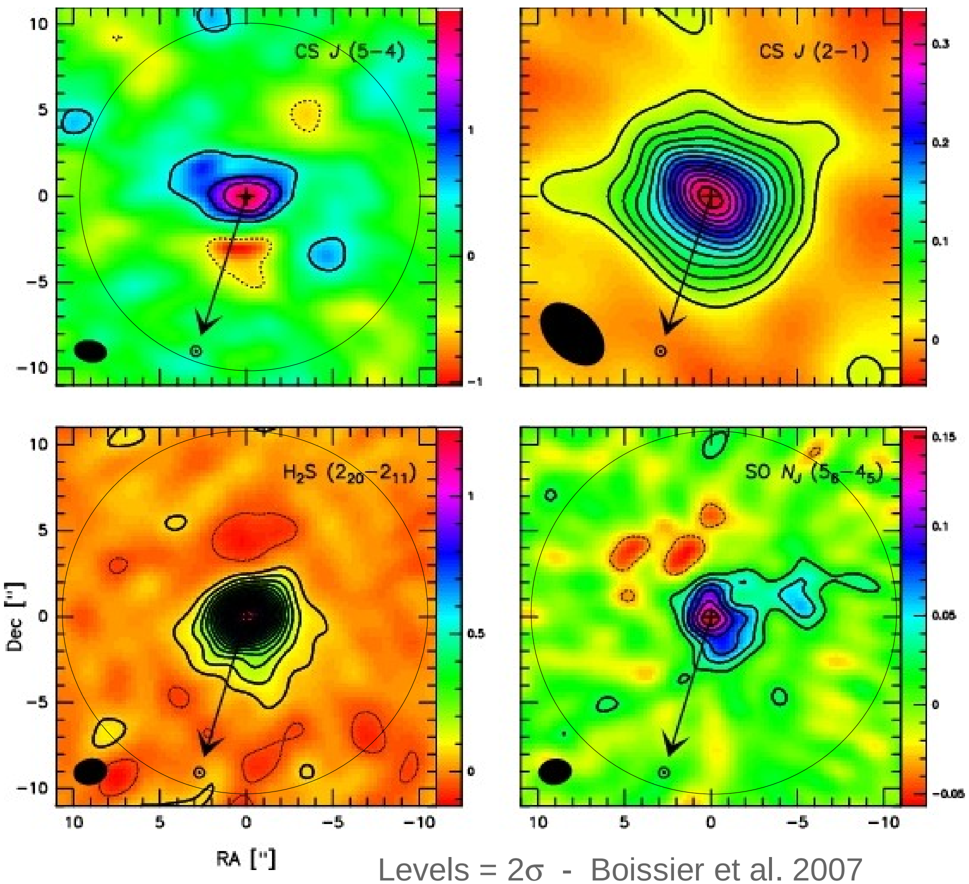
$$\theta_{Int} \propto \frac{\lambda}{B}$$

- Simultaneous continuum measurements
  - Nucleus
  - Dust coma
- BUT
  - Require strong sources
  - Extended coma flux loss

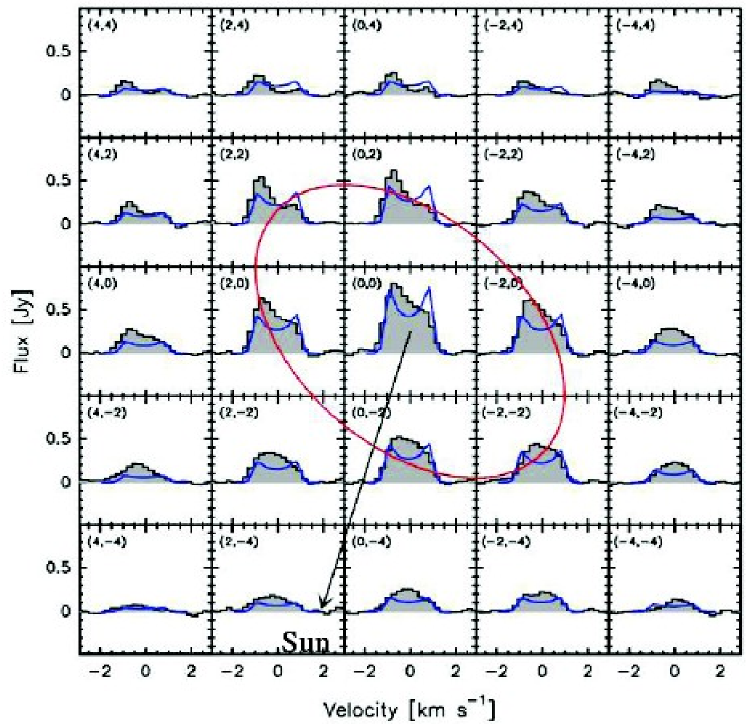
Radio interferometric observations of comets

1985: Halley (VLA)
1987: Wilson (VLA)
1992: 1991 A1 Shoemaker-Levy (VLA)
1996/1997: C/1996 B2 Hyakutake (VLA, PdBI)
1997: C/1995 O1 Hale-Bopp (VLA, BIMA, OVRO, PdBI)
2004: C/2002 T7 Linear (BIMA)
2004: C/2001 Q4 NEAT (BIMA)
2006: 73P/SW3 (SMA)
2007: 17P/Holmes (PdBI, SMA)
2008: 8P/Tuttle (PdBI)
2010: 103P/Hartley 2 (PdBI)

