



Eight Years of Science with CHANDRA

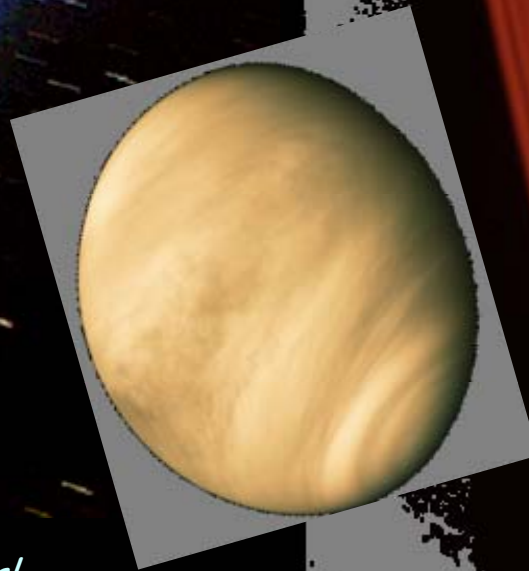
The fourth in a series, this meeting will highlight science results from the past eight years of operation of the Chandra X-ray Observatory with emphasis on recent results. Contributions from the XMM-Newton, Suzaku, and Swift Observatories and related results from INTEGRAL, FOXTE and AGILE will also be presented.

23rd - 25th October 2007

MARRIOTT HUNTSVILLE
HUNTSVILLE, ALABAMA

http://cxc.harvard.edu/symposium_2007/

X-rays from Comets, Venus, and Mars



Konrad Dennerl

*Max-Planck-Institut für extraterrestrische Physik
Garching bei München, Germany*

X-rays from comets and planets are powered by the Sun

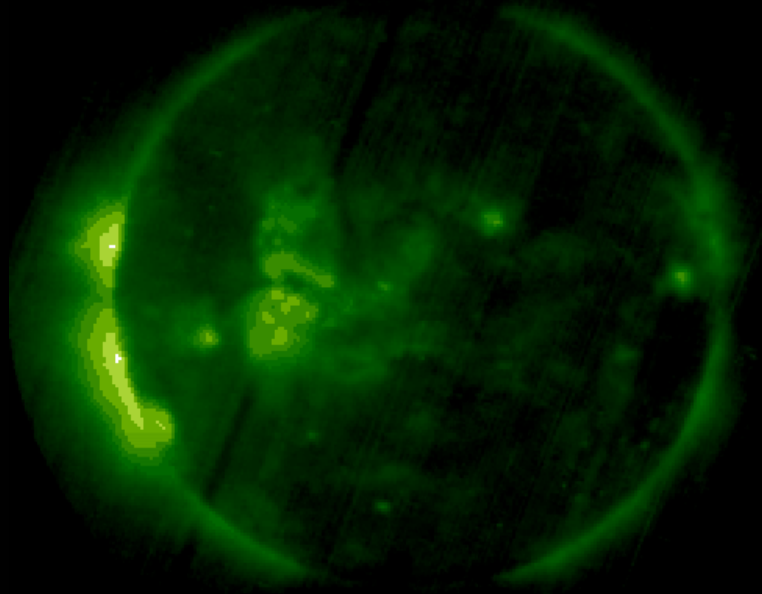
There are two different processes at work:

solar X-rays

GOES-12
NOAA/SEC
Boulder, CO

SXI-0 AR Level-1

905
LIN

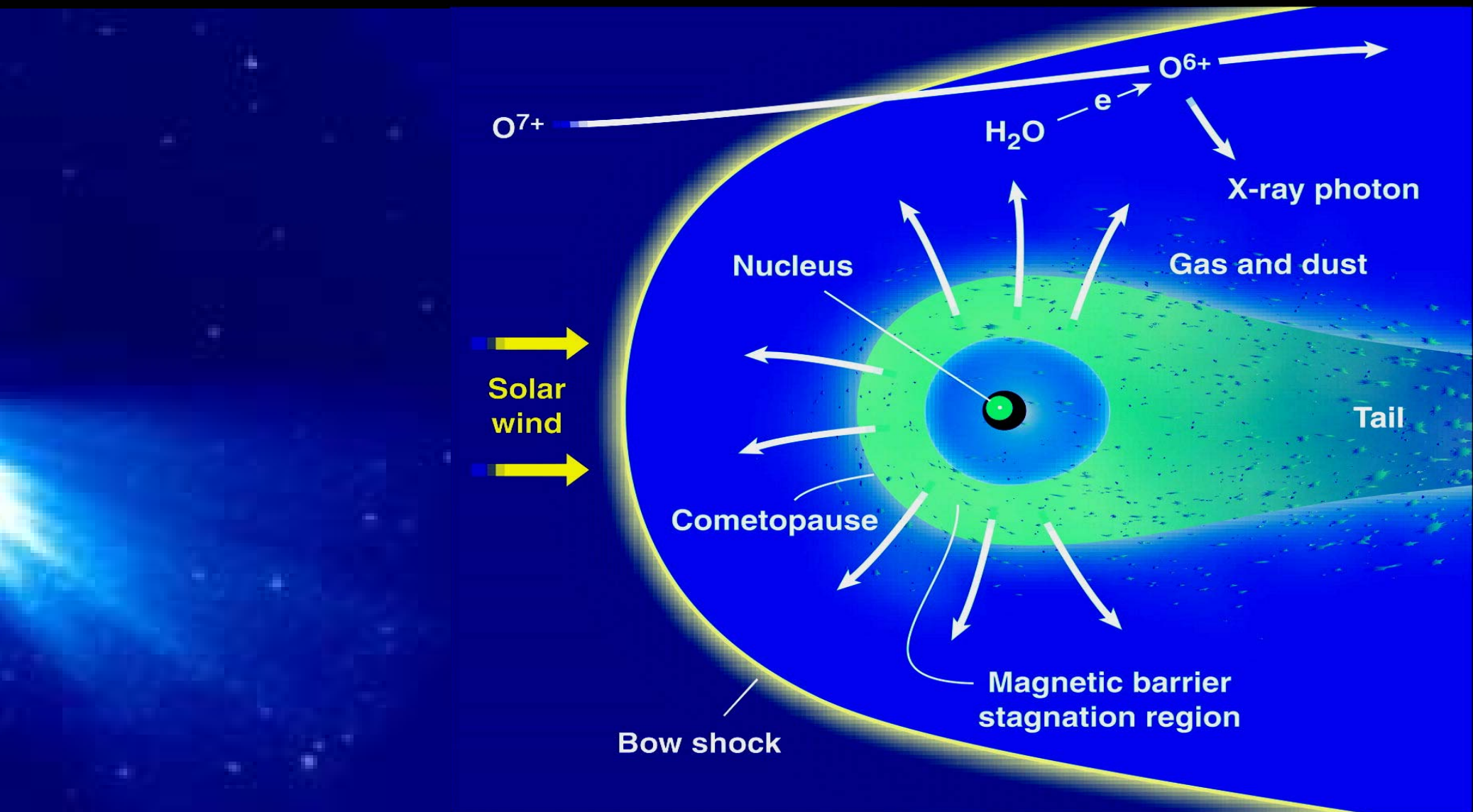


2003/11/17 18:00:56 UTC P_THN_LB 3.000s 500V

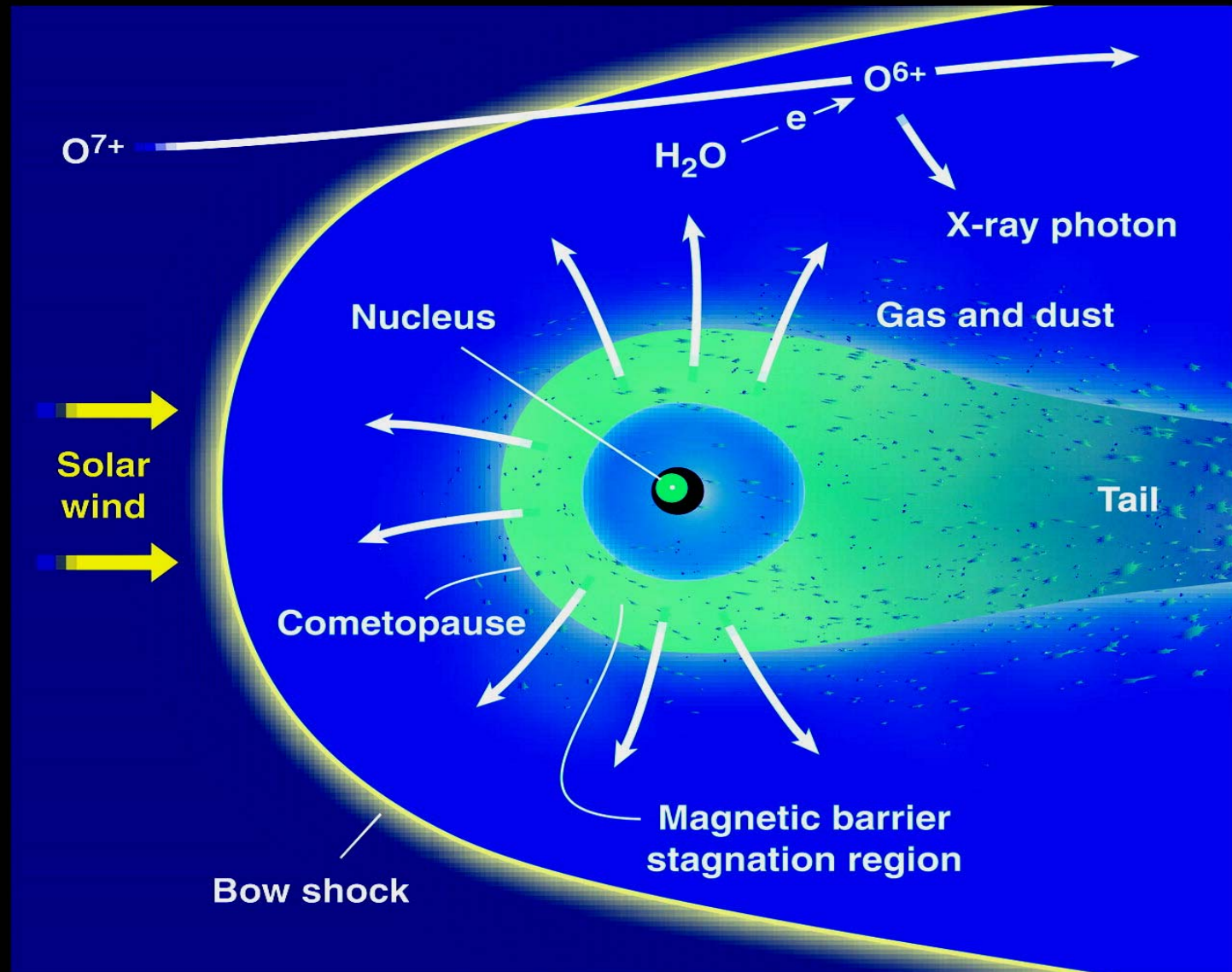
solar wind

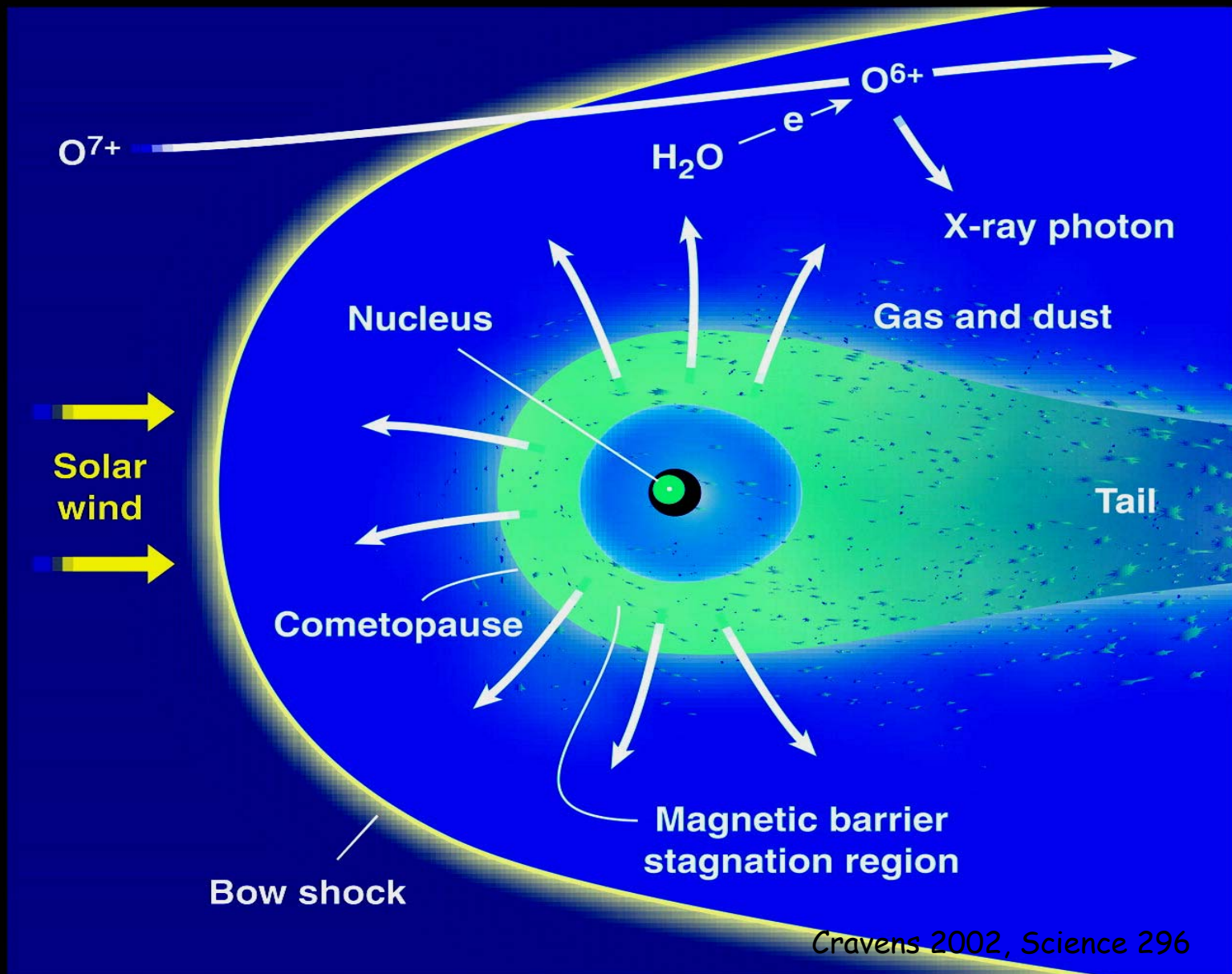
SOHO LASCO C2, 20.3.- 10.4.1999, visible light

Interaction of the solar wind with the cometary gas



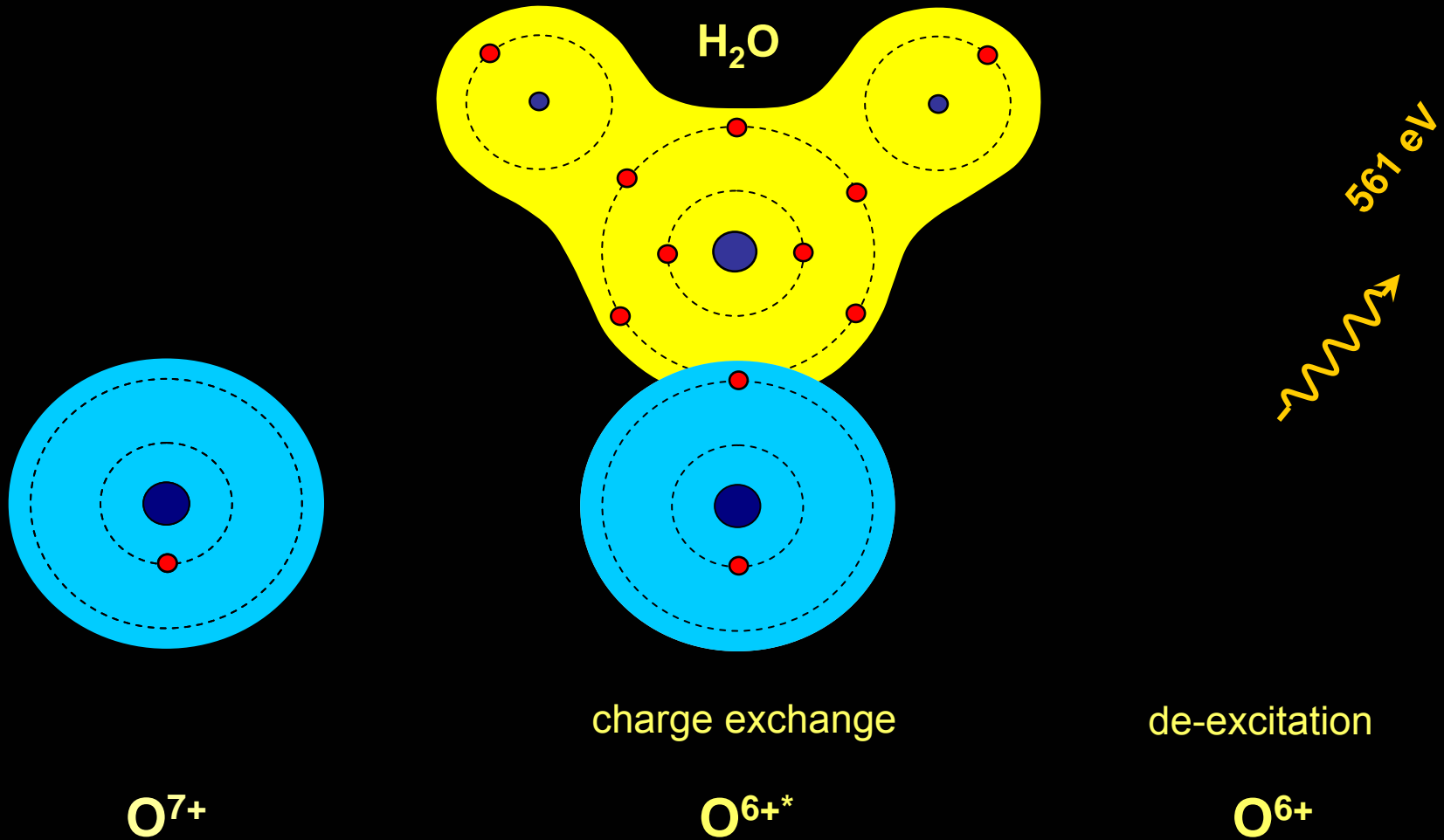
Cravens 1997 (GRL 24), Cravens 2002 (Science 296)



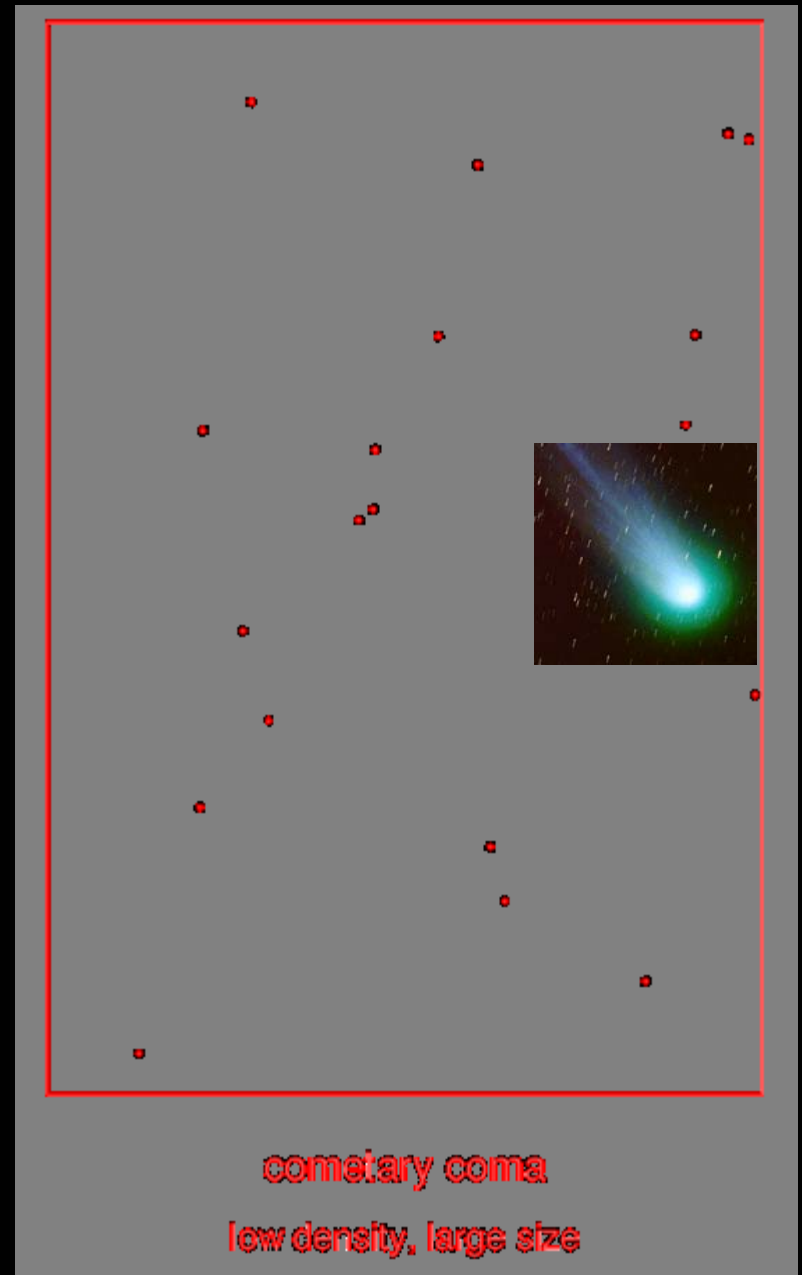
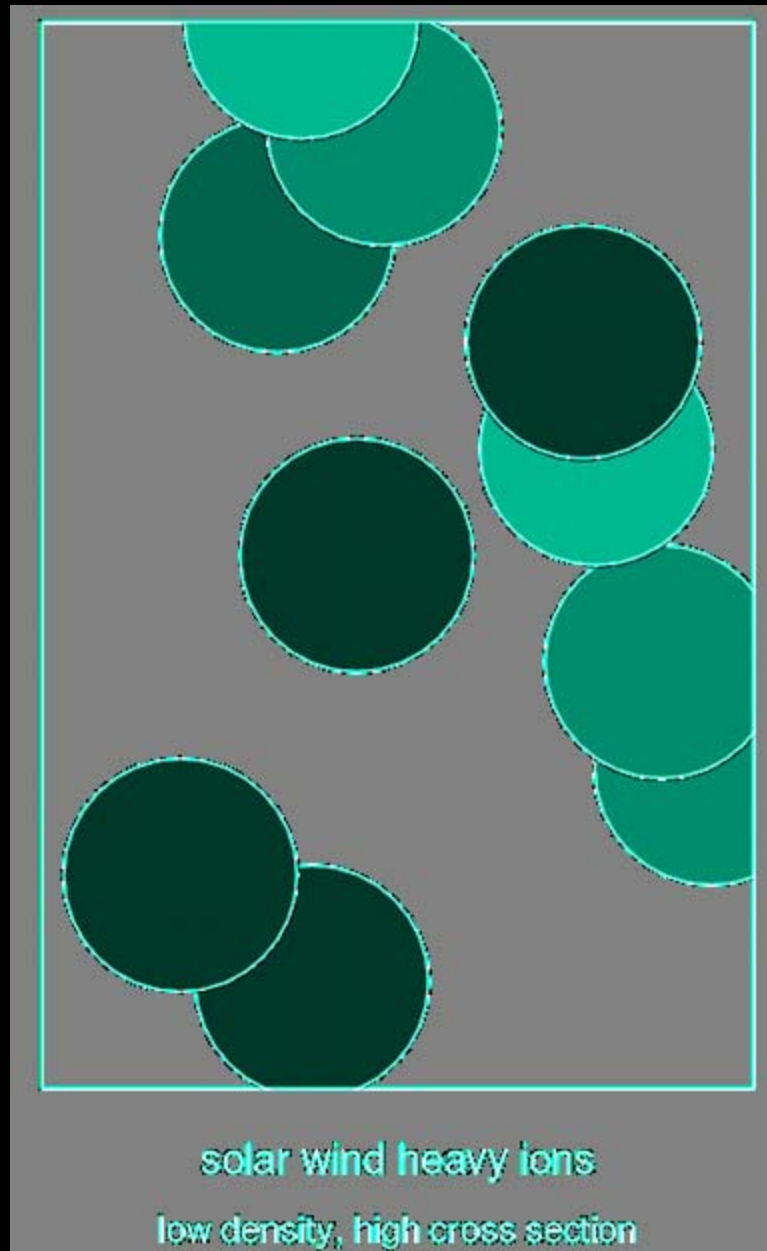


Cravens 2002, Science 296

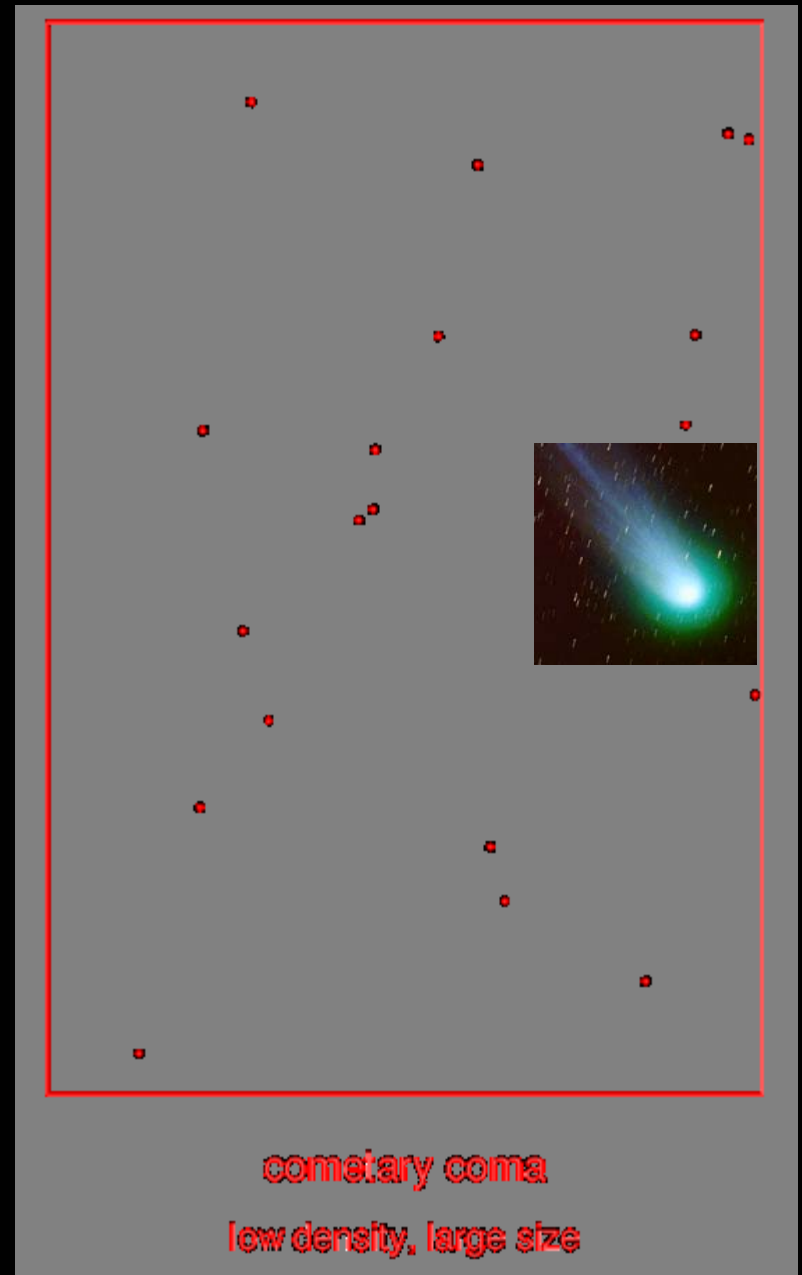
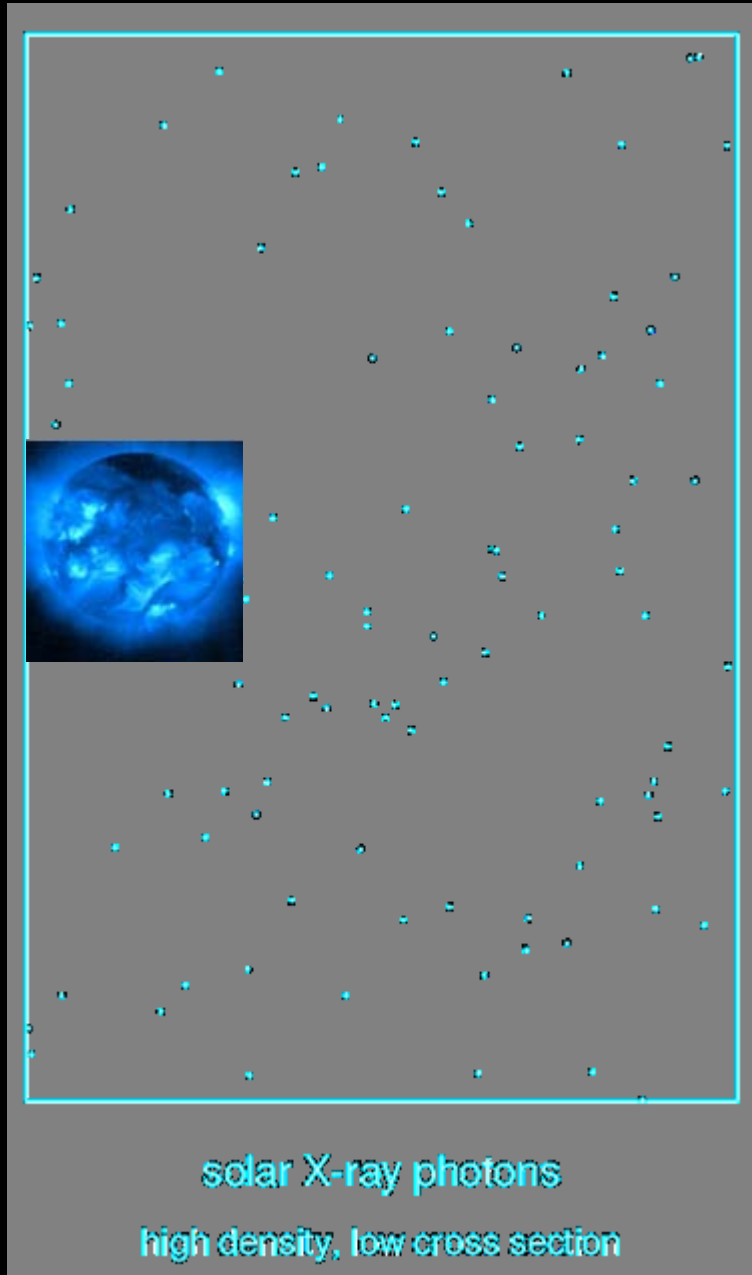
Charge Exchange



