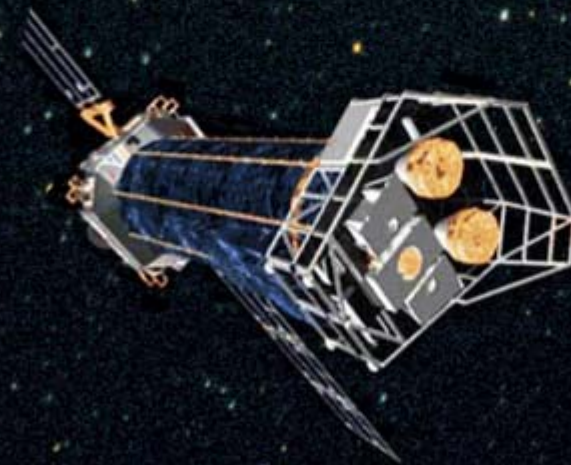


High Resolution X-ray Spectroscopy of Comets

with XMM-Newton / RGS

*Konrad Dennerl
Max Planck Institute for
extraterrestrial Physics
Garching, Germany*



optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerl



Rosat

1990-1999



Chandra

since 1999



XMM-Newton

since 1999



Very Low Resolution X-ray Spectroscopy of Comets
with Rosat / HRI



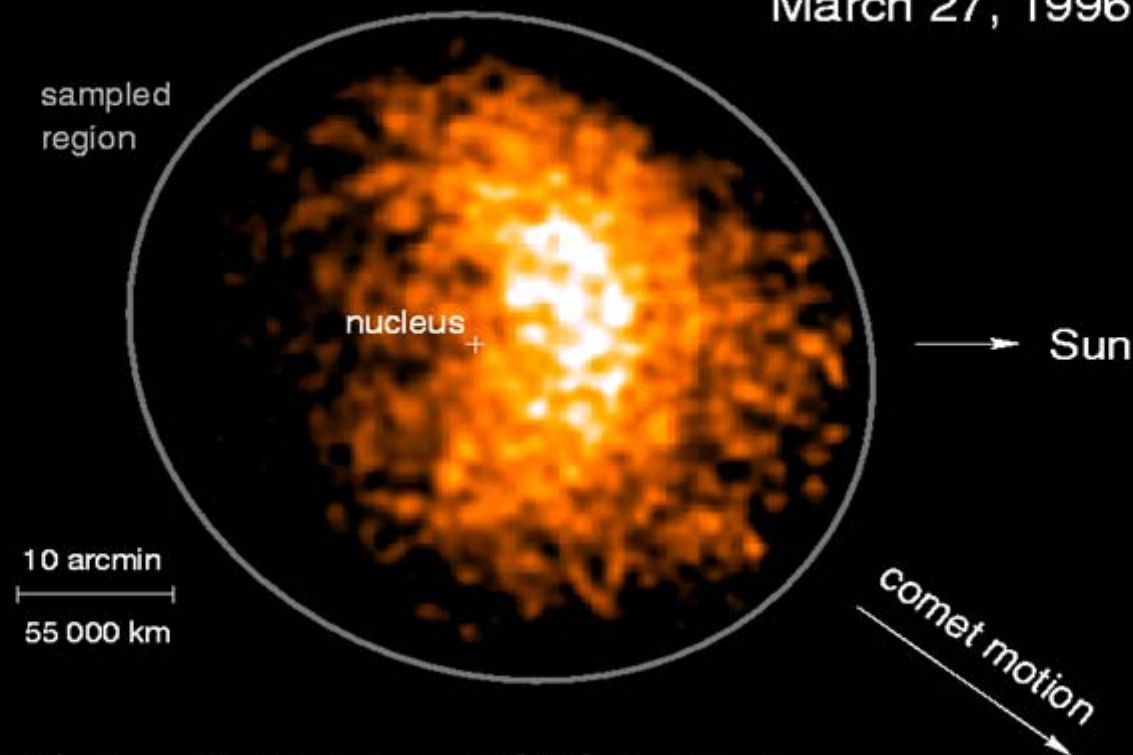
optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerd

FIRST X-RAY IMAGE OF A COMET

Comet Hyakutake · C/1996 B2

ROSAT **HRI**

March 27, 1996



C. Lisse, M. Mumma, NASA GSFC

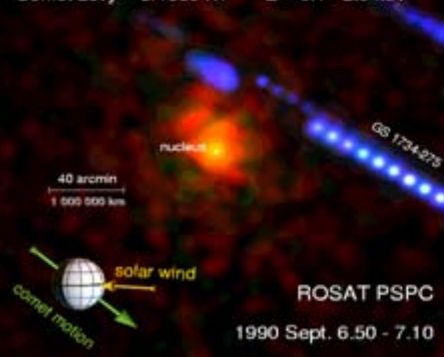
K. Dennerl, J. Schmitt, J. Englhauser, MPE

Low Resolution X-ray Spectroscopy of Comets

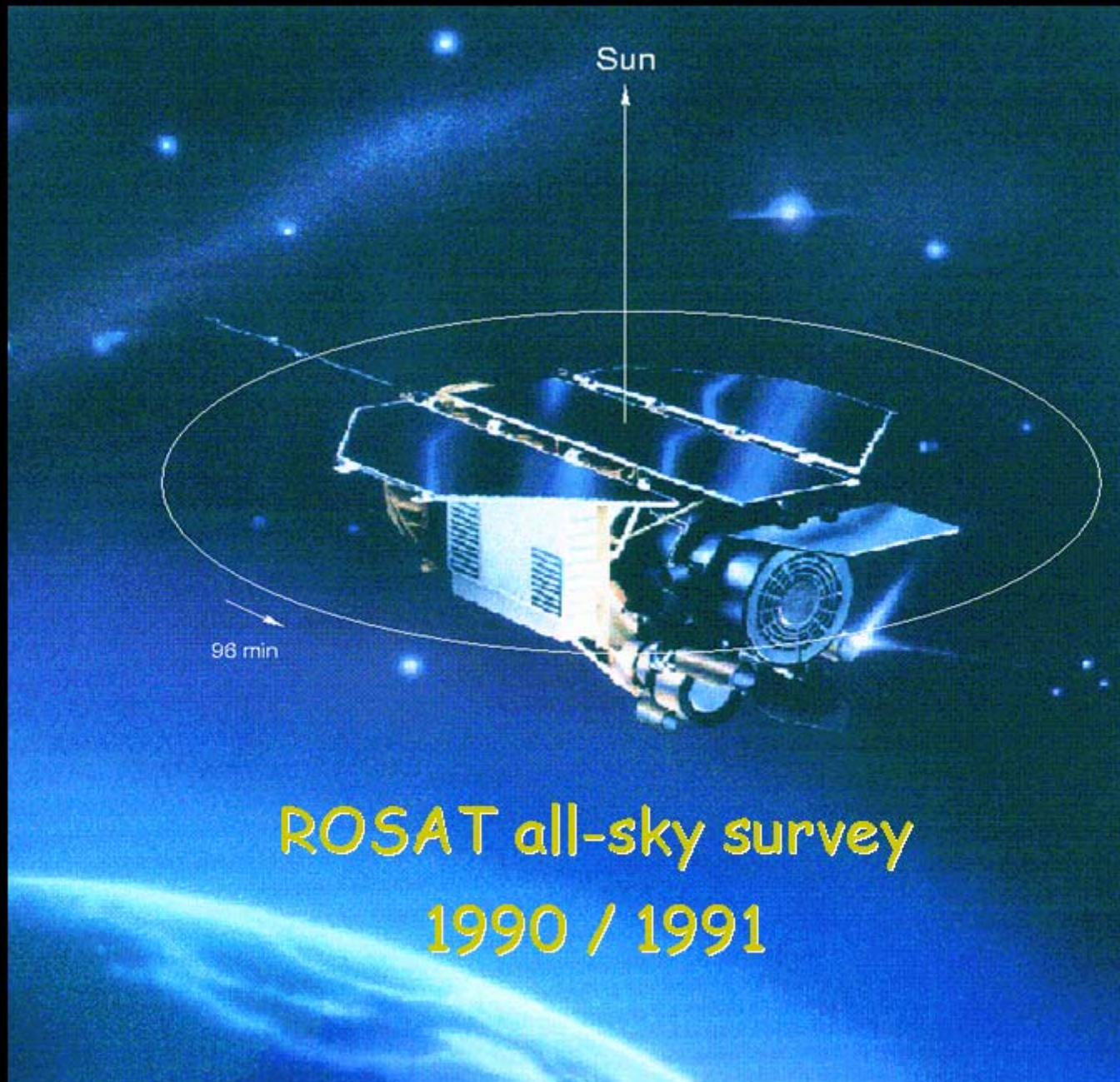
with Rosat / PSPC

FIRST X-RAY COLOR IMAGE OF A COMET

Comet Levy - C/1990 K1 E = 0.1 - 2.0 keV

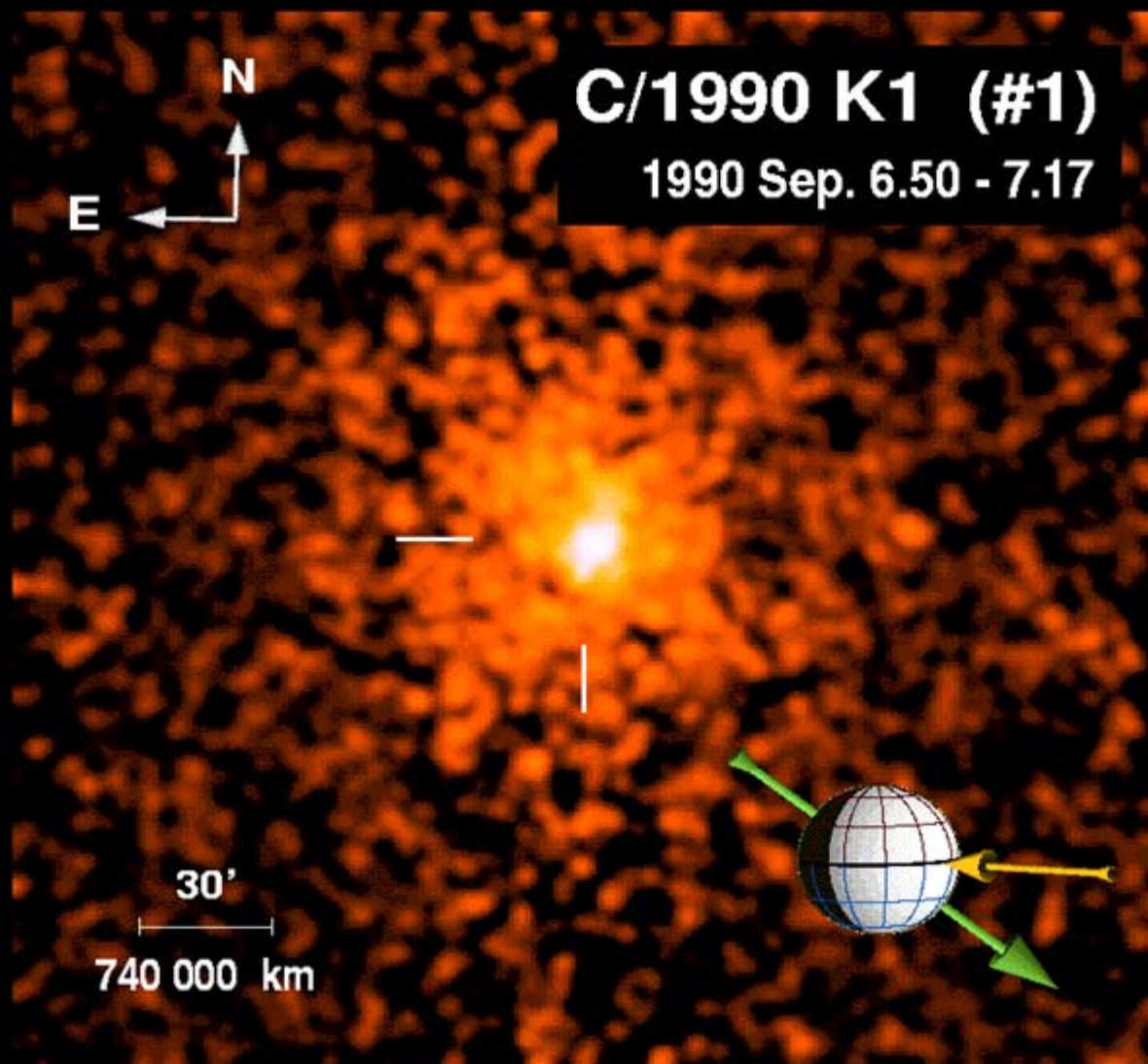


optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerl



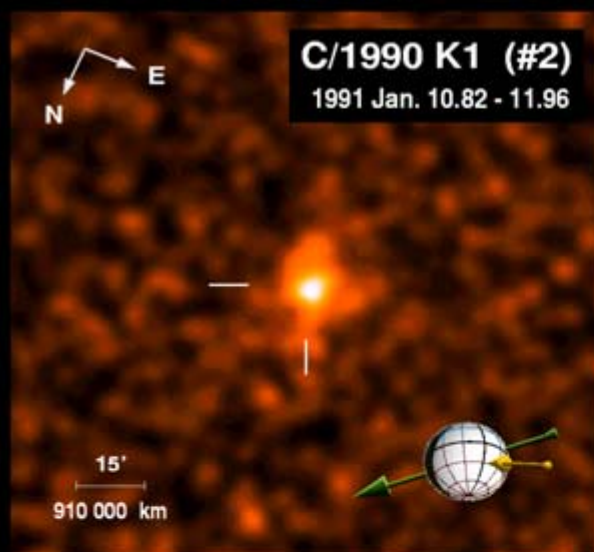
ROSAT all-sky survey 1990 / 1991

Comet Levy



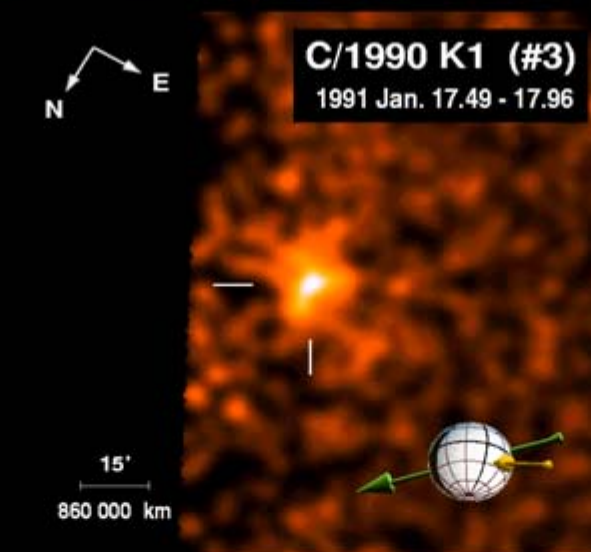
ROSAT PSPC ALL-SKY SURVEY $E = 0.1 - 0.4 \text{ keV}$

Comet Levy



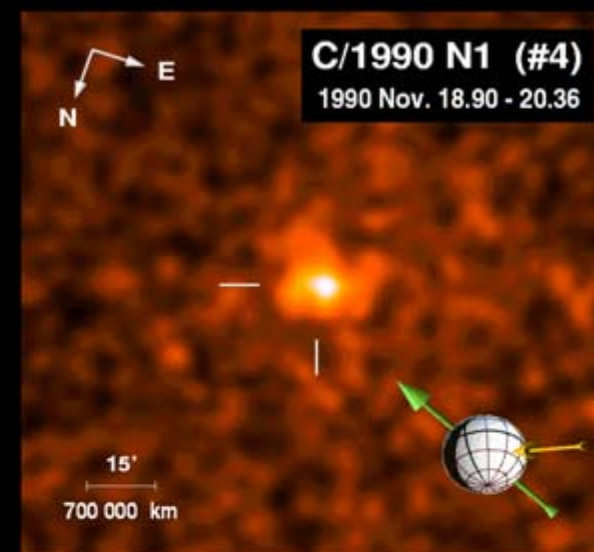
ROSAT PSPC ALL-SKY SURVEY E = 0.1 - 0.4 keV

Comet Levy



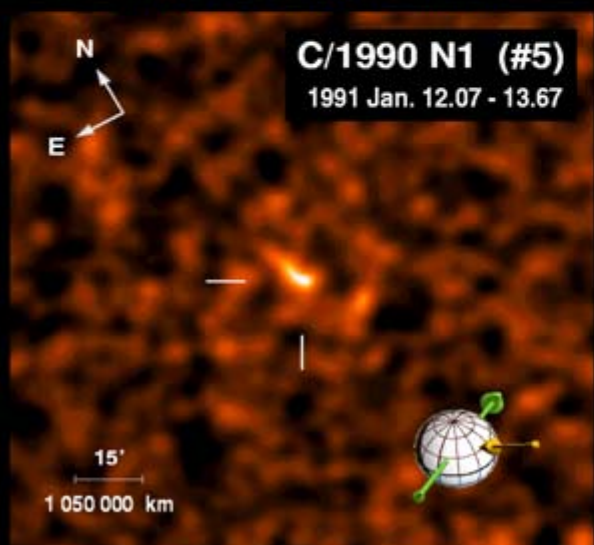
ROSAT PSPC ALL-SKY SURVEY E = 0.1 - 0.4 keV

Comet Tsuchiya-Kiuchi



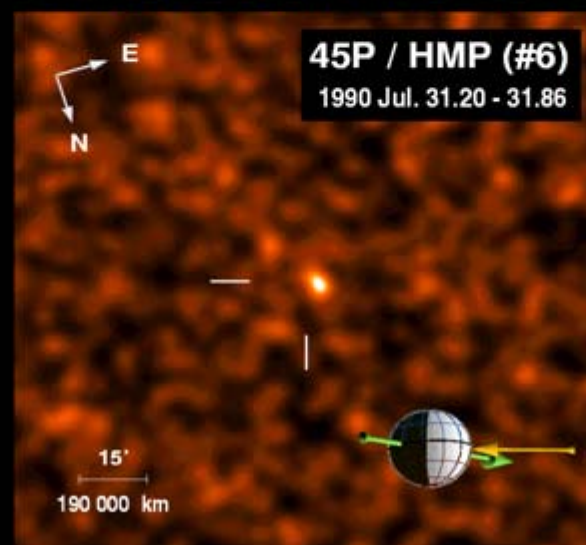
ROSAT PSPC ALL-SKY SURVEY E = 0.1 - 0.4 keV

Comet Tsuchiya-Kiuchi



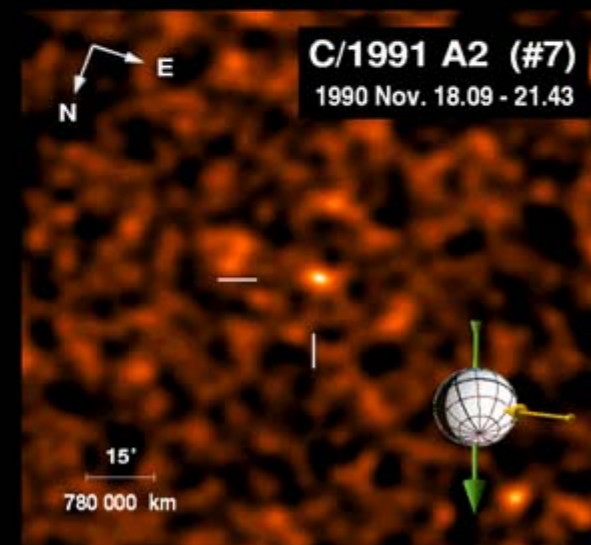
ROSAT PSPC ALL-SKY SURVEY E = 0.1 - 0.4 keV