Interferometric observations

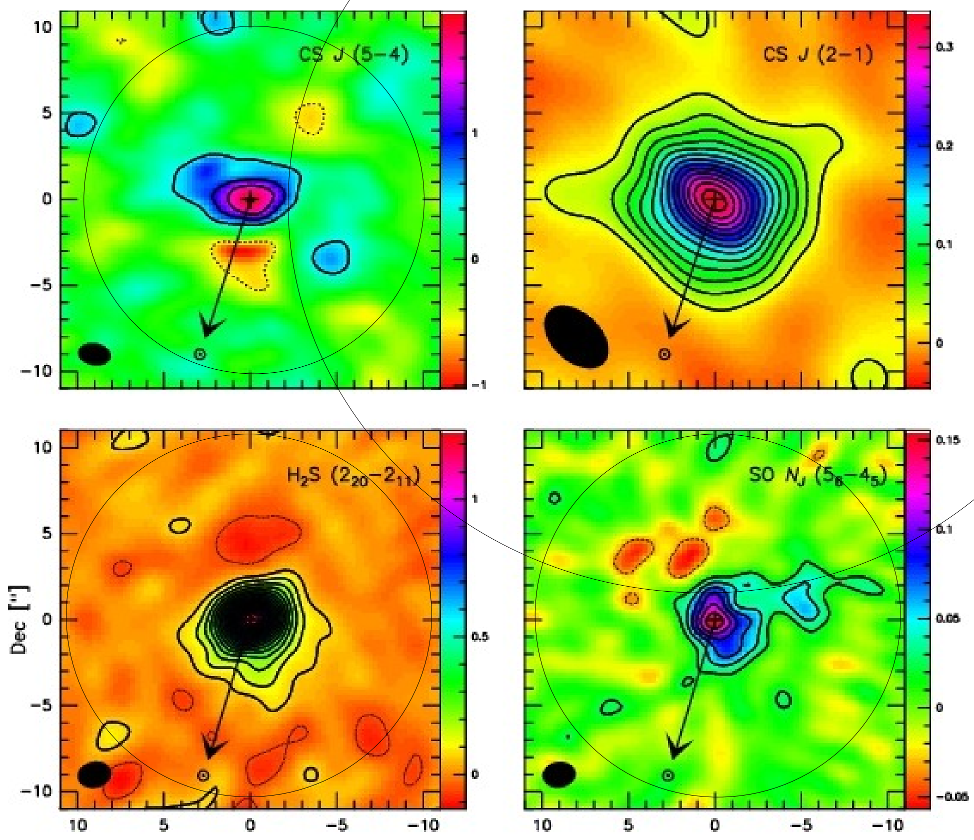


Levels = 2σ - Boissier et al. 2007



CS *J* (2-1) spectral map

Interferometric observations



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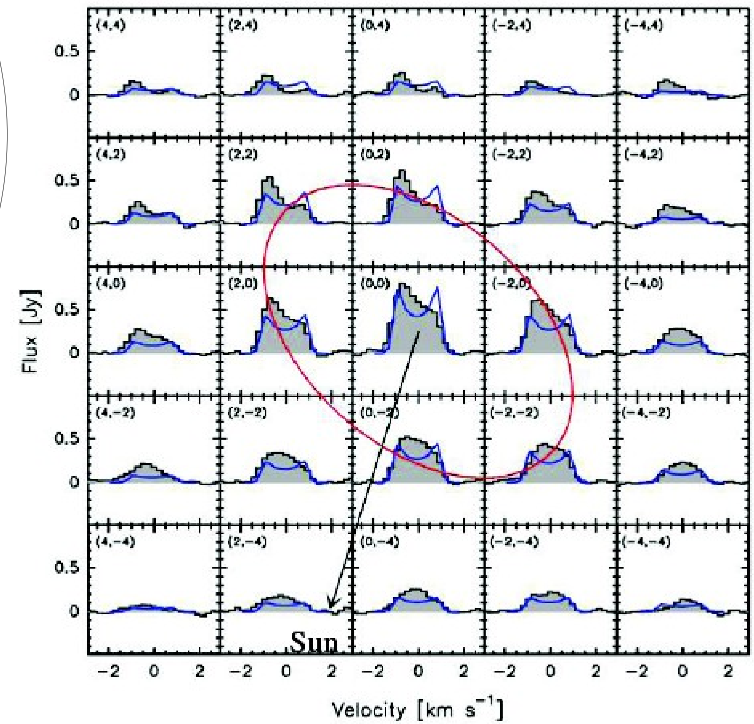
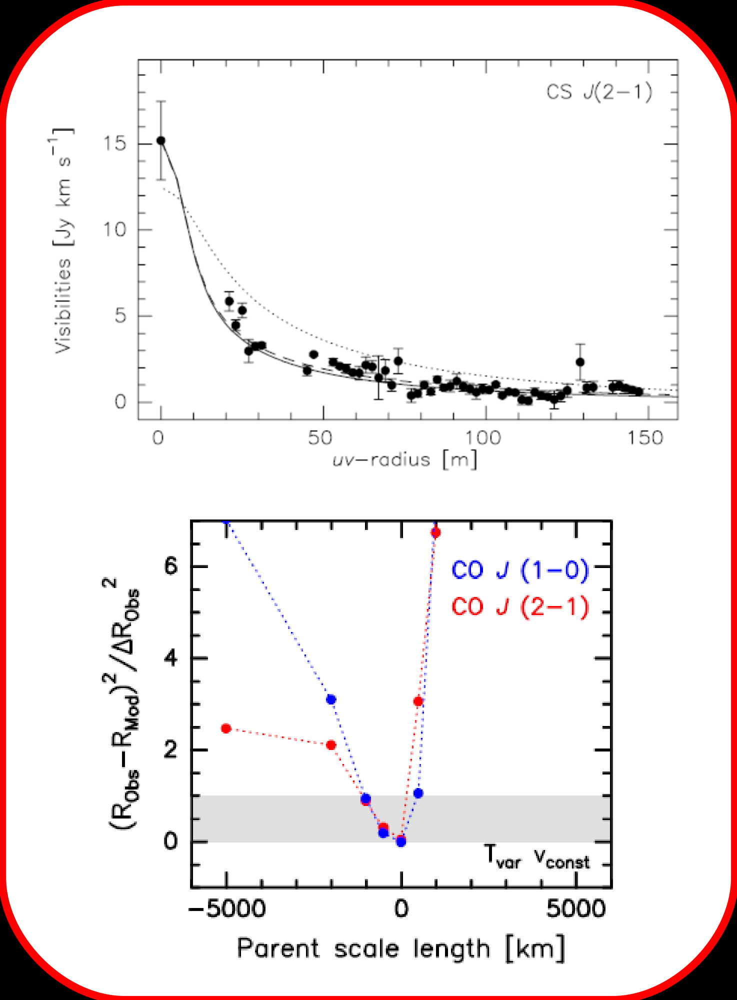