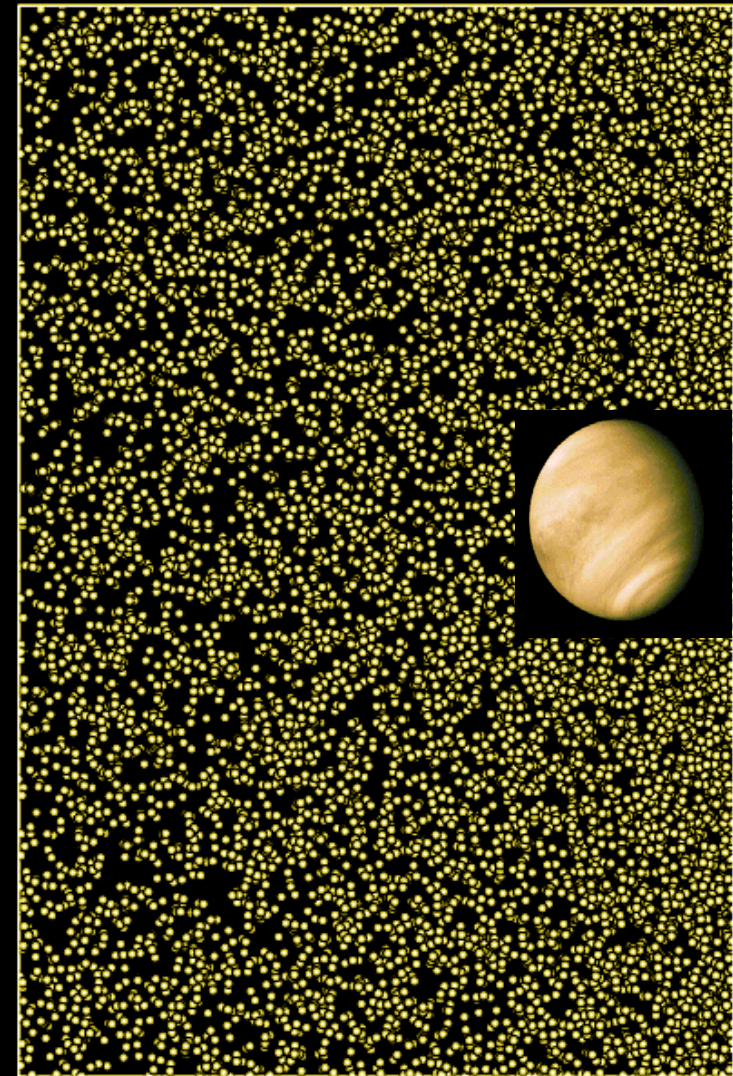
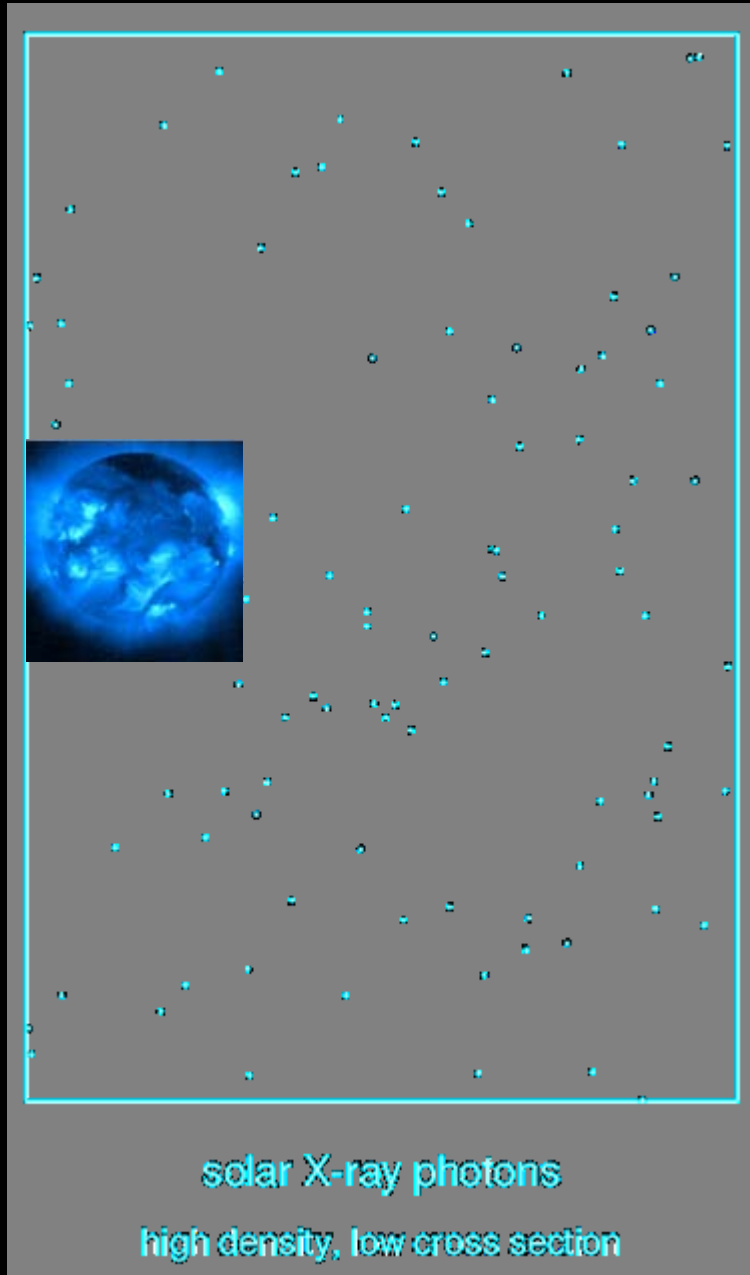
Solar wind charge exchange



Scattering of solar X-rays



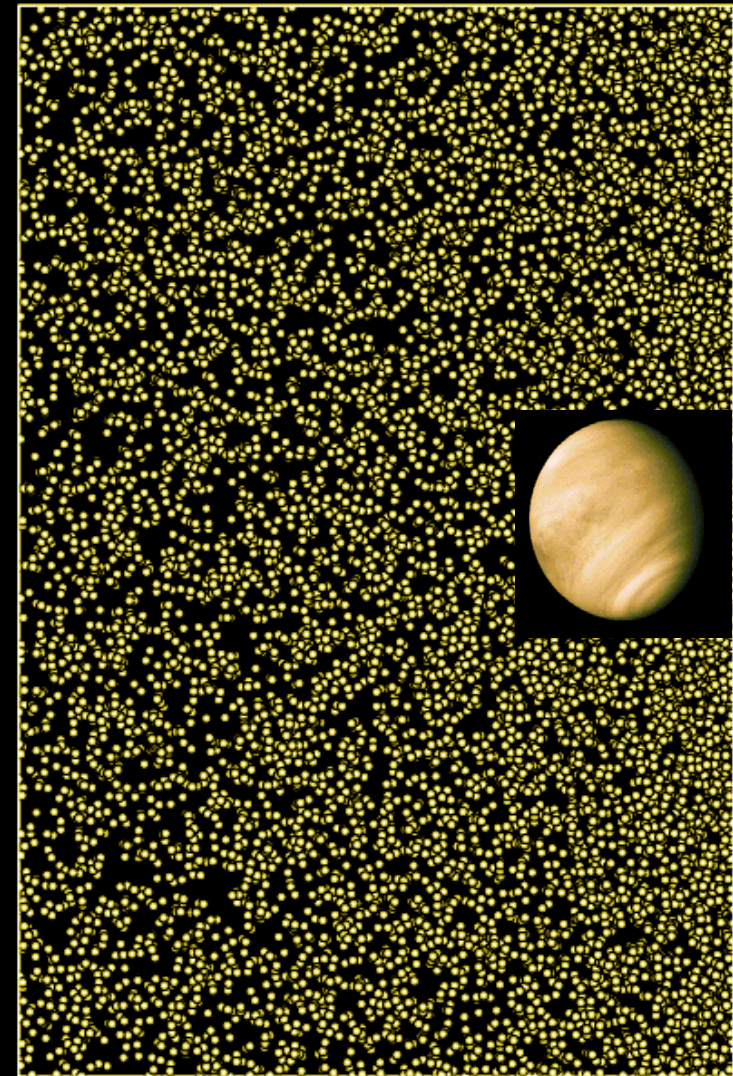
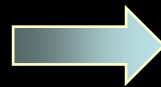
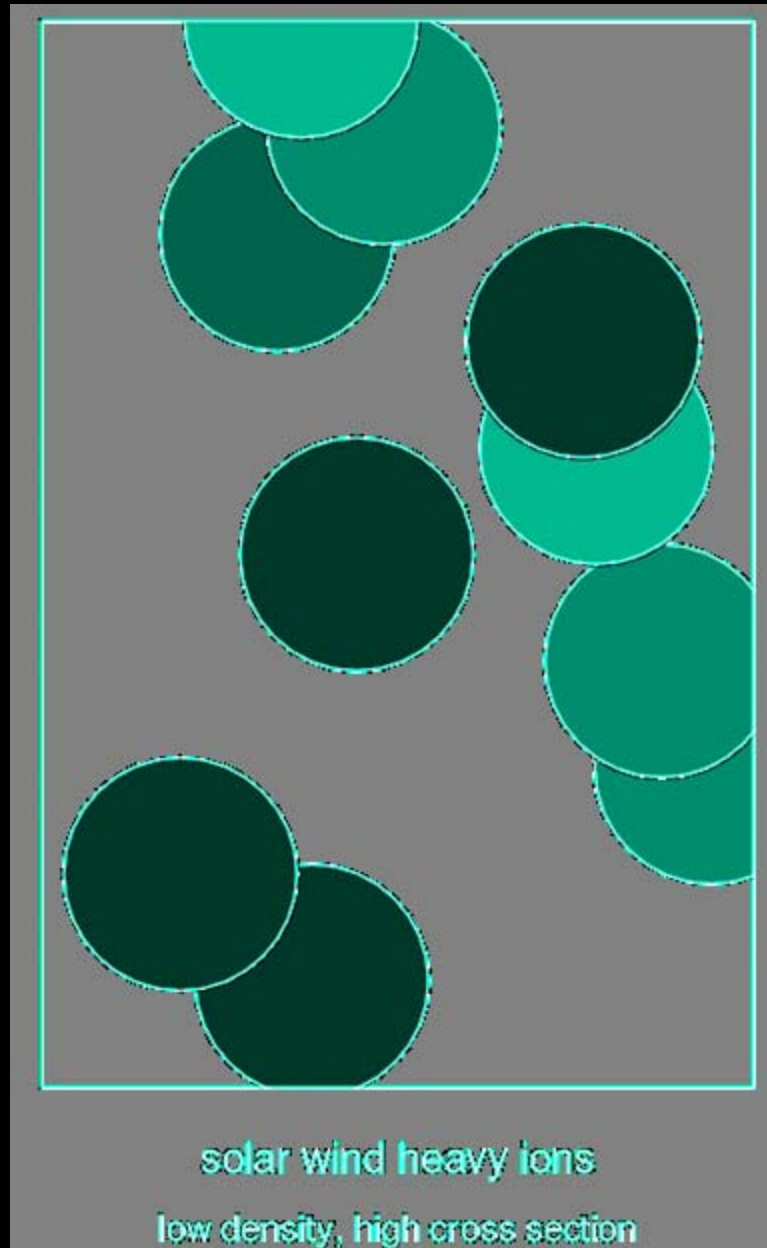
Scattering of solar X-rays



planetary atmosphere

high density, small size

Solar wind charge exchange



1996: Comet Hyakutake (C/1996 B2)



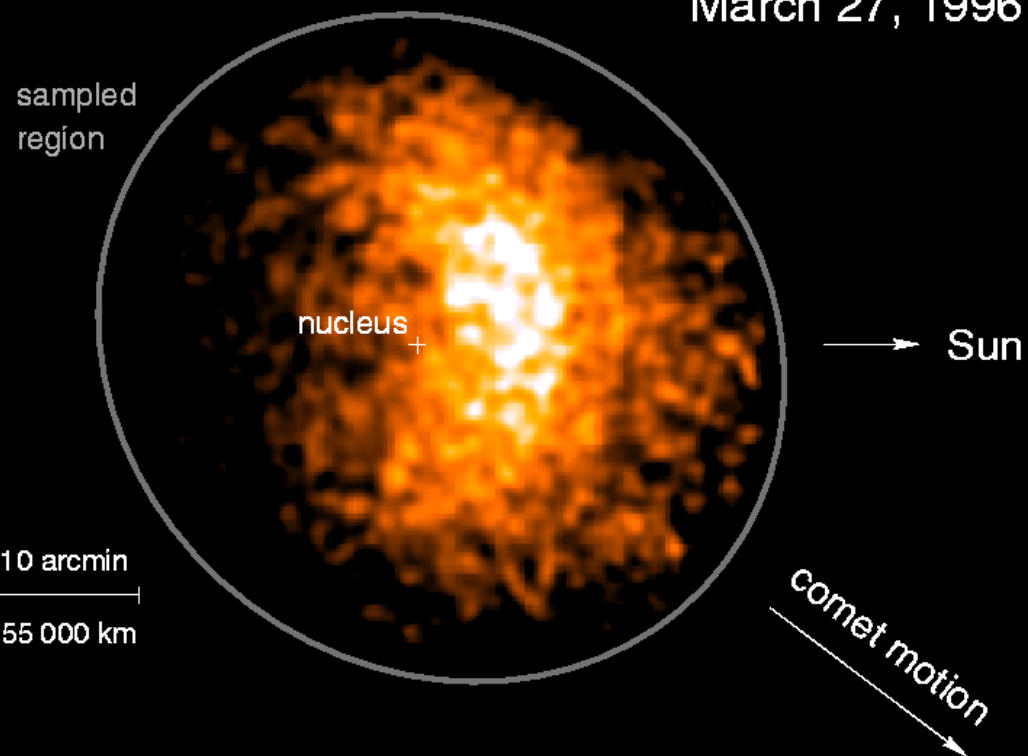
ROSAT

FIRST X-RAY IMAGE OF A COMET

Comet Hyakutake · C/1996 B2

ROSAT HRI

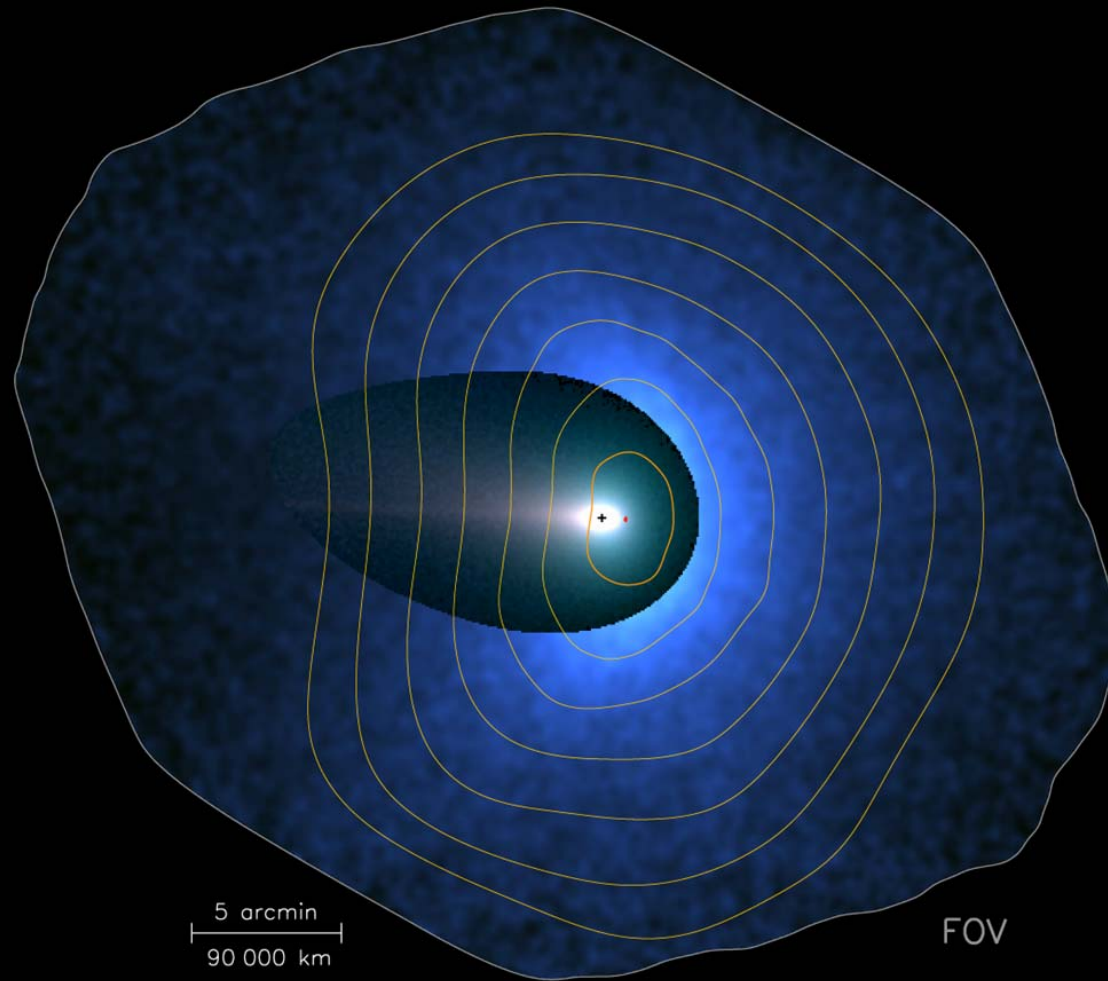
March 27, 1996



C. Lisse, M. Mumma, NASA GSFC

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

Comet C/2000 WM1, 2001 Dec 13 – 14

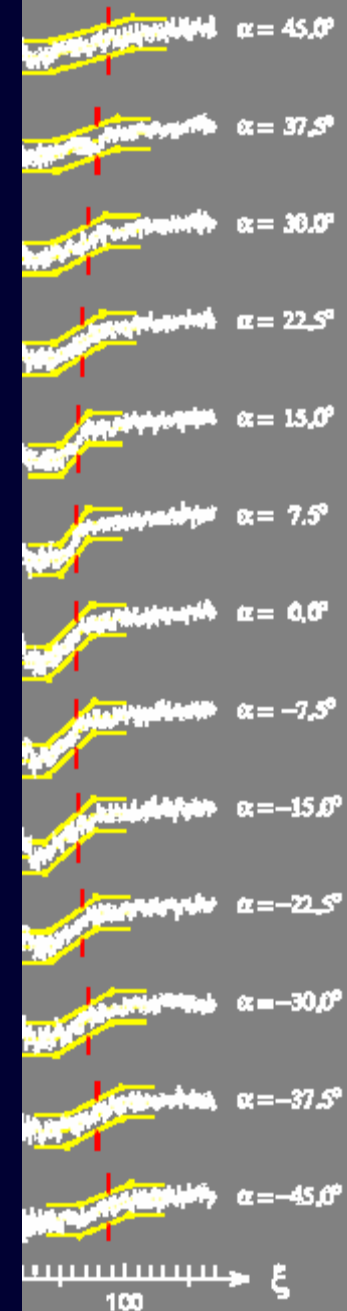
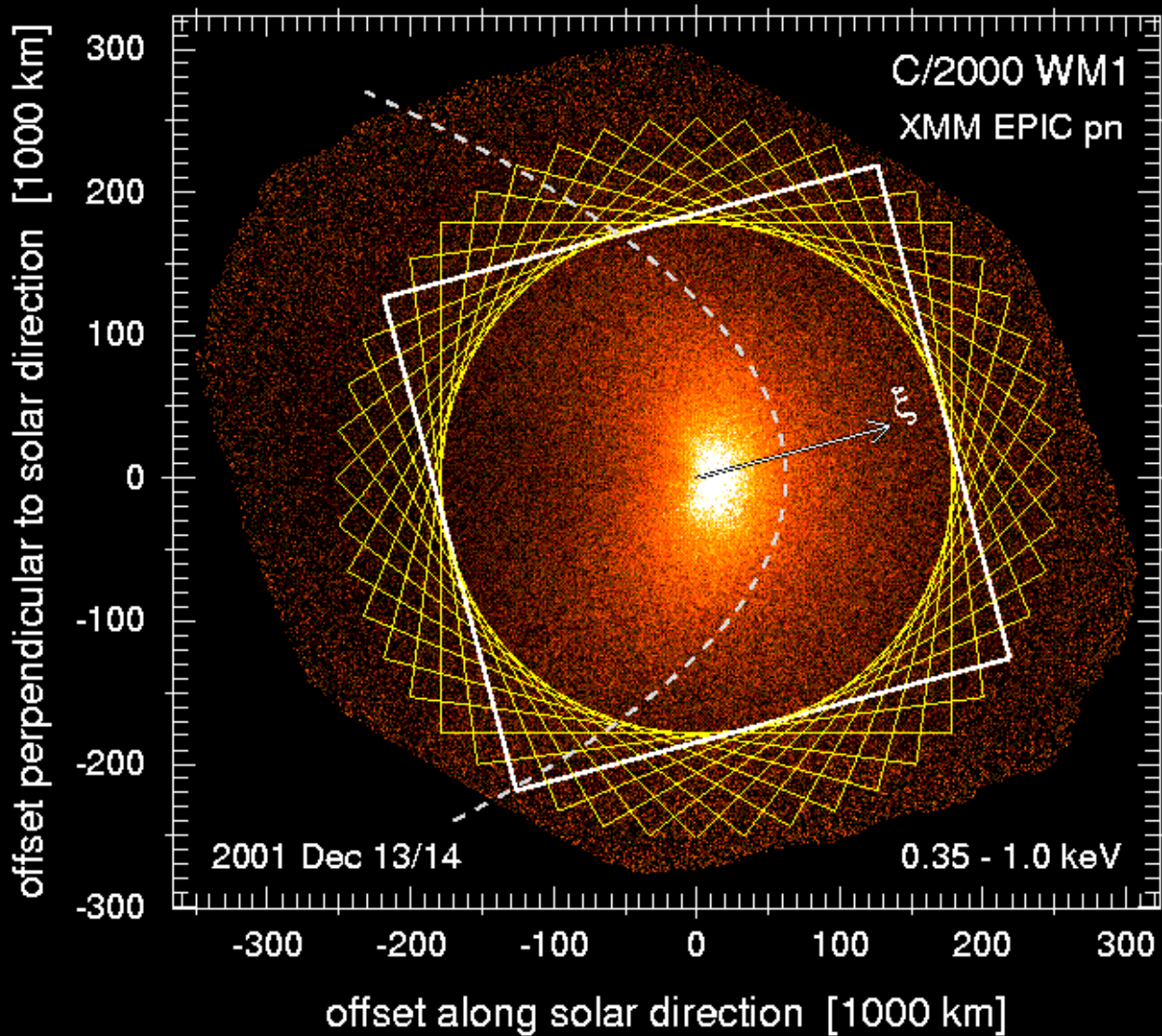


optical image

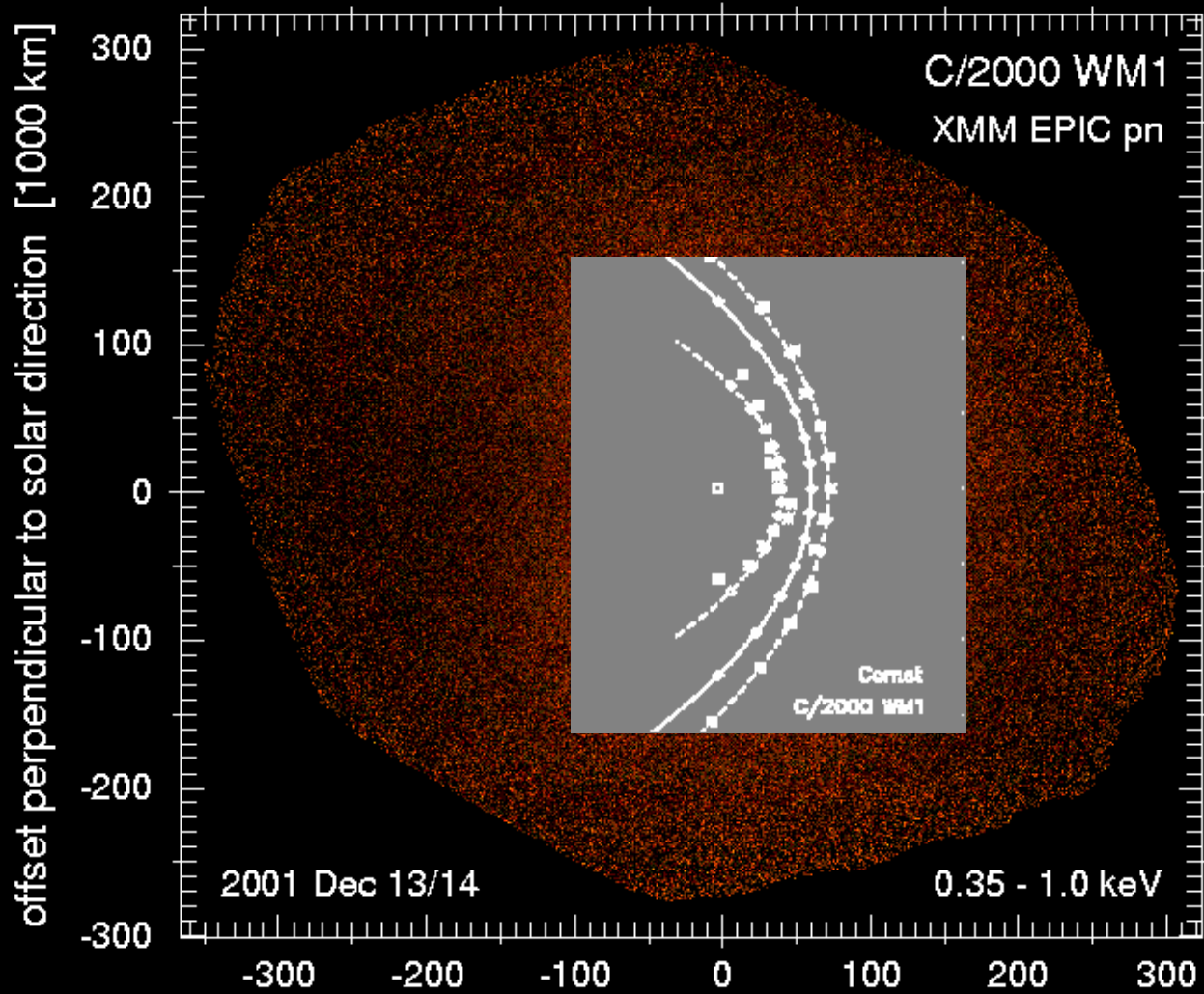
+

*X-ray image
(XMM-Newton)*

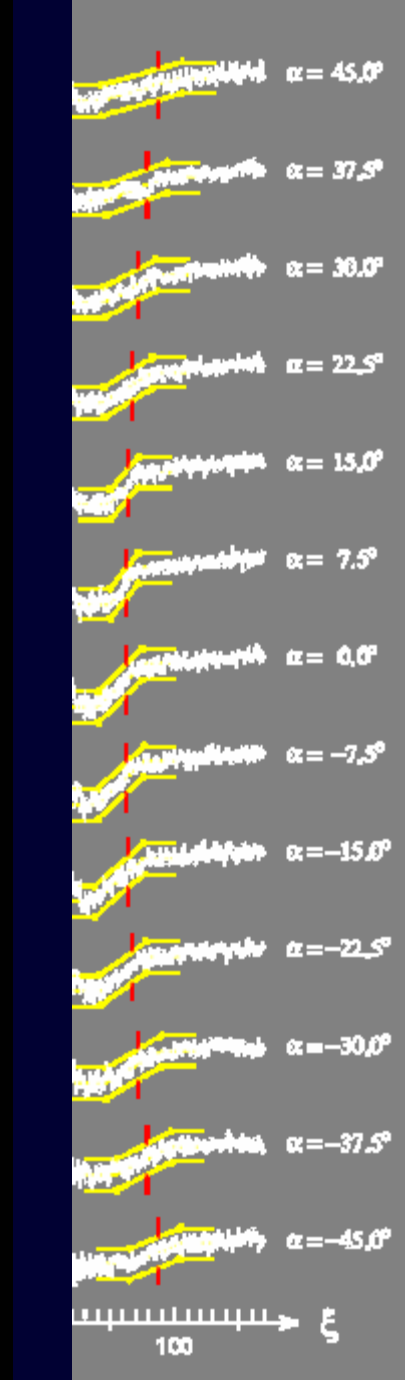
The bow shock of Comet C/2000 WM1



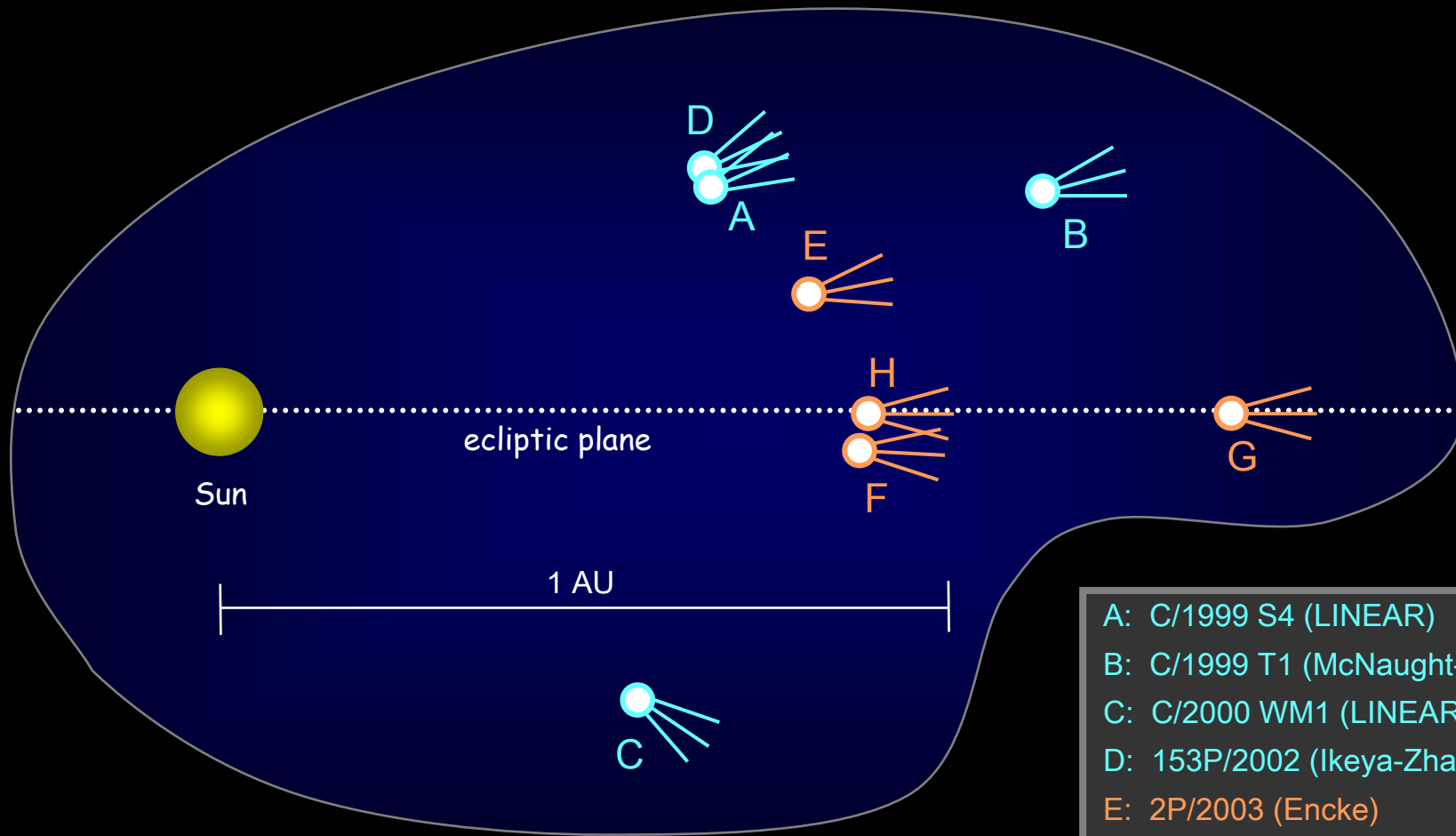
The bow shock of Comet C/2000 WM1



Wiegman & Dennerl 2005, [A&A 436] L33-L36



Comets observed with Chandra, 2000 - 2007

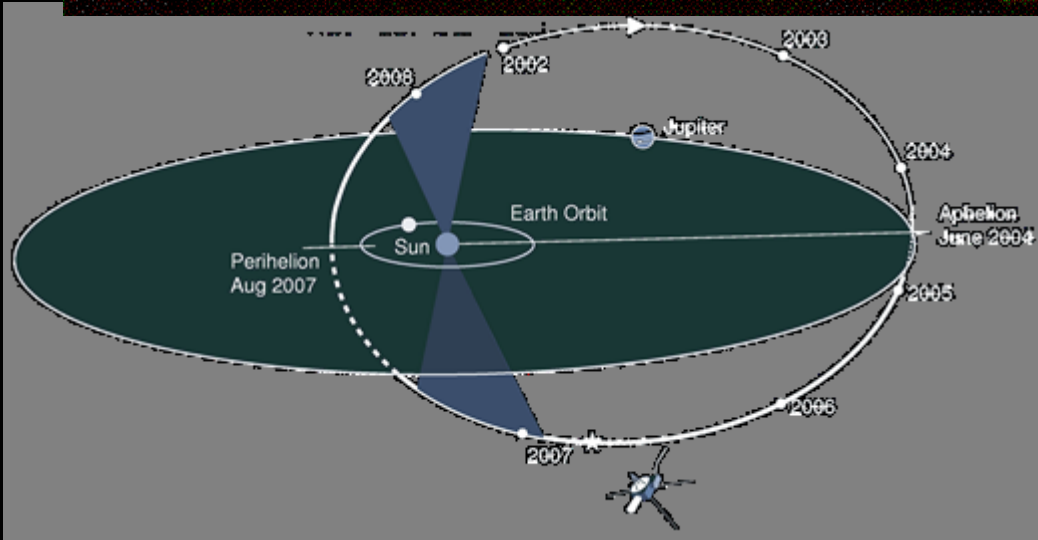
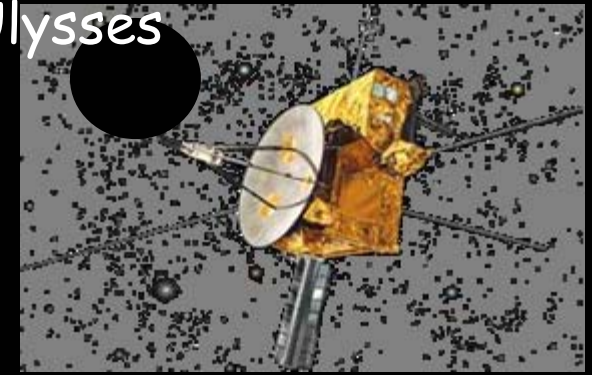
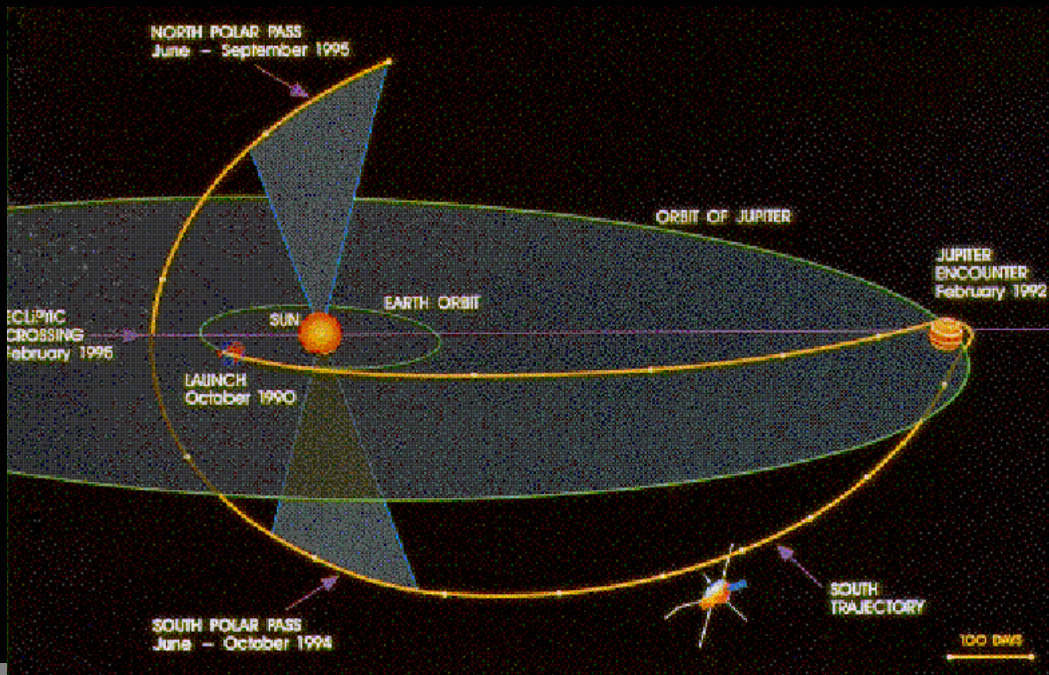


