Comets with ALMA

I. The comets and their chemistry
II. Cometary Observations

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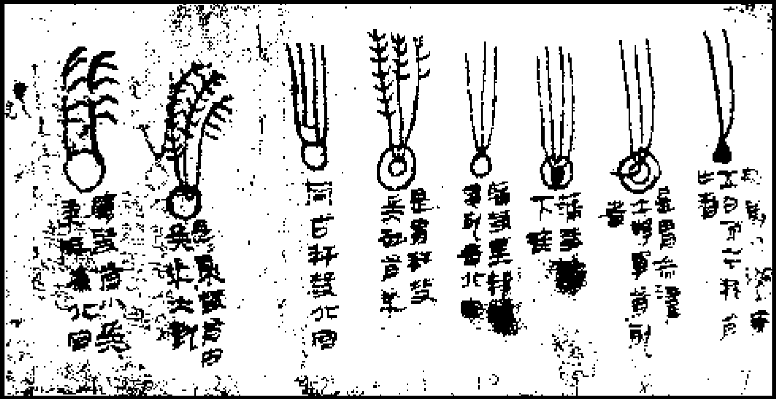
Part I

- History
- Generalities about comets
    - Dynamics
    - Origin
    - Cometary nuclei
    - Cometary atmospheres
- Chemistry of comets
    - Chemical diversity
    - Extended source
    - Advanced chemistry
        - Ortho-to-para ratio
        - Isotopologues

Generalities about comets: Images

Generalities about comets: History

- Comets are observed since centuries
- Mainly for astrology up to 1500



First comet Atlas (-IV century, China)

Comet painted in a chirstmas scene by Giotto
Capella degli Scrovegni (XIV century)

Comet Halley on Bayeux tapestry (XI century)

Generalities about comets: History

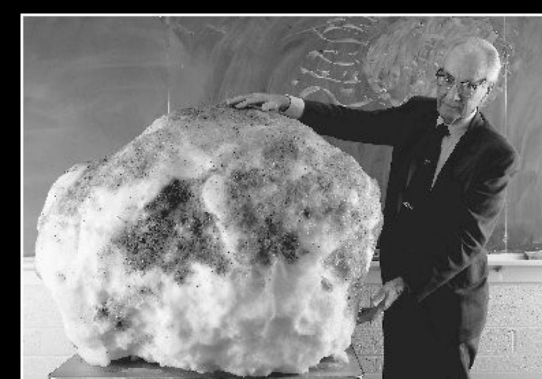
- History of cometary science

Dynamical studies

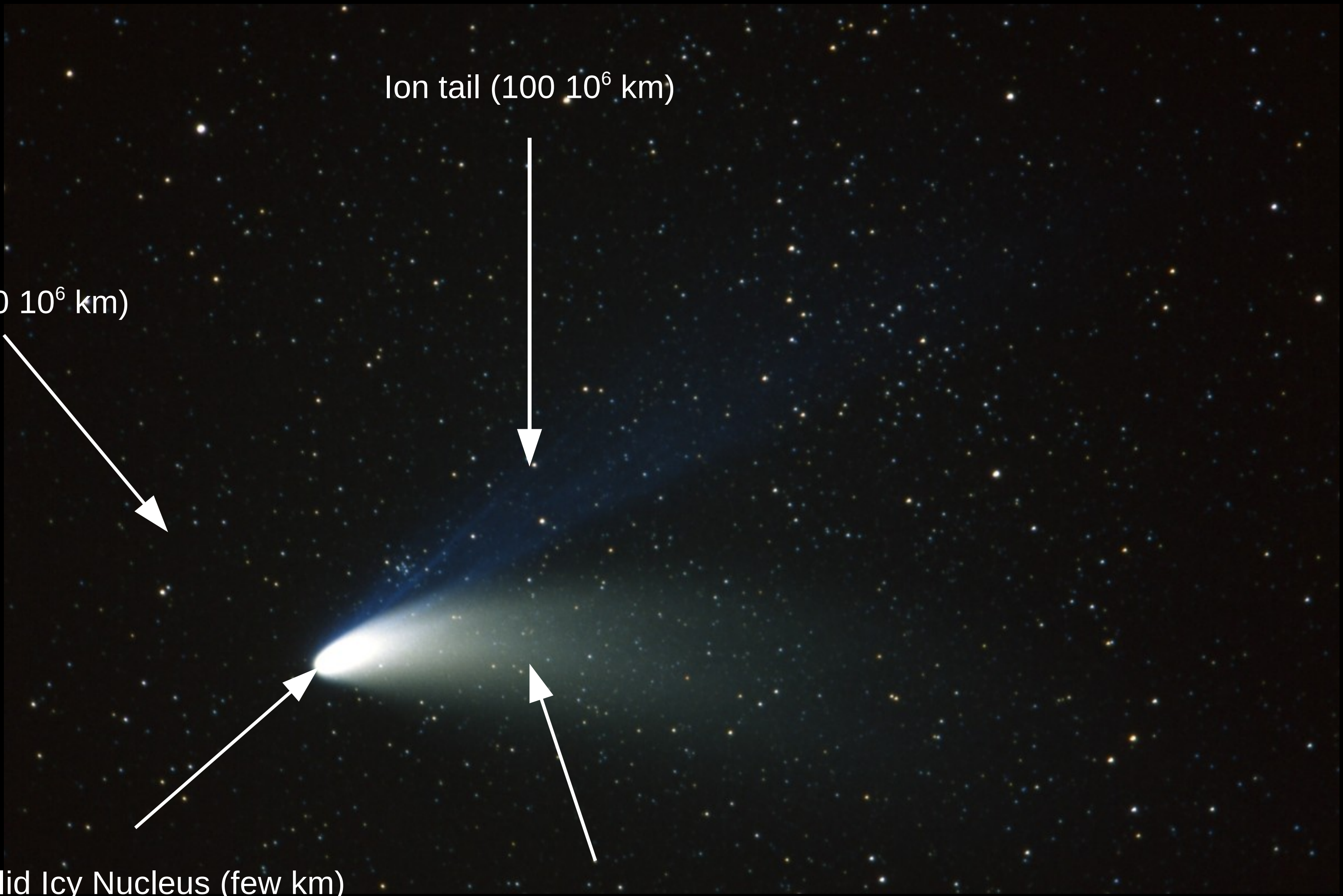
  - 1577: Tycho Brahe measures the paralax of a comet and shows it is beyond the Moon
  - 16**: Kepler find orbit laws, Newton works on comet motions
  - 1705: Halley identifies several apparitions of the same comet and predicts its next approach (observed in 1758)

Physical studies

  - 1819: Arago polarimetric observations show that comets reflect the Sun's light
  - 1850-1900: Photographic and Spectroscopic observations of comets
  - 1950: Whipple imagines the dirty snowball model

