Comets in UV

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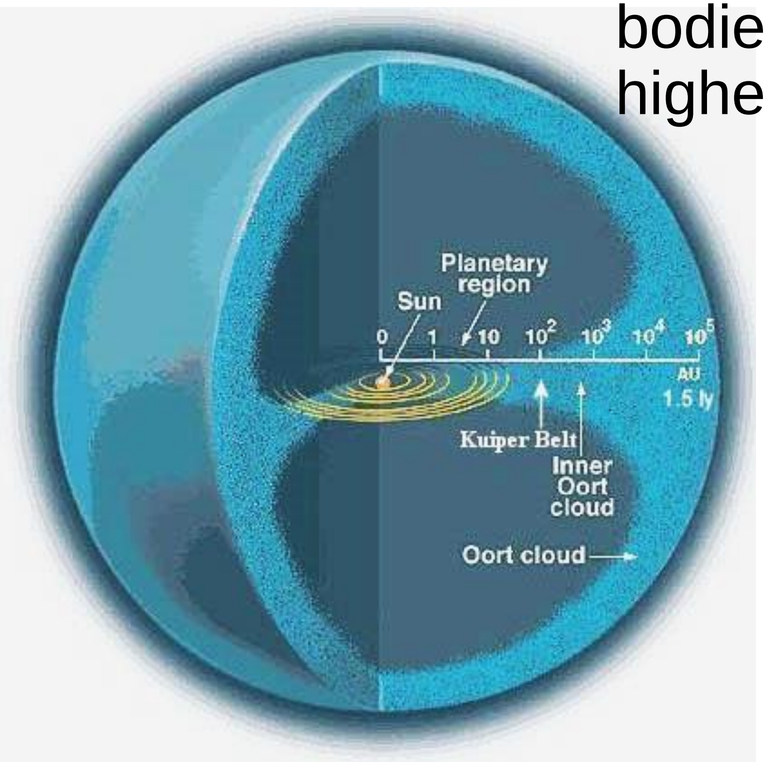
Comets – major part of minor body population of the Solar System



- There are a lot of comets in the Solar System. (Oort cloud contains cometary bodies which total mass is ~ 5 M_E , ~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*).
- Comets are beautiful ☺ .

General comments on UV observations of comets

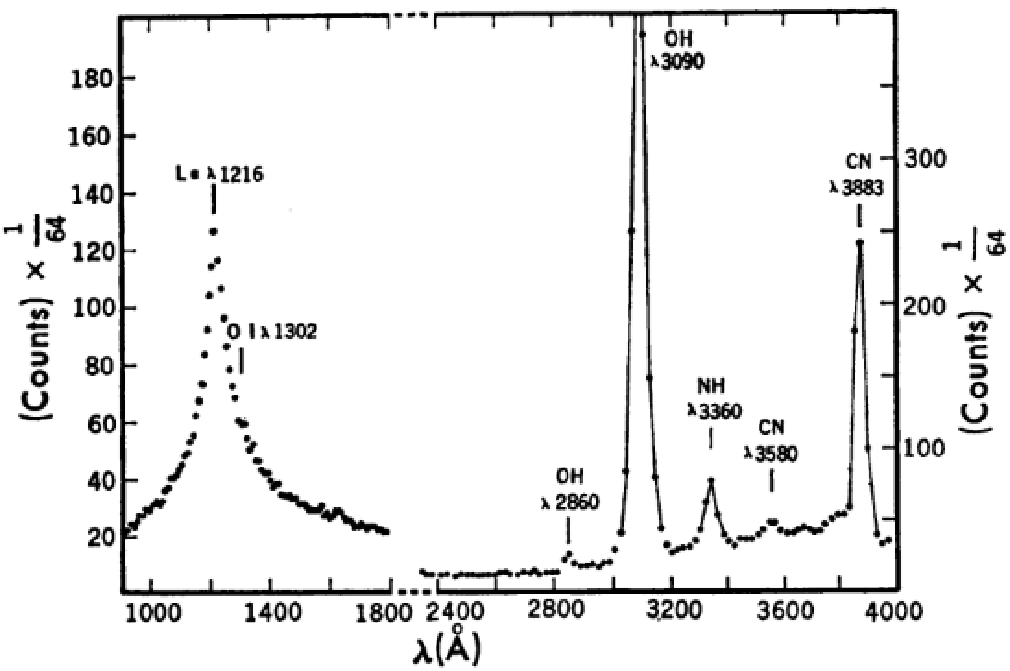
- Observations in the UV range are very informative, because this range contains the majority of astrophysically significant resonance lines of atoms (OI, CI, HI, etc.), molecules (CO, CO2, OH etc.), and their ions.
- UV imaging and spectroscopy are both widely used.
- In order to solve most of the problems, 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	Resolu tion	Spectral range	Comets	Found
Orbiting Astronomical Observatory (OAO-2) 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)
Orbiting Geophysical Observatory (OGO-5) Launched in 1968	~100cm^2			Bennett C/1969 Y1	Lyman-α halo
Aerobee 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
Skylab 3 space station Launched in 1973	D=75mm			Kohoutek C/1969 Y1	Huge Lyman-α halo
NASA 990 Convair aircraft. (1974)	D=300mm			Kohoutek C/1969 Y1	OH (3090Å)

see either *Delsemme1980*

Ultraviolet spectrum of Comet Bennett
(OAO-2)



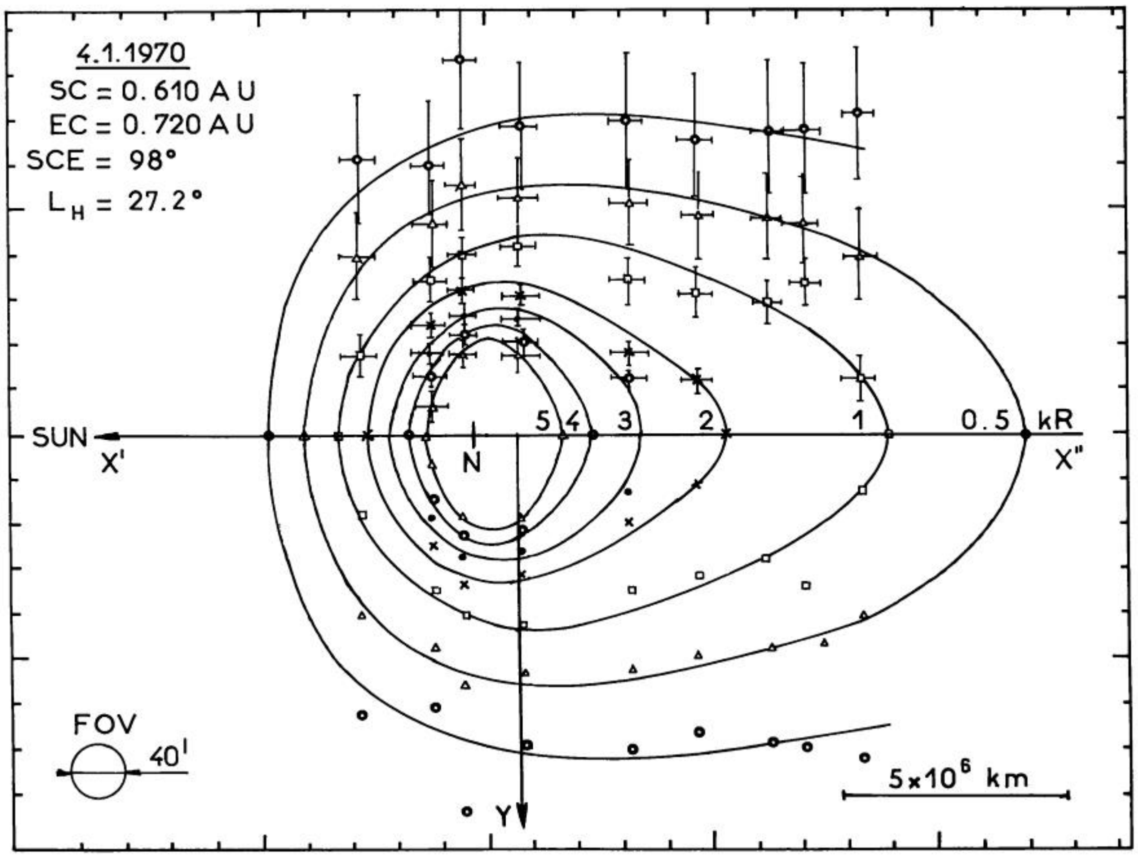
Lyman-α (1216 Å), 0 I (1302 Å), OH (2860 and 3090 Å), NH (3360 Å), and CN (3580 and 3883 Å) spectral features.