- A: C/1999 S4 (LINEAR)
- B: C/1999 T1 (McNaught-Hartley)
- C: C/2000 WM1 (LINEAR)
- D: 153P/2002 (Ikeya-Zhang)
- E: 2P/2003 (Encke)
- F: C/2001 Q4 (NEAT)
- G: 9P/2005 (Tempel 1)
- H: 73P/2006 (SW3-B)

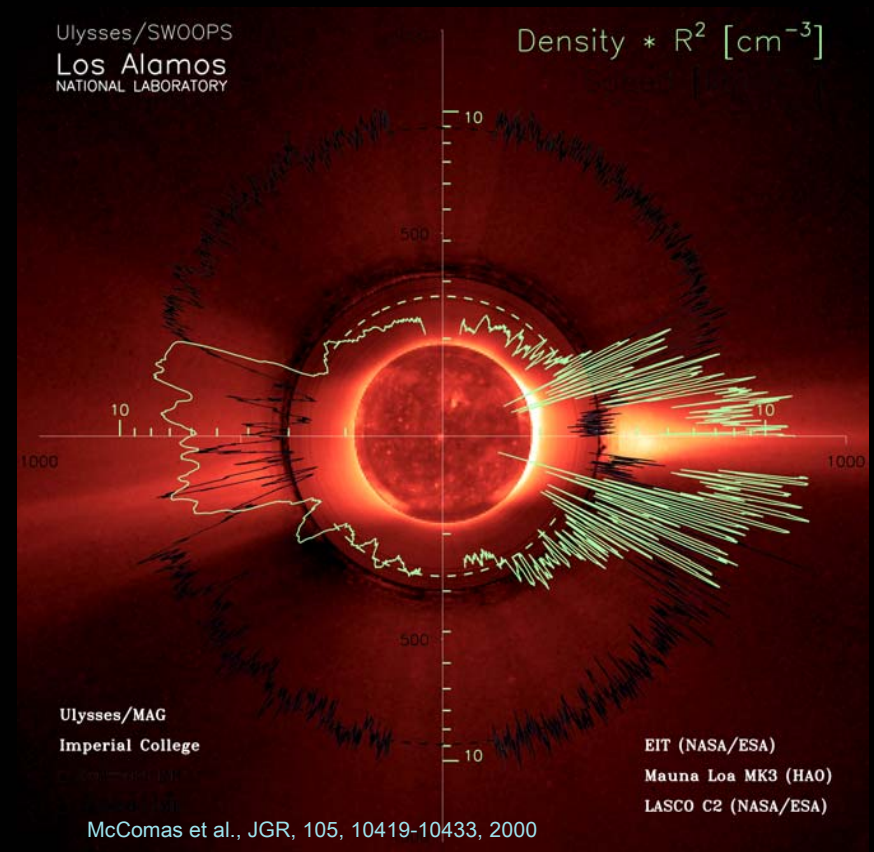
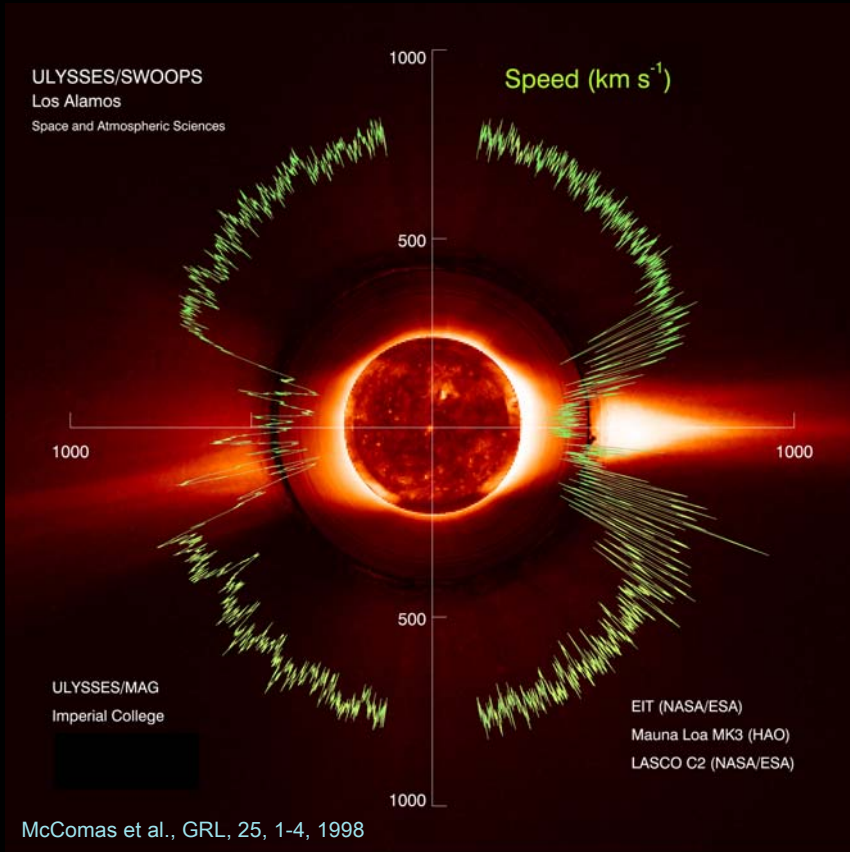
→ ensemble properties of comets

Bodewits et al., A&A 469, 2007

Measuring the solar wind in 3 dimensions: Ulysses



Ulysses: Solar wind properties near solar minimum



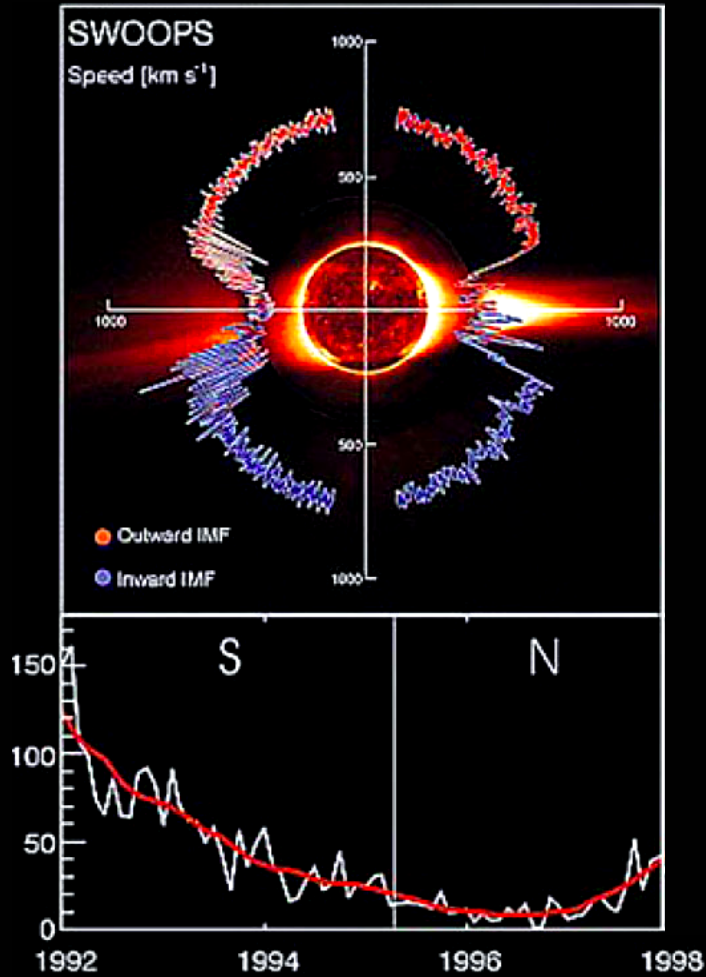
polar wind:

- fast (~700 km/s), low density, cold, less ionized, regular
- fast, cold, less ionized, from coronal holes, disturbed
(found in corotating interaction regions and behind flare related shocks)

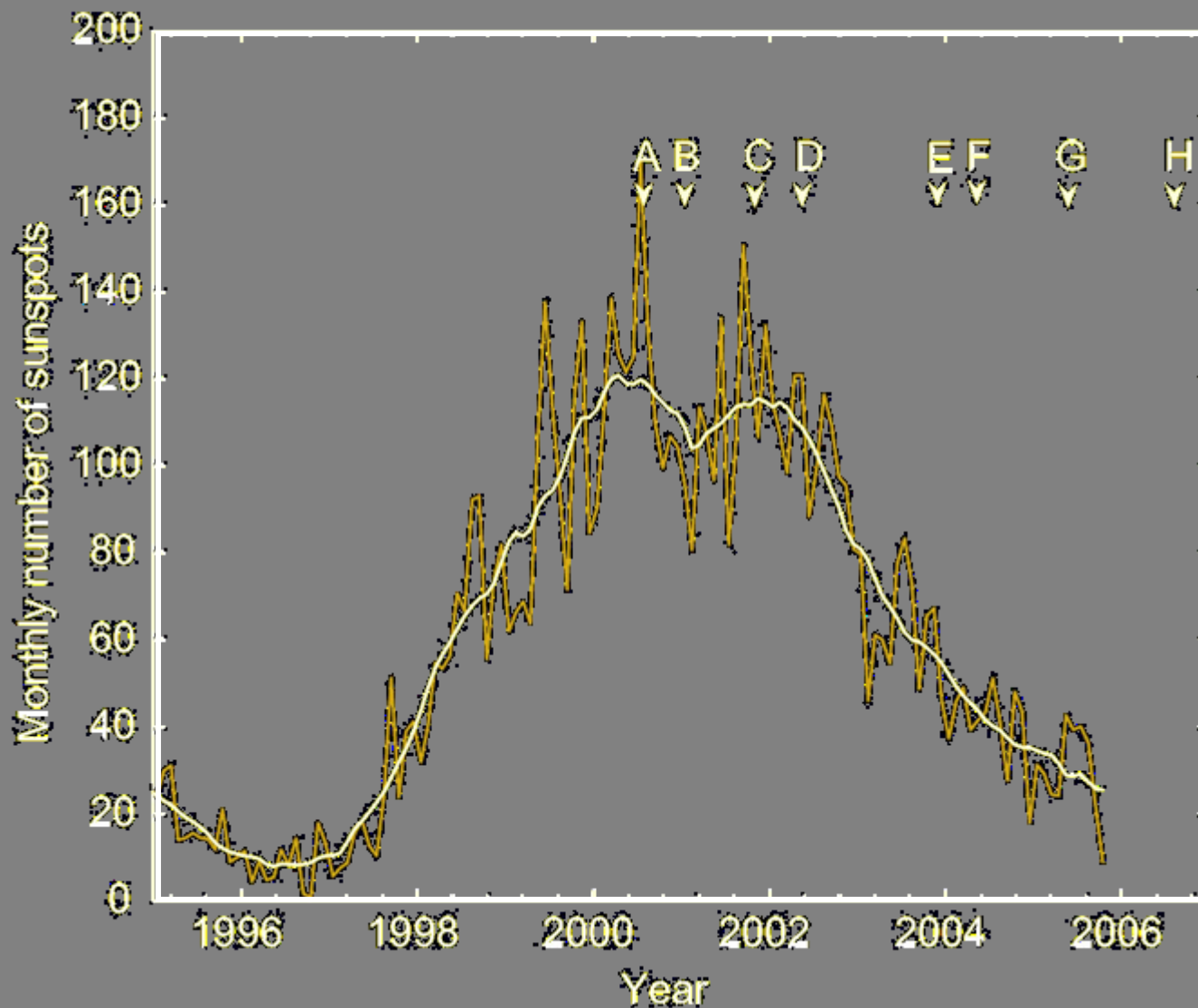
equatorial wind:

- slow, warm, more ionized, high density, quiet
- fast, hot, highly ionized, disturbed, associated with CMEs or flares

Ulysses: Solar wind properties near .. solar minimum

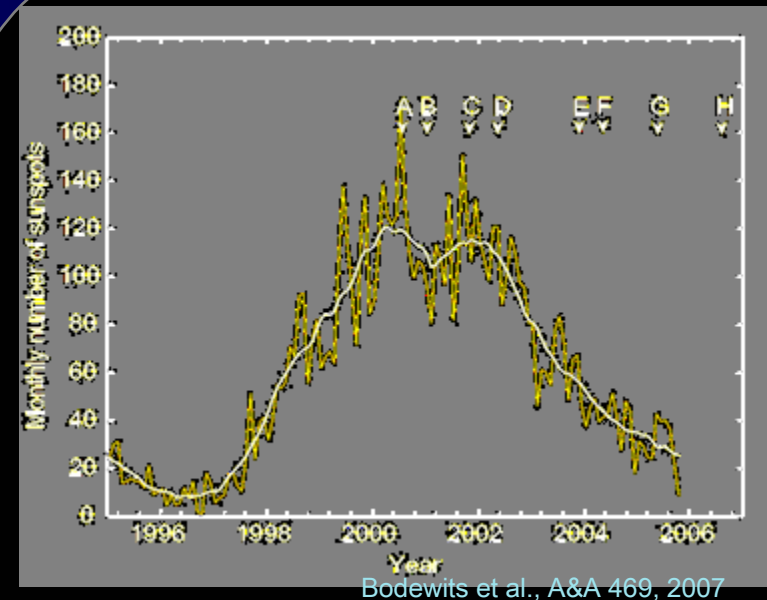
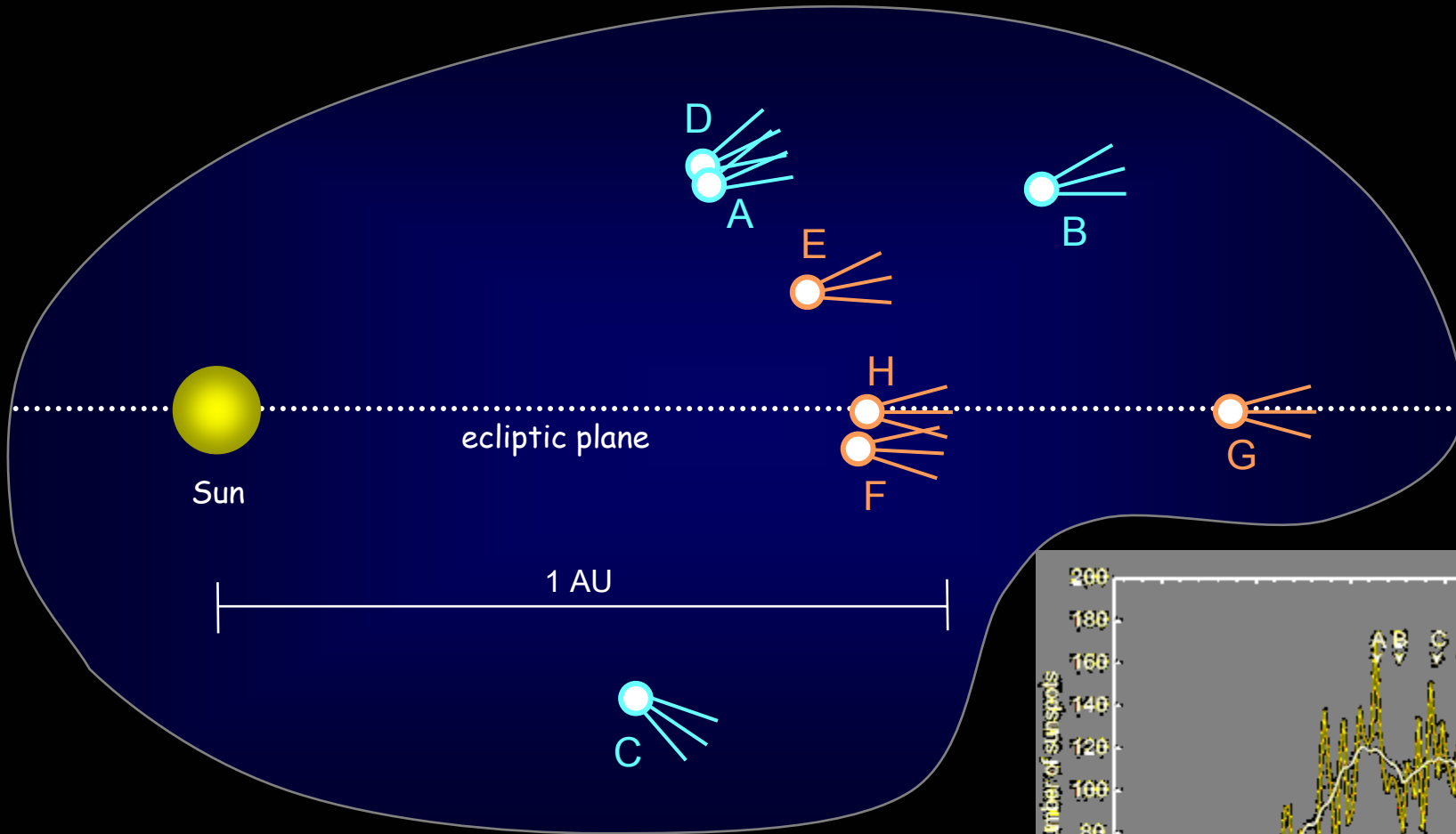


Chandra observations of comets over the solar cycle



Bodewits et al., A&A 469, 2007

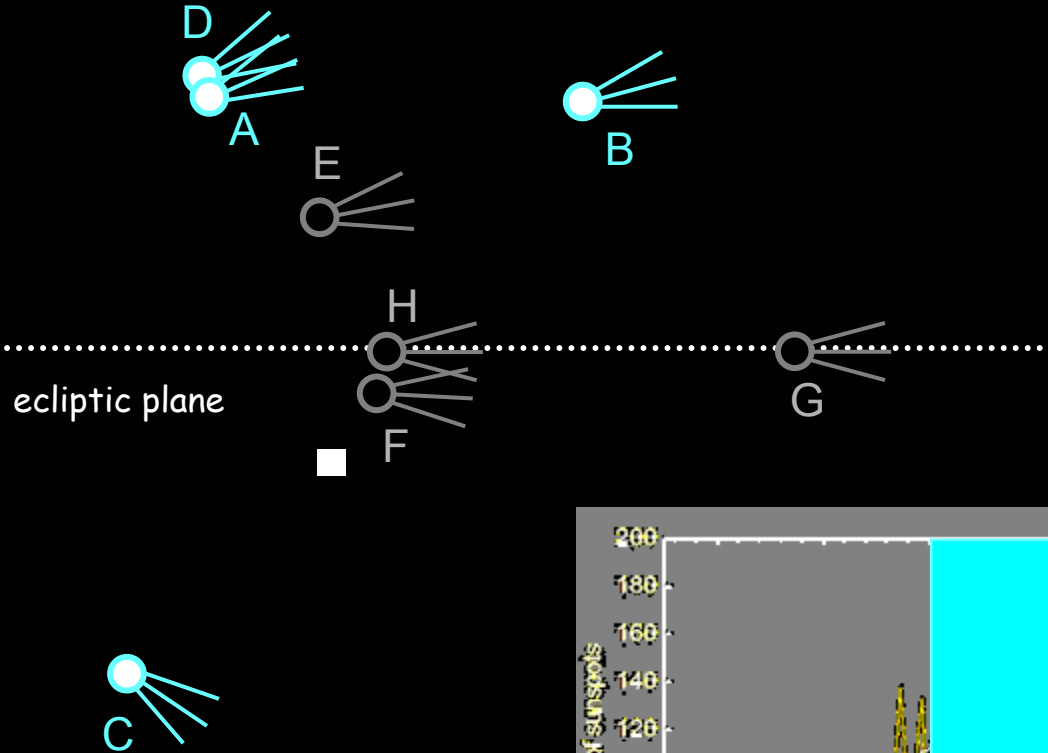
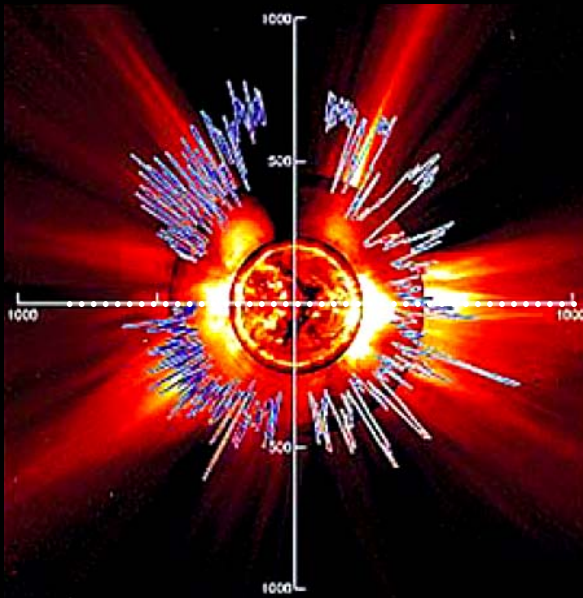
Comets observed with Chandra, 2000 - 2007



- A: C/1999 S4 (LINEAR)
- B: C/1999 T1 (McNaught-Hartley)
- C: C/2000 WM1 (LINEAR)
- D: 153P/2002 (Ikeya-Zhang)

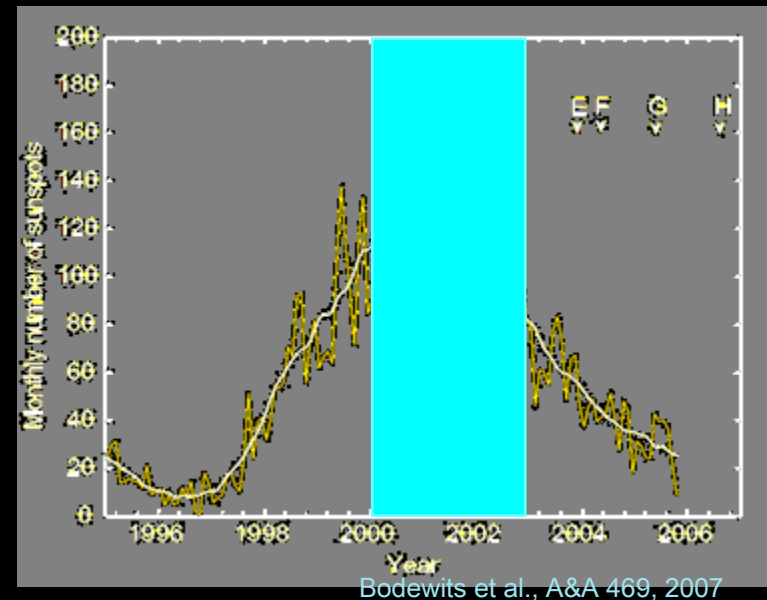
- E: 2P/2003 (Encke)
- F: C/2001 Q4 (NEAT)
- G: 9P/2005 (Tempel 1)
- H: 73P/2006 (SW3-B)

Comets observed with Chandra, 2000 - 2007



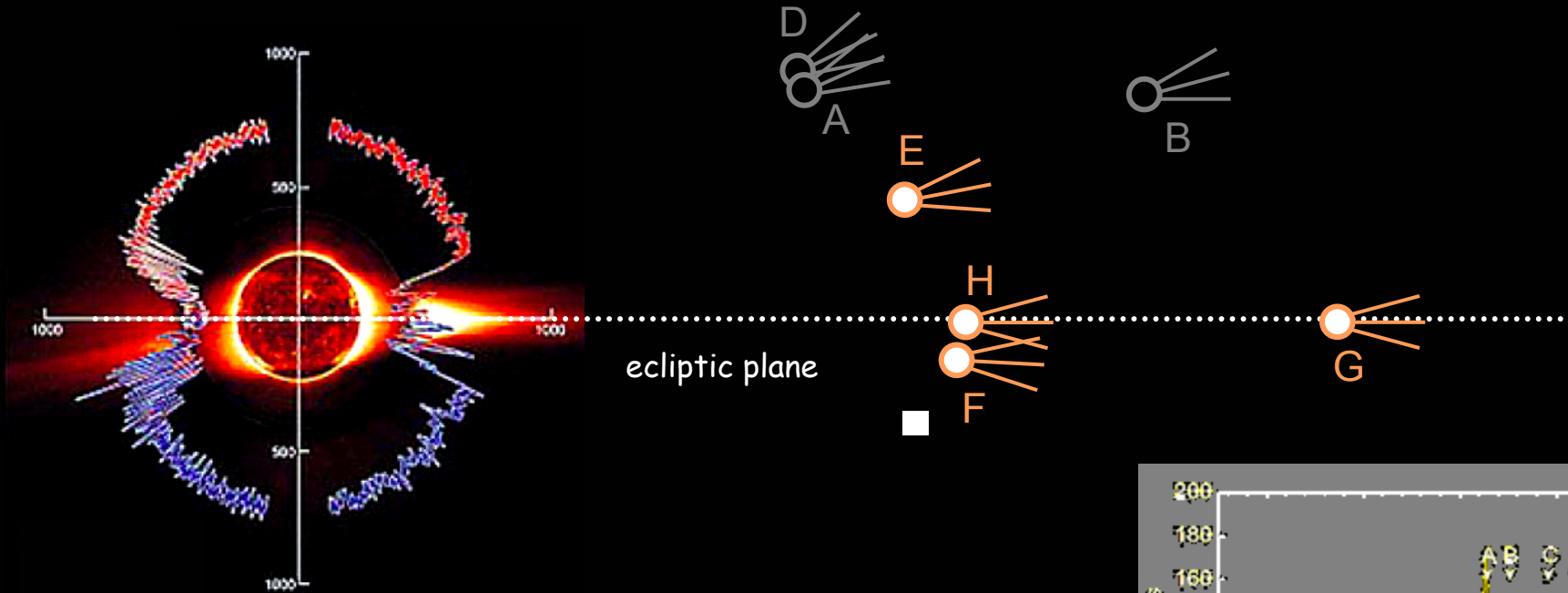
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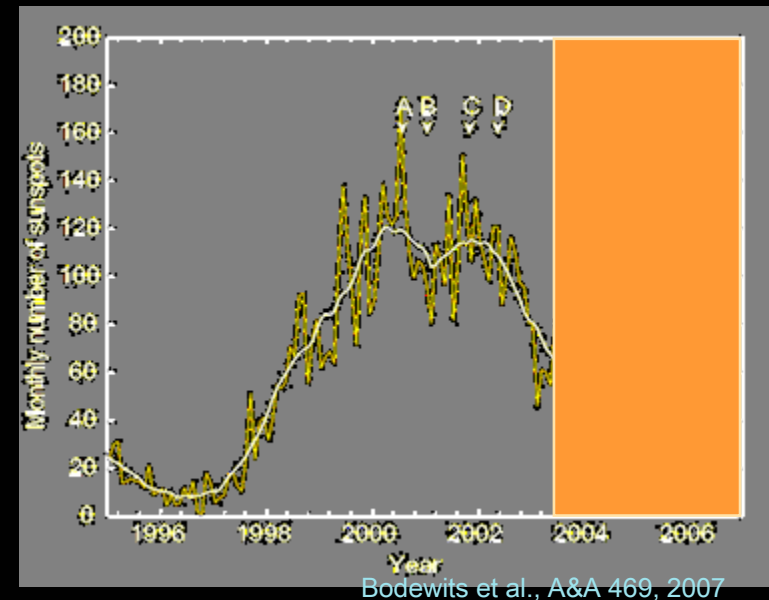
Bodewits et al., A&A 469, 2007

