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

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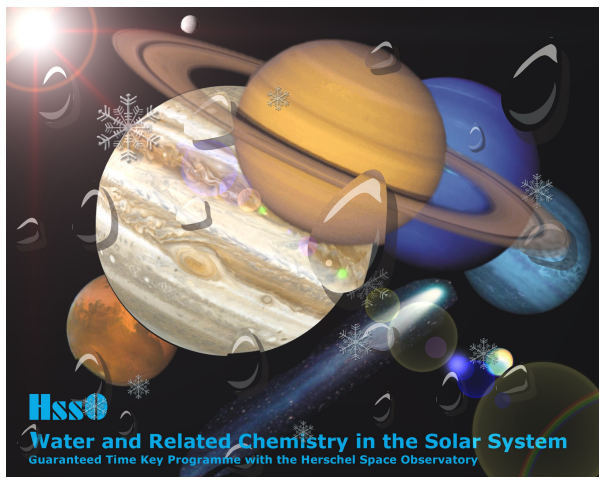

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Outline

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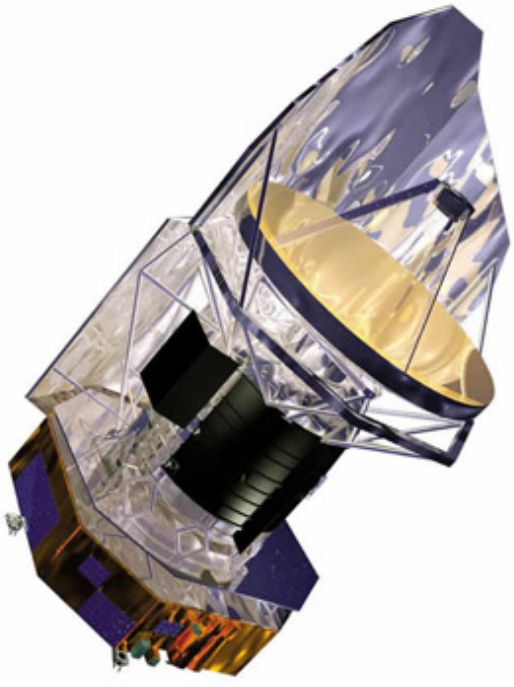
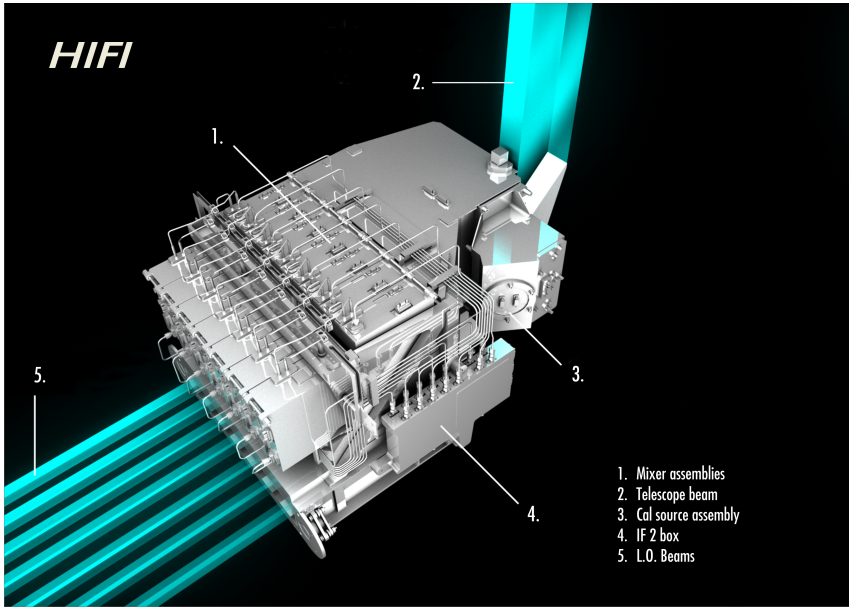
Herschel Space Observatory



- 3.5-m passively cooled telescope on a Lissajous orbit around Lagrange point L_2
- launched on 14 May 2009 – lifetime $\sim$ 3.5 years
- study molecular chemistry of the universe
- 3 complementary instruments:

HIFI	high-resolution heterodyne spectrometer 150–610 μm
SPIRE	camera and imaging spectrometer 194–672 μm
PACS	camera and imaging spectrometer 55–210 μm

Herschel/HIFI (Heterodyne Instrument for the Far Infrared)