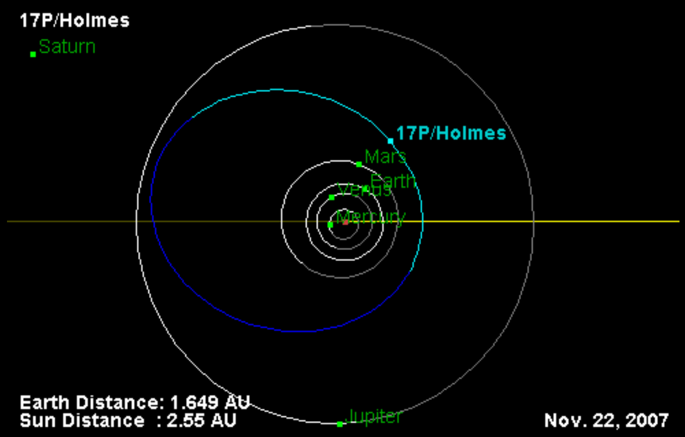


Generalities about comets: Global picture

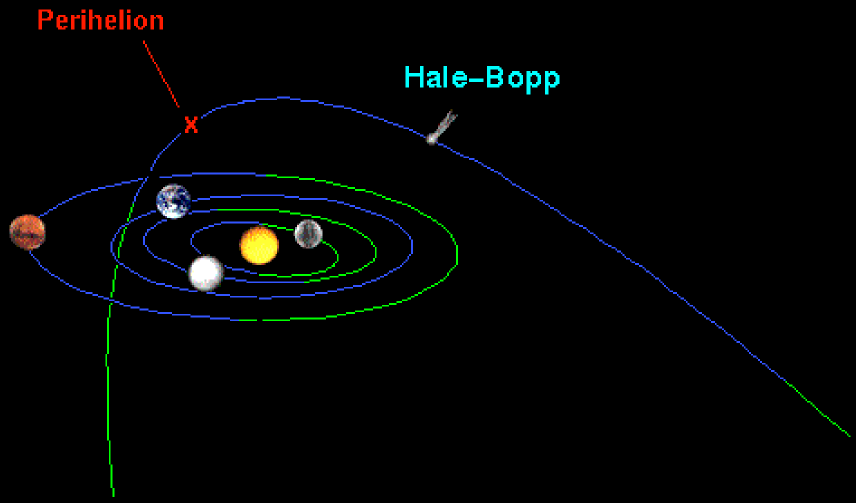


Generalities about comets: Dynamics

- 2 dynamical classes
  - Ecliptic comets
    - Short period, aphelion around Jupiter orbit
    - Orbit in the ecliptic plane
    - Tempel 1, Rosetta's Target
  - Nearly Isotropic Comets
    - Long period, far distant aphelion (when it exist)
    - Random inclination
    - Halley, Hale-Bopp, Hyakutake

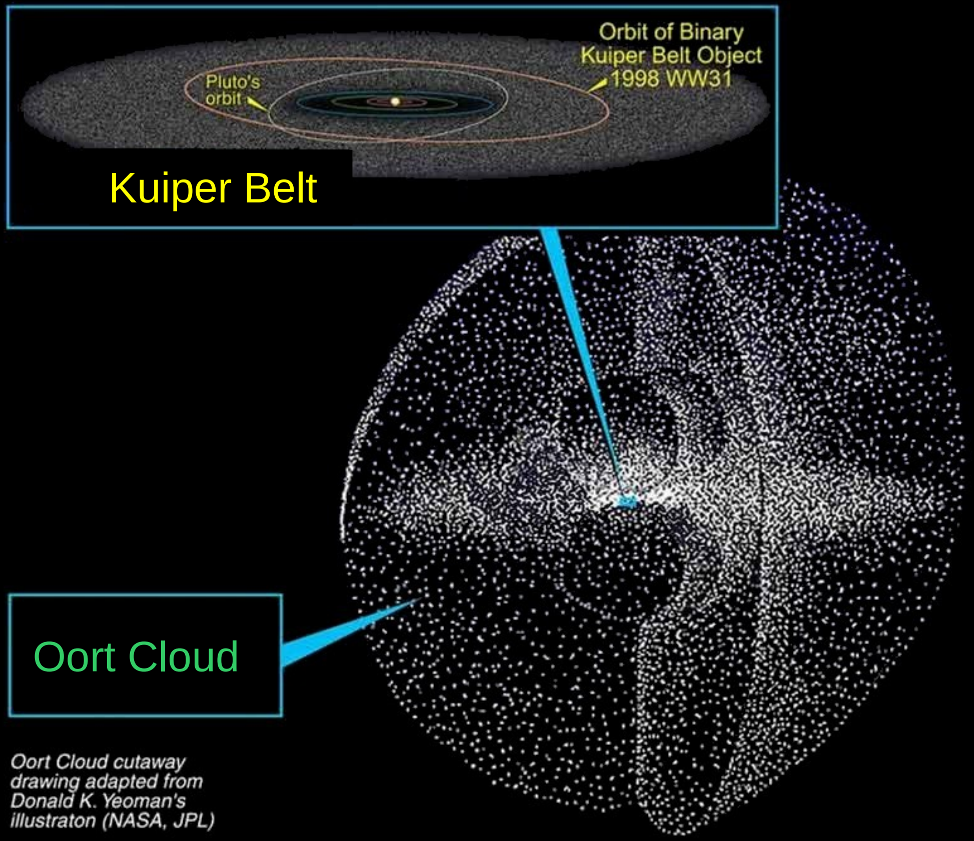


- 2 reservoirs of comets
  - Scattered disk in the Kuiper belt
    - Near ecliptic plane, q>30 AU
  - Oort Cloud
    - Isotropic, q up to 10^5 AU



Generalities about comets: Dynamics

- 2 dynamical classes
  - Ecliptic comets
  - Nearly Isotropic Comets
- 2 reservoirs of comets
  - Planetesimals that can be sent back to the inner Solar System and become comets
  - Scattered disk in the Kuiper belt
    - Near ecliptic plane, q>30 AU
  - Oort Cloud
    - Isotropic, q up to 10^5 AU
- 3^{rd} (recent) class
  - Main belt comets
    - Icy bodies formed in the inner SS

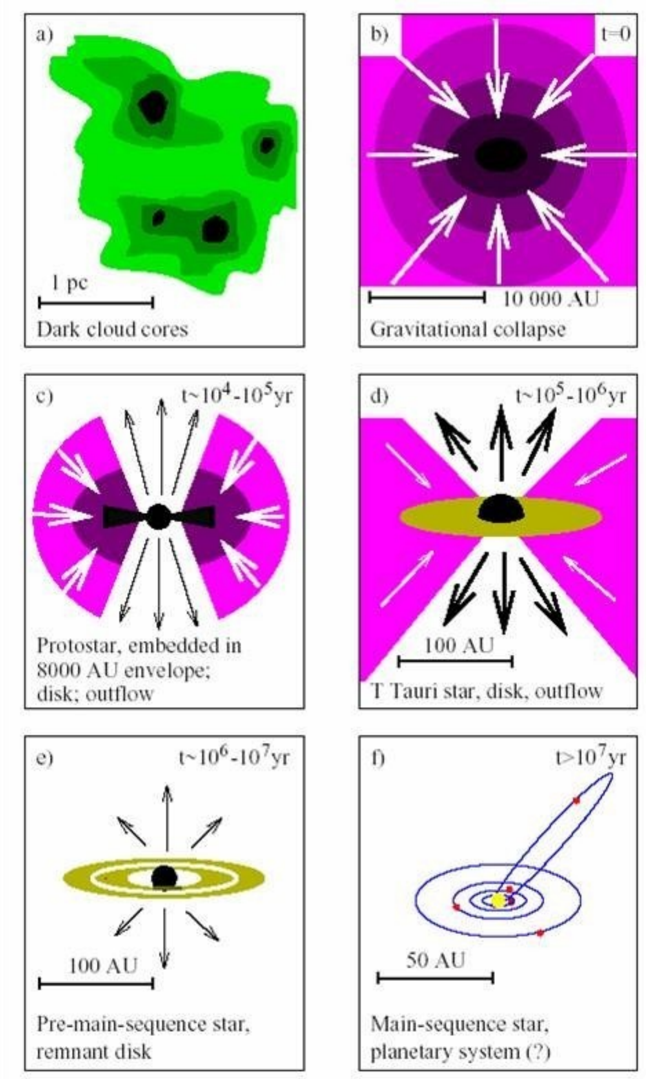


Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

Generalities about comets: Origin

- Origin in the Solar System formation
  - Planetesimals in the outer regions of the disk that escaped the planet formation
    - Preserved in the Kuiper Belt
    - Ejected to the Oort Cloud

