UVES and Comet Science

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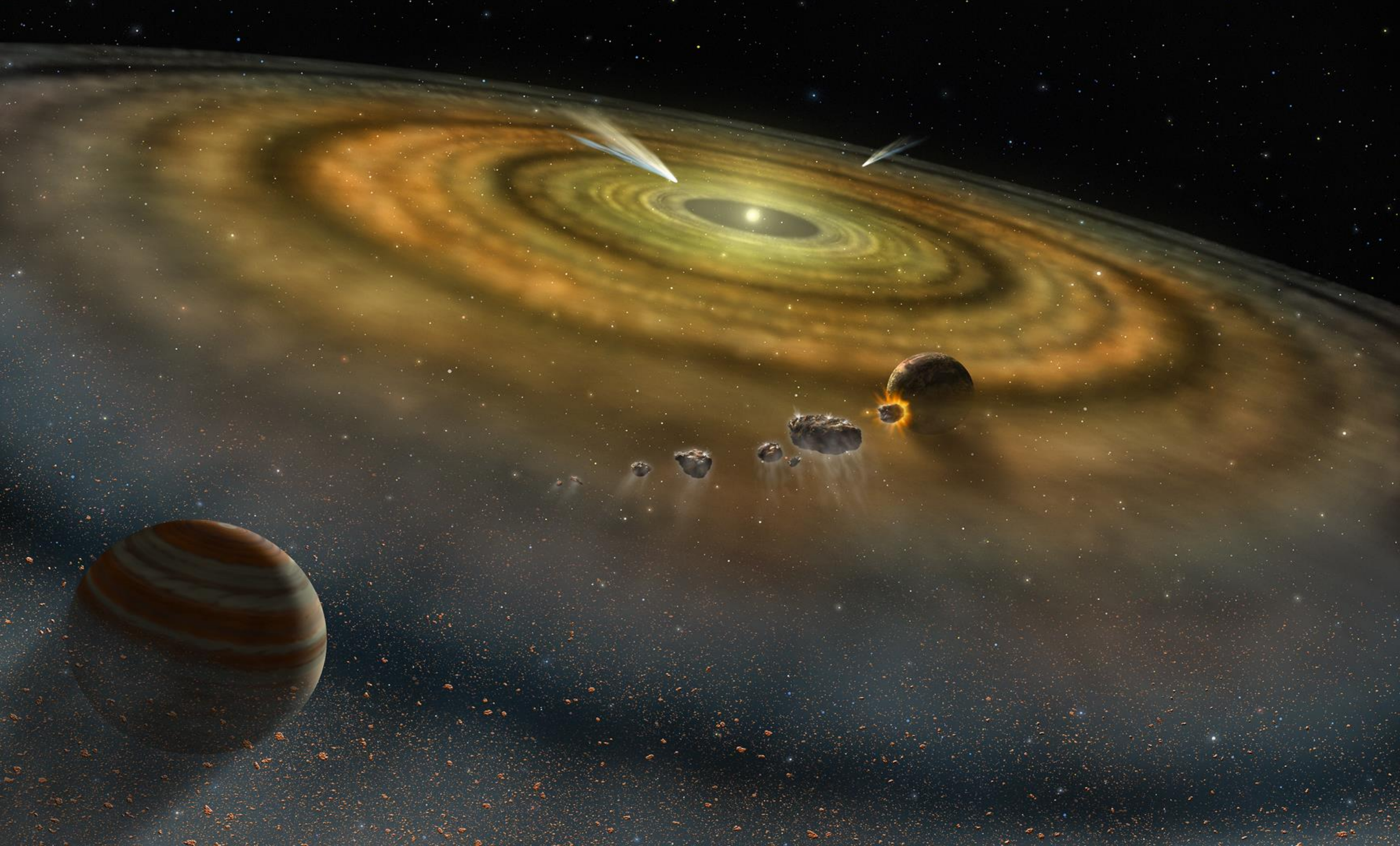
C/2006 P1 (McNaught) E.Jehin 2007

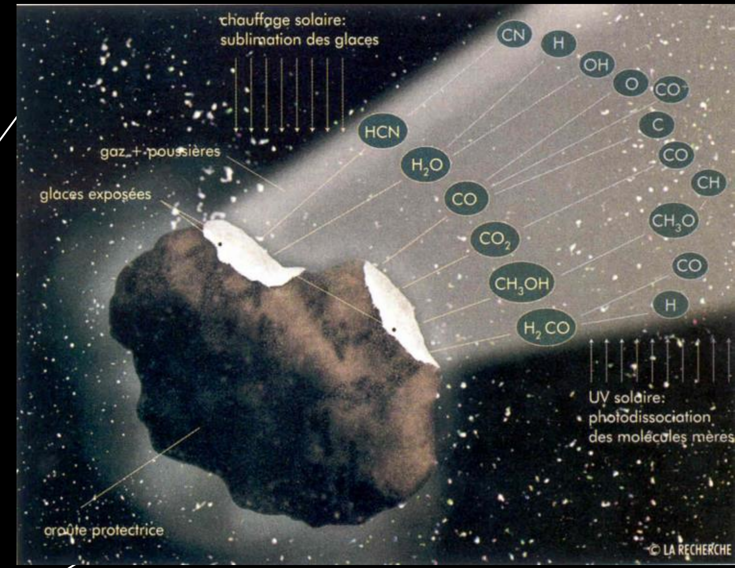
Comets as a window to the early Solar System



The nature of comets

gas + dust coma

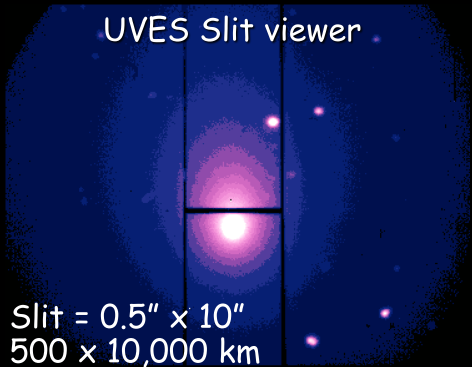
C/2007 Q4 (NEAT)



The nucleus (~1-30 km)

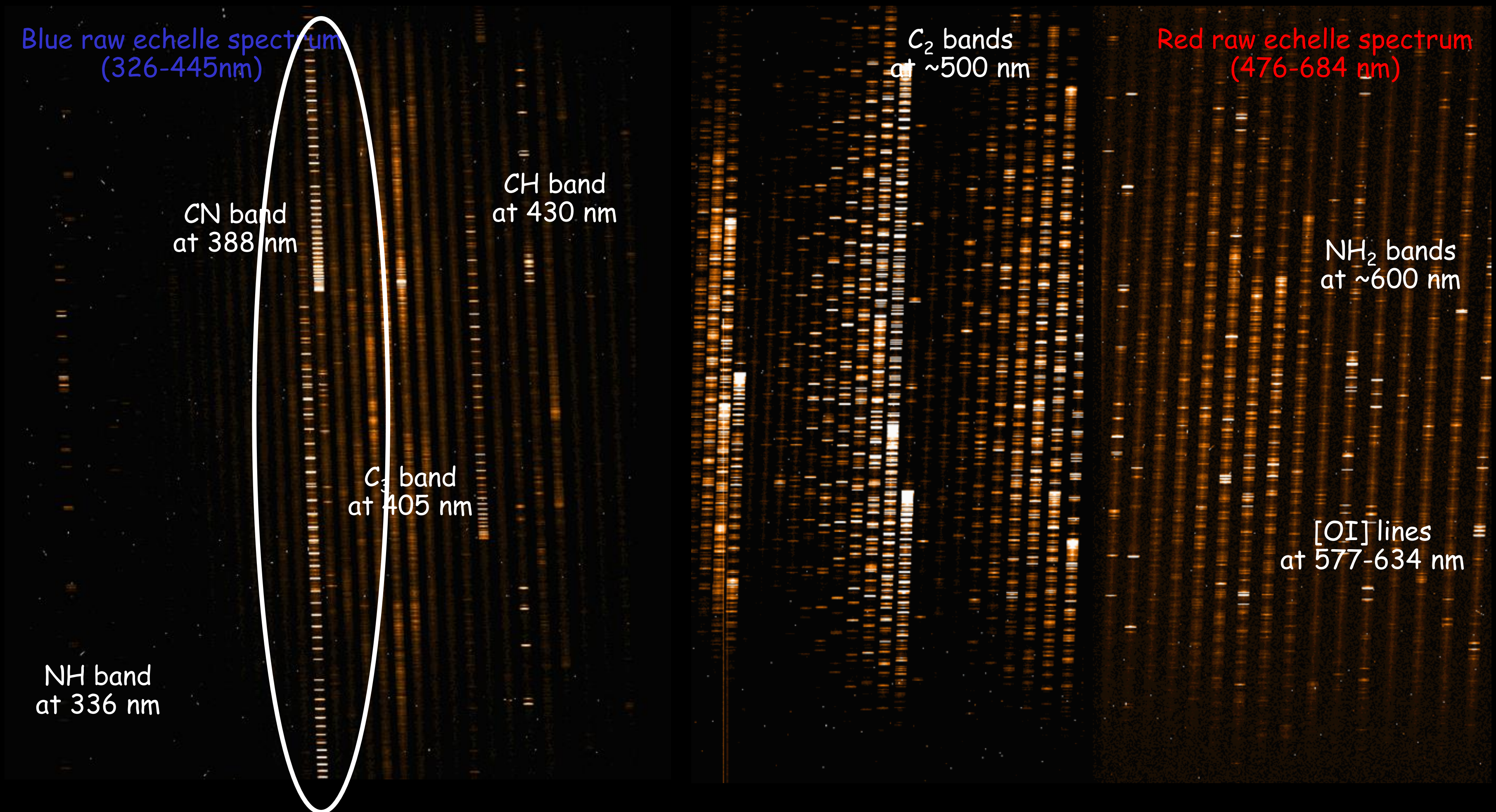
Orbits of comets (LPC > 200 yrs > SPC)

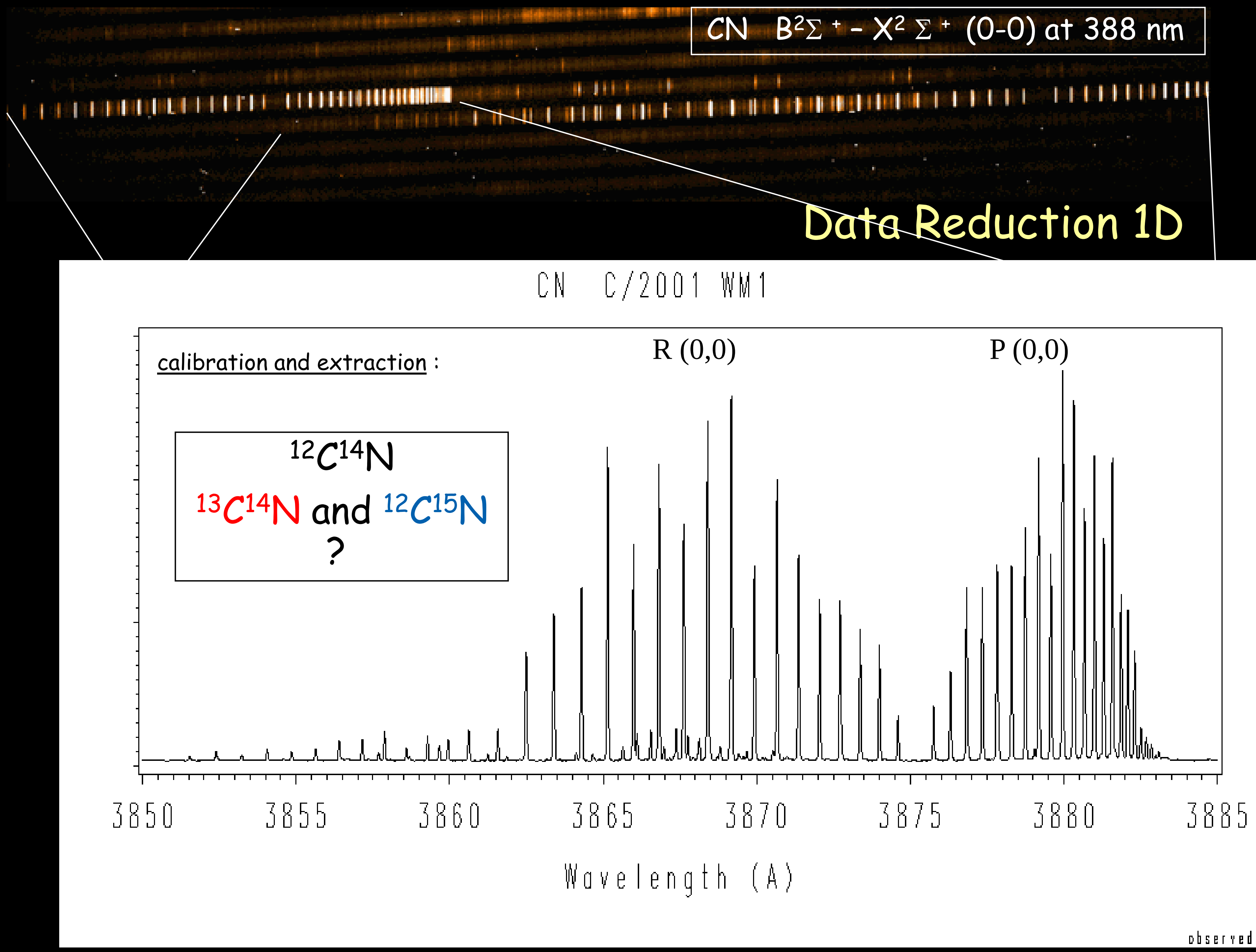
Origins : Oort Cloud and Kuiper Belt



The first UVES spectrum of a comet: C/2000 WM1

m_r = ~8.0 Exptime = 1 hr
R ~80 000   (0.013 Å/pixel)





