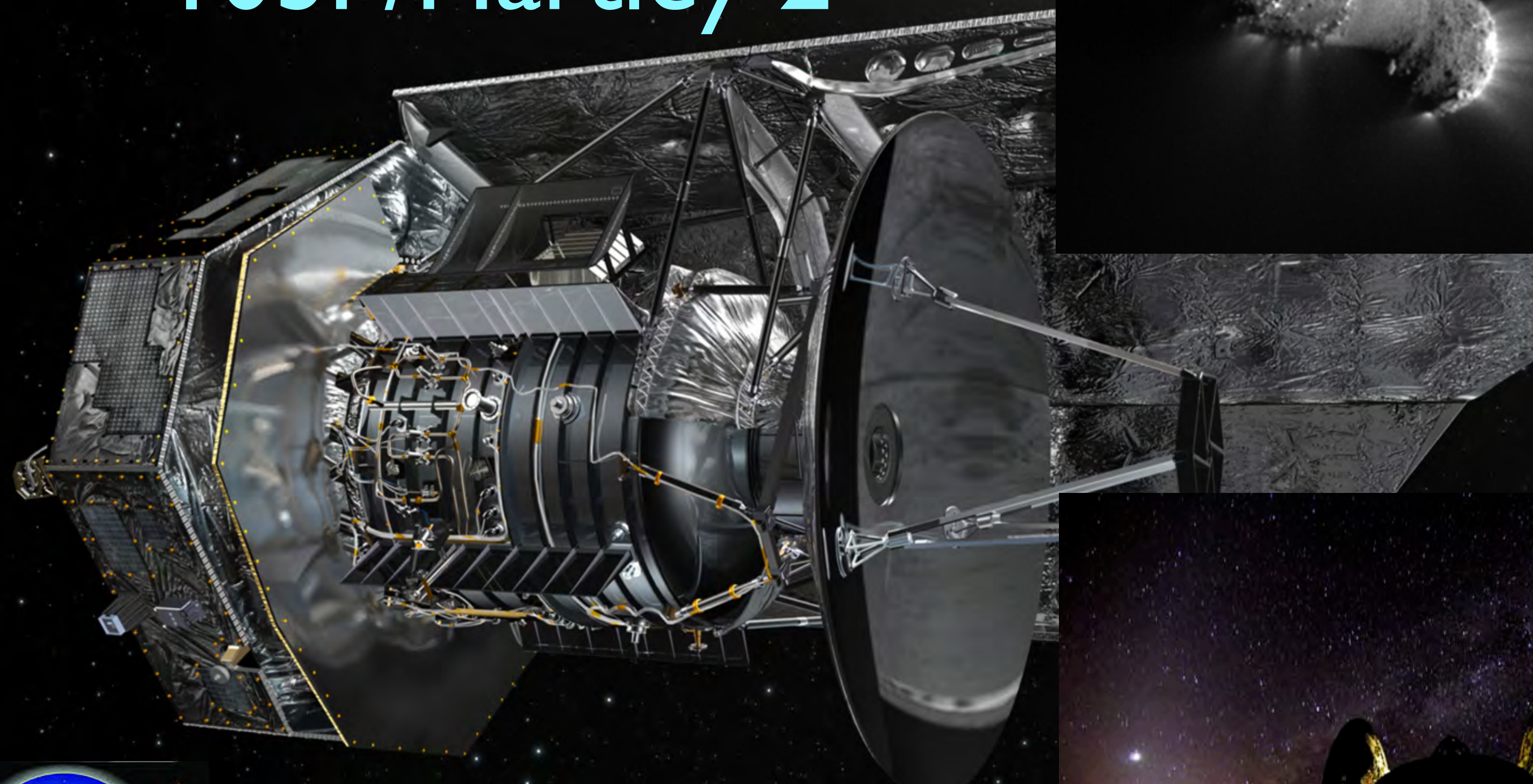
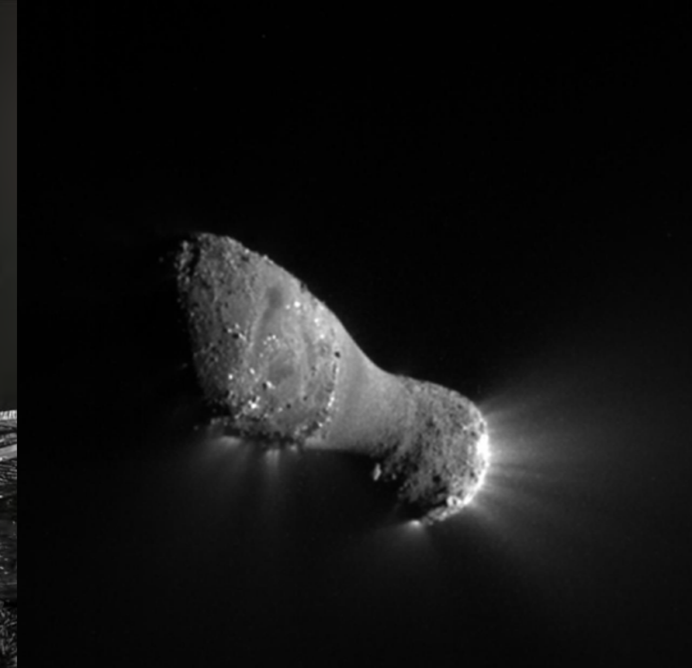
Ocean-Like Water in Comet 103P/Hartley 2