Comets observed with Chandra, 2000 - 2007



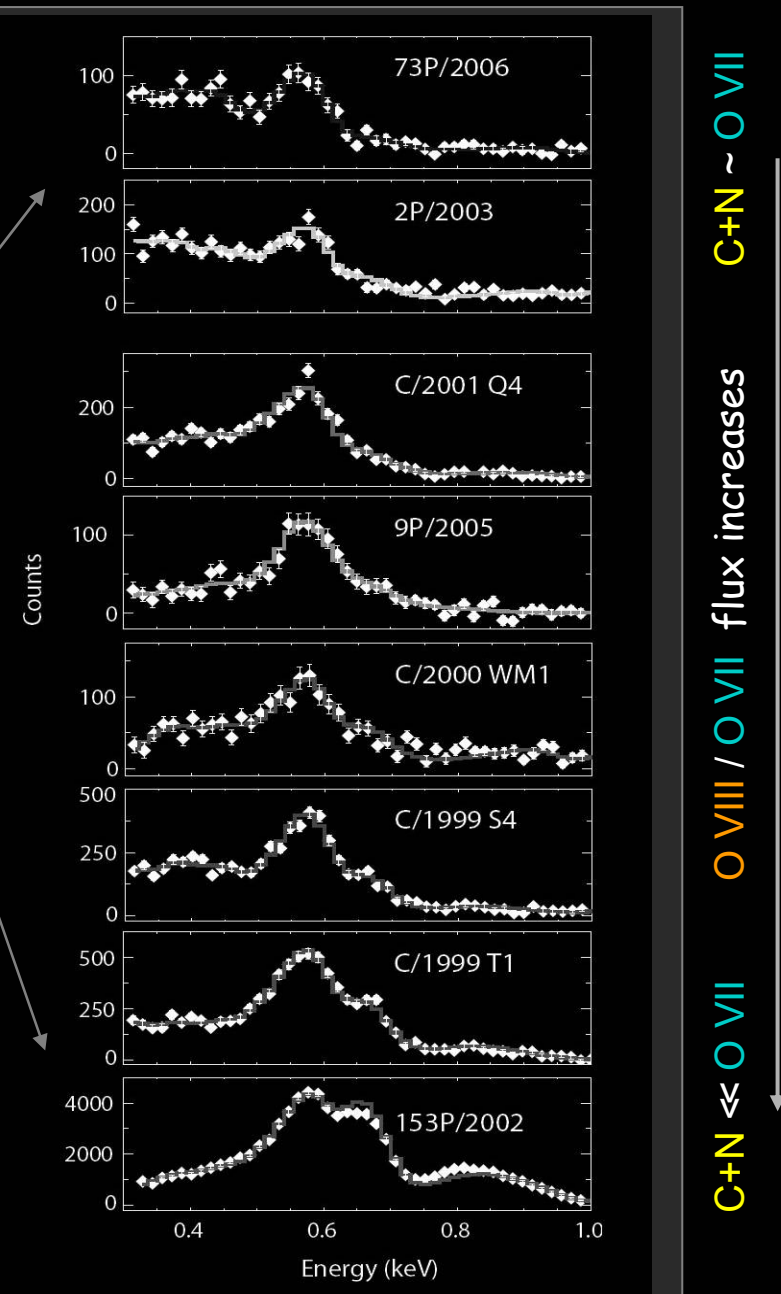
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Chandra spectra of comets:

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



Bodewits et al., A&A 469, 2007

Huntsville, 2007 Oct 23

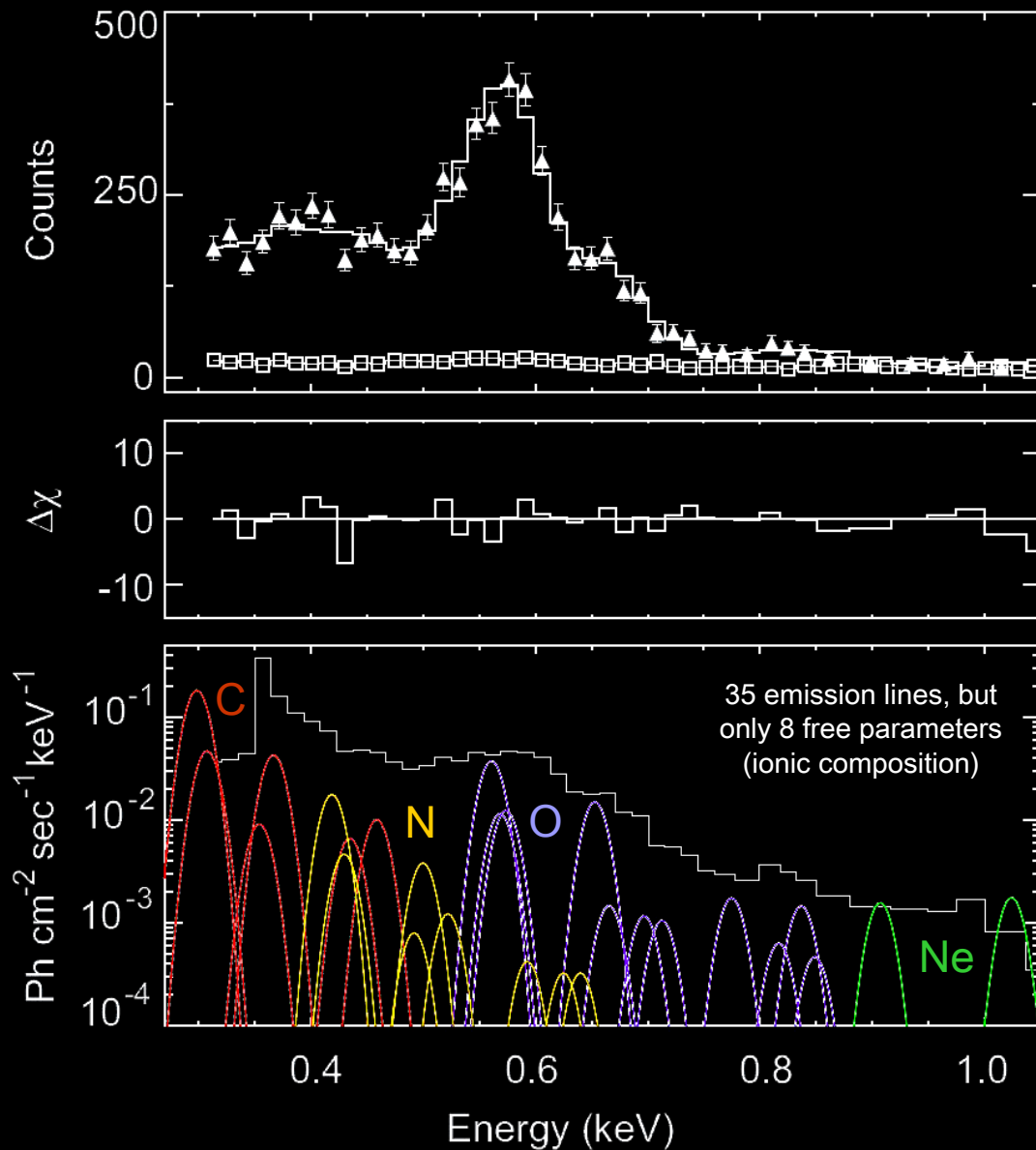
Theoretical, velocity dependent cross sections [10^{-16} cm^2]

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

Comet C/1999 S4 (LINEAR)



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)

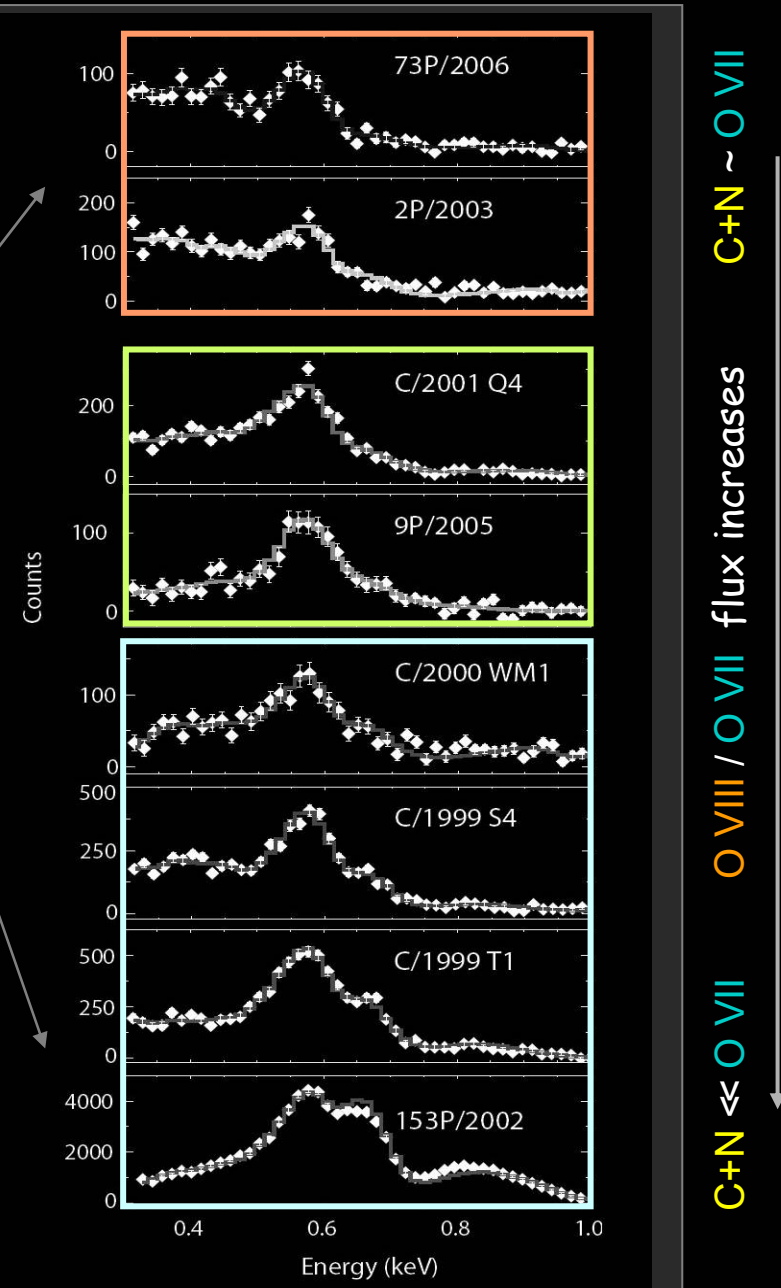
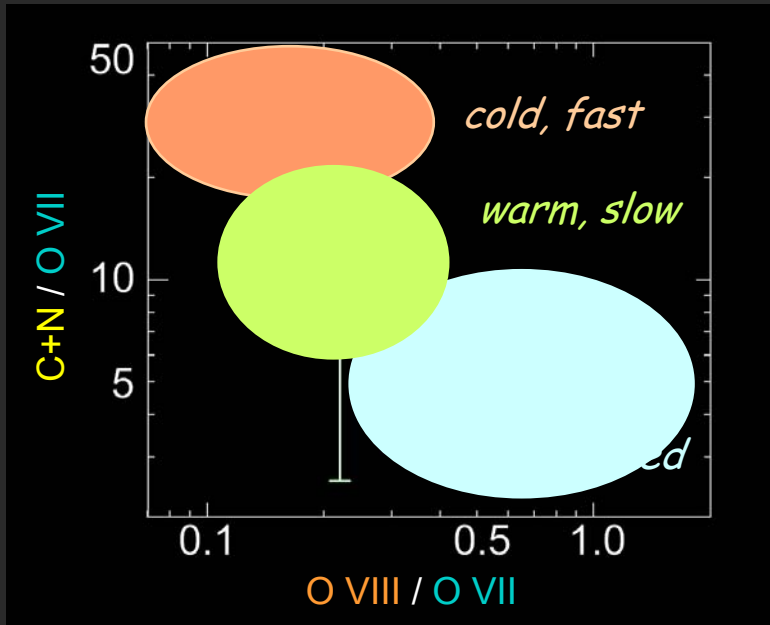
for each ionic species:

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

Chandra spectra of comets:

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

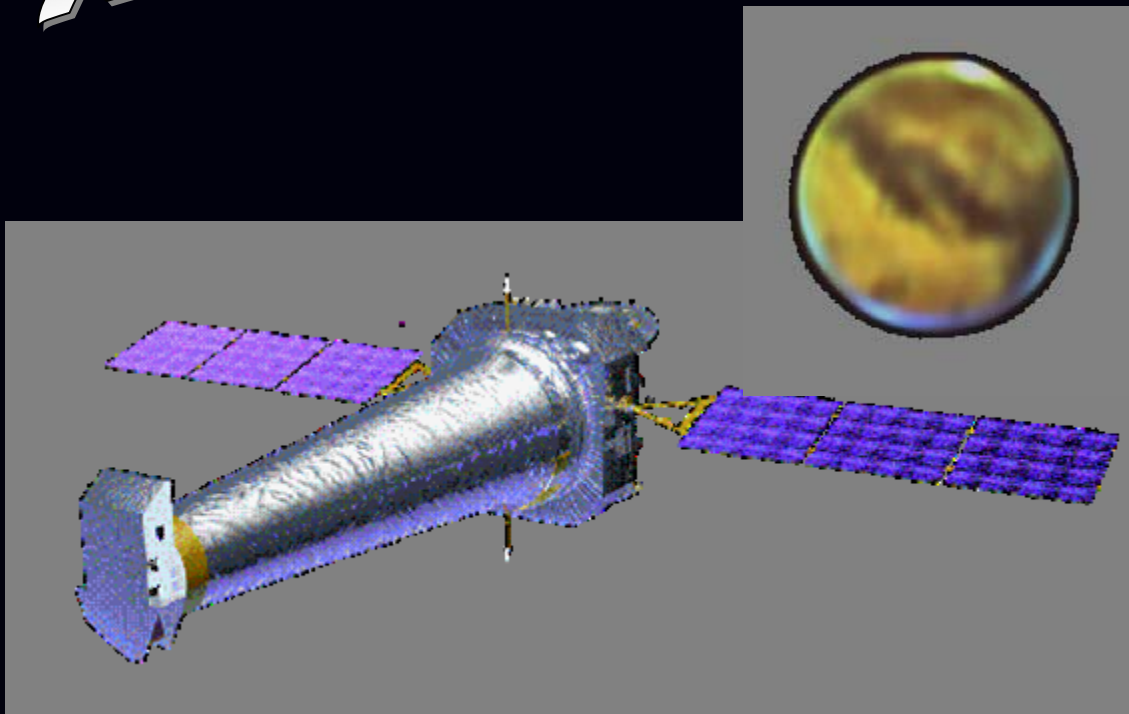
\rightarrow flux ratios of all observed comets:



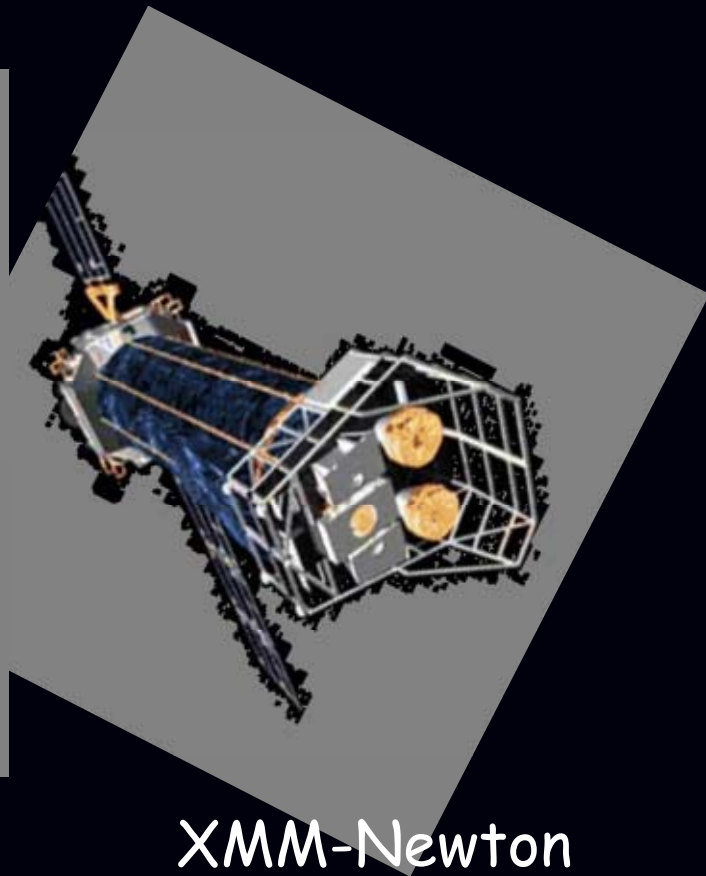


X-rays from Mars

X-rays from Mars



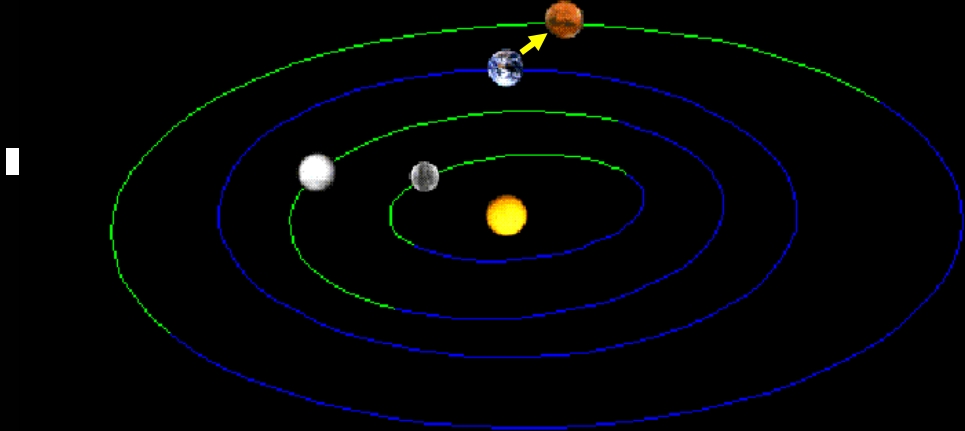
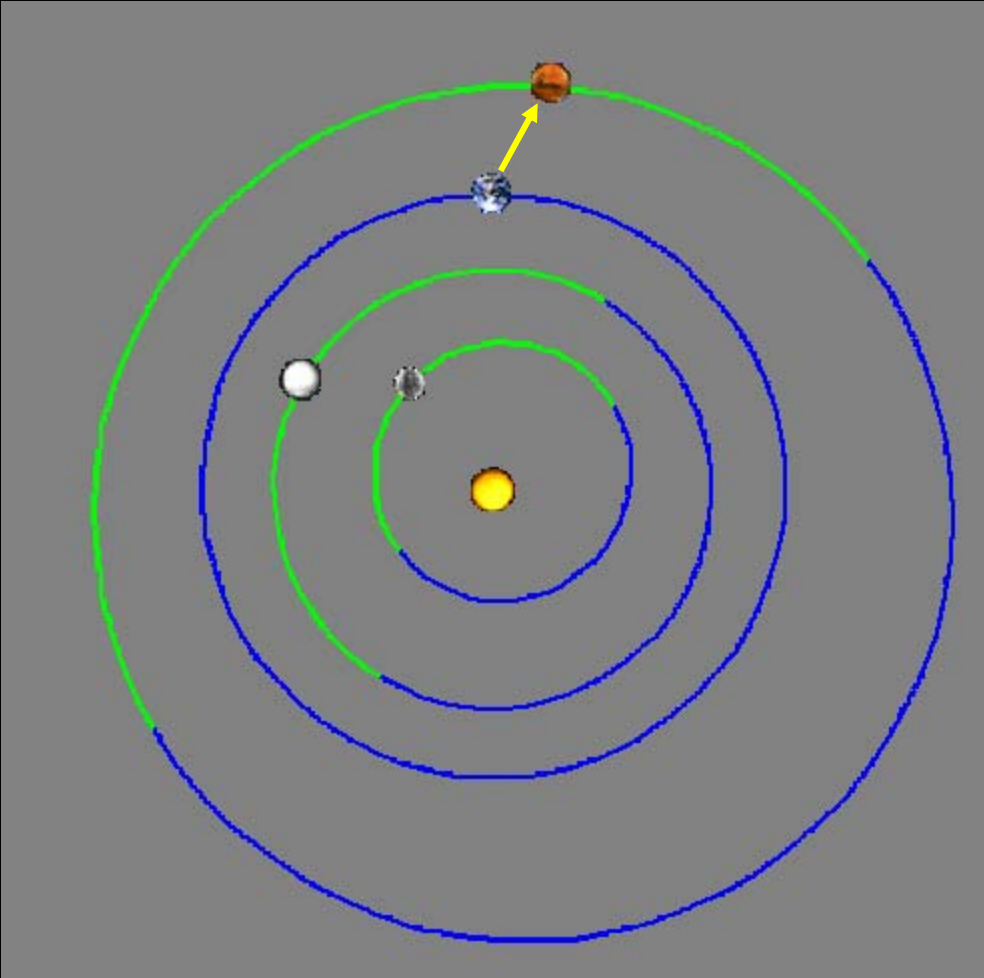
Chandra