Comet Honda-Mrkos-Pajdušáková



ROSAT PSPC ALL-SKY SURVEY E = 0.1 - 0.4 keV

Comet Arai

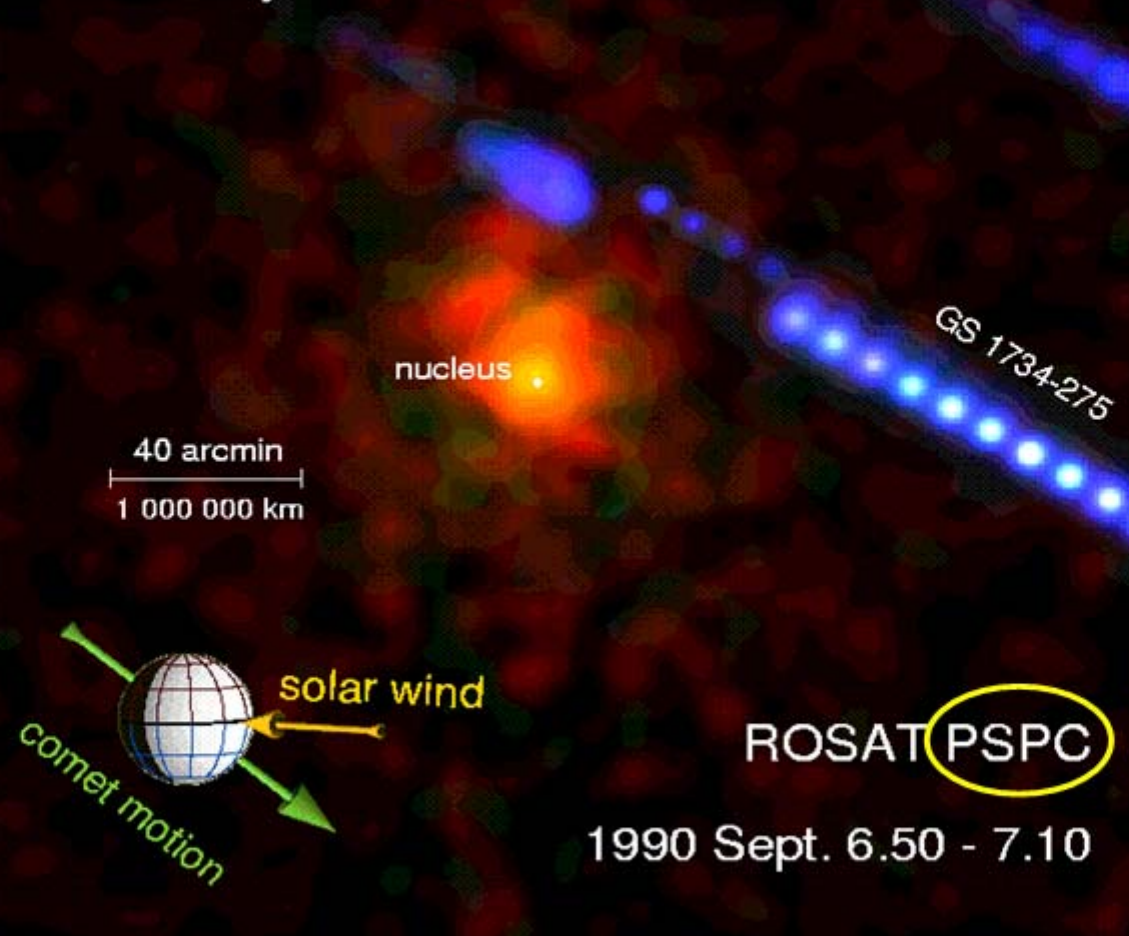


ROSAT PSPC ALL-SKY SURVEY E = 0.1 - 0.4 keV

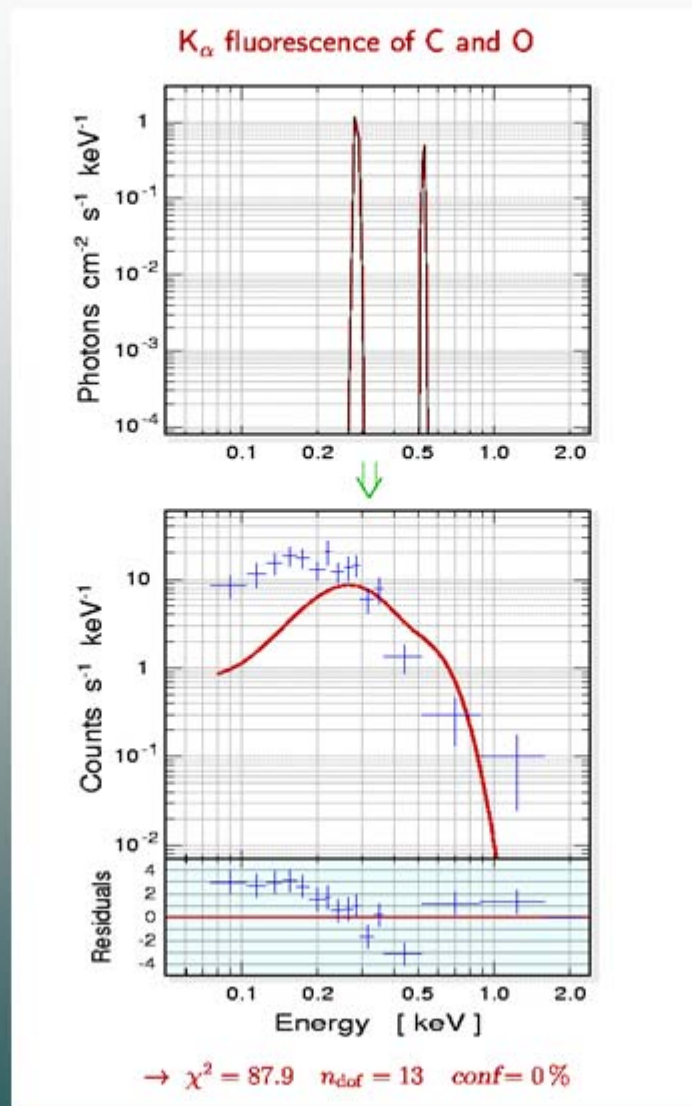
FIRST X-RAY COLOR IMAGE OF A COMET

Comet Levy • C/1990 K1

$E = 0.1 - 2.0 \text{ keV}$

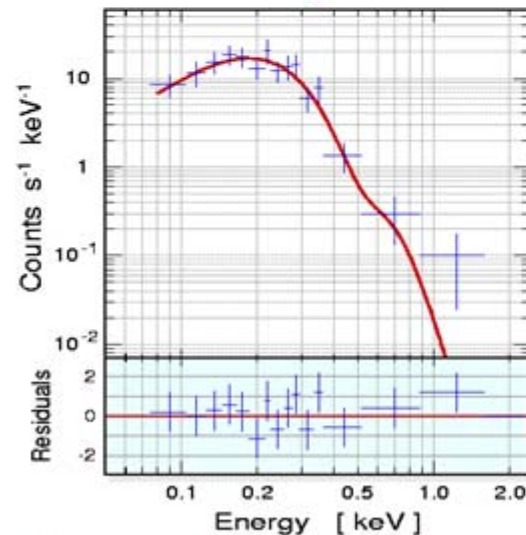
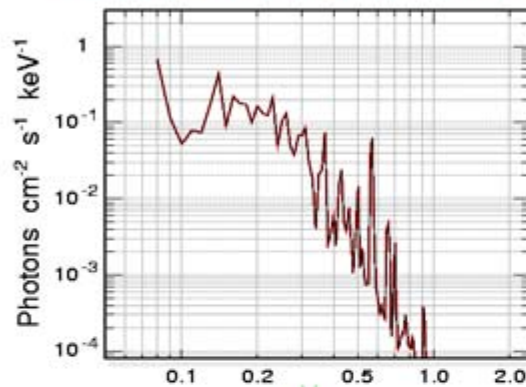


ROSAT PSPC spectra of Comet C/1990 K1 (Levy)

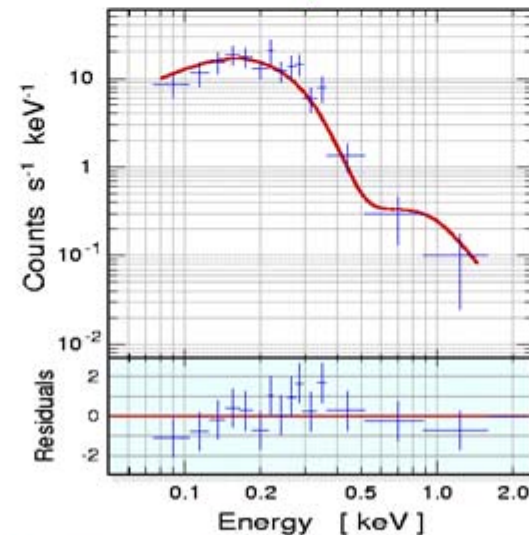
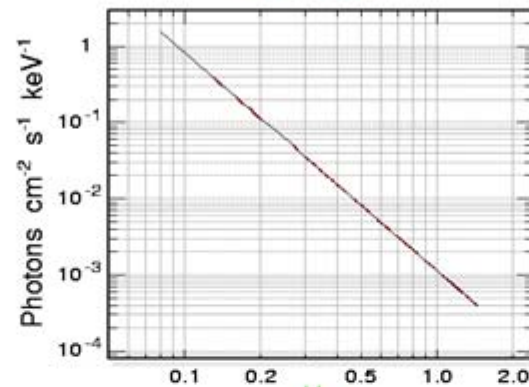


ROSAT PSPC spectra of Comet C/1990 K1 (Levy)

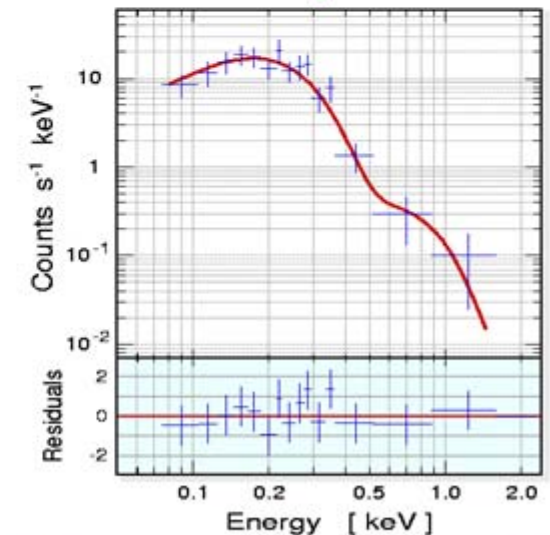
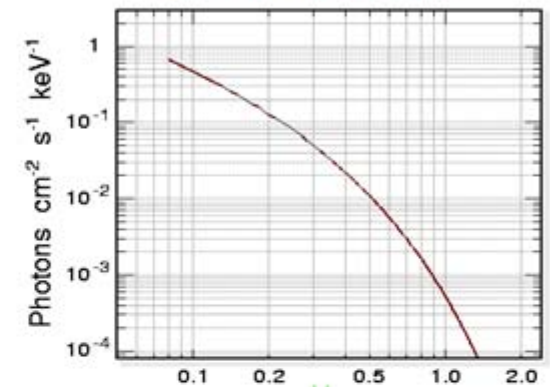
thermal plasma (Raymond-Smith)



power law

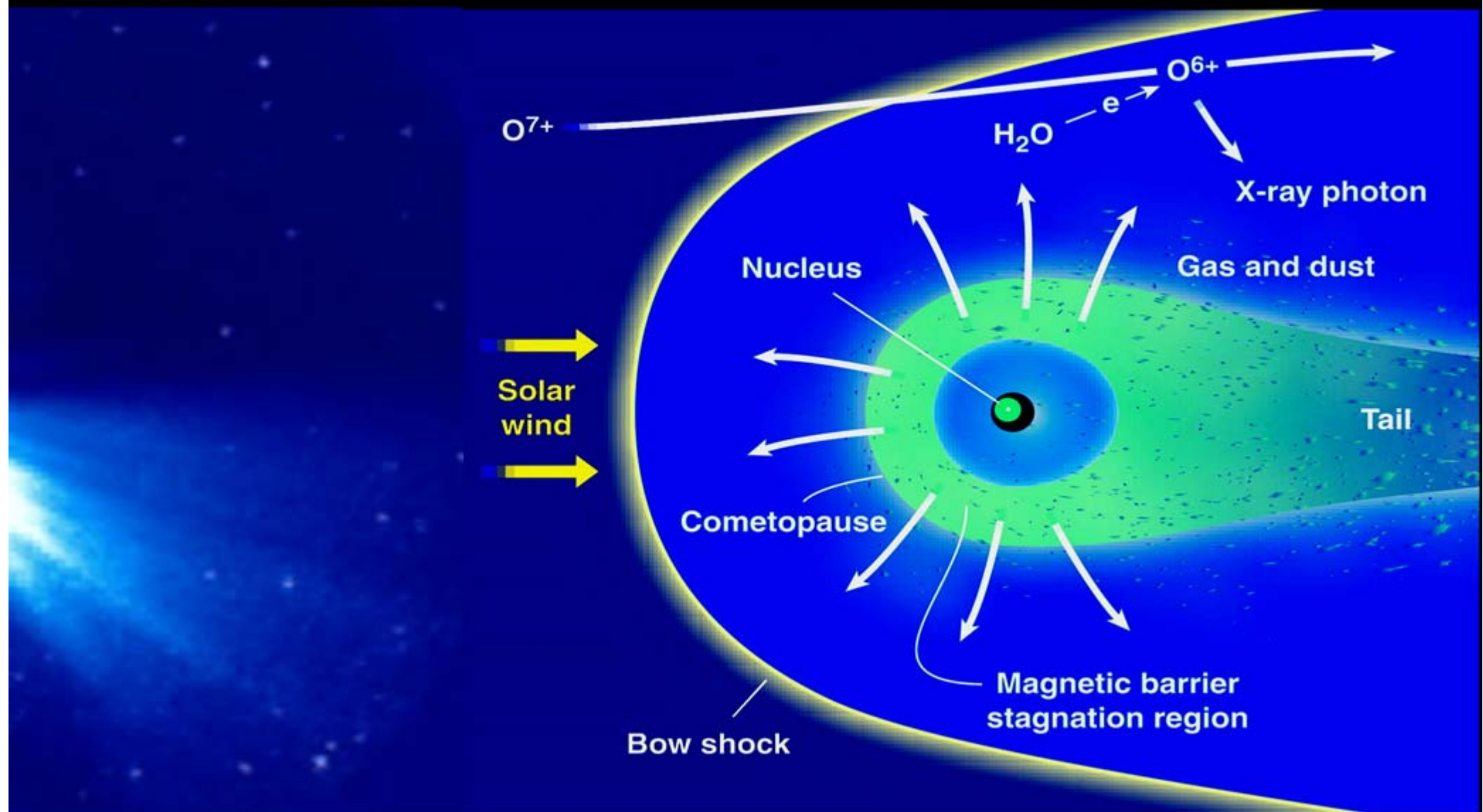


thermal bremsstrahlung



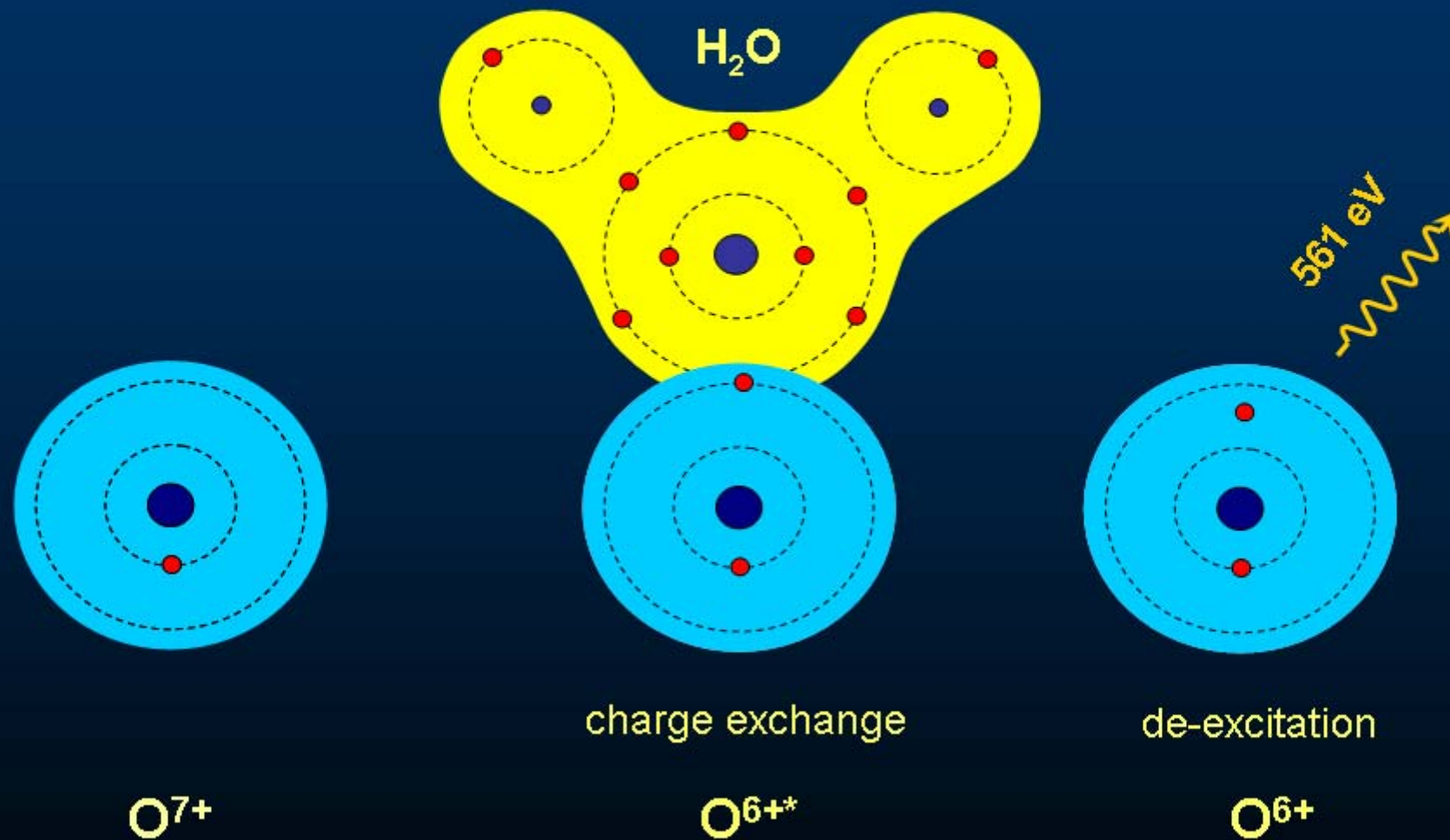
$\chi^2 = 8.19$ $n_{\text{dof}} = 13$ $\text{conf} = 83.1\%$ $kT = (0.12 \pm 0.02)$ keV $\rightarrow$ $\chi^2 = 11.1$ $n_{\text{dof}} = 13$ $\text{conf} = 60.2\%$ $\alpha = (-2.9 \pm 0.3)$ $\chi^2 = 7.15$ $n_{\text{dof}} = 13$ $\text{conf} = 89.4\%$ $kT = (0.23 \pm 0.06)$ keV

Interaction of the solar wind with the cometary gas



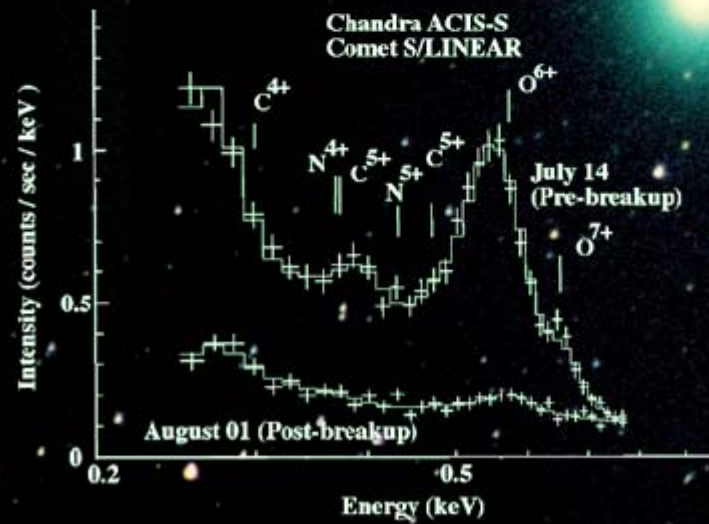
Cravens 1997 (GRL 24), Cravens 2002 (Science 296)

Charge Exchange



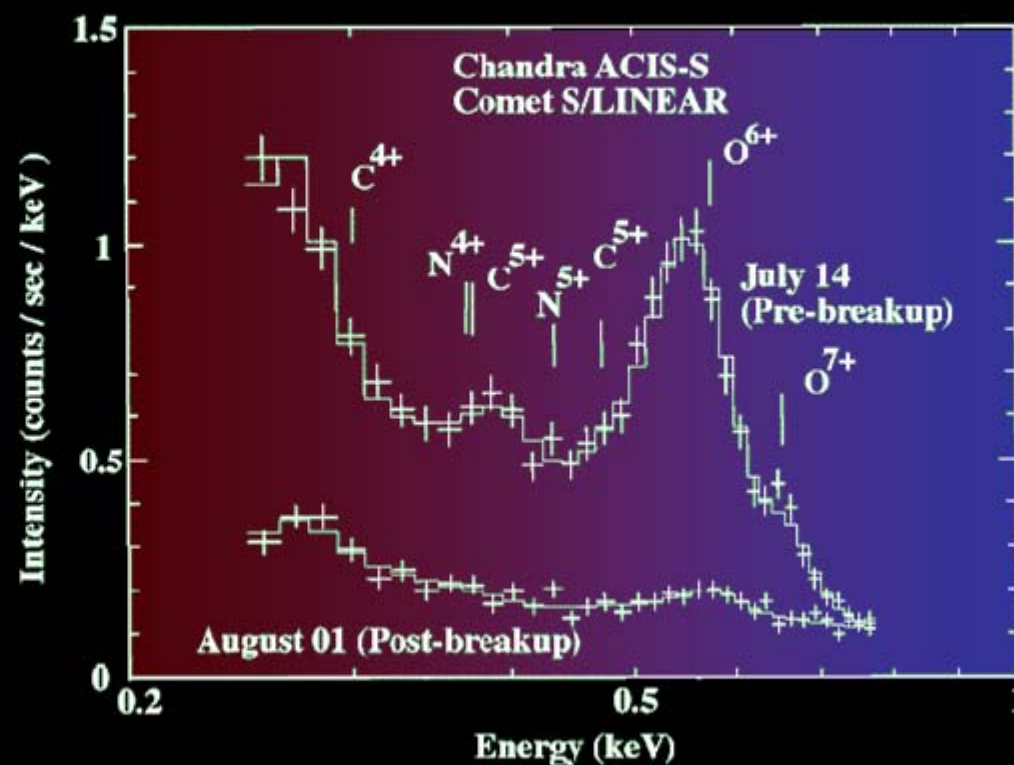
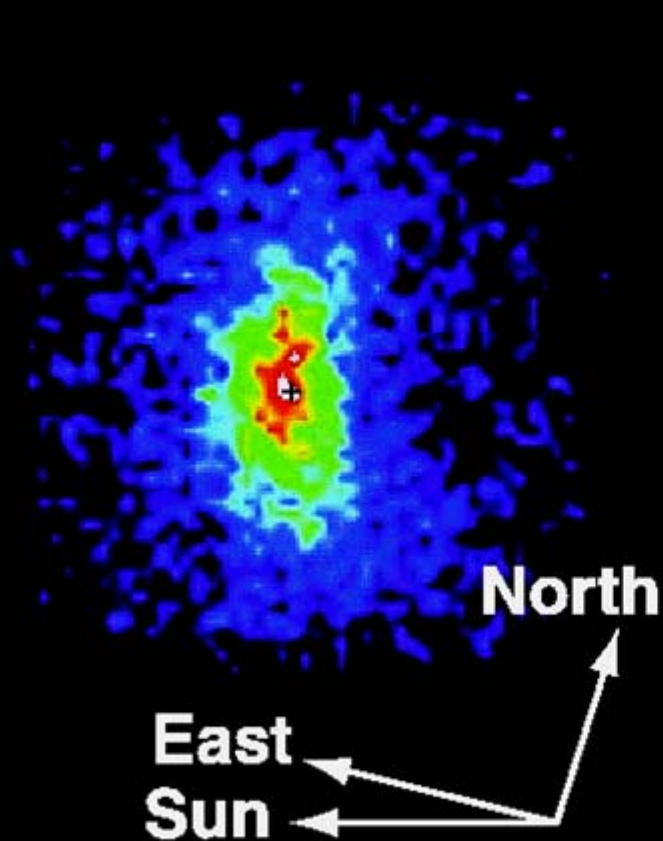
Medium Resolution X-ray Spectroscopy of Comets

with Chandra / ACIS-S



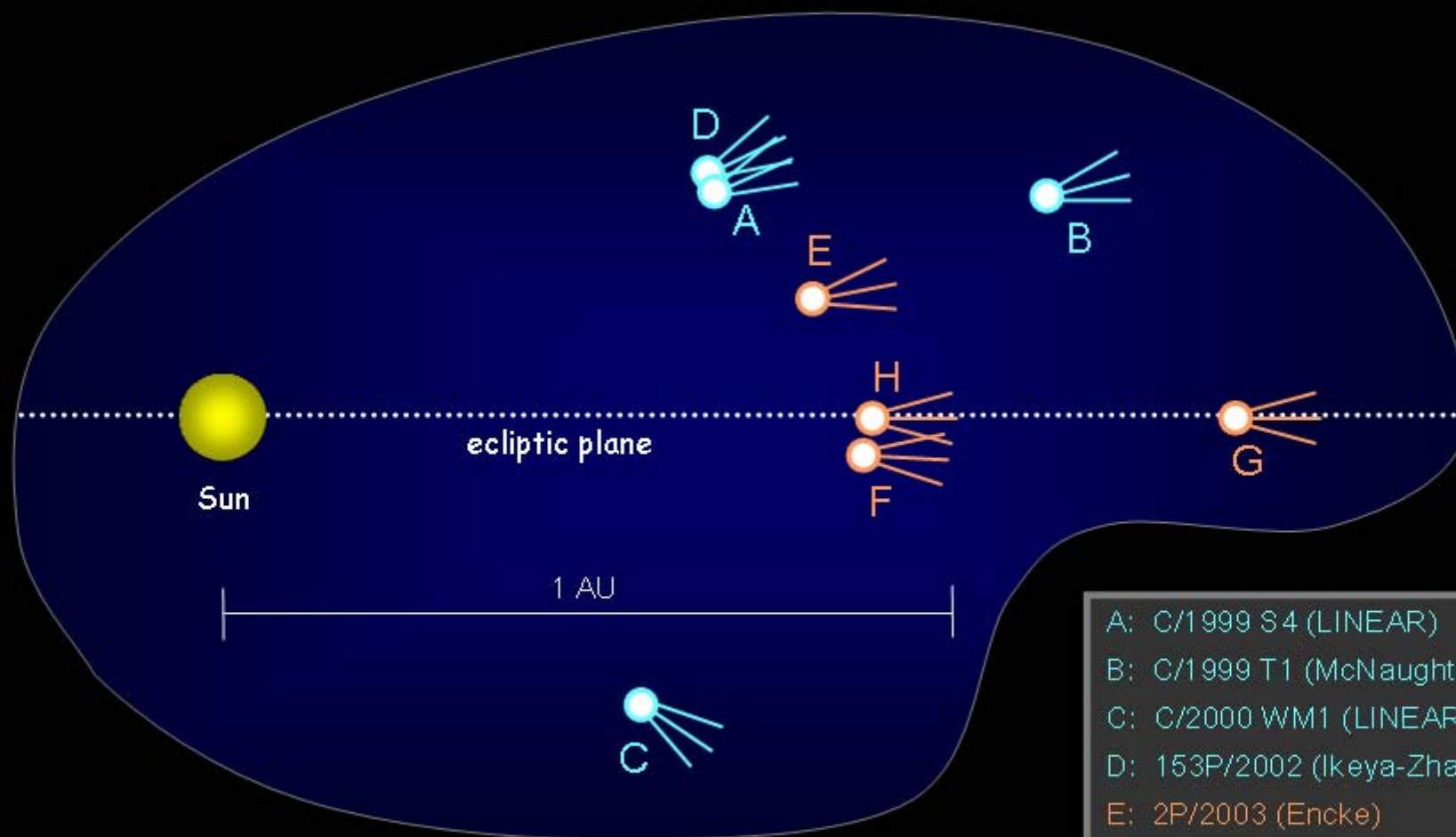
optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerl

July 2000: first direct detection of charge exchange
induced X-ray line emission with Chandra ACIS-S



Lisse et al. 2001, Science 292, 1334-1348

Comets observed with Chandra, 2000 - 2007



→ ensemble properties of comets

- A: C/1999 S4 (LINEAR)
- B: C/1999 T1 (McNaught-Hartley)
- C: C/2000 WM1 (LINEAR)
- D: 153P/2002 (Ikeya-Zhang)
- E: 2P/2003 (Encke)
- F: C/2001 Q4 (NEAT)
- G: 9P/2005 (Tempel 1)
- H: 73P/2006 (SW3-B)

Bodewits et al., A&A 469, 2007

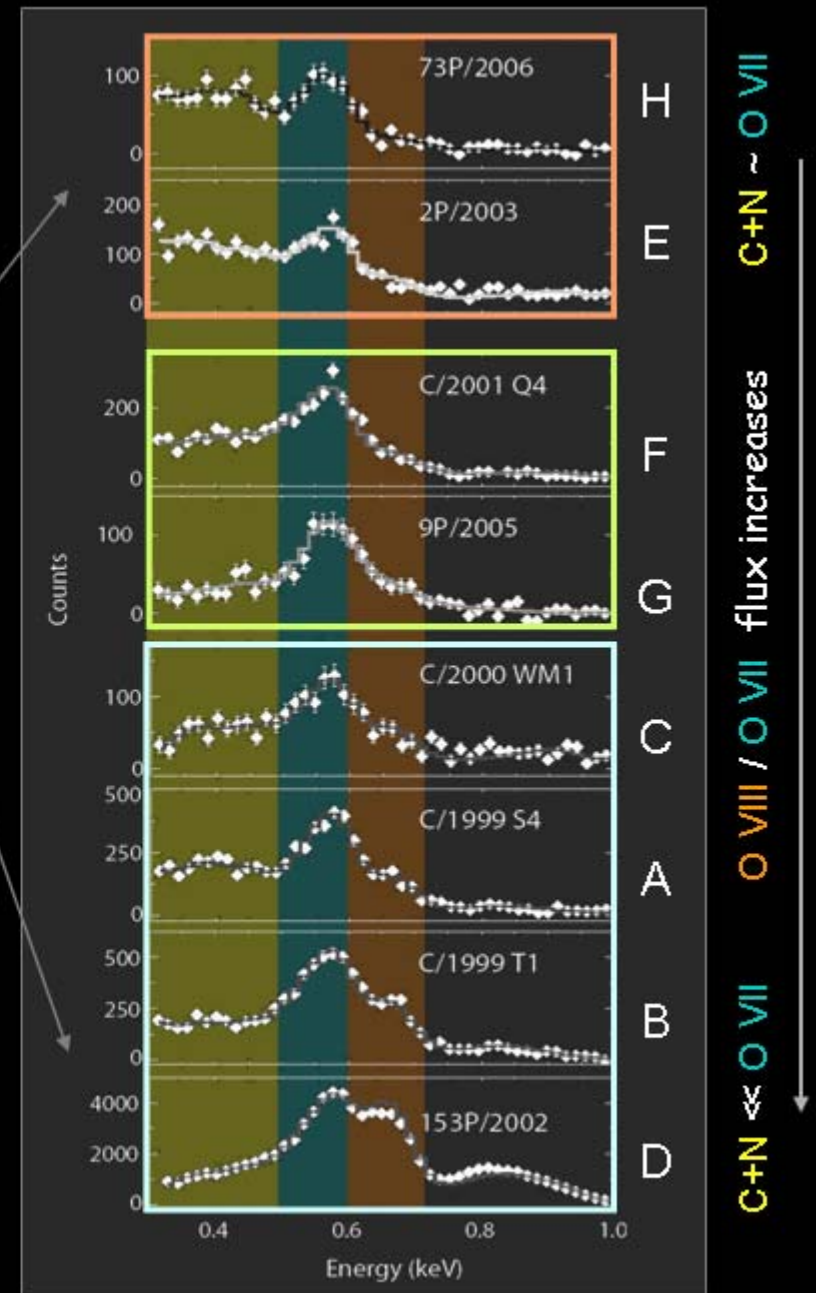
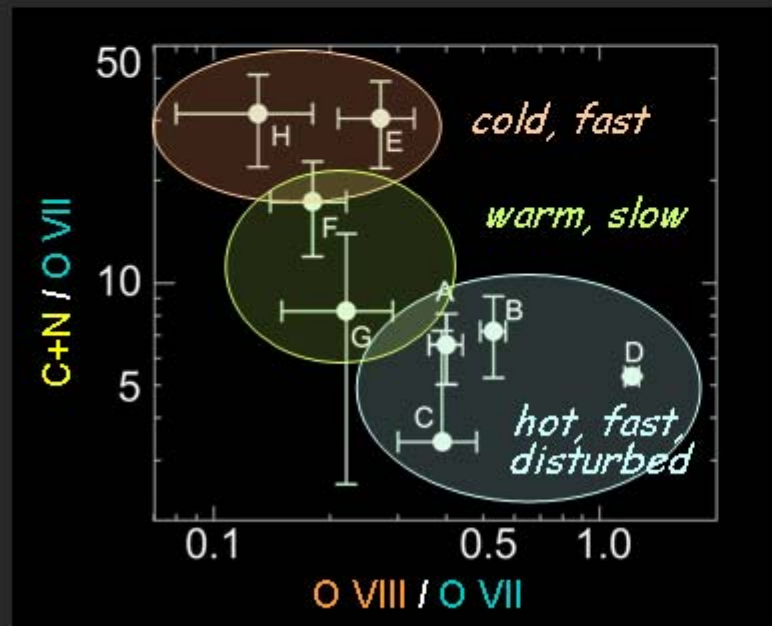
Chandra spectra of comets:

three competing emission features:

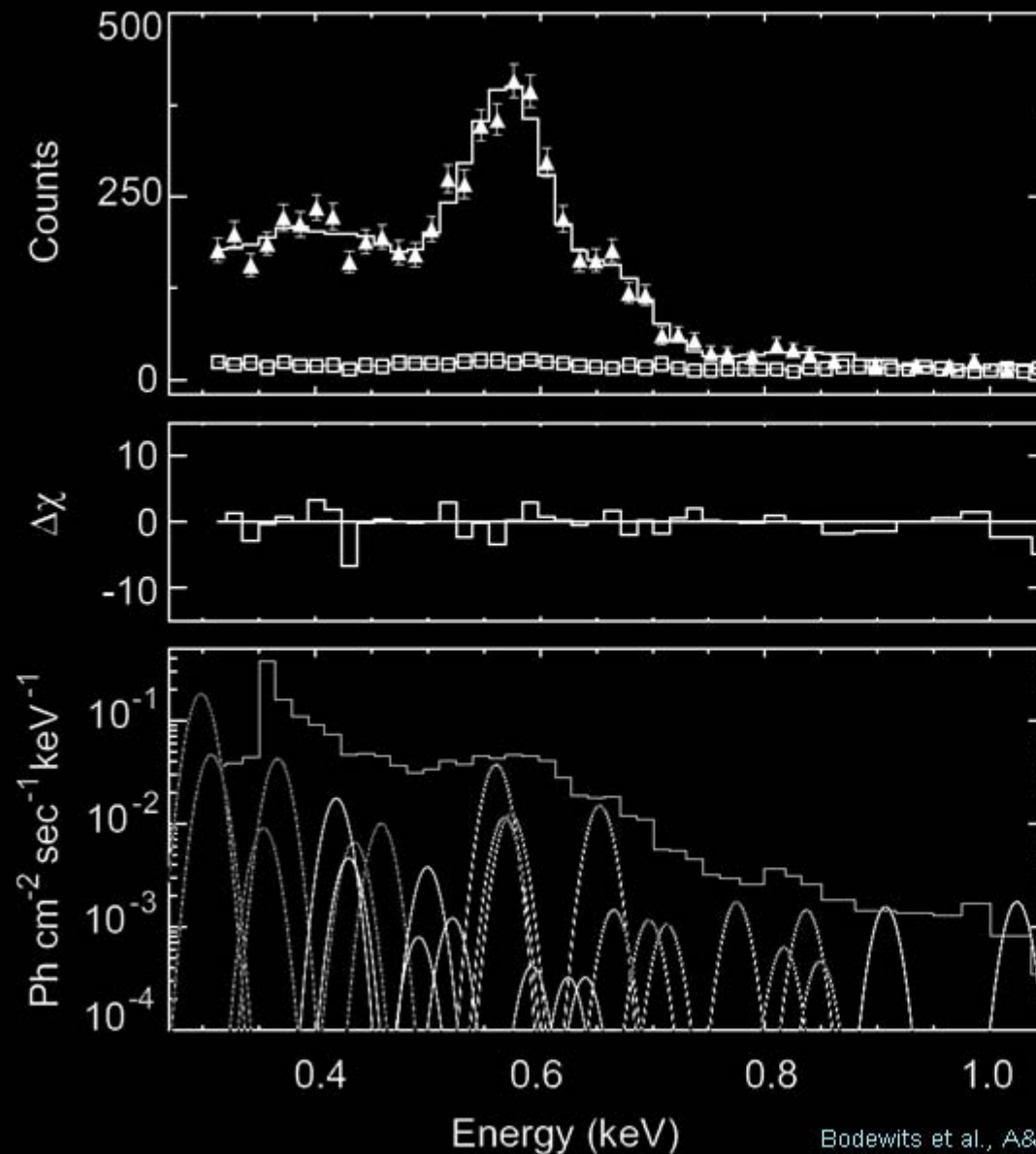
1. C and N emission below 500 eV
2. O VII emission at 565 eV
3. O VIII emission at 654 eV

low abundance of highly charged oxygen $\rightarrow$ cold wind
high abundance of highly charged oxygen $\rightarrow$ hot wind

$\rightarrow$ flux ratios of all observed comets:



Chandra ACIS-S: Comet C/1999 S4 (LINEAR)



Bodewits et al., A&A 469, 2007

35 emission lines (!)

→ line fluxes are
highly coupled,
even if line energies
and line widths are
fixed

Theoretical, velocity dependent cross sections [10^{-16} cm^2]

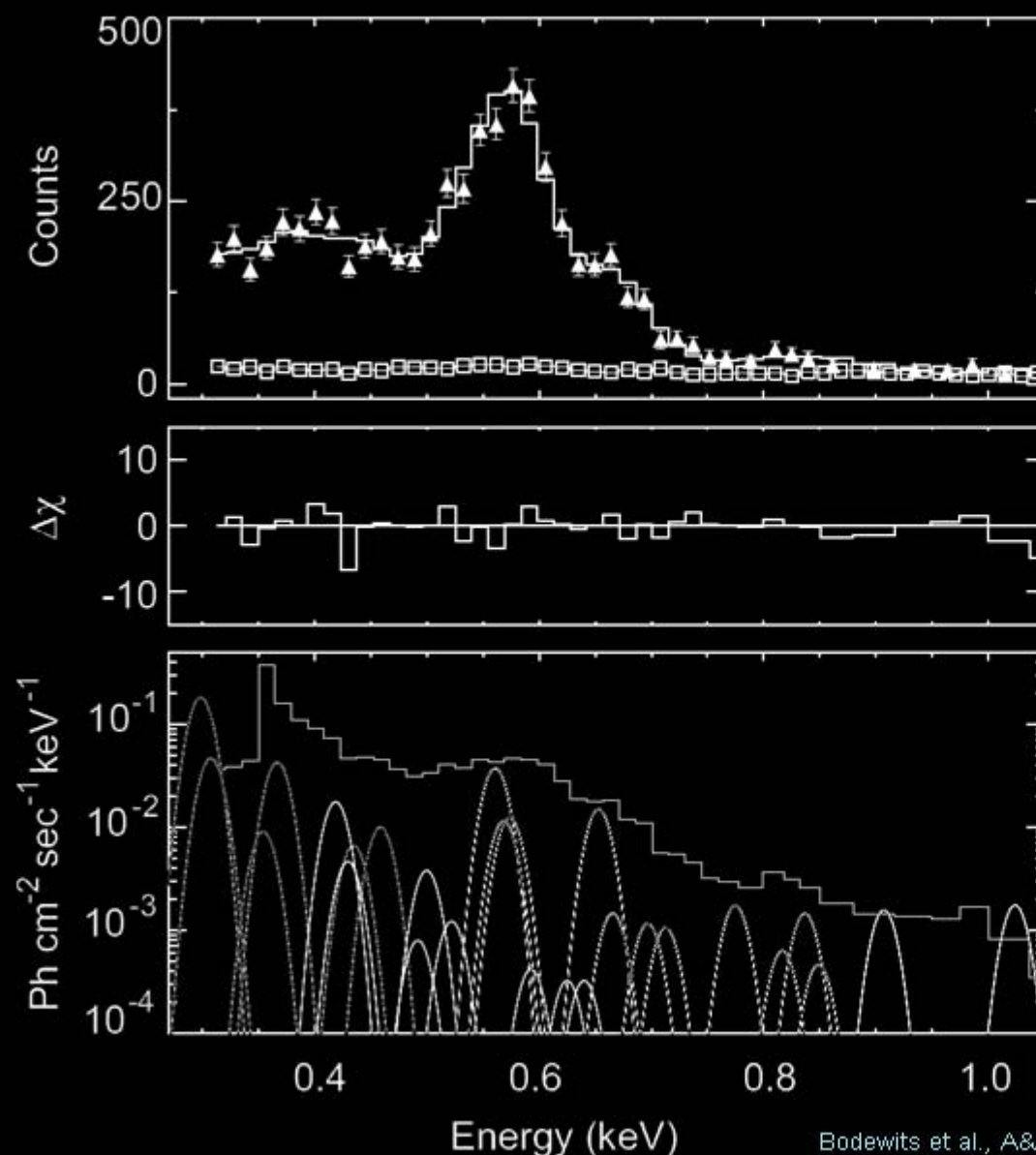
E (eV)	Ion	Transition	200 km s ⁻¹	400 km s ⁻¹	600 km s ⁻¹	800 km s ⁻¹	1000 km s ⁻¹
299.0	C V	z	8.7	12	16	18	20
304.4	C V	x, y	0.65	1.0	1.5	1.7	1.8
307.9	C V	w	1.8	3.0	4.1	4.8	5.2
354.5	C V	$1s3p-1s^2$	0.55	0.71	0.81	1.0	1.3
367.5	C V	$1s4p-1s^2$	0.70	0.66	0.76	0.74	0.72
367.5	C VI	$2p-1s$	15	26	30	33	34
378.9	C V	$1s5p-1s^2$	0.00	0.02	0.05	0.04	0.04
419.8	N VI	z	13	23	28	29	29
426.3	N VI	x, y	2.7	4.3	5.3	5.7	6.0
430.7	N VI	w	3.8	6.0	7.4	8.1	8.5
435.5	C VI	$3p-1s$	1.6	4.0	4.7	4.7	4.8
459.4	C VI	$4p-1s$	2.9	5.9	7.0	6.4	6.0
471.4	C VI	$5p-1s$	0.55	1.0	1.3	0.85	0.54
497.9	N VI	$1s3p-1s^2$	0.43	0.99	1.3	1.3	1.3
500.3	N VII	$2p-1s$	40	45	44	42	42
523.0	N VI	$1s4p-1s^2$	0.81	1.6	1.9	1.8	1.7
534.1	N VI	$1s5p-1s^2$	0.14	0.31	0.33	0.21	0.14
561.1	O VII	z	37	34	33	32	31
568.6	O VII	x, y	10	10	10	9.9	9.7
574.0	O VII	w	9.9	11	11	11	10
592.9	N VII	$3p-1s$	6.3	4.9	4.8	4.5	4.3
625.3	N VII	$4p-1s$	2.9	2.9	3.7	4.3	4.6
640.4	N VII	$5p-1s$	11	5.2	3.7	2.7	2.2
650.2	N VII	$6p-1s$	0.00	0.21	0.13	0.09	0.08
653.5	O VIII	$2p-1s$	27	40	48	51	53
665.6	O VII	$1s3p-1s^2$	1.7	1.3	1.3	1.2	1.2
697.8	O VII	$1s4p-1s^2$	0.81	0.79	1.0	1.2	1.3
712.8	O VII	$1s5p-1s^2$	2.8	1.3	0.92	0.68	0.54
722.7	O VII	$1s6p-1s^2$	0.00	0.06	0.04	0.02	0.02
774.6	O VIII	$3p-1s$	2.6	4.7	5.6	5.3	5.0
817.0	O VIII	$4p-1s$	1.0	1.6	2.0	2.2	2.3
836.5	O VIII	$5p-1s$	2.4	4.0	4.6	4.1	3.7
849.1	O VIII	$6p-1s$	1.6	1.6	1.5	1.1	0.67

33
emission
lines

→ 6
groups

Bodewits et al., A&A 469, 2007

Chandra ACIS-S: Comet C/1999 S4 (LINEAR)

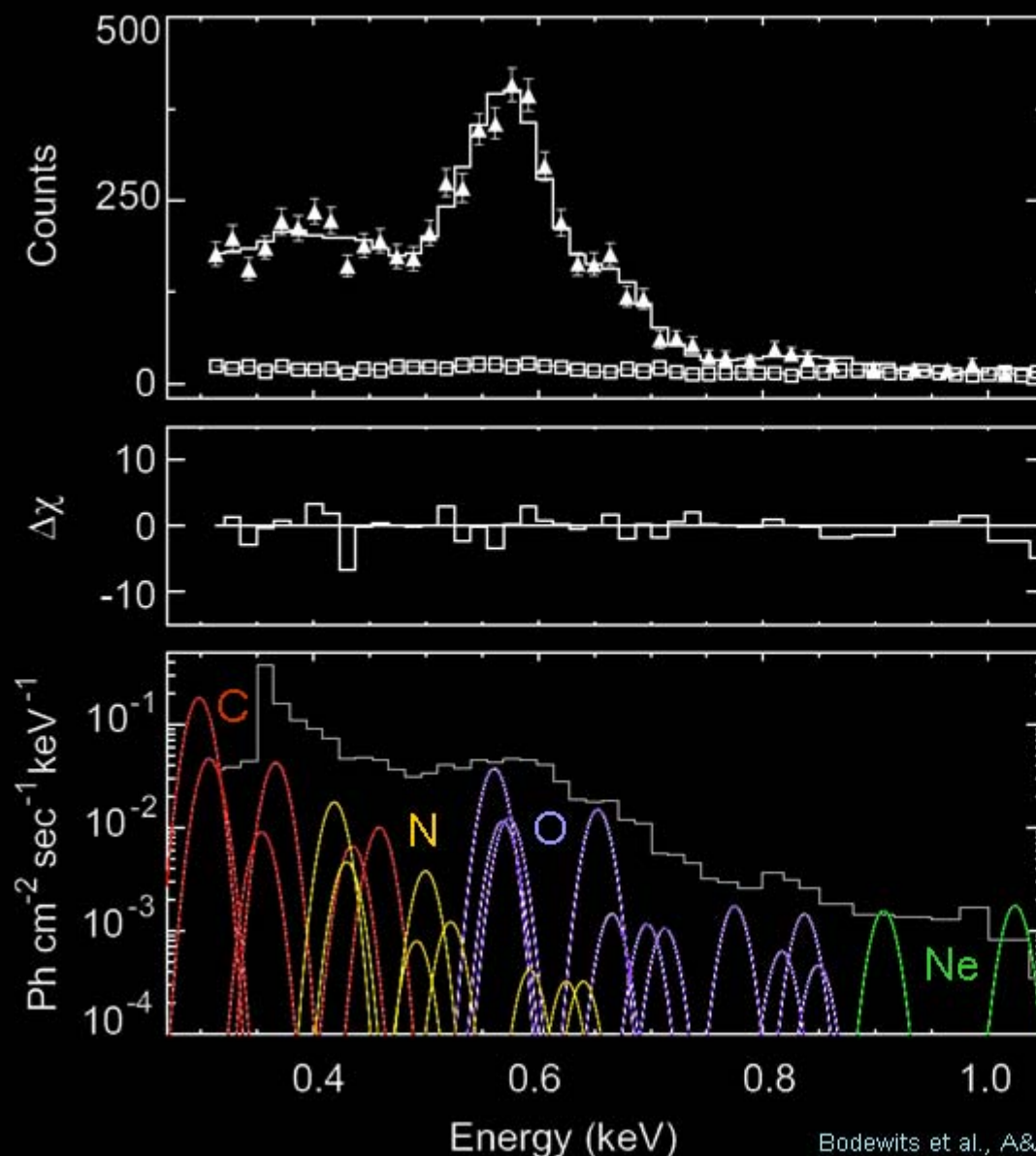


Bodewits et al., A&A 469, 2007

33 free parameters:

E (eV)	Ion	Transition
299.0	C V	z
304.4	C V	x, y
307.9	C V	w
354.5	C V	$1s3p-1s^2$
367.5	C V	$1s4p-1s^2$
367.5	C VI	$2p-1s$
378.9	C V	$1s5p-1s^2$
419.8	N VI	z
426.3	N VI	x, y
430.7	N VI	w
435.5	C VI	$3p-1s$
459.4	C VI	$4p-1s$
471.4	C VI	$5p-1s$
497.9	N VI	$1s3p-1s^2$
500.3	N VII	$2p-1s$
523.0	N VI	$1s4p-1s^2$
534.1	N VI	$1s5p-1s^2$
561.1	O VII	z
568.6	O VII	x, y
574.0	O VII	w
592.9	N VII	$3p-1s$
625.3	N VII	$4p-1s$
640.4	N VII	$5p-1s$
650.2	N VII	$6p-1s$
653.5	O VIII	$2p-1s$
665.6	O VII	$1s3p-1s^2$
697.8	O VII	$1s4p-1s^2$
712.8	O VII	$1s5p-1s^2$
722.7	O VII	$1s6p-1s^2$
774.6	O VIII	$3p-1s$
817.0	O VIII	$4p-1s$
836.5	O VIII	$5p-1s$
849.1	O VIII	$6p-1s$

Chandra ACIS-S: Comet C/1999 S4 (LINEAR)

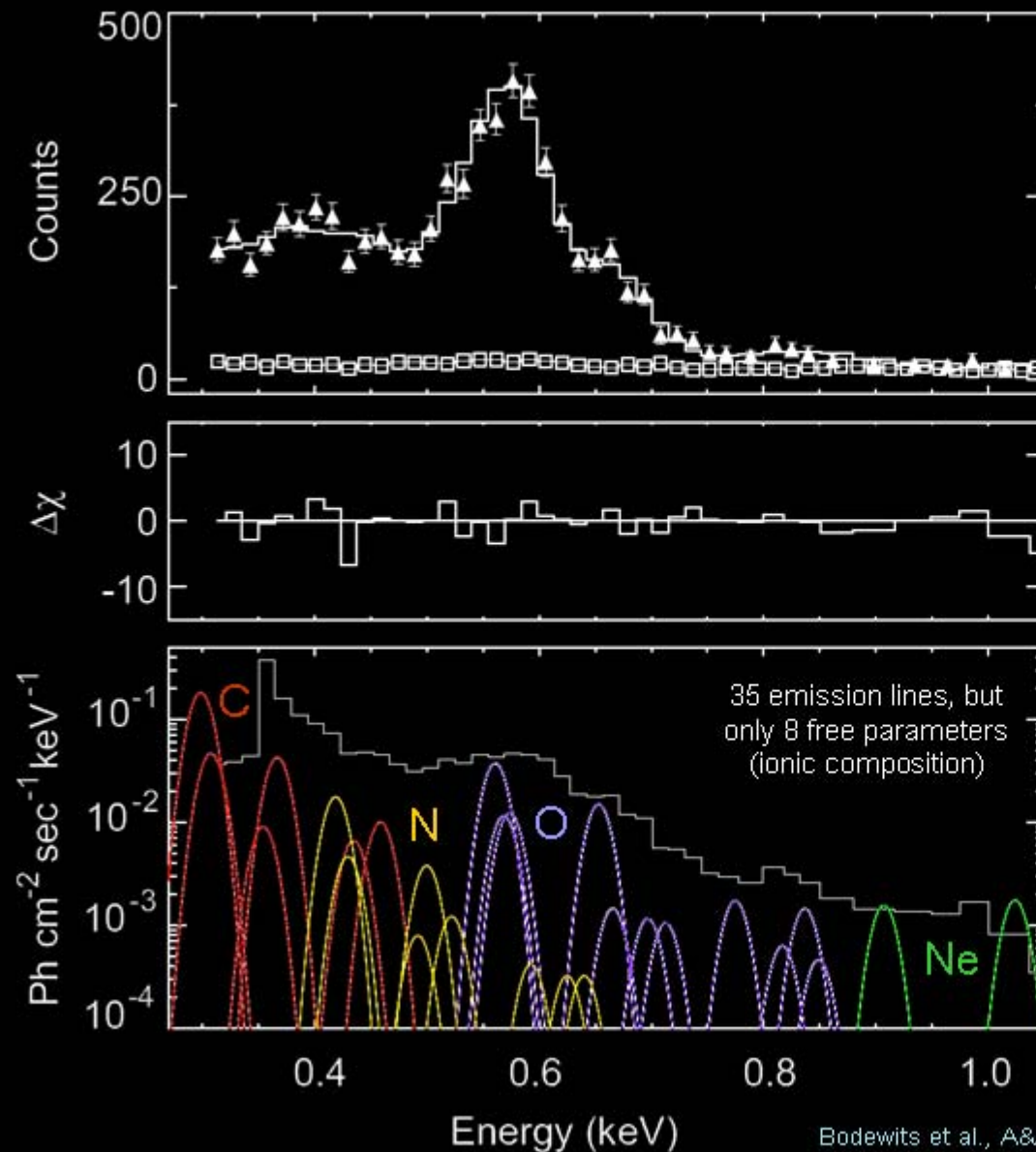


Bodewits et al., A&A 469, 2007

6 free parameters:

<i>E</i> (eV)	Ion	Transition
299.0	C V	<i>z</i>
304.4	C V	<i>x, y</i>
307.9	C V	<i>w</i>
354.5	C V	1s3p–1s ²
367.5	C V	1s4p–1s ²
367.5	C VI	2p–1s
378.9	C V	1s5p–1s ²
419.8	N VI	<i>z</i>
426.3	N VI	<i>x, y</i>
430.7	N VI	<i>w</i>
435.5	C VI	3p–1s
459.4	C VI	4p–1s
471.4	C VI	5p–1s
497.9	N VI	1s3p–1s ²
500.3	N VII	2p–1s
523.0	N VI	1s4p–1s ²
534.1	N VI	1s5p–1s ²
561.1	O VII	<i>z</i>
568.6	O VII	<i>x, y</i>
574.0	O VII	<i>w</i>
592.9	N VII	3p–1s
625.3	N VII	4p–1s
640.4	N VII	5p–1s
650.2	N VII	6p–1s
653.5	O VIII	2p–1s
665.6	O VII	1s3p–1s ²
697.8	O VII	1s4p–1s ²
712.8	O VII	1s5p–1s ²
722.7	O VII	1s6p–1s ²
774.6	O VIII	3p–1s
817.0	O VIII	4p–1s
836.5	O VIII	5p–1s
849.1	O VIII	6p–1s

Chandra ACIS-S: Comet C/1999 S4 (LINEAR)



Bodewits et al., A&A 469, 2007

6 groups of lines:

C V (6 lines)

C VI (4 lines)

N VI (6 lines)

N VII (5 lines)

O VII (7 lines)

O VIII (5 lines)

+ 2 single lines:

Ne IX (907 eV)

Ne X (1024 eV)

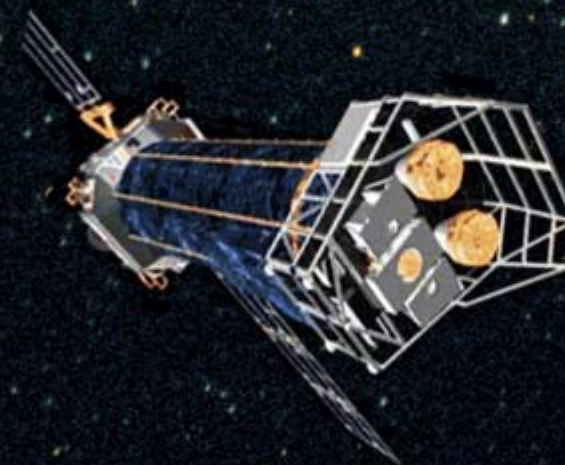
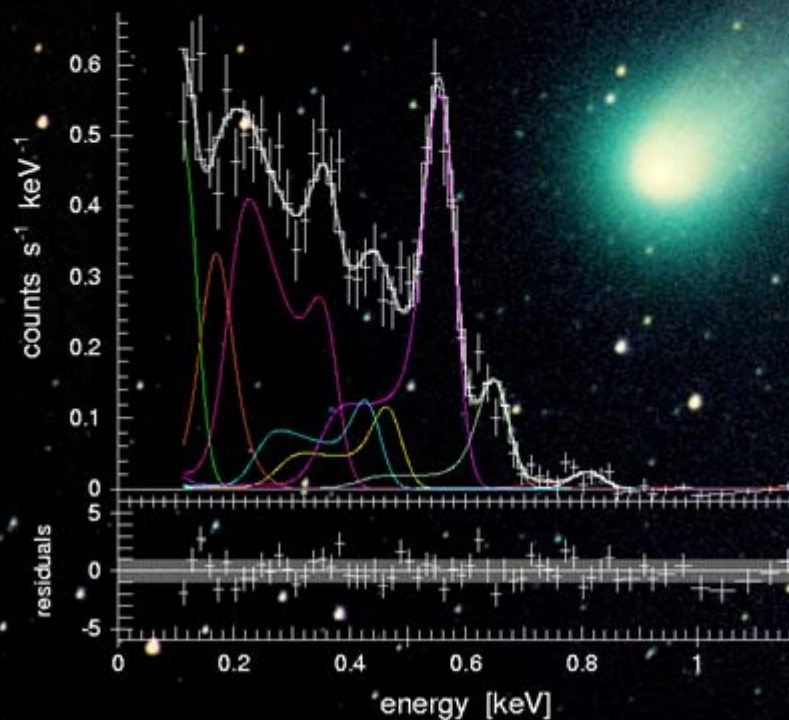
for each ionic species:

line energies, widths, and
relative intensities fixed,
according to their velocity
dependent emission cross
sections

Bodewits et al., A&A 469, 2007

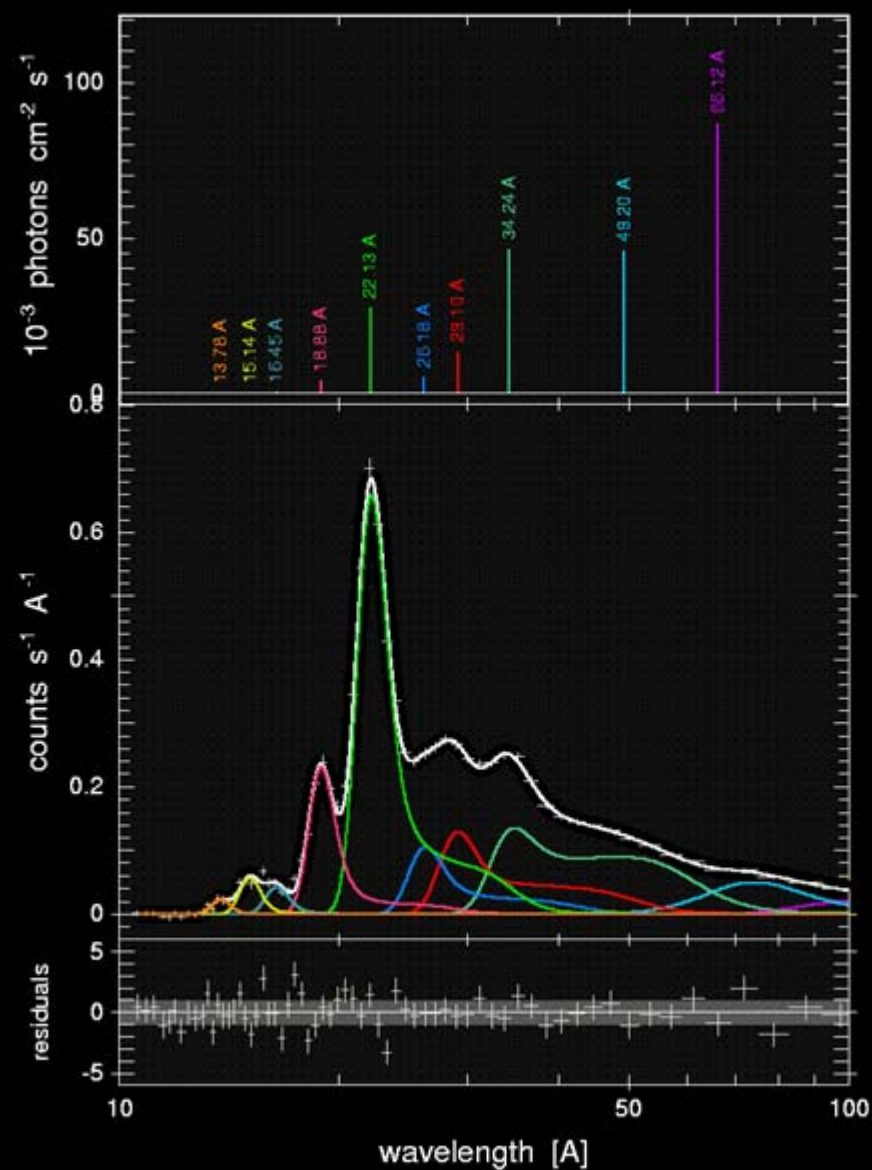
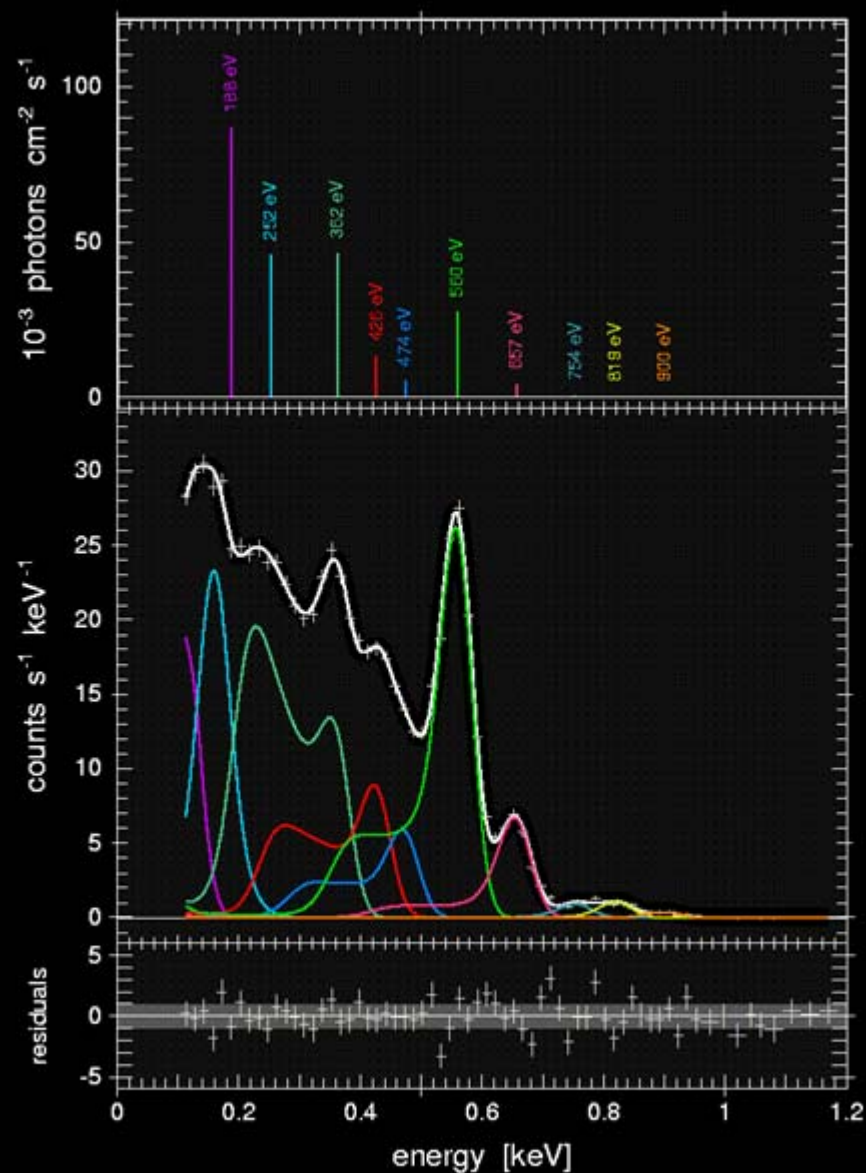
Medium Resolution X-ray Spectroscopy of Comets

with XMM-Newton / EPIC

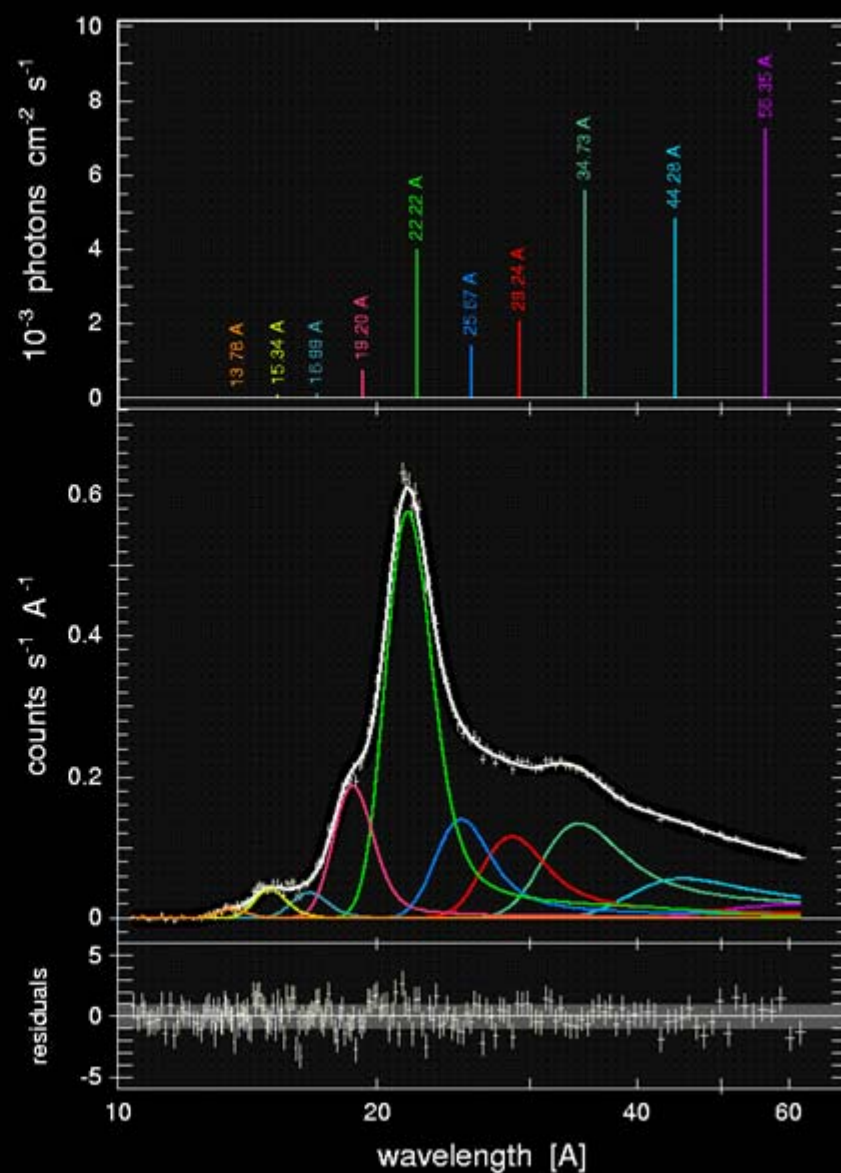
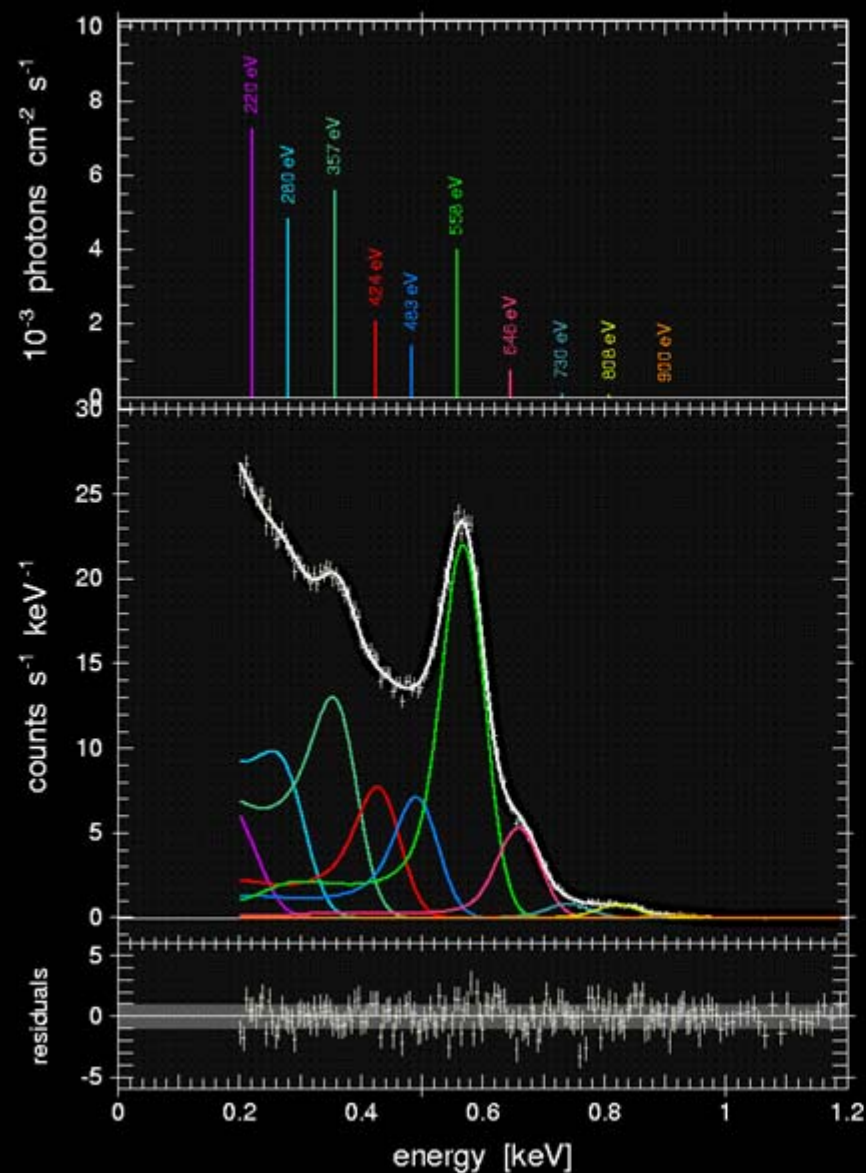


optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerl

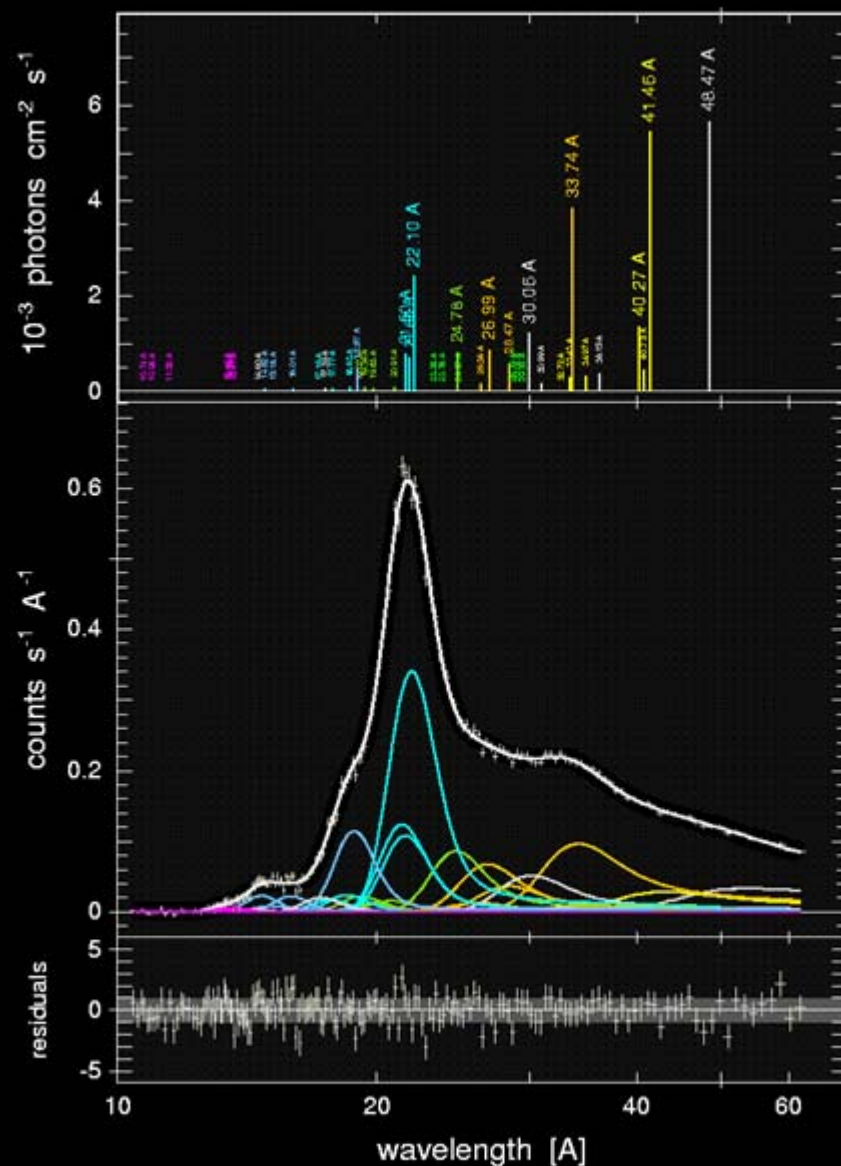
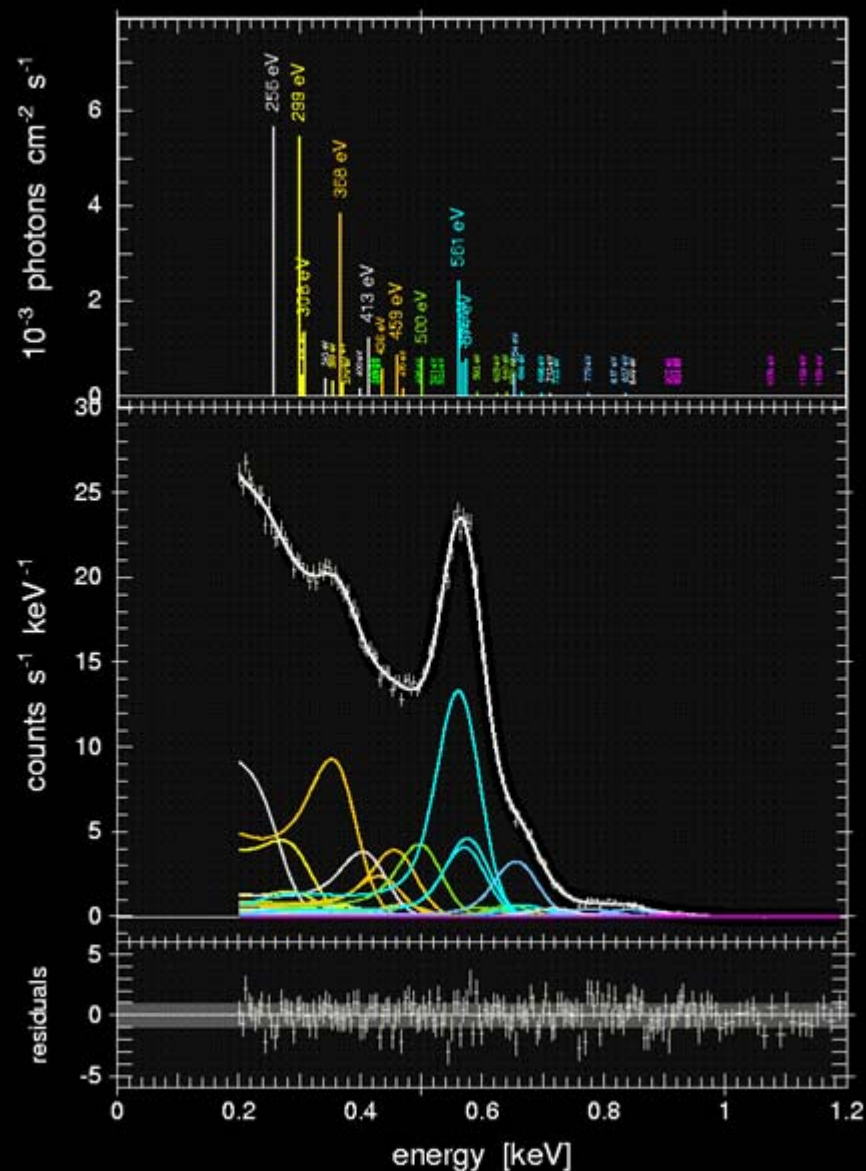
XMM-Newton spectra of Comet C/2000 WM1 *EPIC-MOS 1*



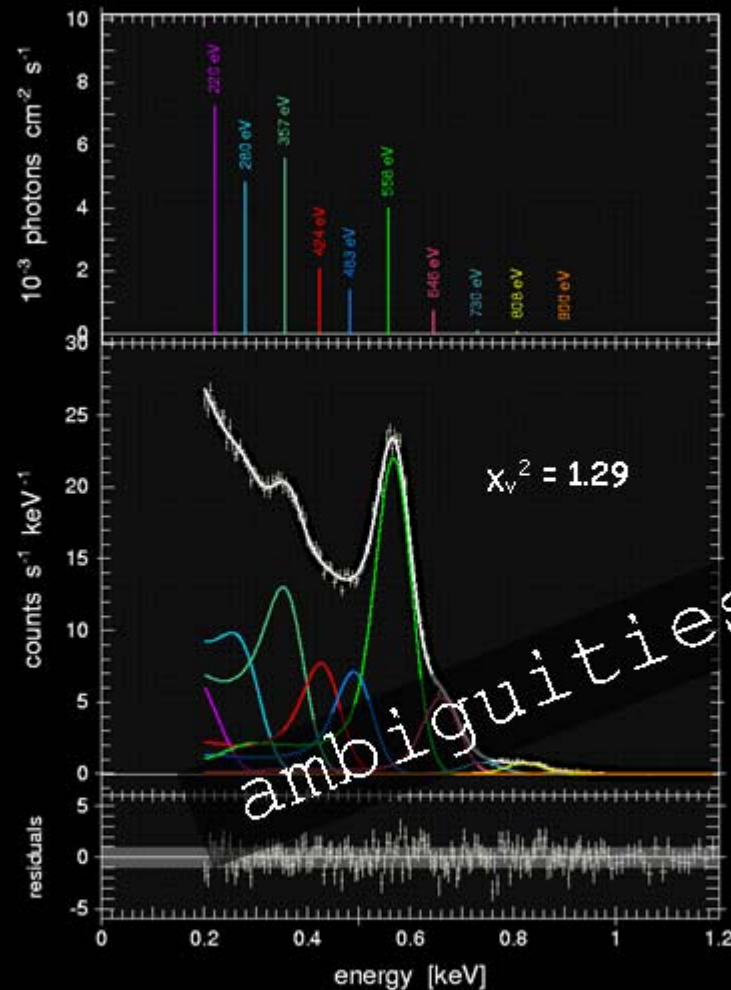
XMM-Newton spectra of Comet C/2000 WM1 *EPIC - pn*



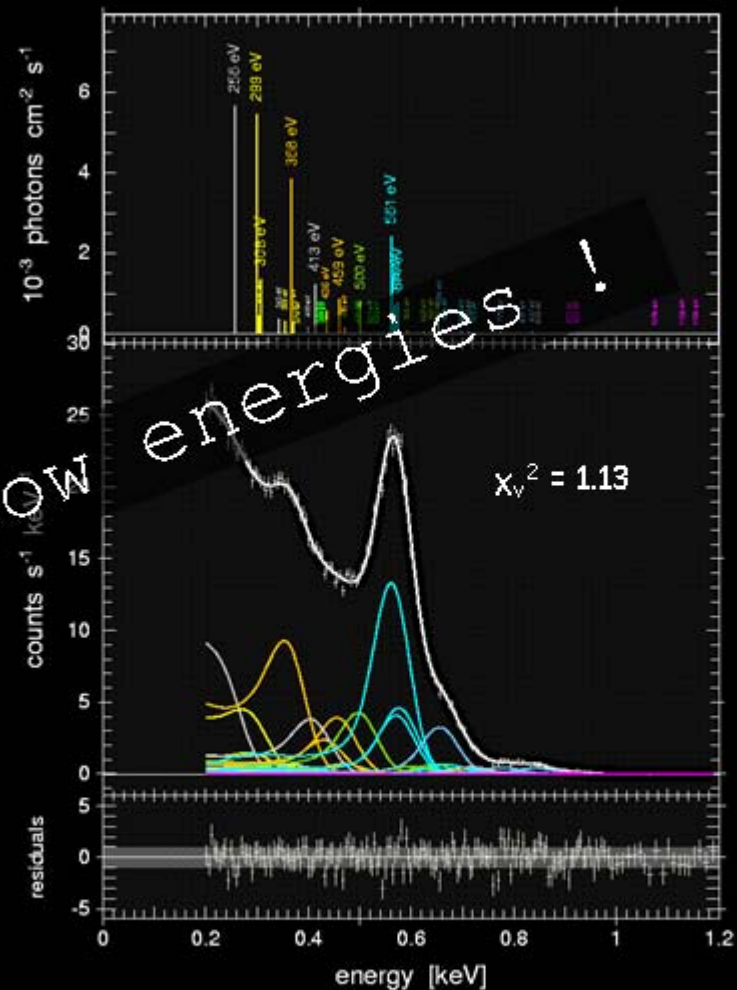
XMM-Newton spectra of Comet C/2000 WM1 *EPIC - pn*



XMM-Newton spectra of Comet C/2000 WM1 *EPIC - pn*



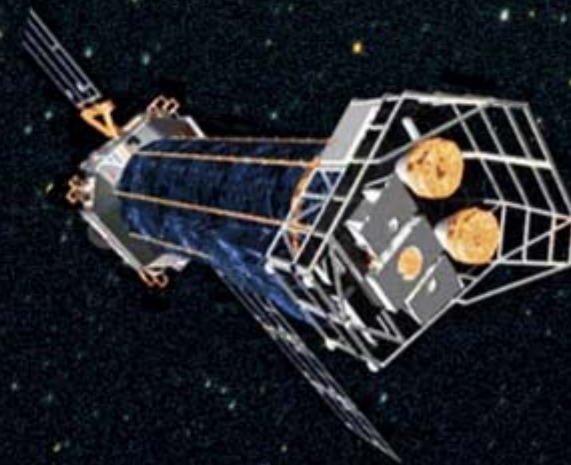
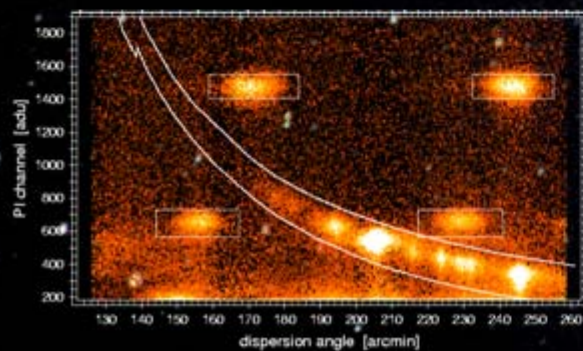
10 intrinsically sharp emission lines,
with energy and flux as free parameters



intrinsically sharp emission lines, with energies fixed
and fluxes as free parameters for 7 groups and 7 individual lines

High Resolution X-ray Spectroscopy of Comets

with XMM-Newton / RGS



optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerl

Comet C/2000 WM1, 2001 Dec 13

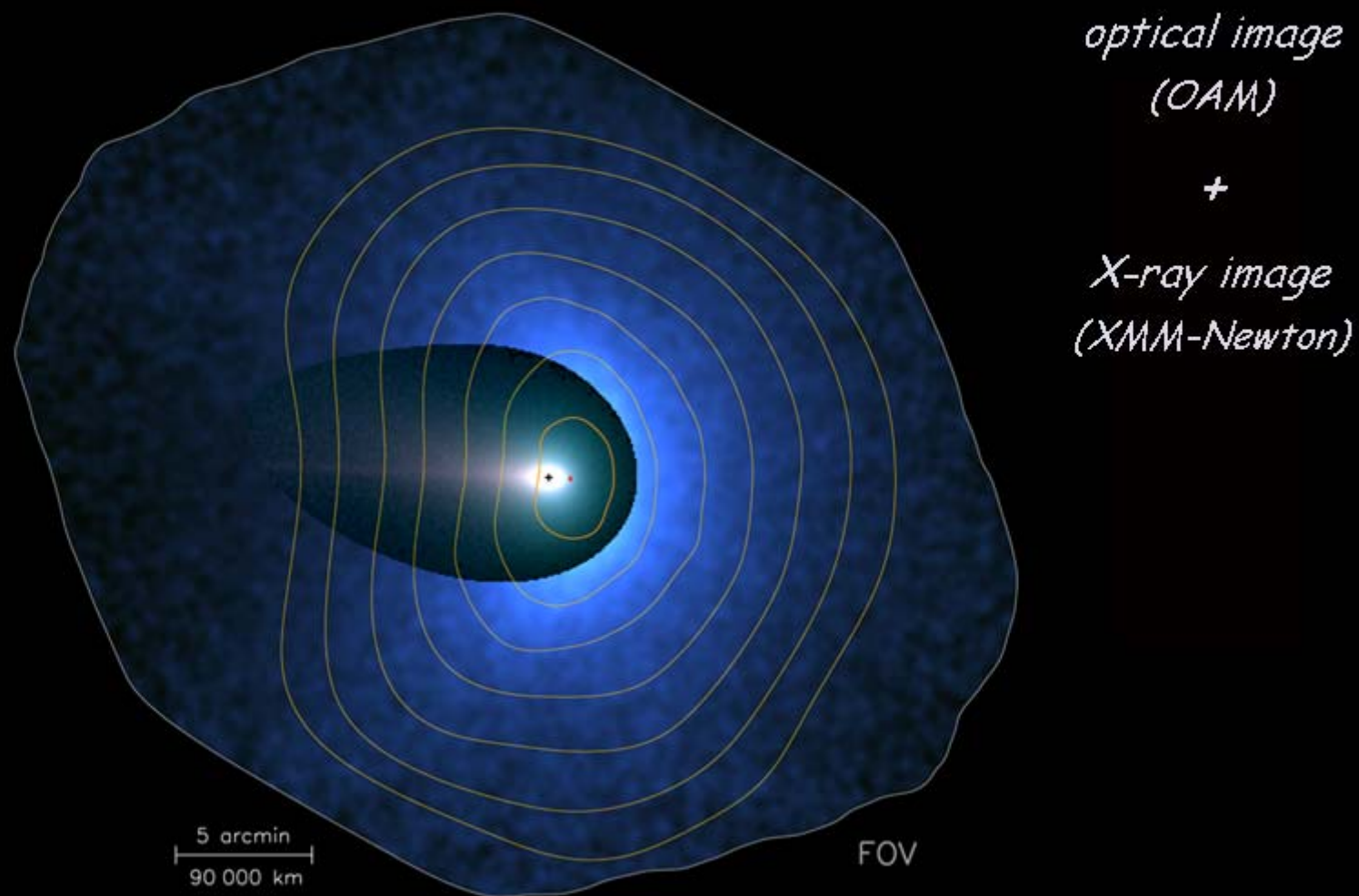


Optical image

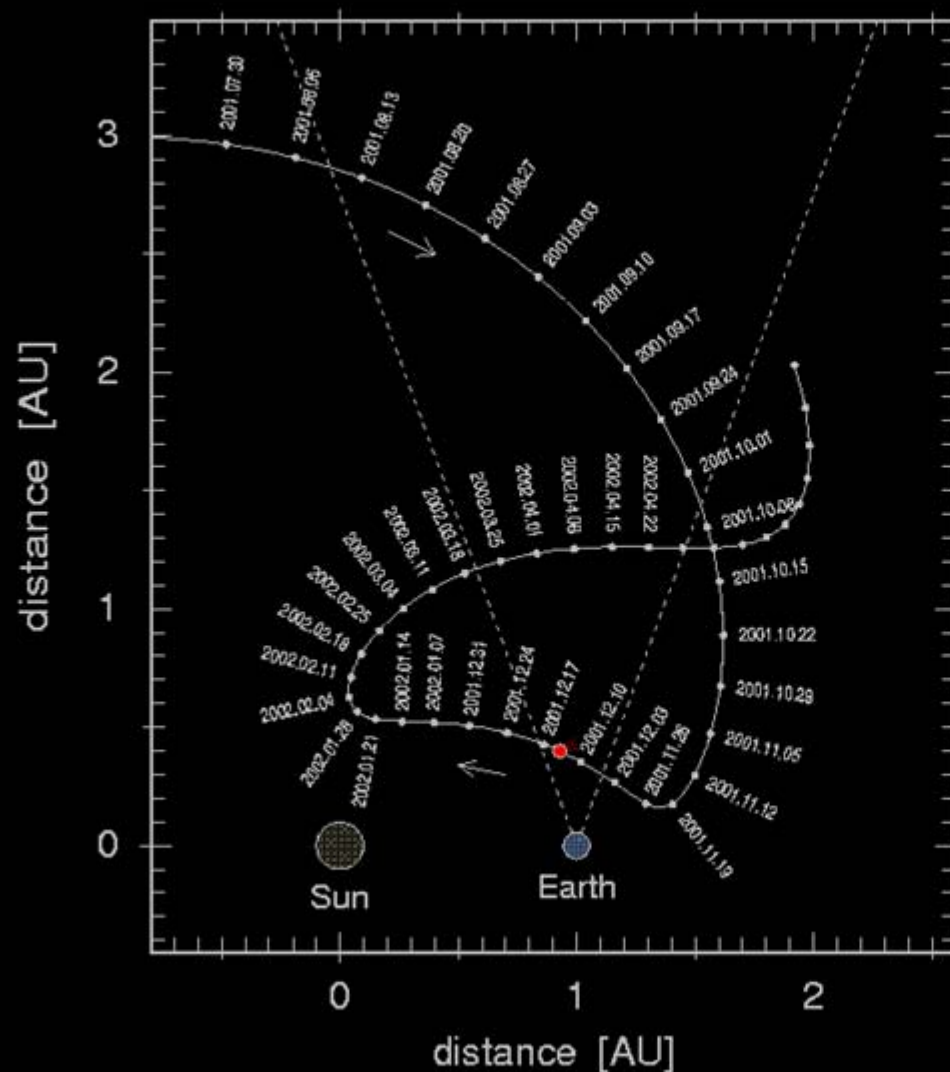
2001 Dec 13, 17:54 – 18:36 UTC

Observatorio Astronomico de Mallorca (OAM)

Comet C/2000 WM1, 2001 Dec 13 – 14



XMM-Newton observation of Comet C/2000 WM1



$t_{obs} = 2001 \text{ Dec } 13/14$

$m_v = 5.6 \text{ mag}$

$dist_{Sun} = 1.02 \text{ AU}$

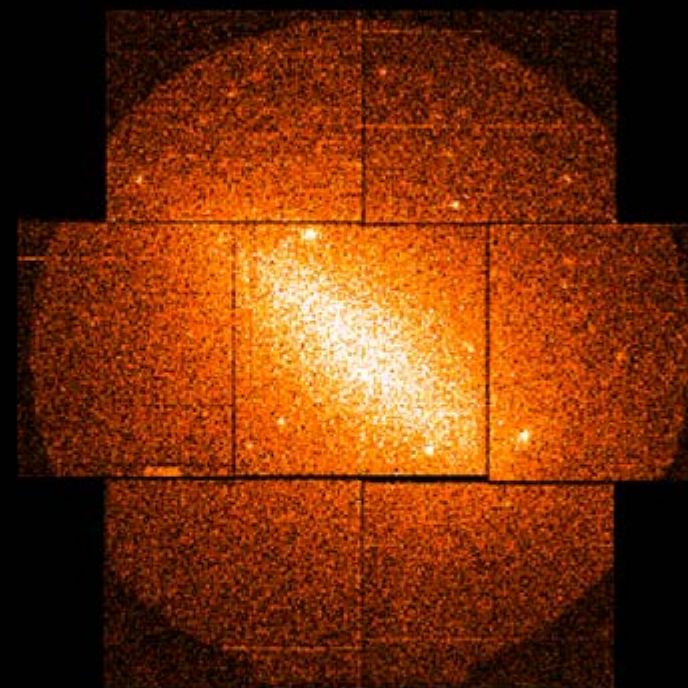
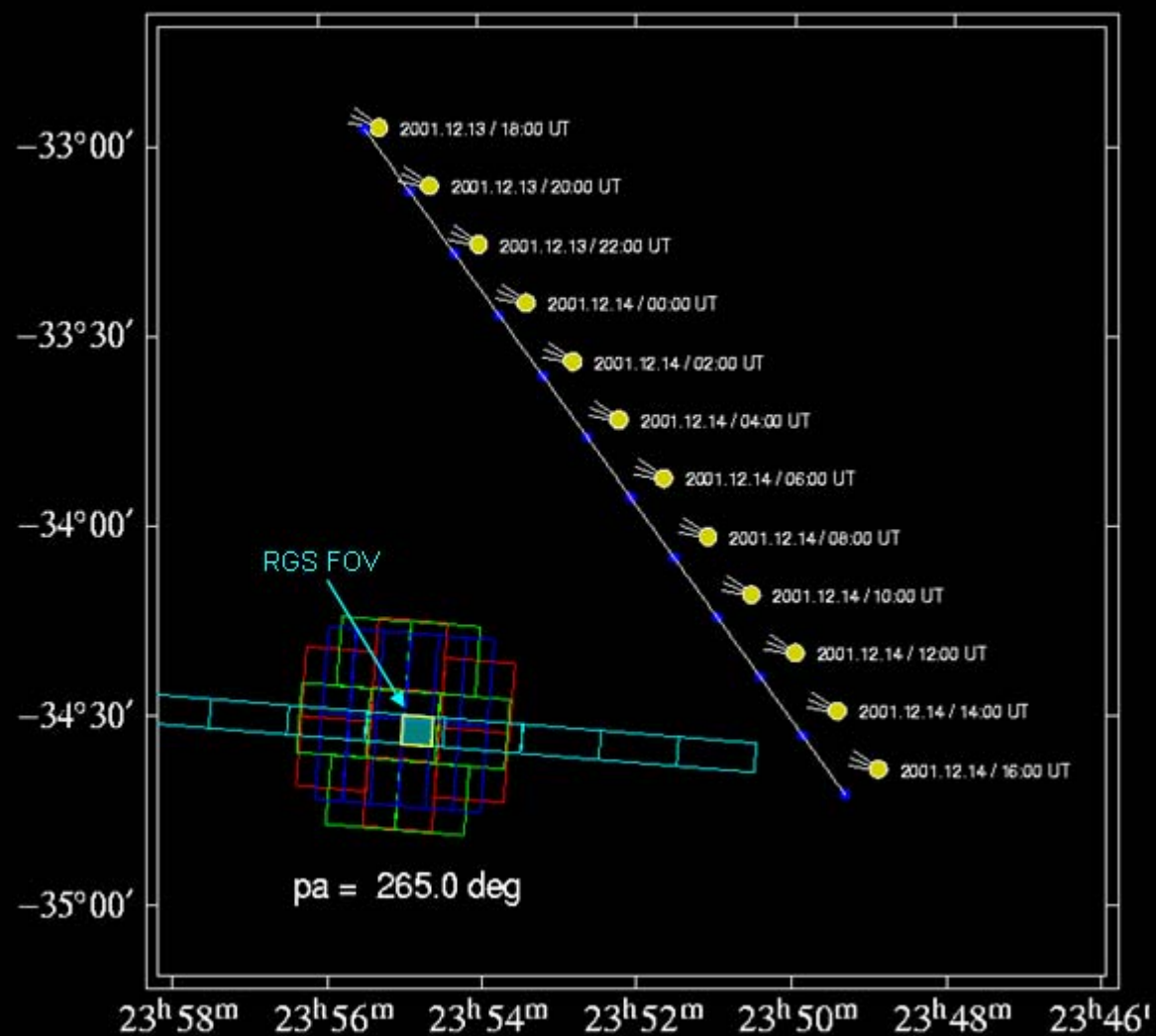
$dist_{Earth} = 0.41 \text{ AU}$

