

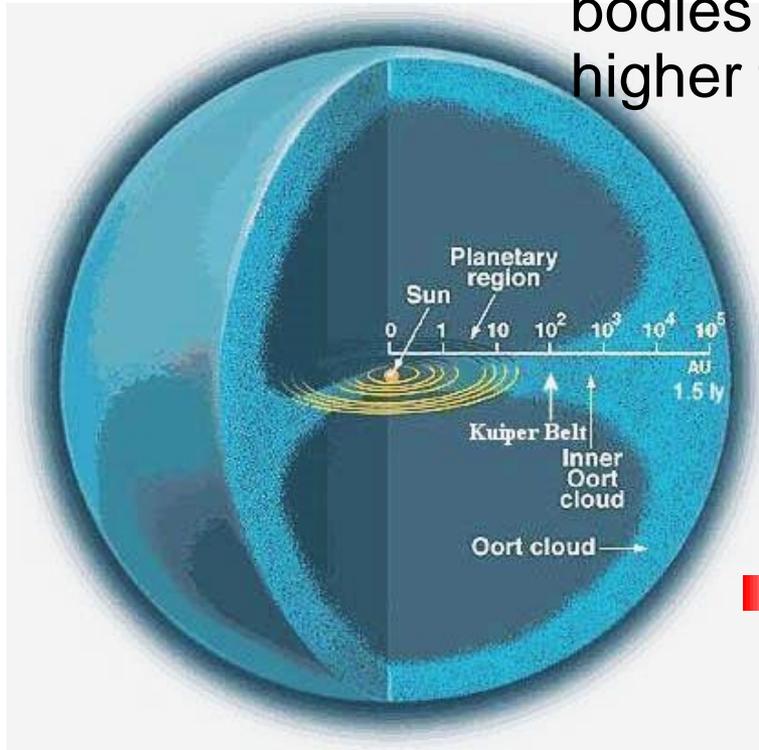
# Comets in UV

*Shustov B., Sachkov M., Savanov I.*



# Comets – major part of minor body population of the Solar System

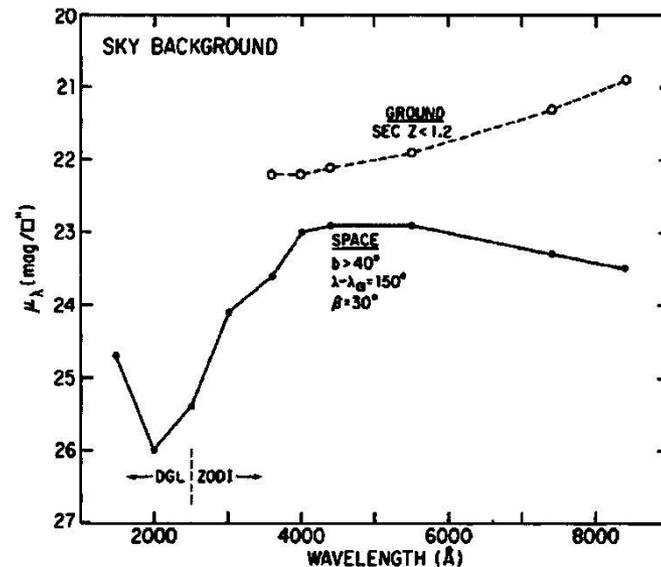
- There are a lot of comets in the Solar System. (Oort cloud contains cometary bodies which total mass is  $\sim 5 M_E$ ,  $\sim 10^4$  higher than mass of the Main Asteroid Belt).



- Comets keep dynamical, mineralogical, chemical, and structural information that is critically important for understanding origin and early evolution of the Solar System.
- Comets are considered as important objects in the aspect of space threats and resources.
- Comets are intrinsically different from one another (*A'Hearn+1995*).

# General comments on UV observations of comets

- Observations in the UV range are very informative, because this range contains the majority of astrophysically significant resonance lines of atoms (OI, Cl, HI, etc.), molecules (CO, CO<sub>2</sub>, OH etc.), and their ions.
- UV background is relatively low.
- UV imaging and spectroscopy are both widely used.
- In order to solve most of the problems, the UV data needs to be complemented observations in other ranges including ground-based observations.

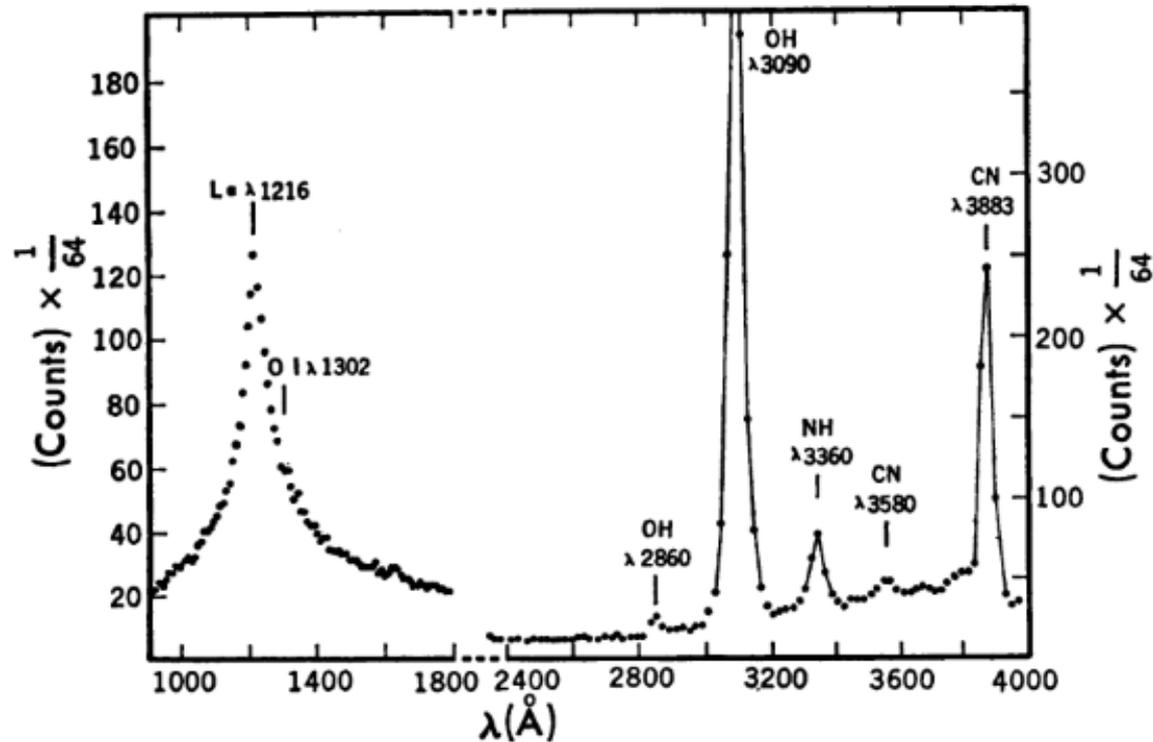


# First UV observations of comets from space

Instruments	Feeding optics	Resolution	Spectral range	Comets	Found
<b>Orbiting Astronomical Observatory (OAO-2)</b> 2 scanning spectrophotometers Launched in 1968	4x200mm	~10 Å ~20 Å	1100-2000 Å 2000-4000 Å	Bennett C/1969 Y1	OH (1657 Å) OI (1304 Å)
<b>Orbiting Geophysical Observatory (OGO-5)</b> Launched in 1968	~100cm <sup>2</sup>			Bennett C/1969 Y1	Lyman-α halo
<b>Aerobee</b> sounding rocket wide-angle all-reflective spectrograph Launched in 1970	D=50mm	~1 Å	1100-1800 Å	Tago-Sato-Kosaka C/1969 Y1	Lyman-α halo
<b>Skylab 3</b> space station Launched in 1973	D=75mm			Kohoutek C/1969 Y1	Huge Lyman-α halo
<b>NASA 990 Convair</b> aircraft. (1974)	D=300mm			Kohoutek C/1969 Y1	OH (3090Å)

see either *Delsemme 1980*

# Ultraviolet spectrum of Comet Bennett (OAO-2)



Lyman- $\alpha$  (1216 Å), O I (1302 Å), OH (2860 and 3090 Å), NH (3360 Å), and CN (3580 and 3883 Å) spectral features.