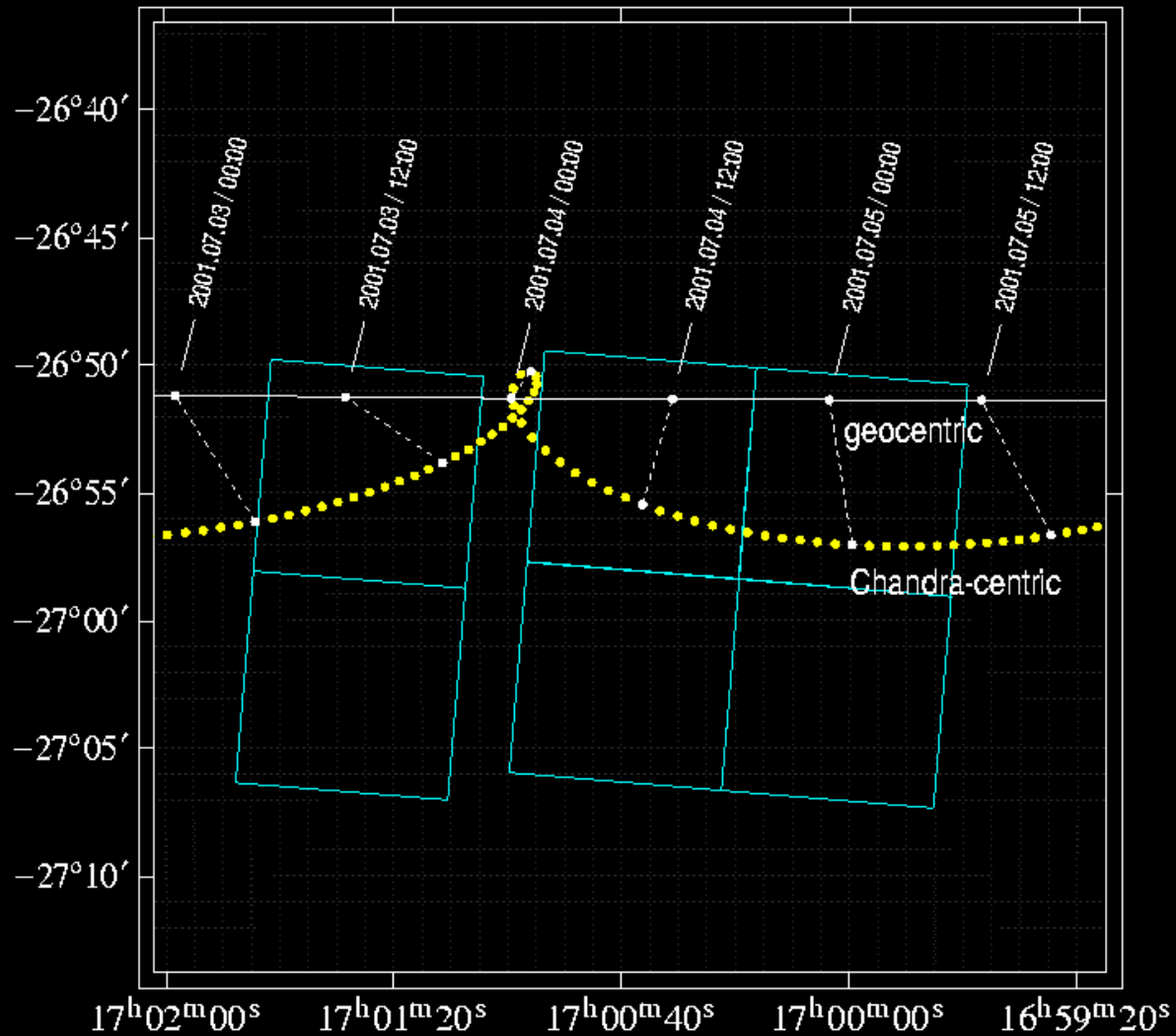
XMM-Newton

Geometry of the first Mars observation

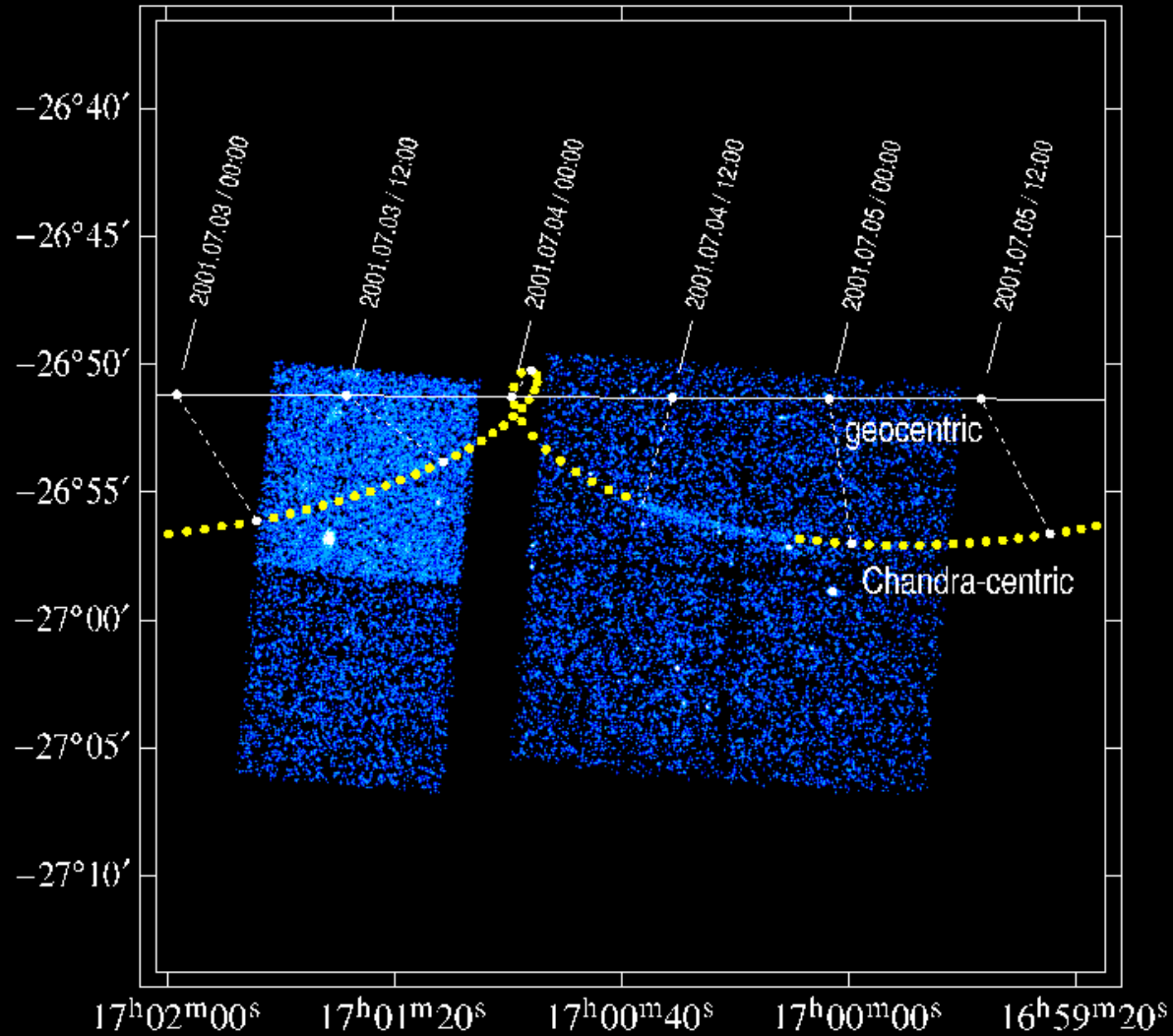
2001 July 4



Catching Mars with Chandra



Catching Mars with Chandra



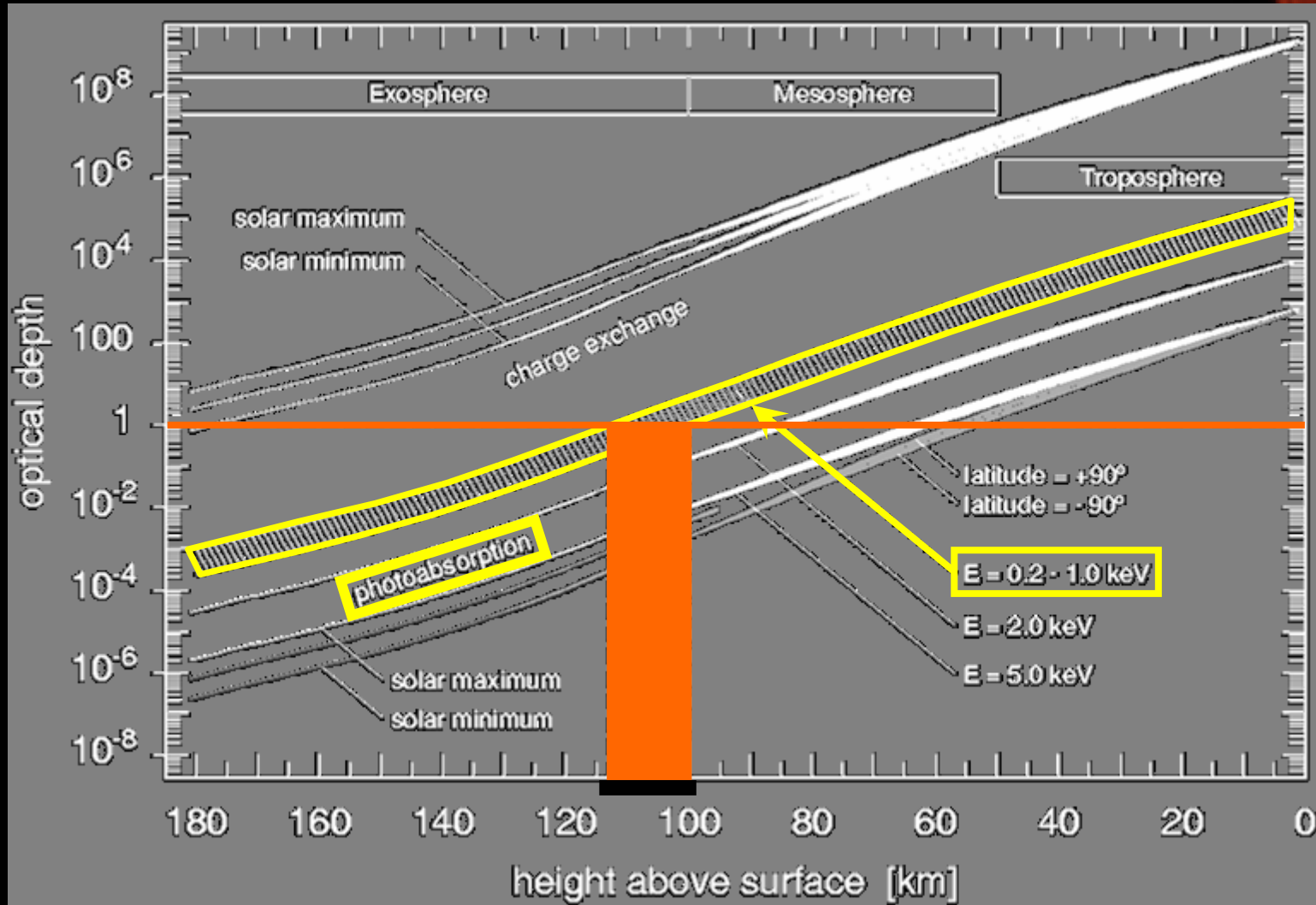
FIRST X-RAY IMAGE OF MARS

Chandra
ACIS-I
E = 0.4 – 0.7 keV

6 800 km
20.3 arcsec

July 4, 2001

Optical depth of the Martian atmosphere



Simulated X-ray images of Mars due to fluorescent scattering of solar X-rays

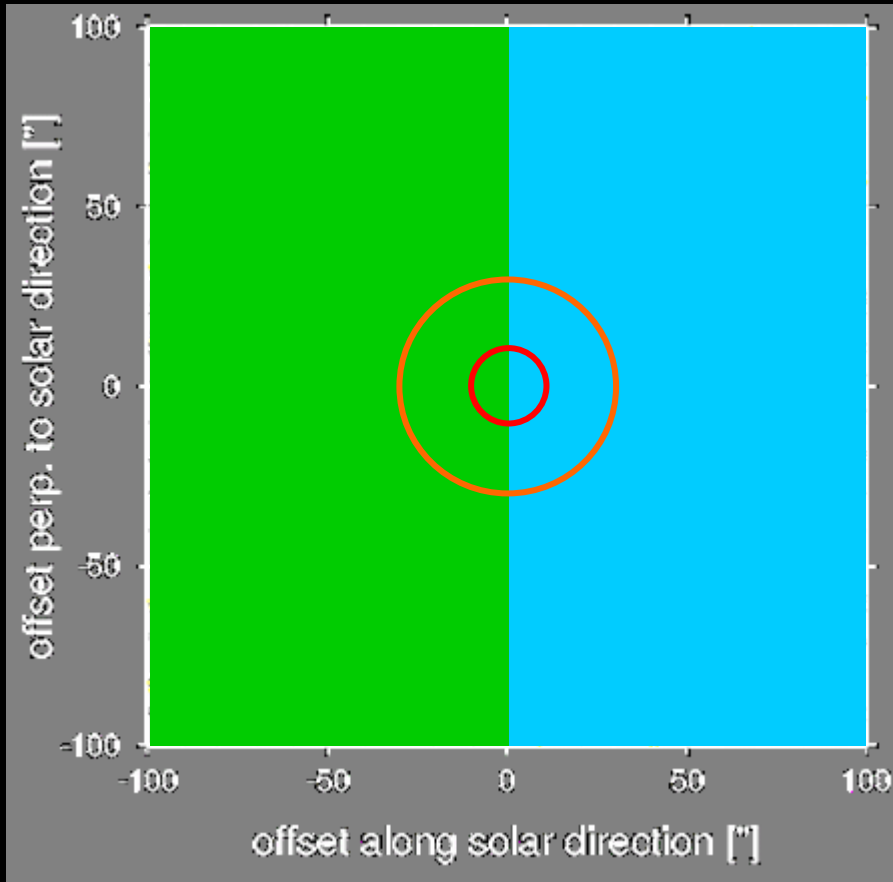


C-K_α
L_x ~ 2.9 MW

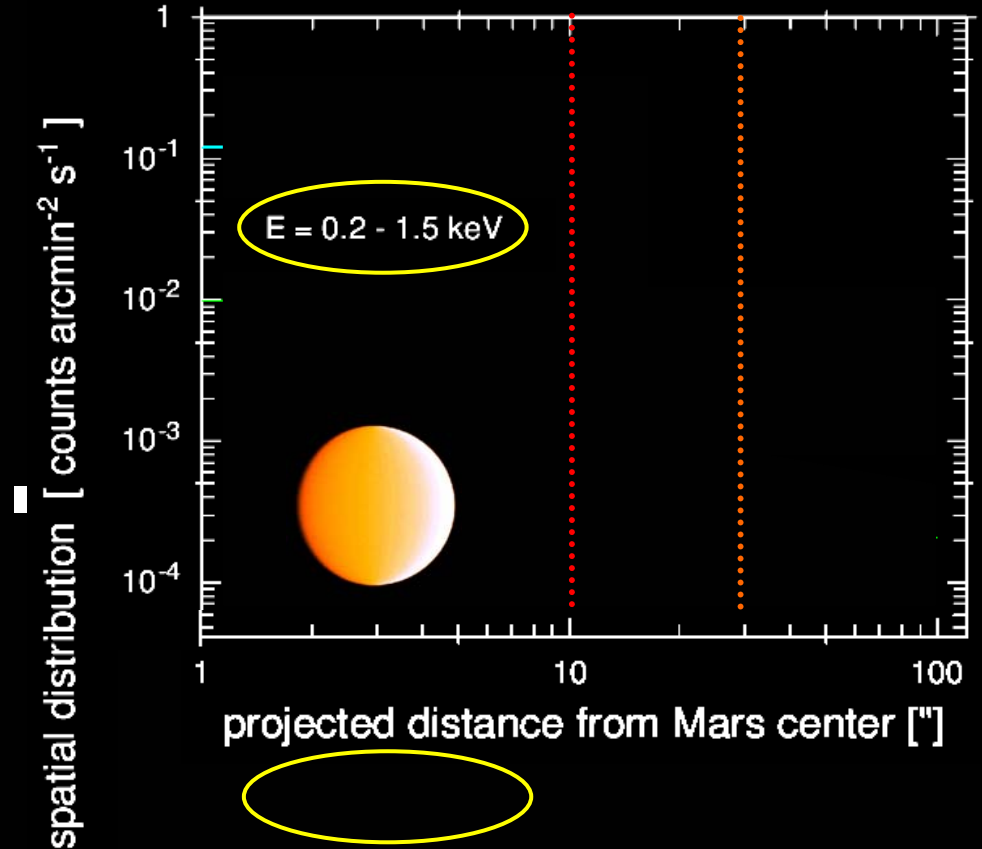
N-K_α
L_x ~ 0.1 MW

O-K_α
L_x ~ 1.7 MW

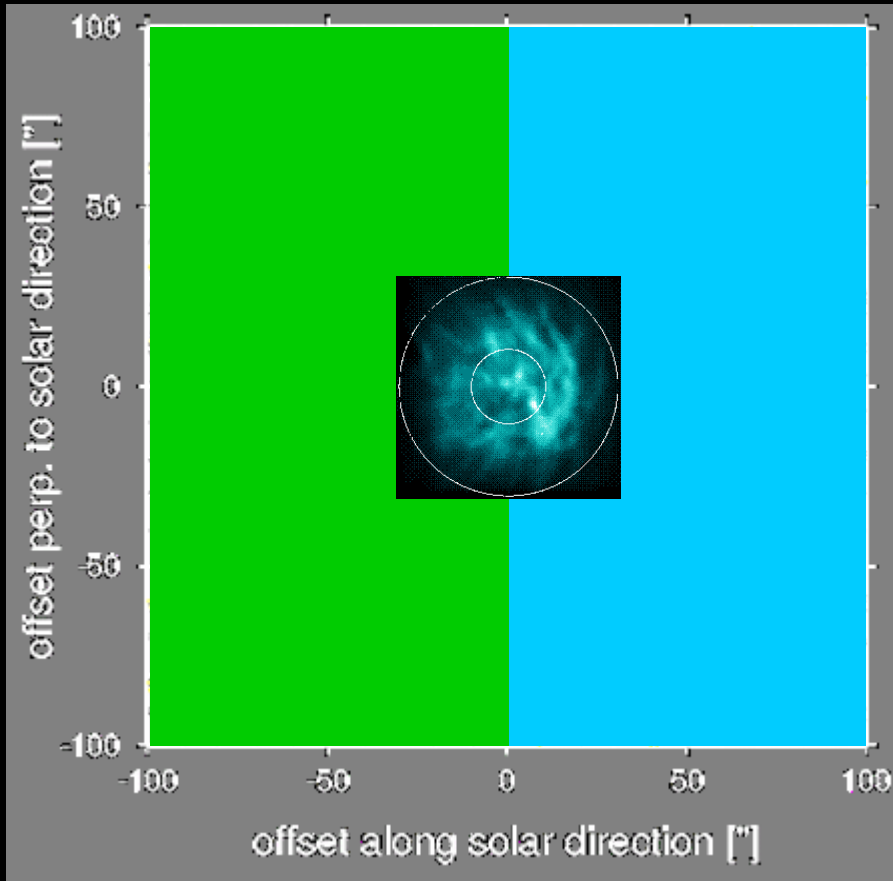
Spatial distribution of X-ray photons around Mars



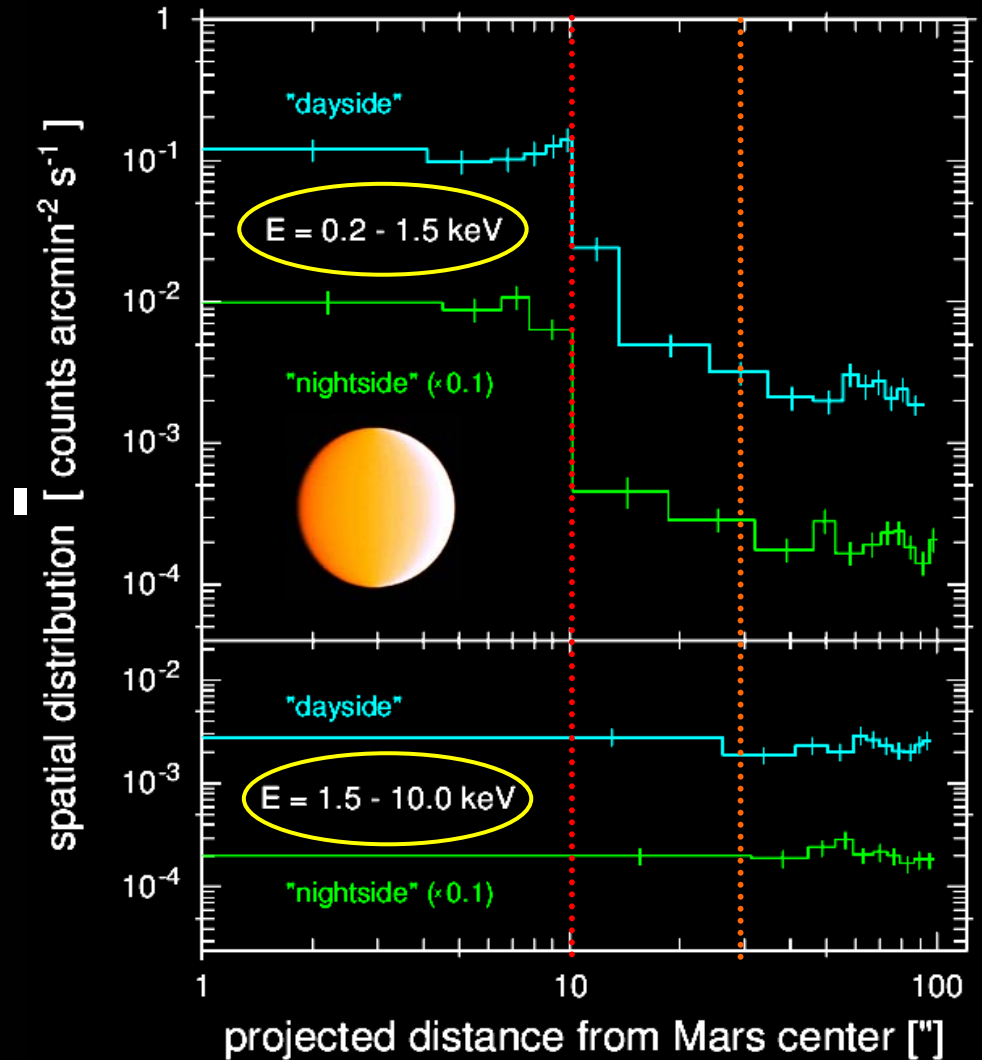
Chandra observation



Spatial distribution of X-ray photons around Mars



Charge exchange simulation
Gunell et al. 2004, *Geoph. Res. Letters* 31

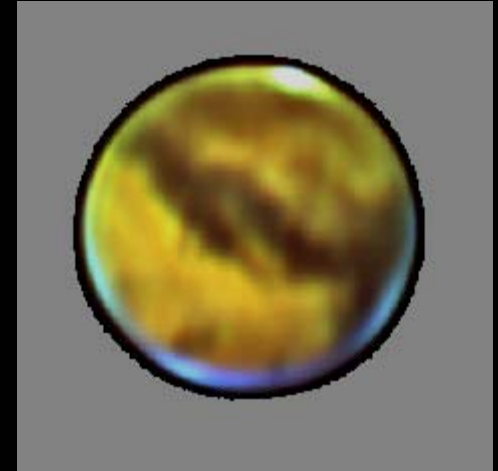


Mars observed with XMM-Newton

2003 Nov 20, 00:08 - Nov 21, 04:57 UTC

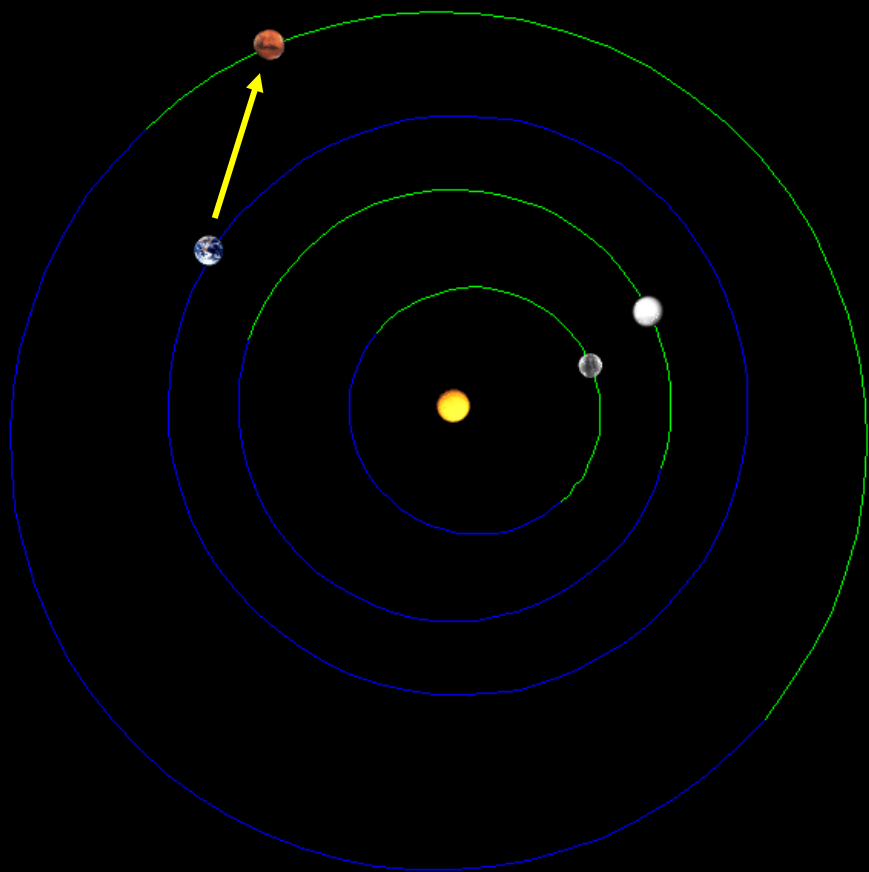


XMM-Newton

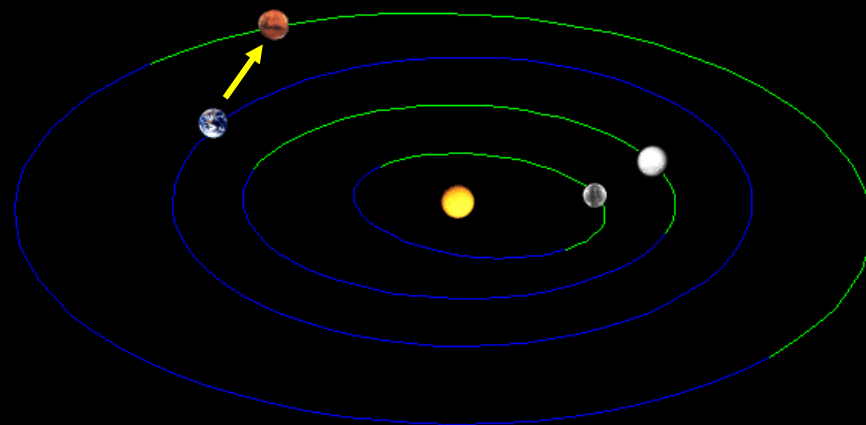


Geometry of the second Mars observation

2003 Nov 20, 00:08 - Nov 21, 04:57 UTC



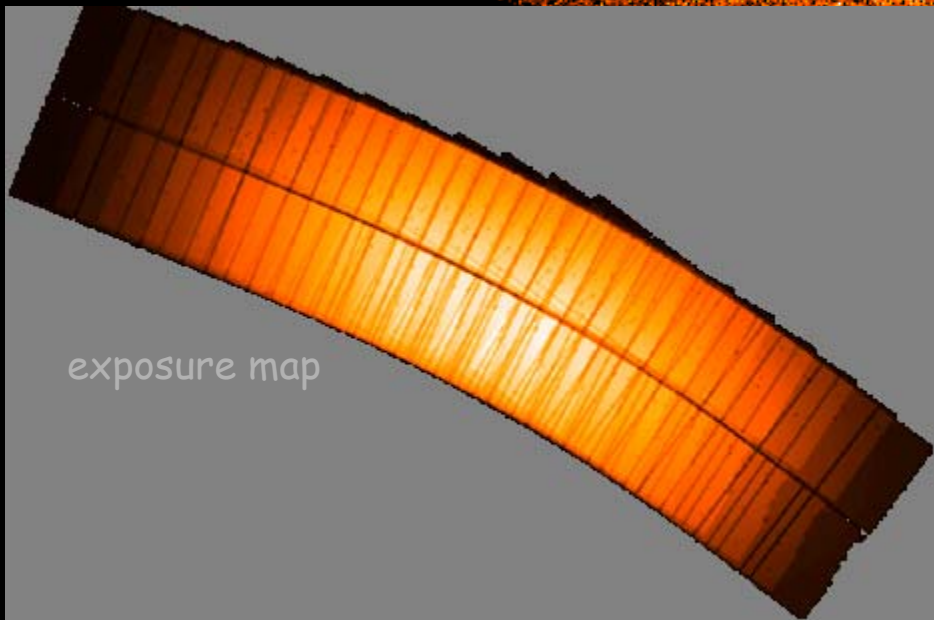
I



XMM-Newton observation of Mars

*EPIC pn
sky coordinates*

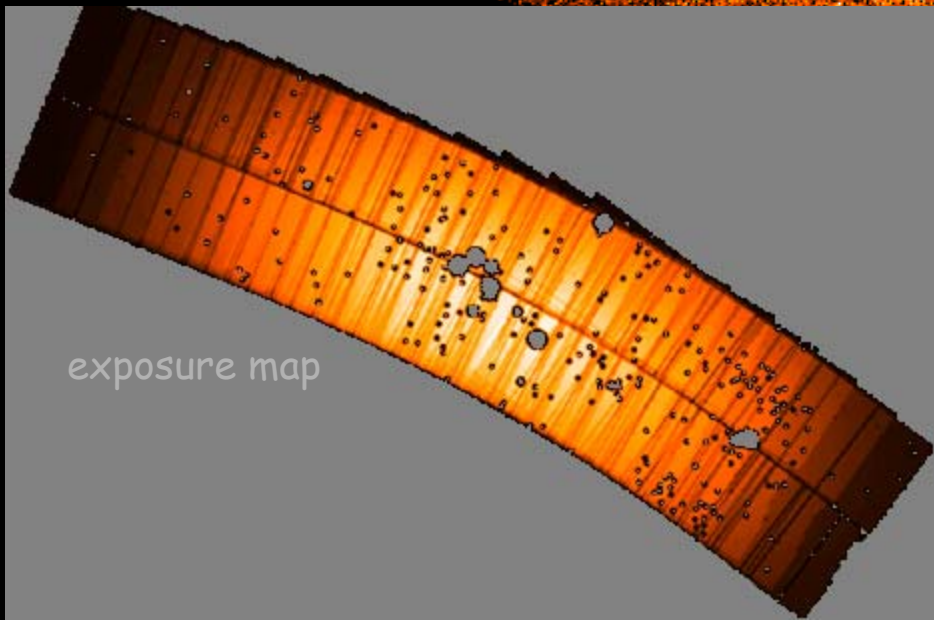
X-ray image



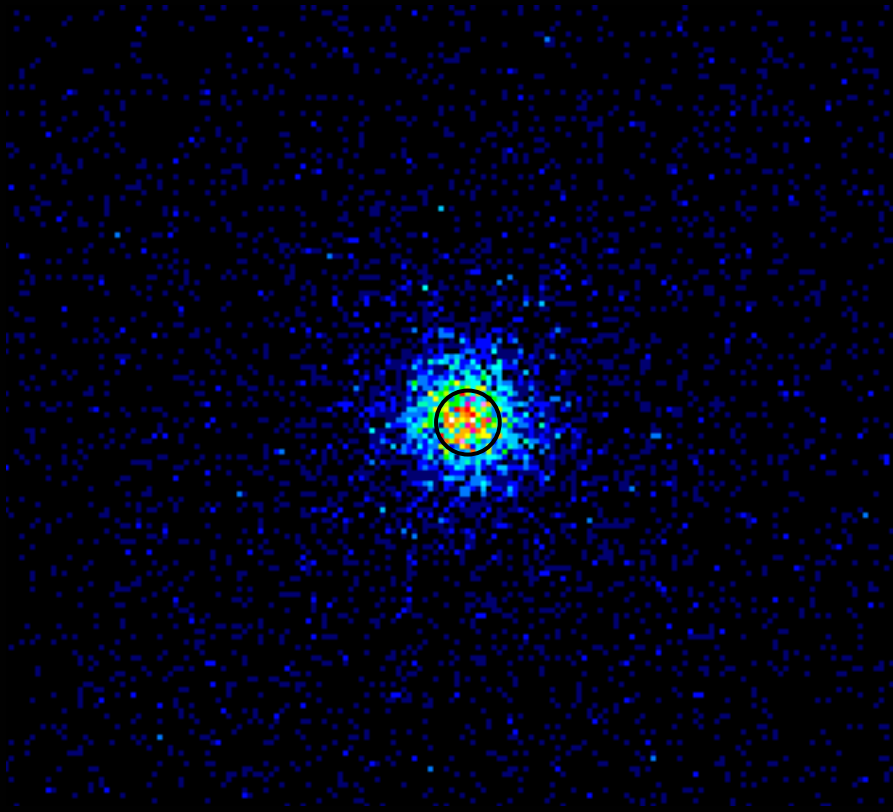
XMM-Newton observation of Mars

*EPIC pn
sky coordinates*

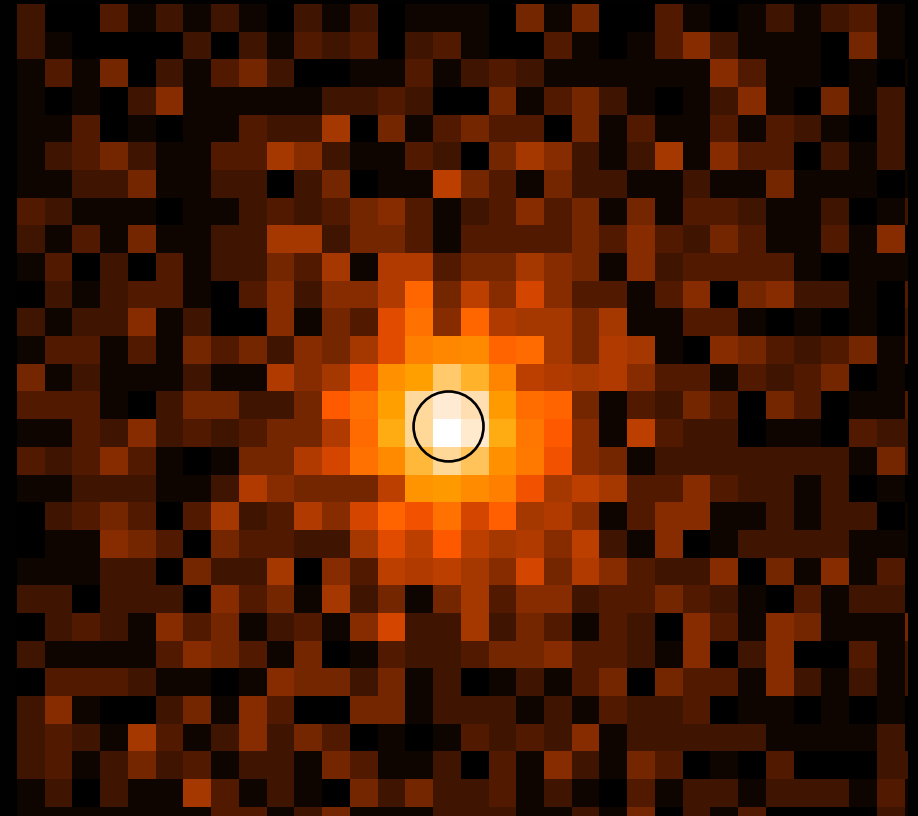
X-ray image



XMM-Newton images of Mars



pixel size: 1"



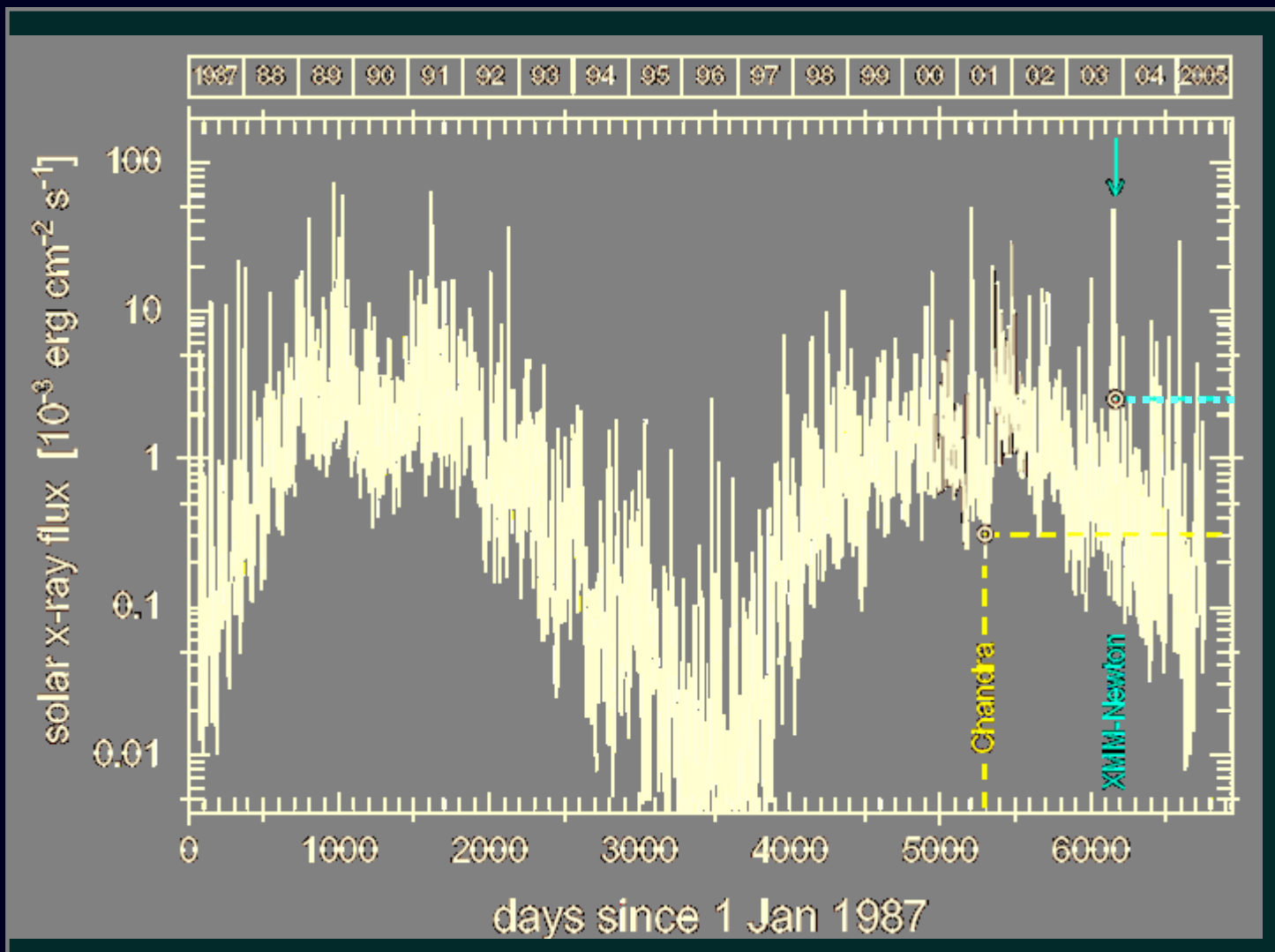
pixel size: 5"

