Tracing the Oxygen-related Gas Composition of Titan’s atmosphere with Herschel

Miriam Rengel
Max-Planck-Institut für Sonnensystemforschung, Germany
European Space Astronomy Centre, Spain


water in the universe : from clouds to oceans- ESTEC, 12-15 april 2016
1. Introduction

Why Titan?

Titan is covered by a dense atmosphere, which is complex and diverse!
Nitrogen ($N_2$) | Methane ($CH_4$)  
---|---
Nitriles e.g. | Hydrocarbons e.g.
Hydrogen cyanide (HCN) | \(C_6H_6\) (Benzene)

How large and how complex?
Nitrogen ($N_2$)  
Methane ($CH_4$)  
Ethane ($C_2H_6$)  
Hydrogen cyanide (HCN)  
Nitriles e.g.
Hydrocarbons e.g.
Water ($H_2O$)  
Carbon monoxide (CO)  
Carbon dioxide ($CO_2$)  
More complex molecules
1. Introduction

• What are the abundances of these species?

• What is the origin of them in Titan’s atmosphere?

• What are the implications for the formation and evolution of Titan?
1. Introduction

Oxygen-related Spectroscopy of Titan has been already performed by:

Voyager 1 – 2/IRIS

ISO/SWS

Coustenis et al. (1998)

ISO/SWS

Coustenis et al. (2003)

ISO/SWS

Coustenis et al. (2007)

Voyager 1 – 2/IRIS

H₂O

Coustenis et al. (1998)

Cassini/CIRS

H₂O

Coustenis et al. (2003)

Cassini/CIRS

Samuelson et al. 1983;

Letourneur and Coustenis 1993

Cassini/CIRS

Cottini et al., 2012

de Kok et al. (2006)
Ground-based observations have also improved our knowledge of Titan’s oxygen-related atmospheric composition:

- 4-m Mayall Telescope
- OVRO
- IRAM 30-m

- Lutz et al. 1983
- Muhleman et al. 1984
- Marten et al. 1988

- IRAM 30-m and JCMT
- APEX
- ALMA

Hidayat et al. 1998
Rengel et al. 2011
Serigano et al. 2016

water in the universe: from clouds to oceans- ESTEC, 12-15 April 2016
How we can further improve our knowledge of Titan’s oxygen-related atmospheric composition?

A new window was opened...
Herschel Era

Instruments onboard Herschel:

**Heterodyne Instrument for the Far-Infrared (HIFI).**

- **P.I.: F. Helmich**, SRON
- Resolutions: 140, 280, 560 kHz, 1.1 MHz
- Frequencies: 480 – 1150 GHz, 1410-1910 GHz

**Photodetector Array Camera and Spectrometer (PACS).**

- **P.I.: A. Poglitsch**, MPE
- 3 bands in total: 55-72 µm, 72-102 µm and 102-210 µm
- 55 – 210 µm

**Spectral and Photometric Imaging Receiver (SPIRE).**

- **P.I.: M. Griffin**, Cardiff University
- Photometer: 250, 350, 500 µm
- Spectrometer: 194- 672 µm
Titan’s Spectroscopy in the Herschel Era

In the framework of the KP "Water and related chemistry in the Solar System" (PI: Hartogh)

Exploration of the FIR and submm range with high sensitivity

• 55 – 671 μm is a rich region with numerous rotational transitions of water and other trace gases
• These line transitions are stronger than those accessible from Earth
• HIFI/PACS/SPIRE higher spectral resolution and sensitivity than previous instruments
Modeling the Titan spectra Method to determine abundances

Step 1: Computation of the synthetic spectra for several abundances
Step 2: Calculation of the best-fit

Input parameters → Abundance profiles → Radiative Transfer

Comparison with data

Synthetic Spectra

Synthetic spectra

Fitting algorithm: $\chi^2$ statistics

160 layers

$\mu_i$ = absorption coefficient

New set of parameters

water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
2. Oxygen-related Gas Composition of Titan’s atmosphere: CO

Is CO primordial or external?

Possible Origin
- Interior or surface
  - Wilson & Atreya 2004

Due to solely external
- Influx of O+ from Saturn’s magnetosphere
  - Horst et al. 2008
  - Krasnopolsky et al. 2009
- Precipitation of O from Enceladus
  - Cassidy & Johnson 2010
- Precipitation of O or O+ from Enceladus torus
  - Hartogh et al. 2011

Best-fit volume mixing ratio: $1.27 \pm 0.03$

Water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
CO with Herschel /PACS and SPIRE

Numerous spectral emission features due to:

- CH$_4$
- CO
- HCN
- H$_2$O

Rengel et al. 2014

PACS:
Full range spectra (51-220 \( \mu m \))
Twice, 0.63h and 1.1h
R = 1000-5000

water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
CO with Herschel/PACS and SPIRE