Code&Savage1972

First imaging of hydrogen corona
(Aerobee instrument)

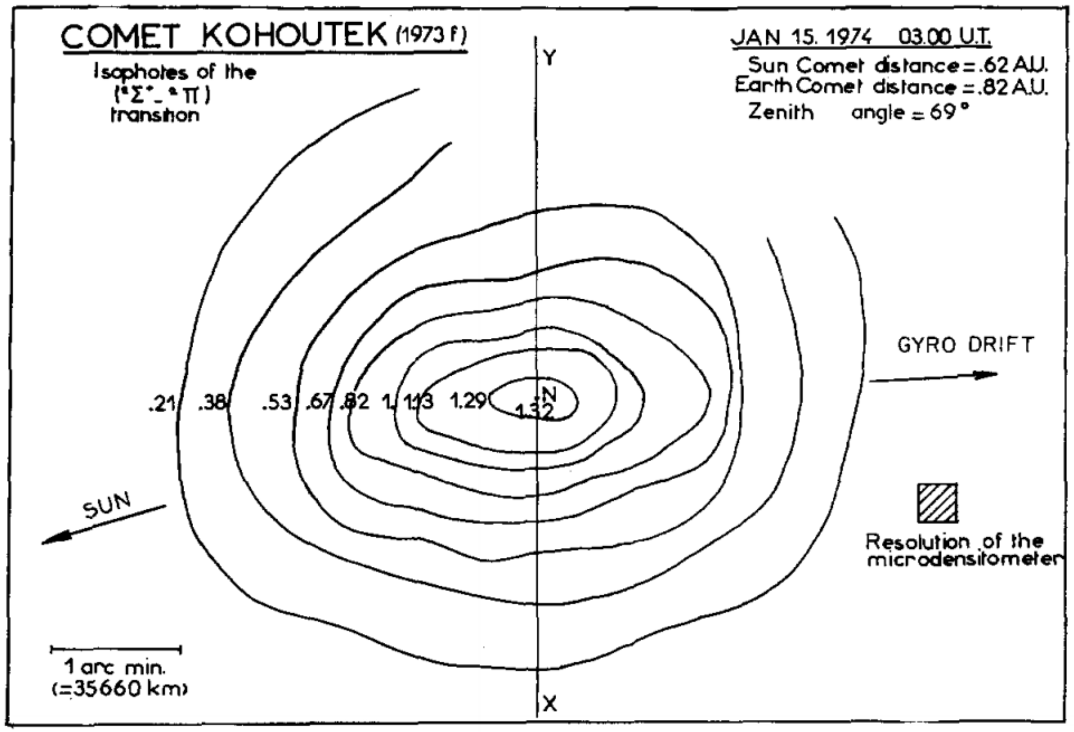
In 1970, huge clouds of Lyman-α emission surrounding comet Tago-Sato-Kosaka 1969g (C/1969 T1) and comet Bennett (C/1969 Y1) were observed with Aerobee instrument (film camera).
These observations marked the discovery of cometary hydrogen coronas.
Jenkins&Wingert1972

Isophotes of comet Bennett
(OGO-5)



Lyman-α 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)



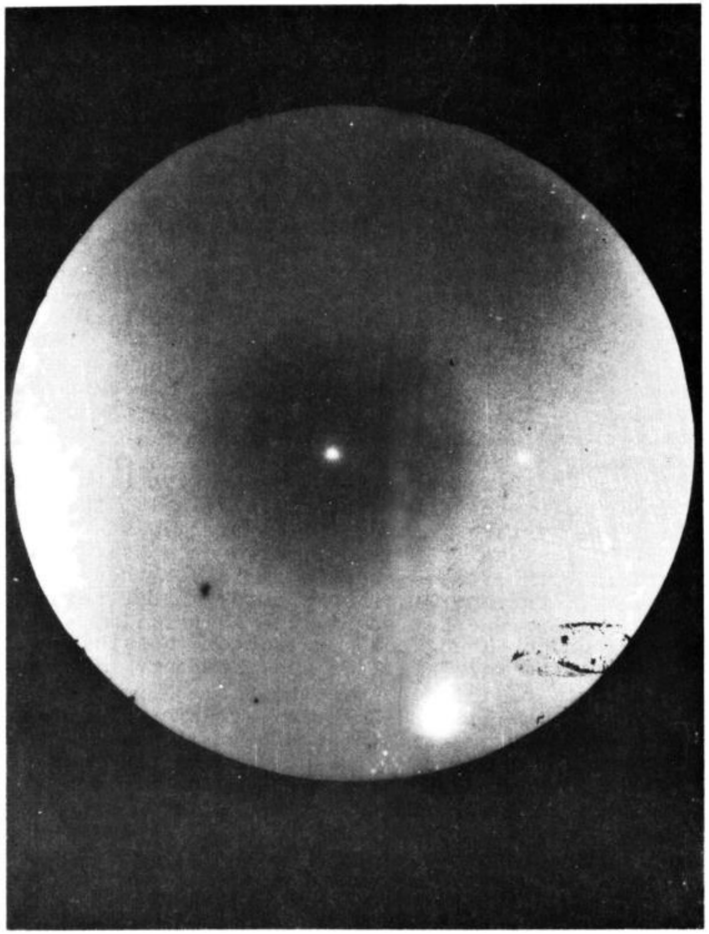
Isophotes of the resonance (0-0) band of OH. Maximum intensity 6kR. *Blamont&Festou1974*

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 (H2O) molecules. This was the first strong observational evidence of the presence of water in the comet’s nucleus.