CN B²Σ⁺ – X²Σ⁺ (0-0) at 388 nm
Data Reduction 1D
CN C/2001 WM1
calibration and extraction :
R (0,0)
P (0,0)
12C14N
13C14N and 12C15N
?
3850
3855
3860
3865
3870
3875
3880
3885
Wavelength (A)
observed

The isotopic ratios of the stable isotopes of the light elements

$^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{16}O/^{18}O$, D/H

probes for the history of Solar System material

Isotopic fractionations are sensitive to physico-chemical conditions (T°,…)

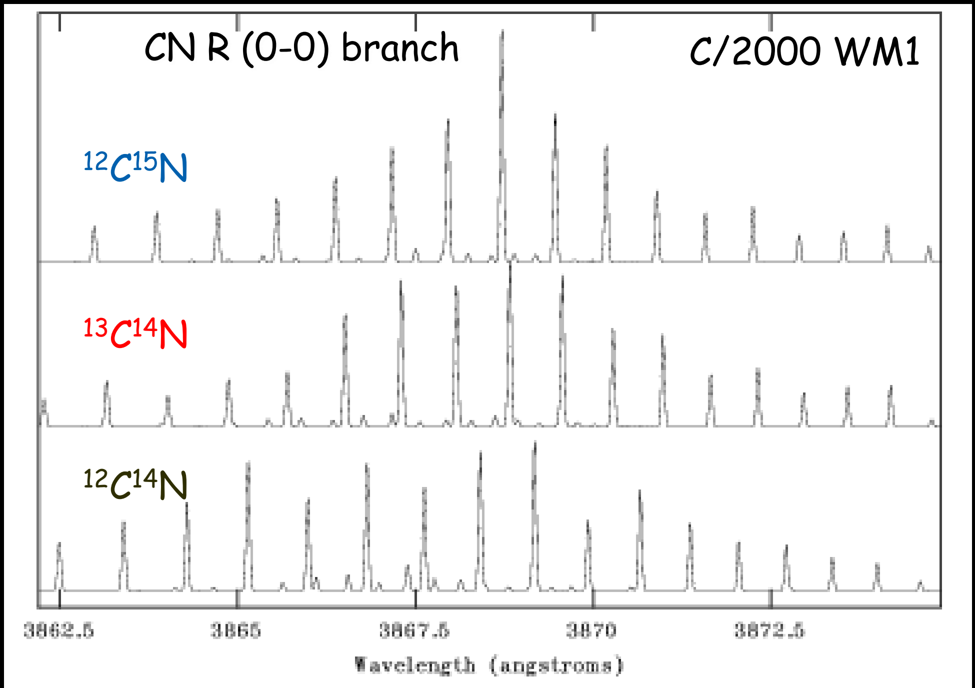
Pros : not sensitive to evolutionary effet (aging, R_h, space weathering, etc.) → genuine

Cons : hard to measure the rare isotopes (SNR, Resolv p, identification, models, variability, calibration etc.) → challenging !

- Do the isotopic ratios depend on comet dynamical class (JFC, OCC) ?
- On their chemical classification/peculiarities (C rich or poor etc.) ?
- Measurements in as many different species as possible

The Synthetic fluorescence Spectra

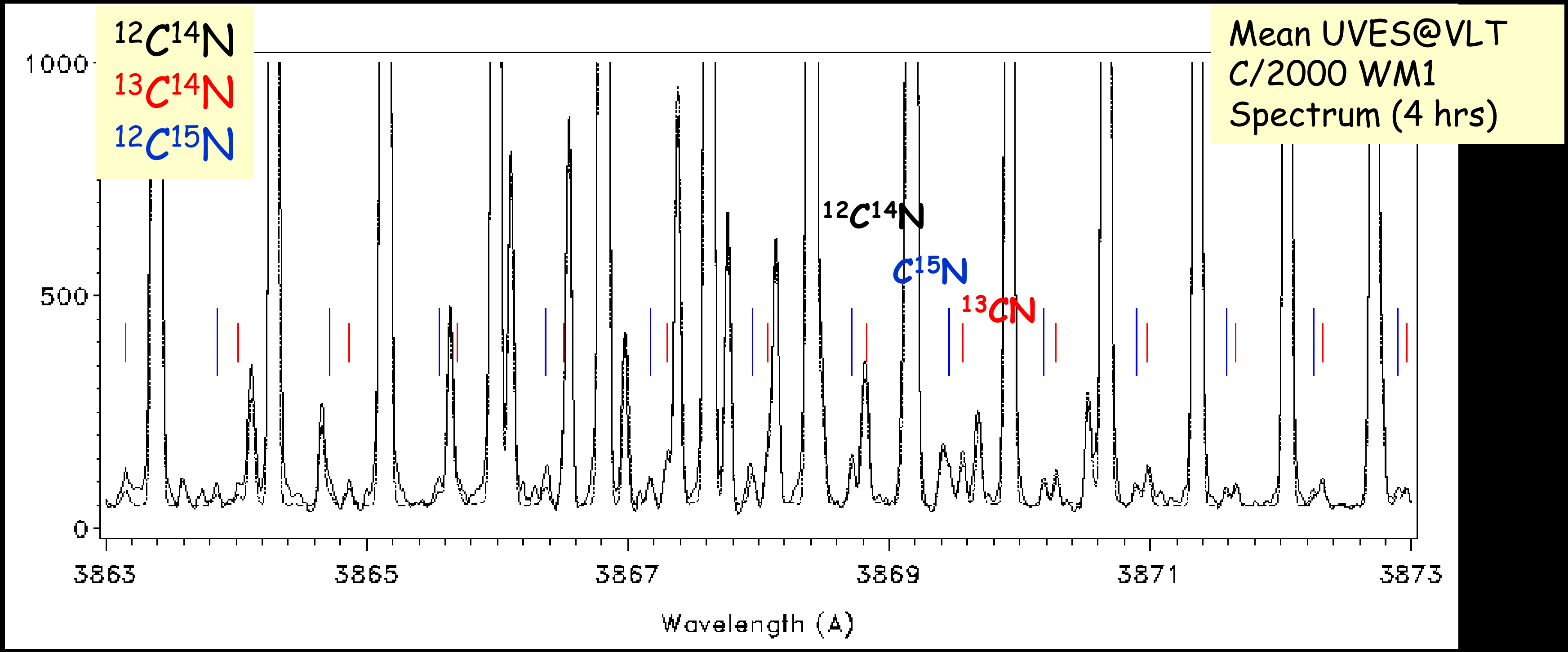
CN is a mixture of: $^{12}C^{14}N$ + $^{13}C^{14}N$ + $^{12}C^{15}N$



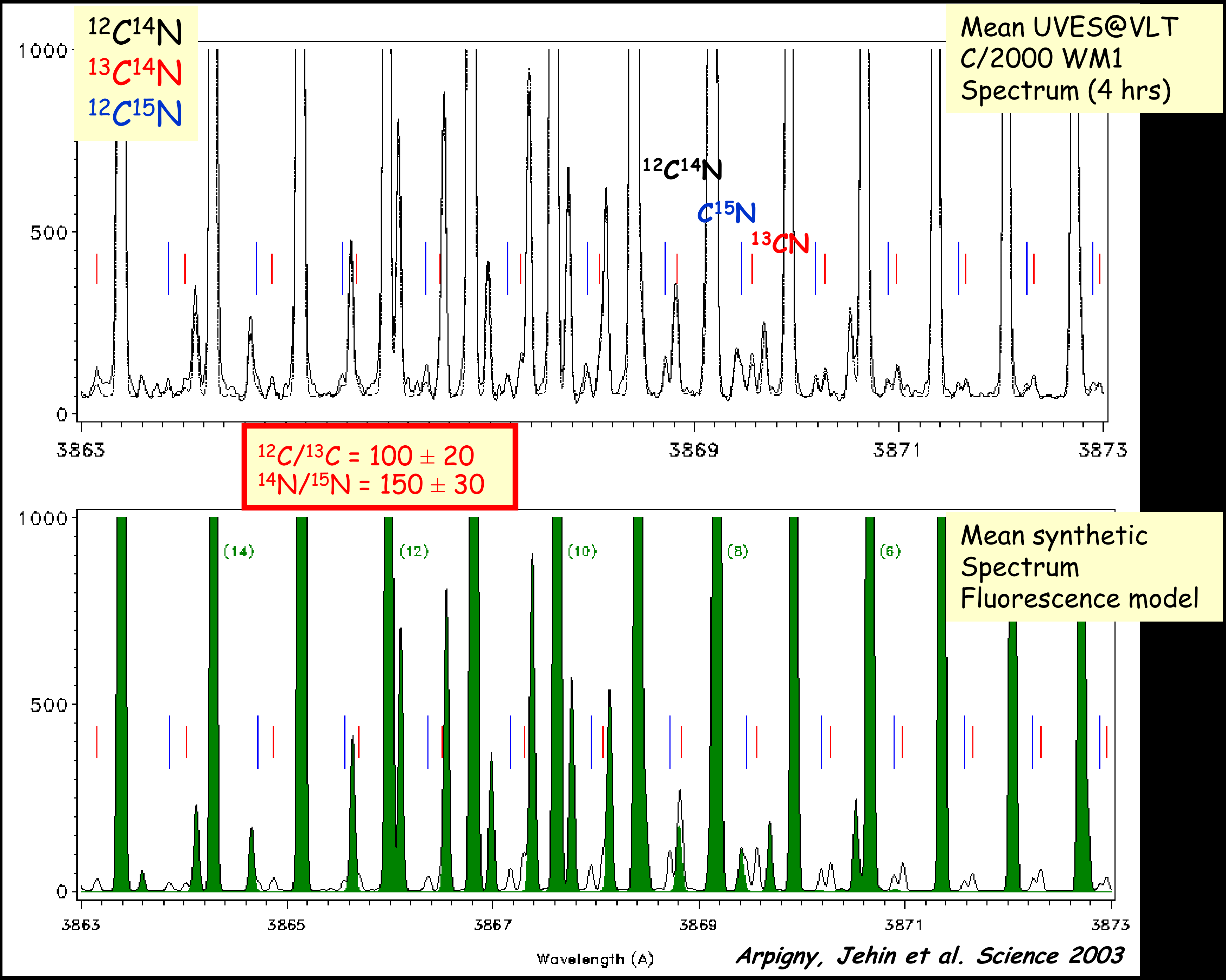
Note the isotopic shifts (Herzberg, 1950)

and the different intensity distributions (Swings effect, 1941)

- Synthetic spectra of the 3 different species are calculated for each observing circumstance (r_H, Δ, v_r, v_Δ)
- Improved Fluorescence model <u>Zucconi & Festou, 1985</u>
- They are convolved with a gaussian profile yielding the same resolution as the corresponding observed spectra
- We fit the CN observed spectrum with a linear combination of the synthetic spectra of the 3 species



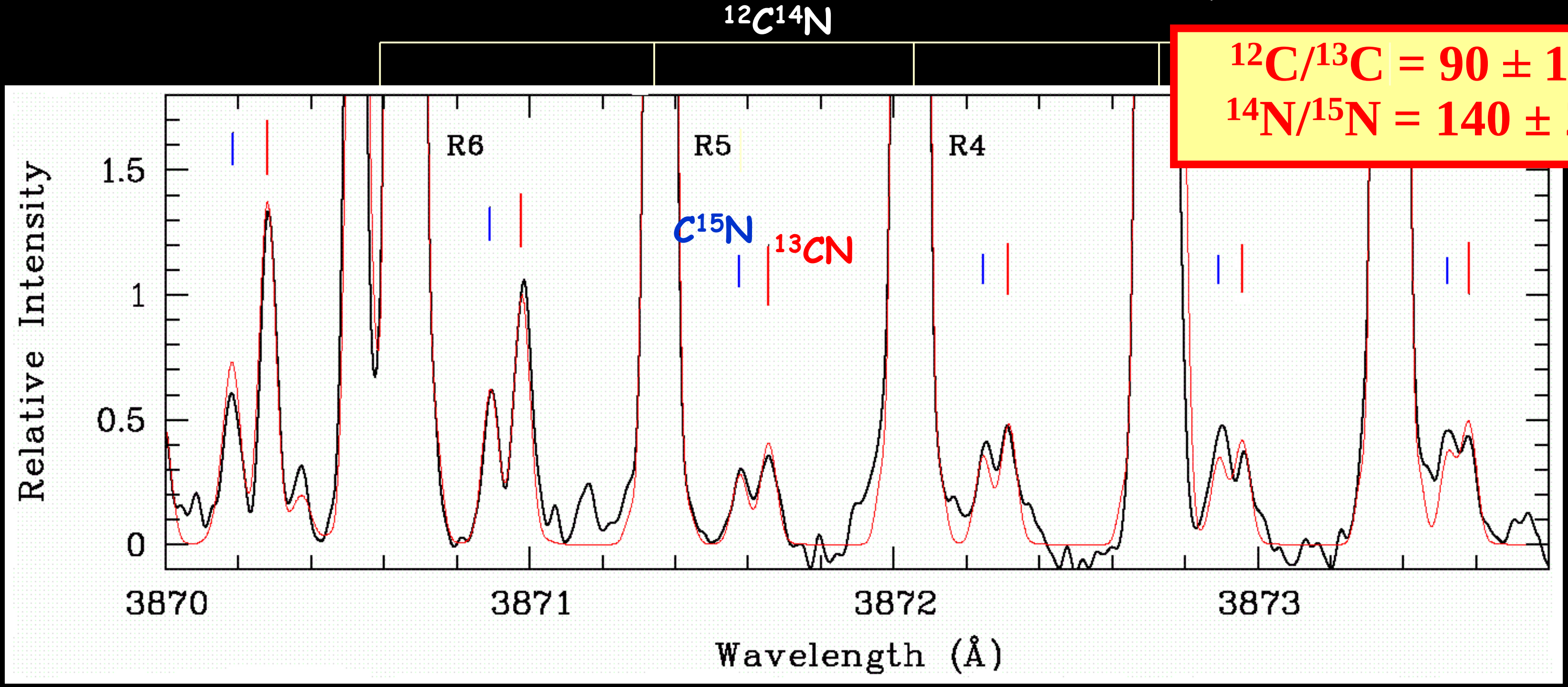
$^{12}C^{14}N$
$^{13}C^{14}N$
$^{12}C^{15}N$
Mean UVES@VLT
C/2000 WM1
Spectrum (4 hrs)
$^{12}C^{14}N$
$C^{15}N$
^{13}CN
1000
500
0
3863
3865
3867
3869
3871
3873
Wavelength (A)



