A comparative study of Uranus and Neptune with Herschel

E. Lellouch, R. Moreno, T. Cavalié, H. Feuchtgruber, C. Jarchow, P. Hartogh, B. Swinyard

and the “Water and related chemistry in the Solar System (HSSO)” Herschel Key Program team
Why study Uranus and Neptune?

- Uranus and Neptune are “twins” in the outer Solar System: similar masses (~15 \( M_E \)), radii (4 \( M_E \)), rotation rates (~17 h)
- They are representative of the “icy giant” family, where most of the mass is in solid phase
- The majority of exoplanets / exoplanet candidates are in the Uranus/Neptune size/mass regime
Why study Uranus and Neptune?

- But they are “fraternal twins”, exhibiting large differences
  - Uranus has large tilt of polar axis, hence large seasonal variations
  - Uranus has virtually no internal heat source, while Neptune has the largest of all Giant Planets → difference in internal structure
  - Winds are x 2 stronger in Neptune’s atmosphere, despite larger distance to Sun
  - Vertical transport is more sluggish in Uranus, indicating a less well mixed atmosphere
  - All this implies also differences in atmospheric composition
Goals and approach of the Herschel observations

- Observe the sub-millimeter spectrum of Uranus and Neptune to measure expected species in this range:
  - $\text{H}_2\text{O}, \text{CO} \rightarrow$ nature of external/internal source of oxygen
  - $\text{CH}_4 \rightarrow$ meteorology and vertical mixing
  - $\text{HD} \rightarrow \text{D/H} \rightarrow$ composition of original icy grains
- Search for new species (e.g. $\text{PH}_3$, diagnostic of convection): none found
- Probed region: upper troposphere and stratosphere (~500 mbar – 0.1 mbar)
- Improve atmospheric models for calibration purposes

- Approach: combination of PACS and SPIRE full range spectra with dedicated line observations (PACS, HIFI)
PACS spectrum: Neptune (line/continuum)

Lellouch et al. A & A 2010
PACS spectrum: Uranus (line/continuum)

Line/Continuum

H2O and HD

Wavelength (micrometer)

HD
R(1)

HD
R(0)
Methane

Abundance and vertical profile determination

Lellouch et al. 2010, Moreno et al DPS 2012
• Large stratospheric abundance \((\text{CH}_4 = 0.1-0.15 \%\)) at 10 mbar, decreasing downwards

• Supersaturated by factor 10 compared to value « allowed » by 56 K tropopause → \textbf{injection from warm polar region}
Methane in Uranus: seasonal changes

- In upper troposphere, methane close to saturation (100% relative humidity)
- Strong depletion in middle stratosphere (~3 mbar) due to low homopause (i.e. poor mixing)
- Still, methane much more abundant in Herschel observations (Equinox) compared to Solstice conditions (Voyager, ISO): seasonal/latitudinal variability
$\text{H}_2\text{O}$: the origin of external oxygen in outer planets
$\text{H}_2\text{O}$ 557 GHz line spectrally resolved by HIFI

Shoemaker-Levy 9 collision
Enceladus torus absorption
Enceladus plumes

Jupiter
Saturn
Uranus
Neptune
External water in Uranus and Neptune

- Vertical profile difficult to retrieve (less information in HIFI line-resolved profiles) → source of water still unknown
- Data still confirm ISO-derived result that amount of external H$_2$O is ~2.5 times higher at Neptune than at Uranus
- Input fluxes (ISO-based)
  - $(0.5-1.5) \times 10^5$ cm$^{-2}$s$^{-1}$ at Uranus
  - ~$10^5$ - $10^7$ cm$^{-2}$s$^{-1}$ at Neptune, depending on eddy diffusion coefficient profile
Carbon monoxide

First observation of CO at submillimeter wavelengths in Uranus (HIFI @ 922 GHz)

Moreno et al. in prep.

Cavalié et al., submitted

NEPTUNE
A dual origin of carbon monoxide

• An *external* source in both planets, producing a stratospheric mixing ratio of $\sim 10^{-6}$ at Neptune and $\sim 10^{-8}$ at Uranus
  – A permanent influx of interplanetary CO-rich grains
  – Cometary impact (or a distribution of); favored at Neptune (large CO/H$_2$O flux ratio)

• An *internal* source, producing a tropospheric mixing ratio smaller than the stratospheric by $\sim 1$ order of magnitude at Neptune. Source not visible at Uranus
  – Disequilibrium thermochemistry: CO produced from H$_2$O ($\text{H}_2\text{O} + \text{CH}_4 = \text{CO} + 3\text{H}_2\text{)}$ and transported upwards
  – Permits to estimate deep H$_2$O, i.e. O/H ratio
For « reasonable » vertical transport (eddy $K_{zz} = 10^7$ - $10^9$ cm$^2$ s$^{-1}$), internal CO = 0.2 ppm implies 500-700 solar O/H ratio!
(i.e. O/H ~ 60 % by volume in Neptune’s gaseous envelope)

**Problems:**
- C/H is only 30-50 solar !
- Current internal structure models are inconsistent with O/H > 200 solar

Much larger diffusion coefficient ?
D/H ratio
**NEPTUNE**

\[ \text{D/H} = (4.1 \pm 0.4) \times 10^{-5} \]

Feuchtgruber et al. 2013

**URANUS:**

\[ \text{D/H} = (4.4 \pm 0.4) \times 10^{-5} \]
D/H: interpretation

- D/H higher in U & N than in J & N due to mixing of their atmosphere with D-rich icy grains
- Can be used to constrain D/H in proto-planetary grains

\[
(D/H)_{\text{ices}} = \frac{(D/H)_{\text{planet}} - x_{\text{H}_2}(D/H)_{\text{proto}}}{1 - x_{\text{H}_2}}
\]

where \(D/H_{\text{planet}} = (D/H)_{\text{H}_2}\)

\[
x_{\text{H}_2} = \frac{n_{\text{H}_2}}{n_{\text{H}_2} + n_{\text{H}_2\text{O}}}
\]

- Requires an internal structure model, incl. \(n_{\text{H}_2}\), ice/rock fraction
- Fundamental assumption: the planets have been fully mixed during their history, i.e. equilibration of deuterium between \(\text{H}_2\) and ices has occurred
Implication

- Proto-uranian and -neptunian ices are less D-rich than comets!
Alternatives

- May be the D/H in protoplanetary ices do not have to be equal to that in cometary ices?
  - Alexander et al. (2012) find evidence for low D/H (<10 x 10^{-5}) component in formation region of comets
- U & N are less ice (H$_2$O)-rich than internal structure models say
  - “Inverting” the problem indicates rock-rich planets (14-32 % ice fraction)!
- The planets were never fully mixed during their history
  - Formation models suggest the gas envelopes of the early planets were well mixed, but not necessarily the cores
Conclusions

• Even from the mere “observable atmosphere” point of view, and just from a limited spectral range, Uranus and Neptune appear rather different
• There remains fundamental unresolved questions related to the “large abundance” of CO in Neptune and the “low” D/H ratio in both planets
• We do not have a good “reference” Uranus or Neptune for comparison with exoplanets.