CS J (2-1) spectral map

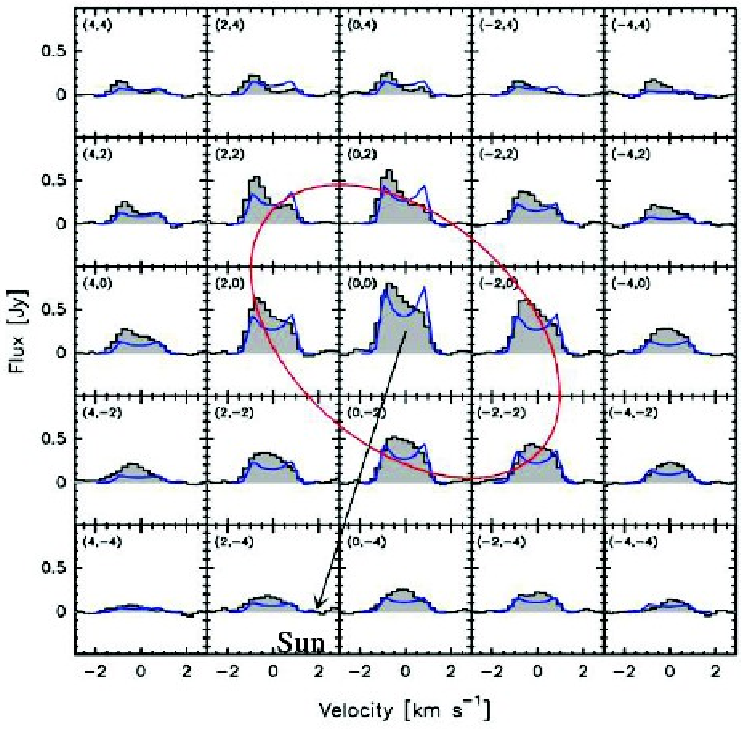
Gas radial extent (in Hale-Bopp)

- Study the origin of molecules
  - Nucleus origin vs extended sources
  - Constraints on Lp
    - HNC, H2CO (Wink et al. 1999)
    - H2S, SO (Boissier et al. 2007)
    - CO (Bockelée-Morvan et al. 2010)
- Measure life scalelengths
  - Debated L_{CS}
    - Snyder et al. 2000
    - Boissier et al. 2007
- Method
  - Works if $\theta_{Primary} \geq L \geq \theta_{Int}$
  - Visibility vs uv-radius evolution
    - F vs radius on maps is not safe
  - When available F_{SD}/F_{Int} is an indicator

$$n_d(r) = \frac{Q}{4\pi\, r^2\, v_{exp}} \frac{L_d}{L_p - L_d} \left(e^{\frac{r}{L_p}} - e^{\frac{r}{L_d}}\right)$$



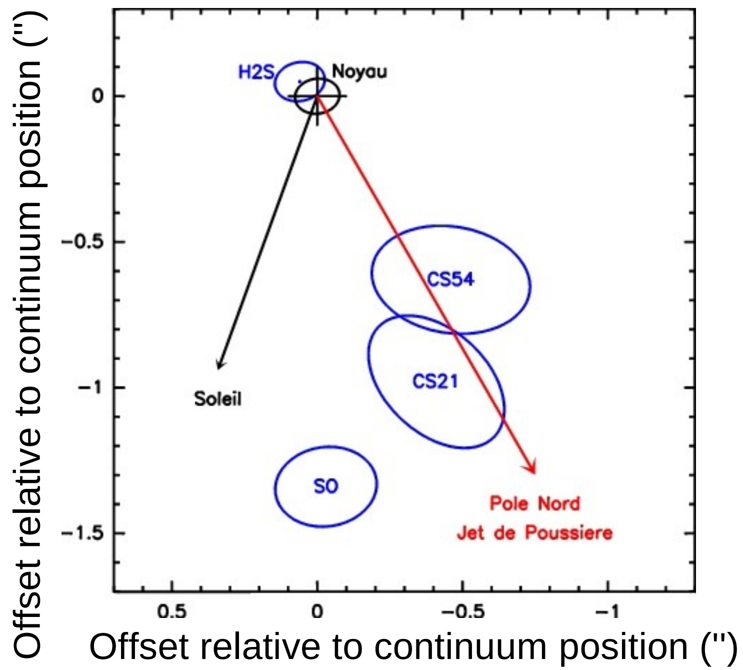
Coma morphology (in Hale-Bopp)