Darek Lis (Caltech)

Grenoble, March 23, 2011

Water and Related Chemistry in the Solar System: A Guaranteed Time Key Program for Herschel

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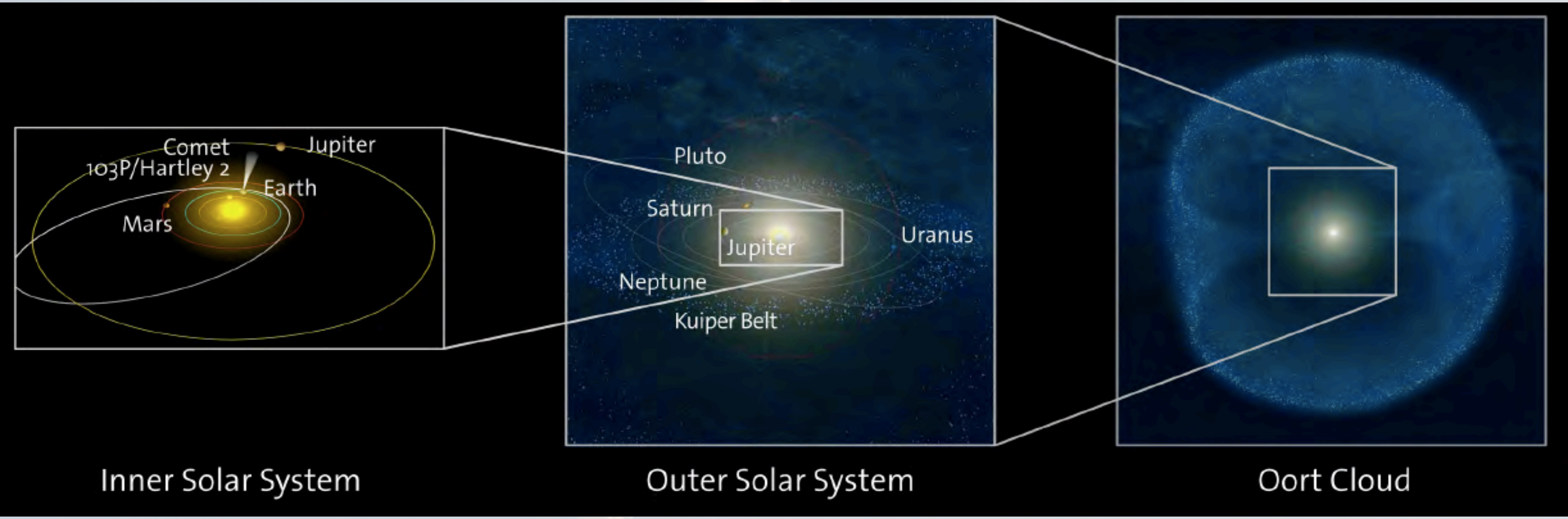
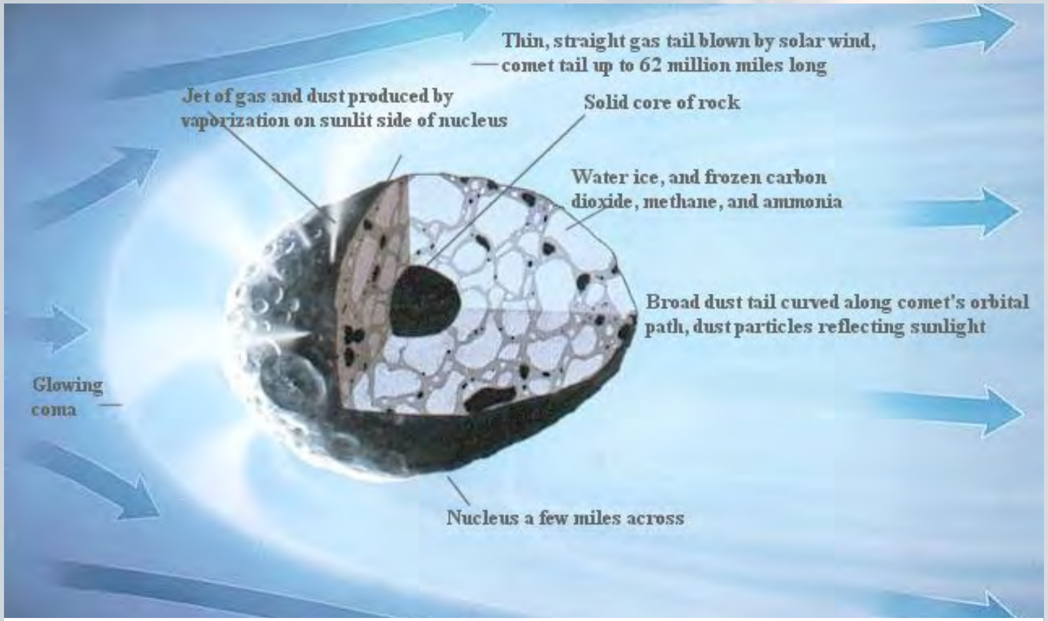
M. Rengel, R. Moreno, S. Szutowicz, and G.A. Blake
(MPIfS Germany, Caltech USA, Obs. Paris France, ESA Spain, U. Michigan USA, SRC Poland)