$^{12}C^{14}N$
$^{13}C^{14}N$
$^{12}C^{15}N$
Mean UVES@VLT
C/2000 WM1
Spectrum (4 hrs)
$^{12}C^{14}N$
$C^{15}N$
^{13}CN
1000
500
0
3863
3869
3871
3873
$^{12}C/^{13}C = 100 \pm 20$
$^{14}N/^{15}N = 150 \pm 30$
(14)
(12)
(10)
(8)
(6)
Mean synthetic
Spectrum
Fluorescence model
3865
3867
Wavelength (A)
Arpigny, Jehin et al. Science 2003

The first C and N ratios in a Jupiter Family Comet 88P/Howell :

Hutsemékers et al. A&A 2005

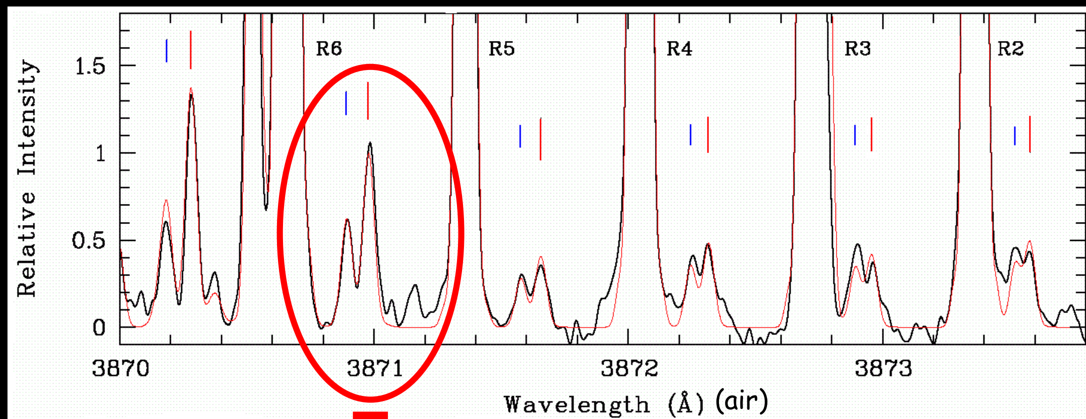


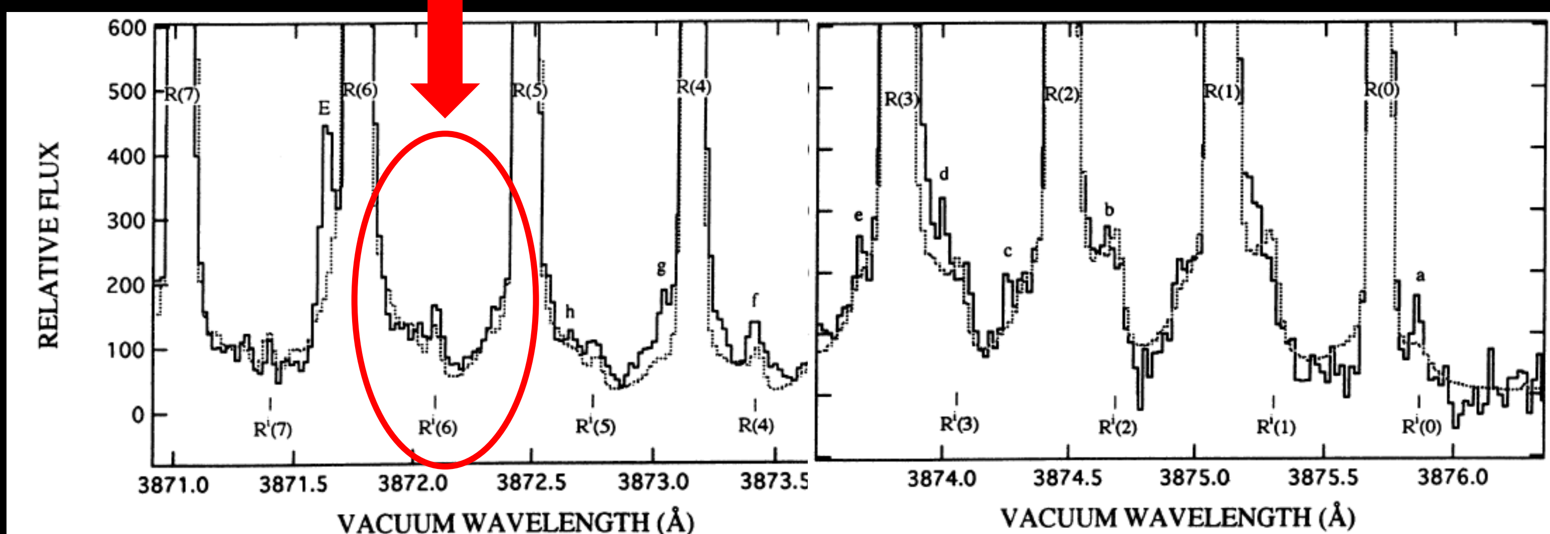
$^{12}C/^{13}C = 90 \pm 15$
$^{14}N/^{15}N = 140 \pm 20$

A section of the 12h UVES spectrum of the CN (0,0) violet band in comet 88P/Howell (m_r~10.0)

Data quality improvement with UVES + VLT !

88P/Howell (UVES @ 8m VLT 12hrs 2004)





1P/Halley (4m telescope 4hrs), Kleine et al. 1995

15 years of ^{12}CN/^{13}CN and C^{14}N/C^{15}N measurements

Comet	Type	R_h (au)	$^{12}C/^{13}C$	$^{14}N/^{15}N$	Instrument	Ref.
122P/de Vico	HTC	0.66	90±10	145±20	2DCoudé	2
C/1995 O1 (Hale-Bopp)	OCC	0.92	90±20	150±30	2DCoudé, SOFIN	1,3
C/1999 S4 (LINEAR)	Split OCC	0.88	90±30	150±50	2DCoudé	4
C/1999 T1 (McNaught-Hartley)	OCC	1.35	80±20	160±50	2DCoudé	
C/2000 WM1 (LINEAR)	OCC	1.21	100±20	150±30	UVES	1
153P/Ikeya-Zhang	HTC	0.92	80±30	140±50	2DCoudé	2
C/2002 V1 (NEAT)	OCC	1.20	100±20	160±35	UVES	
C/2002 X5 (Kudo-Fujikawa)	OCC	0.71	90±20	130±20	UVES	
C/2002 Y1 (Juels-Holvorcem)	OCC	1.15	90±20	150±35	UVES	
C/2002 T7 (LINEAR)	OCC	0.70	85±20	160±25	UVES	
C/2001 Q4 (NEAT)	OCC	0.98	90±15	135±20	UVES	3
C/2003 K4 (LINEAR)	OCC	1.21	90±20	145±25	UVES	3
88P/Howell	JFC	1.41	90±15	140±20	UVES	4
9P/Tempel 1 (pre-impact)	JFC	1.51	95±15	145±20	UVES	5
(impact + 1-4 hours)	JFC	1.51	110±20	170±35	Keck I	5
C/2006 M4 (SWAN)	OCC	0.99	95±25	145±50	2DCoudé	
73P/Schwassmann-Wachmann C	Split JFC	0.95	100±20	220±40	UVES	6
B	Split JFC	0.95	100±30	210±50	UVES	6
17P/Holmes	Outburst JFC	2.46	90±20	165±40	2DCoudé + KeckI	7
8P/Tuttle	HTC	1.03	90±20	150±30	UVES	8
103P/Hartley 2 (EPOXI NASA)	JFC	1.06	95±15	155±25	UVES	9

References : [1] Arpigny et al. Science 2003, [2] Jehin et al. 2004, [3] Manfroid et al. A&A 2005, [4] Hutsemékers et al. A&A 2005, [5] Jehin et al. ApJ 2006, [6] Jehin et al. ACM 2008, [7] Bockelée et al. 2008 ApJ, [8] Bockelée et al. ACM 2008 #8190, [9] Jehin et al. 11

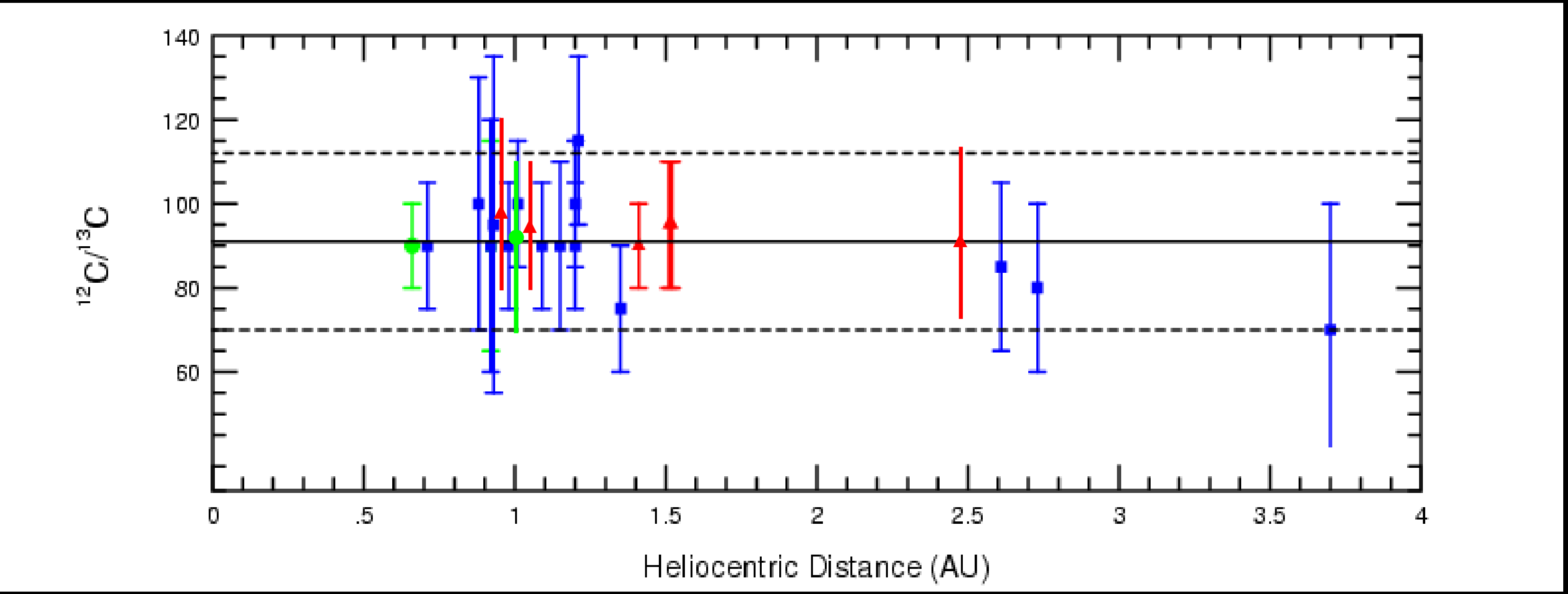
$^{12}CN/^{13}CN$ with heliocentric distance

Jehin et al. ESLAB 2016

- ■ OCC = Oort Could Comets (11)
- ▲ JFC = Jupiter Family Comets (5)
- ● HT = Halley type (3)

$^{12}C/^{13}C = 91.0 \pm 3.6$

Sun = Earth = 89[a] and ISM= 77[b]



Conclusion : the C ratio in comets is solar/terrestrial and minimum isotopic fractionation of C in the pre-solar molecular cloud and the solar nebula.

References : [a] Anders et Grevesse 1989; [b] Dahmen et al. 1995

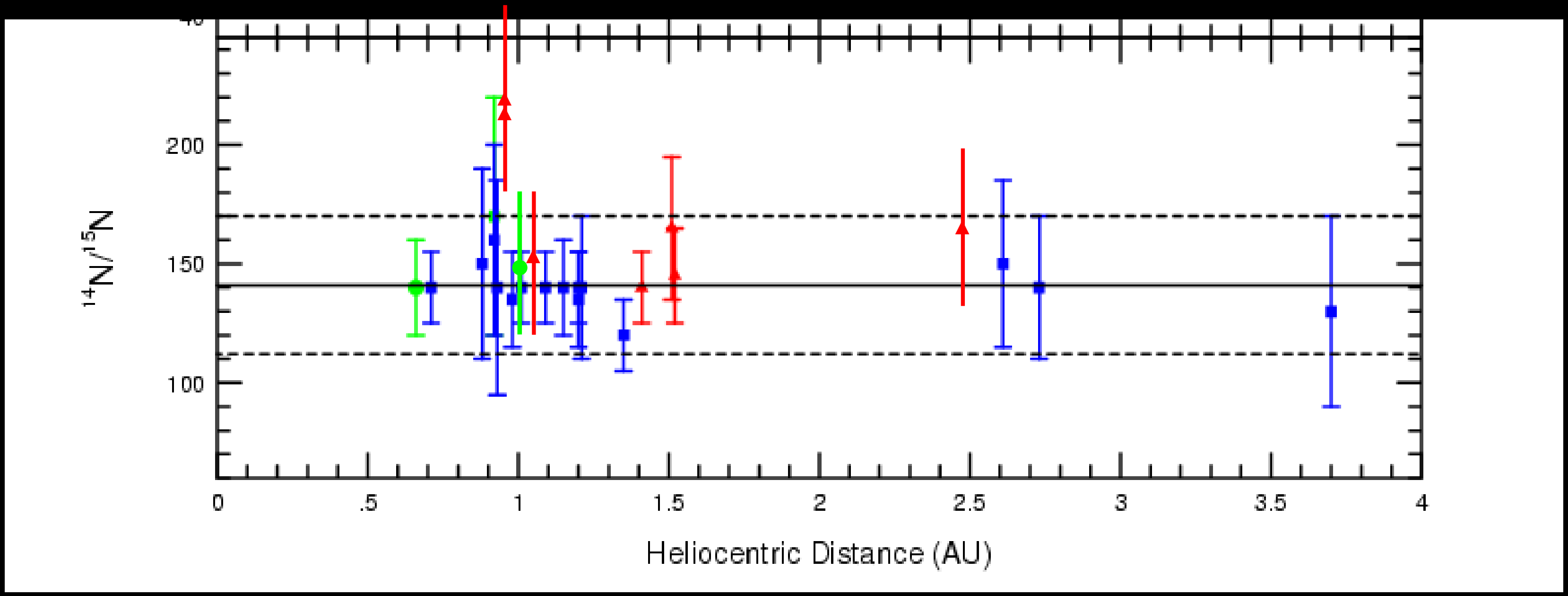
$C^{14}N/C^{15}N$ with heliocentric distance