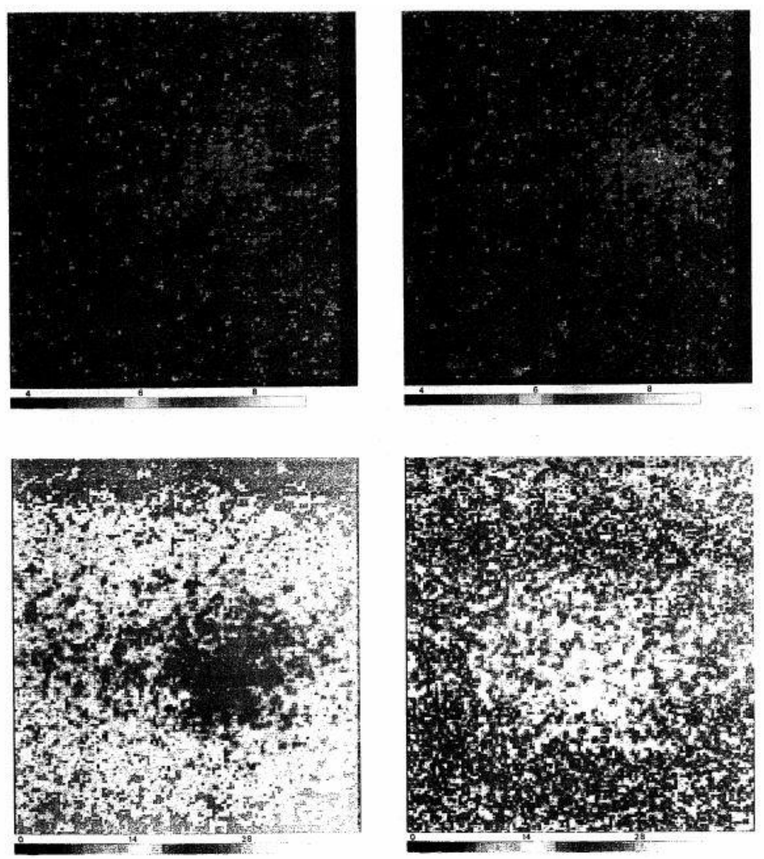
Huge halo around Comet Kohoutek

(Skylab 3)

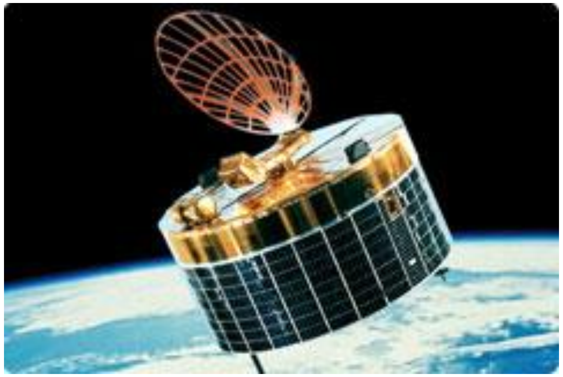


Lyman-α halo was observed 25 Dec 1973 with 3-inch aperture S201 Camera, LiF optics, at 2.5 sec exposure, *Page1974*

Lyα 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 H2O production rates exceed preperihelion (60 tons/s) ones by factor 2-3.

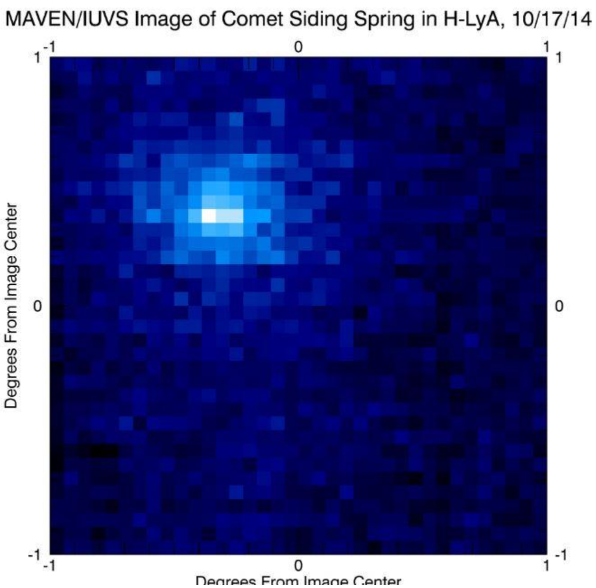
Collision of Shoemaker-Levy 9 with Jupiter in UV (HST)

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 H2O remnant of comet S-L 9 in Jovian atmosphere.

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



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)

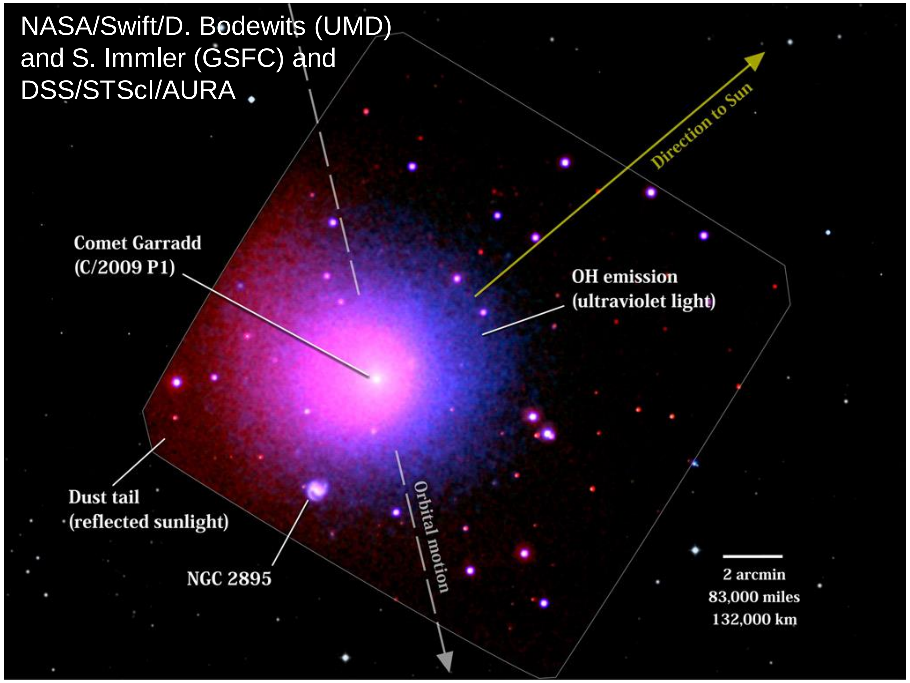
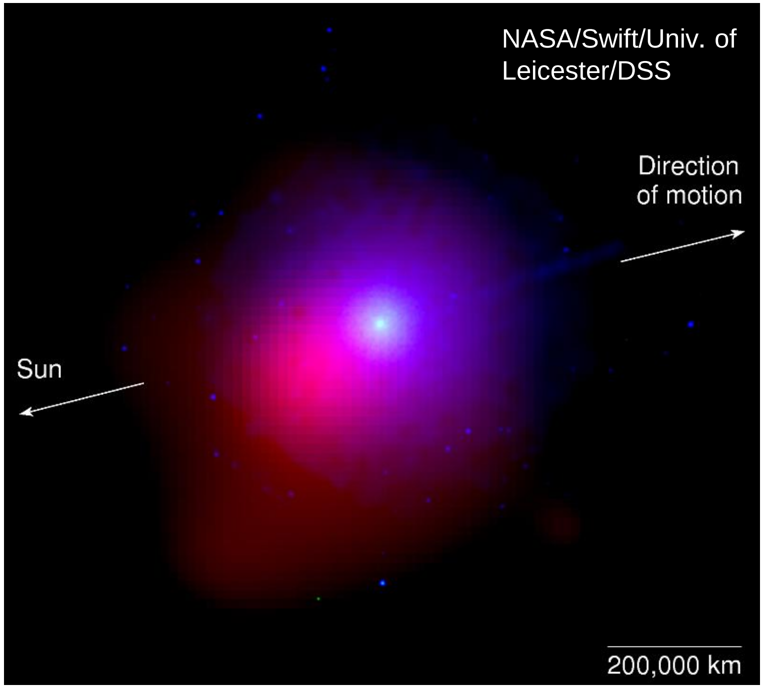


Image of Comet C/2009 P1 (Garradd) was taken on April 1, 2012, when the comet was 229 million kilometers away. Red shows sunlight reflected from the comet's dust; violet shows ultraviolet light produced by OH).
Bodewits+2012

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 grisms provide low-resolution spectroscopy at UV (1700 – 5200 Å) and optical (2900 – 6500 Å) wavelengths. These grisms 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 simultane-ous 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 coma 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+, CO, CO+, CO2 +, S, and CS
- Space structure and time variations of outflows deduced from the spectra help to reveal structure and composition of cores.
- N2 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.