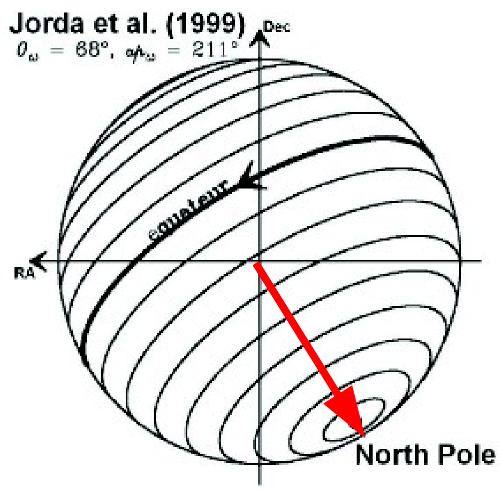


CS *J* (2-1) spectral map

Coma morphology (in Hale-Bopp)

- Astrometric studies
  - Polar jet (Boissier et al. 2007)

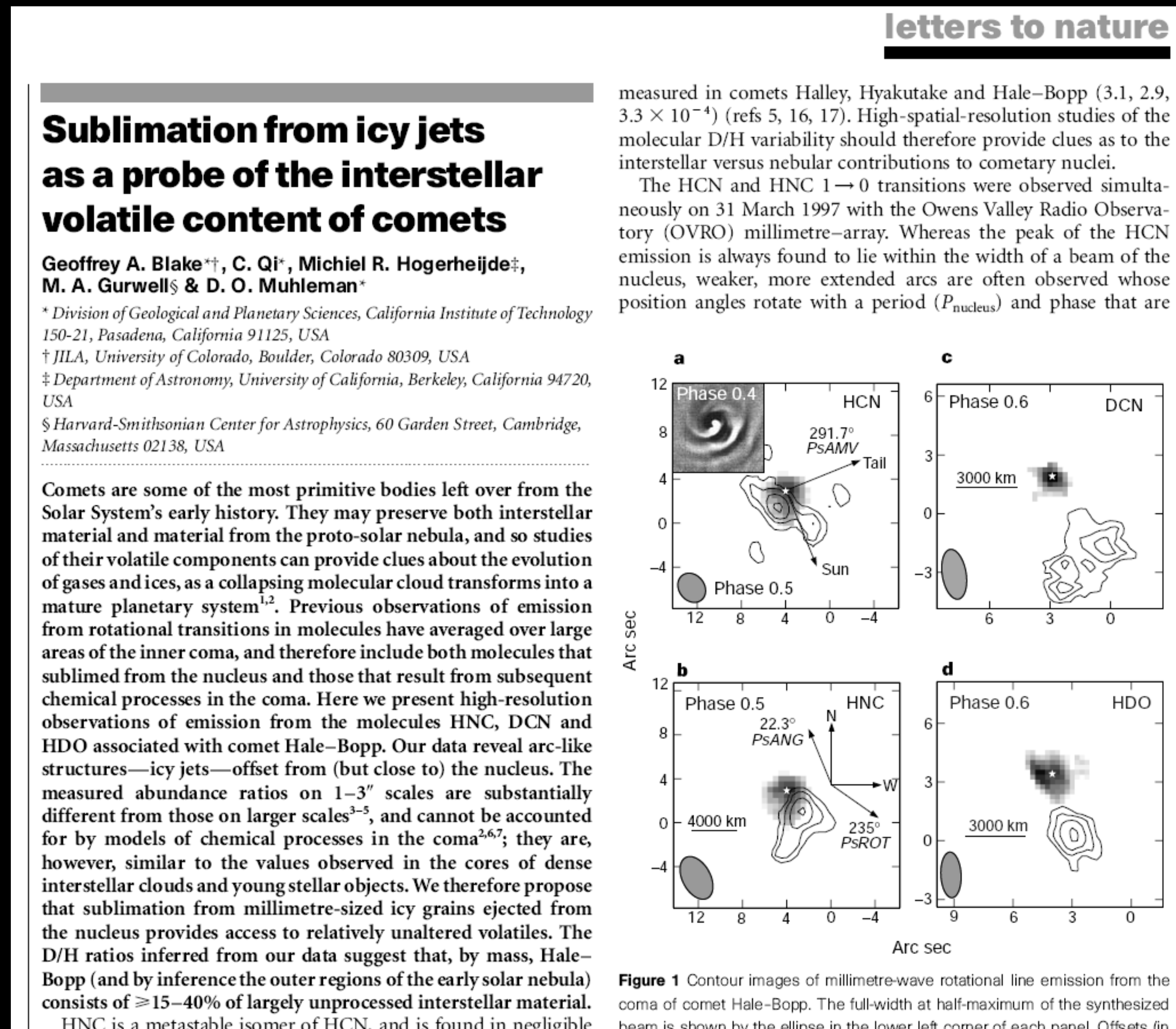




A dust jet was observed at high latitude (Jorda et al. 1999)

Coma morphology (in Hale-Bopp)

- D/H higher in jets
  - OVRO obs
  - Preserved from ISM
  - Blake et al. 1999



letters to nature

Sublimation from icy jets as a probe of the interstellar volatile content of comets