Jehin et al. ESLAB 2016

- ■ OCC = Oort Could Comets (11)
- ▲ JFC = Jupiter Family Comets (5)
- ● HT = Halley type (3)

$^{14}N/^{15}N = 147.8 \pm 5.7$

Sun= 441±5[a] and ISM= 450[b] Earth = 272

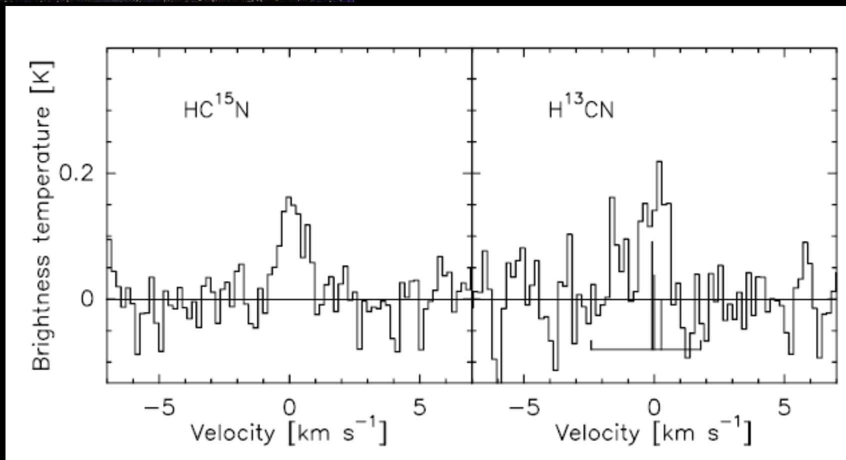


<u>Conclusion</u> : Isotopic anomaly, fractionation of N-bearing volatiles in the pre-solar cloud ? ^{15}N x2-10 by ion-molecule (N_2) and gas-grain reactions in very cold (~10K) ISM (Terzevia and Herbst 2000, Rodgers & Charnley 2008) , Self-shielding during photodissociation of N_2 in solar nebula (Clayton 2009)

<u>References</u> : [b] Marty el al. 2011; [b] Wielen (1997)

The $^{14}N/^{15}N$ ratio from HCN and CN in 17P/Holmes

Bockelée-Morvan et al. (2008)



IRAM Spectra of the J=3-2 lines (27-28 Oct. 07)

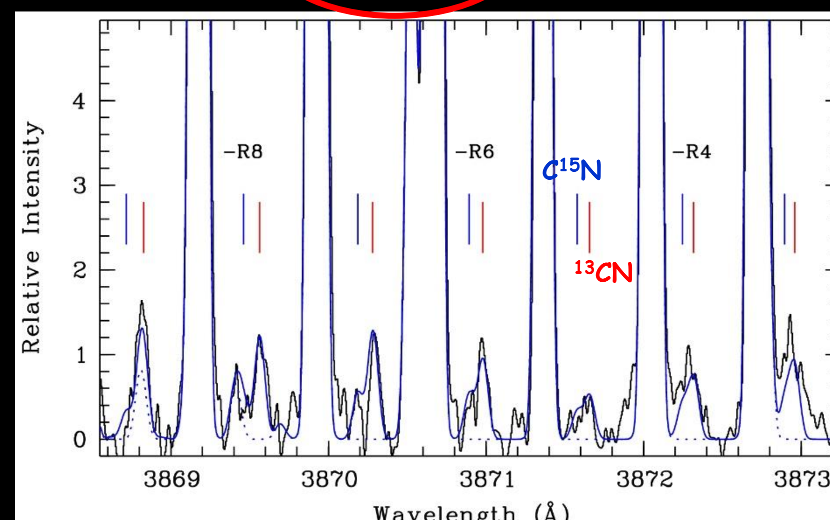
- $H^{12}CN/H^{13}CN$ = 114 ± 26
- $HC^{14}N/HC^{15}N$ = 139 ± 26

- $^{12}CN/^{13}CN$ = 90 ± 20
- $C^{14}N/C^{15}N$ = 165 ± 40

New analysis of Hale-Bopp data :

- $H^{12}CN/H^{13}CN$ = 94 ± 8
- $HC^{14}N/HC^{15}N$ = [138-239]

(old value ~ 325 ± 75) [1,2]



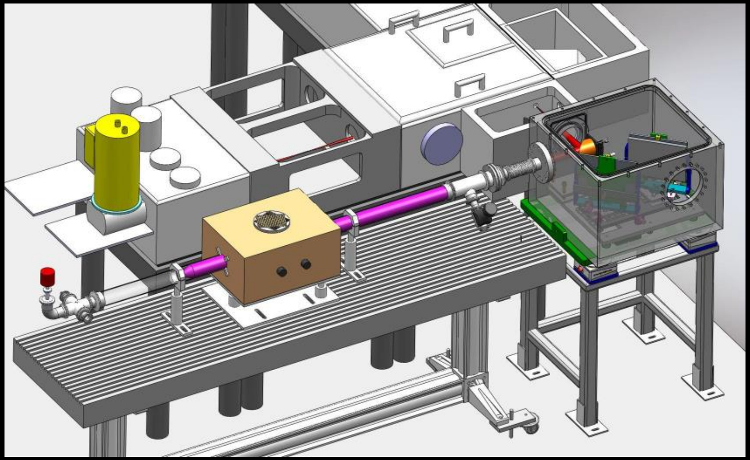
[1] Jewitt el al. 1997, [2] Ziurys et al. 1999

The search for $^{15}NH_2$

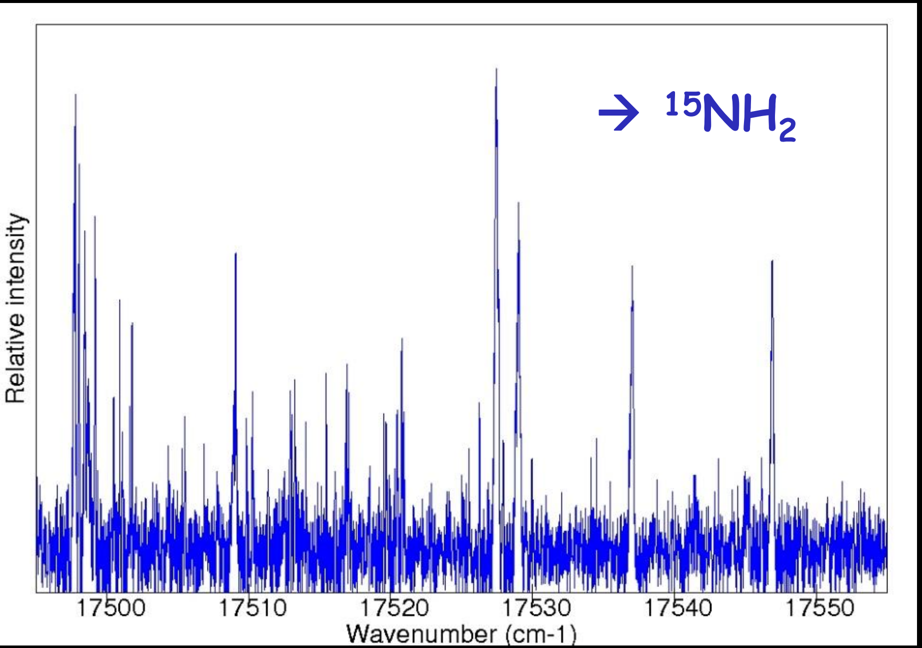
Rousselot et al. 2013

Measuring $^{14}N/^{15}N$ in an other N reservoir : NH_3

→ many bright $^{14}NH_2$ lines but no precise $^{15}NH_2$ lines list !



Laboratory experiment performed with AILES beamline of synchrotron SOLEIL near Paris.

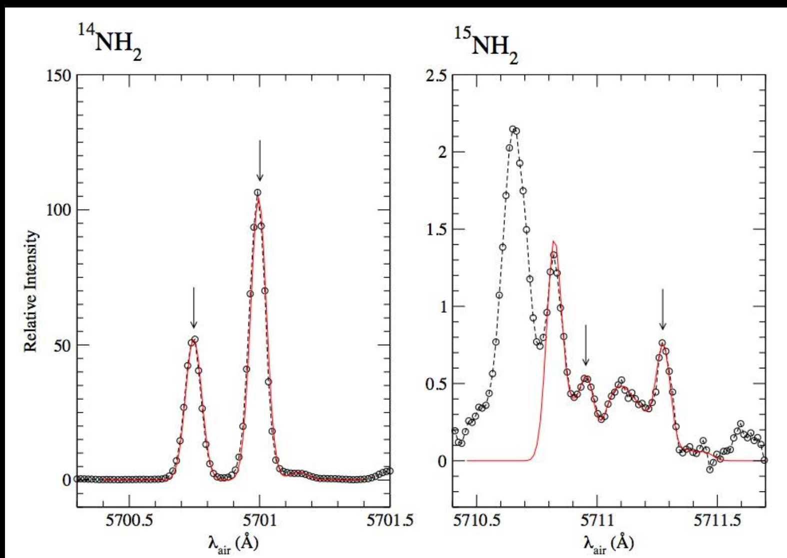


→ Detailed analysis of FT spectra for identifying the $^{15}NH_2$ lines mixed with $^{15}N_2$ and H_2 emission lines and measuring their wavelengths.

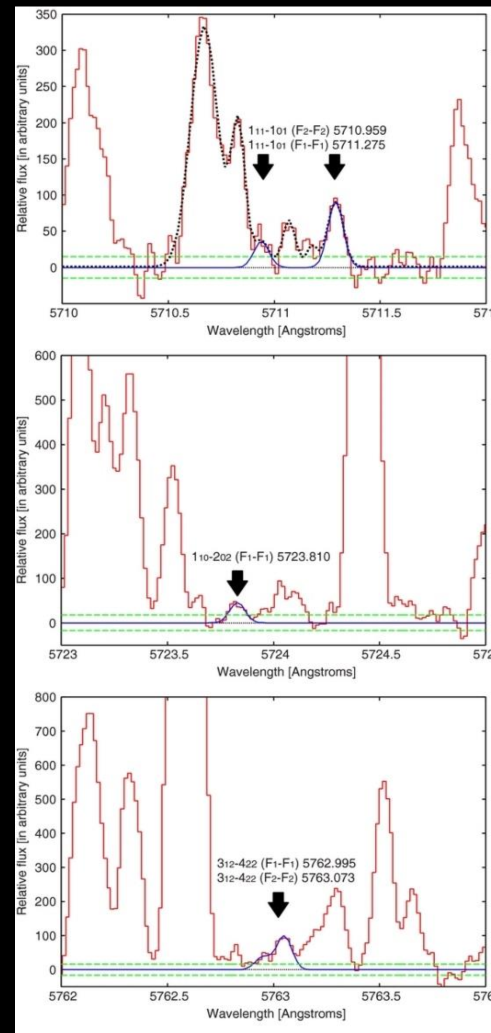
The search for $^{15}NH_2$

Rousselot et al. (2013) and Shinnaka et al. (2014)

« Master » comet spectrum



$^{14}NH_2/^{15}NH_2 \approx 130$

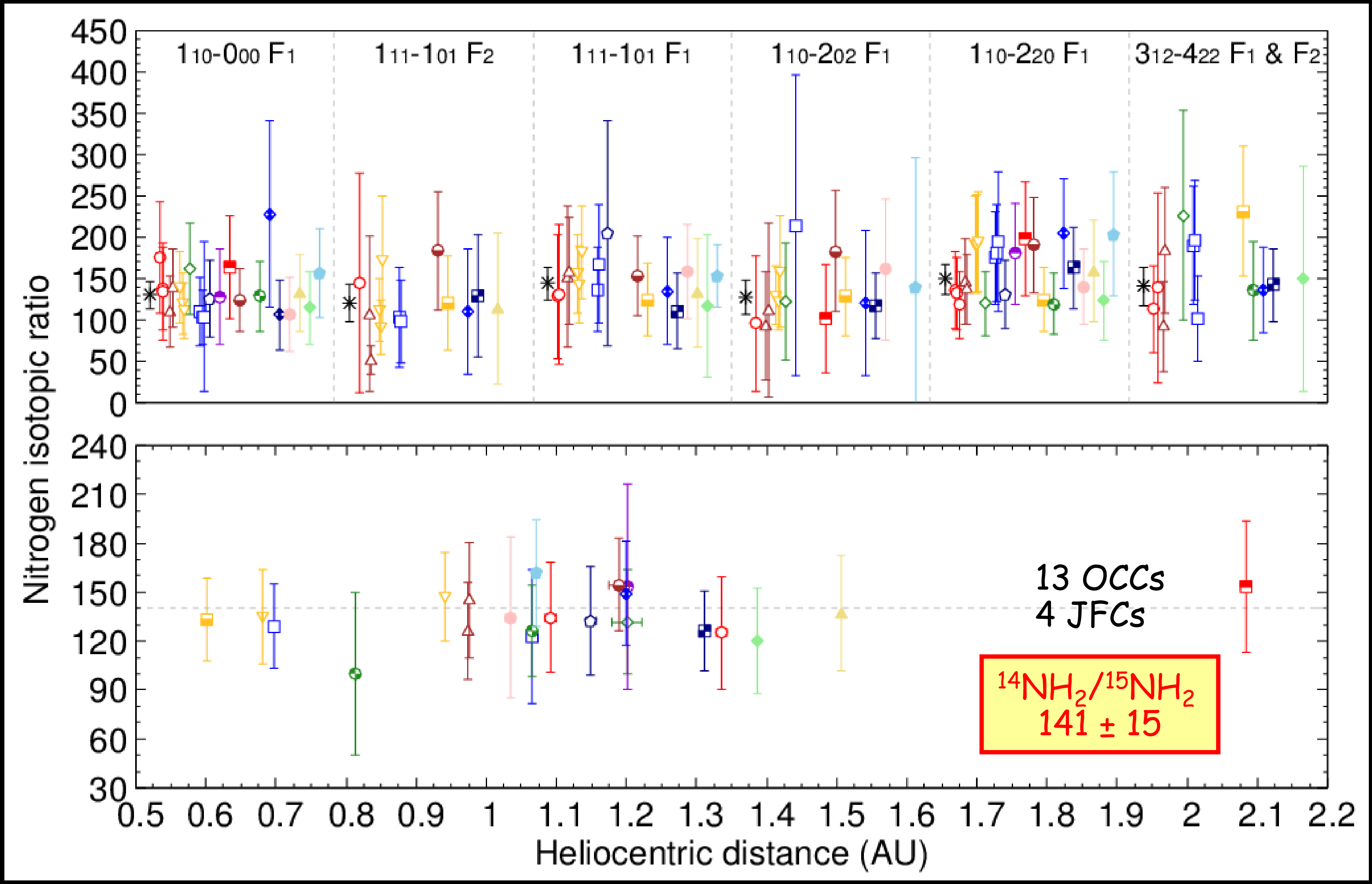


<u>Confirmation</u> :
Bright comet C/2012 S1 (ISON) in outburst with HDF spectro at Subaru