*Code&Savage1972*

# First imaging of hydrogen corona (Aerobee instrument)

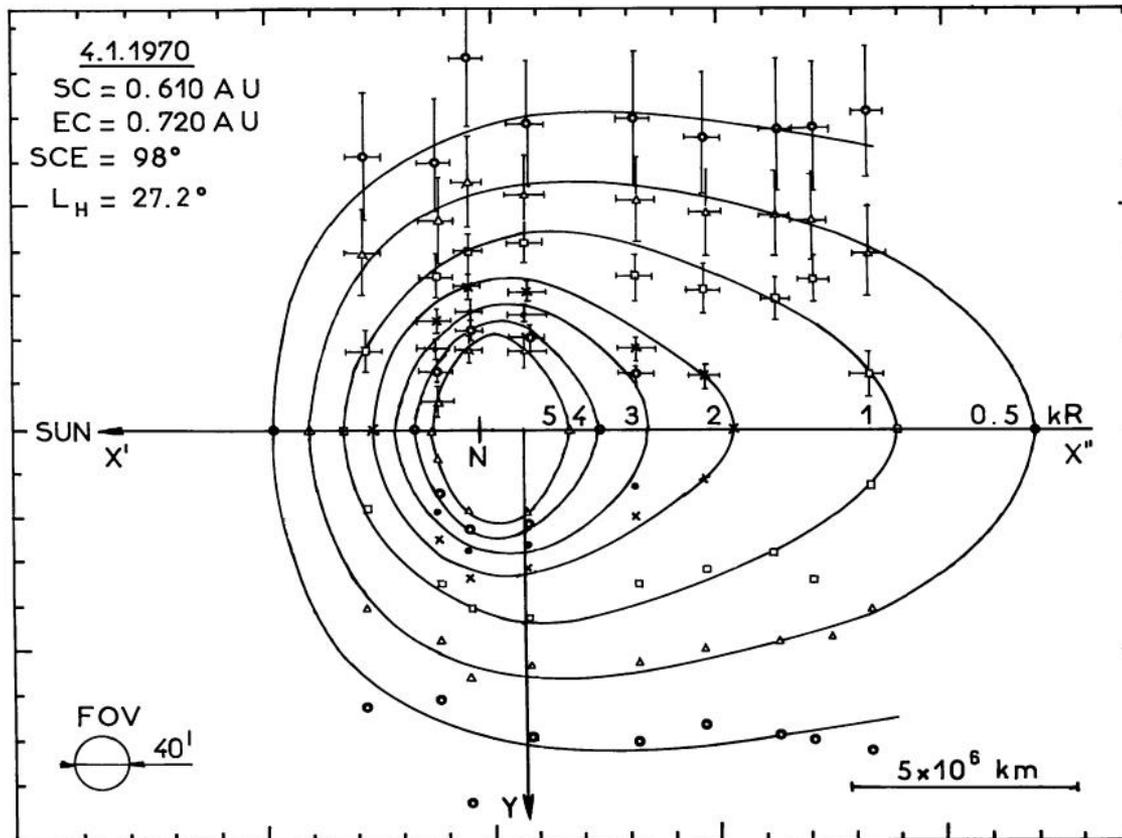
In 1970, huge clouds of Lyman- $\alpha$  emission surrounding comet Tago-Sato-Kosaka 1969g (C/1969 T1) and comet Bennett (C/1969 Y1) were observed with Aerobee instrument (film camera).

These observations marked the discovery of cometary hydrogen coronas.

*Jenkins&Wingert1972*

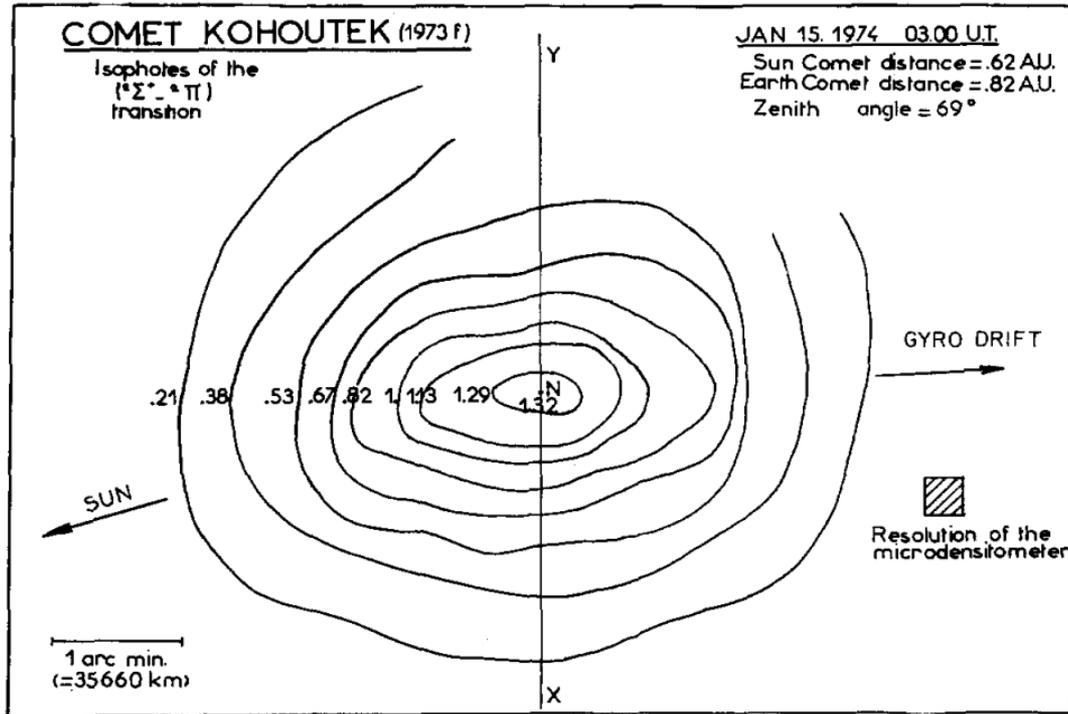


# Isophotes of comet Bennett (OGO-5)



Lyman-alpha isophotes of comet Bennet (April 1, 1970).  
(to compare: dark night sky – 250 R, aurora – up to 1000 kR). *Bertaux+1973*