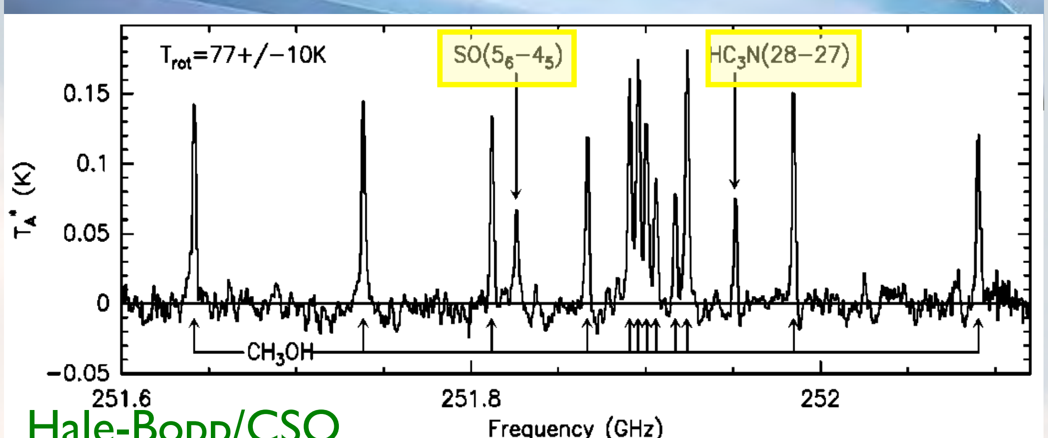
Solar System: Comets



- Comets are among the most primitive bodies left from the planetesimal building stage of the Solar Nebula
- *Jupiter Family comets* are thought to originate in the Kuiper Belt, or associated scattered disc, beyond the orbit of Neptune
- *Long-period comets* come from the Oort cloud located well beyond the Kuiper Belt, but formed in the Jupiter-Neptune region (ejected by giant planets)
- Sent toward the Sun by gravitational perturbations from the outer planets (Kuiper Belt objects) or nearby stars (Oort Cloud objects), or due to collisions

Submillimeter Studies

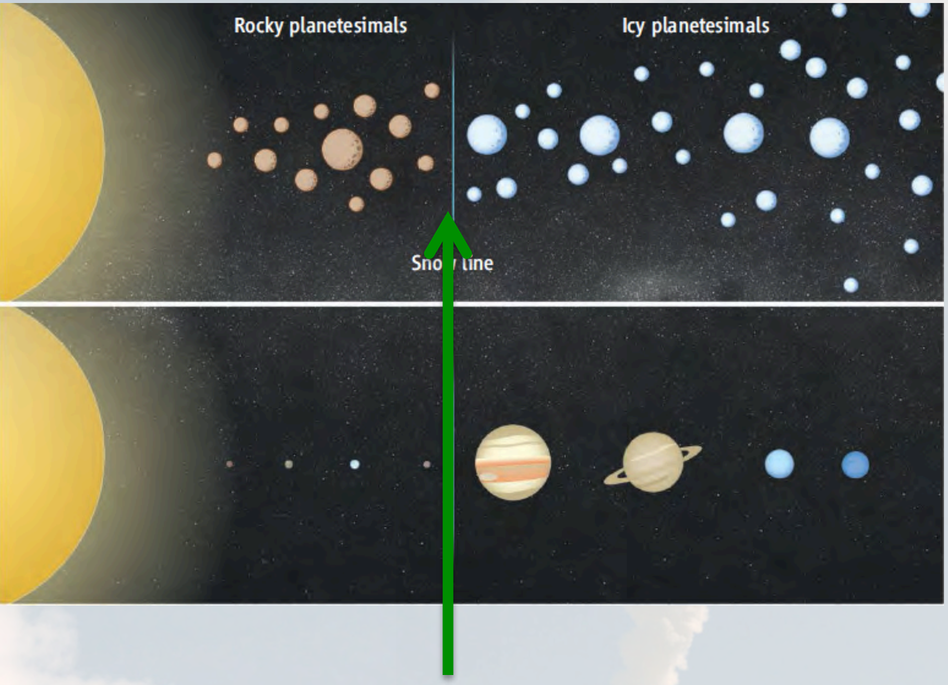




Hale-Bopp/CSO

- (Sub)millimeter wavelengths are well matched to the cold environments of cometary atmospheres (T~40–100 K)
- Over two dozen species detected in cometary atmospheres, primarily using radio techniques
- Some complex species, such as methyl formate ($HCOOCH_3$) and ethylene glycol ($HOCH_2CH_2OH$)
- Heterodyne techniques allow velocity-resolved kinematic studies
- Isotopic ratios provide key information about the origin and evolution of cometary ices (possible links with ISM)