First remote detections of molecules
in cometary comae

CO, CS	UV	1976	West C/1975 V1
S_2	UV	1983	IRAS-Araki-Alcock C/1983 H1
NH_3[a)]	Radio	1983	IRAS-Araki-Alcock C/1983 H1
HCO	Visible	1983	IRAS-Araki-Alcock C/1983 H1
HCN,	Radio	1985–1986	1P/Halley
H_2CO[a)]	Radio	1985–1986	1P/Halley
H_2O	IR	1985–1986	1P/Halley
H_2O, CO_2	IR	1985–1986	1P/Halley
H_2CO	Radio	1990	Austin C/1989 X1, Levy C/1990 K1
H_2S, CH_3OH	Radio	1990	Austin C/1989 X1, Levy C/1990 K1
CS_2	UV	1995	122P/de Vico
NH_3	Radio	1996	Hyakutake C/1996 B2
HNC	Radio	1996	Hyakutake C/1996 B2
CH_3CN	Radio	1996	Hyakutake C/1996 B2
OCS	Radio	1996	Hyakutake C/1996 B2
HNCO[a)]	Radio	1996	Hyakutake C/1996 B2
CH_4, C_2H_6	IR	1996	Hyakutake C/1996 B2
C_2H_2	IR	1996	Hyakutake C/1996 B2
OCS, SO, HNCO, HC_3N,	Radio	1997	Hale-Bopp C/1995 O1
NH_2CHO, CN·, SO_2, HCOOH, $HCOOCH_3$	Radio	1997	Hale-Bopp C/1995 O1
H_2CS	Radio	1997	Hale-Bopp C/1995 O1
CH_3CHO	Radio	1997	Hale-Bopp C/1995 O1
NS	Radio	1997	Hale-Bopp C/1995 O1
$HOCH_2CH_2OH$, c-C_2H_4O, C_2H_5OH, CH_3COOH, $HOCH_2CHO$	Radio	1997	Hale-Bopp C/1995 O1
H_2	UV	2001	C/2001 A2 (LINEAR)

U.Meierhenrich
Comets and their origin
Wiley-VCH 2015

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 ~ 6^m appeared in 1978-1996.   59 passages of 55 comets were observed.

<u>Important results (in general):</u>
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)

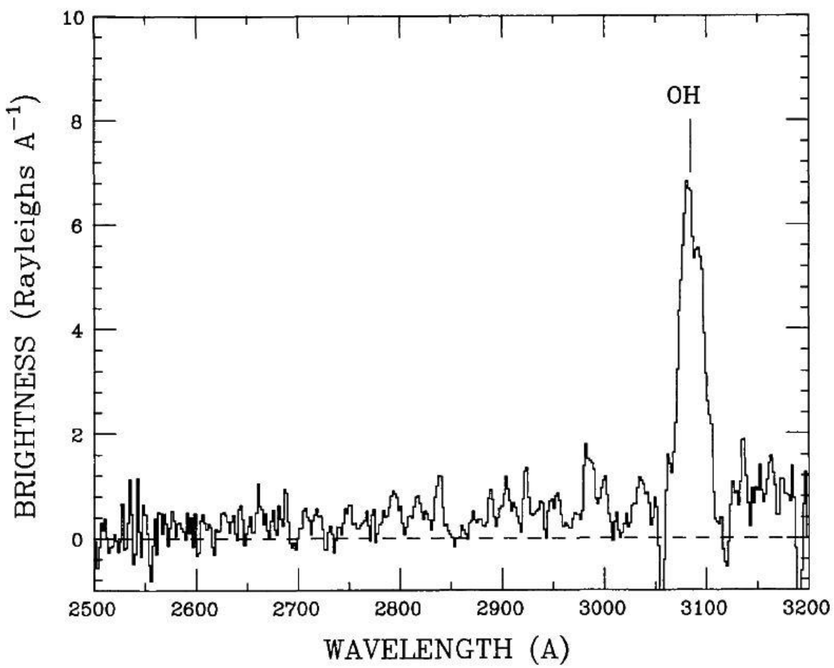


Fig. 1. Long-wavelength spectrum of P/Halley (LWP 6720) obtained on 1985 September 12. The exposure time was 180 minutes