# Comet Kohoutek (NASA 990 Convair )

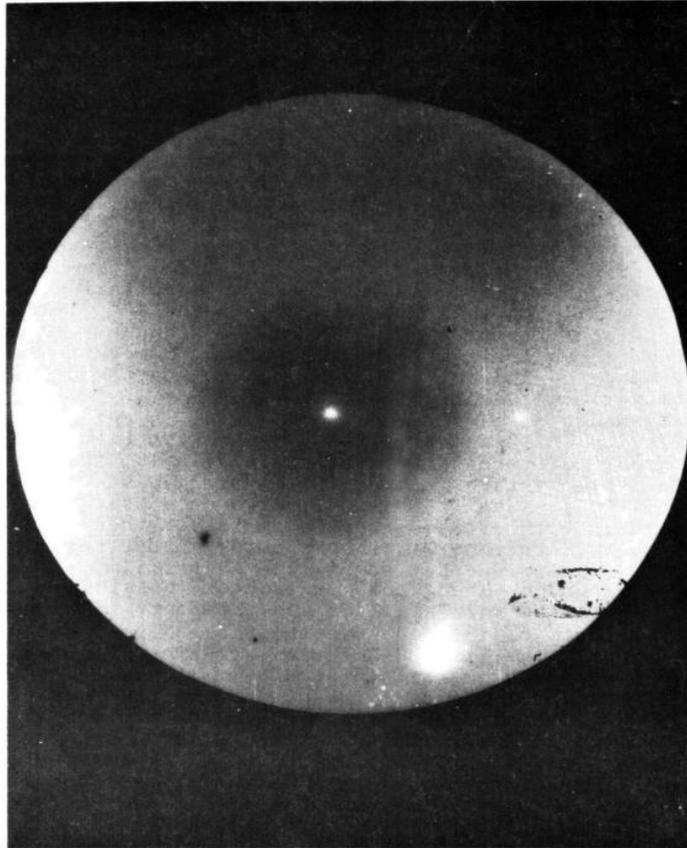


Isophotes of the resonance (0-0) band of OH. Maximum intensity 6kR. *Blamont&Festou1974*

# First detection of OH emission from comet (from ground)

In 1941 a team led by the Belgian astronomer *Polidore Swings* observed for the first time the spectrum of a comet in UV (U band). They were able to identify the ultraviolet bands of the hydroxyl radical OH at 3078 - 3100 Å in the nuclear region of comet C/1940 R2 (Cunningham). Swings suggested that the hydroxyl was probably produced by the photodissociation of water (H<sub>2</sub>O) molecules. This was the first strong observational evidence of the presence of water in the comet's nucleus.

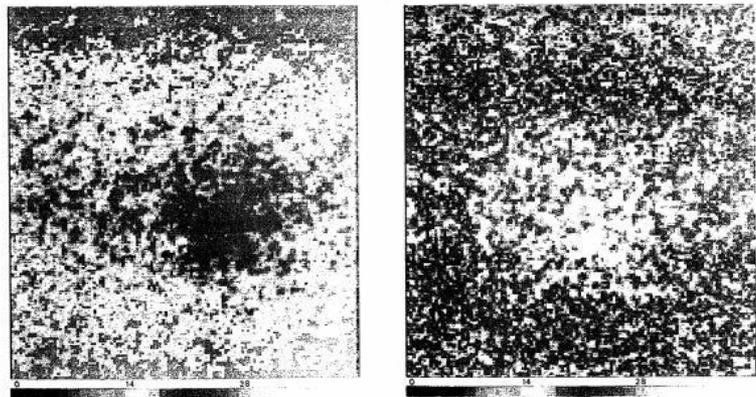
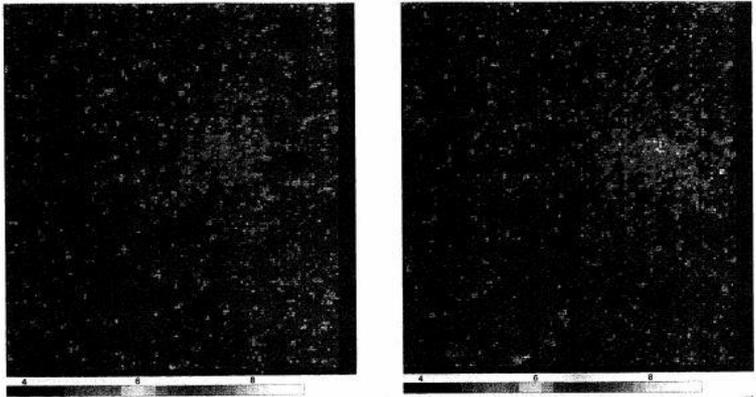
# Huge halo around Comet Kohoutek (Skylab 3)



Lyman- $\alpha$  halo was observed 25 Dec 1973 with 3-inch aperture S201 Camera, LiF optics, at 2.5 sec exposure,

*Page 1974*

# Ly $\alpha$ imaging of Halley comet (Suisei)



Ly $\alpha$  imaging of Halley comet  
with Suisei (1985-86)  
*Kaneda+86*



CCD UV imaging system and  
6 images/day.

## Results:

Strong breathing of comet Halley  
with a period 2.2 days was  
observed. Postperihelion H<sub>2</sub>O  
production rates exceed  
preperihelion (60 tons/s) ones by  
factor 2-3.

# Collision of Shoemaker-Levy 9 with Jupiter in UV (HST)



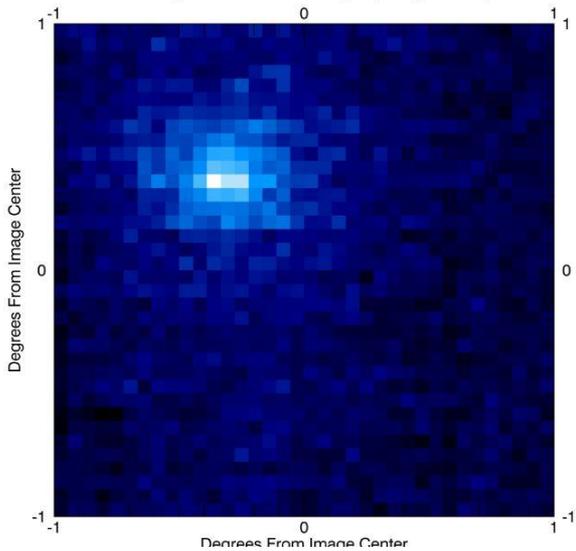
UV Image of spots on the Jupiter atmosphere after collision with comet Shoemaker-Levy 9 (*HST Comet team*).

[HST: Cycle 17 observations \(from July 13 2009\)](#)

Attempt to follow H<sub>2</sub>O remnant of comet S-L 9 in Jovian atmosphere.

# Comet C/2013 A1 in the vicinity of Mars (UIVS MAVEN)

MAVEN/IUVS Image of Comet Siding Spring in H-LyA, 10/17/14



UV photo of Siding Spring comet was made at a distance of 8.5 million kilometers.

NASA's Ultraviolet Spectrograph (IUVS) (aperture 13×20 mm,  $\lambda\lambda$ 110-340 nm) aboard the Mars Atmosphere and Volatile Evolution (MAVEN) orbiting S/C constructed images of the hydrogen coma of planet-grazing comet C/2013 A1 (Siding Spring) 2 days before its close encounter with Mars.

Some results: Water production rate is of  $1.1 \pm 0.5 \times 10^{28}$  molecules/s, the total impacting fluence of atoms and molecules corresponding to the photodissociation of water and its daughter species to be  $2.4 \pm 1.2 \times 10^4$  kg. These observations were used to confirm predictions that the mass of delivered hydrogen is comparable to the existing reservoir above 150 km.