Origin of Earth Water



Snow Line

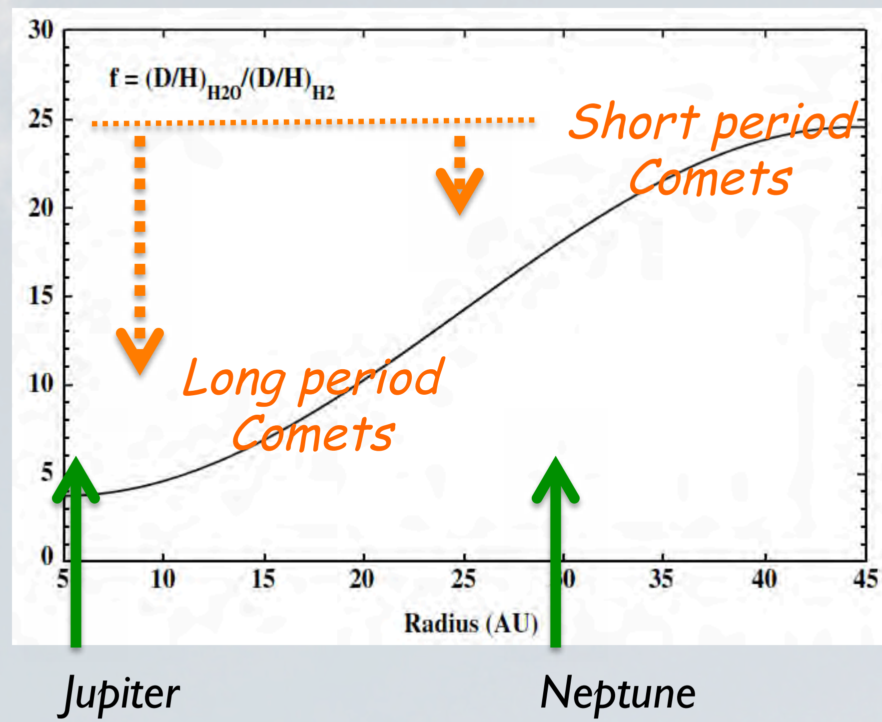
Akeson 2011

- Volatile-depleted primitive materials similar to current chondritic meteorites have long been considered the "building blocks" of terrestrial planets (Drake & Righter 2002)
- Origin of the Earth's oceans is intimately associated with the nature of these building blocks
- Prevailing model:
  - Temperature at 1 AU was too high for water ice to exist in the accretion disk ("snow line" at 2.7 AU)
  - Earth accreted dry
  - Water, and probably also organics, were most likely delivered by external sources, such as comets or meteorites
  - The last ~1% added as the "late veneer"
- Measurements of the D/H ratio can help determine the source of Earth water
- Forensic "isotopic fingerprinting"

“Textbook” D/H in Water in the Solar Nebula

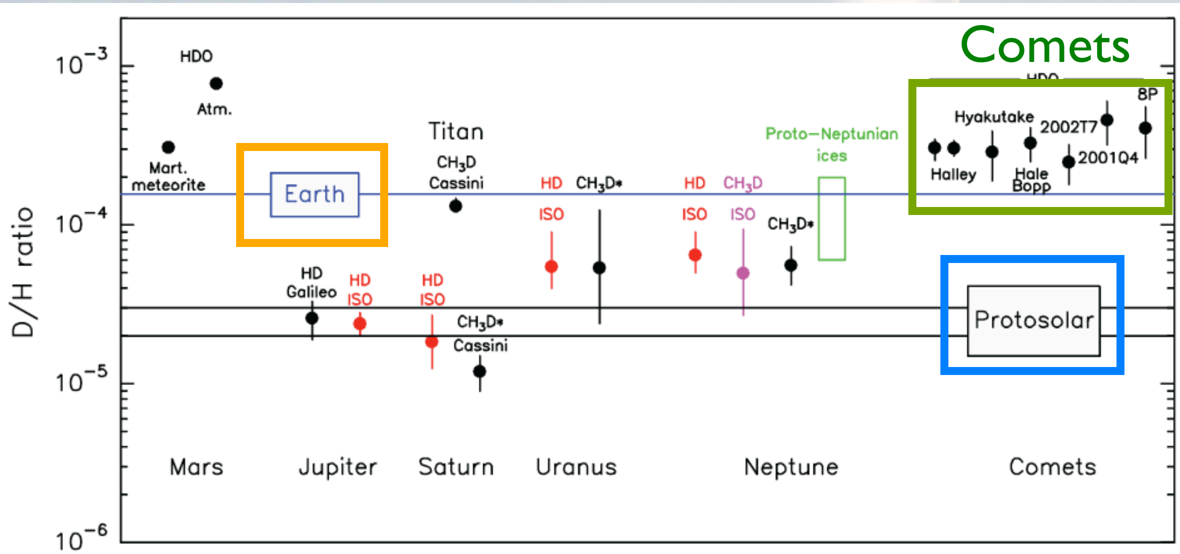
- Variations in the D/H ratio in solar system materials can be explained as the result of progressive isotopic exchange reactions between HDO and H_2
- Water was initially synthesized by interstellar chemistry with a high D/H ratio (>7.2×10^{-4}; highest value measured in clay minerals)
- The D/H ratio in the solar nebula then gradually decreased with time
- During this process a D/H gradient was established in the nebula
- The isotopic heterogeneity results from turbulent mixing of grains condensed at different epochs and locations in the solar nebula