$phase = 74 \text{ deg}$

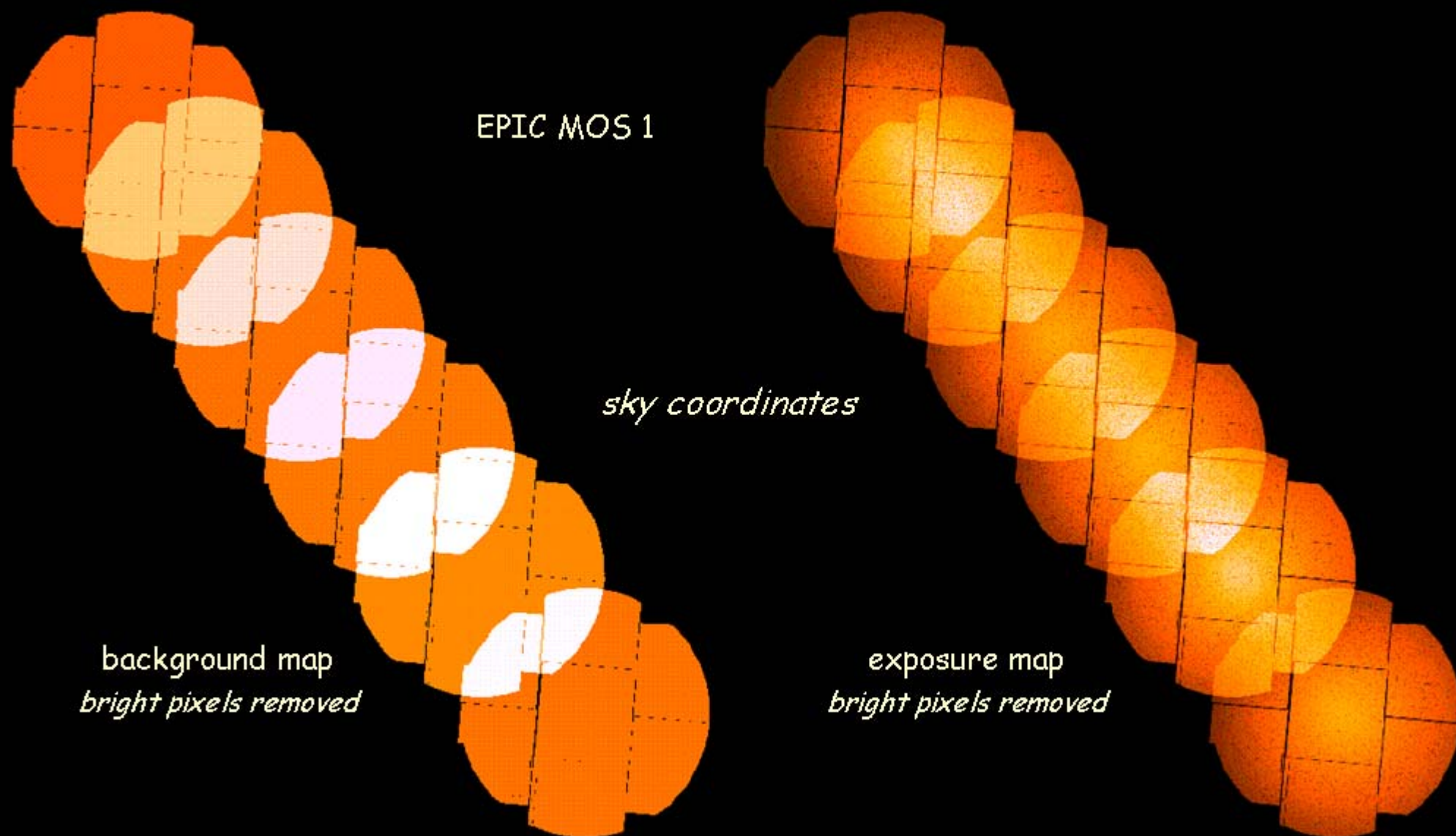
$elong = 83 \text{ deg}$

$hel. \text{ lat.} = -11 \text{ deg}$

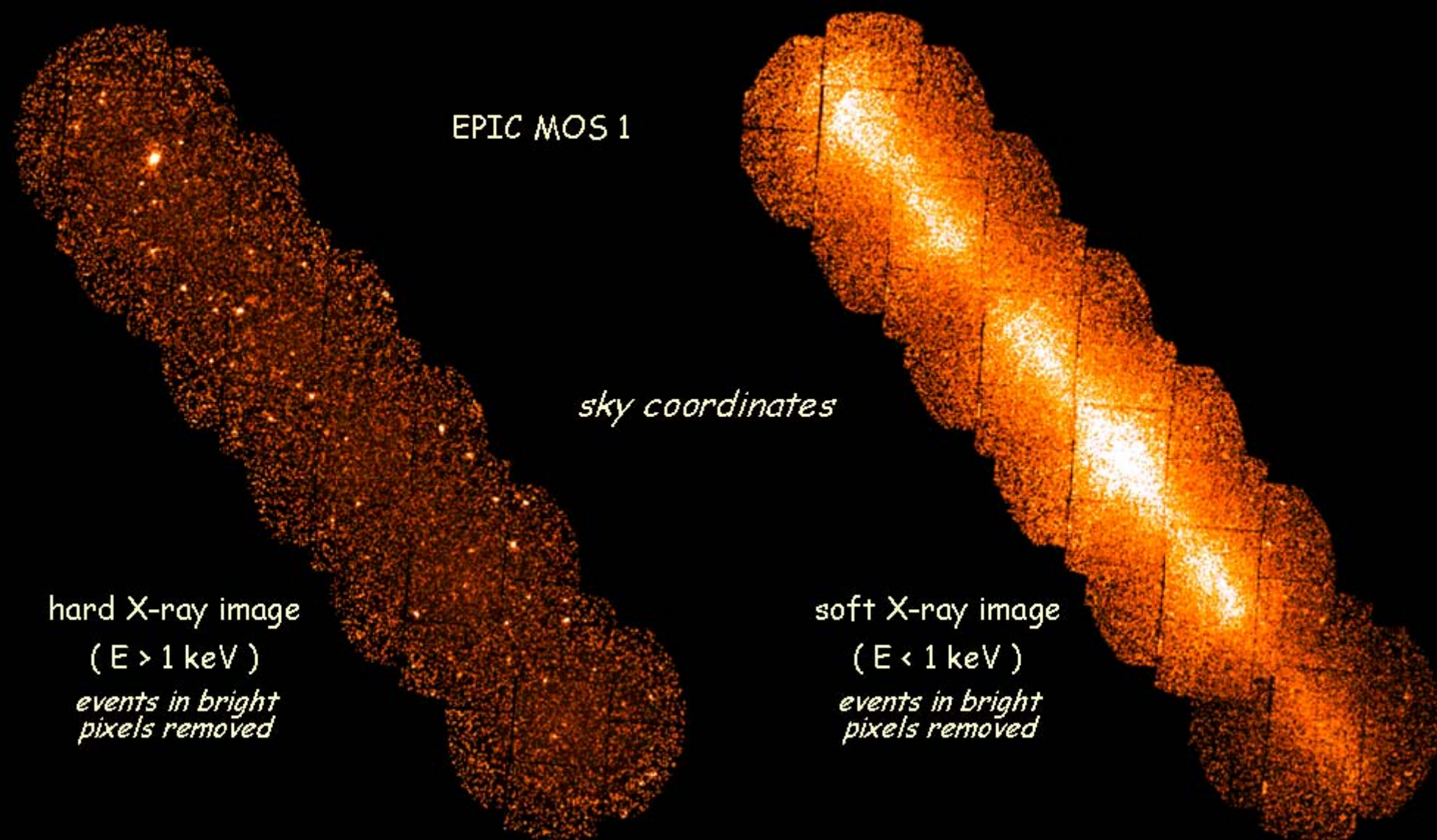
XMM-Newton observation of Comet C/2000 WM1



XMM-Newton observation of Comet C/2000 WM1



XMM-Newton observation of Comet C/2000 WM1



XMM-Newton observation of Comet C/2000 WM1

EPIC MOS 1

sky coordinates

hard X-ray image
($E > 1 \text{ keV}$)

*events in bright
pixels removed*

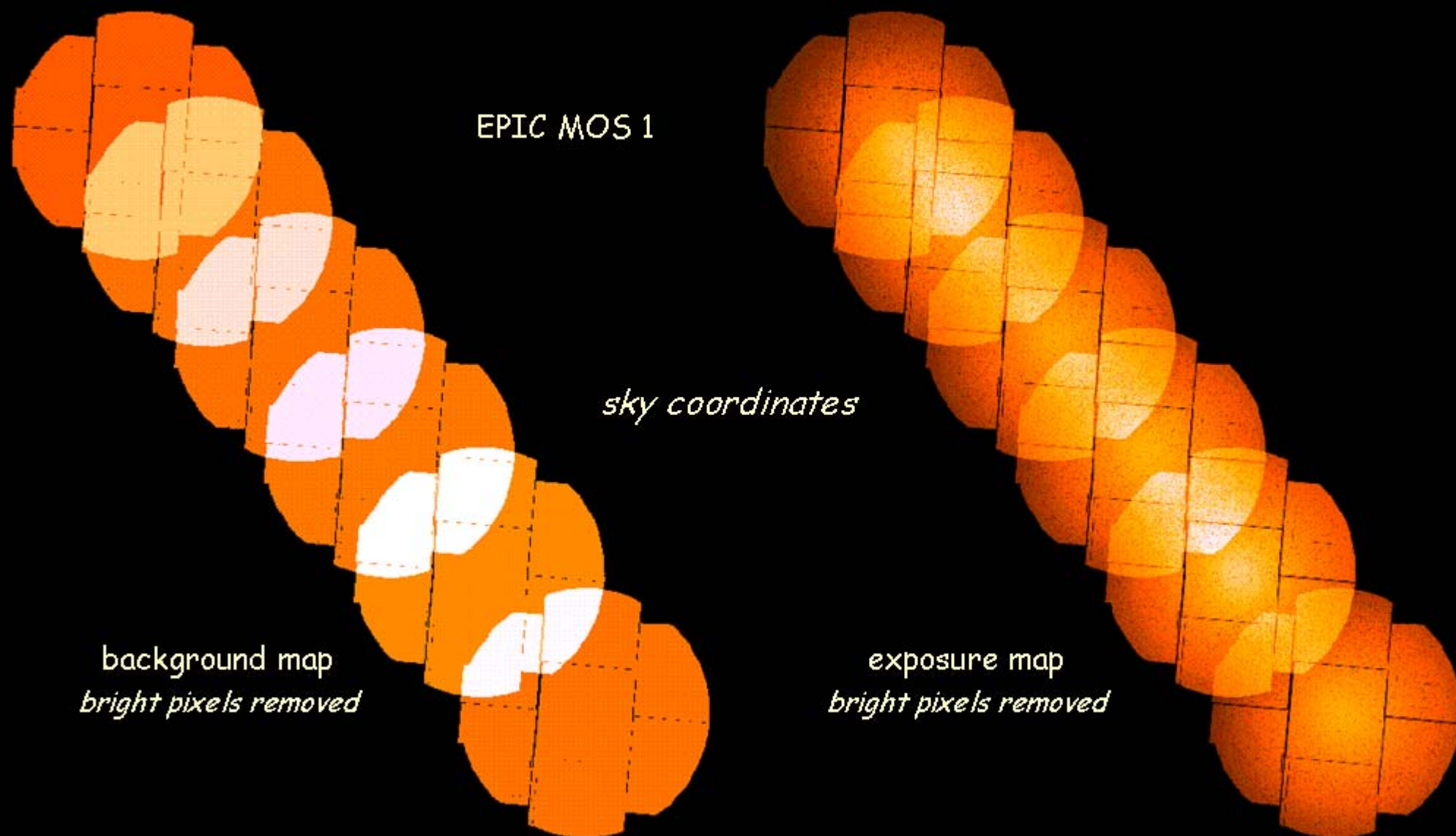
*events around point
sources removed*

soft X-ray image
($E < 1 \text{ keV}$)

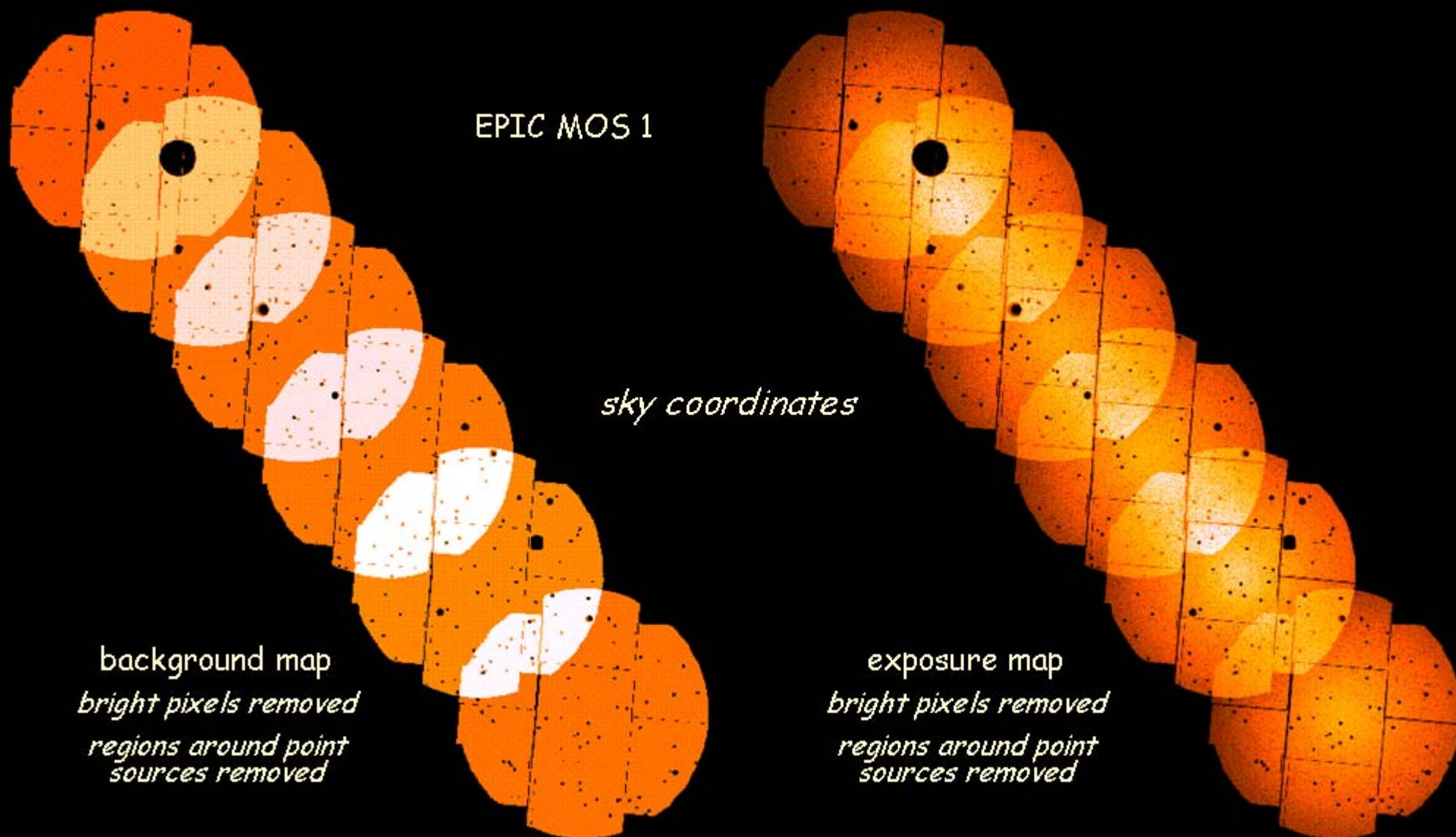
*events in bright
pixels removed*

*events around point
sources removed*

XMM-Newton observation of Comet C/2000 WM1



XMM-Newton observation of Comet C/2000 WM1



XMM-Newton observation of Comet C/2000 WM1

background map for one pointing
bright pixels removed
regions around point sources removed

EPIC MOS 1

EPIC pn

comet coordinates

XMM-Newton observation of Comet C/2000 WM1

background map for all pointings

bright pixels removed

regions around point sources removed

EPIC MOS 1

EPIC pn

comet coordinates

XMM-Newton observation of Comet C/2000 WM1

exposure map for all pointings
bright pixels removed
regions around point sources removed

EPIC MOS 1

EPIC pn

comet coordinates

XMM-Newton observation of Comet C/2000 WM1

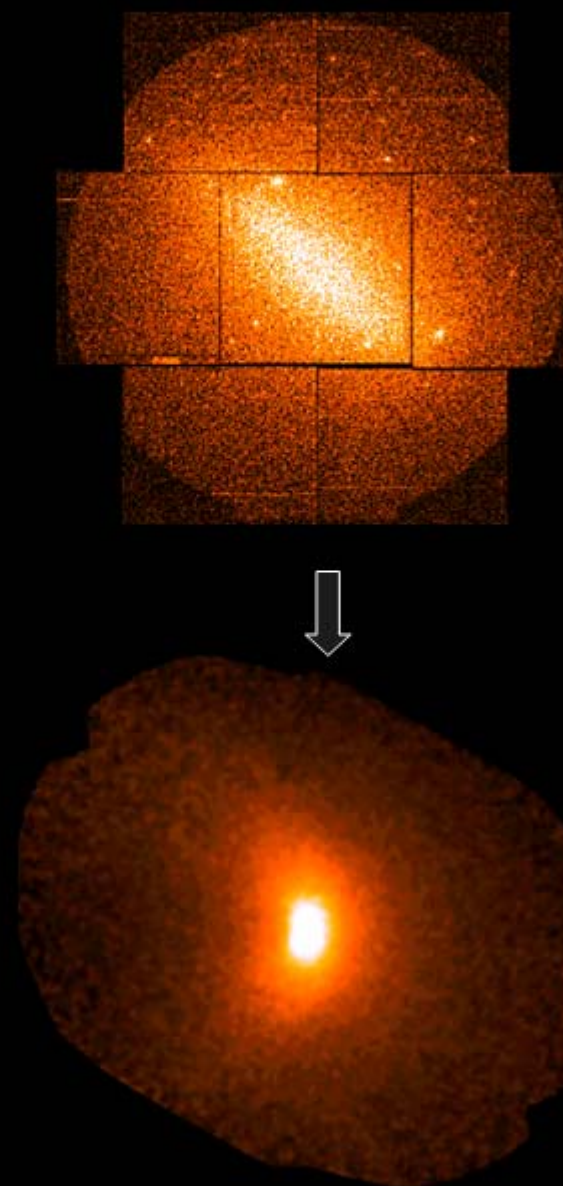
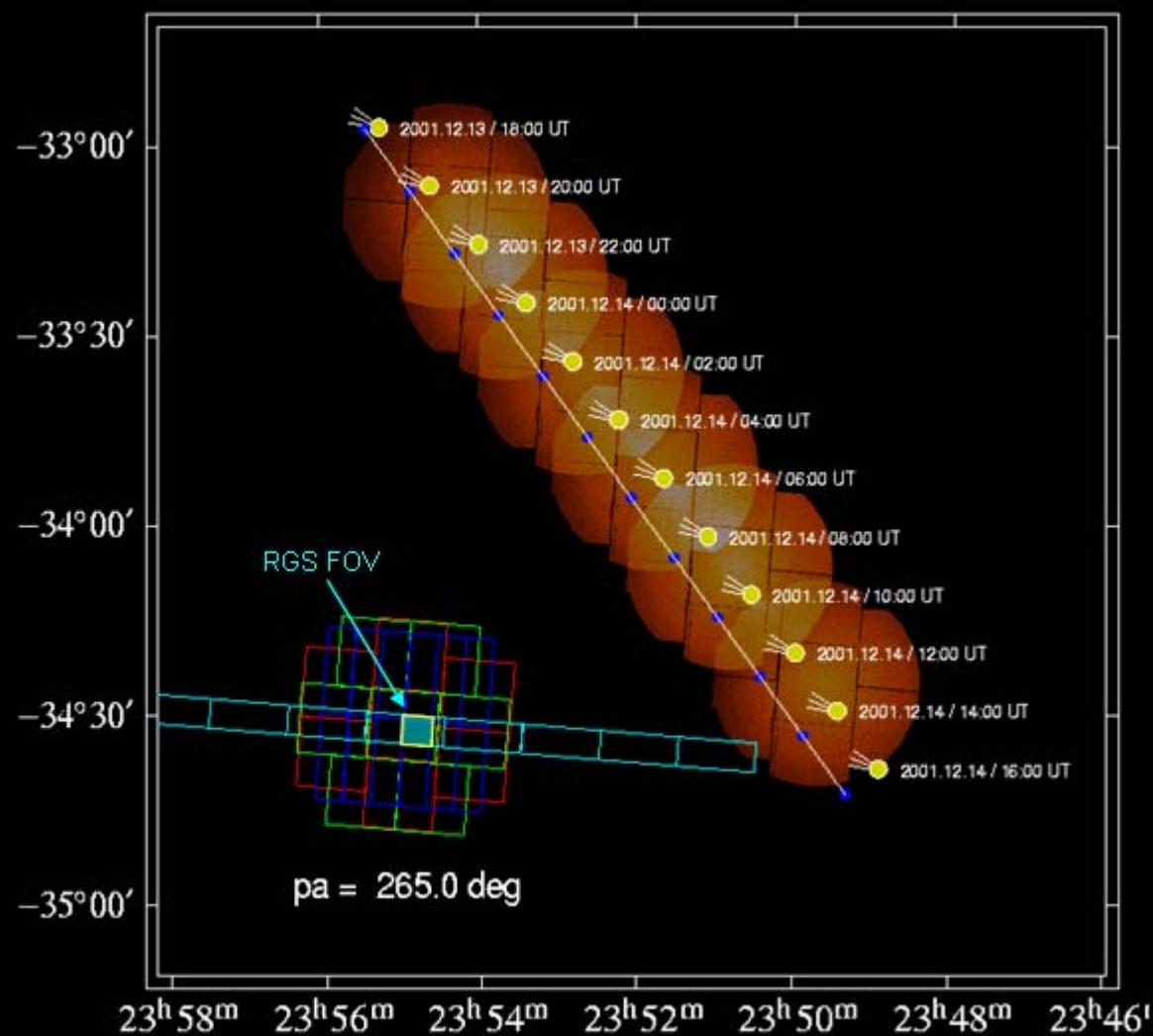
exposure corrected comet image
bright pixels removed
regions around point sources removed