*Crismani+2015*

# Imaging of comet C/2009 P1 (Garradd) (Swift's UVOT)

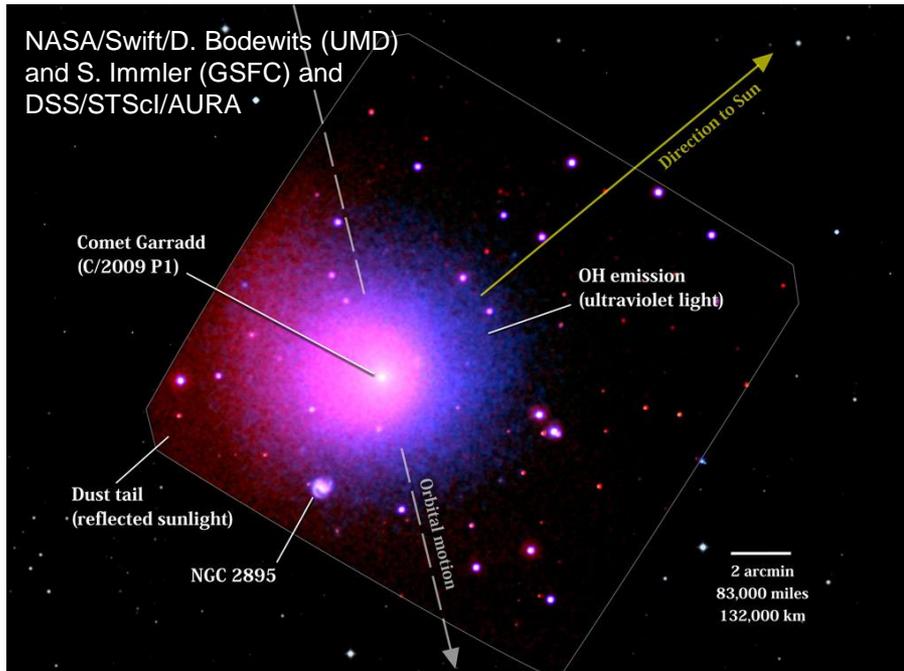
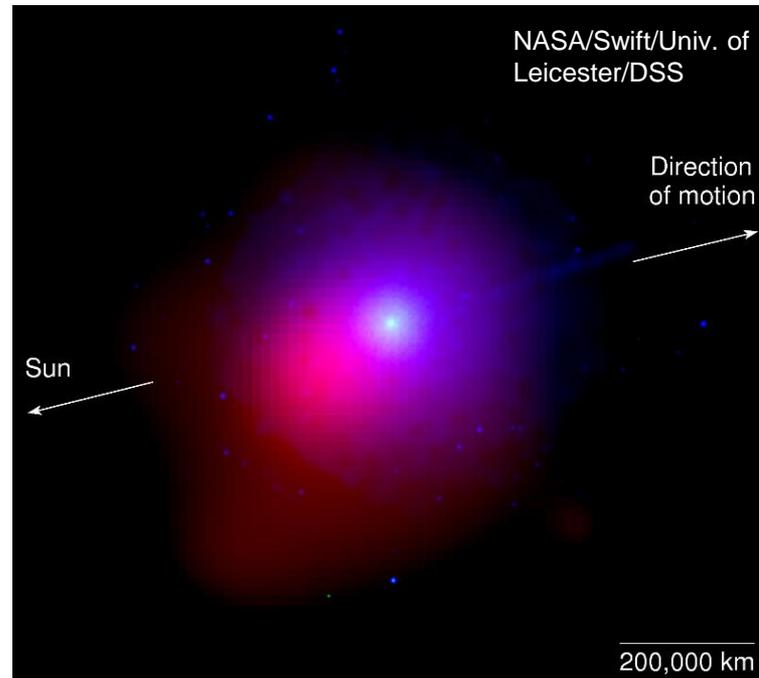


Image of Comet C/2009 P1 (Garradd) was taken on April 1, 2012, when the comet was 229 million kilometers away. Red shows sunlight reflected from the comet's dust; violet shows ultraviolet light produced by OH).

*Bodewits+2012*

Ultraviolet and Optical Telescope (UVOT) has a 30 cm aperture that provides a 17 x 17 arc min field of view with a spatial resolution of 0.5 arcsecs/pixel in the optical/UV band (range 1700 - 6500 Å). Seven broadband filters allow color discrimination, and two gratings provide low-resolution spectroscopy at UV (1700 – 5200 Å) and optical (2900 – 6500 Å) wavelengths. These gratings provide a resolving power ~ 100 for point sources

# Imaging of comet Comet C/2007 N3 Lulin (Swift's UVOT)



Images of Comet C/2007 N3 Lulin were taken Jan. 28 2009 by: UVOT (in blue and green) and X-Ray Telescope (in red) to provide the first ever simultaneous X-ray and UV image of a comet. The UV and X-ray emission are on opposite side because comet Lulin has two oppositely-directed tails. *Bodewits+2011*

# Remarks on UV spectroscopy of comets

- Cometary spectra in the UV and visible range include lines of two components: lines that are formed by scattering of sunlight on solid dust particles, and emission lines from the gas in coma.
- Ultraviolet spectroscopy provides important information about the composition of a comet's coma. In general, cometary comas are dominated by emission features that originate from the dissociation products of water: OH, H and O and that correspond to secondary atomic, molecular, and ionic species, such as C, C<sup>+</sup>, CO, CO<sup>+</sup>, CO<sub>2</sub><sup>+</sup>, S, and CS
- Space structure and time variations of outflows deduced from the spectra help to reveal structure and composition of cores.
- N<sub>2</sub> and the noble gases are both chemically inert and highly volatile, so they are particularly interesting as clues on the comet's thermal history. But they have not yet been detected by UV instruments in cometary comas.

# UV observations of comets (IUE)

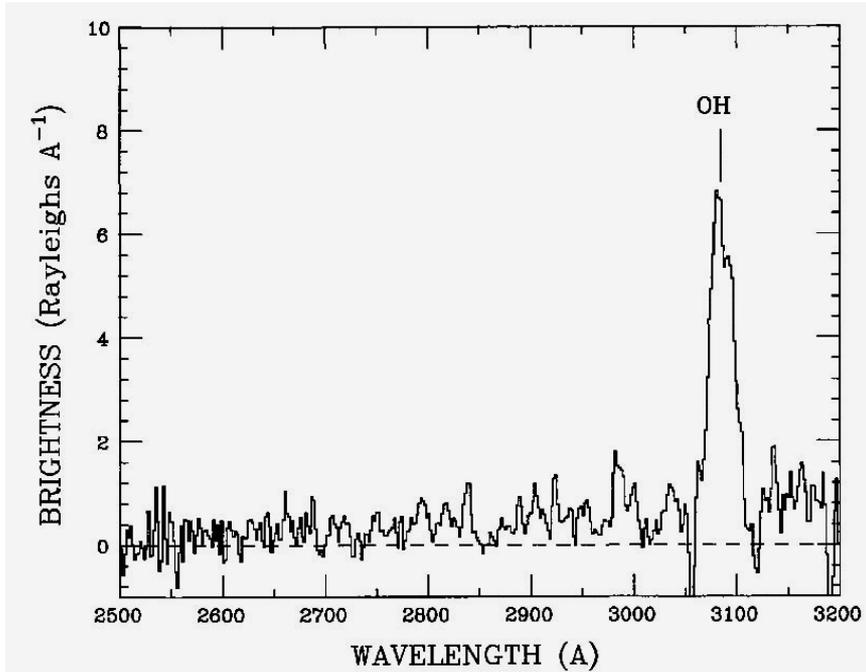
*Festou M.C. 18 Years of Systematic UV Studies of Comets with IUE. 1998ESASP.413...45F*

Almost all comets brighter than  $\sim 6^m$  appeared in 1978-1996. 59 passages of 55 comets were observed.