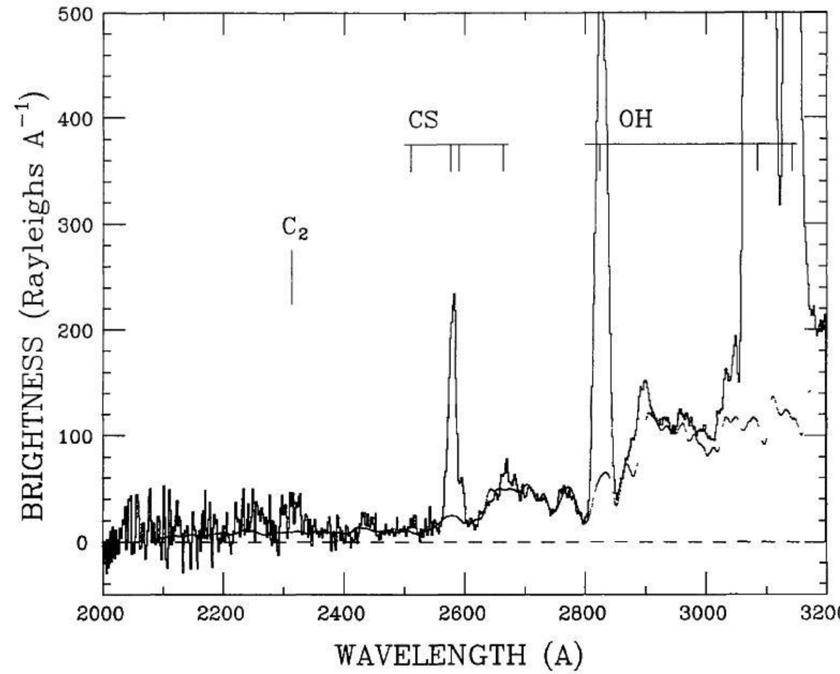
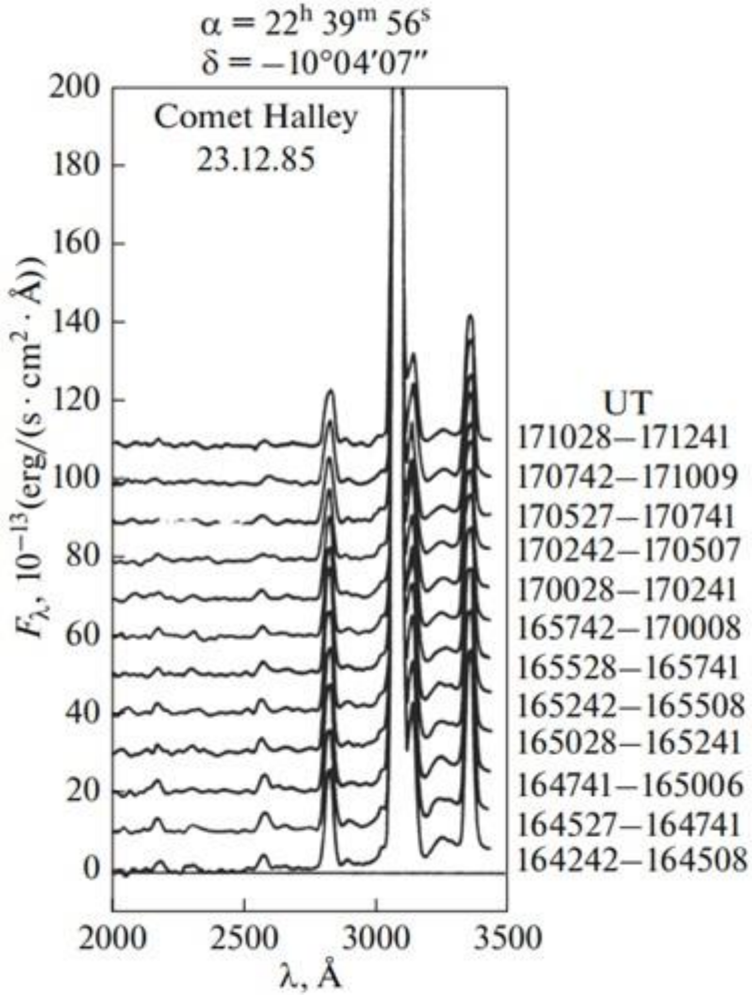
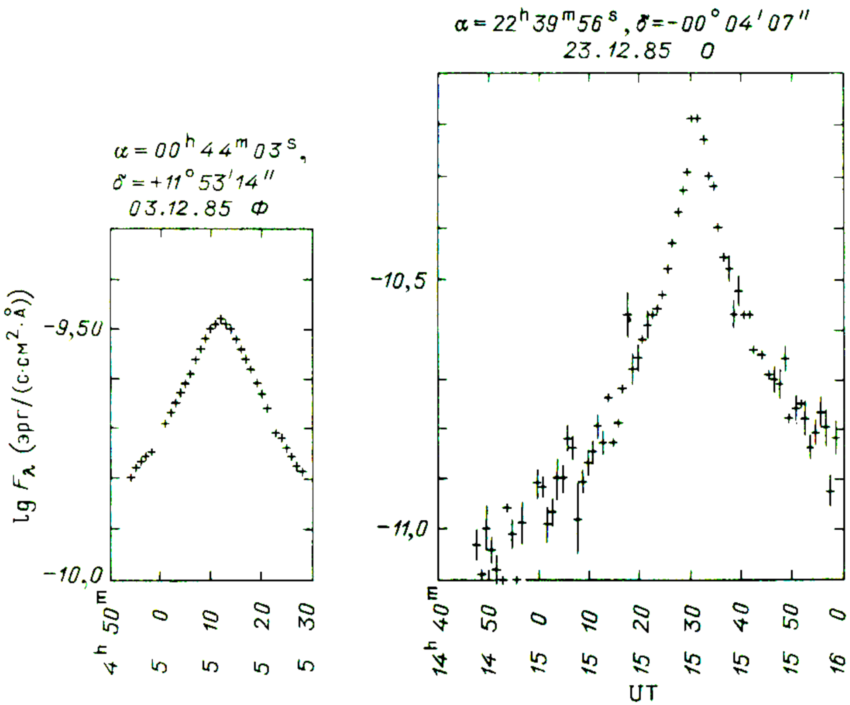


Fig. 2. A long wavelength 15 minute exposure of P/Halley (LWP 7773) obtained on 1986 March 11

Feldman+1987

Halley comet spectra
(ASTRON)





Boyarchuk, 1994

Observations of comets
(HST)

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

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

Some results from observation with HST

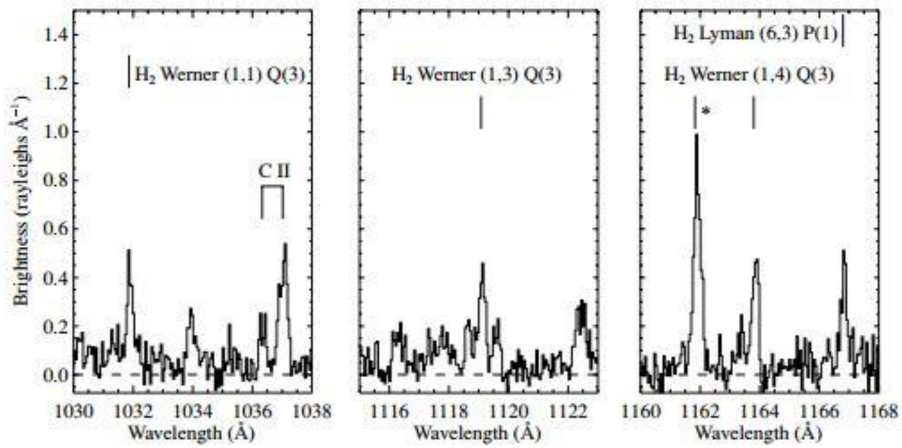
Four comets have been observed in FUV by the Cosmic Origins Spectrograph (COS): 103P/Hartley 2, C/2009 P1 (Garradd), C/2012 S1 (ISON), and C/2014 Q2 (Lovejoy).

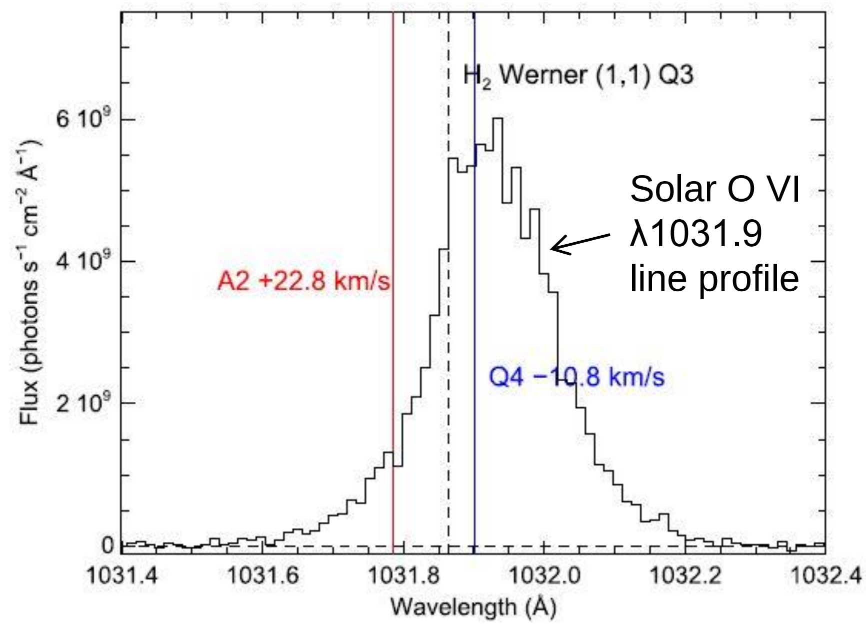
- The principal objective was to determine the relative CO abundance from measurements of the CO Fourth Positive system in the spectral range of 1400 to 1700 Å. In the two brightest comets, nineteen bands of this system were clearly identified.
- The water production rate was derived observations of the OH (0,0) band at 3085 Å by the Space Telescope Imaging Spectrograph (STIS). The derived CO/H_2O 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_2 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, λλ 905-1187 Å, Δλ ~0.4 Å).