The Sun in Oct/Nov 2003

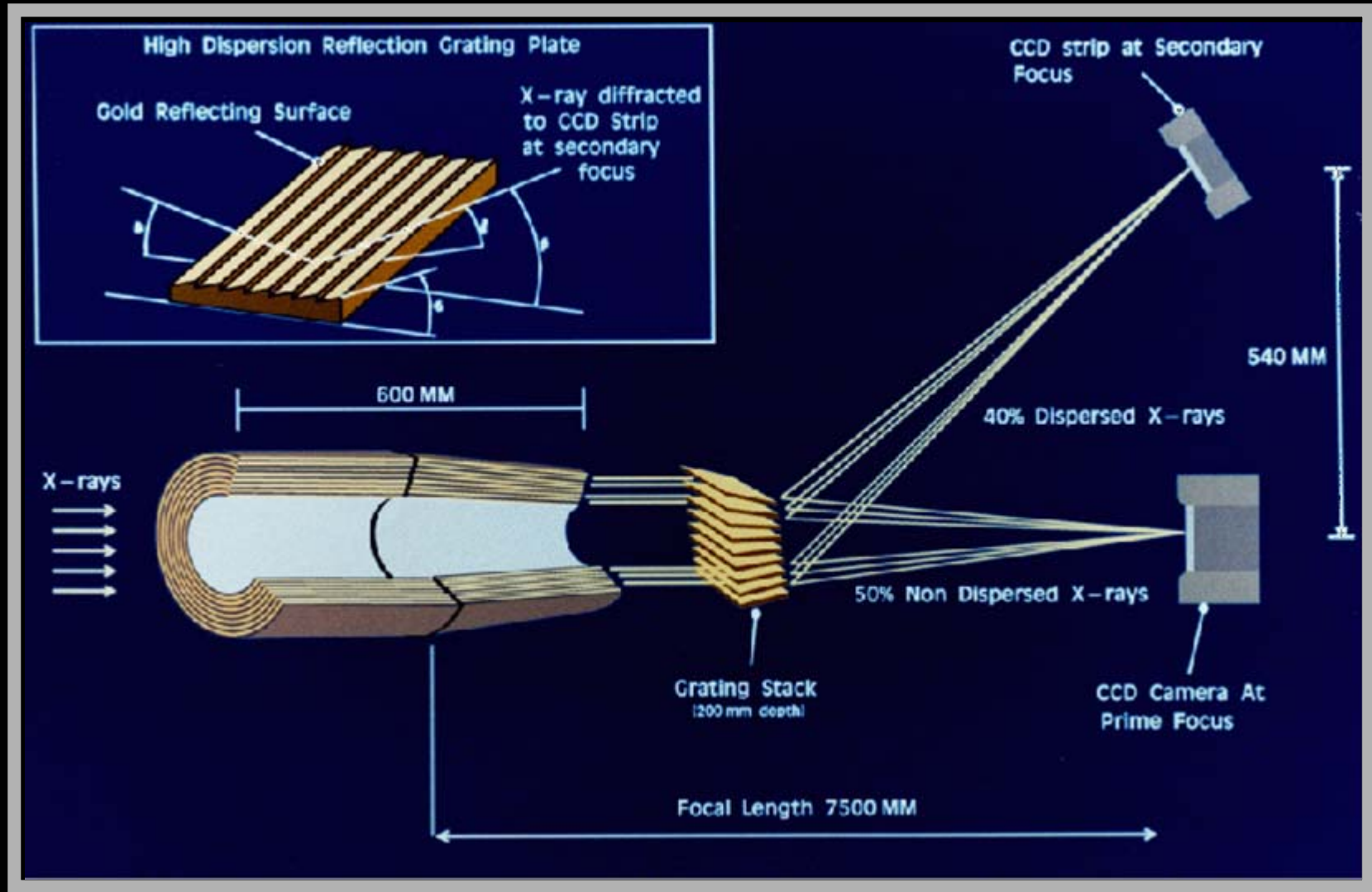


2003/10/27 17:36

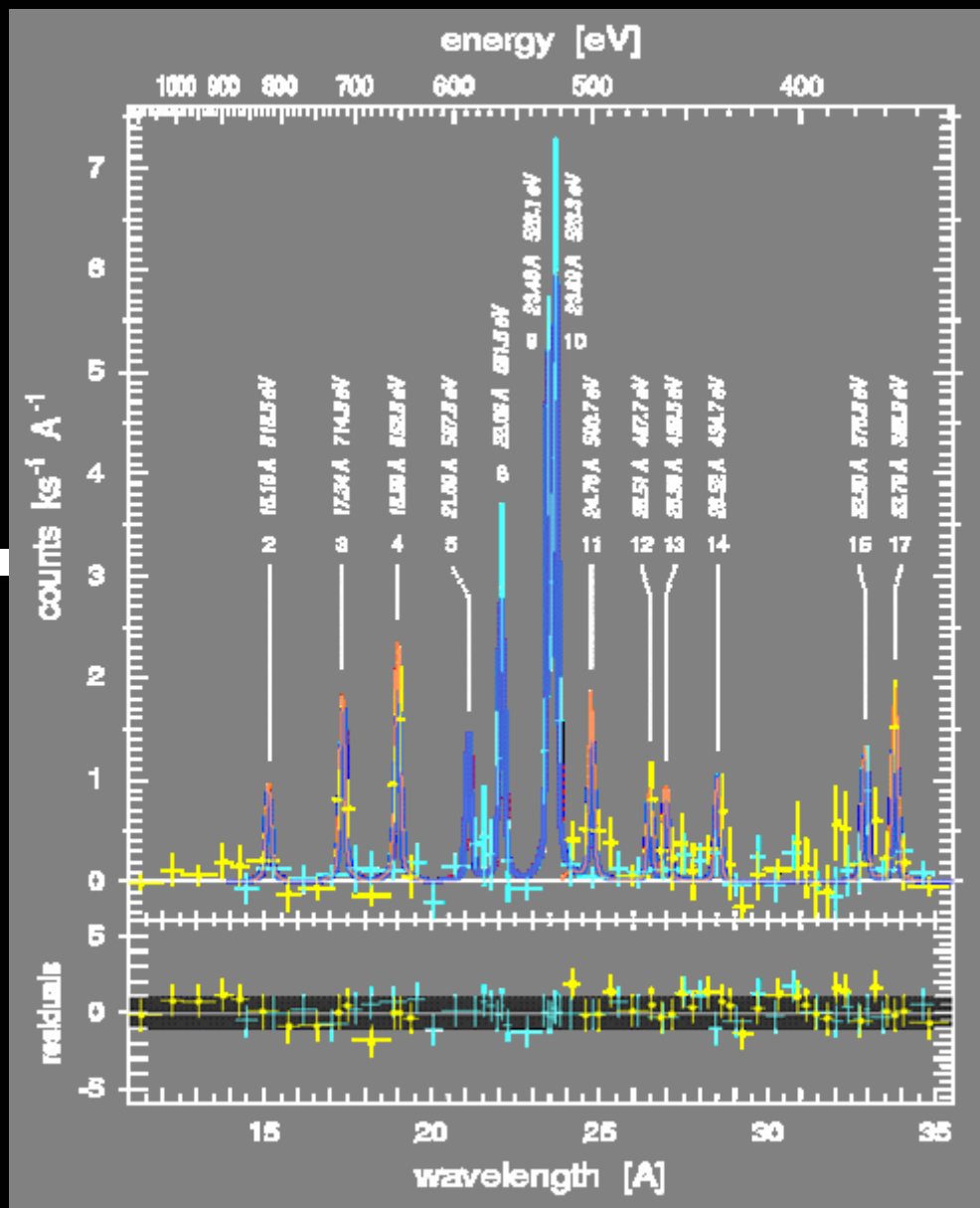
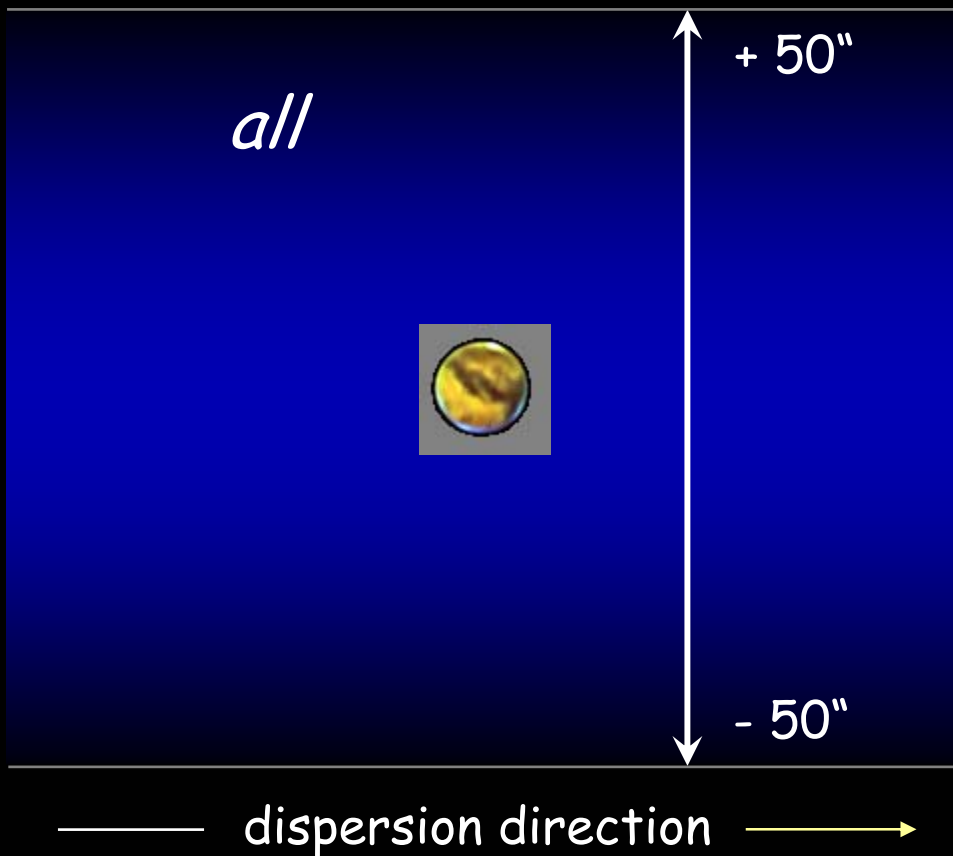
Solar X-ray flux (1.55 - 12.4 keV)



High resolution X-ray spectroscopy of Mars with RGS

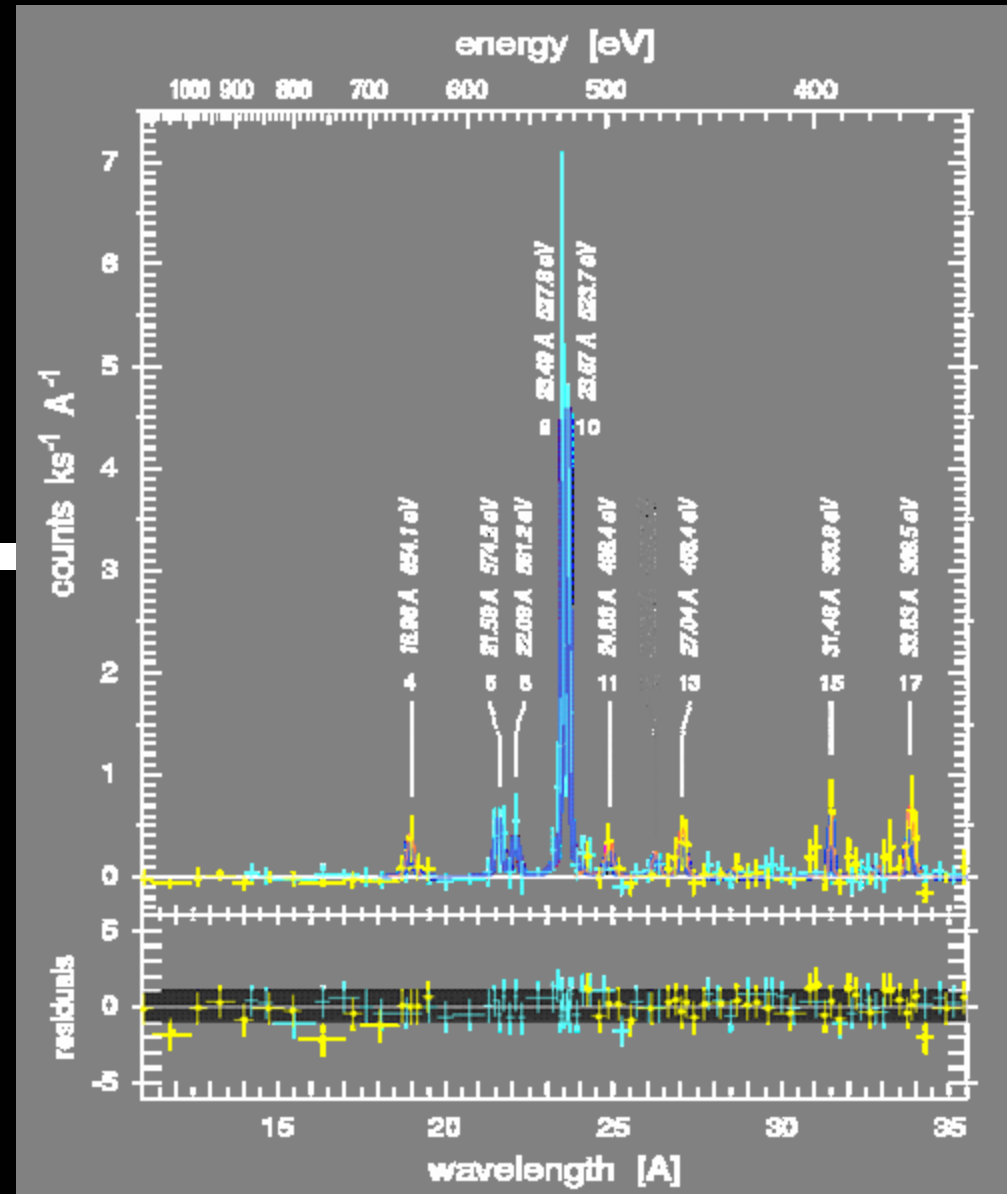


High resolution X-ray spectroscopy of Mars with RGS



High resolution X-ray spectroscopy of Mars with RGS

"disk"



High resolution X-ray spectroscopy of Mars with RGS

"halo"

+ 50"

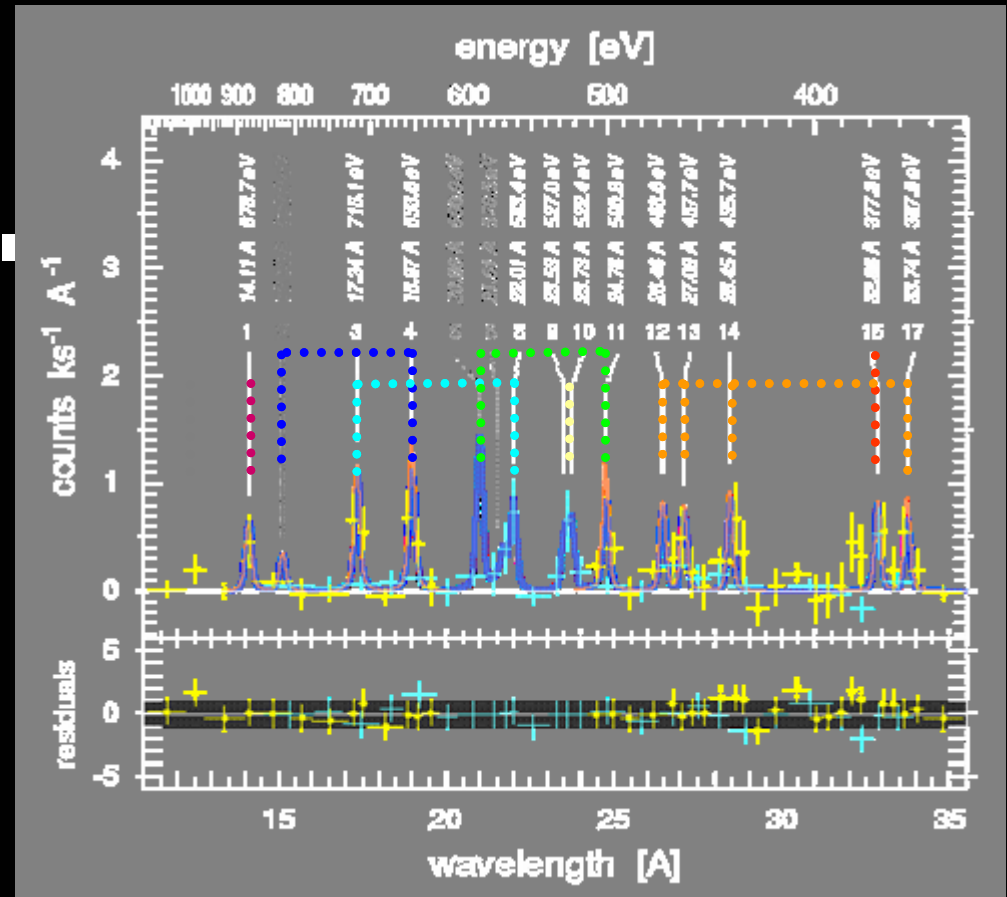
+ 15"



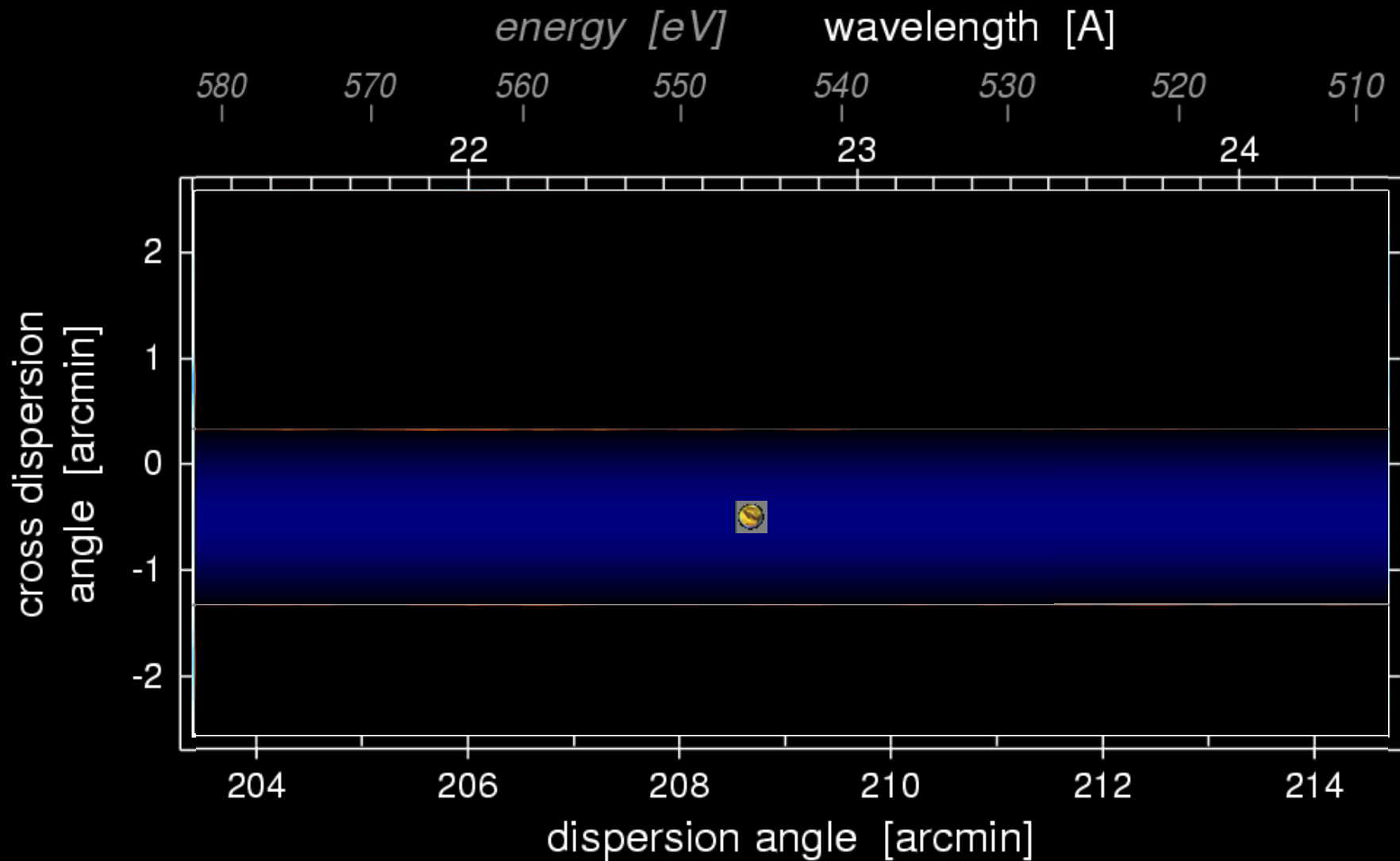
- 15"

- 50"

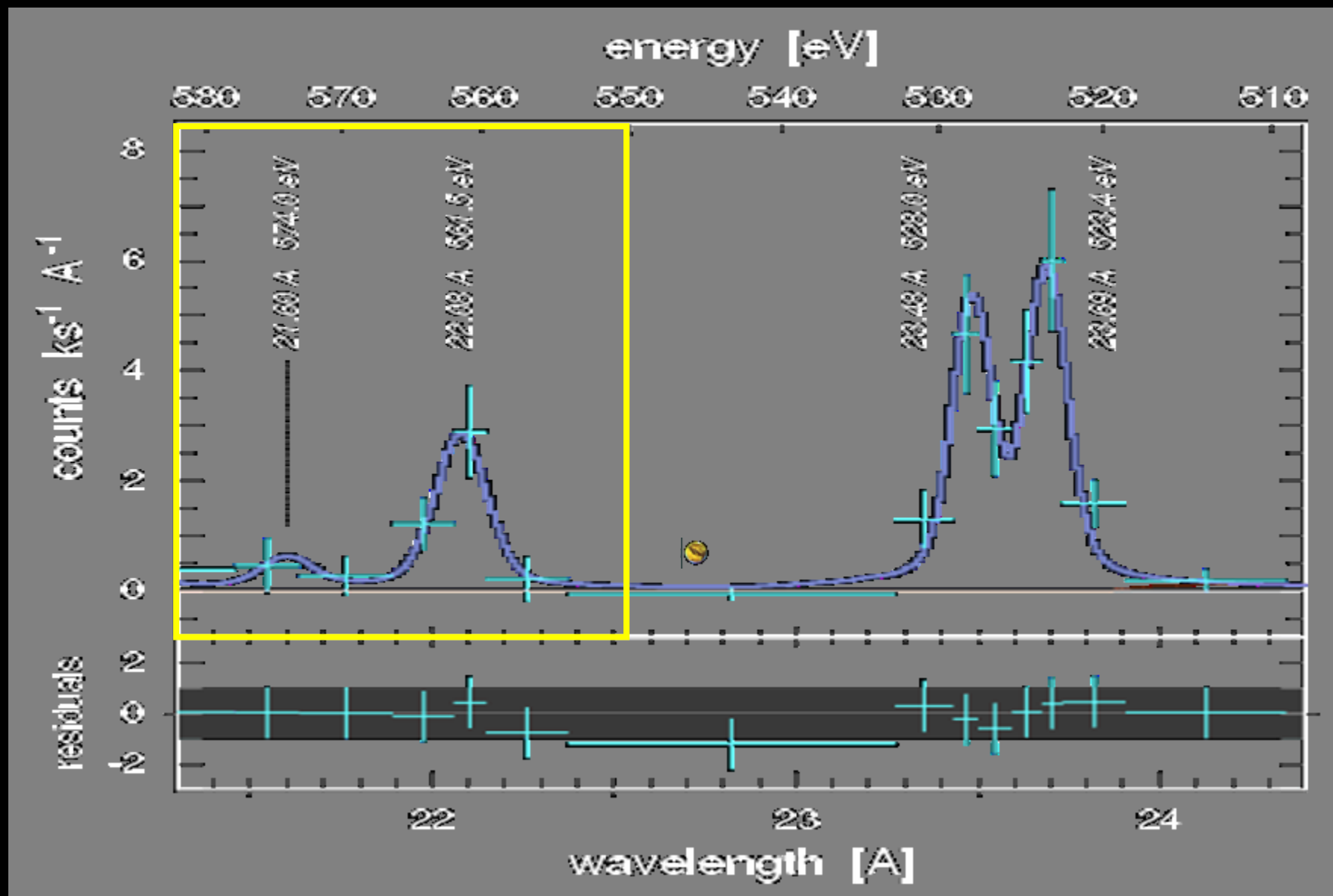
? Ne⁷⁺ O⁷⁺ O⁶⁺ N⁶⁺ CO₂ C⁵⁺ C⁴⁺



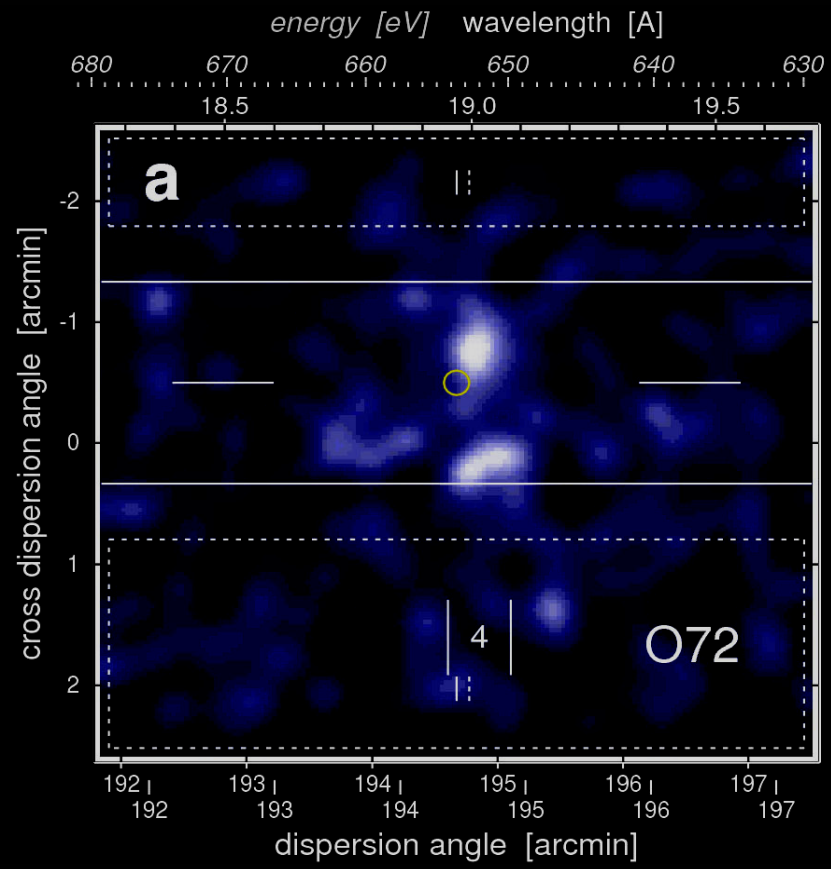
High resolution X-ray spectroscopy of Mars with RGS



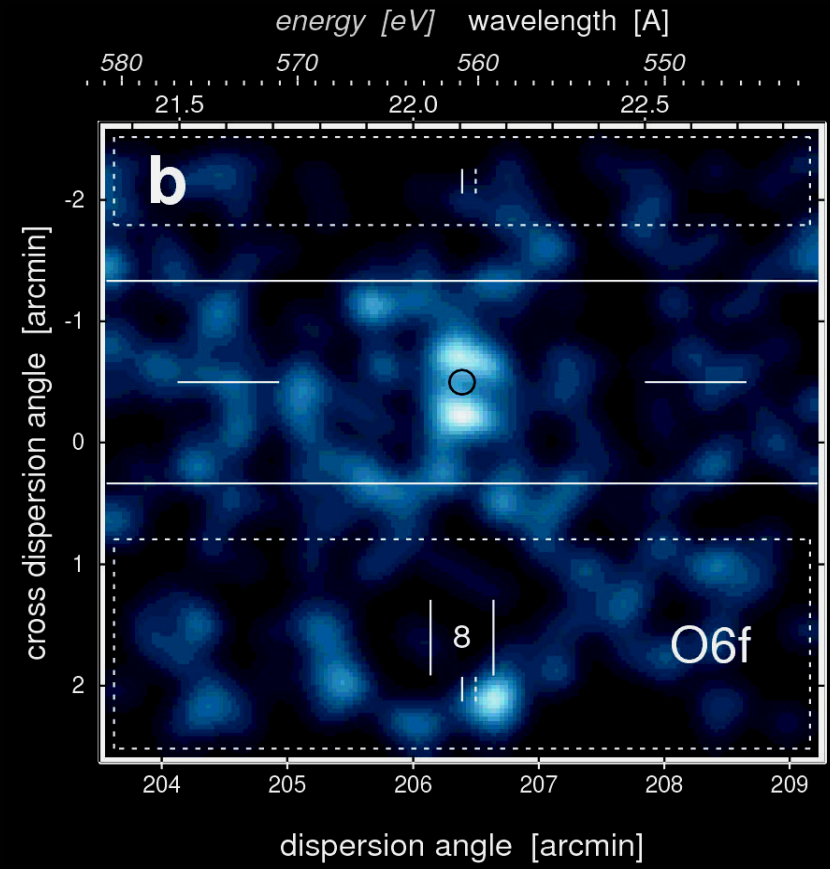
High resolution X-ray spectroscopy of Mars



X-ray images of Mars in individual emission lines (!)



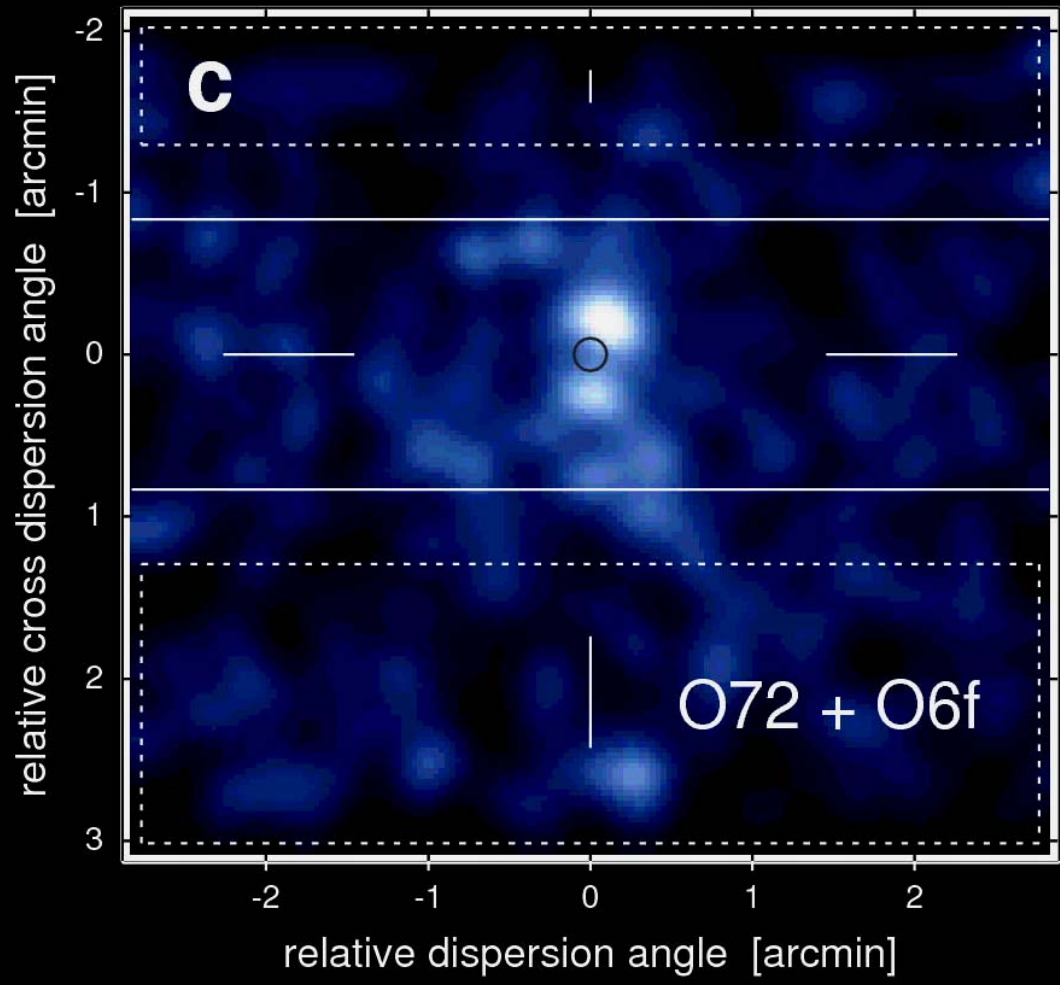
$O^{7+}: 2p \rightarrow 1s$



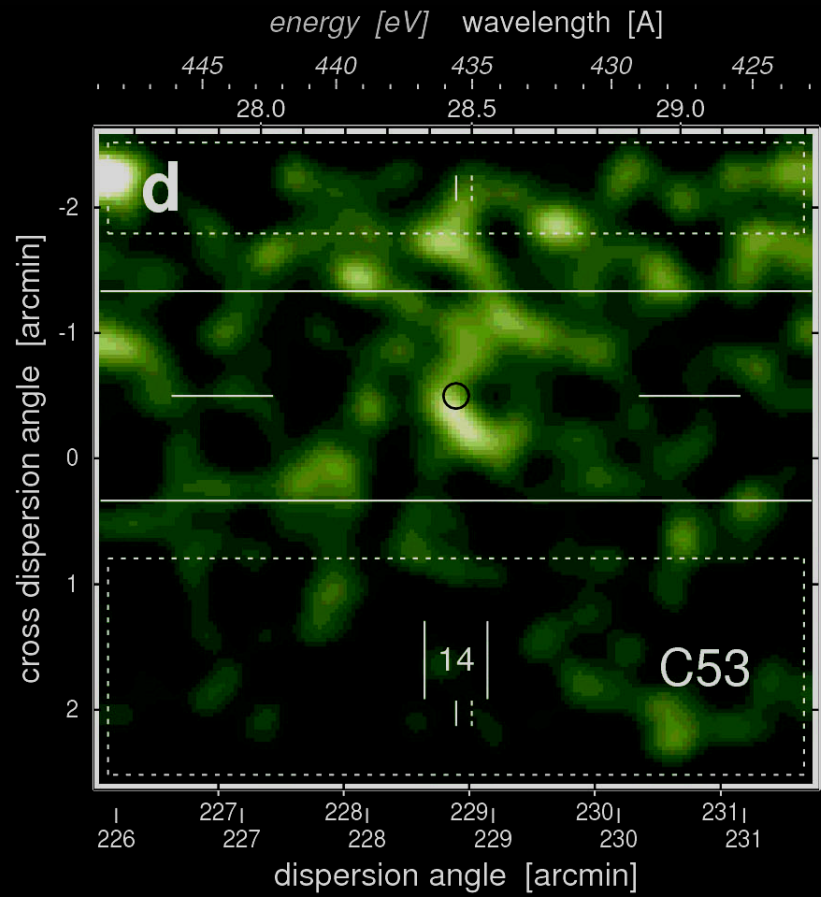
$O^{6+}: 2^3S_1 \rightarrow 1^1S_0$

X-ray images of Mars in individual emission lines (!)

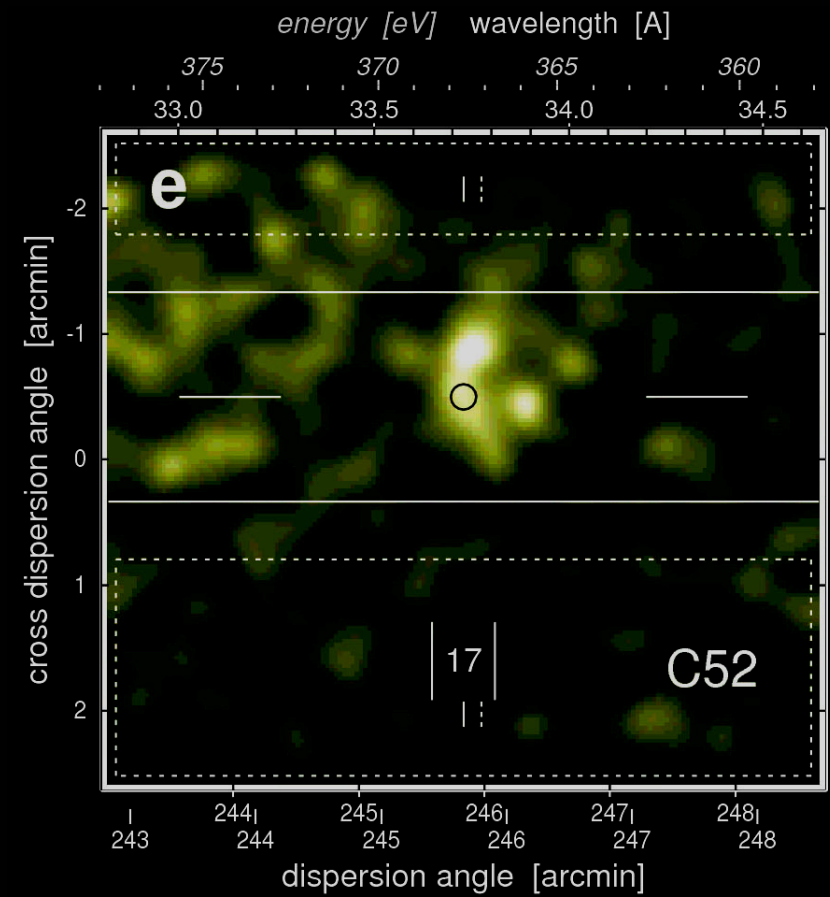
ionized oxygen



X-ray images of Mars in individual emission lines (!)