- 5 bands in the 480–1150 GHz
- dual frequency bands 1410–1910 GHz
- Wide Band Spectrometer (WBS) - 1.1 MHz
- High Resolution Spectrometer (HRS) - 140 KHz
- HIFI observes two polarizations simultaneously

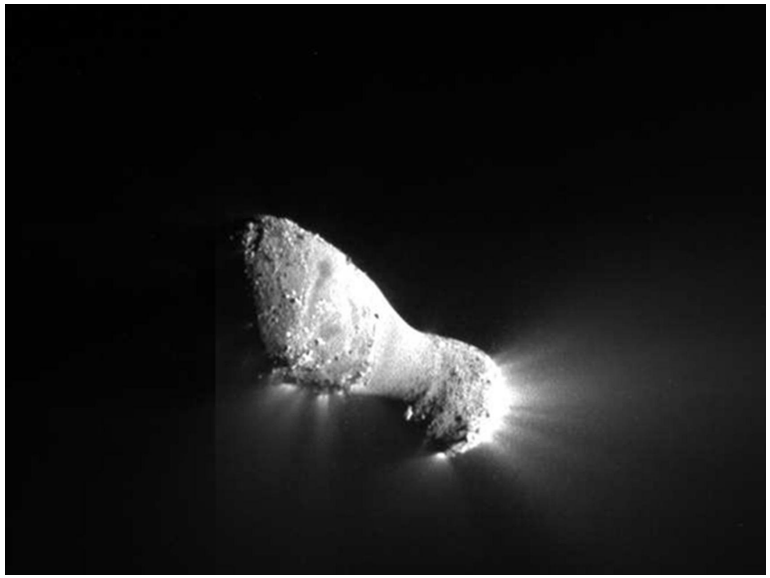
- HIFI's high spectral resolution and sensitivity allows for the detection of multiple rotational water lines
- accurate determinations of water production rates in comets (Hartogh et al. 2010)

Water in comets

Hyakutake (Wainscoat)

- Water is the main component of cometary nucleus
- $Q_{\mathrm{H_2O}}$ has been estimated from the ground through the OH radical and water high vibrational bands
- 1_{10}–1_{01} ortho-H_2O at 557 GHz was observed in several comets by SWAS and Odin
- Other ortho- and para-H_2O, HDO and $H_2^{18}O$ transitions observed by *Herschel* (Hartogh et al. 2010)