$^{14}NH_2/^{15}NH_2$
139 ± 38

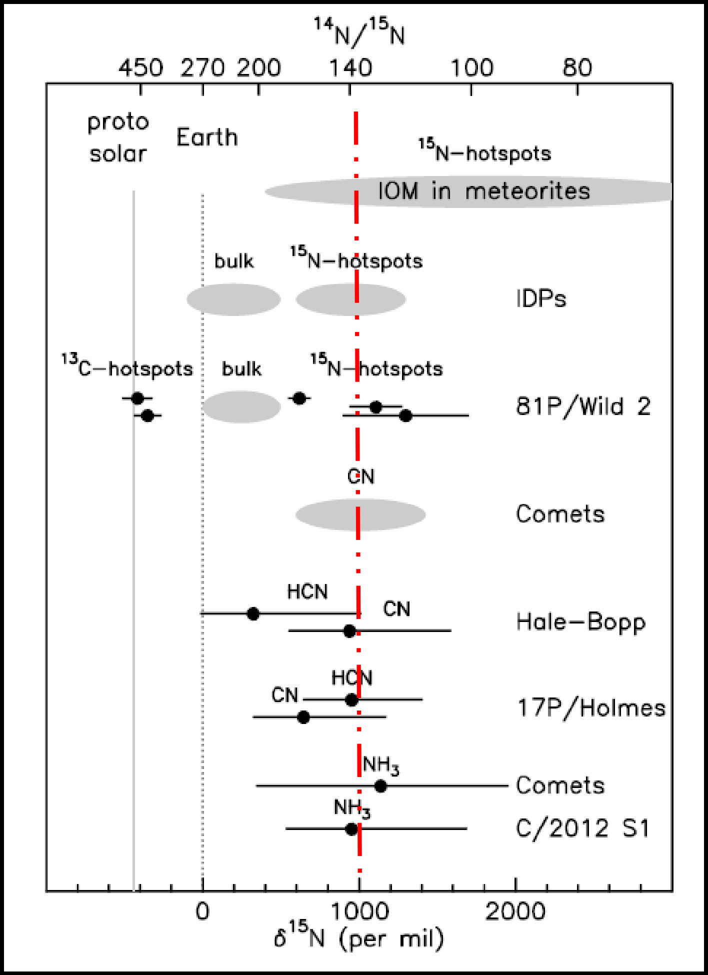
The search for $^{15}NH_2$

Shinnaka et al. 2016



High ^{15}N-fractionation in cometary ices

^{14}N/^{15}N in primitive solar system material



Bockelée-Morvan et al. 2015

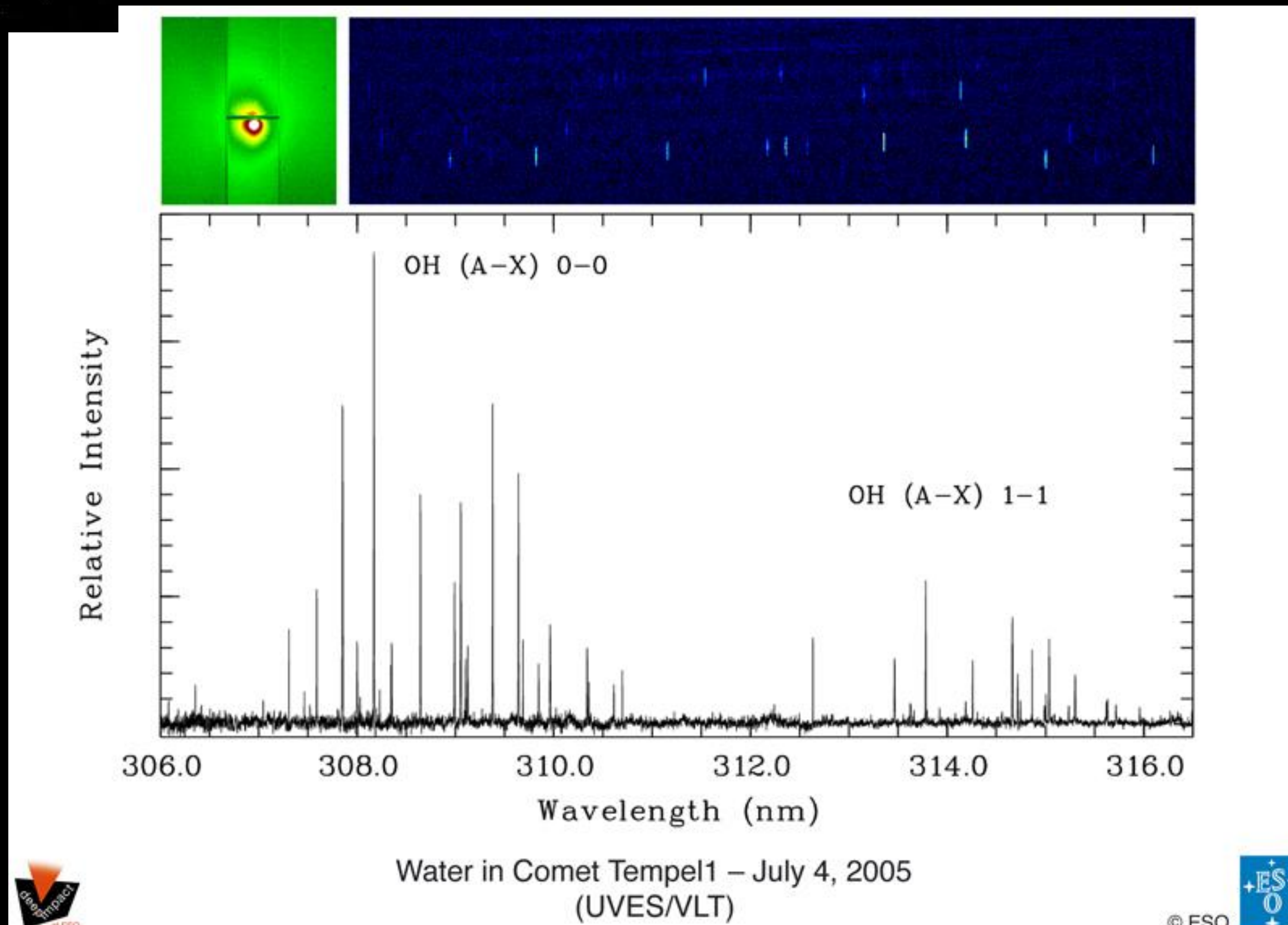
- ❑ $HC^{14}N/HC^{15}N$ = $^{14}NH_3/^{15}NH_3$ ≈ 145
  and ≈ 150 in N_2 in 67P (Altwegg 2019) !
- ❑ ≠ NH_3 in Jupiter (450) 3x
- ❑ ≠ N_2 in Earth (272) 2x
- ❑ ≈ N_2 in Titan (150) → common origin ?

<u>Conclusions</u> :
→cometary ices are made of gas uniformly enriched in ^{15}N
→ High ^{15}N-fractionation from self-shielding effect of N_2 in early SS (CO_2)
→ vertical mixing in the solar nebula
→3 distinct isotopic reservoirs : the protosolar nebula, the inner solar system and cometary ices

See Rubin et al. 2020 for more

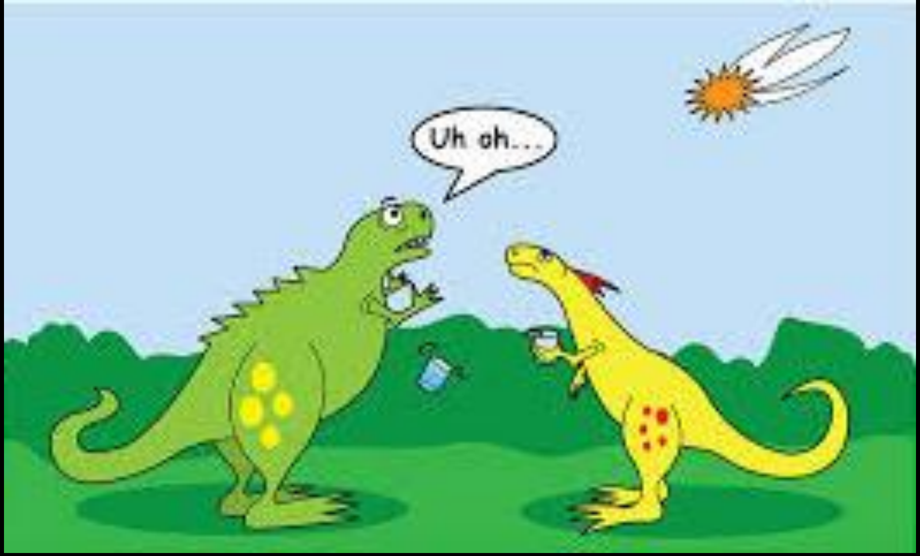
Tracing water in comets thanks to UVES

$$H_2O + h\nu \rightarrow OH + H$$



Water in Comet Tempel1 – July 4, 2005
(UVES/VLT)

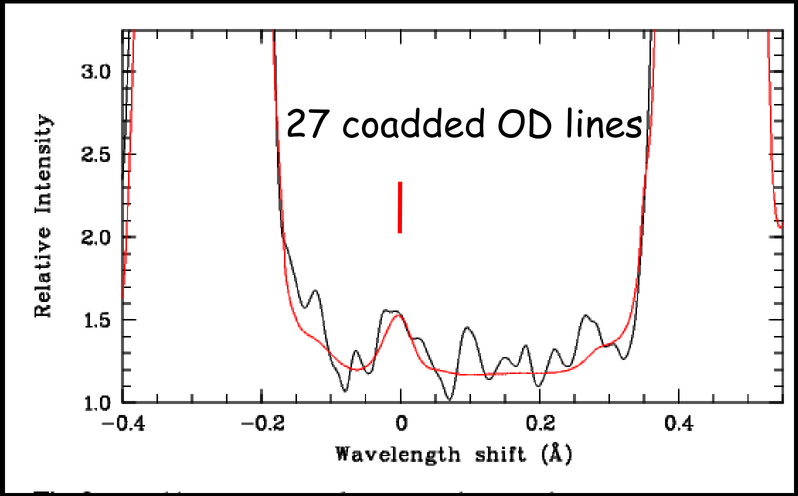
Origin of water on Earth (HDO/H_2O) ?



OD/OH in C/2002 T7 (LINEAR)

from OH (A-X) at 309nm (UVES R=80.000)

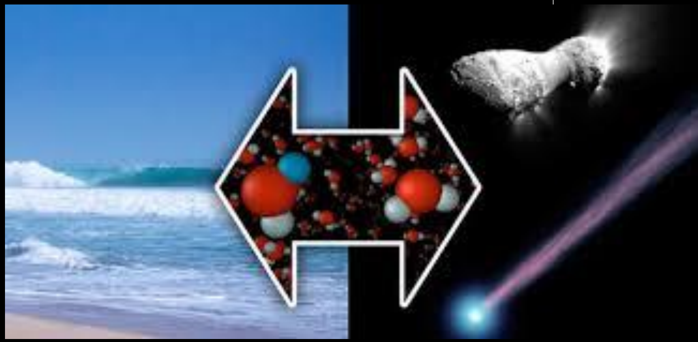
R_h=0.68 UA m_r=5.0 $Q(H_2O)=10^{29}$/s

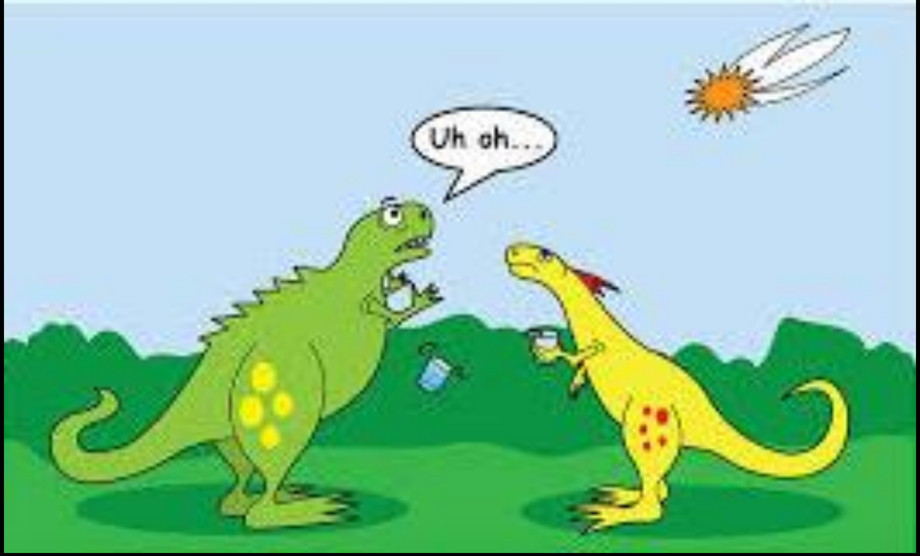


D/H = (2.5 ± 0.7) 10^{-4}

Hutsemékers et al. 2008

Origin of water on Earth ?