<u>Some results.</u>
The relative strengths of the observed H2 line intensities vary predictably based on the comet's heliocentric velocity Doppler shift relative to the exciting solar Lyα and O VI lines.
Feldman+2009,2015





Observations of comets
(GALEX)

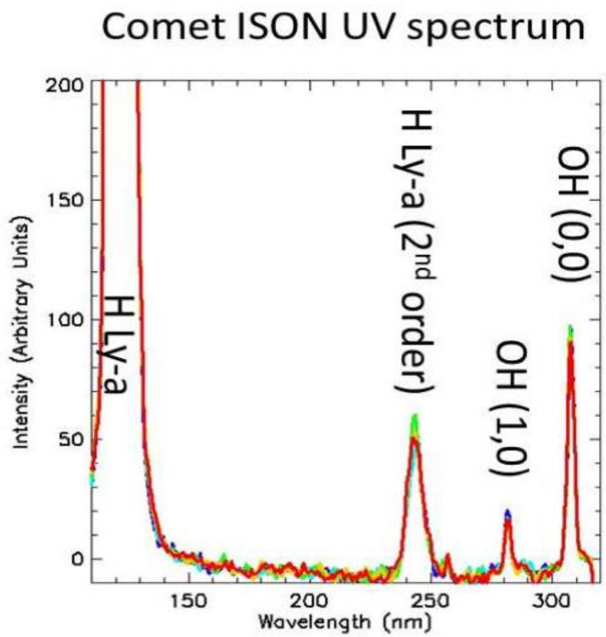
GALEX (grism): feeding apetrure 50cm, $\Delta\lambda$ ~ 10-20 Å
$\lambda\lambda$ 1350-1750 Å, 1750-2800 Å.
GALEX has observed 6 comets in 2005-2009 (C/2004 Q2 (Machholz), 9P/Tempel 1, 73P/Schwassmann-Wachmann 3 Fragments B and C, 8P/Tuttle and C/2007 N3 (Lulin). GALEX is designed to map the history of star formation in the Universe. It is also well suited to cometary coma studies because of its high sensitivity and large field of view.

<u>Some results:</u>
OH and CS in the NUV (1750-3100 Å Å) are clearly detected in all of the comet data. The FUV detected the bright C I 1561 and 1657 Å multiplets and evidences for S I 1475 Å in the FUV.
NEW: CO^+ emission in the NUV and CO Fourth positive band emission in the FUV are clearly detected.
(The $A^1\Pi$-$X^1\Sigma$ Fourth Positive system is the most prominent system of CO in UV (280-128 nm))

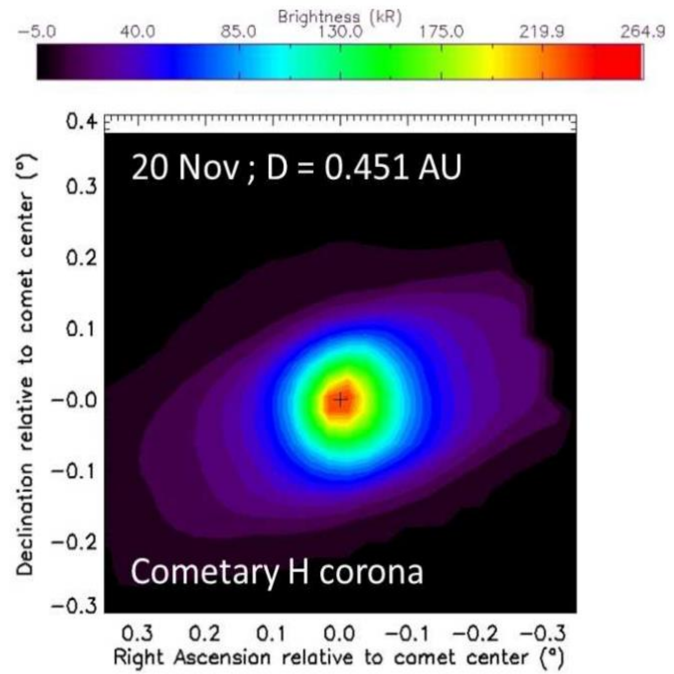
Morgenthaler+2009

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.

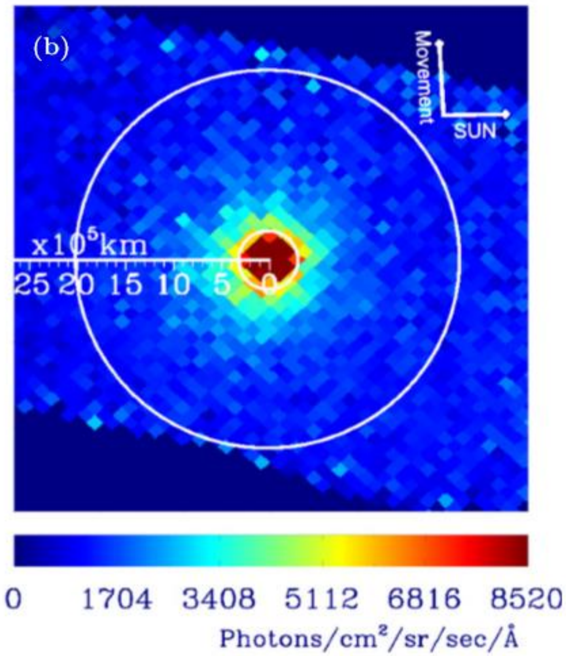


Example of map of the Lyman-α emission around ISON obtained by SPICAV-UV

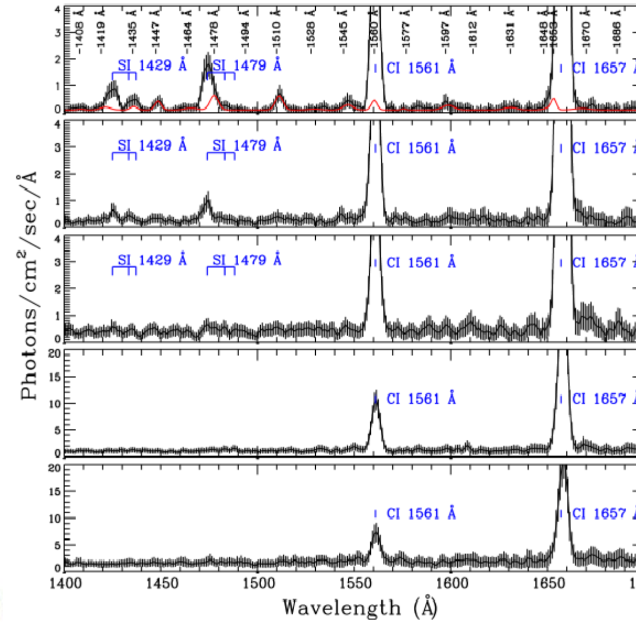
Chaufray&Bertaux2015

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 *λ/Δλ* ~ 550 for both channels) with large imaged fields of view (S-channel 4.0°×4.6', L-channel 7.5 °× 4.3', and angular resolution~5–10') 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.