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Comets are some of the most primitive bodies left over from the Solar System's early history. They may preserve both interstellar material and material from the proto-solar nebula, and so studies of their volatile components can provide clues about the evolution of gases and ices, as a collapsing molecular cloud transforms into a mature planetary system[1,2]. Previous observations of emission from rotational transitions in molecules have averaged over large areas of the inner coma, and therefore include both molecules that sublimed from the nucleus and those that result from subsequent chemical processes in the coma. Here we present high-resolution observations of emission from the molecules HNC, DCN and HDO associated with comet Hale–Bopp. Our data reveal arc-like structures—icy jets—offset from (but close to) the nucleus. The measured abundance ratios on 1–3″ scales are substantially different from those on larger scales[3–5], and cannot be accounted for by models of chemical processes in the coma[2,6,7]; they are, however, similar to the values observed in the cores of dense interstellar clouds and young stellar objects. We therefore propose that sublimation from millimetre-sized icy grains ejected from the nucleus provides access to relatively unaltered volatiles. The D/H ratios inferred from our data suggest that, by mass, Hale–Bopp (and by inference the outer regions of the early solar nebula) consists of ≥15–40% of largely unprocessed interstellar material.

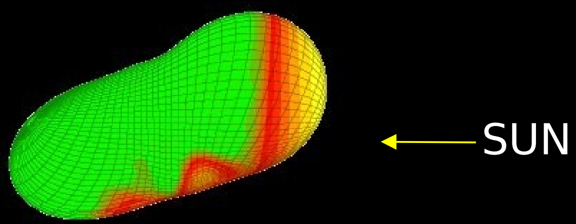
HNC is a metastable isomer of HCN, and is found in negligible measured in comets Halley, Hyakutake and Hale–Bopp (3.1, 2.9, 3.3×10^{-4}) (refs 5, 16, 17). High-spatial-resolution studies of the molecular D/H variability should therefore provide clues as to the interstellar versus nebular contributions to cometary nuclei.

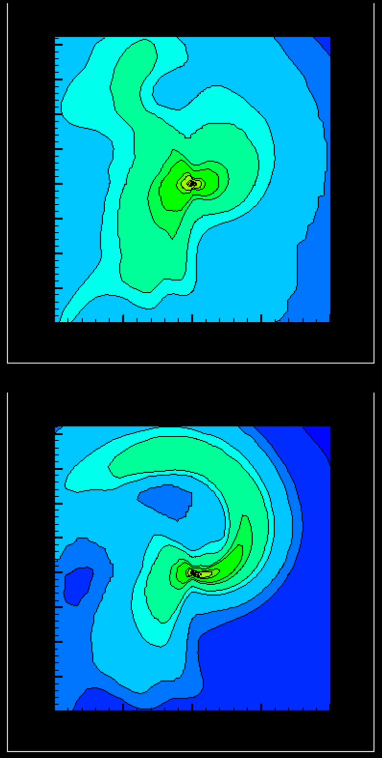
The HCN and HNC $1 \rightarrow 0$ transitions were observed simultaneously on 31 March 1997 with the Owens Valley Radio Observatory (OVRO) millimetre–array. Whereas the peak of the HCN emission is always found to lie within the width of a beam of the nucleus, weaker, more extended arcs are often observed whose position angles rotate with a period ($P_{nucleus}$) and phase that are

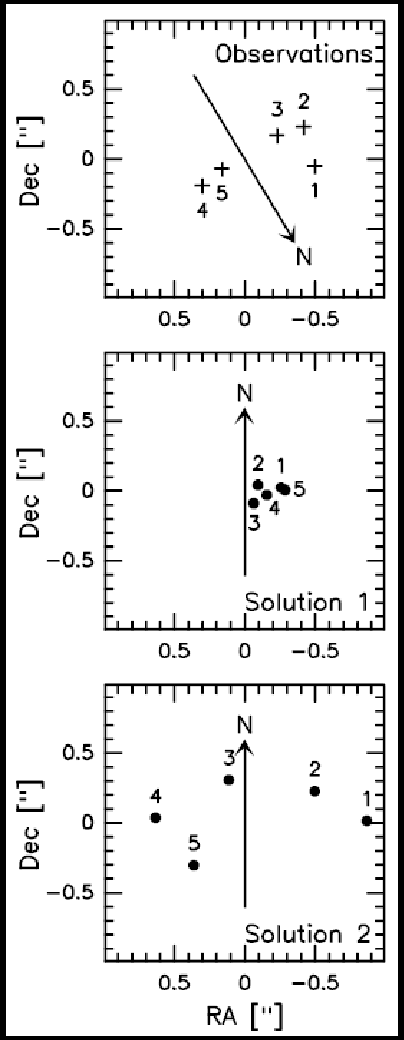
Figure 1 Contour images of millimetre-wave rotational line emission from the coma of comet Hale-Bopp. The full-width at half-maximum of the synthesized beam is shown by the ellipse in the lower left corner of each panel. Offsets (in

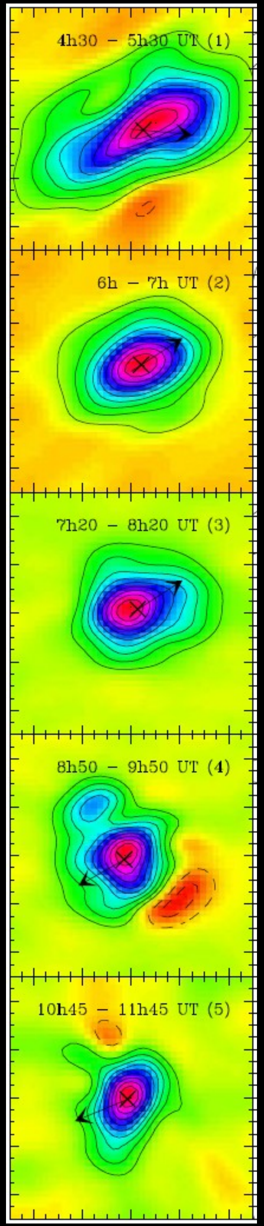
Coma morphology (in Hale-Bopp)