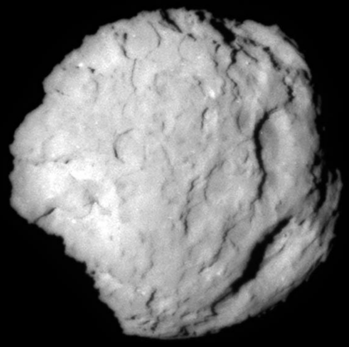
- ***Comets come back as remnants of the Planet formation era.***
- ***Their composition and structure may provide information about the physical and chemical conditions in the Early SS.***
- ***Cometary impacts could have impacted the evolution of planets.***



Hogerheijde 1998, after Shu et al. 1987

The dirty snowball: Nucleus

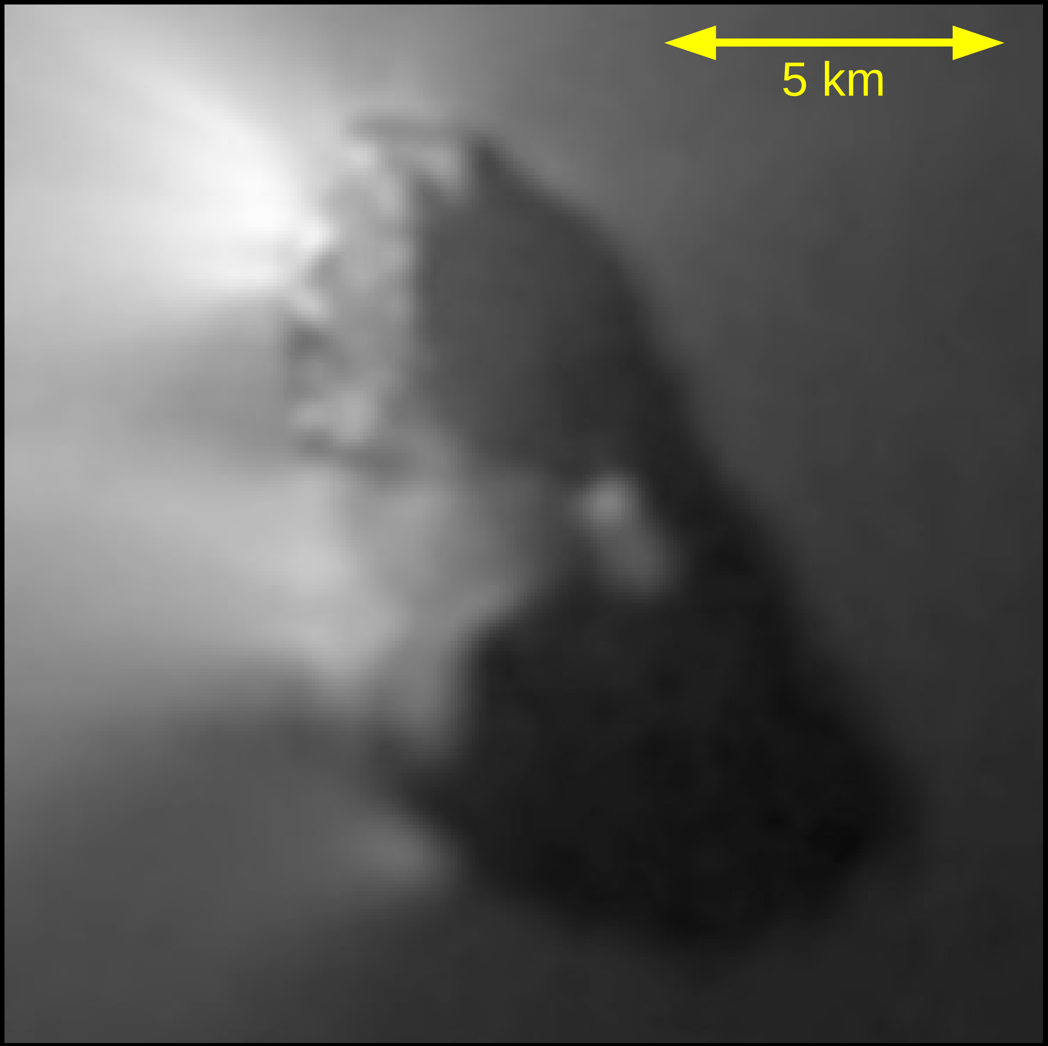
- Physical properties
  - km sized objects (~1 km to ~40 km)
  - Low density (~0.6 g/cm^3)
  - Low albedo (0.04)
- Structure
  - Different aspects suggests heterogene structure
  - Low cohesion (comet splitting)
- Composition
  - Ice (water + volatiles)
  - Refractory dust (silicates)
- Studies
  - Remote studies difficult (distance and/or coma)
  - Space missions expensive
  - Detailed study of the atmosphere helps

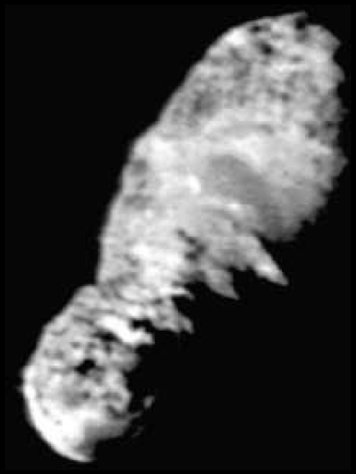


Wild 2 (5 x 5 km) as seen by Star Dust (2004)

Hartley 2 (2x0.7 km) as seen by Deep Impact (2010)

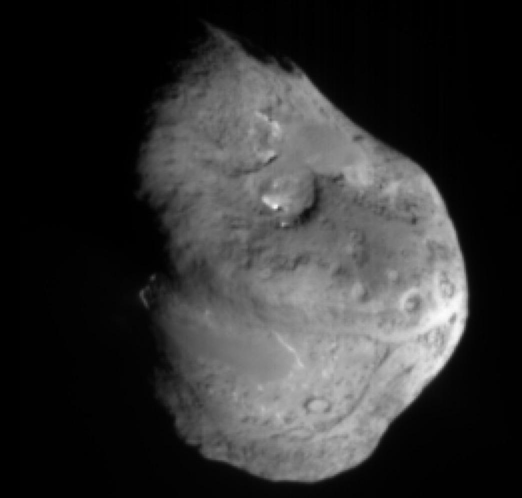
Nucleus images





Borelly (8 x 3 x 3 km) as seen by Deep Space (2001)

Wild 2 (5 x 5 km) as seen by Star Dust (2004)



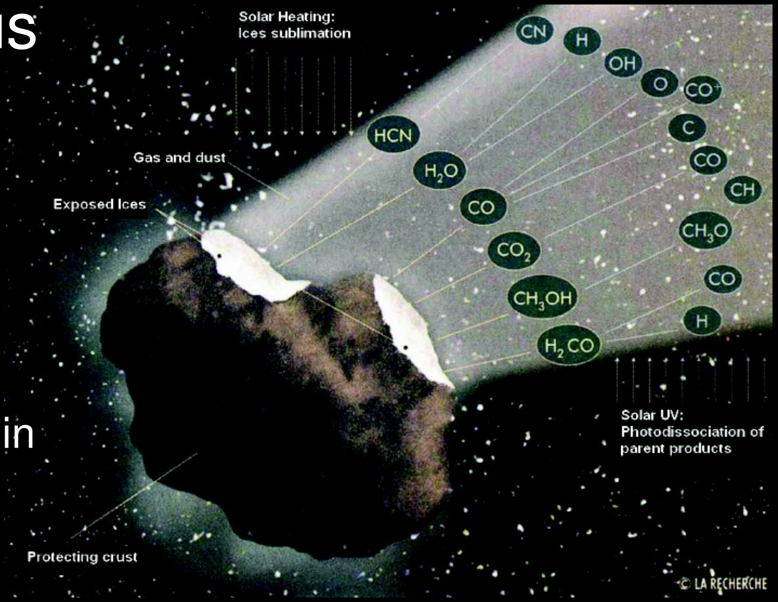
Halley (14 x 7 x 7 km) as seen by the Giotto spacecraft (1986)