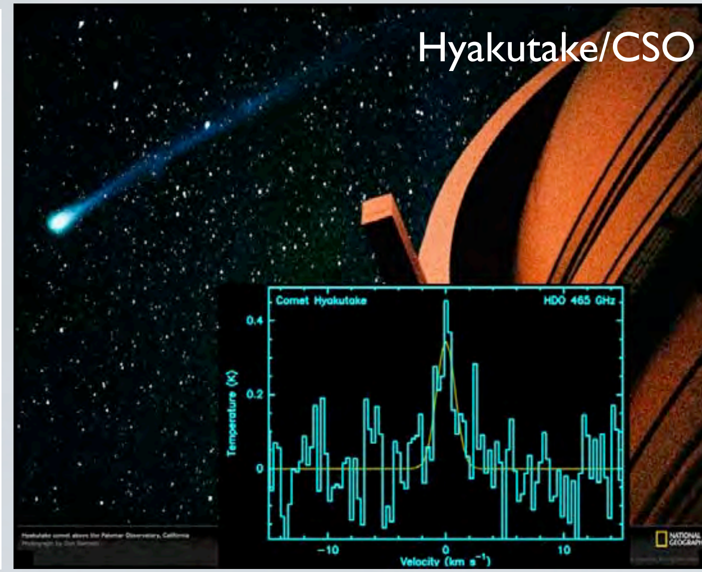
D/H Gradient



Horner et al. 2007

D/H in Solar System (Pre-Herschel)





- Protosolar D/H ratio in H_2 is ~2.5×10^{-5} (same as the Big Bang)
- Earth ocean ratio (Vienna Standard Mean Ocean Water) is 1.56×10^{-4}
- D/H measured in several Oort cloud comets is ~3×10^{-4}
- Cometary D/H ratios represent a factor of ~12 enrichment over the protosolar value and 2 times enrichment over the Earth ocean value
- Based on the isotopic measurements and dynamical models, most probable source of Earth water was ice-rich reservoir in the outer asteroid belt
- Comets could have contributed less than 10% of the Earth water

Ocean-like water in the Jupiter-family comet 103P/Hartley 2

Paul Hartogh[1], Dariusz C. Lis[2], Dominique Bockelée-Morvan[3], Miguel de Val-Borro[1], Nicolas Biver[3], Michael Küppers[4], Martin Emprechtinger[2], Edwin A. Bergin[5], Jacques Crovisier[3], Miriam Rengel[1], Raphael Moreno[3], Slawomira Szutowicz[6] & Geoffrey A. Blake[2]

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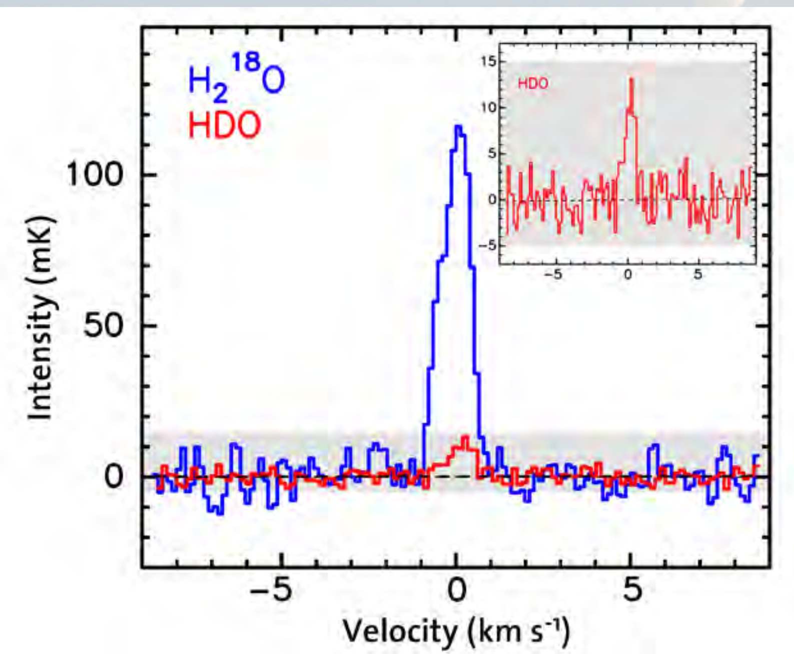
News