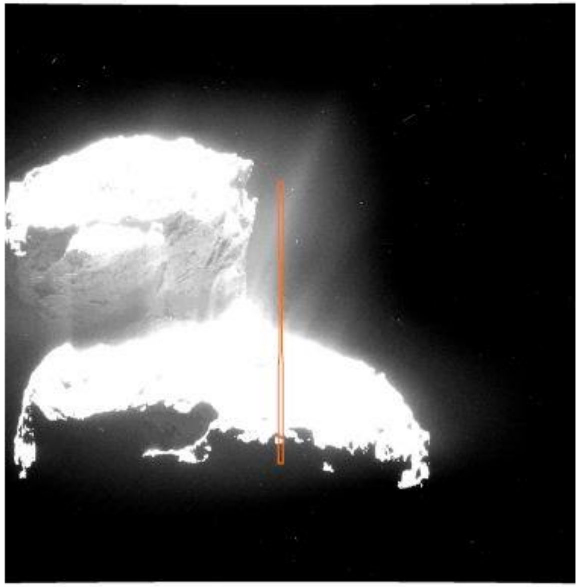


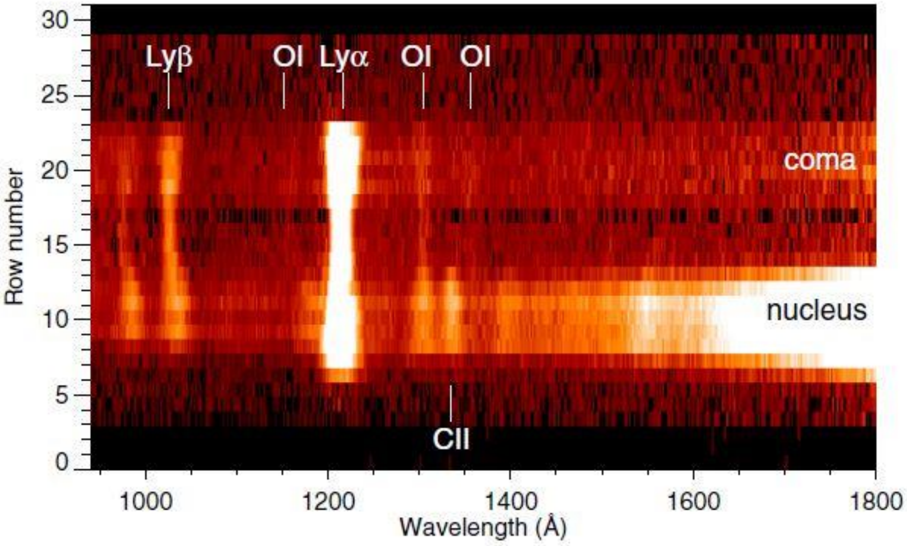
FIMS FUV spectral flux of comet C/2001 Q4 (NEAT) observed during the second campaign of 2004 May 14 and 15.

Lim et al., 2014

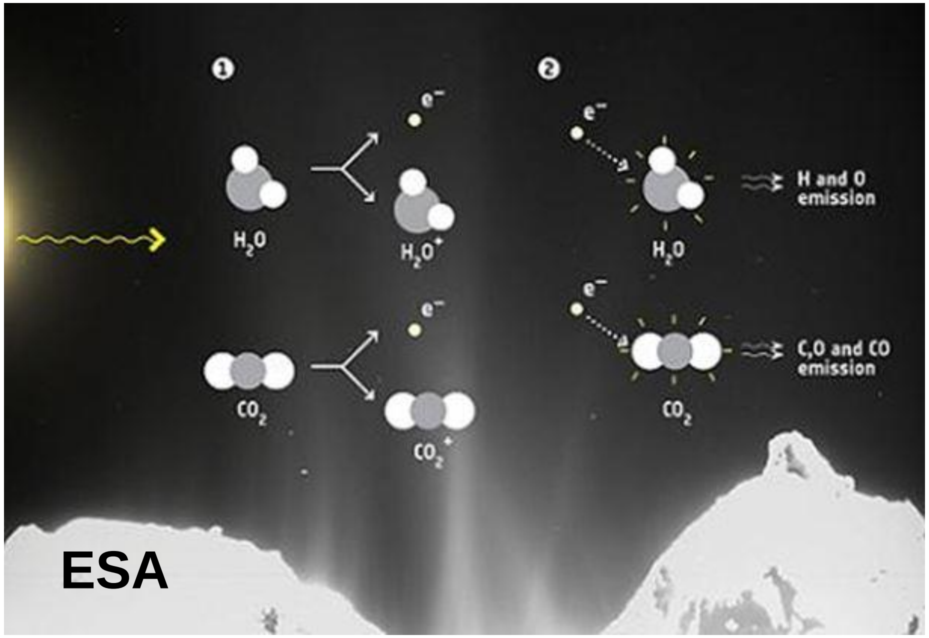
Comet 67P/Churyumov-Gerasimenko in Far UV (ALICE)

ALICE is imaging spectrograph in the λλ70−205 nm, Δλ 0.8 -1.2 nm. The slit, 5.5° long, with a width of 0.05 ° - 0.10 °. Alice employs an off-axis telescope feeding a 0.15-m normal incidence Rowland circle spectrograph with a concave holographic reflection grating. MCP detector utilizes solar-blind opaque photocathodes (KBr and CsI).