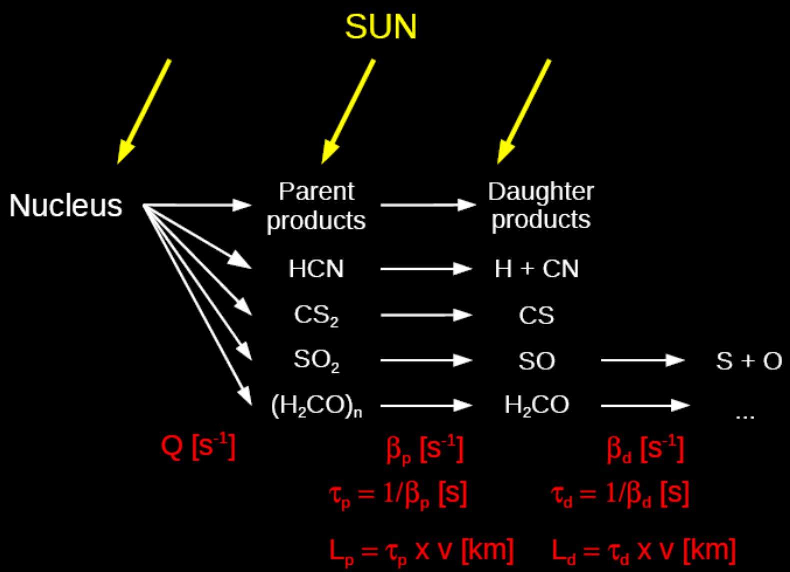
Tempel 1 (5 x 7 km) as seen by Deep Impact (2005)

Hartley 2 (2x0.7 km) as seen by Deep Impact (2010)

The dirty snowball: The Coma

- Gas and Dust released from the nucleus
- Outgassing
  - Ice sublimation
    - Mainly driven by H_2O
    - CO a large heliocentric distances
    - Other species in separated ice or trapped in water/CO ?
  - Grains are driven by the gas
- Coma chemistry
  - Only destructive chemistry
  - Photodissociation
  - Thermal degradation



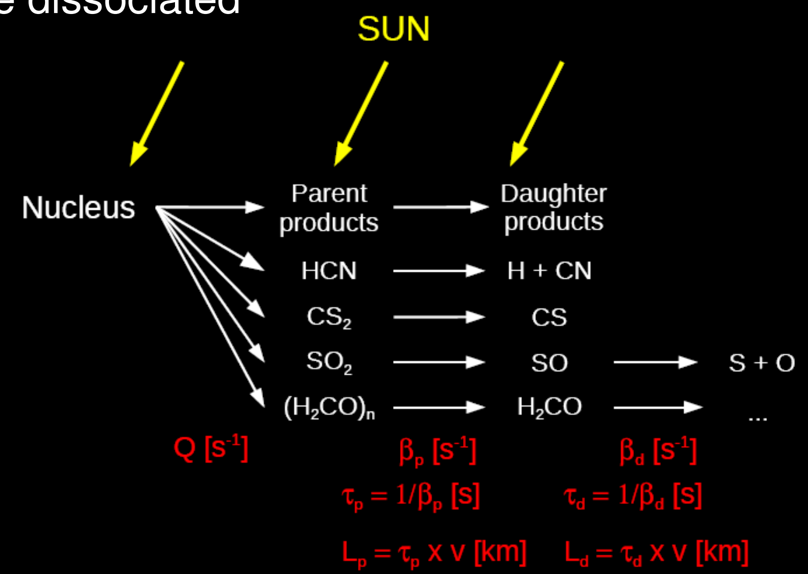


The dirty snowball: Coma most simple model

- Haser Model
  - 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

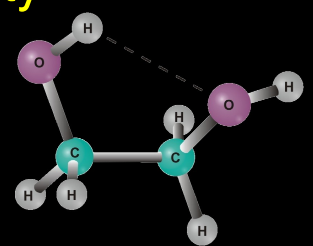
$$n_p(r) = \frac{Q}{4\pi\, r^2\, v_{exp}} e^{-\frac{r}{L_p}}$$

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

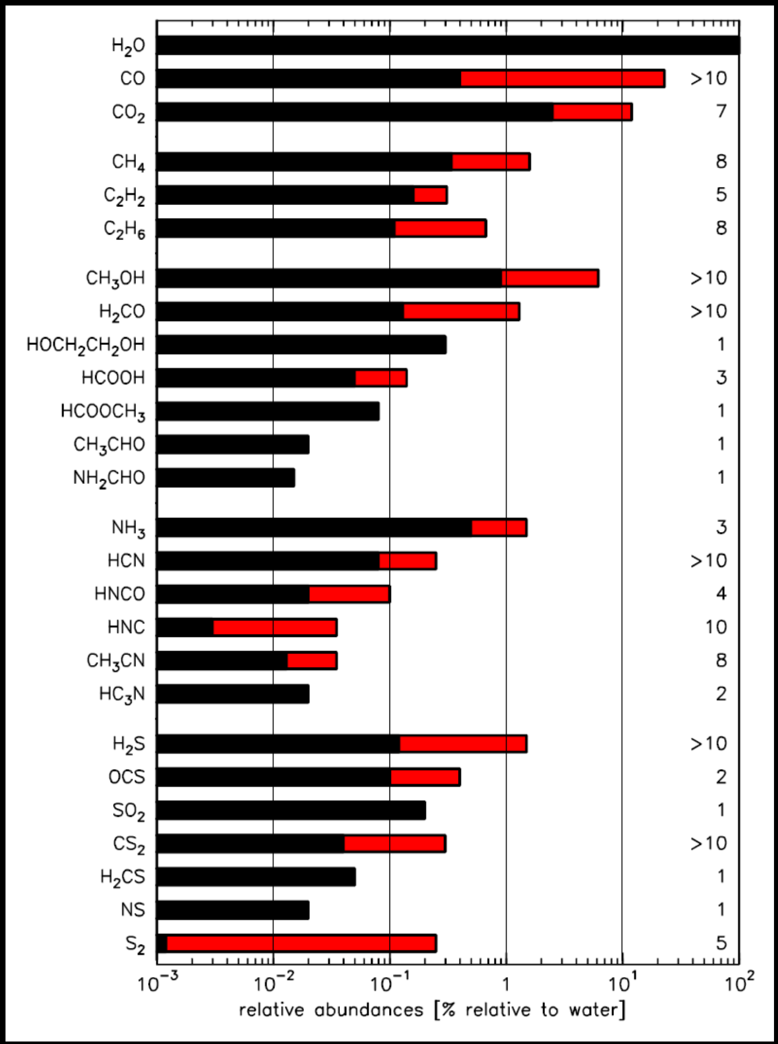


Composition: Overview

- Refractory
  - Amorphous and Cristalline silicates
  - Organic grains
- Volatiles
  - Abundances: $A_{mol} = Q_{mol}/Q_{H2O}$
  - High level of chemical diversity
  - Complex molecules
    - Ethylene glycol
    - More complex molecule ?
  - Minor species
    - Isotopologues (Water, HCN)
    - HNC