Comet 103P/Hartley 2



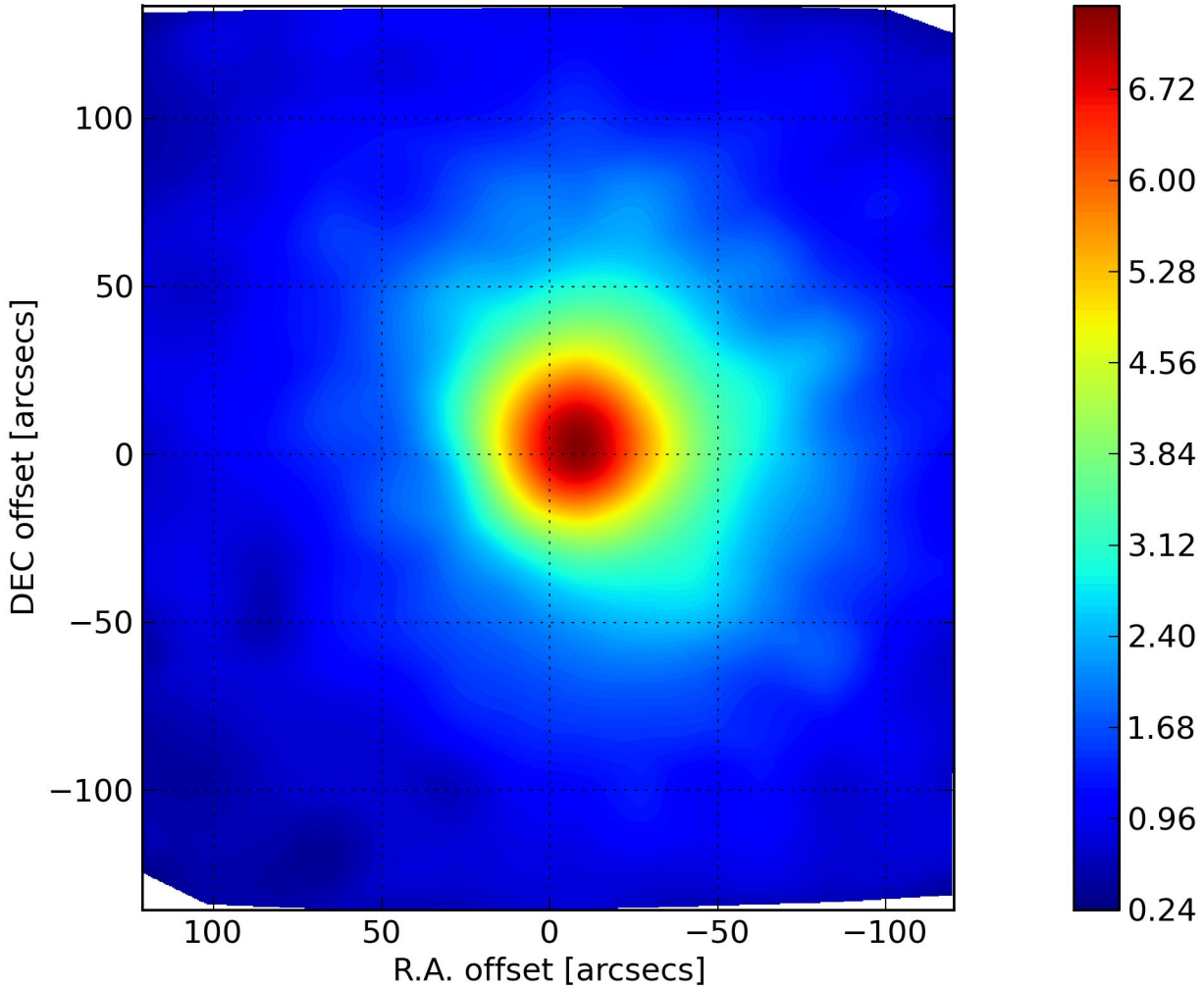
EPOXI's MRI camera

- JFC (6.45 year period)
- Target of NASA's EPOXI mission on 4 Nov 2010
- Elongated nucleus with 18 h period
- Typical water production rate 10^{28} s^{-1}
- Perihelion on 28 Oct 2010 at $r_\mathrm{h} = 1.05$ AU
- Closest approach to Earth on 20 Oct 2010 at 0.12 AU
- *Herschel* observed far-IR and sub-mm spectrum and imaged thermal dust at 70-672 μm (Oct 24–Nov 17)