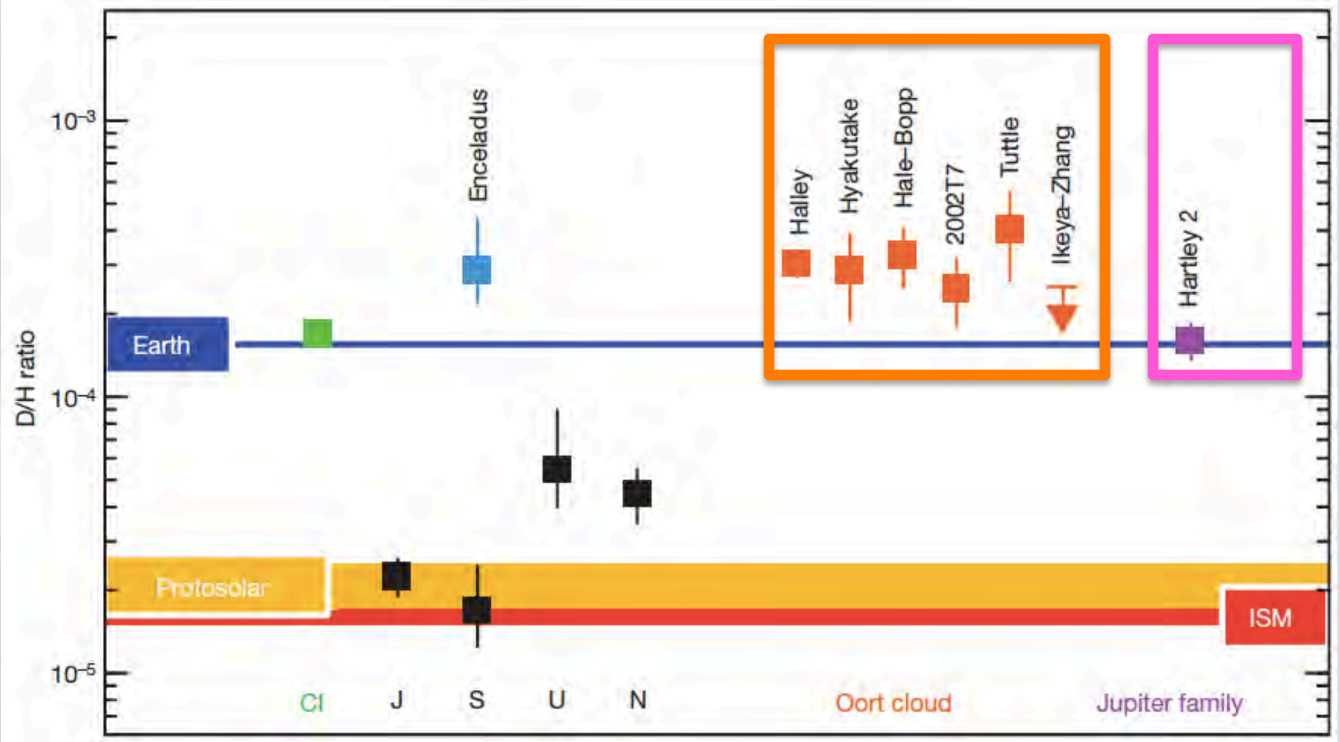
Comets take pole position as water bearers

Matching chemical signatures indicate that Kuiper comets brought water to Earth.



- Using HIFI on Herschel, we measured the D/H ratio in comet Hartley 2
- The first Kuiper Belt (Jupiter Family) comet in which D/H in water has ever been measured
- HDO clearly detected (11σ)
- D/H in water $(1.61\pm0.24)\times10^{-4}$ (1σ)
- A factor of 2 lower than the earlier measurements in Oort cloud comets and the same as VSMOW!
- Surprising result, because Jupiter Family comets, having formed farther away from the Sun, were expected to have higher D/H values than Oort cloud comets!

What are the Implications?