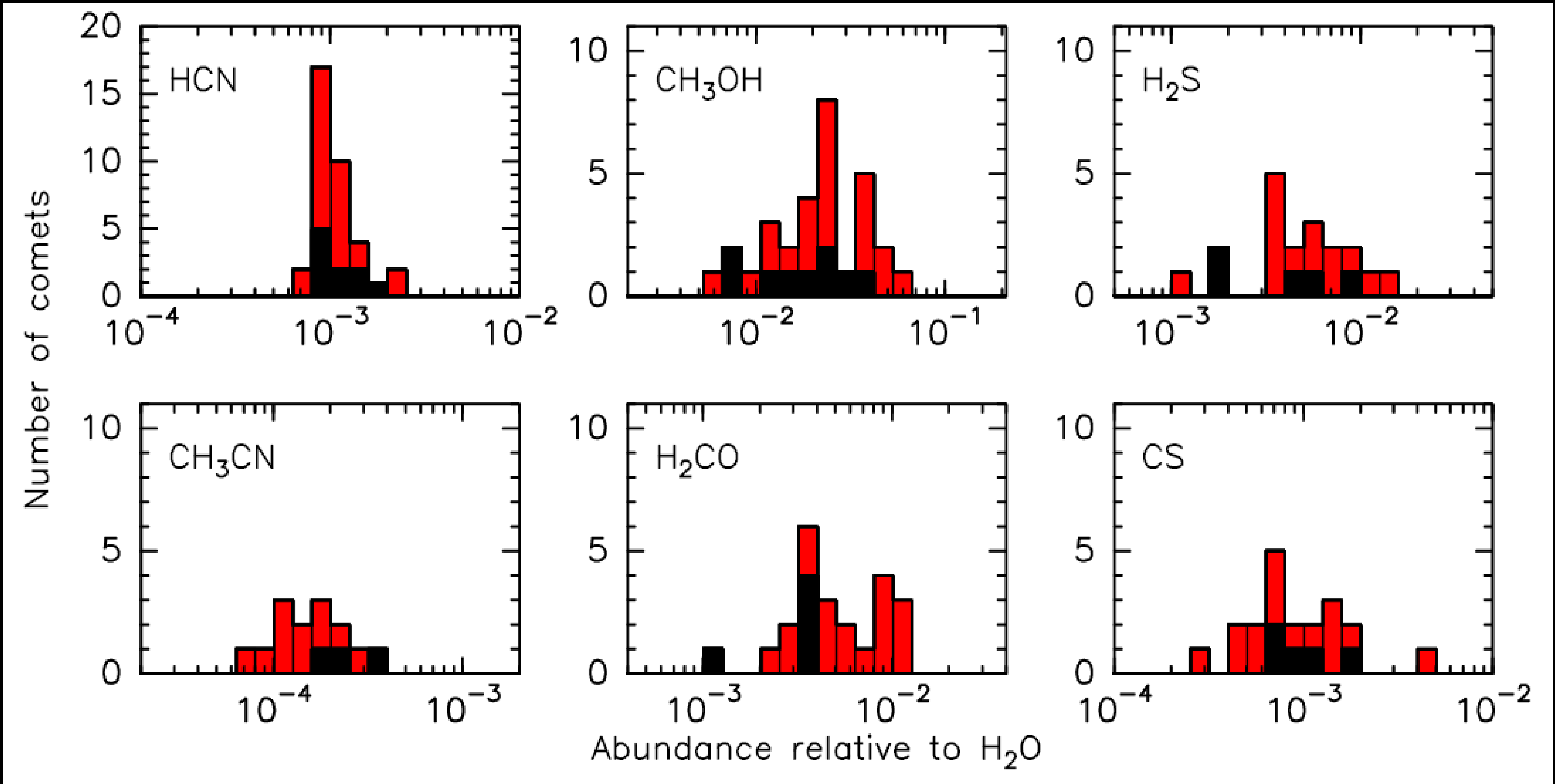


Parent molecules in comets



Composition: Chemical diversity

- Abundancies vary a lot from a comet to another
  - No link with dynamical classes



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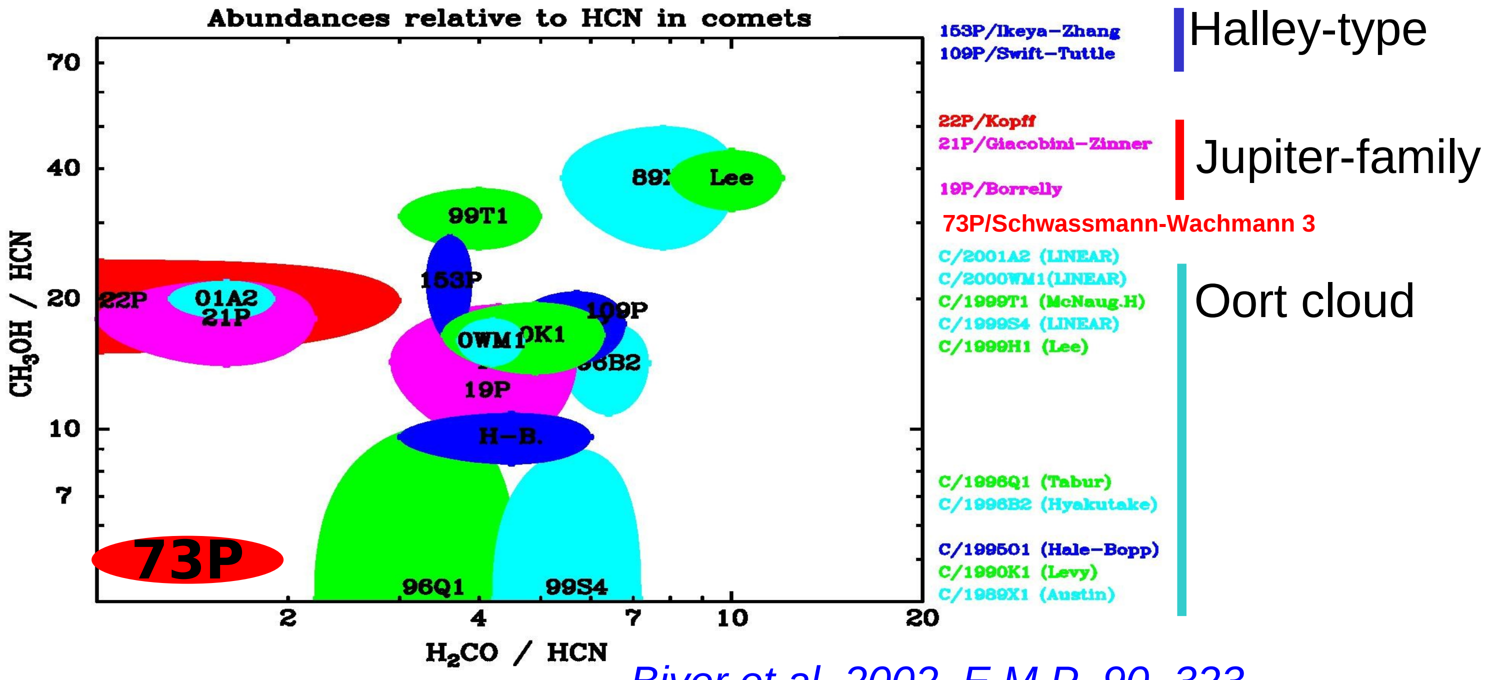