Numerous spectral emission features due to:

- CH$_4$
- CO
- HCN
- H$_2$O

water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
CO with Herschel /PACS and SPIRE
Numerous spectral emission features due to:

CH$_4$, CO, HCN, H$_2$O

SPIRE:
Full range spectrum (194 - 671 µm)
July 2010, ~8.9h,
SR= 0.04 cm$^{-1}$

Rengel et al. 2014

H$_2$O

Courtin et al. 2011

CH$_4$, CO, HCN
Numerous spectral emission features due to: CO, CO, HCN, H$_2$O

- CH$_4$
- CO
- HCN

Rengel et al. 2014

Courtin et al. 2012
### Facility | Value [ppm] | Reference
--- | --- | ---
SPIRE | 40±5 | Courtin et al. 2011
CIRS | 47±8 | De Kok et al 2007
APEX | 30±15 | Rengel et al. 2011
SMA | 51±4 | Gurwell et al. 2012
PACS | 49±2 | Rengel et al. 2014
ALMA | 46±2 | Serigano et al. 2016

For the [60-170] km range altitude, the observed and best-fit simulated CO lines are consistent with other studies.
Isotopic ratio $^{12}\text{C}/^{13}\text{C}$ in CO

Results:

$^{12}\text{C}/^{13}\text{C}$ in CO: $122 \pm 62$  
$87 \pm 6$

Detection of the isotopes:

- $^{13}\text{CO}(15-14)$ and $(16-15)$ but marginal

Consistent with previous works

Isotopes in Titan

PACS – SPIRE / Herschel

Observations  Best-fit

Rengel et al. 2014

Wavelength [$\mu$m]
Isotopic ratio $^{12}\text{C}/^{13}\text{C}$ in CO

Deriving isotopic ratios

Deviations from values of other bodies?

No

Yes

Primordial differences

Emerged on time

No significant fractionation

Terrestrial value: 89.3

No significant carbon fractionation occurred during CO formation
### Isotopic ratio $^{16}\text{O}/^{18}\text{O}$ in CO

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$^{16}\text{O}/^{18}\text{O}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCMT</td>
<td>~250</td>
<td>Owen et al. 1999 (never-published)</td>
</tr>
<tr>
<td>SMA</td>
<td>400 ± 41</td>
<td>Gurwell 2008 (unpublished)</td>
</tr>
<tr>
<td><strong>Herschel/SPIRE</strong></td>
<td>380 ± 60</td>
<td>Courtin et al. 2012</td>
</tr>
<tr>
<td>ALMA</td>
<td>414 ± 45</td>
<td>Serigano et al. 2016</td>
</tr>
</tbody>
</table>

- First documented measurement of Titan’s $^{16}\text{O}/^{18}\text{O}$ in CO
- Value 24% lower than the Terrestrial ratio (Earth = 500)

$^{16}\text{O}/^{18}\text{O}$ depletion in Titan (enrichment of $^{18}\text{O}$).

**What is the origin?**

---

water in the universe: from clouds to oceans- ESTEC, 12-15 april 2016
Isotopic ratio $^{16}\text{O}/^{18}\text{O}$ in CO

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$^{16}\text{O}/^{18}\text{O}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCMT</td>
<td>~250</td>
<td>Owen et al. 1999 (never-published)</td>
</tr>
<tr>
<td>SMA</td>
<td>400 ± 41</td>
<td>Gurwell 2008 (unpublished)</td>
</tr>
<tr>
<td>Herschel/SPIRE</td>
<td>380 ± 60</td>
<td>Courtin et al. 2012</td>
</tr>
<tr>
<td>ALMA</td>
<td>414 ± 45</td>
<td>Serigano et al. 2016</td>
</tr>
</tbody>
</table>

- First documented measurement of Titan’s $^{16}\text{O}/^{18}\text{O}$ in CO
- Value 24% lower than the Terrestrial ratio (Earth = 500)

$^{16}\text{O}/^{18}\text{O}$ depletion in Titan (enrichment of $^{18}\text{O}$).

What is the origin?

Precipitation of O$^+$ or O from the Enceladus Torus

Further investigations:
- evolution of oxygen on Titan
- Oxygen processes in Titan's atmosphere

water in the universe: from clouds to oceans- ESTEC, 12-15 april 2016
3. Oxygen-related Gas Composition of Titan’s atmosphere: $\text{H}_2\text{O}$

**What is the origen of water in Titan?**

---

**Possible Origin**

- Permanent flux from interplanetary dust particles
- Local sources from planetary environments (rings, satellites)
- Cometary impacts

---

**What is the vertical profile of $\text{H}_2\text{O}$?**

Can we disentangle the various sources?