HIFI Observations of 103P/Hartley 2 on Nov 17.28–17.64

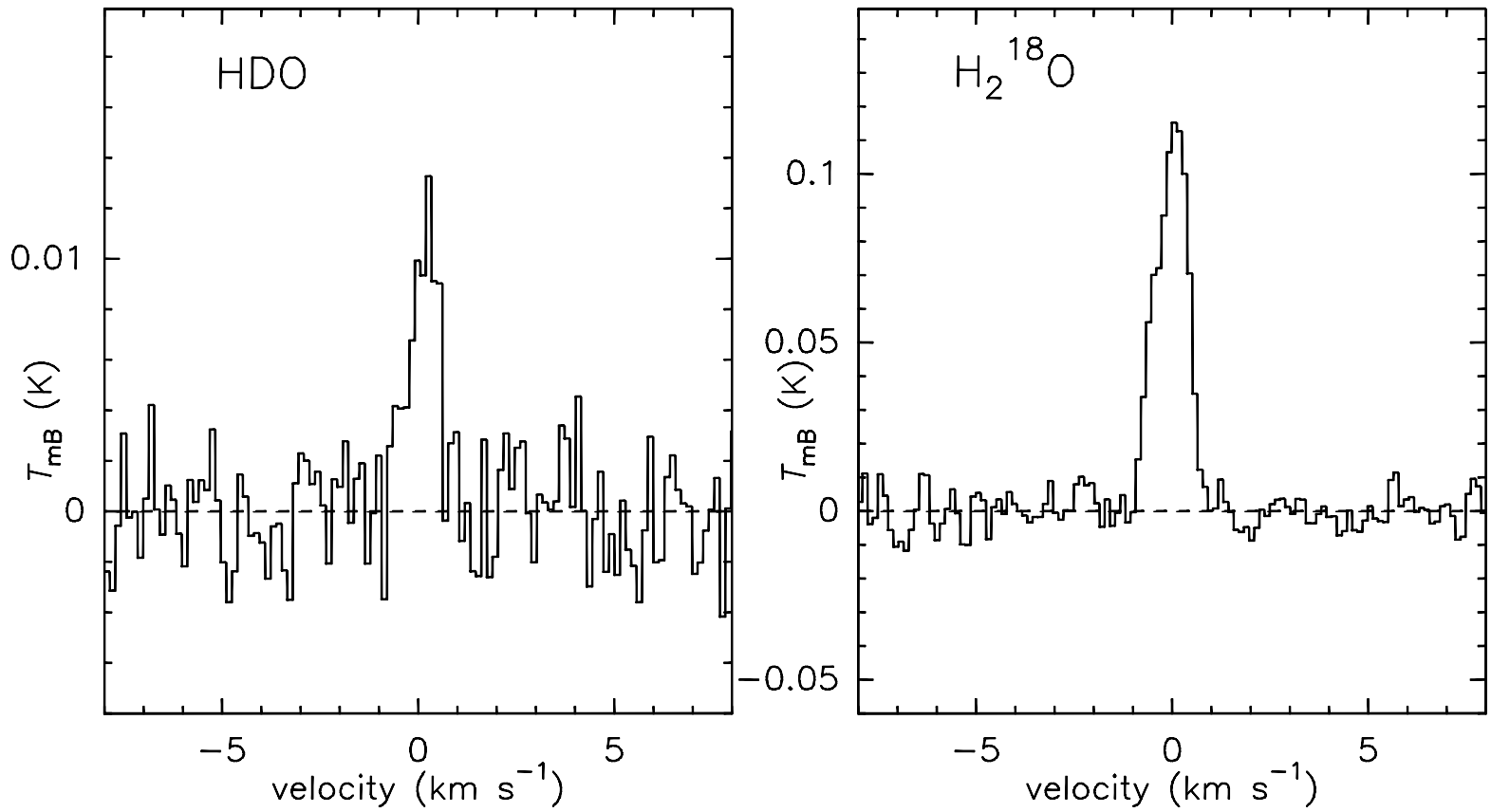
- 20 days post-perihelion ($r_{\rm h} = 1.095$ AU, $\Delta = 0.212$)
- Observing sequence
  - 10 32-min scans of HDO 1_{10}–1_{01} at 509.292 GHz
  - 10 6-min scans of H_2O and $H_2^{18}O$ 1_{10}–1_{01} at 556.936 and 547.676 GHz
  - 5 16-min on-the-fly maps of the H_2O 1_{10}–1_{01} transition
- Single-point observations in frequency switched mode (94.5 MHz throw)
- Similar beam sizes (FWHM 38.1, 38.7 and 41.6″, ∼6500 km)
- Spectra acquired with WBS and HRS simultaneously
- All lines were observed in H+V polarizations

HIFI HRS H_2O 556.936 GHz Nov 17.27 UT



- line peaks approximately 10″ westward of the nucleus
- $Q_{\mathrm{H_2O}} = 10^{28}\ \mathrm{s}^{-1}$