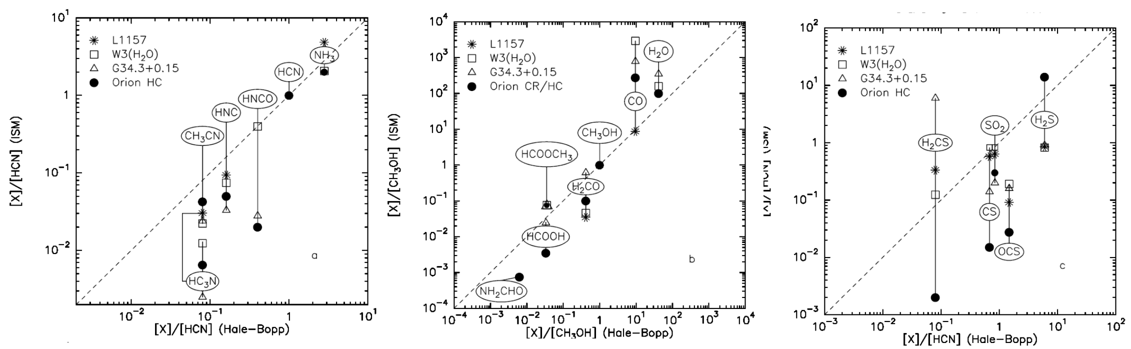
Biver et al. 2002, E.M.P. 90, 323

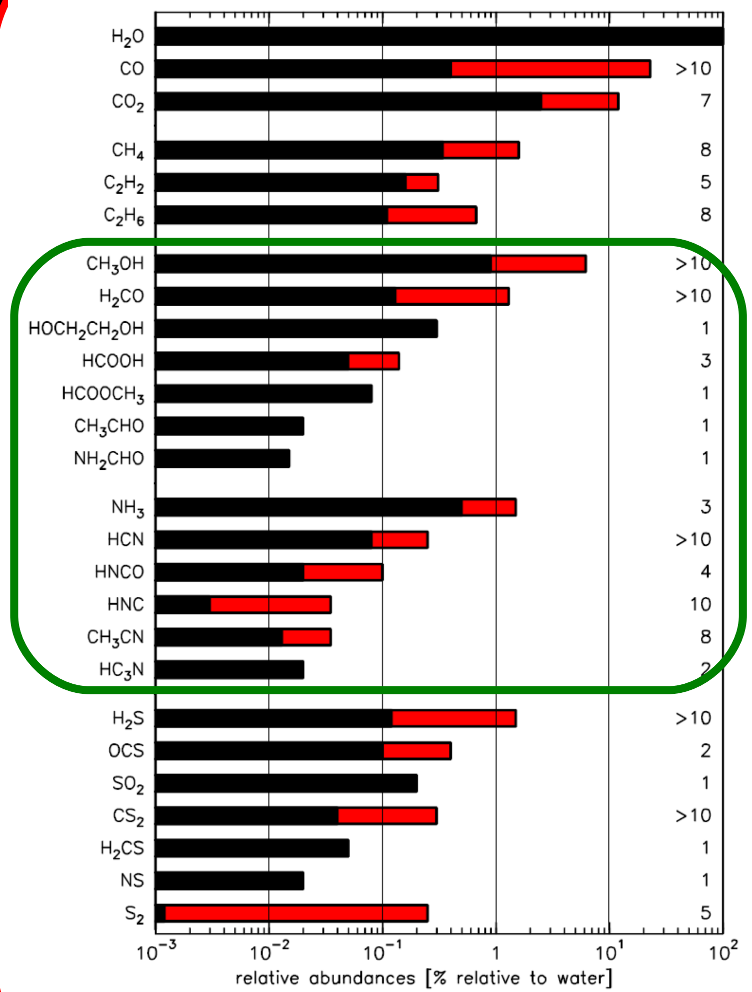
Composition: Chemical diversity

- Abundancies vary a lot from a comet to another
  - No link with dynamical classes
  - Chemical classes ?
  - Reflects the time and the place of formation
  - Reflects also the evolution of the comet
  - Reflects the mixing of the Solar Nebula
    - Ice and refractories : radial mixing
    - of small grain and gas ?
    - of planetesimals ?
      - Heterogeneity of some nucleus
- Need for more statistics
  - Ecliptic comets
- Need to inlcude more species (including more complex molecules)

Composition: Comparison to other objects

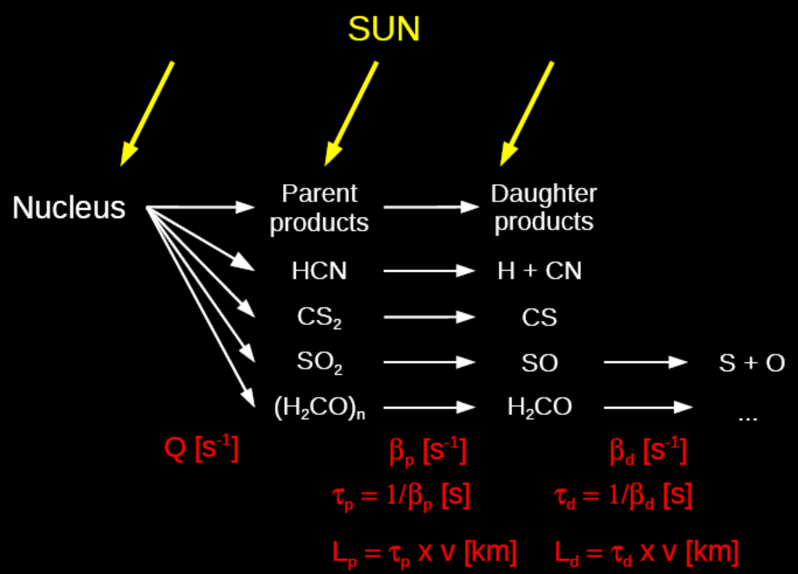
- Origin of cometary material
  - Analogies with hot cores and ISM
  - Molecules created by similar chemistry
    - Ion-Molecule or grain surface reactions
    - Preserved from insterstellar Medium or created in the Solar Nebula ?





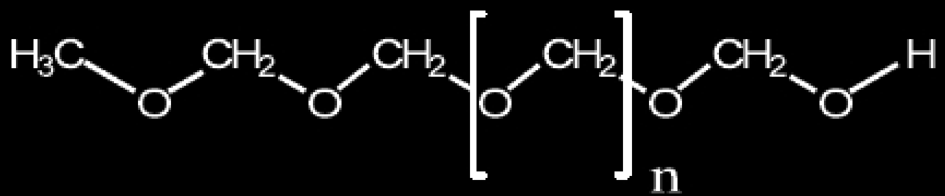
Composition: Extended sources

- Photodissociation
  - Main extended source in comet
  - Creates molecules, radicals, ions, atoms (OH, CN, CS,...)
- Organic grain degradation
  - H_2CO and POM degradation
- Unidentified
  - HNC (C_2H_2 and NH_3 polymers?)
  - SO (?)
- Debated
  - CO from the nucleus or from organic grair

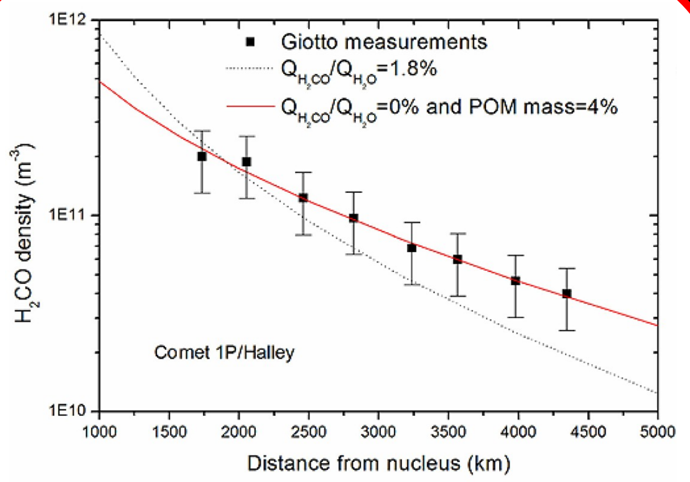


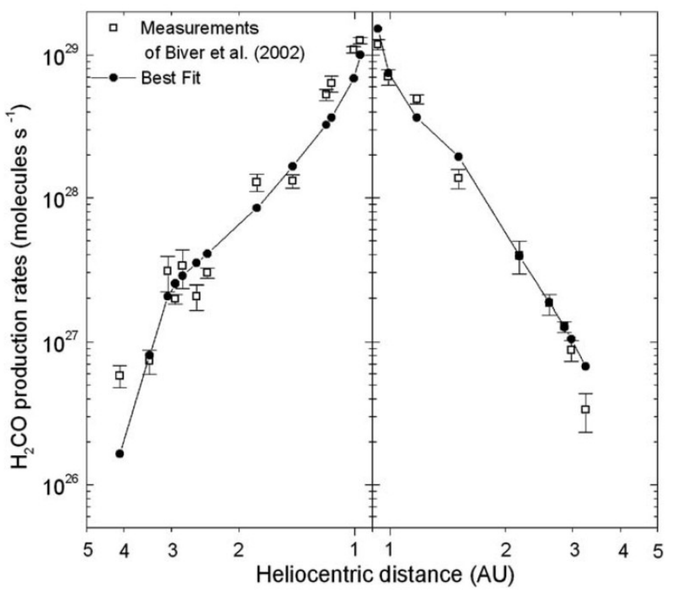
Focus on H_2CO: The role of the laboratory

- 2^{nd} most abundant CHO molecules
  - Extended source in most observations
    - No suitable parent in known large molecules
    - Degradation of POM (polyoxymethylene) ?