- Coma kinematics (CO*J*(2-1))
  - Time variations in the data
  - 3D+t simulations
  - Inhomogeneous outgassing
    - Bockelée-Morvan et al. 2009
    - Boissier et al. 2010









Coma morphology and nucleus homogeneity

- Different molecules have different outgassing patterns :
  - Polar jet (CS, SO), equatorial jet (CO), no jet (H_2S)
  - D/H higher in jets
- Evidences for nucleus heterogeneity
  - Several cometesimals with different compositions
  - Planetesimals radial mixing ?
- Related results
  - Deep Impact images show surface heterogeneity
  - Chemical investigation of 73P/SW3 fragments suggests homogeneity

Something else than Hale-Bopp

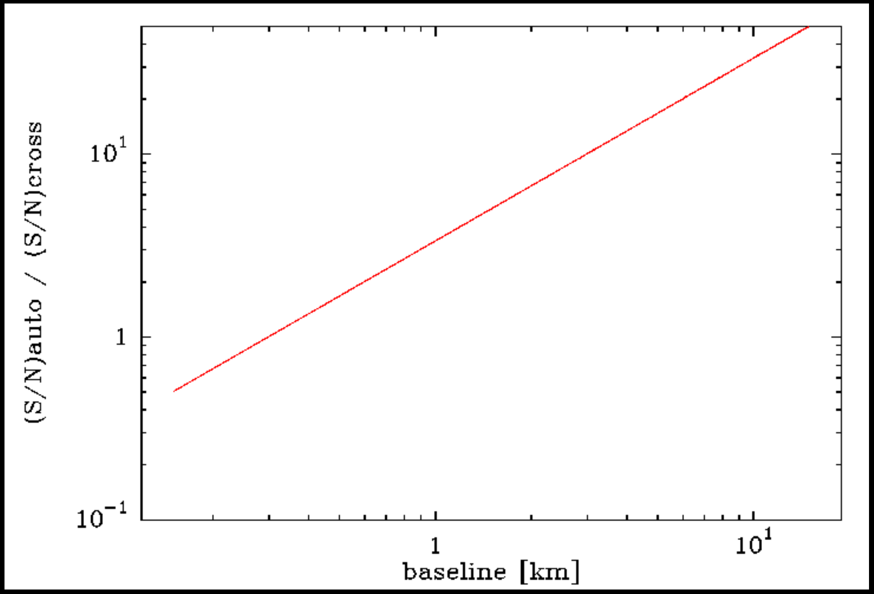
- 17P/Holmes @ PdB (and SMA)
  - Observation after an outburst
  - HCN and dust emission
  - Outburst caracterisation
    - Boissier et al. 2009
- 8P/Tuttle @ PdBI
  - Detection of the mm emission of the nucleus
    - Boissier et al. 2011
- 103P/Hartley 2 @ PdBI
  - HCN, CH_3OH and continuum (dust+nucleus)
    - Temperature profile in the coma
    - Coma structure with 100 km resolution
    - Work in progress

Cometary science with ALMA

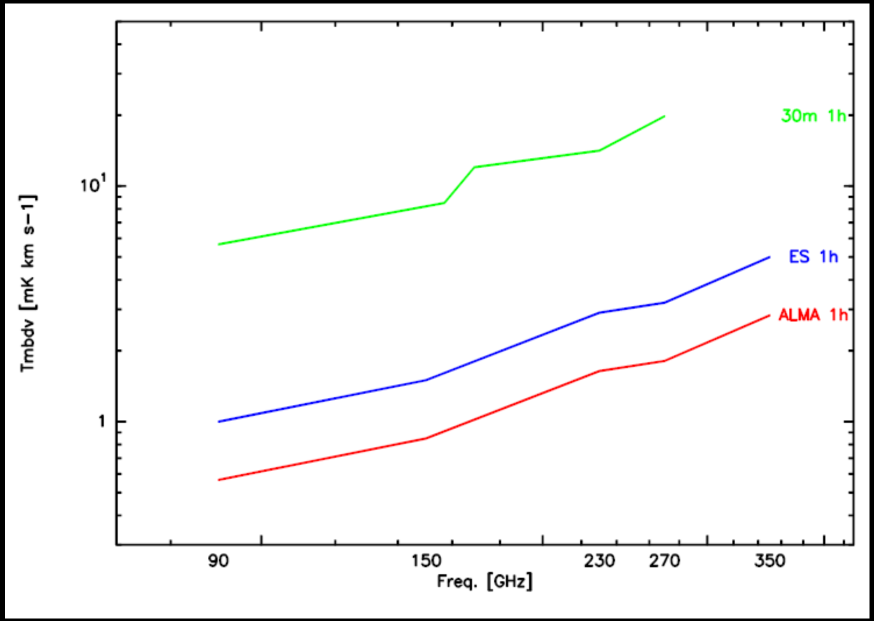
ALMA: Volatile inventory

- Cometary atmospheres are extended sources
  - What configuration to use ?
  - Flux loss
  - For pure detection most compact or Single-Dish
    - ALMA 10 times better than 30m in On-Off