EPIC MOS 1

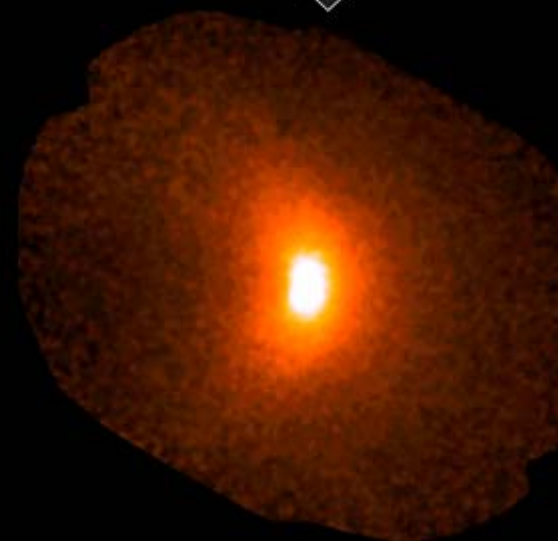
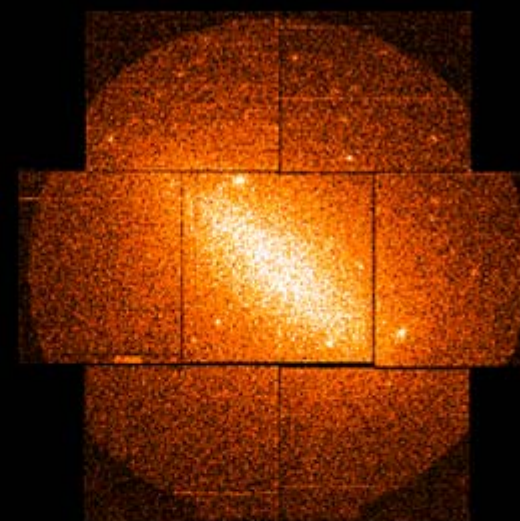
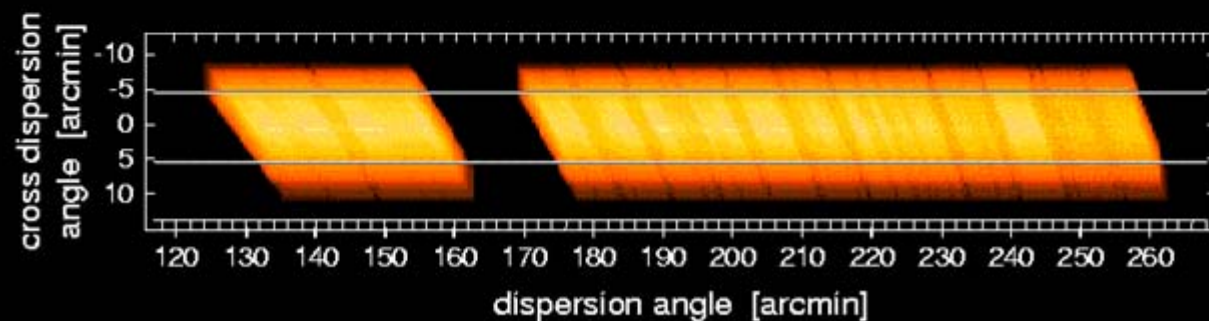
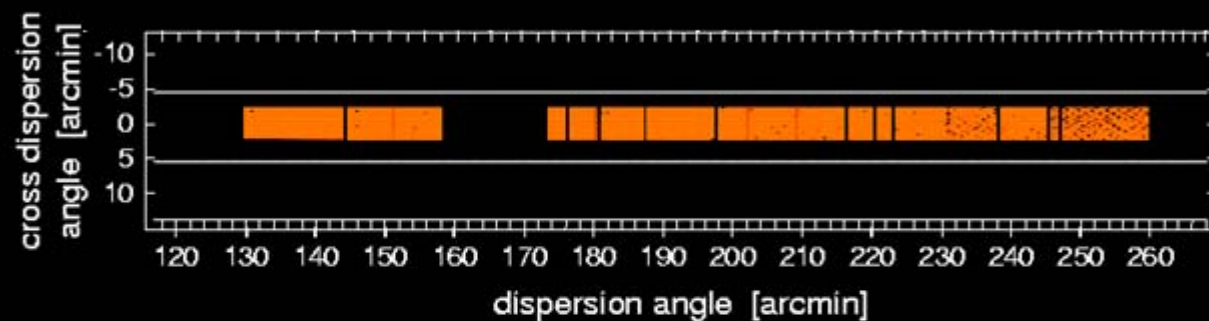
EPIC pn

comet coordinates

XMM-Newton observation of Comet C/2000 WM1

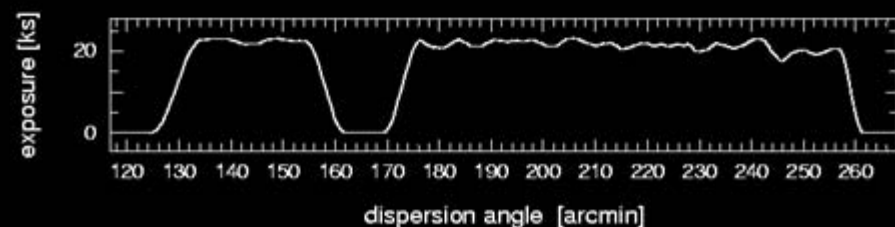
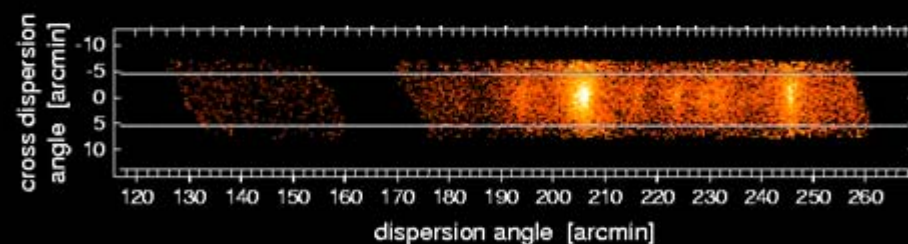
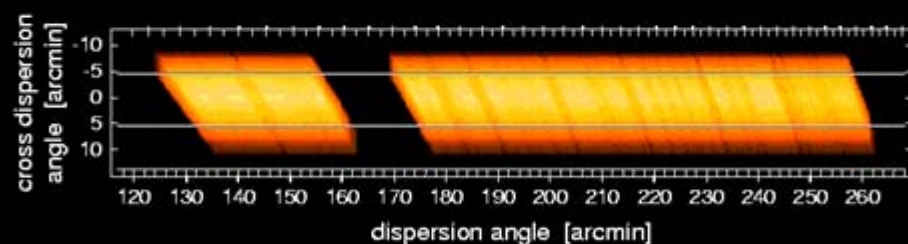
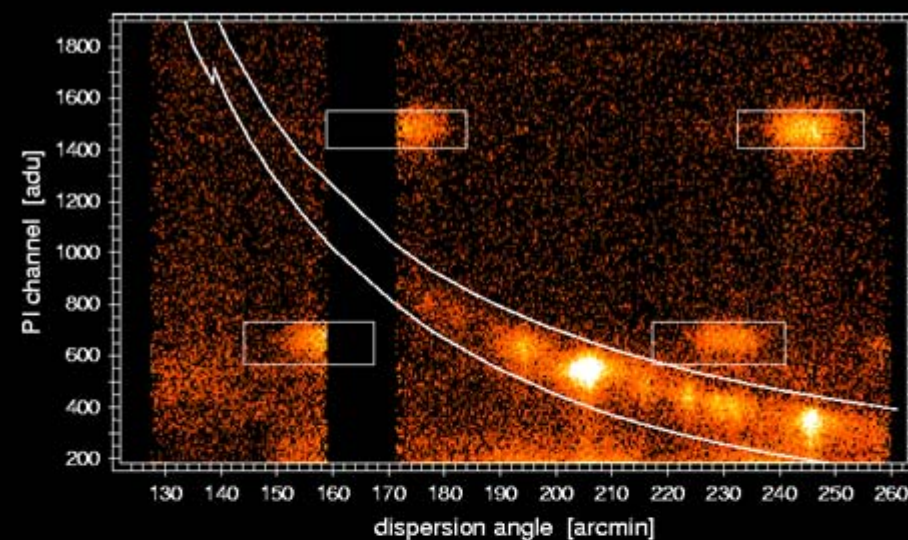


XMM-Newton observation of Comet C/2000 WM1



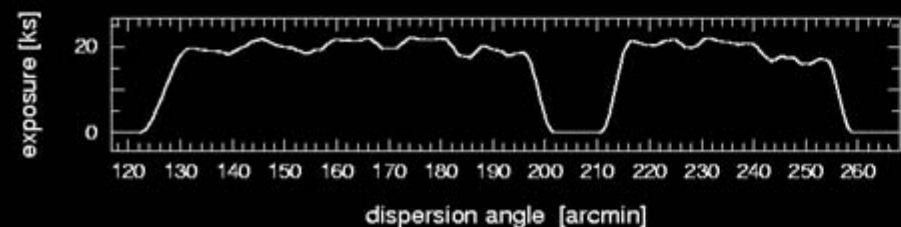
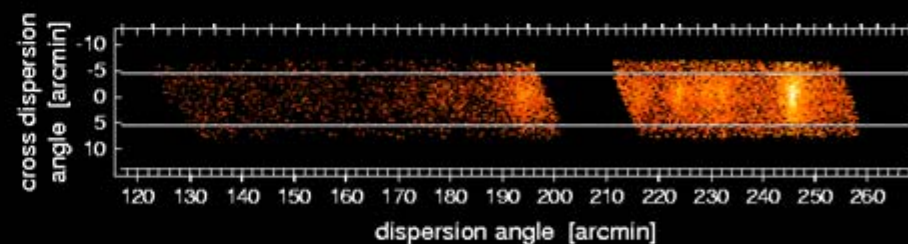
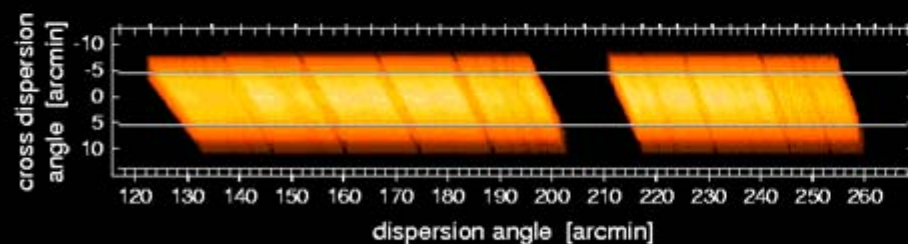
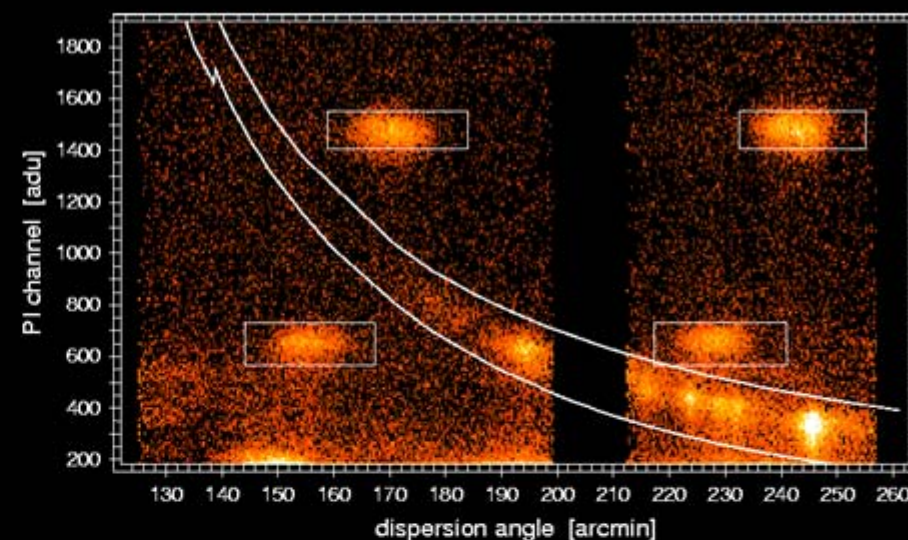
XMM-Newton observation of Comet C/2000 WM1

*RGS 1 data
after transformation into
comet reference frame*



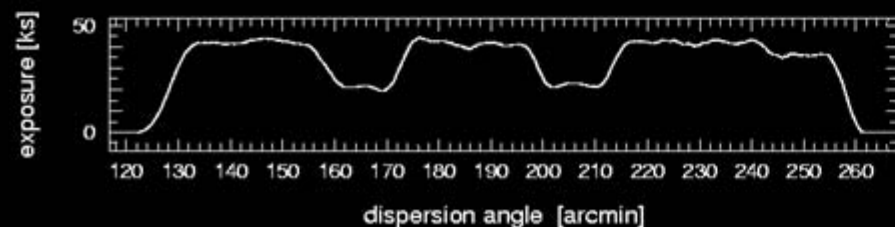
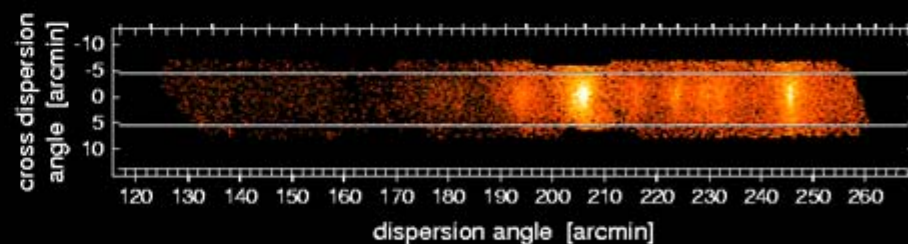
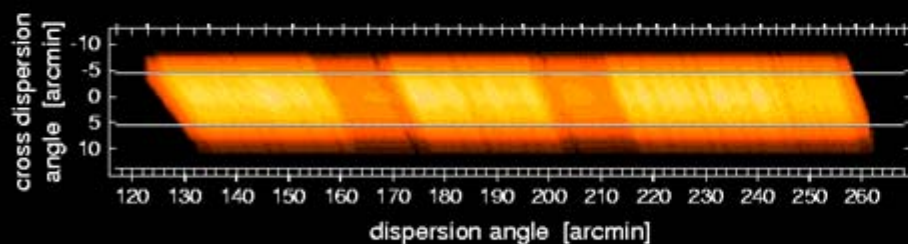
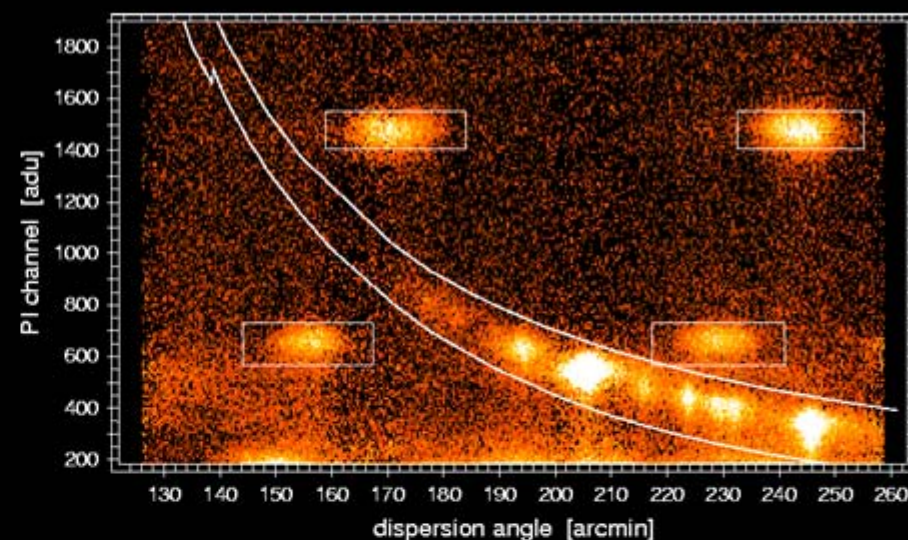
XMM-Newton observation of Comet C/2000 WM1

*RGS 2 data
after transformation into
comet reference frame*



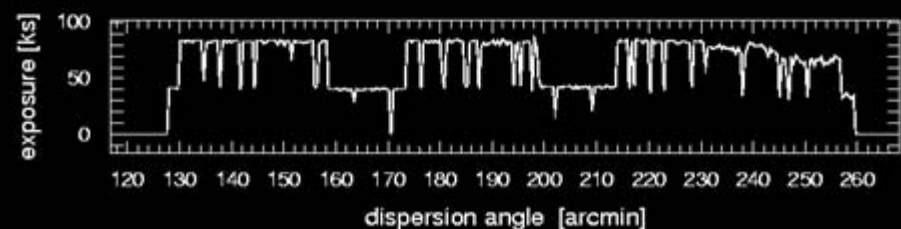
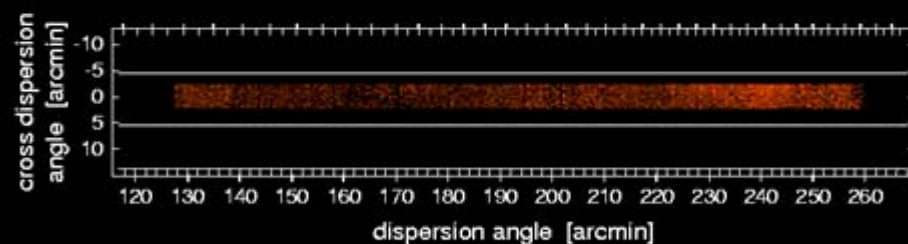
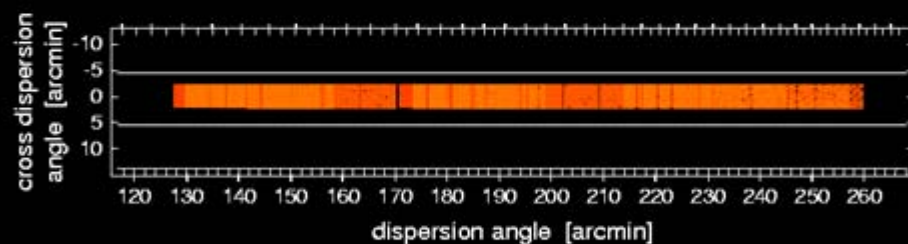
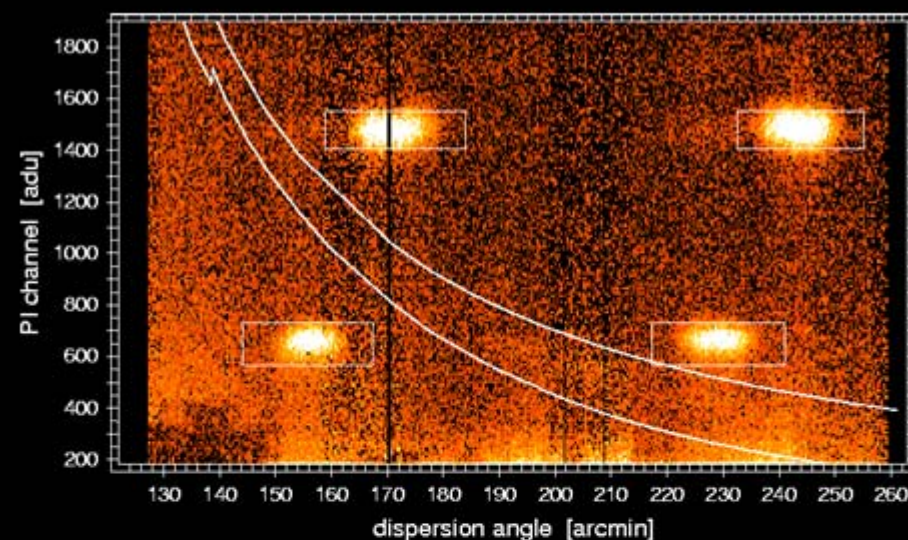
XMM-Newton observation of Comet C/2000 WM1