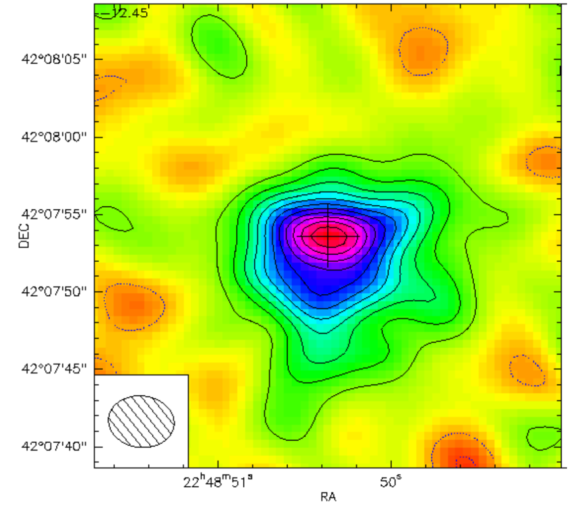
  - Experiments on POM degradation
    - Create only gaseous H_2CO
    - Measure kinematics of the degradation
  - Back to observations
    - OK with Halley radial distribution
      - Cottin et al. 2004
    - OK with Hale-Bopp evolution with r_h
      - Fray et al. 2006
  - More comets, parent scalength ?



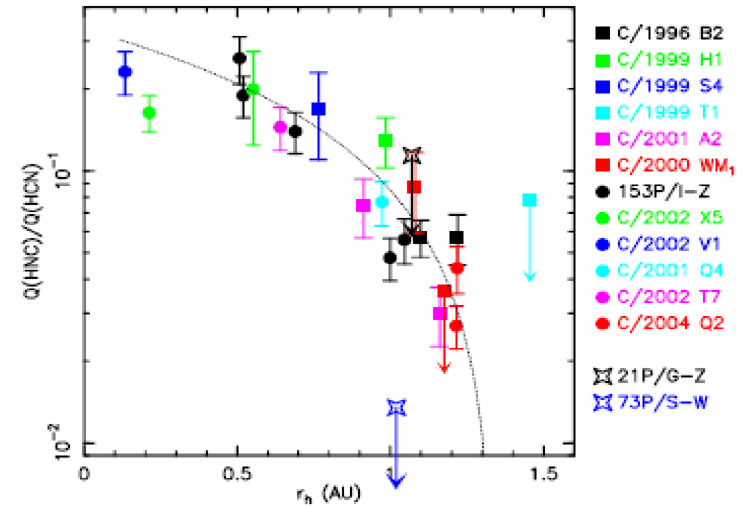


Focus on HNC: The role of chemical models

- Unexpected metastable isomer of HCN
  - Slightly extended source
  - HNC/HCN depends on r_h
    - Not preserved from ISM
    - Thermal dependent process
    - Ion chemistry ?
  - High HNC in moderately active comets
    - NO ion chemistry
    - Thermal degradation of polymers ?
  - 73P/SW3
    - HNC depletion, normal HCN
    - Depletion of C_2H_2 and NH_3
    - Degradation of C_2H_2 and NH_3 polymers ?
    - Lis et al. 2007
  - More comets, parent scalength ?



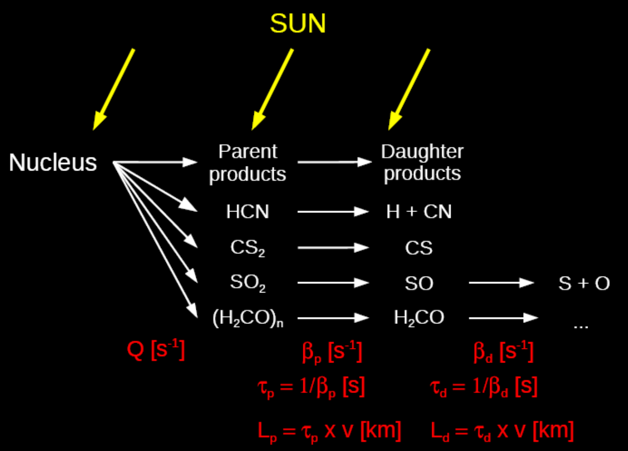
HNC map observed with the Plateau de Bure



HNC/HCN vs heliocentric distance

Composition: Extended sources

- Photodissociation
  - Main extended source in comet
  - Creates molecules, radicals, ions, atoms (OH, CN, CS,...)
- Organic grain degradation
  - H_2CO and POM degradation
- Unidentified
  - HNC (C_2H_2 and NH_3 polymers?)
  - SO (?)
- Debated
  - CO from the nucleus or from organic grains ?
- Needs more studies
  - Observations with high spatial resolution
  - Monitoring over r_h
  - Synergies with chemical models and lab experiments



Composition: Ortho-to-Para ratios

- Ortho and Para states for molecules with symmetric H atoms
  - Different nucleus spin configurations
  - H_2O, H_2S, H_2CO, CH_3OH,...
  - Different energy levels and spectral lines
- Measurements
  - T_{spin}~ 30 K in H_2O and NH_3
- Ortho-to-Para ratio fixed in solid phase
  - Nucleus evolution: NO
  - Formation conditions of the molecules ?
  - Fractionation on grains ?
    - ISM or Comet ?

H_2O

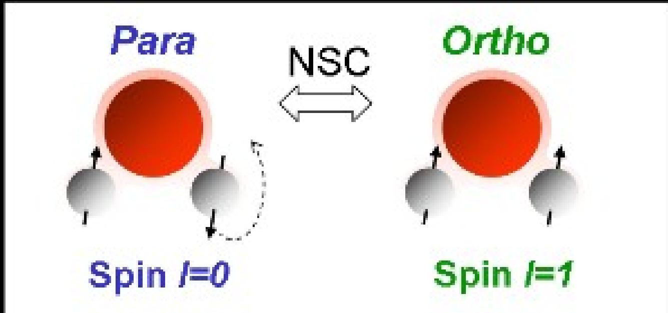
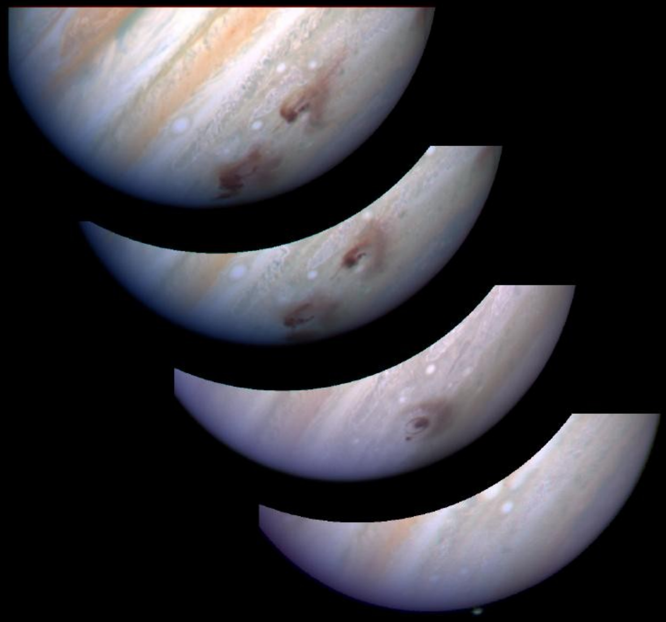


Fig 1. Schematic representation of *ortho* and *para* water and Nuclear Spin Conversion (NSC).