Comparison of S/N ratios with ALMA
On-off versus various configurations

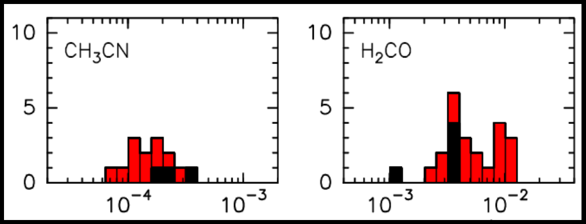


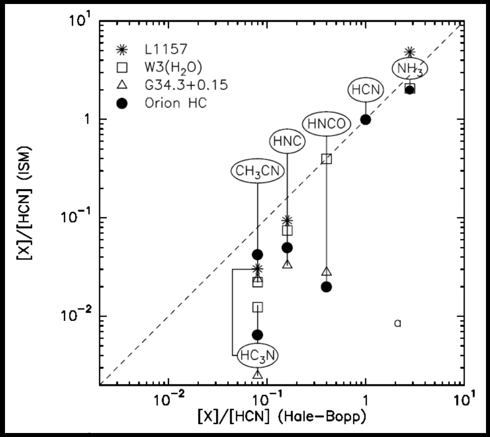
On-Off sensitivities

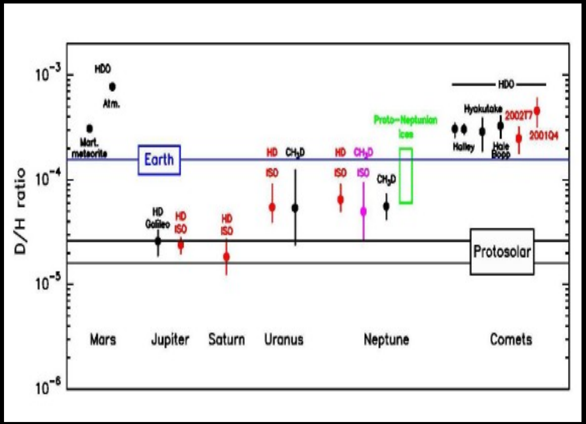


ALMA: Volatile inventory

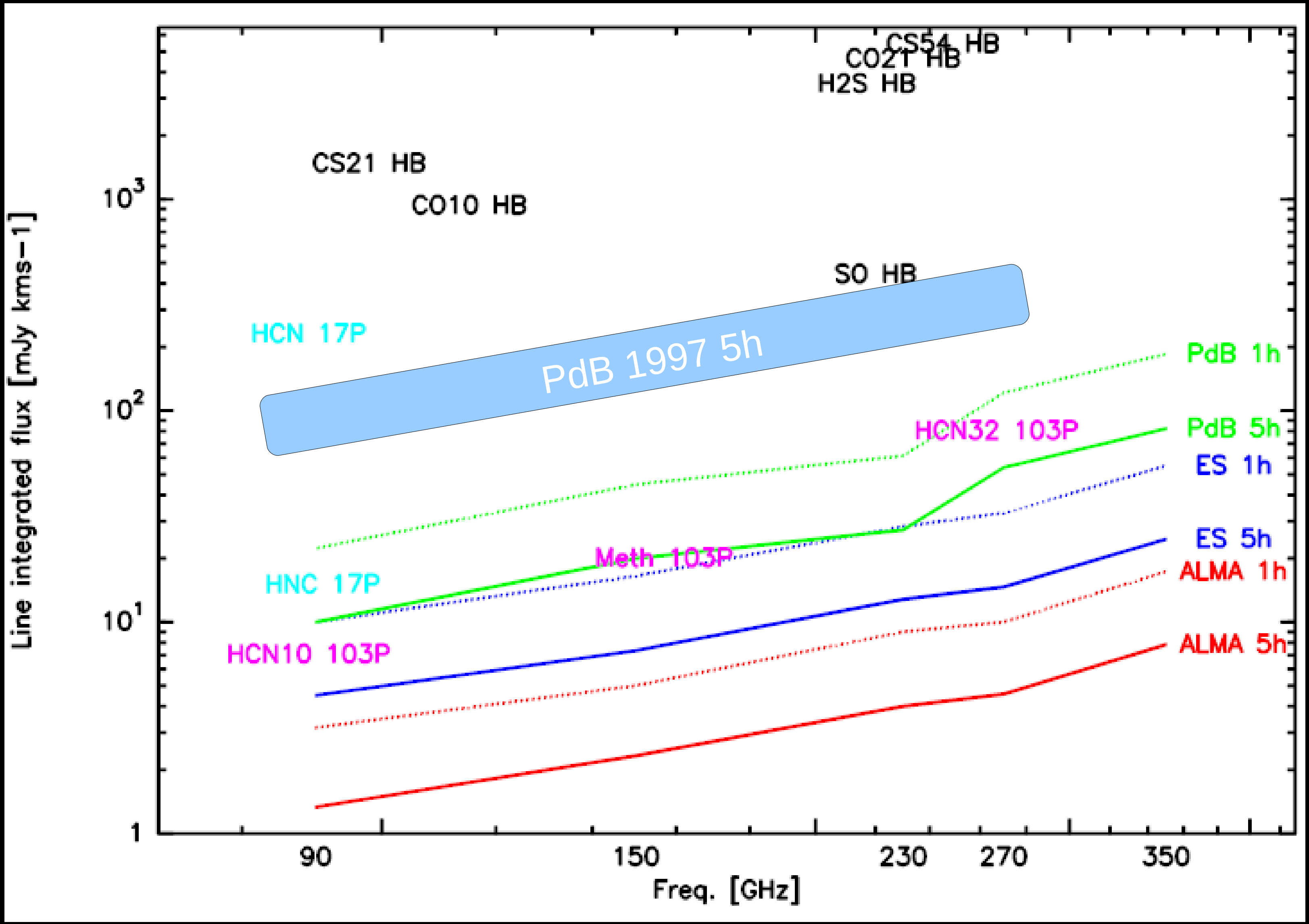
- Sensitivity, spectral flexibility
- Chemical diversity:
  - Observe more (ecliptic, main belt(?)) comets
- Complex molecules
  - Hale-Bopp like results in normal comets
  - 2.5 times more molecules in Hale-Bopp
- Isotopic diagnostic
  - HDO, DCN in more comets
  - $^{14}N/^{15}N$ in other comets and molecules
  - New ratios available
    - To be compared to results in other fields
- Ortho-to-Para ratio