Observed spectra

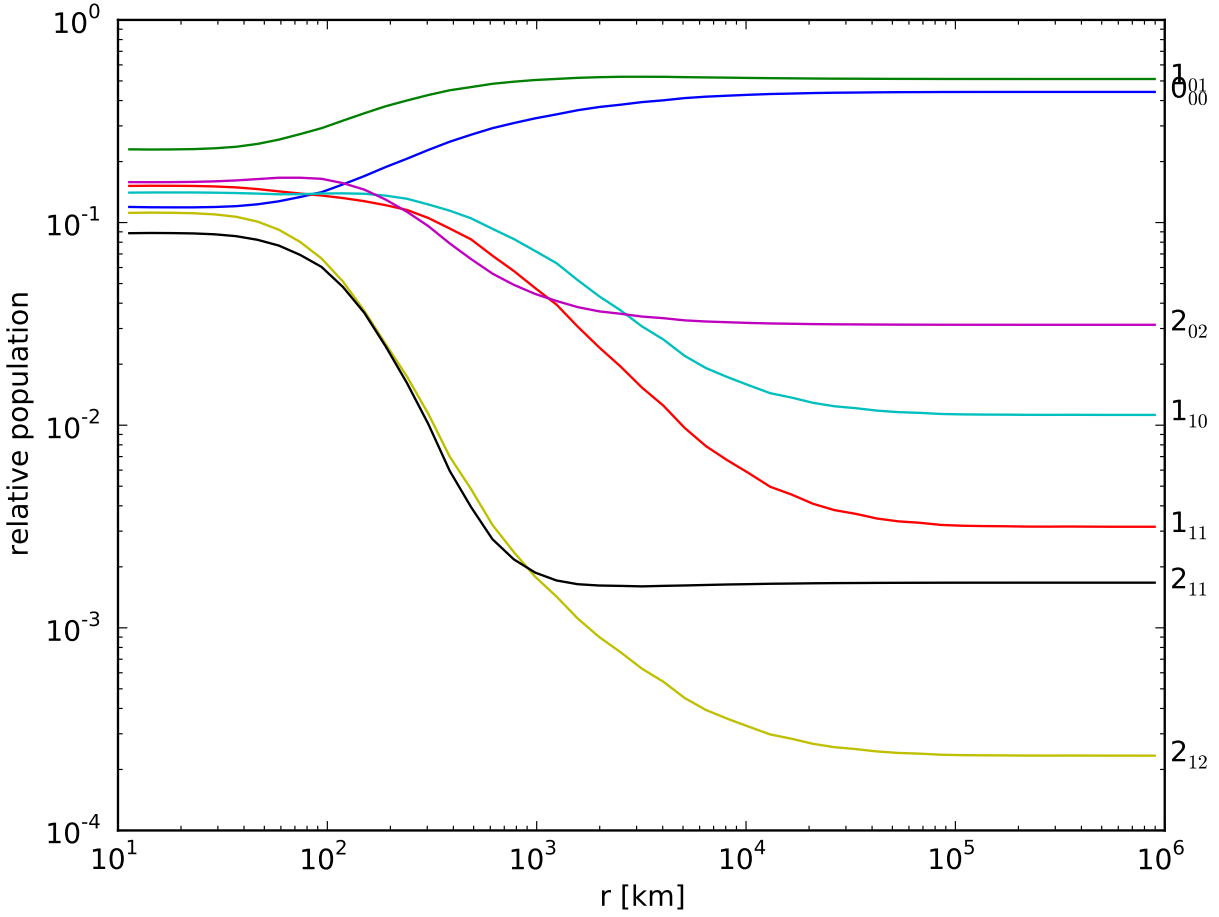


1_{10}–1_{01} lines of HDO (509 GHz) and $H_2^{18}O$ (548 GHz)

HDO and $H_2^{18}O$ excitation models

- collision excitation with H_2O and electrons dominate the excitation in the inner coma
- solar infrared pumping of vibrational bands lead to fluorescence equilibrium in the outer coma
- self-absorption effects are negligible
- standard Haser distribution with isotropic outgassing
- level populations depend on collisional rates and $T_{\rm kin}$
- $T_{\rm kin} = 50$ K from CH_3OH mm observations
- $T_{\rm kin} \sim 70$–85 K from ro-vibrational IR lines at scales of 0.5-2″
- electron density $x_{n_{\rm e}} = 0.2$ wrt measurements in 1P/Halley
- $v_{\rm exp} = 0.6\ {\rm km\,s^{-1}}$
- ortho-to-para ratio of 2.8 (consistent with IR measurements)