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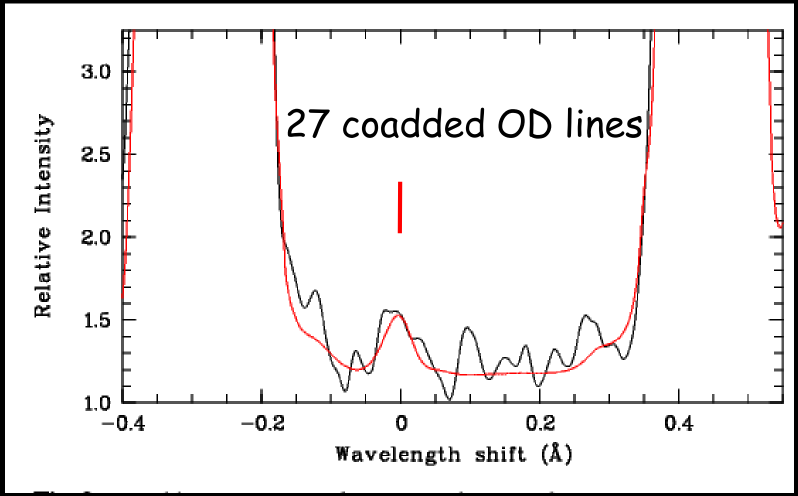
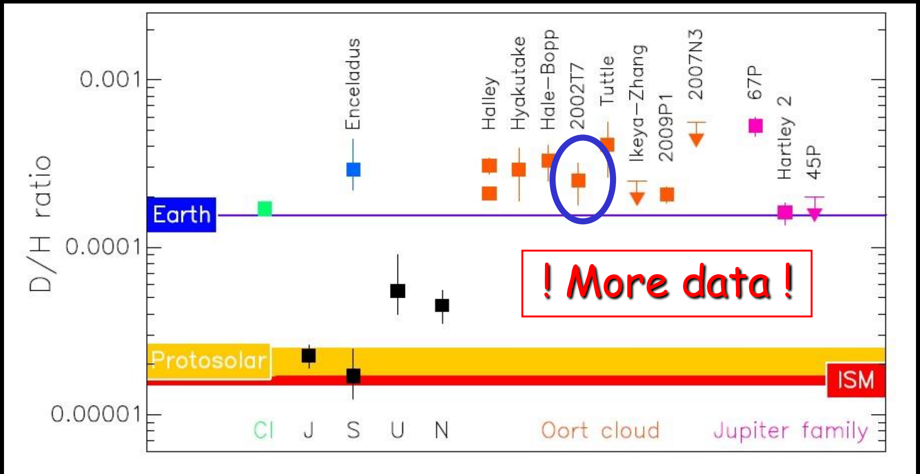




$D/H = (2.5 \pm 0.7)\ 10^{-4}$

Hutsemékers et al. 2008

Bockelée-Morvan et al. 2015

Forbidden Oxygen lines [OI] in comets

Decock et al. 2013, 2015

Energy-level for [OI] lines

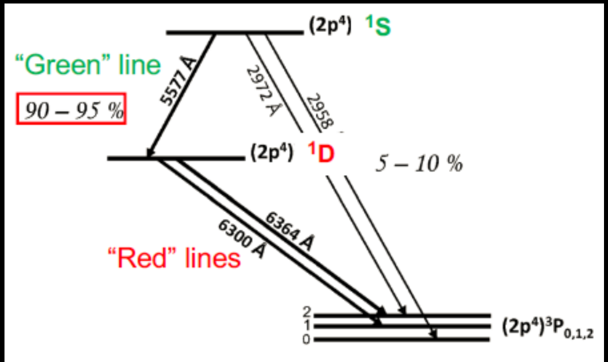
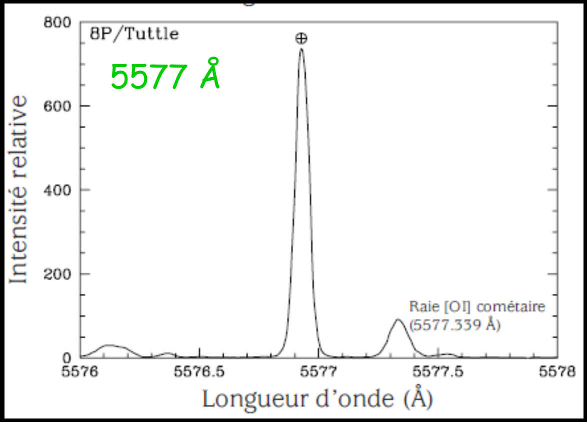
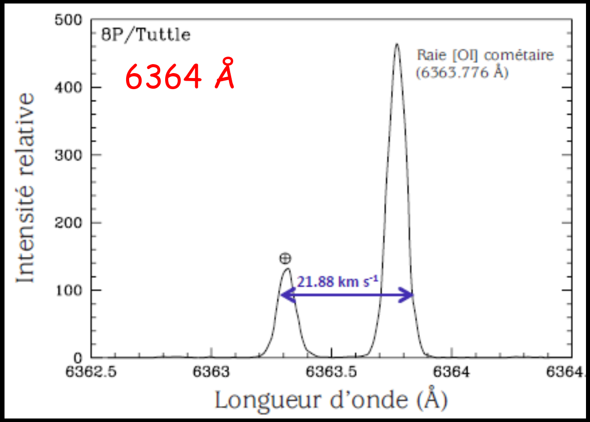


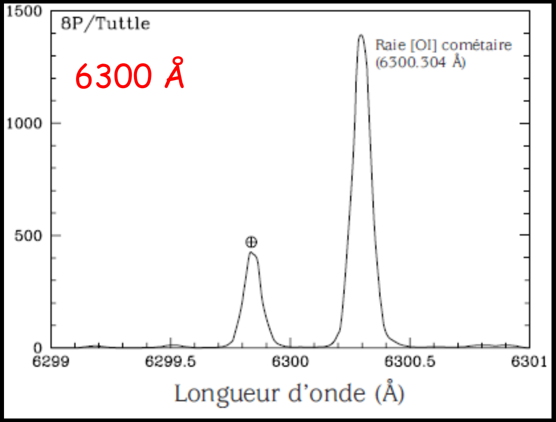
Fig. 1. Energy-level diagram for [OI] lines.

Forbidden oxygen emission lines arise from atomic oxygen in meta-stable states of 1S and 1D, excited by chemical reactions

The three [OI] lines in 1h UVES spectrum of comet 8P/Tuttle







The comet lines are Doppler shifted with the terrestrial auroral lines (high resolution needed !)

Forbidden Oxygen lines [OI] in comets

Decock et al. 2013, 2015

Energy-level for [OI] lines

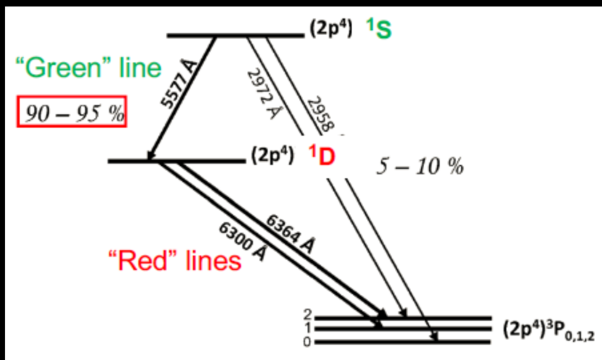


Fig. 1. Energy-level diagram for [OI] lines.

$H_2O + h\nu \xrightarrow{8.0\ 10^{-7}} H_2 + O^*(^1D)$

$H_2O + h\nu \xrightarrow{6.4\ 10^{-8}} H_2 + O^*(^1S)$

$\frac{(^1S)}{(^1D)}$ ~0.080

$CO_2 + h\nu \xrightarrow{1.2\ 10^{-6}} CO + O^*(^1D)$

$CO_2 + h\nu \xrightarrow{7.2\ 10^{-7}} CO + O^*(^1S)$

$\frac{(^1S)}{(^1D)}$ ~0.600

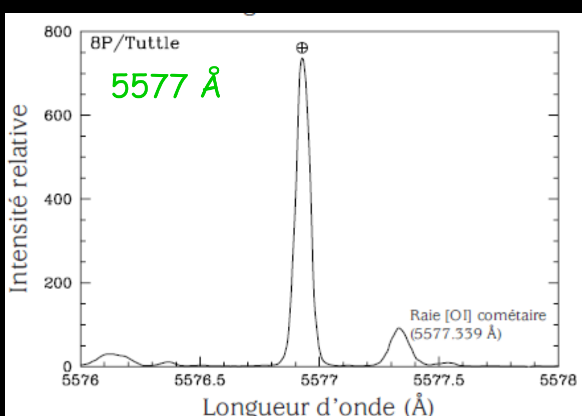
Bhardwaj et al. 2012

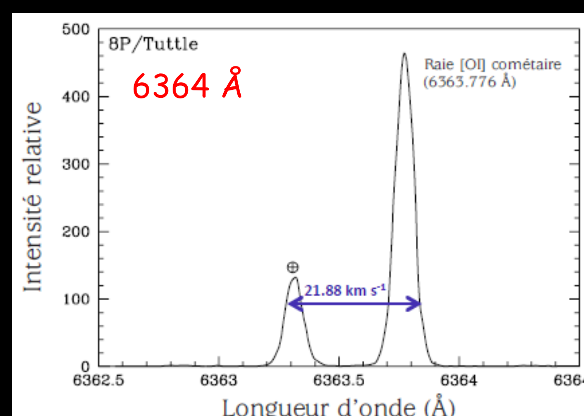
→ G/R ratio = $\frac{I_{5577}}{I_{6300}+I_{6364}}$

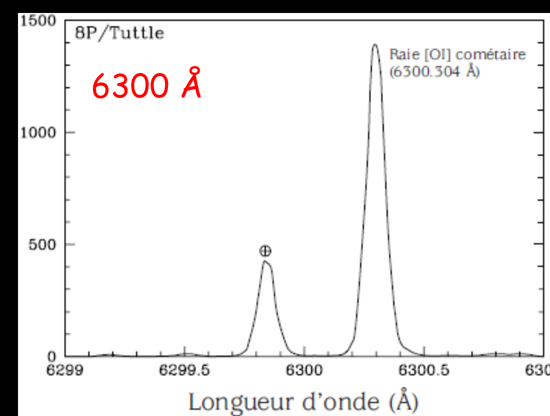
→ CO_2/H_2O

CO_2 only from space

The three [OI] lines in 1h UVES spectrum of comet 8P/Tuttle



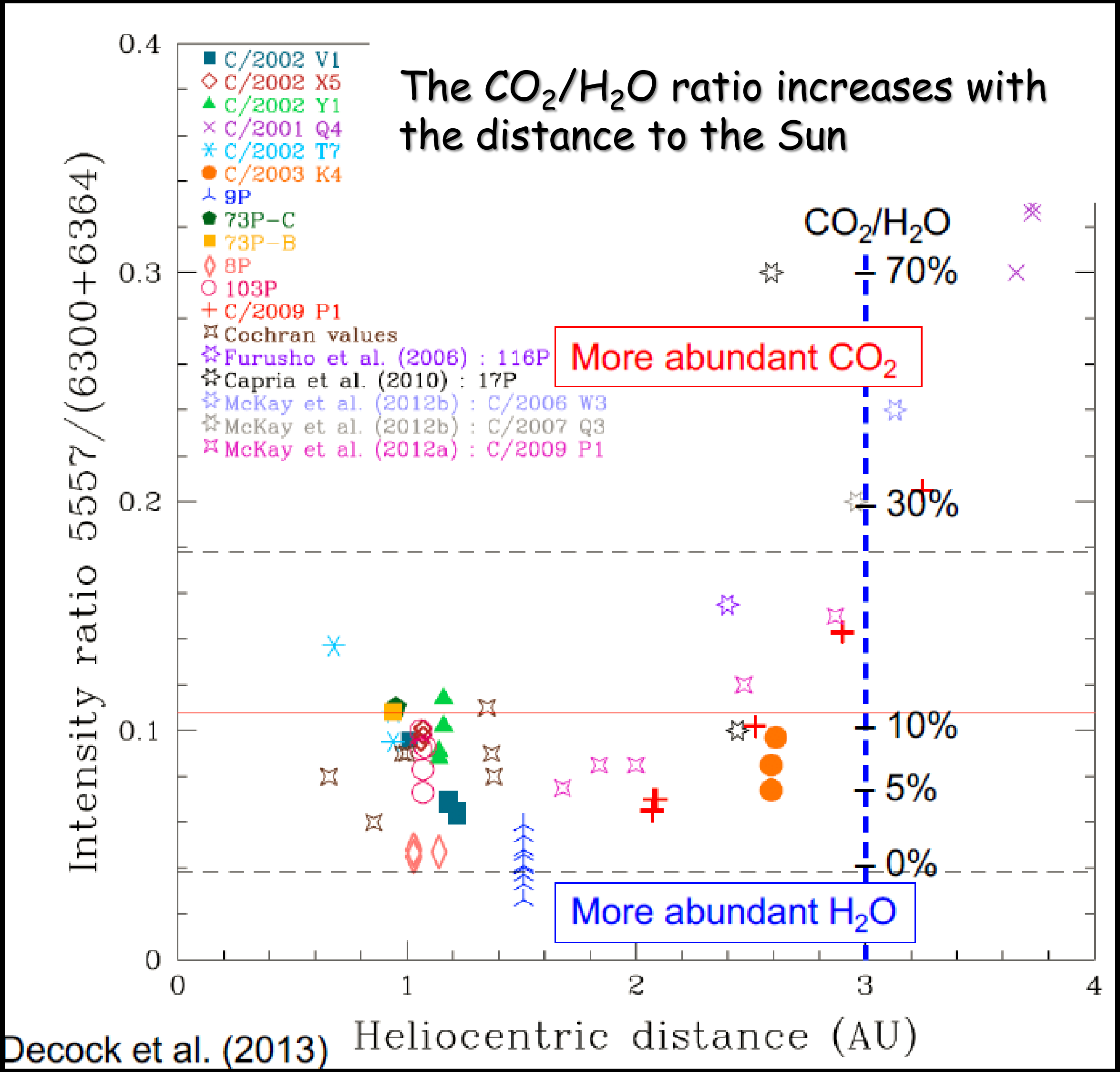




The comet lines are Doppler shifted with the terrestrial auroral lines (high resolution needed !)