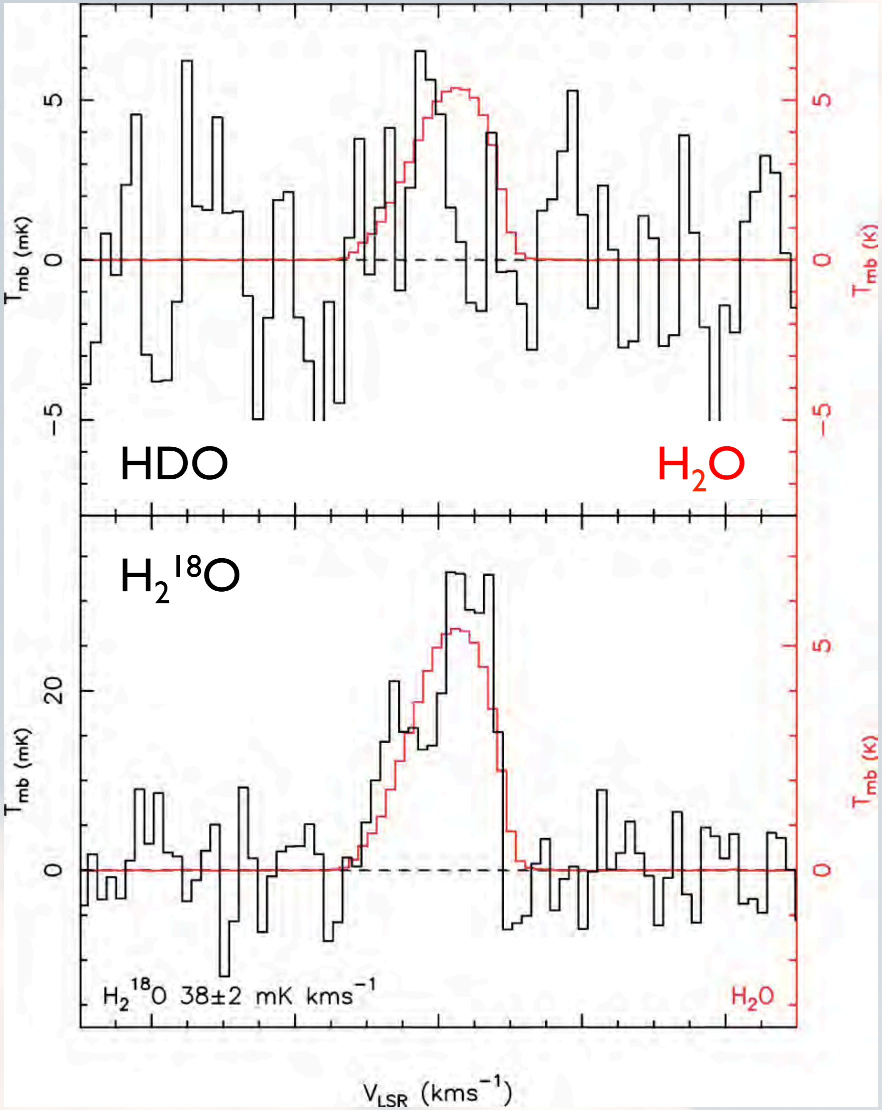


- Hartley 2 potentially traces a different, *large reservoir* of water ice rich material in the outer Solar system—Kuiper belt
- HIFI observations show that the high D/H values previously measured in Oort cloud comets are not representative of all comets
- Current understanding of deuteration in different solar system reservoirs, or *solar system dynamics*, is incomplete and has to be revisited
- Much higher fraction (all?) ocean water could have been delivered by comets
- These comets also might have seeded the early Earth with organics!

Complex Dynamics of the Solar System

- 2005 Niece model (Gomes et al. 2005; Morbidelli et al. 2005): migration of Saturn into 1:2 orbital resonance with Jupiter may have triggered disruption of the outer disk (15–35 AU)
- Comets ejected from the outer disk later entered both the Oort cloud and the Kuiper belt
- Comets that formed in the giant-planet zone (5–14 AU) probably entered both the Oort cloud and outer disk—subsequent disruption of the outer disk contributed some of the mass impacting the Earth during the LHB and could have contributed to Earth's oceans (Gomes et al. 2005)
- Up to 90% of comets in the Oort cloud may have been captured from other stars in the Sun's birth cluster (Levison et al. 2010)
- About 10% of JFC may in fact originate from the Trojan asteroid swarms (Horner et al. 2007)
- "Grand Tack model"—strong radial mixing of planetesimals (Walsh et al. 2011)
- Significant variations in the cometary D/H ratio are expected—increasing emphasis on classifying comets based on their composition and isotopic ratios rather than orbital dynamics (Mumma & Charnley 2011)

45P/Honda-Mrkos-Pajdušáková



Lis et al. 2012

- Period 5.3 years—only other Jupiter family comet accessible to HIFI
- Water production rate was ~3 times lower than in Hartley 2 ($H_2{}^{18}O$ line intensity 38±2 vs. 117 mK kms^{-1})
- $H_2{}^{18}O$ clearly detected (20 vs. 60σ), but only upper limit for HDO: 3.8±1.36 mK kms^{-1}
- Preliminary upper limit for D/H in water 1.8×10^{-4} (3σ)—consistent with Hartley 2 and VSMOW
- The Oort cloud D/H ratio is excluded at the 5σ level
- D/H intermediate between the Oort cloud value and VSMOW cannot be excluded by the observations
- No more JFC accessible to HIFI—ALMA, CCAT, near-IR, UV…

How much water is there in a disk?