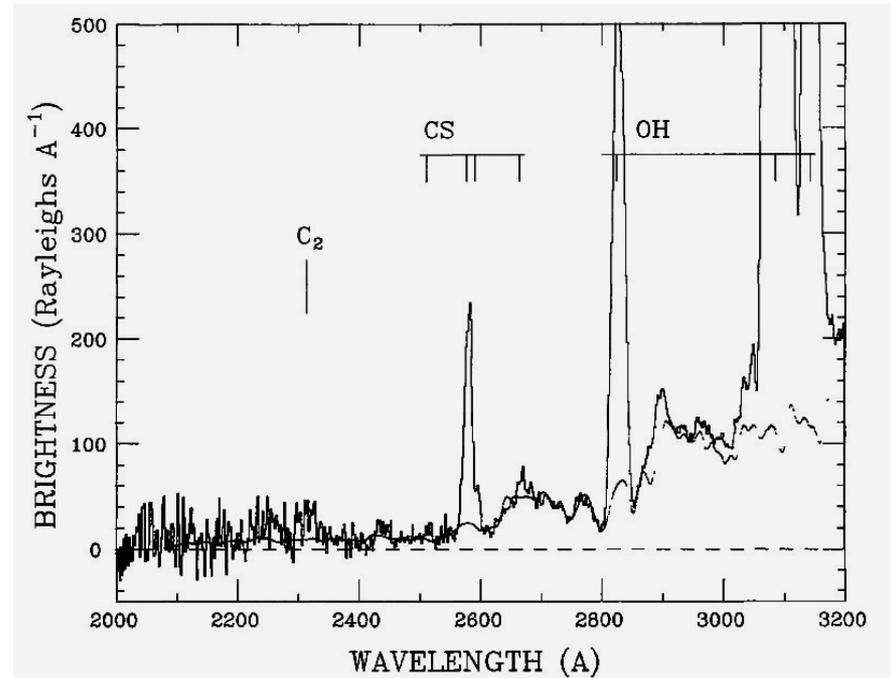
Important results (in general):

New species have been discovered in the coma, and some of the most abundant nuclear species have been studied through the spatial distribution of their dissociation products. Time variations (at scale – few months to few hours) have been investigated in details.

# Halley comet spectra (IUE)



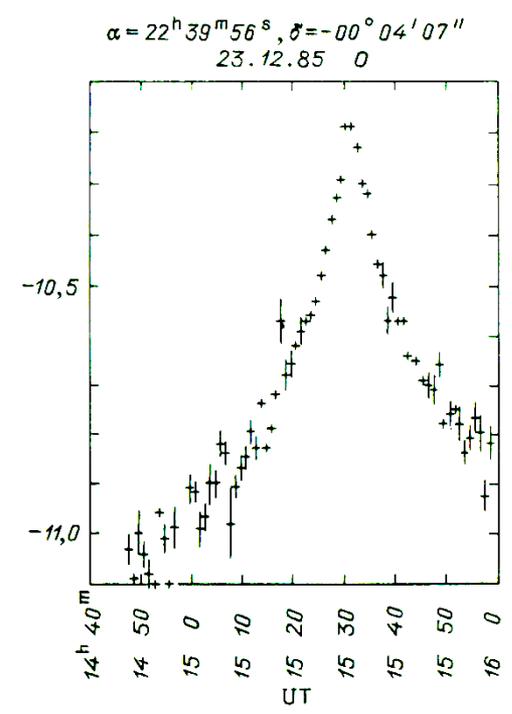
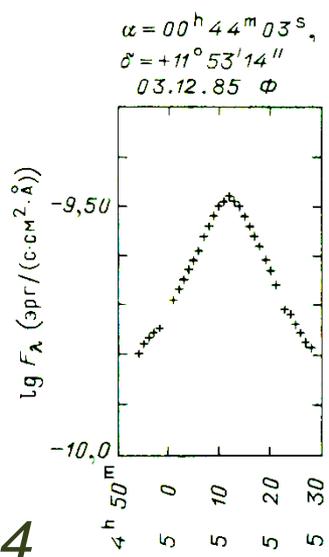
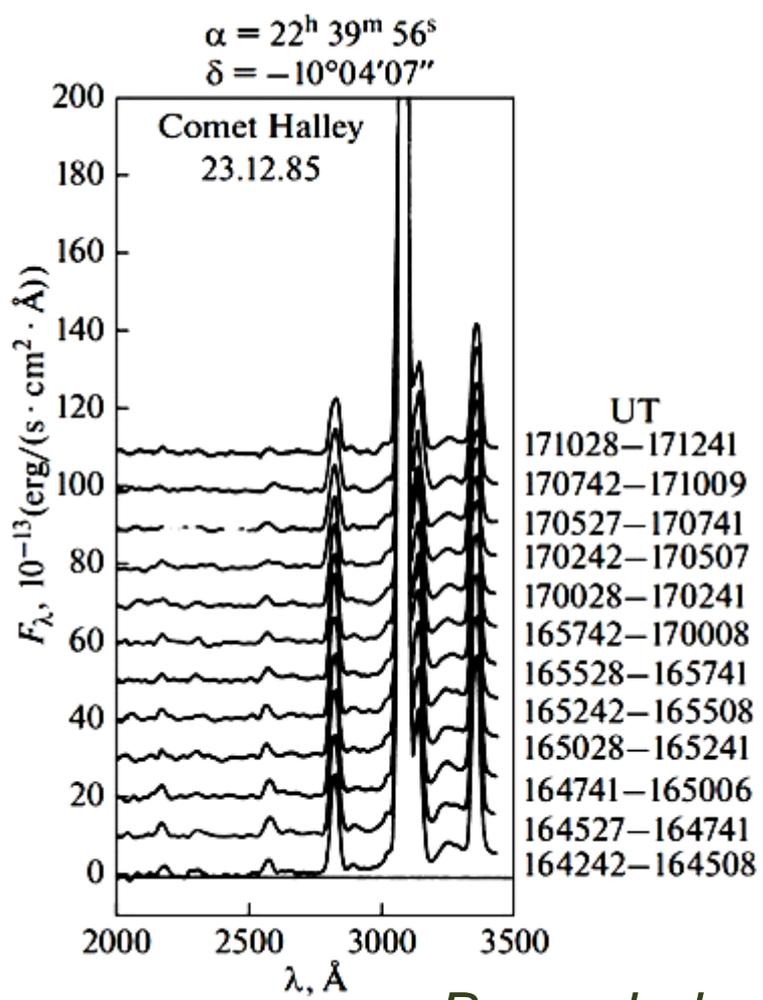
**Fig. 1.** Long-wavelength spectrum of P/Halley (LWP 6720) obtained on 1985 September 12. The exposure time was 180 minutes