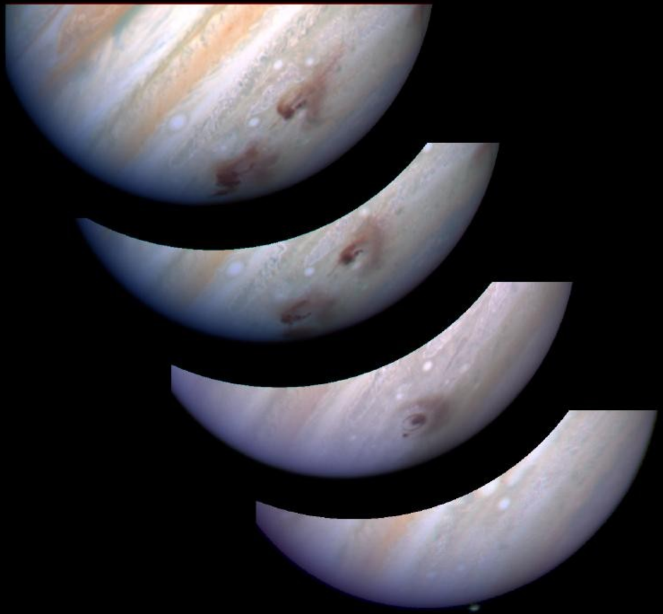
Composition: Isotopic diagnostic

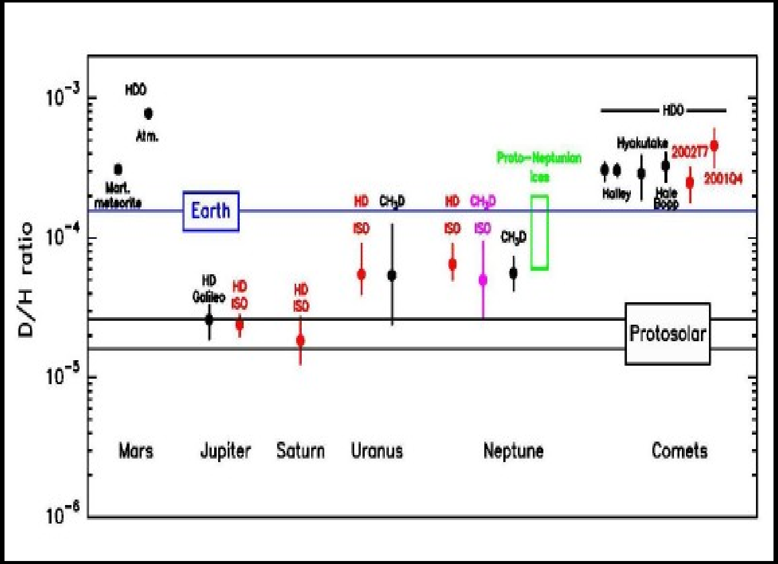


- Measuring isotopic ratios allows to:
  - Probe the origin of cometary material
  - Assess the role of cometary impacts in planetary evolution
- Isotopologues difficult to observe
  - Limited set of measurements so far
  - Mainly based on Oort cloud comets
  - Few molecules

Composition: Deuteration

- HDO in few comets, mainly Oort Cloud
  - D/H ~ 3-4 x 10^{-4} ~ 2 x Earth Value
- DCN in Hale-Bopp
  - D/H ~ 2.3 x 10^{-3}
- Strong enrichments require ion-molecule or grain surface reactions
  - Strong constraints on the early history of the Solar System
- Ocean water does not come from comets





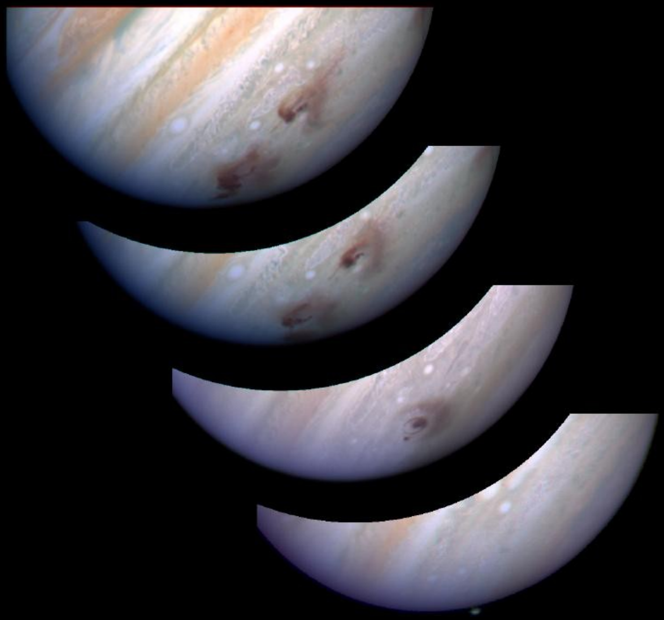
Composition: Others isotopes

	$^{12}C/^{13}C$	[C_2]	93 ± 10	4 comets	Wyckoff et al. (2000)
Solar: 89		[CN]	95 ± 12	1P/Halley	Kleine et al. (1995)
		[HCN]	111 ± 12	Hale-Bopp	Jewitt et al. (1997)
	$^{14}N/^{15}N$	[HCN]	323 ± 46	Hale-Bopp	Jewitt et al. (1997)
Solar: 270		[CN]	140 ± 35	Hale-Bopp	Arpigny et al. (2003)
	$^{16}O/^{18}O$	[H_2O]	518 ± 45	1P/Halley	Balsiger et al. (1995)
Solar: 500		[H_2O]	470 ± 40	1P/Halley	Eberhardt et al. (1995)
		[H_2O	450 ± 50	153P	Lecacheux et al. (2003)
	$^{32}S/^{34}S$	[CS]	27 ± 3	1P/Halley	Jewitt et al. (1997)
Solar: 24		[S]	23 ± 6	1P/Halley	Altwegg (1996)
		[H_2S]	16 ± 3	Hale-Bopp	Crovisier et al. (2004)

- Most recent results about ^{15}N are $^{14}N/^{15}N$ = 140 in HCN in Holmes
  - Bockelée-Morvan et al. 2008
- ^{15}N enrichment in the outer regions of the Solar Nebula

Composition: Isotopic diagnostic

- Measuring isotopic ratios allows to:
  - Probe the origin of cometary material
    - Ion-molecule, grain surface reactions
    - Enrichment in ^{15}N in the Solar Nebula
  - Assess the role of cometary impacts in planetary evolution
    - Water on Earth does not come from comets
- Isotopomers difficult to observe
  - Limited set of measurements so far
  - Mainly based on Oort cloud comets
  - Few molecules
- More observations required
  - More comets, more molecules
  - Detailed comparison to other objects



Evolution of cometary material

- Is cometary material still primordial ?
- Evidences for evolution
  - Low albedo: crust
  - Surface erosion
  - Splitting, exploding, dying comets
- Processes:
  - Formation time
    - Collisions ?
  - In reservoirs
    - Differentiation: No
    - Cosmic rays
  - During orbits:
    - Successive perihelion passages
    - Volatile depletion ?

Summary

- Comets are remnants of the planet formation era
  - Their study should bring insight to 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
  - Complex species

Open questions

- Origin of cometary material
  - Preserved from ISM vs processed in the Solar Nebula
- Detailed composition
  - Most complex molecules
  - Organic grains
  - What could have been brought to the Earth ?
- Relation with Solar Nebula and circumstellar disk chemistry
- Evolution of cometary material
  - Are the comet still primordial ?
- Nucleus structure ?
  - Ices, clatrates, homogeneity ?
- Nucleus processes ?
  - Jets, comet splits, outbursts