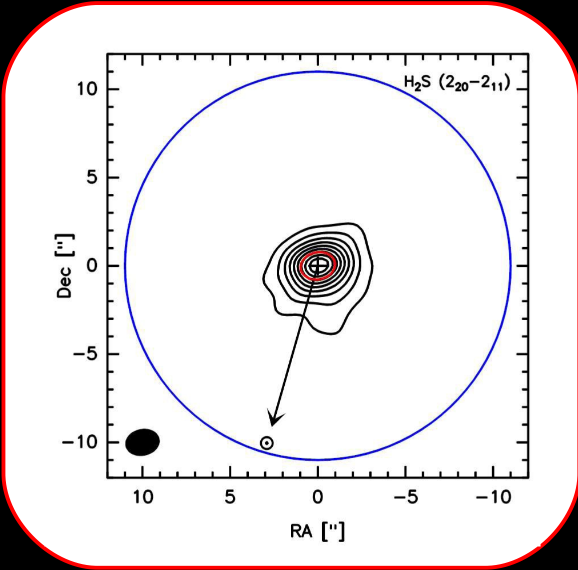


ALMA interferometric sensitivity



ALMA: Extended sources

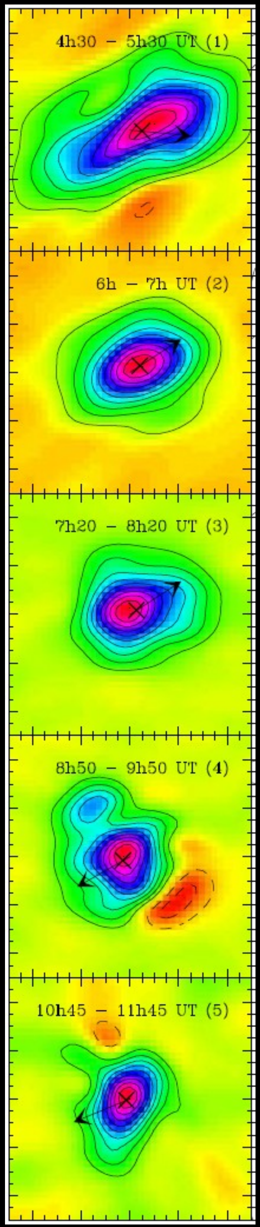
- ALMA gain in sensitivity and angular resolution will allow to:
  - Make more detailed study of known extended sources
    - Measure creation/degradation scalelength
      - H_2CO, HNC
    - Observations at different heliocentric distances
      - Different temperatures, solar fluxes
    - Constraint on physical processes
  - Study new potential extended sources
    - OCS, SO, CO...
    - Including very close to the nucleus (~ 100 km)



- To be combined to lab studies and chemical models
- ***What is the role of organic grains in extended sources ? What kind of grains ?***

ALMA: Coma morphology

- ALMA Sensitivity
  - More comets, more molecules
- ALMA Spatial resolution
  - Identify gas sources on the nucleus
- ALMA Good instantaneous uv coverage
  - Snapshots make the kinematics studies easier
- ALMA Simultaneous Continuum
  - Compare dust and gas coma
- ***Assess the nature of material in the nucleus and the processes in action (jets,...)***



ALMA: other than gas phase volatiles

- Dust and nucleus thermal emission
  - Grain population and nature
    - Size distribution
    - Opacities
  - Nucleus sizes and properties
    - Size distribution and collisionnal history of comets
    - Surface properties (thermal inertia, mm emissivity,...)
  - Nucleus astrometry
    - Astrometric measurements more precise than in the visible
    - Improve orbits
    - Support to space missions
    - Study of non gravitational forces

Summary: Cometary science with ALMA

- Gain in sensitivity
  - Observe more comets
- Gain in spectral flexibility
  - Observe more molecules
- Gain in angular resolution
  - Look closer to the nucleus
- Better instanteaneous uv-coverage
  - Study coma kinematics
- Simultaneous continuum observations
  - Dust and nucleus studies

ALMA will offer the possiblity to switch from comet-dependent science cases to science case-dependent cometary observations

Specificity of cometary observations

- Fixed time observations
- Targets of opportunity
- Time variable objects
- Need for On-Off observations with the whole array
- Special tracking (moving bodies)
  - Science verification...

Thanks !

From lines to abundances

- Abundance = Q_{mol}/Q_{H_2O}
- $\langle N_u \rangle = \int_{beam} p_u(r)\, n(r)$
- Numerical integration in the coma to get Q_{mol}
  - Density distribution
  - Excitation
- Iterative process:
  - Measure v (line width)
  - Measure T if possible (multiple lines)
  - First estimate of Q
  - Excitation with (measured) Temperature (depends on Q)