Detection of the Water Reservoir in a Forming Planetary System

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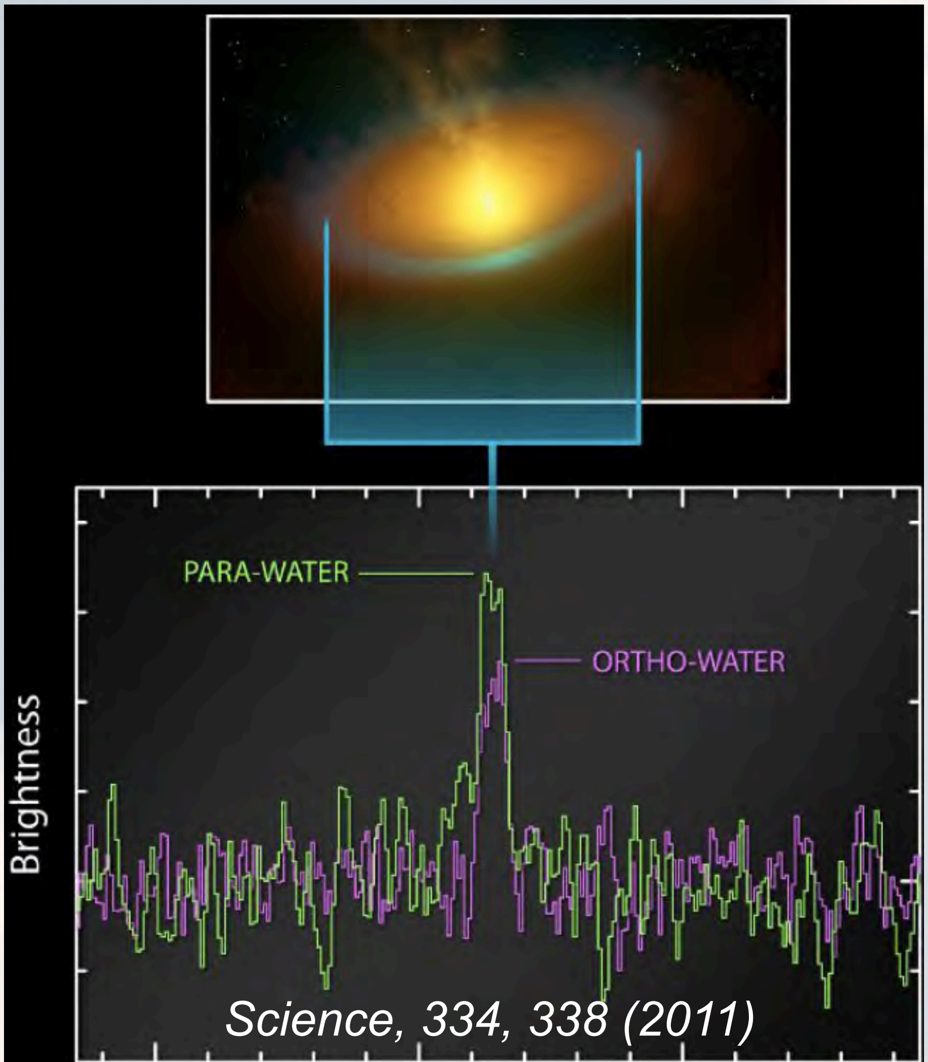
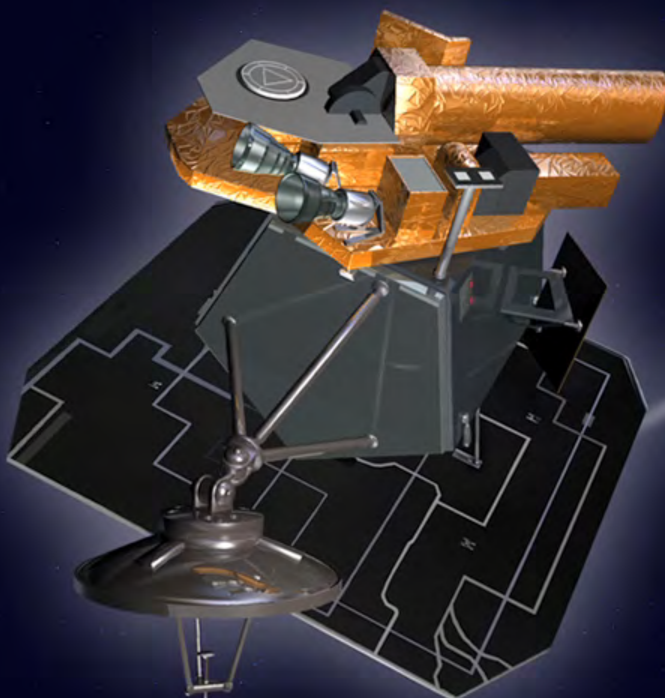


Science, 334, 338 (2011)

- Lines of ortho and para water detected for the first time with Herschel/HIFI in TW Hydrae
- 10 mln years old T Tauri star, 0.6 $M_{\odot}$, 54 pc from the Sun
- Several thousand oceans worth of water ice, at 100–200 AU from the star
- If other disks are similar to TW Hydrae, ample water exists in the outer disk, where comets form
- Water-covered planets like Earth may be common
- Another important step in our quest to understand the origin of life on Earth and assess possibilities of life in other planetary systems



EPOXI Mission Captures Jets in Action