Forbidden Oxygen lines [OI] in comets

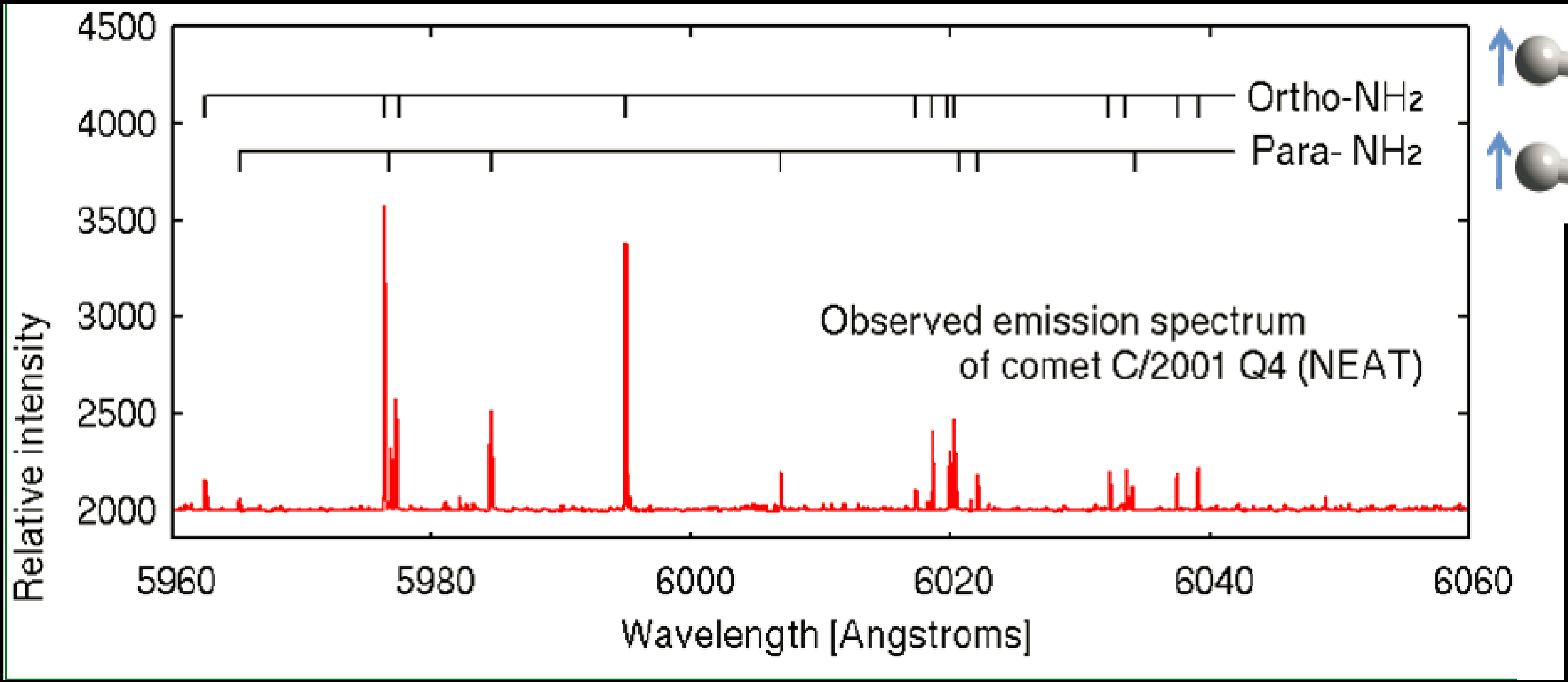
Decock et al. 2013, 2015

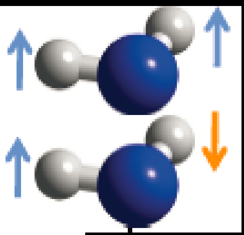


Ortho-to-Para Ratio (OPR) of NH_2 in comets

Shinnaka et al. 2016

Certain symmetric molecules comes in two states, ortho and para , which differ by their nuclear spin alignment
The OPR is characterized by a “spin Temperature”

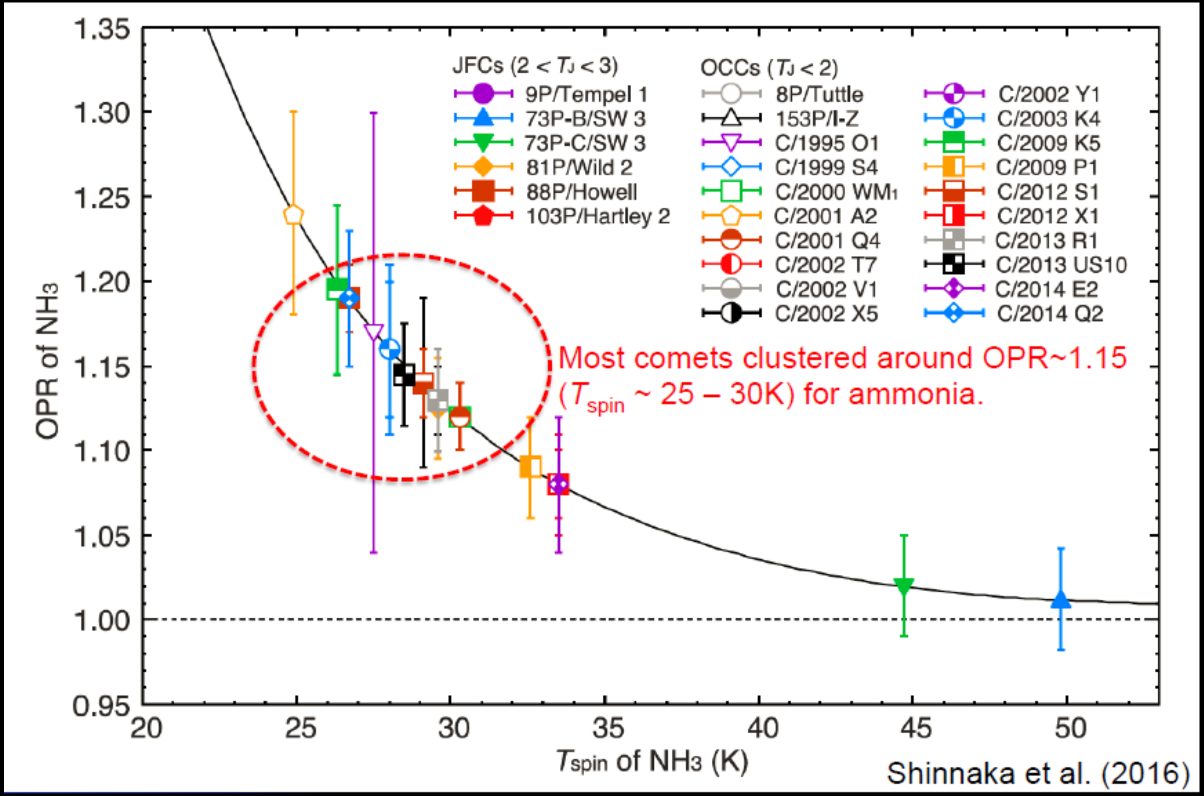




Ortho-to-Para Ratio (OPR) of ammonia in comets

Shinnaka et al. 2016

Is the Spin Temperature an old memory of comet formation ? (does not change in solid phase)

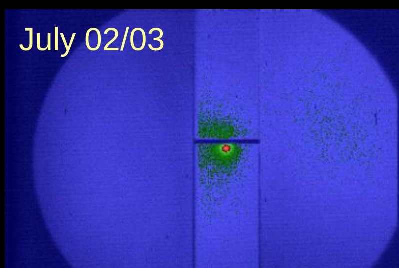


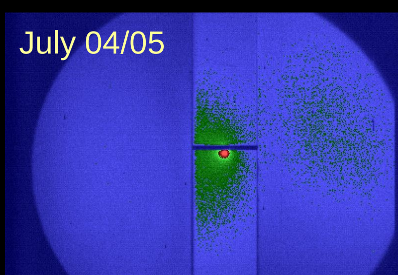
- does not depend on comet type
- does not change with distance to the Sun
- same $Spin_T$ for H_2O !

Challenged by laboratory measurements (Hama et al. 2016, 2018) !
Does it reflect some conditions in the coma ?

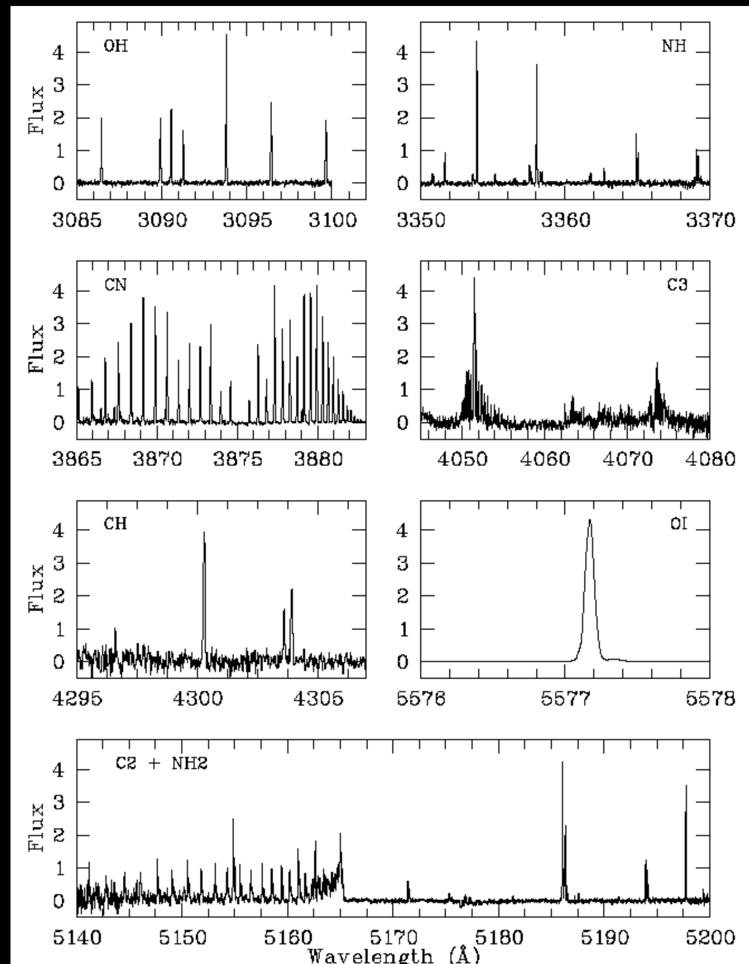
UVES and the NASA Deep Impact

Jehin et al. 2006, Manfroid et al. 2007





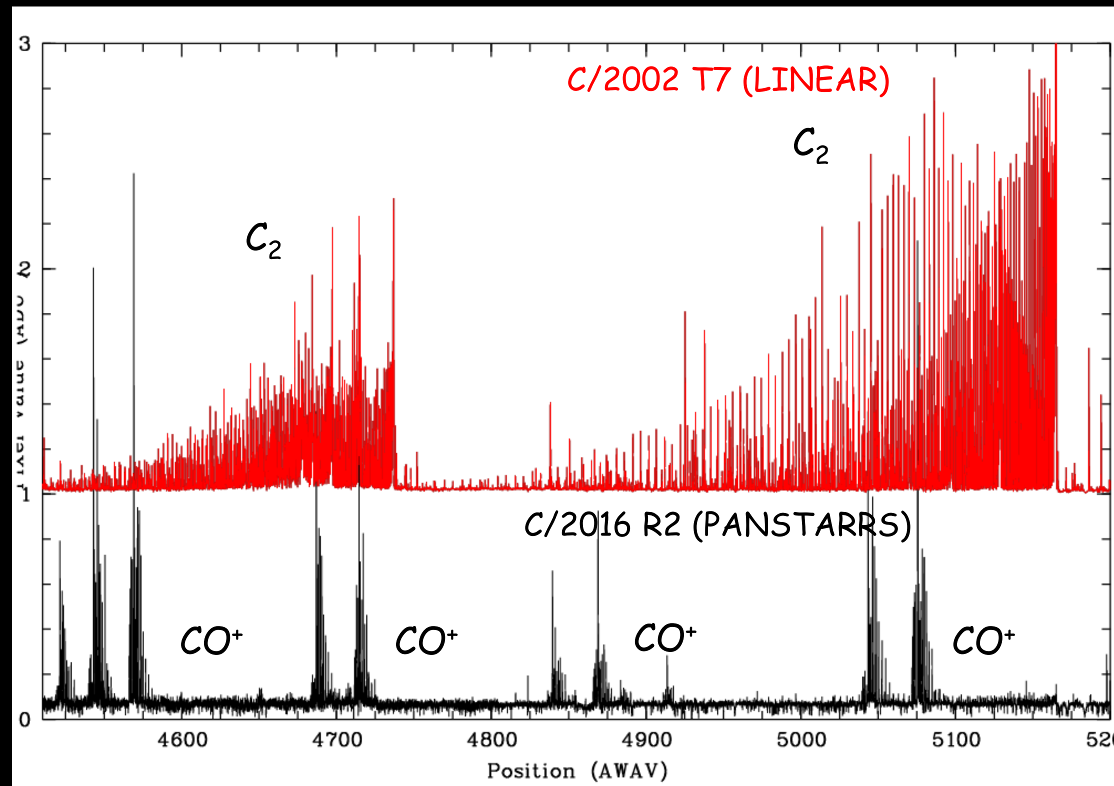
UVES Blue slit viewer 45”