HDO level population

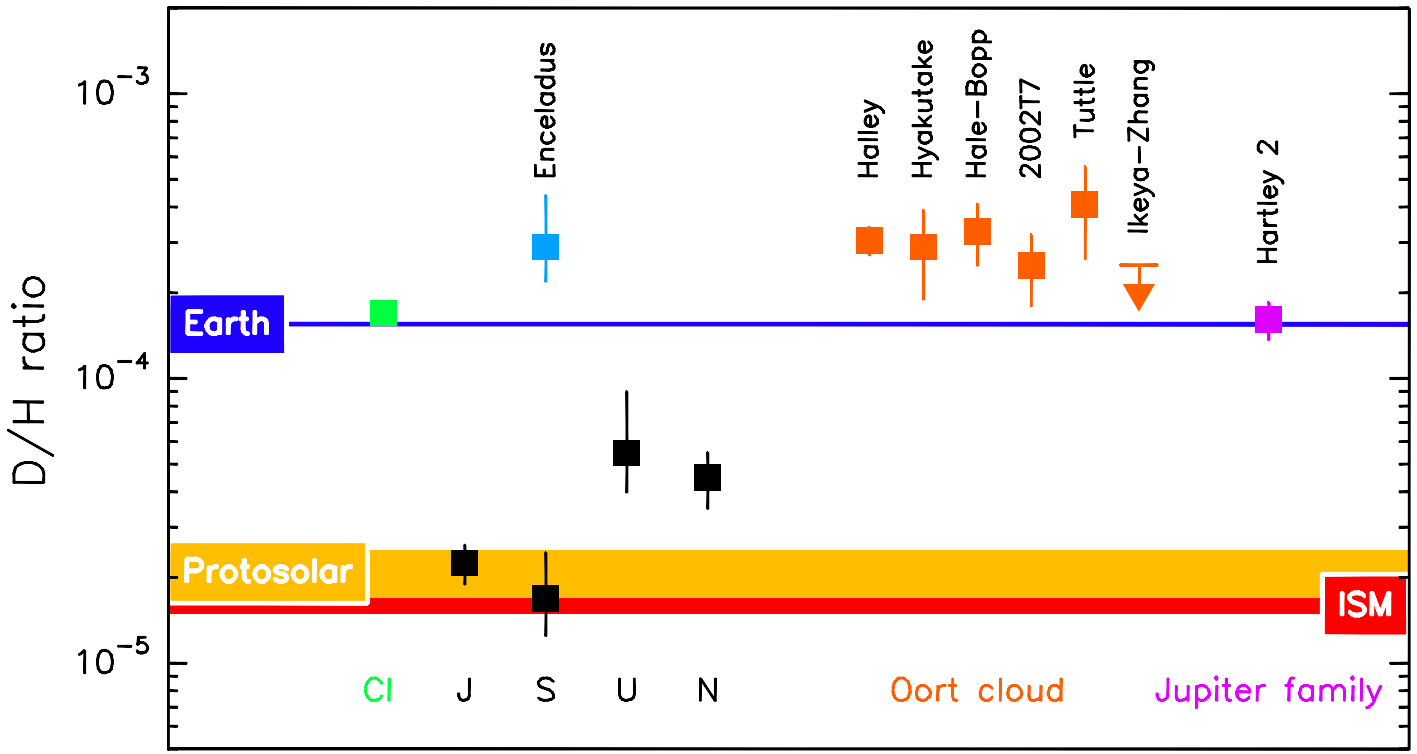


HIFI observations sample molecules with an excitation state intermediate between LTE and fluorescence equilibrium

D/H ratio in 103P/Hartley 2

- Assuming VSMOW $^{16}O/^{18}O = 500 \pm 50$ (520 ± 30 in 4 comets with Odin):
- $D/H = (1.61 \pm 0.24) \times 10^{-4}$
- $HDO/H_2^{18}O$ production rate ratio is not very sensitive to the model parameters
- close to terrestrial VSMOW D/H value $(1.558 \pm 0.001) \times 10^{-4}$
- factor of two smaller than in OCCs $(2.96 \pm 0.25) \times 10^{-4}$
- larger than the protosolar value (2.1×10^{-5}) and the ISM value (1.6×10^{-5}) in H_2

D/H ratios in the solar system



- Oort cloud comets have twice the value of the Earth's ocean
- JFC 103P/Hartley 2 and the CI values in carbonaceous chondrites are consistent with VSMOW
- 1-σ uncertainties

Explaining the low D/H ratio in 103P/Hartley 2

D enhancement in H_2O predicted to increase with distance from the Sun (not yet confirmed by observations)

1. 103P/Hartley 2 may not come from the Kuiper belt
   - Is it a Trojan (Horner et al. 2007) originating near Jupiter?
   - Perhaps OCCs did not form in the vicinity of the giant planets or do not represent the solar system (Levison et al. 2010)
2. Model of D/H fractionation with heliocentric distance
   - In the early phase of the solar system formation material was mixed over large distances (Walsh 2011).
   - Models of the dynamical evolution of the solar system?

Summary

- *Herschel* 103P/Hartley 2 observations on Oct 24–Nov 17 2010 at $r_{\rm h} = 1.06$–1.09 AU, $\Delta = 0.11$–0.21 AU
- Excess emission in the anti-solar direction
- $Q_{\rm H_2O} \sim 0.8$–1.2×10^{28} mol s^{-1} at perihelion
- 1_{10}–1_{01} lines HDO (509 GHz) and $\rm H_2^{18}O$ (548 GHz) detected
- $\rm D/H = (1.61 \pm 0.24) \times 10^{-4}$
- Ocean like water found for the first time in a comet
- Finding does not fit present models on origin of cometary material and isotopic fractionation with heliocentric distance
- Paradigm of maximum 10% cometary water in hydrosphere based on composition arguments needs to be revisited
- Further JFC measurements required to increase sample size