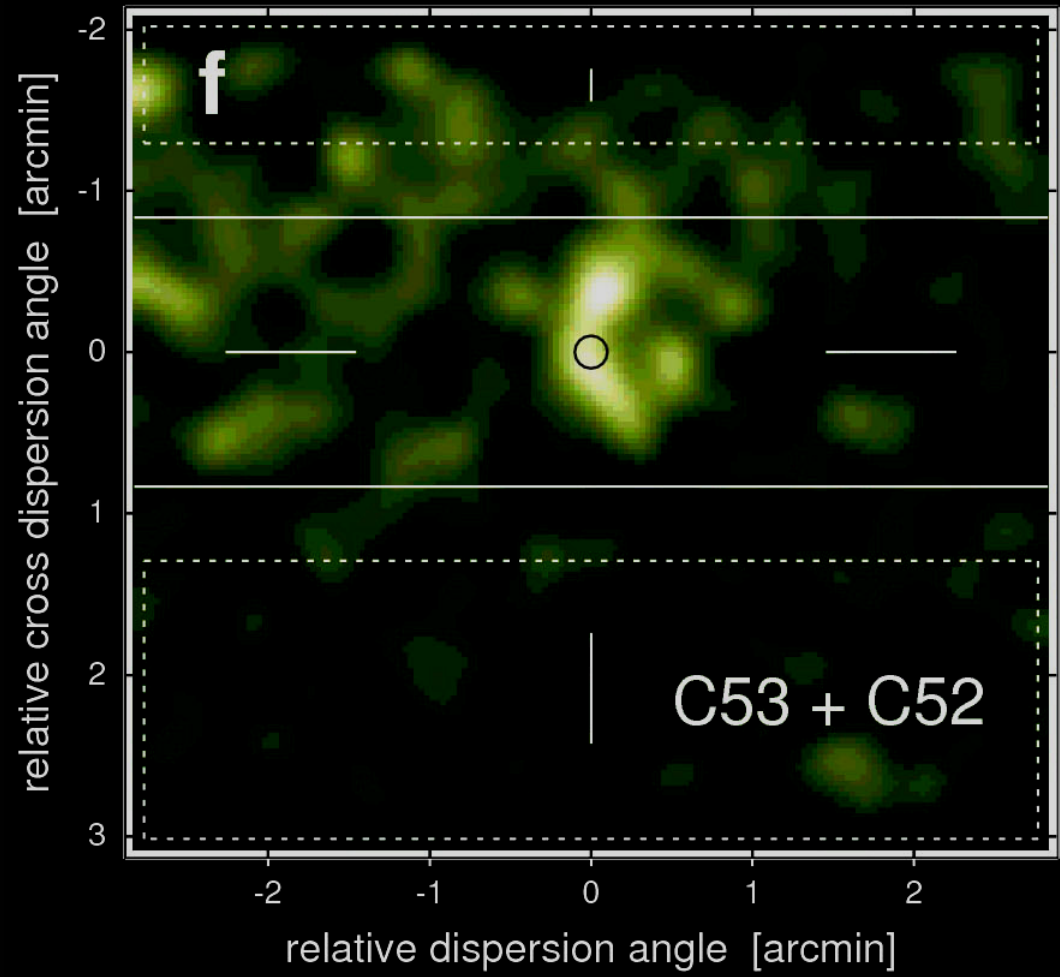
$C^{5+}: 3p \rightarrow 1s$



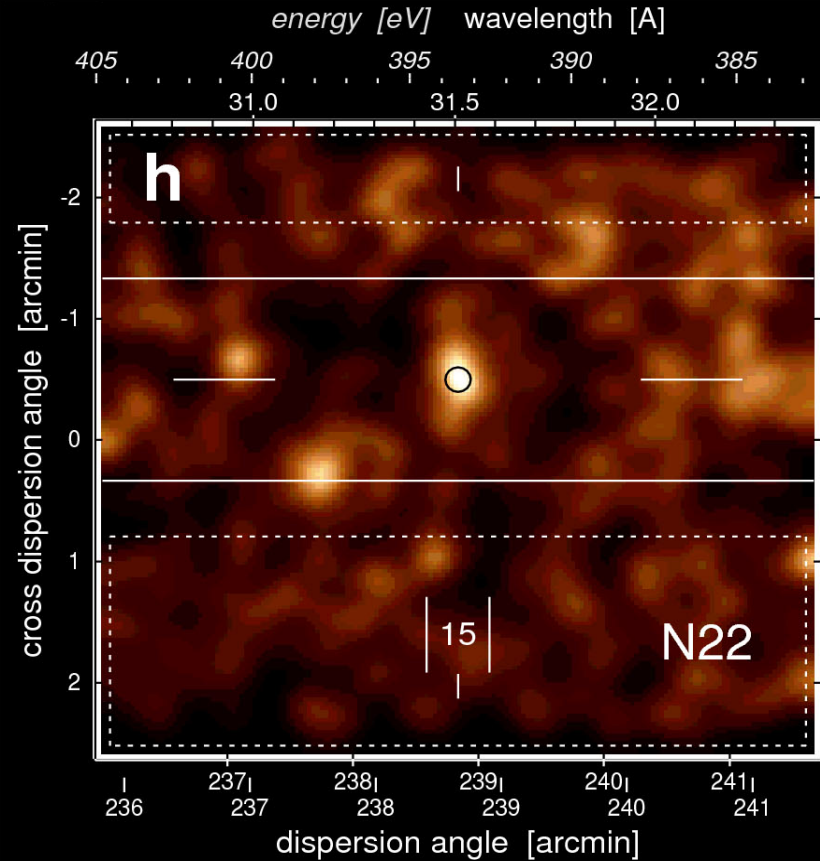
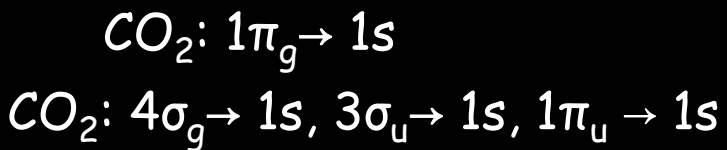
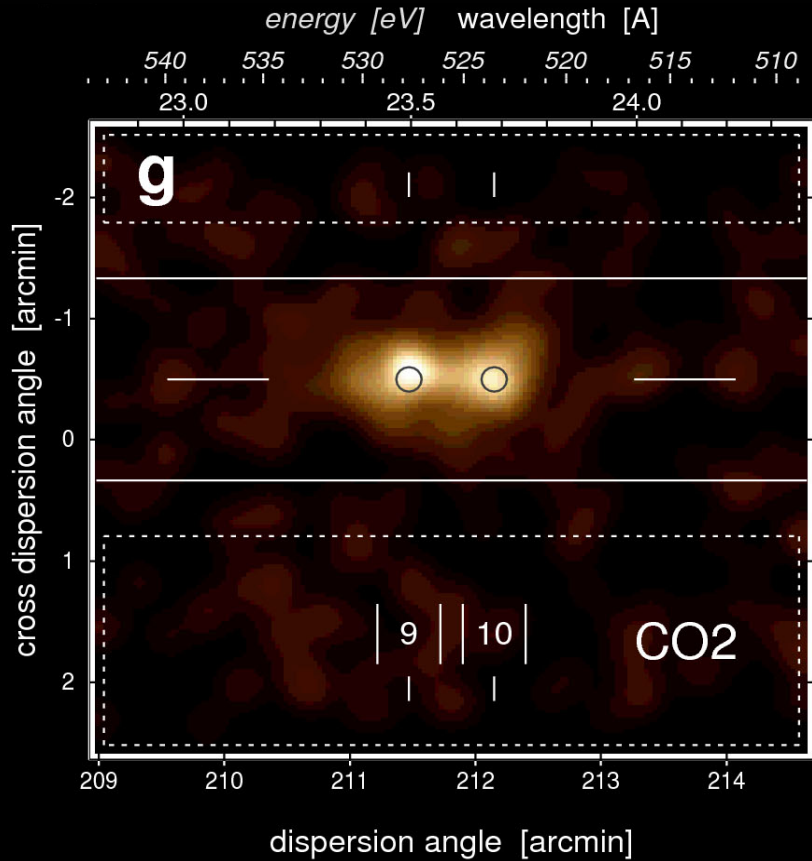
$C^{5+}: 2p \rightarrow 1s$

X-ray images of Mars in individual emission lines (!)

ionized carbon

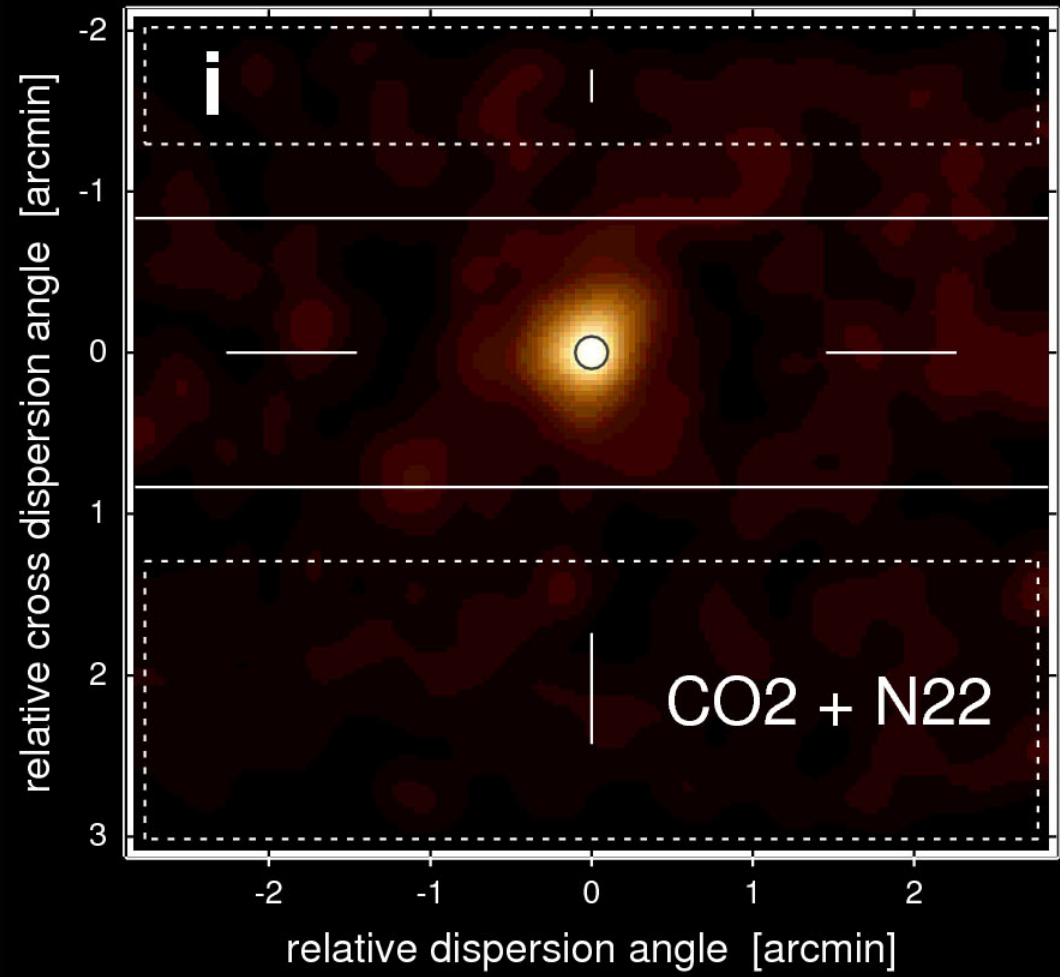


X-ray images of Mars in individual emission lines (!)

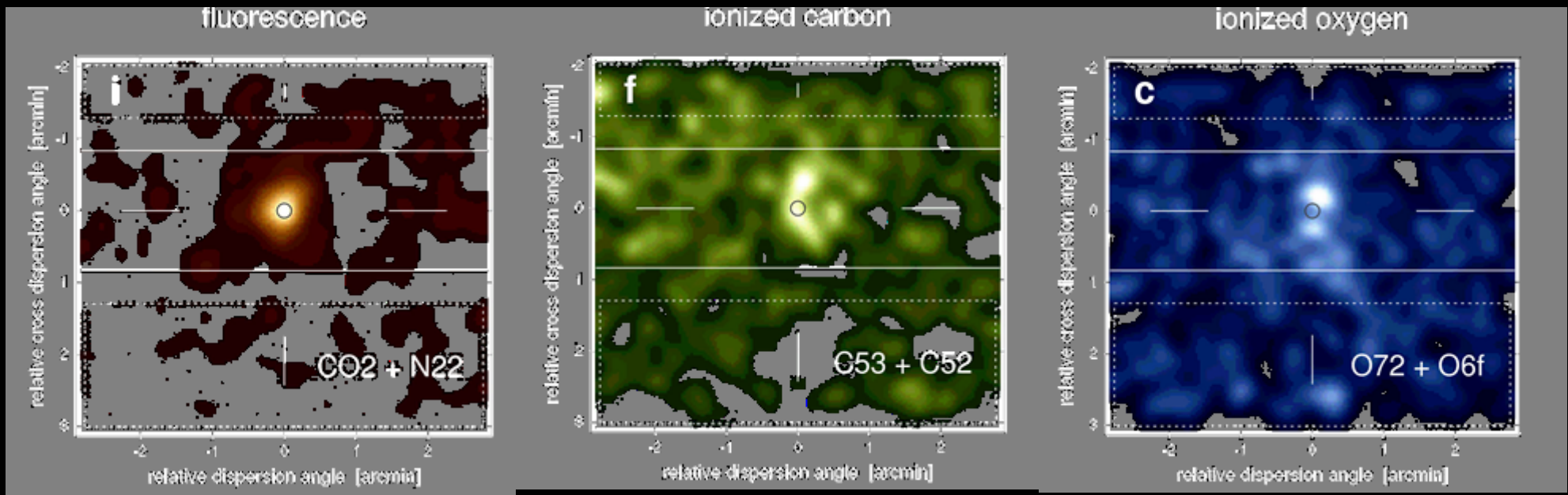


X-ray images of Mars in individual emission lines (!)

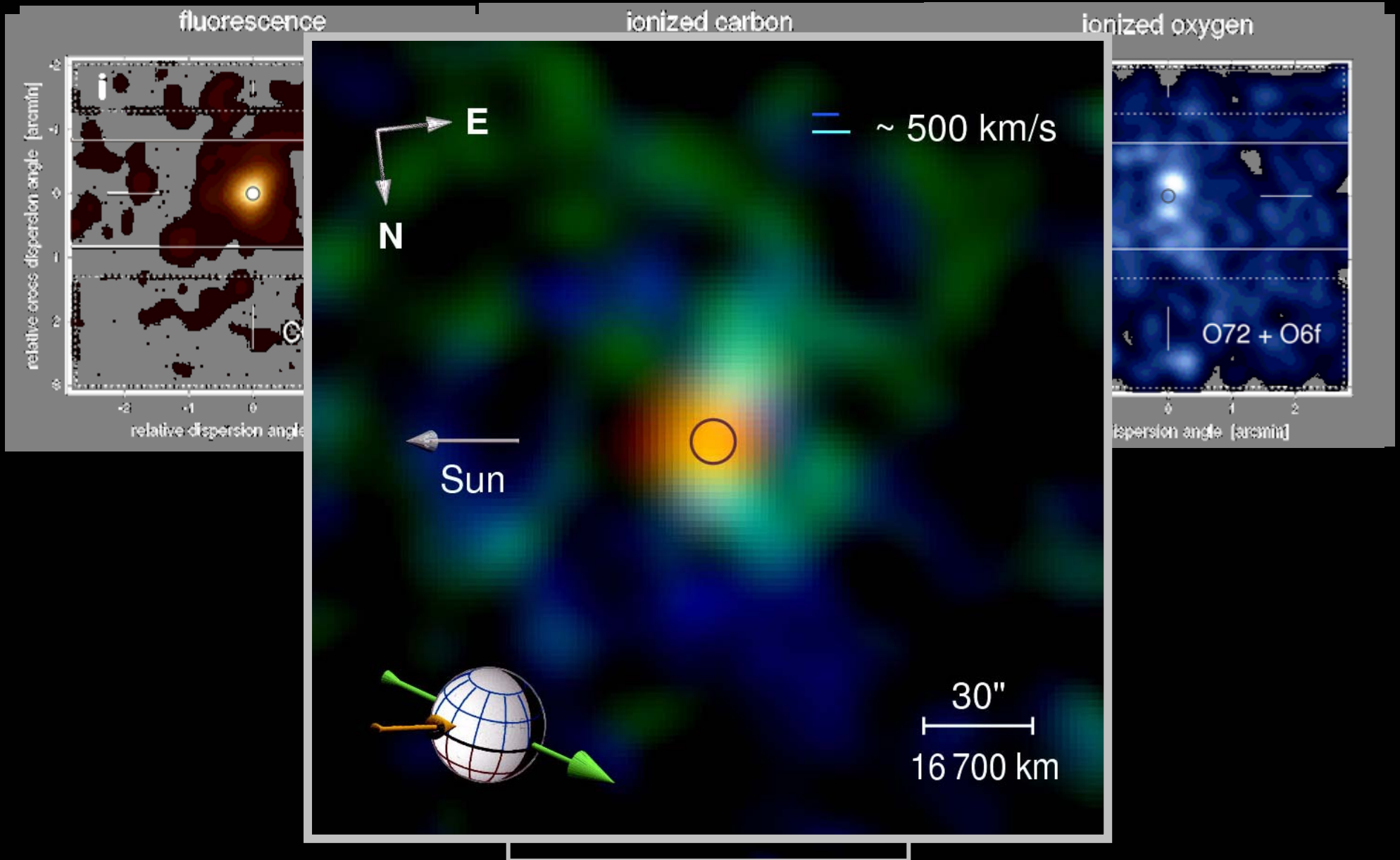
fluorescence



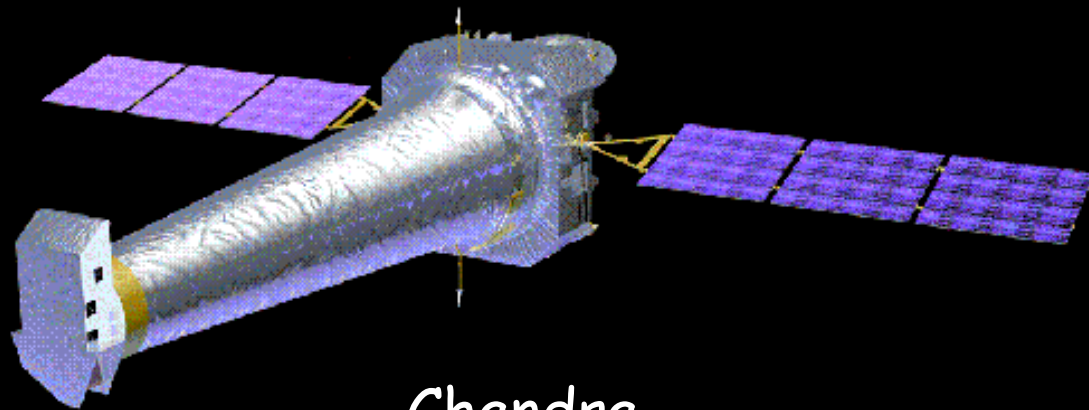
X-ray images of Mars in individual emission lines (!)



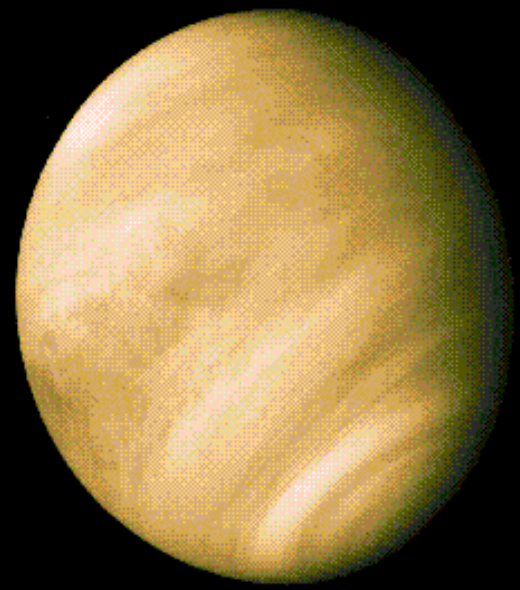
First X-ray colour image of Mars



X-rays from Venus



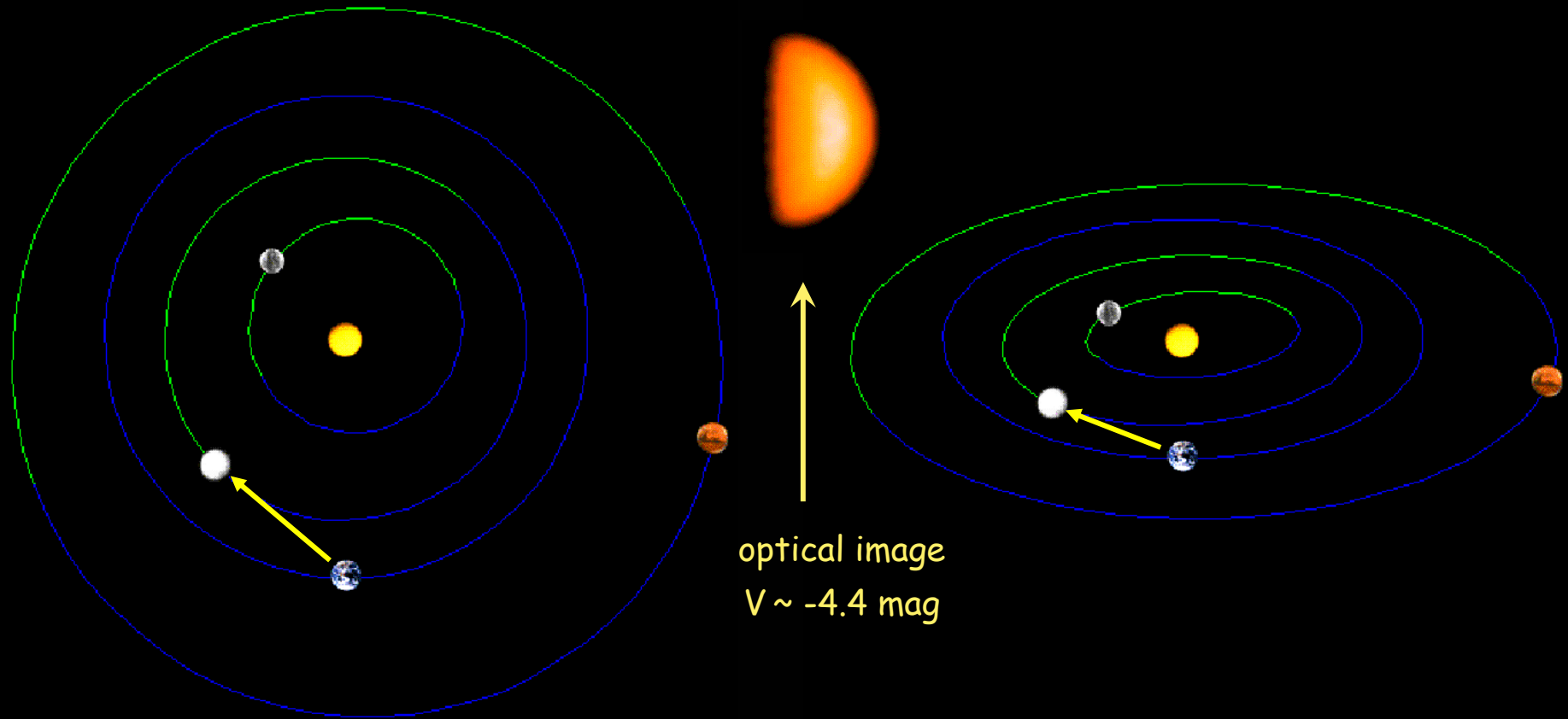
Chandra



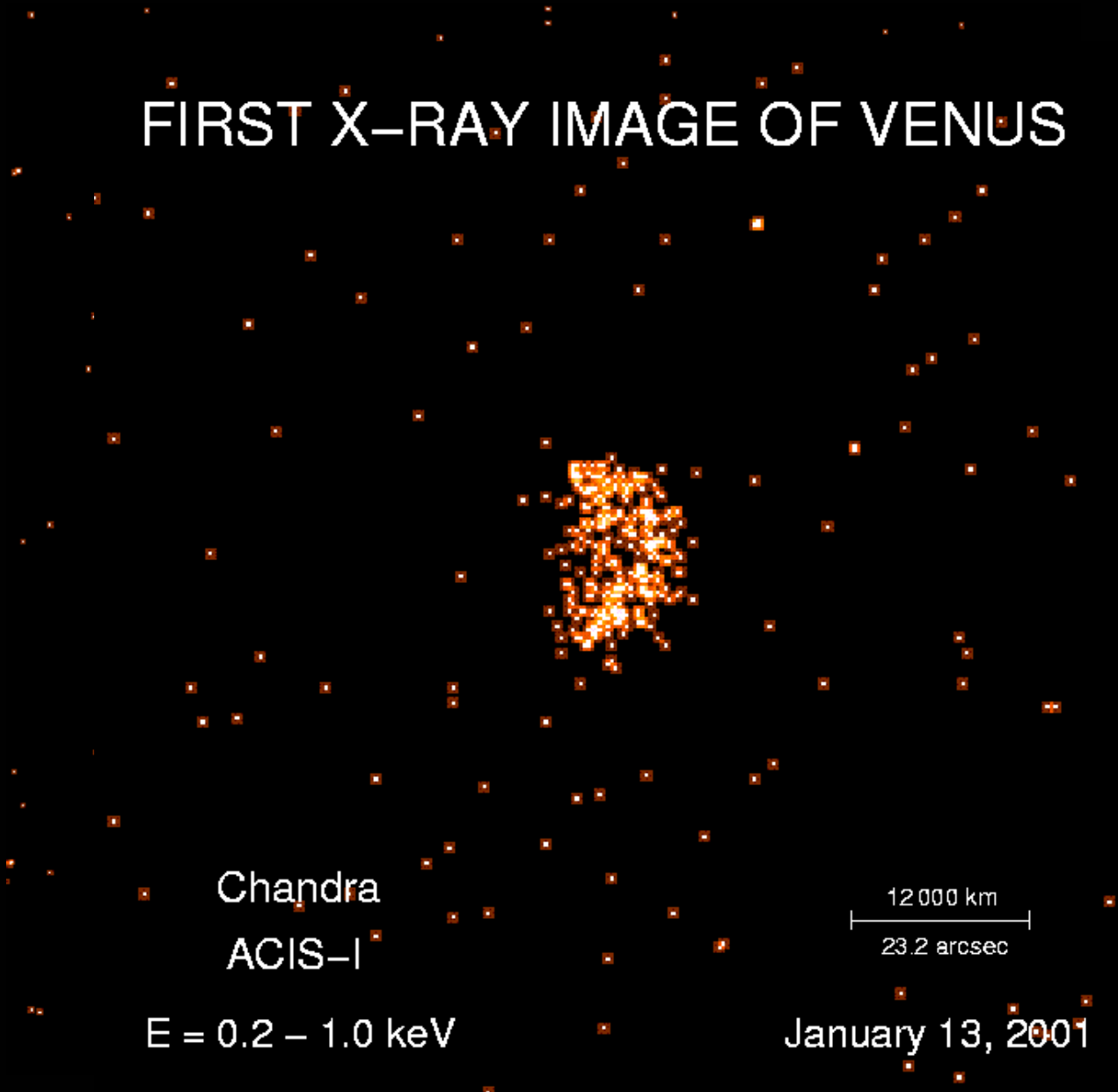
Venus

Geometry of the first X-ray observation of Venus

2001 January 13



FIRST X-RAY IMAGE OF VENUS



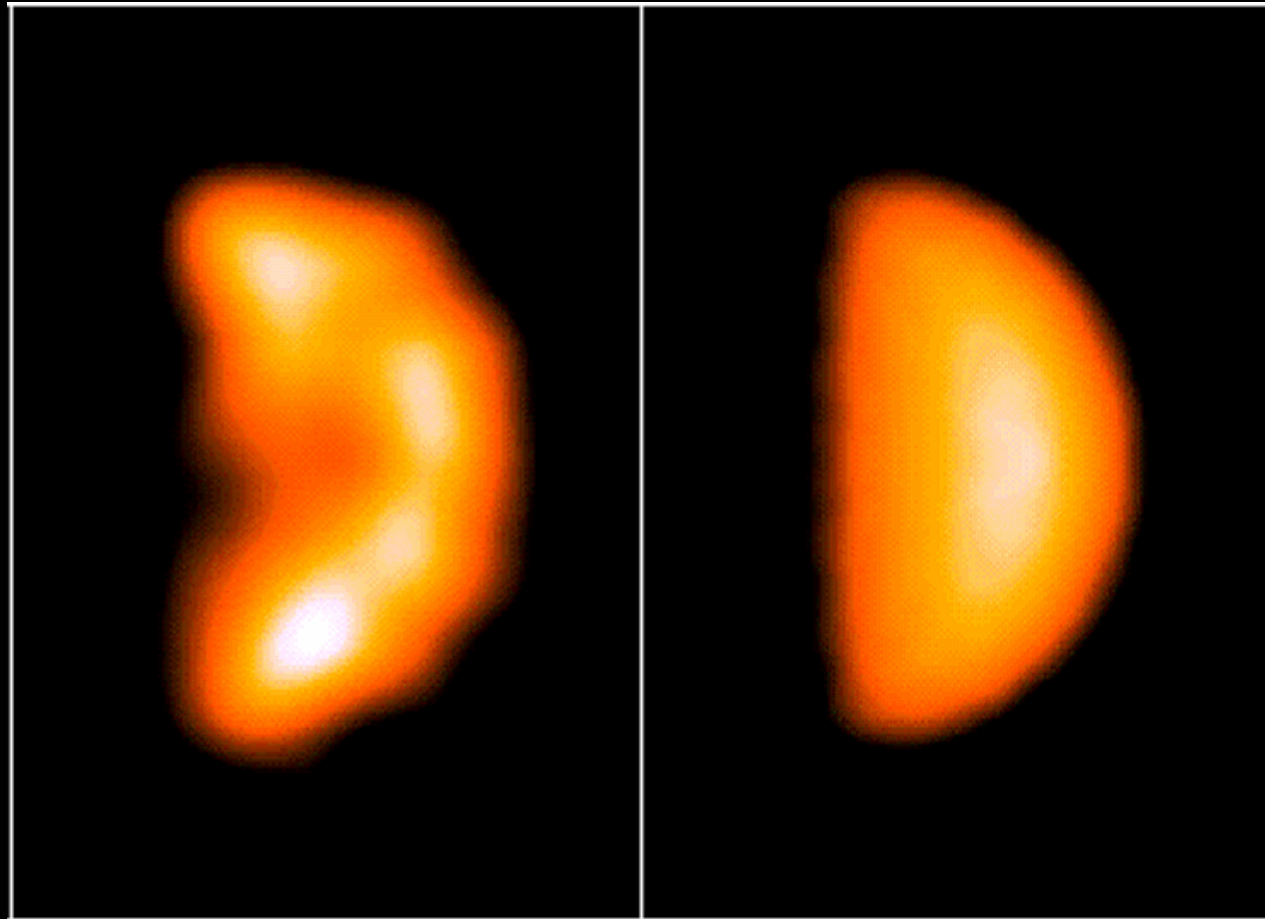
Chandra
ACIS-I

$E = 0.2 - 1.0 \text{ keV}$

12 000 km
23.2 arcsec

January 13, 2001

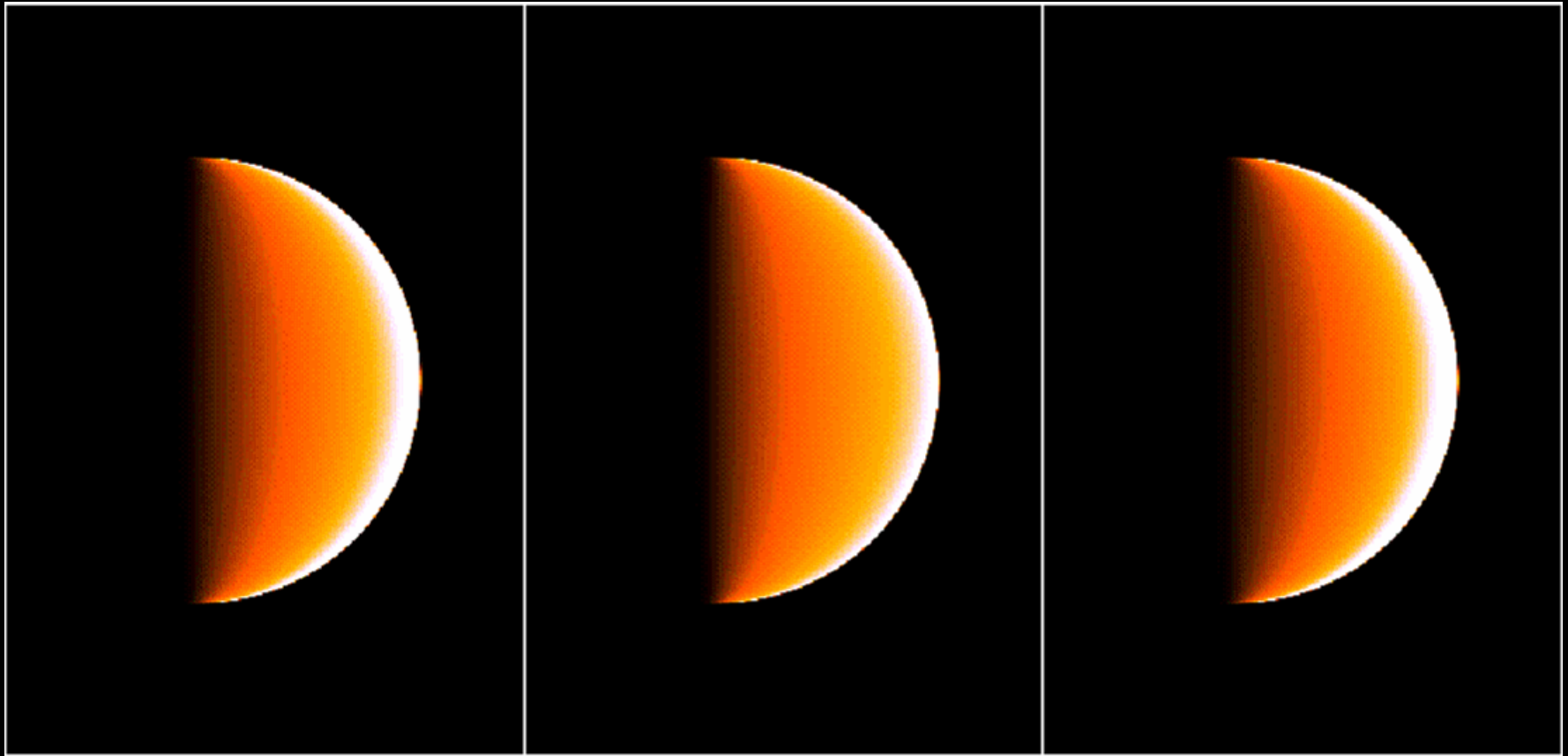
Comparison of the Venus morphology



X-ray (Chandra)

optical (4" Newton)