**Fig. 2.** A long wavelength 15 minute exposure of P/Halley (LWP 7773) obtained on 1986 March 11

*Feldman+1987*

# Halley comet spectra (ASTRON)



Boyarchuk, 1994

# Observations of comets (HST)

Com	Number of comet studies:
<a href="#">Cycle 14 observations (from March 13 2006 to June 30 2006)</a>	1
<a href="#">Cycle 15 observations (from July 1 2006)</a>	0
<a href="#">Cycle 16 observations (from July 1 2007)</a>	4
<a href="#">Cycle 17 observations (from July 13 2009)</a>	2 (+1 remnant☺- S-L)
<a href="#">Cycle 18 observations (from August 30 2010)</a>	1(+1 main belt comet or comet-like asteroid??, MBC)
<a href="#">Cycle 19 observations (from October 3 2011)</a>	1 (+1 new MBC)
<a href="#">Cycle 20 observations (from October 1 2012)</a>	4+2'MBC'
<a href="#">Cycle 21 observations (from October 1 2013)</a>	9+2' <a href="#">MBC</a> ' +1'infl. tail to Mars atm.'
<a href="#">Cycle 22 observations (from October 1 2014)</a>	4+2MBC+ <a href="#">1exocomet</a>
<a href="#">Cycle 23 observations (from October 1 2015)</a>	4+1MBC+2exocomet
<a href="#">Cycle 24 observations (from October 1 2016)</a>	1MBC

44 observation objects (the total number of observation programs is ~5000 for 10 years) are comets!

# Some results from observation with HST

Four comets have been observed in FUV by the Cosmic Origins Spectrograph (COS): 103P/Hartley 2, C/2009 P1 (Garradd), C/2012 S1 (ISON), and C/2014 Q2 (Lovejoy).

- The principal objective was to determine the relative CO abundance from measurements of the CO Fourth Positive system in the spectral range of 1400 to 1700 Å. In the two brightest comets, nineteen bands of this system were clearly identified.
- The water production rate was derived observations of the OH (0,0) band at 3085 Å by the Space Telescope Imaging Spectrograph (STIS). The derived CO/H<sub>2</sub>O production rate ratio ranged from ~0.3% for Hartley 2 (Weaver et al., ApJ 734:L5, 2011) to ~20% for Garradd.
- In addition, strong partially resolved emission features due to multiplets of S I, centered at 1429 Å and 1479 Å, and of C I at 1561 Å and 1657 Å, were observed in all four comets. Weak emission from several lines of the H<sub>2</sub> Lyman band system, excited by solar Lyman-α and Lyman-β pumped fluorescence, were detected in comet Lovejoy. *Feldman+2016*

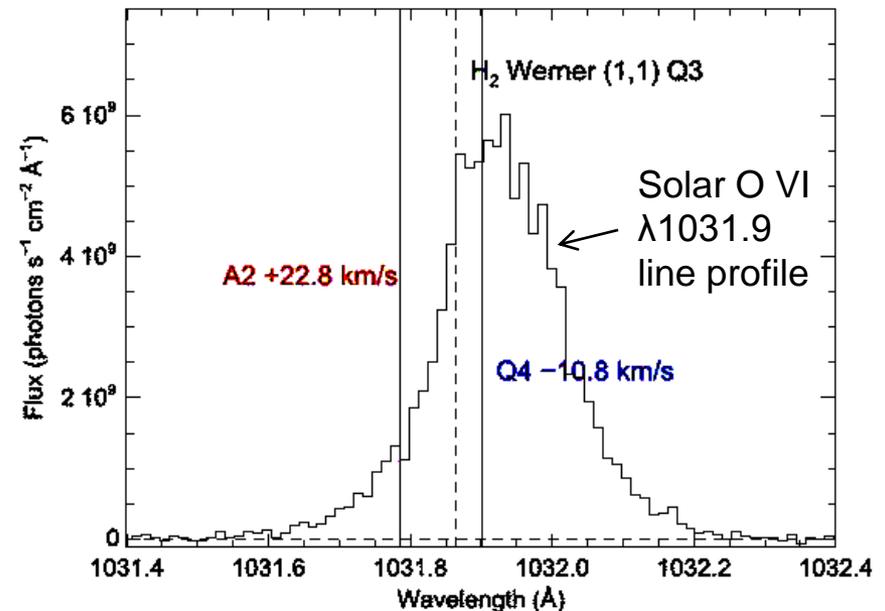
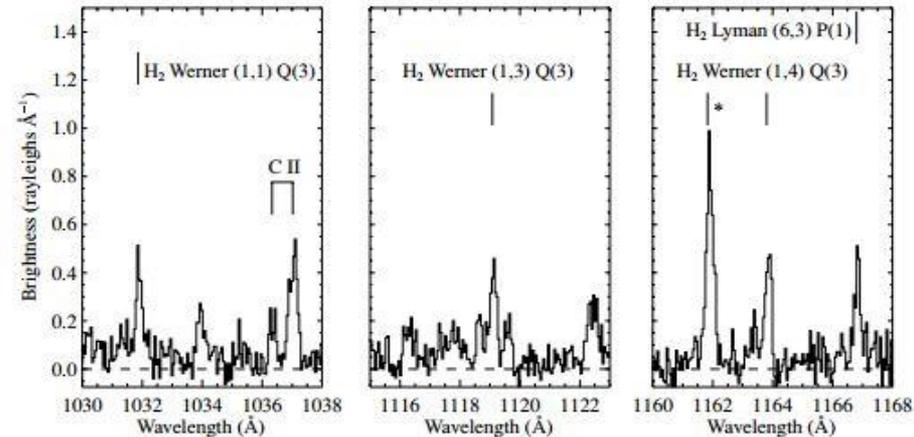
# Comets in far UV (FUSE)

FUSE (4 mirrors 39cm x 35cm,  
 $\lambda\lambda$  905-1187 Å,  $\Delta\lambda \sim 0.4$  Å).

## Some results.

The relative strengths of the observed H<sub>2</sub> line intensities vary predictably based on the comet's heliocentric velocity Doppler shift relative to the exciting solar Ly $\alpha$  and O VI lines.

*Feldman+2009,2015*



# Observations of comets (GALEX)

GALEX (grism): feeding aperture 50cm,  $\Delta\lambda \sim 10\text{-}20 \text{ \AA}$   
 $\lambda\lambda$  1350-1750  $\text{\AA}$ , 1750-2800  $\text{\AA}$ .

GALEX has observed 6 comets in 2005-2009 (C/2004 Q2 (Machholz), 9P/Tempel 1, 73P/Schwassmann-Wachmann 3 Fragments B and C, 8P/Tuttle and C/2007 N3 (Lulin). GALEX is designed to map the history of star formation in the Universe. It is also well suited to cometary coma studies because of its high sensitivity and large field of view.

## Some results:

OH and CS in the NUV (1750-3100  $\text{\AA}$ ) are clearly detected in all of the comet data. The FUV detected the bright C I 1561 and 1657  $\text{\AA}$  multiplets and evidences for S I 1475  $\text{\AA}$  in the FUV.

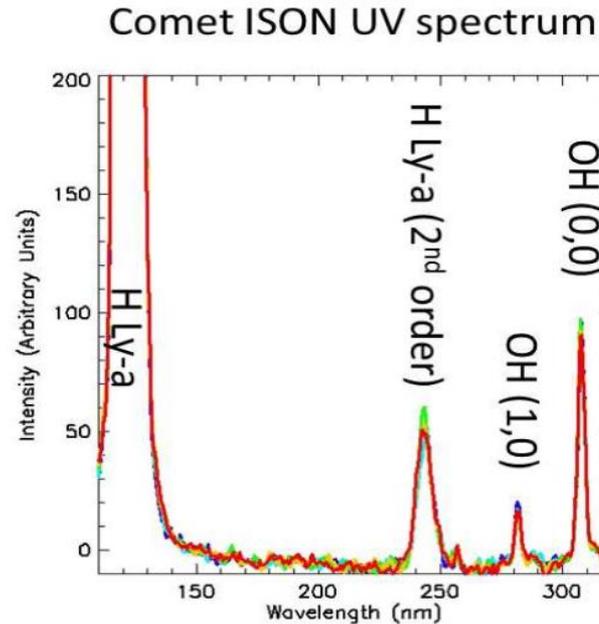
NEW: CO<sup>+</sup> emission in the NUV and CO Fourth positive band emission in the FUV are clearly detected.