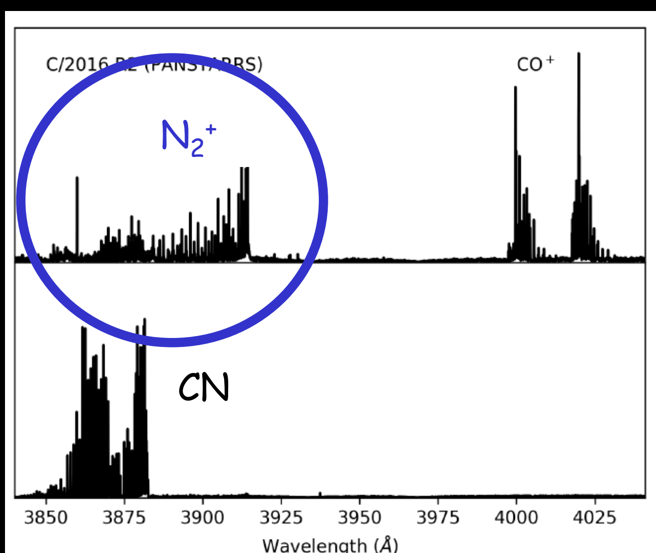


- The composition before and after impact is the same → nucleus/surface homogeneous material

The blue water poor comet C/2016 R2 (PANSTARRS)

Opitom et al. 2019, Jehin et al. 2019, Bhardwaj et al. 2020





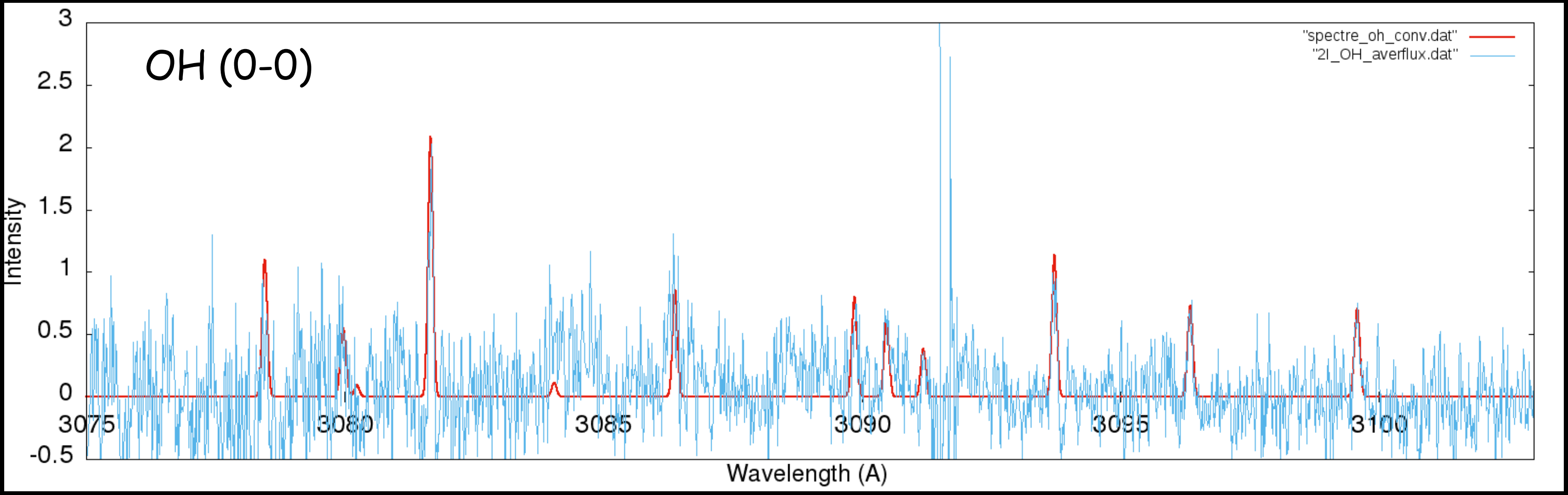
- ❑ A unique spectrum depleted in usual OH, CN, C_2, etc. bands, but rich on CO^+ and N_2^+ !

→ Pristine comet ? With hyper volatiles not processed ? Birthplace ?

The Interstellar comet 2I/Borisov… pushing UVES

Jehin et al. 2020 in prep

- 2x 6600s (24 and 26 Dec. 2019) ,
- slit 2.0", V~17.5 at r_h=2.05 au

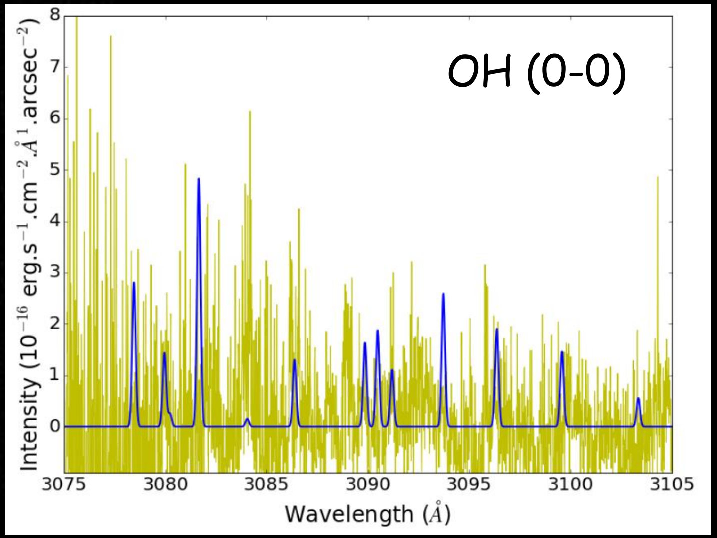


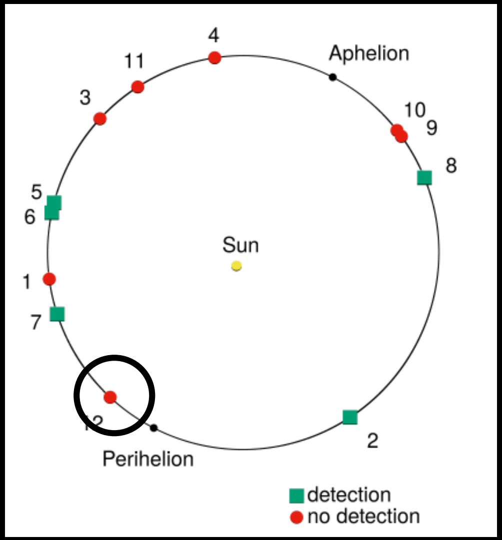
→ $Q(H_2O)$ = 2 E26 molec/s ~ 6,5 kg H_2O s^{-1}

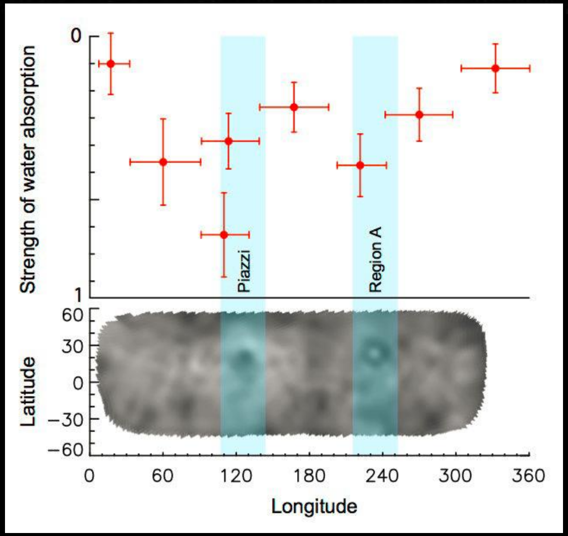
CO-rich from ALMA (Cordiner et al. Nature, 2020)

Looking for water escaping dwarf planet Ceres

Rousselot et al. 2011 and 2019



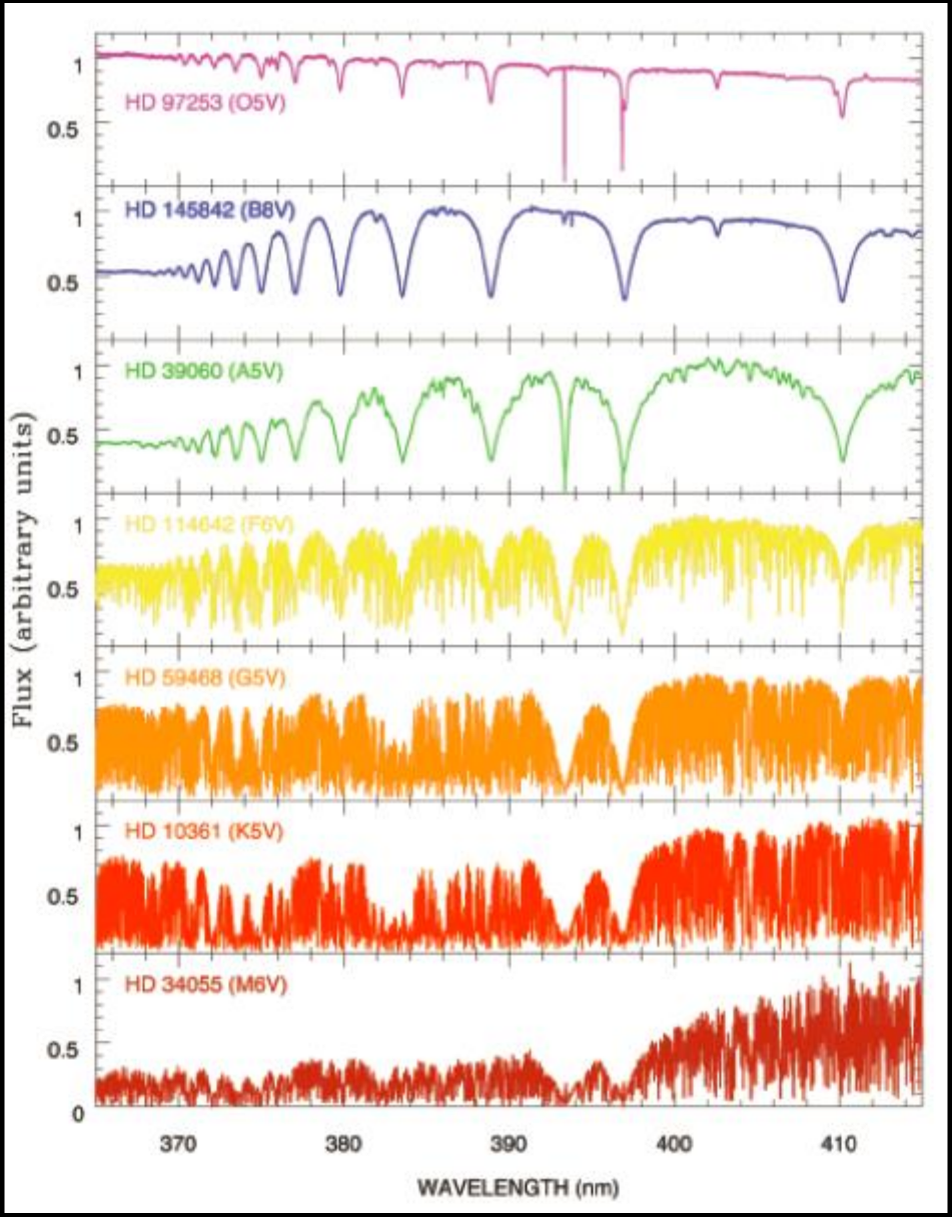




Herschel (far IR): water forms a exosphere (Küppers et al., 2014)

N	Date	Instrument	Water production rate (10^{26} molecules s^{-1})	Heliocentric distance (au)	Reference
1	14 Jan 1990	IUE+LWP	<0.53	2.64	A'Hearn & Feldman (1992)
2	29 May 1991	IUE+LWP	1.4	2.66	A'Hearn & Feldman (1992)
3	24 Oct 2007	VLT+UVES	<0.7	2.83	Rousselot et al. (2011)
4	23 Nov 2011	HSO+HIFI	<1.0 [a]	2.94	Küppers et al. (2014)
5	11 Oct 2012	HSO+HIFI	3–4 [a]	2.72	Küppers et al. (2014)
6	24 Oct 2012	HSO+HIFI	2.0 [a]	2.71	Küppers et al. (2014)
7	6 Mar 2013	HSO+HIFI	2.0	2.62	Küppers et al. (2014)
8	19 Jun 2015	Dawn+GRaND	3.0	2.93	Jia et al. (2017)
9	26 Aug 2015	HST+COS	<4	2.95	Roth et al. (2016)
10	3–7 Sep 2015	HST+STIS	<2.2	2.96	Roth (2018)
11	26 Oct 2016	HST+COS	<1.8	2.88	Roth (2018)
12	16 Feb 2018	VLT+UVES	<2	2.57	This work

The UVES Paranal Observatory Project (UVES POP)



http://www.eso.org/uvespop/
Bagnulo, Jehin, Ledoux et al. 2003, The Messenger

A Library of High-Resolution and high SNR Spectra of Stars across the Hertzsprung-Russell Diagram




UVES wish list

❑ Keep UVES running as long as possible !!
compare data on a long time

❑ Improve Near-UV sensitivity

❑ Polarimeter ?

❑ Pipeline working for all the modes (2D)

❑ Continue to improve the calibration plan (346 nm)

20TH ANNIVERSARY OF SCIENCE EXPLORATION WITH UVES