Simulated X-ray images of Venus for fluorescent scattering

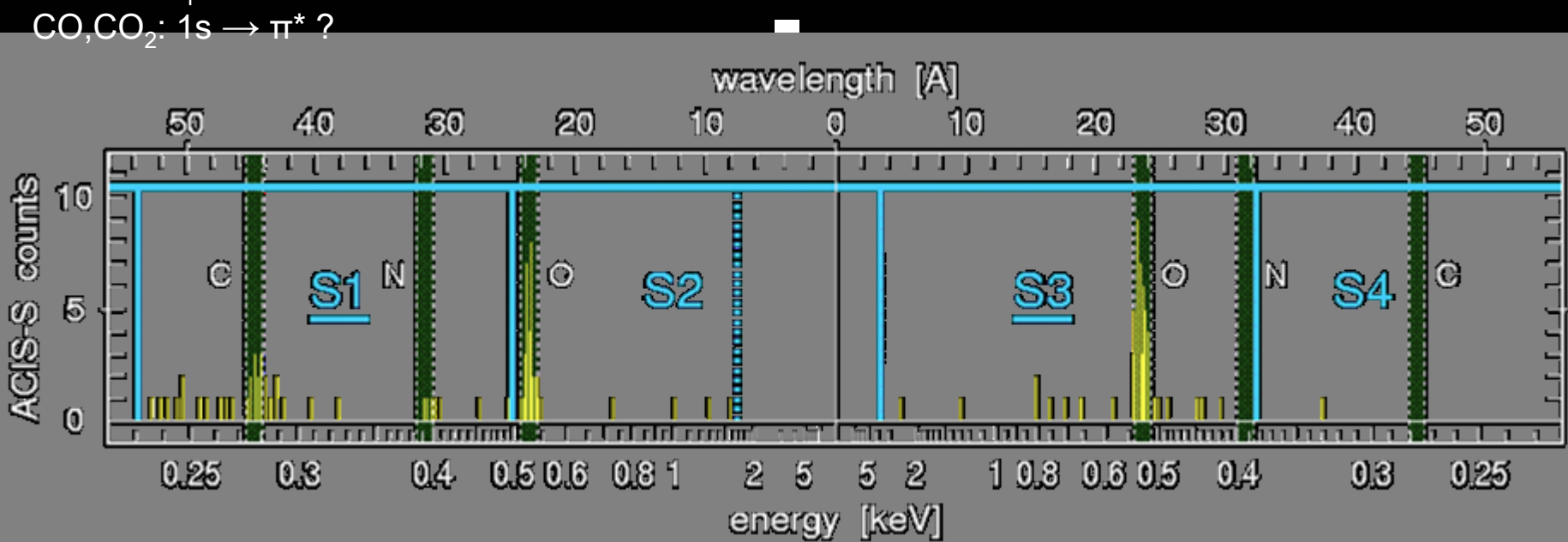
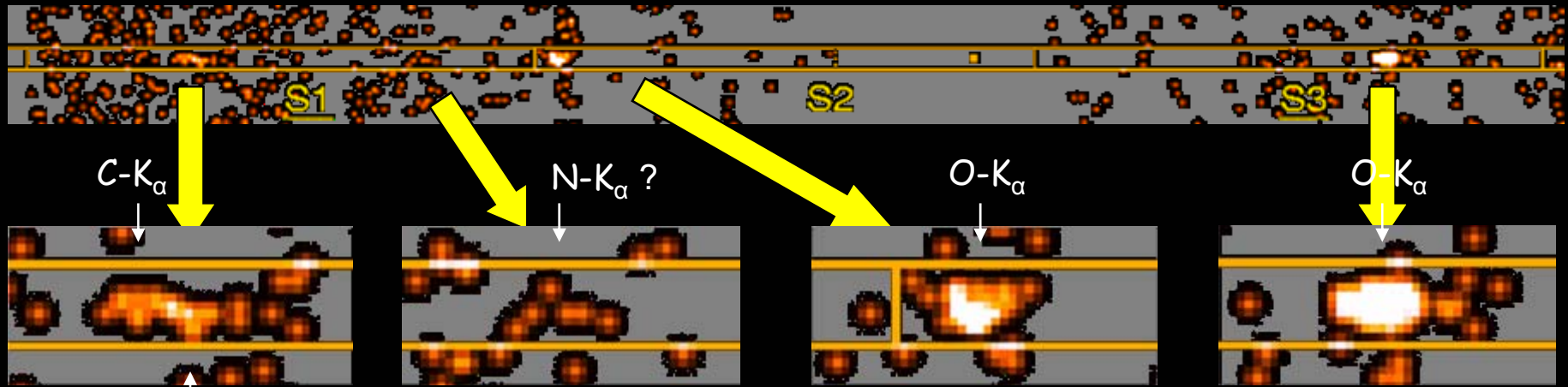


$C-K_{\alpha}$
 $L_x \sim 16 \text{ MW}$

$N-K_{\alpha}$
 $L_x \sim 1 \text{ MW}$

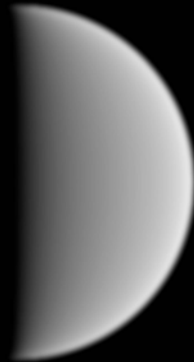
$C-K_{\alpha}$
 $L_x \sim 40 \text{ MW}$

X-ray grating spectrum of Venus (Chandra LETG/ACIS-S)



Simulated X-ray images of Venus for ..

.. scattering of solar X-rays
(logarithmic intensity scale)



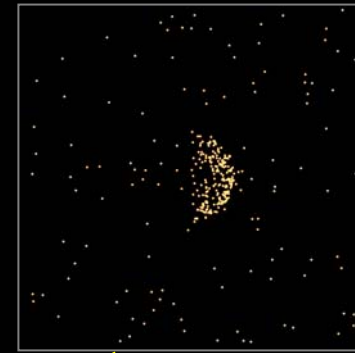
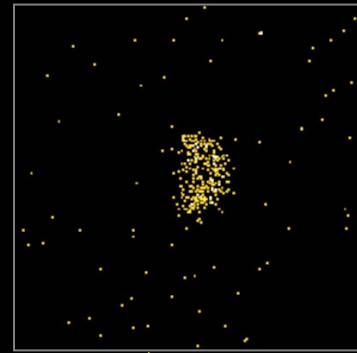
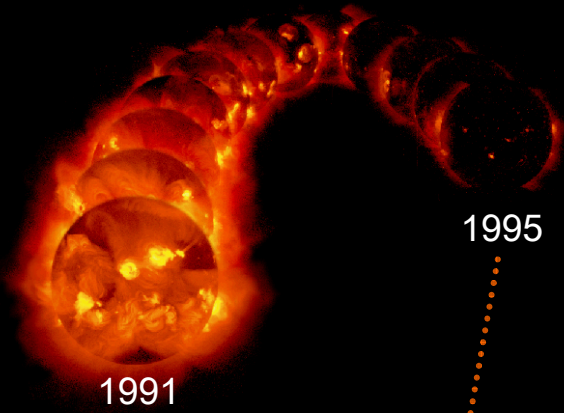
Dennerl et al. 2002, A&A 386

.. solar wind charge exchange
(logarithmic intensity scale)

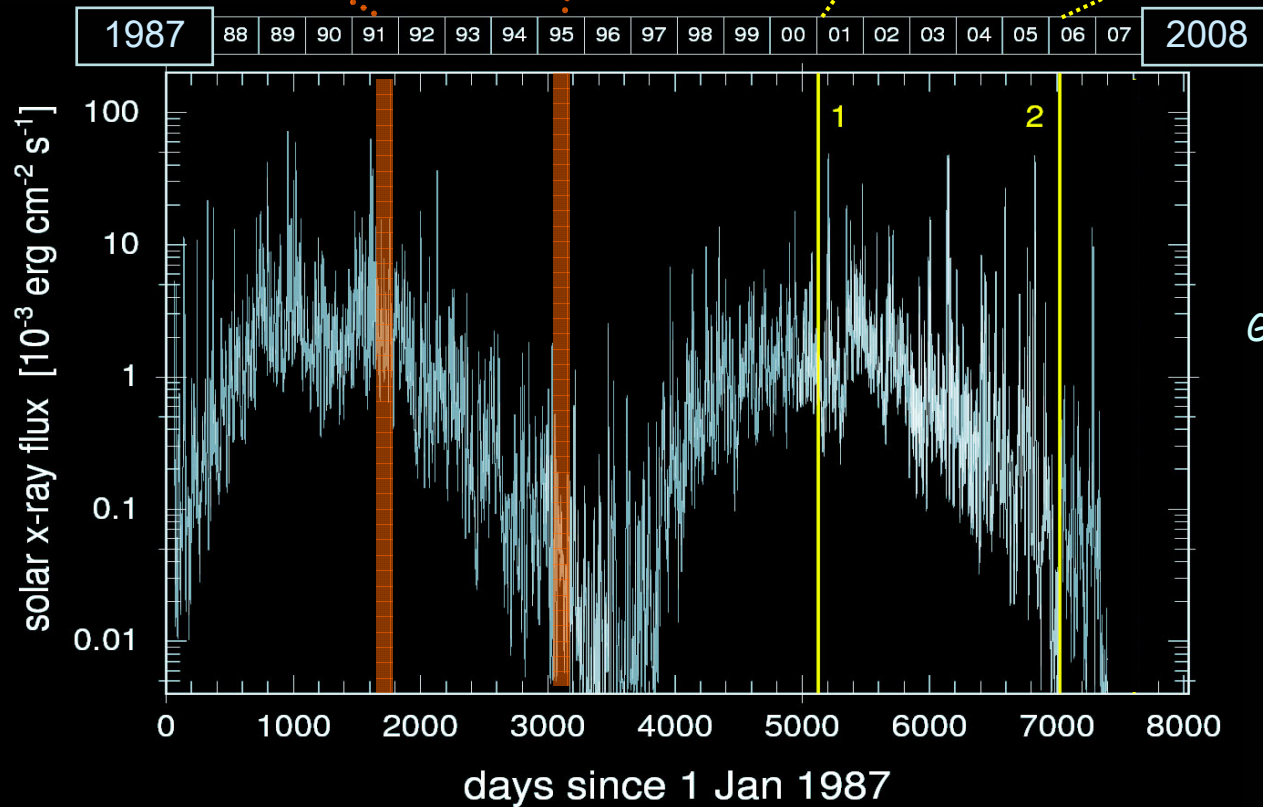


Gunell et al. 2007, GRL 34

Yohkoh SXT
0.25 - 4.0 keV

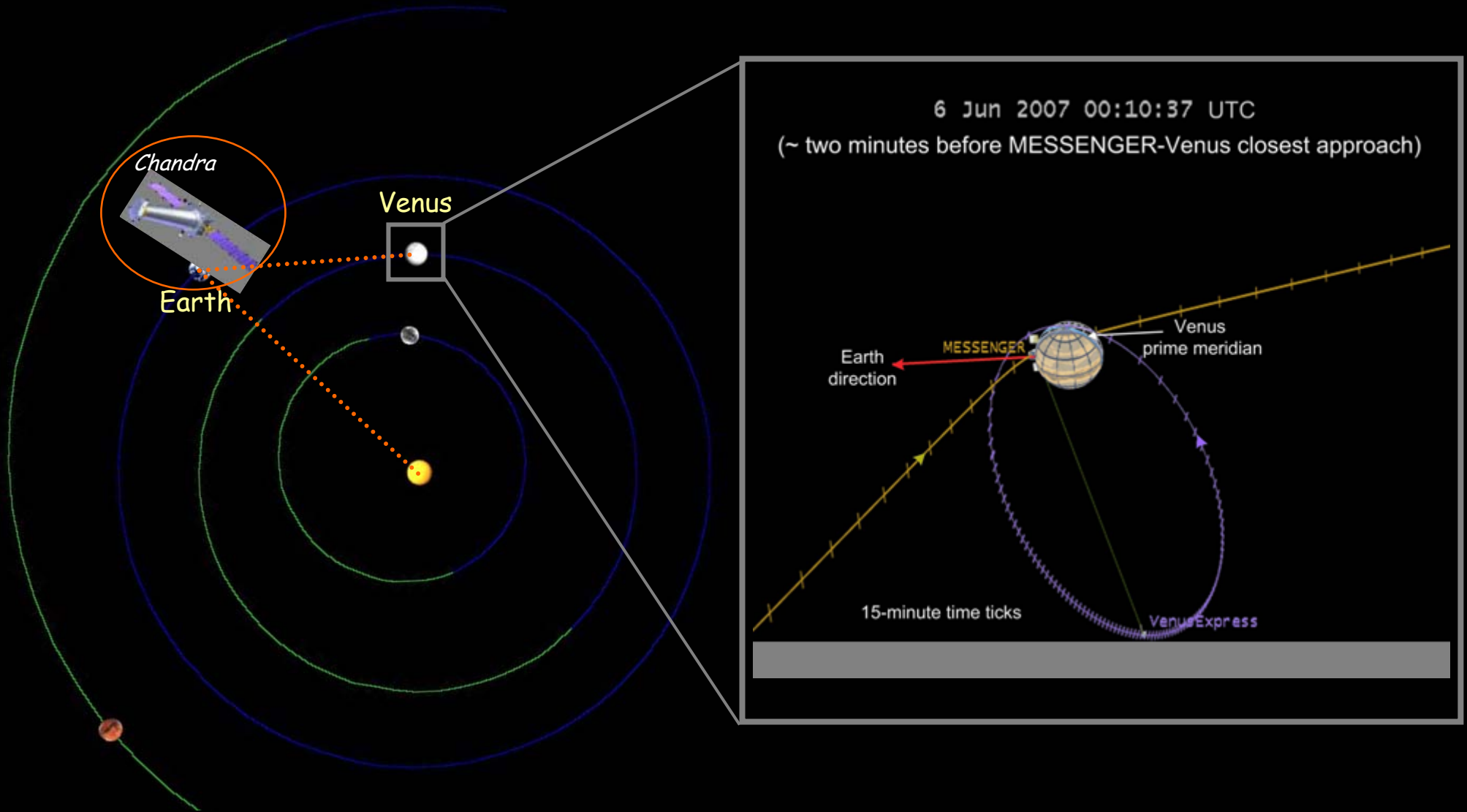


Chandra ACIS-I
0.2 - 1.0 keV

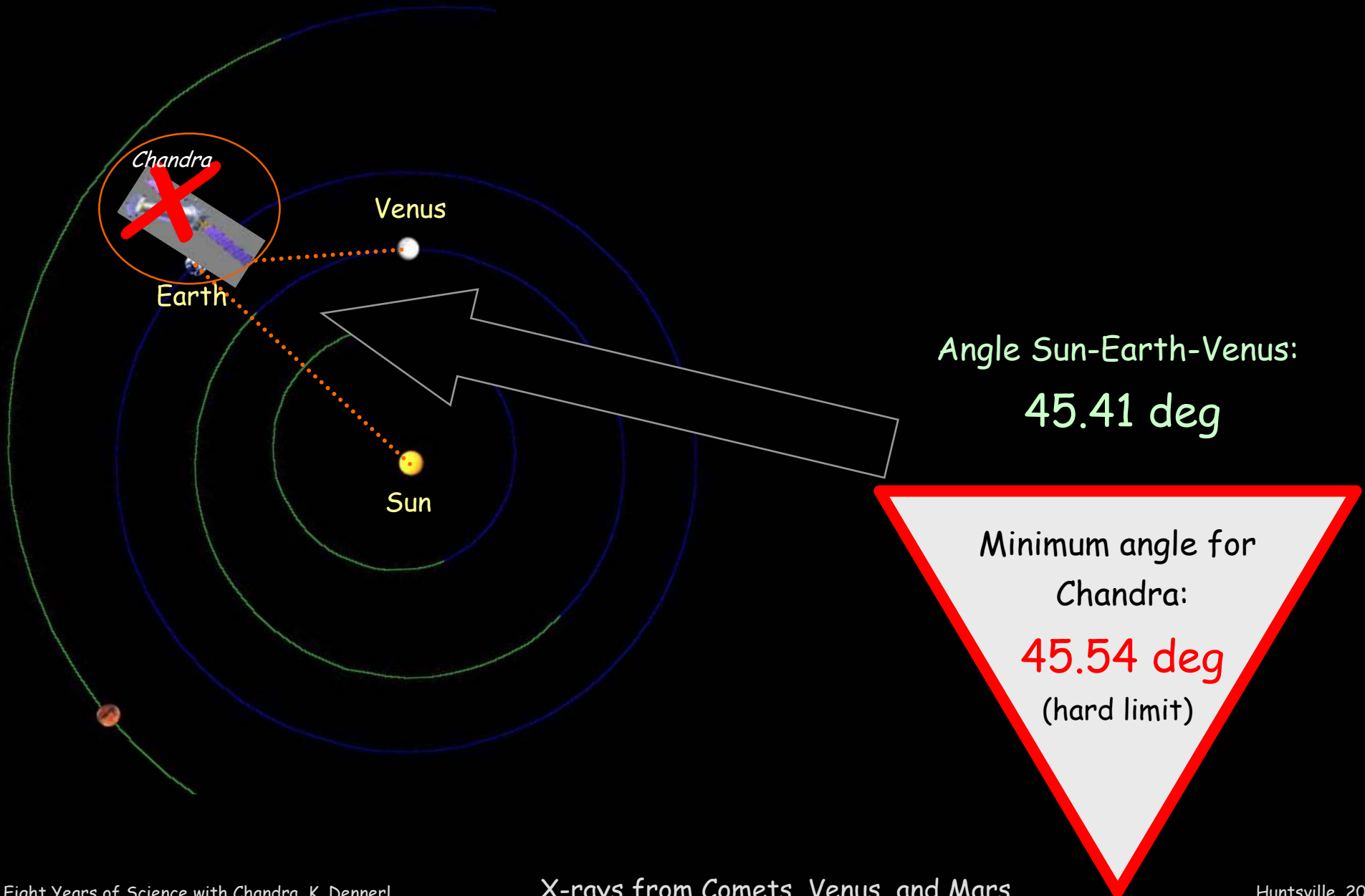


GOES-7, 8, 10, 12
1.6 - 12.4 keV

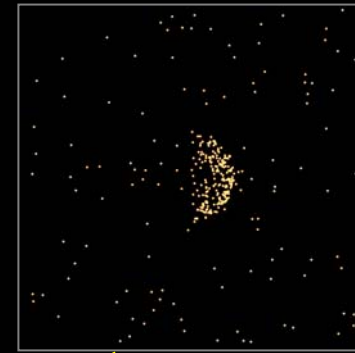
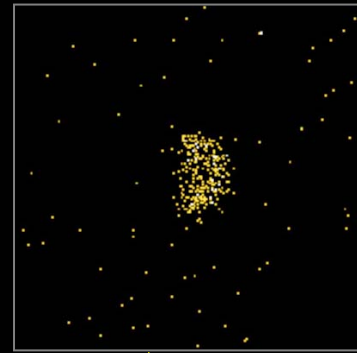
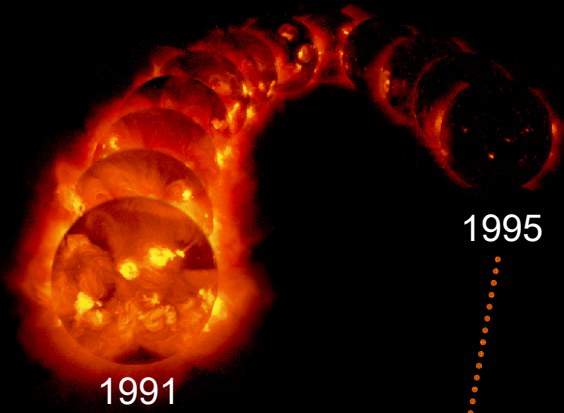
The inner solar system on 2007-Jun-06



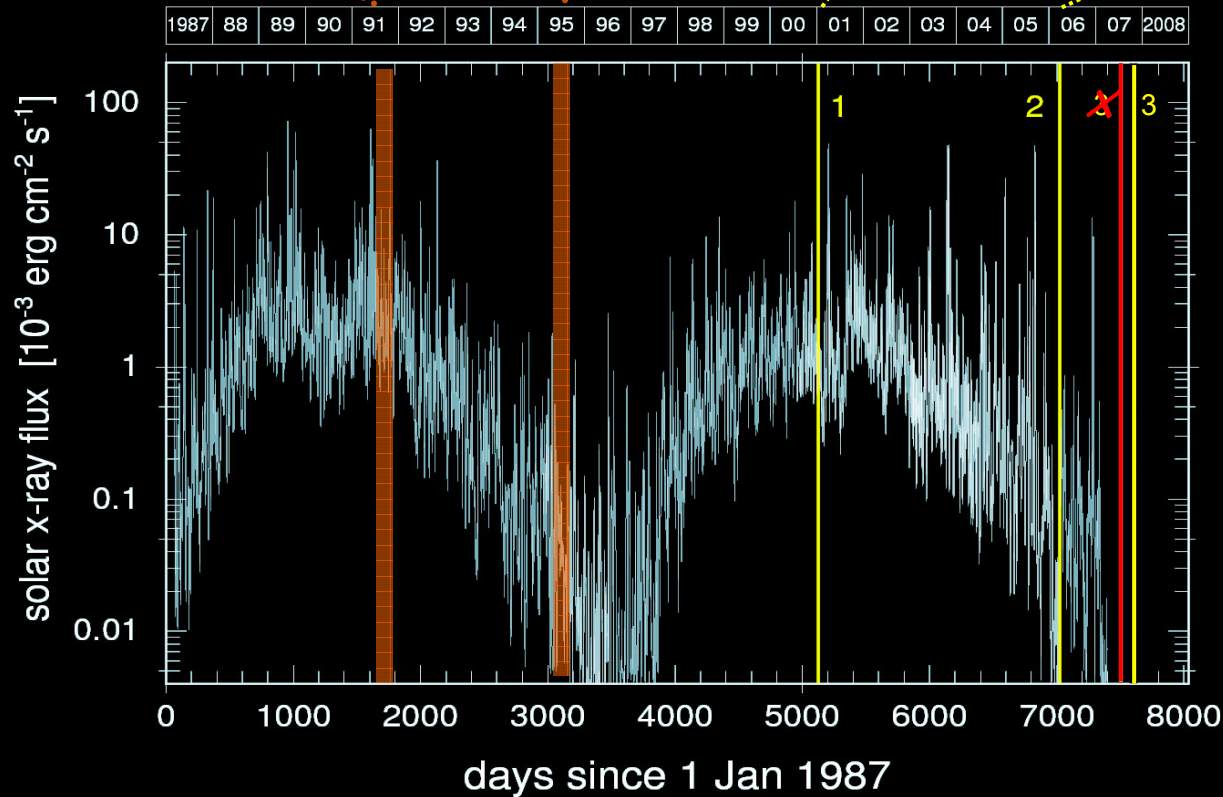
The inner solar system on 2007-Jun-06



Yohkoh SXT
0.25 - 4.0 keV



Chandra ACIS-I
0.2 - 1.0 keV



GOES-7, 8, 10, 12
1.6 - 12.4 keV

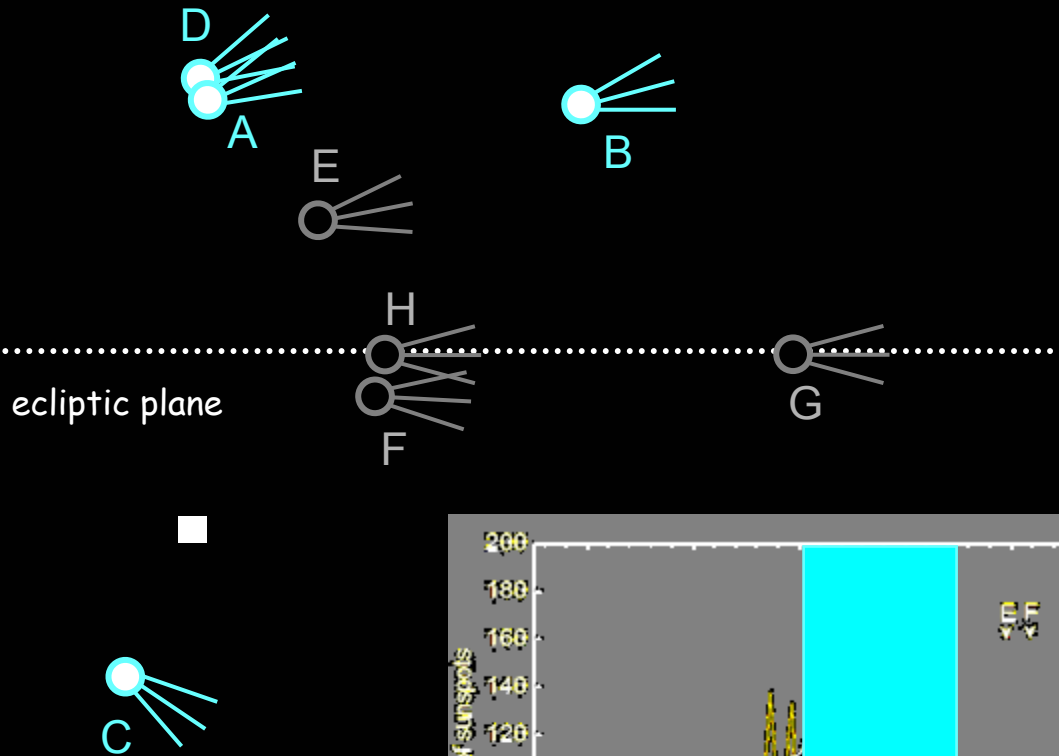
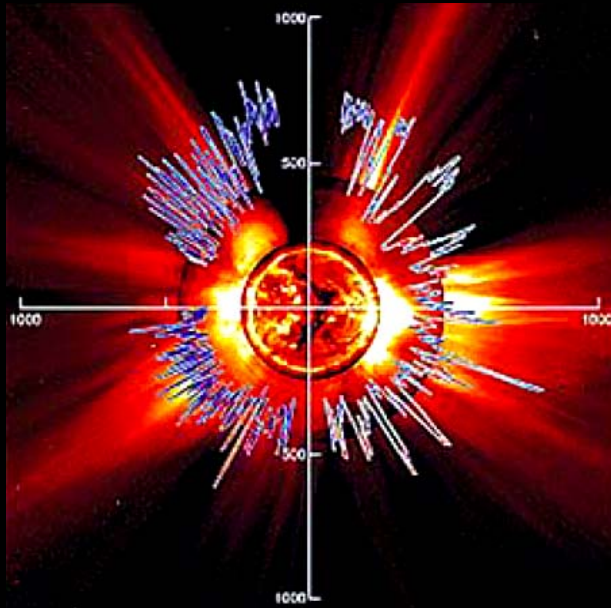
Per recommendations of the SOC and the Chandra Users Committee, we ask that you mention in your presentation

(a) investigations that existing x-ray missions (especially Chandra) should perform

and

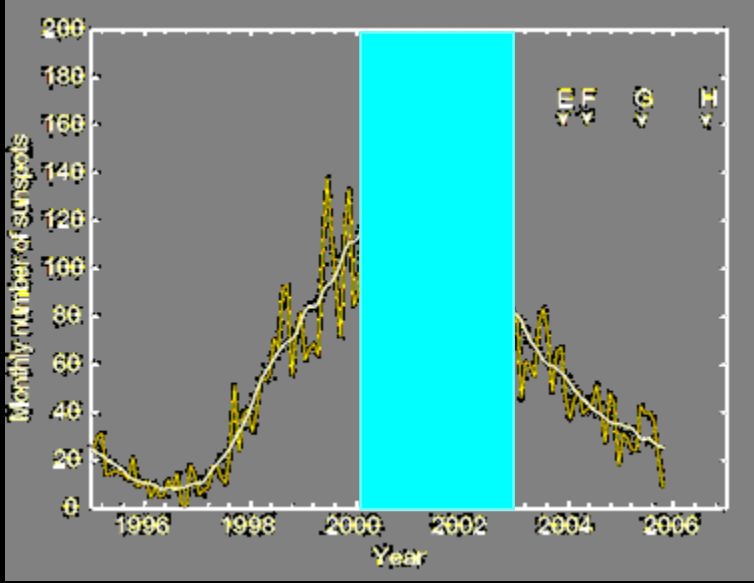
(b) those observations that require the capabilities of planned x-ray missions, in order to advance the topic addressed in your presentation.

Comets observed with Chandra, 2000 - 2007



By coincidence, all comets that were observed at higher latitudes were observed around solar maximum
 → disturbed solar wind, no cool fast wind sampled

Prediction of a class of cooler cometary X-ray spectra





Eight Years of Science with CHANDRA

The fourth in a series, this meeting will highlight science results from the past eight years of operation of the Chandra X-ray Observatory with emphasis on recent results. Contributions from the XMM-Newton, Suzaku, and Swift Observatories and related results from INTEGRAL, FOXTE and AGILE will also be presented.

23rd - 25th October 2007

MARRIOTT HUNTSVILLE
HUNTSVILLE, ALABAMA

http://cxc.harvard.edu/symposium_2007/