(The A<sup>1</sup>Π-X<sup>1</sup> Σ Fourth Positive system is the most prominent system of CO in UV (280-128 nm))

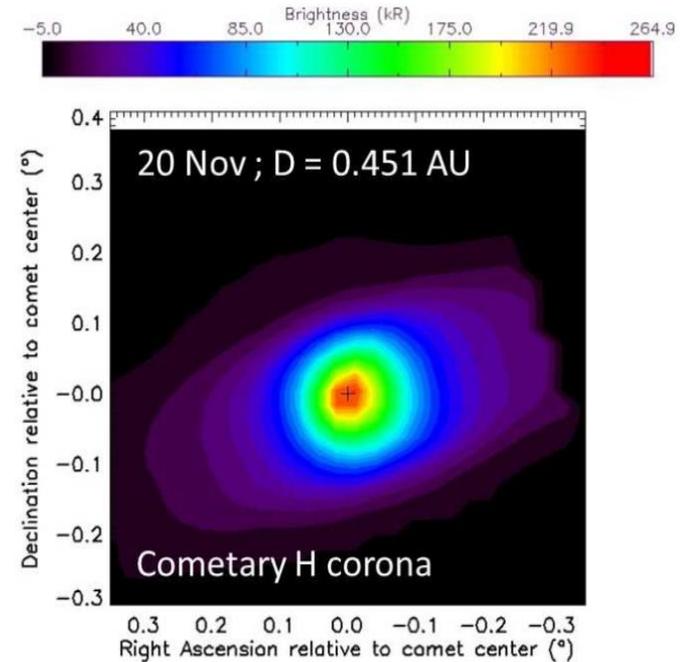
*Morgenthaler+2009*

# C/2012 S1 ISON comet (SPICAV-UV)

SPICAV is one of the Venera-Express instruments. The UV channel of SPICAV is a full UV imaging spectrometer: 40 mm aperture  $\lambda\lambda$  118–320 nm  $\Delta\lambda$  0.54 nm



Example of UV spectrum of the comet ISON measured by SPICAV-UV.

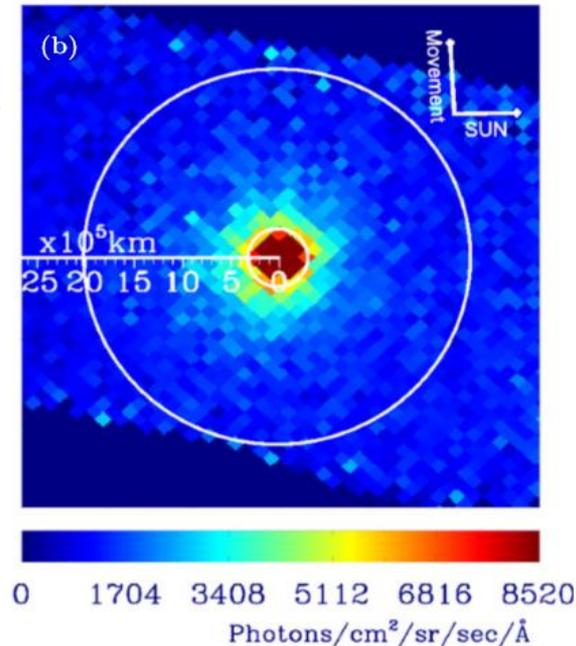


Example of map of the Lyman- $\alpha$  emission around ISON obtained by SPICAV-UV

*Chaufray&Bertaux2015*

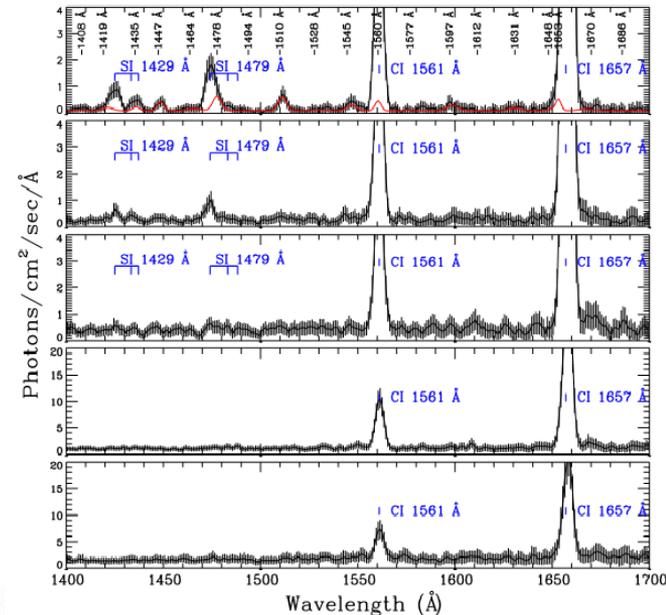
# C/2001 Q4 (NEAT) comet (FIMS)

Far-Ultraviolet Imaging Spectrograph (FIMS), on board the Korean satellite *STSAT-1*, (launched in 2003) FIMS is a dual-channel FUV imaging spectrograph (S-channel 900–1150 Å, L-channel 1350–1710 Å, and  $\lambda/\Delta\lambda \sim 550$  for both channels) with large imaged fields of view (S-channel  $4.0^\circ \times 4.6'$ , L-channel  $7.5^\circ \times 4.3'$ , and angular resolution  $\sim 5\text{--}10'$ ) optimized for observation of FUV radiation that originated from hot gases in our Galaxy,



FIMS L-channel image of comet C/2001 Q4 (NEAT) created from the observations of 2004 May 14 and 15.