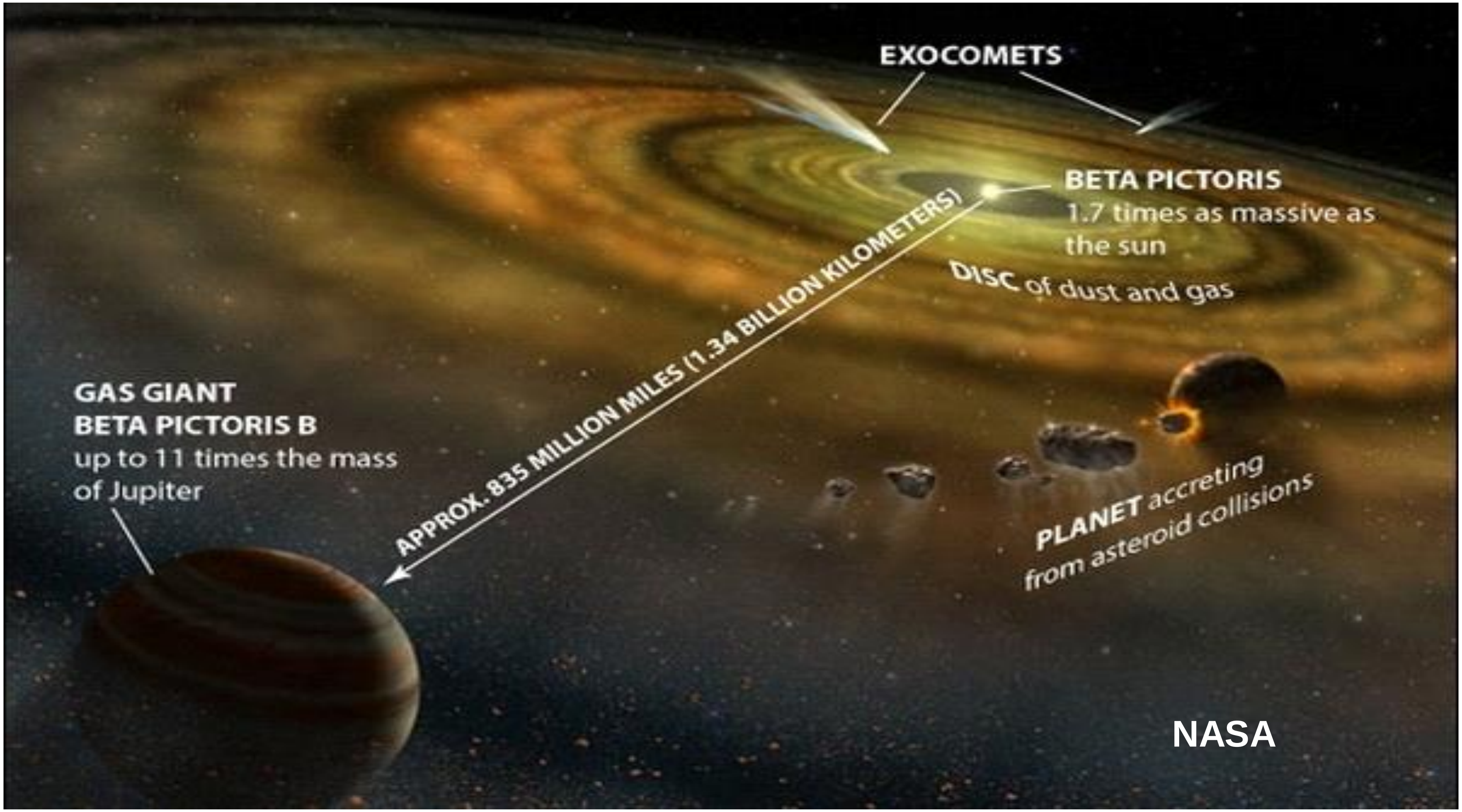
Discoveries with ALICE



Analysis of the relative line intensities suggests photoelectron impact dissociation of H2O vapor as the source of the observed HI and OI emissions. The electrons are produced by photoionization of H2O within 1 km above the comet nucleus. The observed Ci emissions are also attributed to electron impact dissociation, of CO2, and their relative brightness to Hi reflects the variation of CO2 to H2O column abundance in the coma.

Feldman+2015

Exocomets



There are more than ten stars in which the existence of exocomets is found.

Exocomets were first discovered in UV

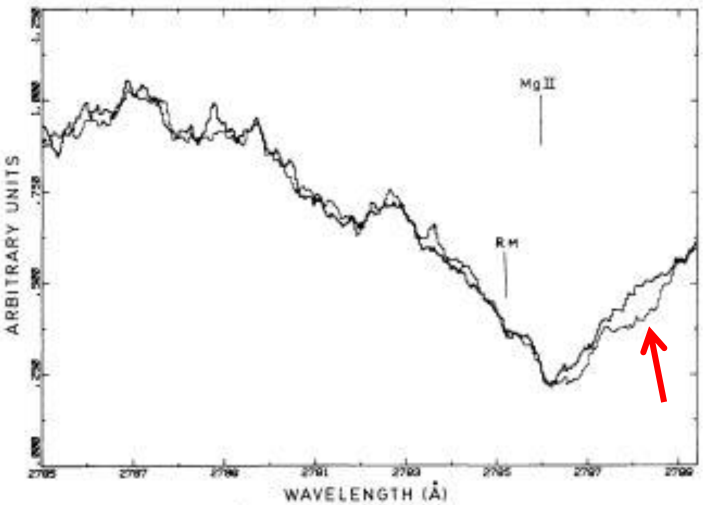


Fig. 3a. Mg II line 2795 Å; β Pictoris line in May, 1985 (thin line) over β Pictoris line in December, 1984 (thick line). Data from LWP 5891 (β Pictoris, May 1985) and LWP 5016 (β Pictoris, December 1984) (also in Fig. 3b)

The infalling bodies were first suggested by *Lagrange+87.* Time variation of redshifted wings of MgII 2796 and FeII 2586 (IUE obs.)

V_{fall} 20-120 km/s

Astron. Astrophys. 290, 245–258 (1994)

HST-GHRS observations of β Pictoris: additional evidence for infalling comets*

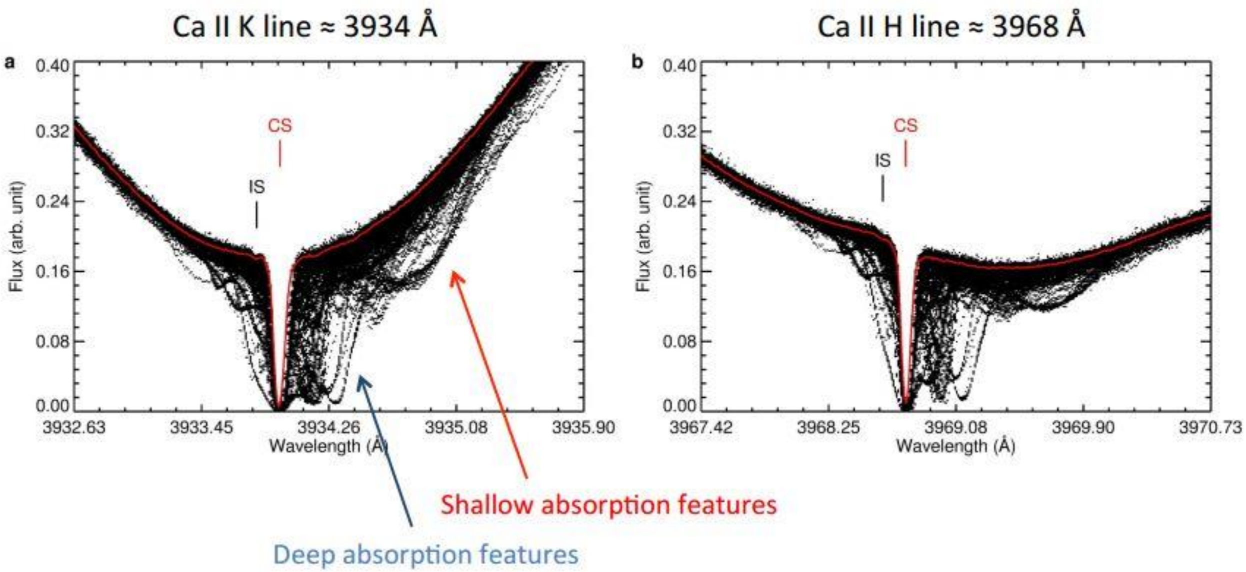
A. Vidal-Madjar[1], A-M. Lagrange-Henri[2], P.D. Feldman[3], H. Beust[1,2,8], J.J. Lissauer[4], M. Deleuil[5], R. Ferlet[1], C. Gry[5], L.M. Hobbs[6], M.A. McGrath[7], J.B. McPhate[3], and H.W. Moos[3]

Data obtained in 1992 with GHRS at high resolution and sensitivity reinforces the model that both the changes in spectral line shapes as well as the very presence of CI, CIV and CO observed in the environment of β Pic may be explained by the evaporation of several kilometer-sized bodies as they approach the star.

Exocomets in visual domain

Spectroscopic follow up of variable absorption features in the β Pictoris Ca II doublet with HARPS

- 1106 spectra collected with **HARPS** between 2003 and 2011,
- An average of 6 variable absorption feature detected per spectrum in Ca II doublet,
- A total of 493 individual exocomets identified.



F.Kiefer - Two families of exocomets in the β Pictoris system at Conf. «Thirty years of Beta Pic and debris disks studies» Paris, 2014

To date, the search for exocomets has focused on young (<50 Myr) A-type stars, which can provide a promising environment for studying young planetary system evolution and may be relatively rich in comet-like debris.

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.

Thanks you for attention! תודה על תשומת הלב שלך!