*RGS 1+2 data
after transformation into
comet reference frame*



XMM-Newton observation of Comet C/2000 WM1

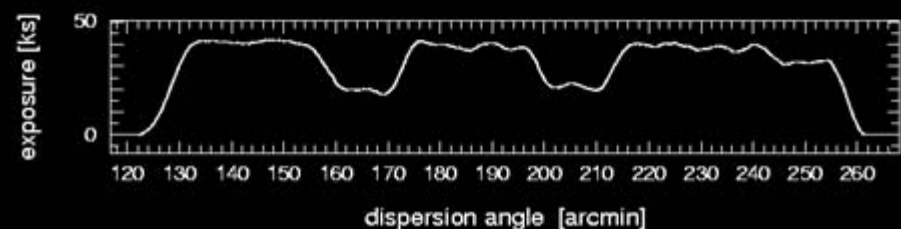
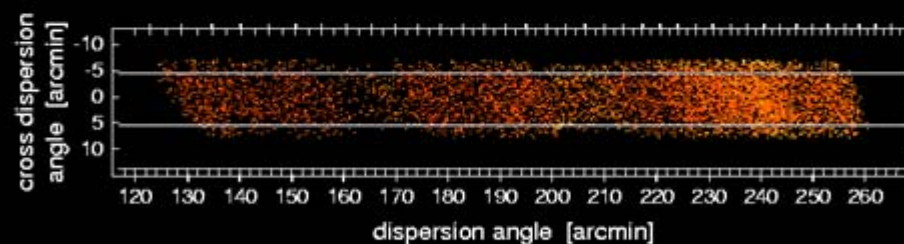
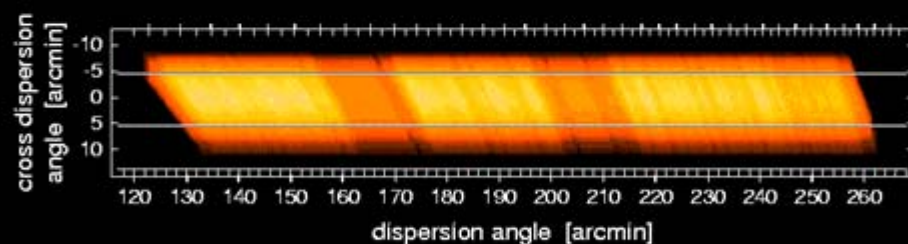
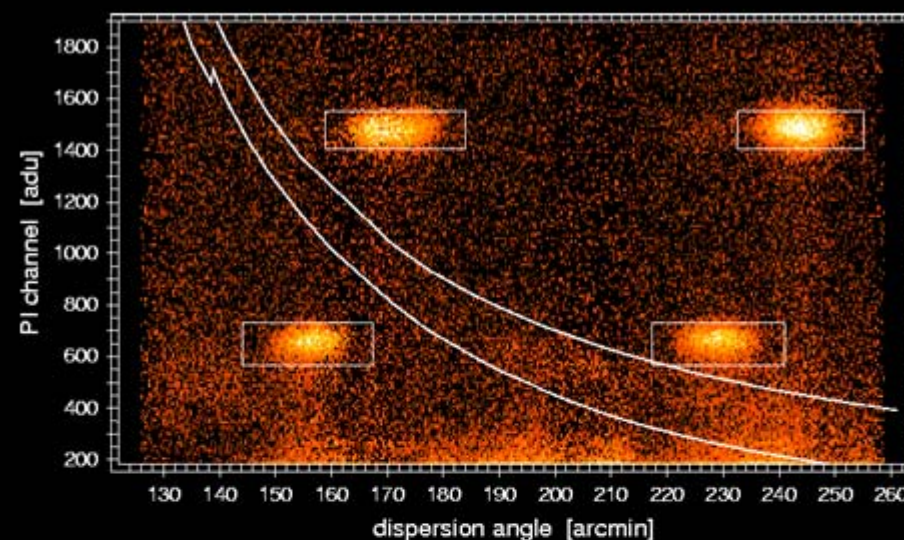
*RGS 1+2 background
(Hubble Deep Field)*



XMM-Newton observation of Comet C/2000 WM1

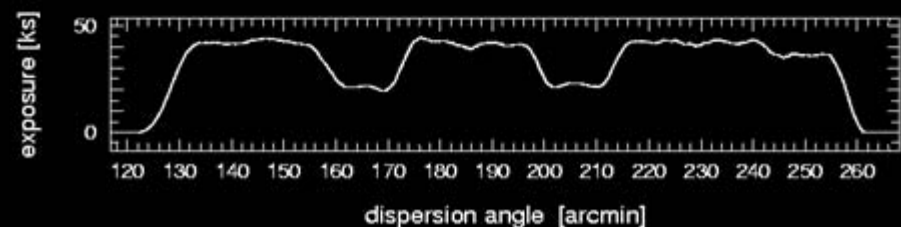
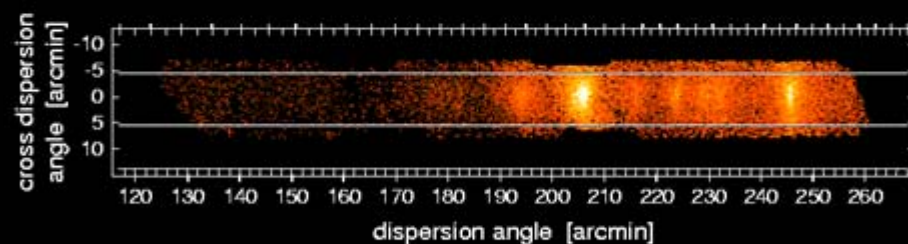
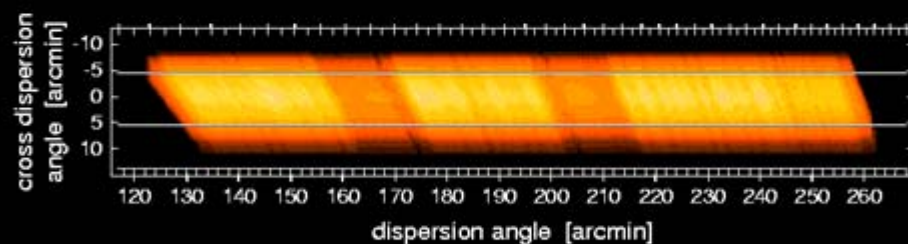
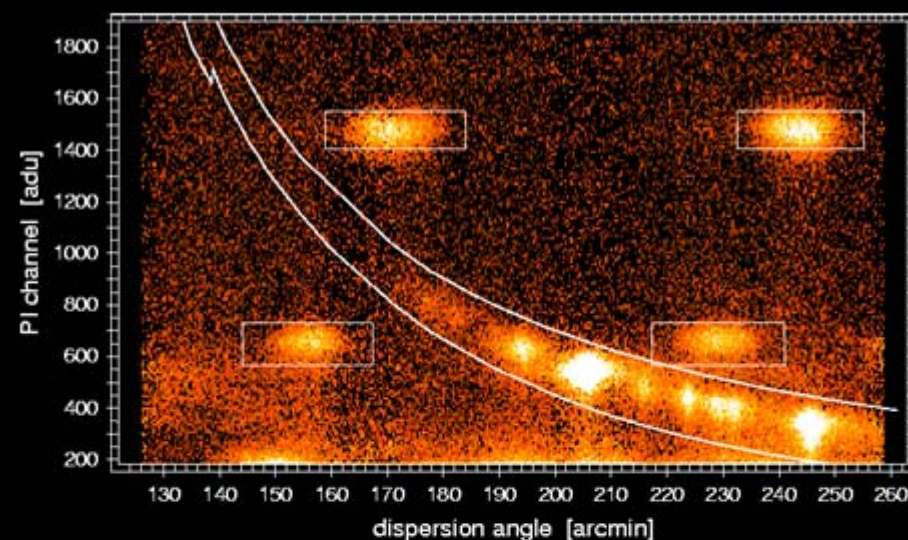
RGS 1+2 background

*HDF data, after transformation into the
reference frame of a virtual comet,
which would have passed the HDF in the
same way as C/2000 WM1 had passed
half a year later a different field*

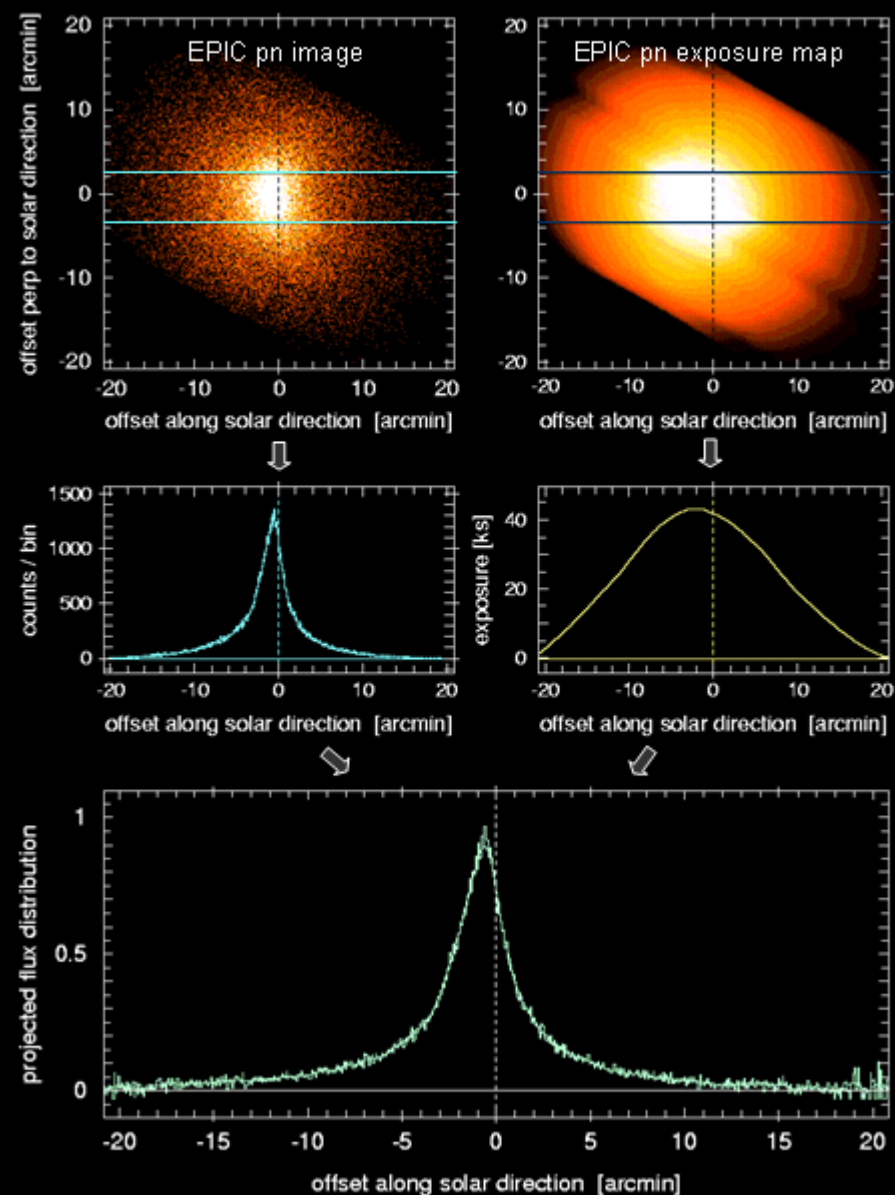
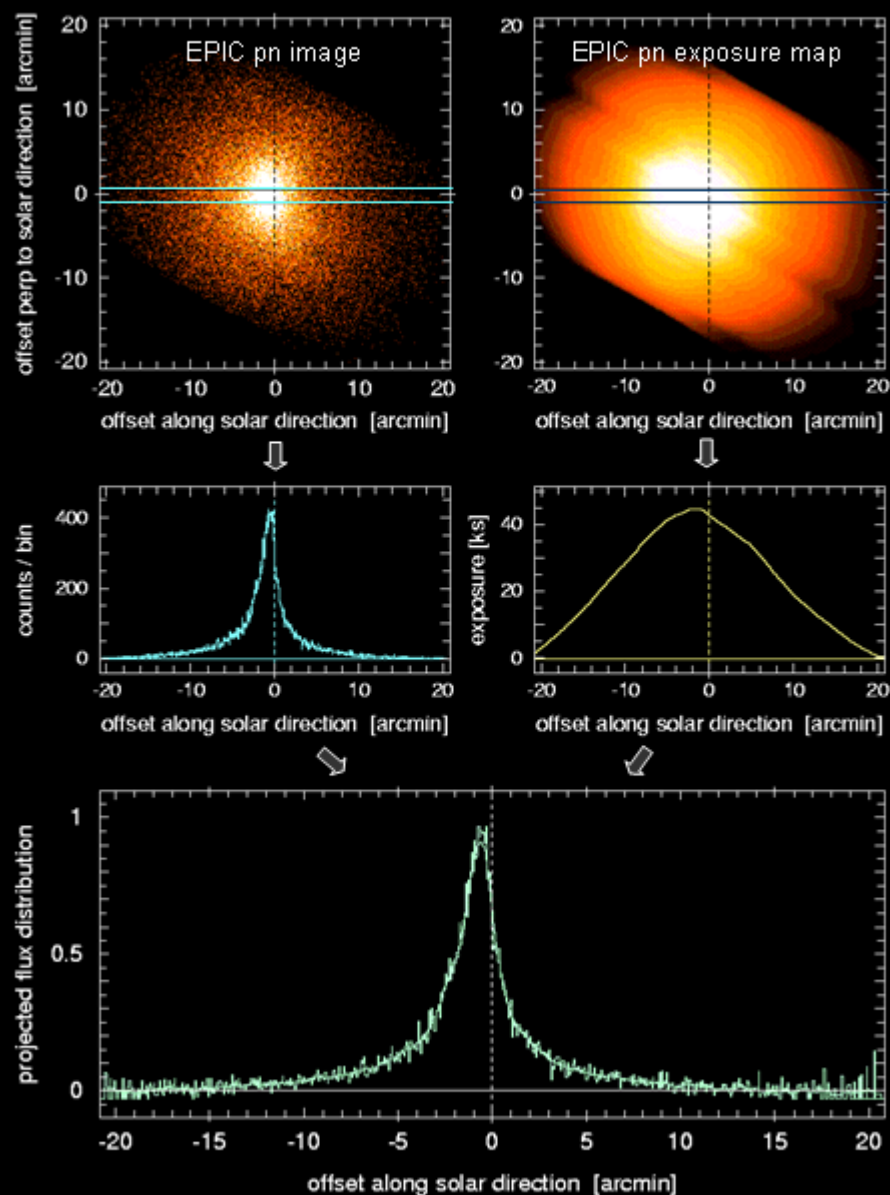


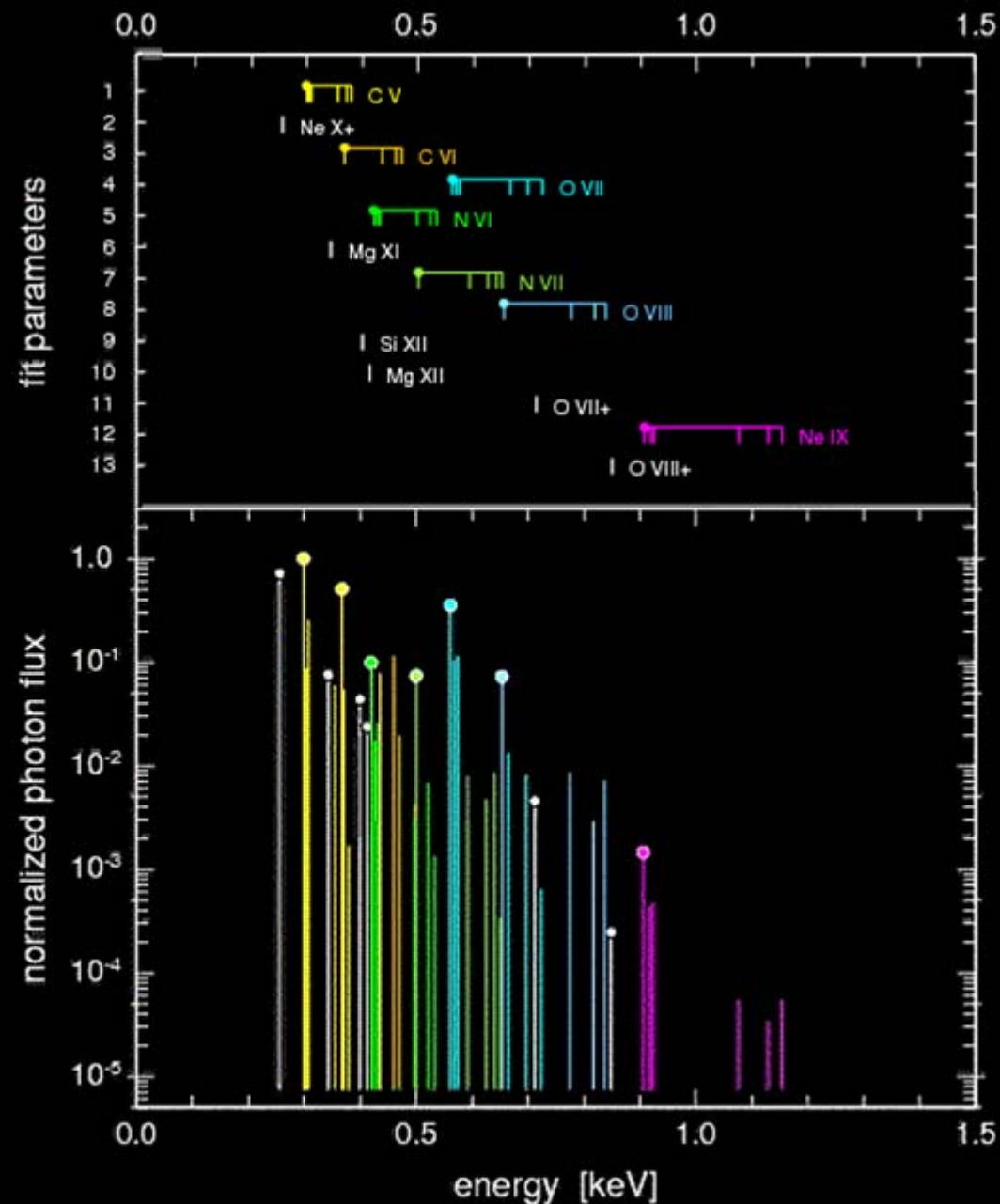
XMM-Newton observation of Comet C/2000 WM1

*RGS 1+2 data
after transformation into
comet reference frame*



Including the spatial extent into the spectral resolution





7 groups of lines:

C V (6 lines)

C VI (4 lines)

N VI (6 lines)

N VII (5 lines)

O VII (6 lines)

O VIII (4 lines)

Ne IX (6 lines)

+ 6 single lines:

Ne X (255.8 eV)

Mg XI (343.0 eV)

Mg XII (412.5 eV)

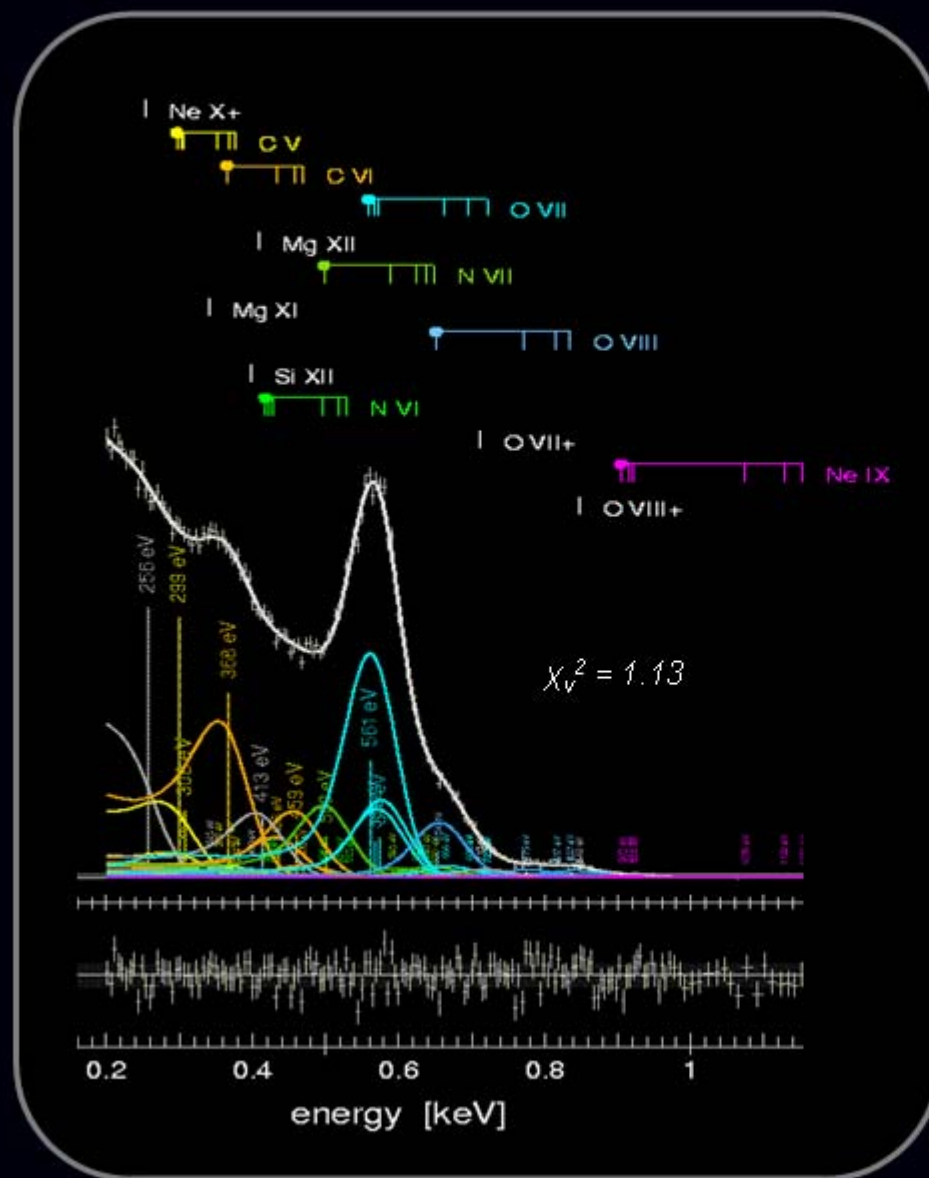
Si XII (400.0 eV)

O VII (712.8 eV)

O VIII (849.1 eV)

→ 43 lines, 13 free parameters

XMM-Newton spectra of Comet C/2000 WM1 *EPIC - pn*



intrinsically sharp emission lines,
with energies fixed

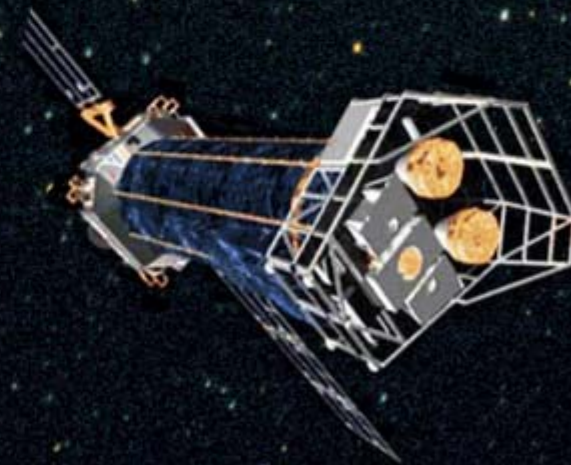
and fluxes as free parameters
for 7 groups and 7 individual lines

spectral model consistent with
RGS

High Resolution X-ray Spectroscopy of Comets

with XMM-Newton / RGS

*Konrad Dennerl
Max Planck Institute for
extraterrestrial Physics
Garching, Germany*



optical image: Comet C/1996 B2 (Hyakutake), taken by K. Dennerl