*Lim et al., 2014*

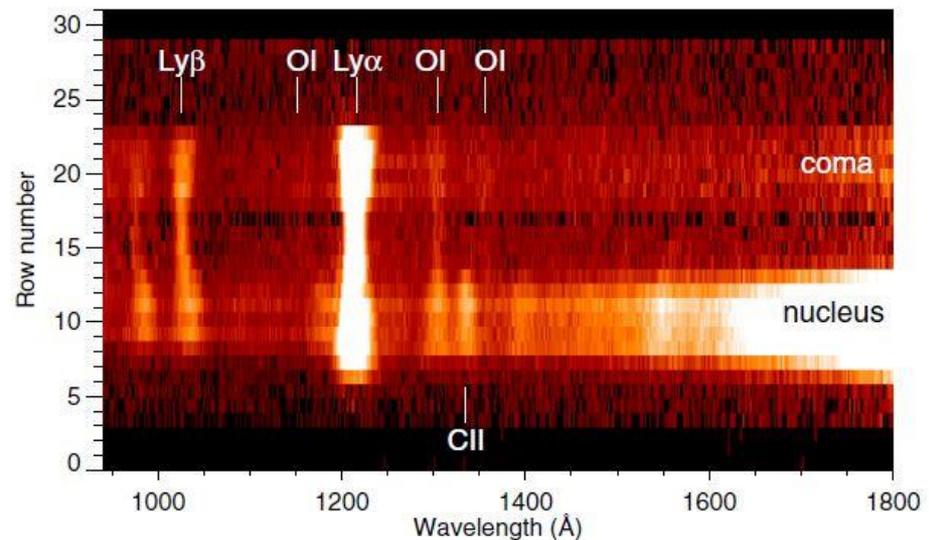
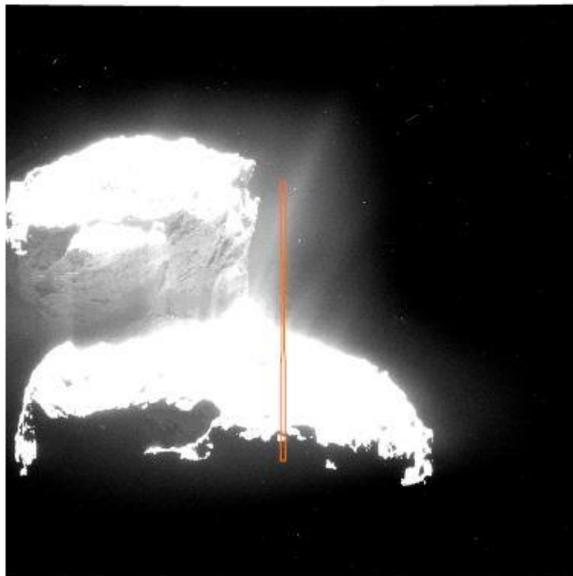


FIMS FUV spectral flux of comet C/2001 Q4 (NEAT) observed during the second campaign of 2004 May 14 and 15.

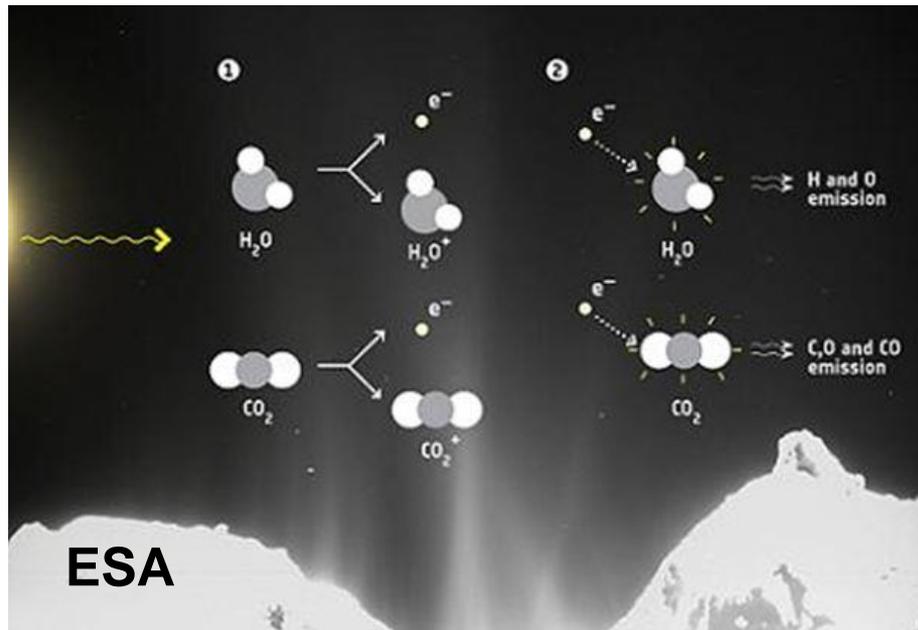
# Comet 67P/Churyumov-Gerasimenko in Far UV (ALICE)



ALICE is imaging spectrograph in the  $\lambda\lambda 70\text{--}205\text{ nm}$ ,  $\Delta\lambda 0.8\text{--}1.2\text{ nm}$ . The slit,  $5.5^\circ$  long, with a width of  $0.05^\circ\text{--}0.10^\circ$ . Alice employs an off-axis telescope feeding a 0.15-m normal incidence Rowland circle spectro-graph with a concave holographic reflection grating. MCP detector utilizes solar-blind opaque photo-cathodes (KBr and CsI).



# Discoveries with ALICE



Analysis of the relative line intensities suggests photoelectron impact dissociation of  $\text{H}_2\text{O}$  vapor as the source of the observed HI and OI emissions. The electrons are produced by photoionization of  $\text{H}_2\text{O}$  within 1 km above the comet nucleus.

*Feldman+2015*

# Exocomets were first discovered in UV

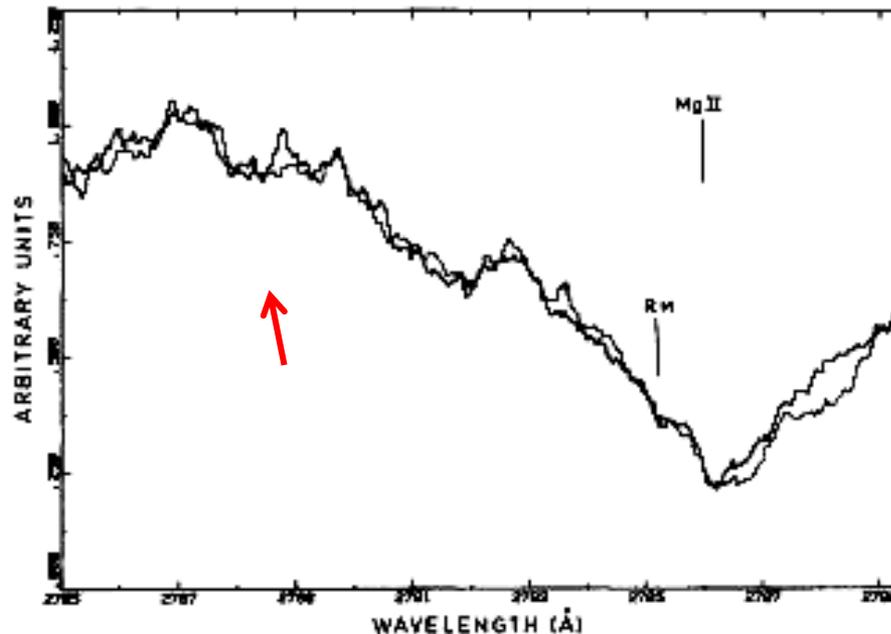


Fig. 3a. Mg II line 2795 Å;  $\beta$  Pictoris line in May, 1985 (thin line) over  $\beta$  Pictoris line in December, 1984 (thick line). Data from LWP 5891 ( $\beta$  Pictoris, May 1985) and LWP 5016 ( $\beta$  Pictoris, December 1984) (also in Fig. 3b)

The infalling bodies were first suggested by *Lagrange+87*.  
Time variation of redshifted wings of Mg II 2796 and Fe II 2586 (IUE obs.)  $V_{\text{fall}}$  20-120 km/s.

# Comets (incl. exocomets) in UV: future

- Future UV observatories will have comets and exocomets as important targets. The topic is included in the scientific program of the WSO-UV observatory.
- Long slit, low and high resolution spectroscopy is vitally important for future progress.
- Imaging and photometry of comas remain to be in demand.
- UV spectroscopy “in situ” is very scientifically productive but still not frequent.
- Even relatively small UV instruments will make a significant contribution to cometary science.
- UV instruments to be included in future space observatories.

# Thanks you for attention!