1.27 ± 0.03

Best-fit volume mixing ratio

---

water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
Water Inventory with Herschel/PACS and HIFI

Five dedicated Water vapour line emission with Herschel/PACS and HIFI

Water Vapour in Titan
HIFI / Herschel

Water Vapour in Titan
PACS / Herschel

Moreno et al. 2012
Water Inventory with Herschel/PACS and SPIRE

**Surprise:** Unexpected detection of hydrogen isocyanide (HNC) → a species not previously identified in Titan’s atmosphere.
• None of the previous water models provides an adequate simultaneous match to the PACS and HIFI observations

→ Photochemical models for water must be revised

water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
Pressure dependence law as 
\[ q = q_0 (p_0/p)^n \]

\( q_0 \) is the mixing ratio at the reference pressure level \( p_0 \)

\[ S_a \] 

\[ q_0 = 2.3 \times 10^{-11} \text{ at } p_0 = 12.1 \text{ mbar} \]
\[ n = 0.49 \]

Column density: \( 1.2 (\pm 0.2) \times 10^{14} \text{ cm}^{-2} \).
Determination of the abundance of the trace constituents: Water vertical distribution

Pressure dependence law as:

\[ q = q_0 \left( \frac{p_0}{p} \right)^n \]

$q_0$ is the mixing ratio at the reference pressure level $p_0$

\[ q_0 = 2.3 \times 10^{-11} \text{ at } p_0 = 12.1 \text{ mbar} \]

$n = 0.49$

Column density: $1.2 (\pm 0.2) \times 10^{14} \text{ cm}^{-2}$. 

 Moreno et al. 2012
Observed and synthetic spectra

Water Vapour in Titan
PACS – HIFI / Herschel

Moreno et al. 2012
The $S_a$ distribution is also compatible with the PACS lines from the full scan: computations of the synthetic spectra with $S_a$ (Moreno et al. 2012).
3. Oxygen-related Gas Composition of Titan’s atmosphere: $\text{H}_2\text{O}$

What is the origin of water in Titan?

- Permanent flux from interplanetary dust particles
- Local sources from planetary environments: Enceladus activity
- Cometary impacts

- Titan is hit by a $\text{D} > 1.5$ km comet every $\sim 4$ million years on average
- Scarcity of primordial noble gases in its atmosphere

$\text{H}_2\text{O}$ profile can be reproduced by invoking a $\text{OH}/\text{H}_2\text{O}$ influx of $(2.7-3.4) \times 10^5 \text{mol cm}^{-2}\text{s}^{-1}$

Reflects a temporal change in the oxygen influx into Titan

Best-fit volume mixing ratio: $1.27 \pm 0.03$

Water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016

Hartoogh et al. 2011
Moreno et al. 2012
4.- Conclusion

• New Survey between 51 and 671 µm: CH$_4$, CO, HCN, H$_2$O, isotopes
• Determination of abundances
• Unexpected detection of HNC
• Measurement of $^{12}$C/$^{13}$C and $^{16}$O/$^{18}$O ratio

Emerged oxygen-related Implications:

• $^{18}$O enrichment in Titan’s atmosphere: Precipitation of O$^+$ or O from the Enceladus plume activity ($^{16}$O/$^{18}$O)

• We now know the content of water vapour in Titan (different as the predictions) and from where is coming from water in the universe: from clouds to oceans - ESTEC, 12-15 April 2016
Acknowledgments

- HIFI has been designed and built by a consortium of institutes and university departments from across Europe, Canada and the United States under the leadership of SRON Netherlands Institute for Space Research, Groningen, The Netherlands and with major contributions from Germany, France and the US. Consortium members are: Canada: CSA, U.Waterloo; France: CESR, LAB, LERMA, IRAM; Germany: KOSMA, MPIfR, MPS; Ireland, NUI Maynooth; Italy: ASI, IFSI-INAF, Osservatorio Astrofisico di Arcetri-INAF; Netherlands: SRON, TUD; Poland: CAMK, CBK; Spain: Observatorio Astronómico Nacional (IGN), Centro de Astrobiología (CSIC-INTA). Sweden: Chalmers University of Technology - MC2, RSS & GARD; Onsala Space Observatory; Swedish National Space Board, Stockholm University - Stockholm Observatory; Switzerland: ETH Zurich, FHNW; USA: Caltech, JPL, NHSC.

- PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KUL, CSL, IMEC (Belgium); CEA, OAMP (France); MPIA (Germany); IFSI, OAP/AOT, OAA/CAISMI, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI (Italy), and CICT/MCT (Spain). Additional funding support for some instrument activities has been provided by ESA.

- SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC, UKSA (UK); and NASA (USA).