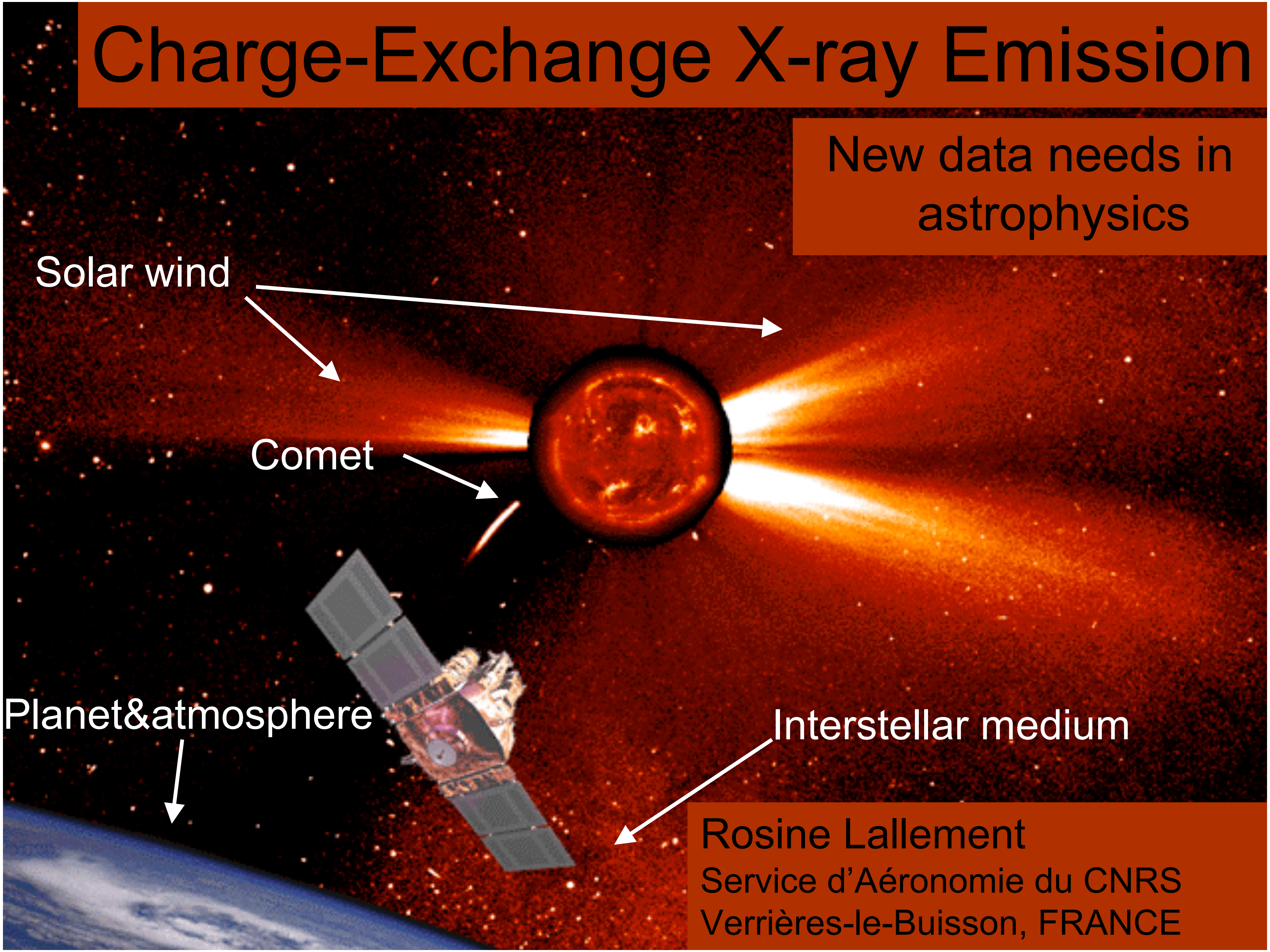
Charge-Exchange X-ray Emission

New data needs in astrophysics



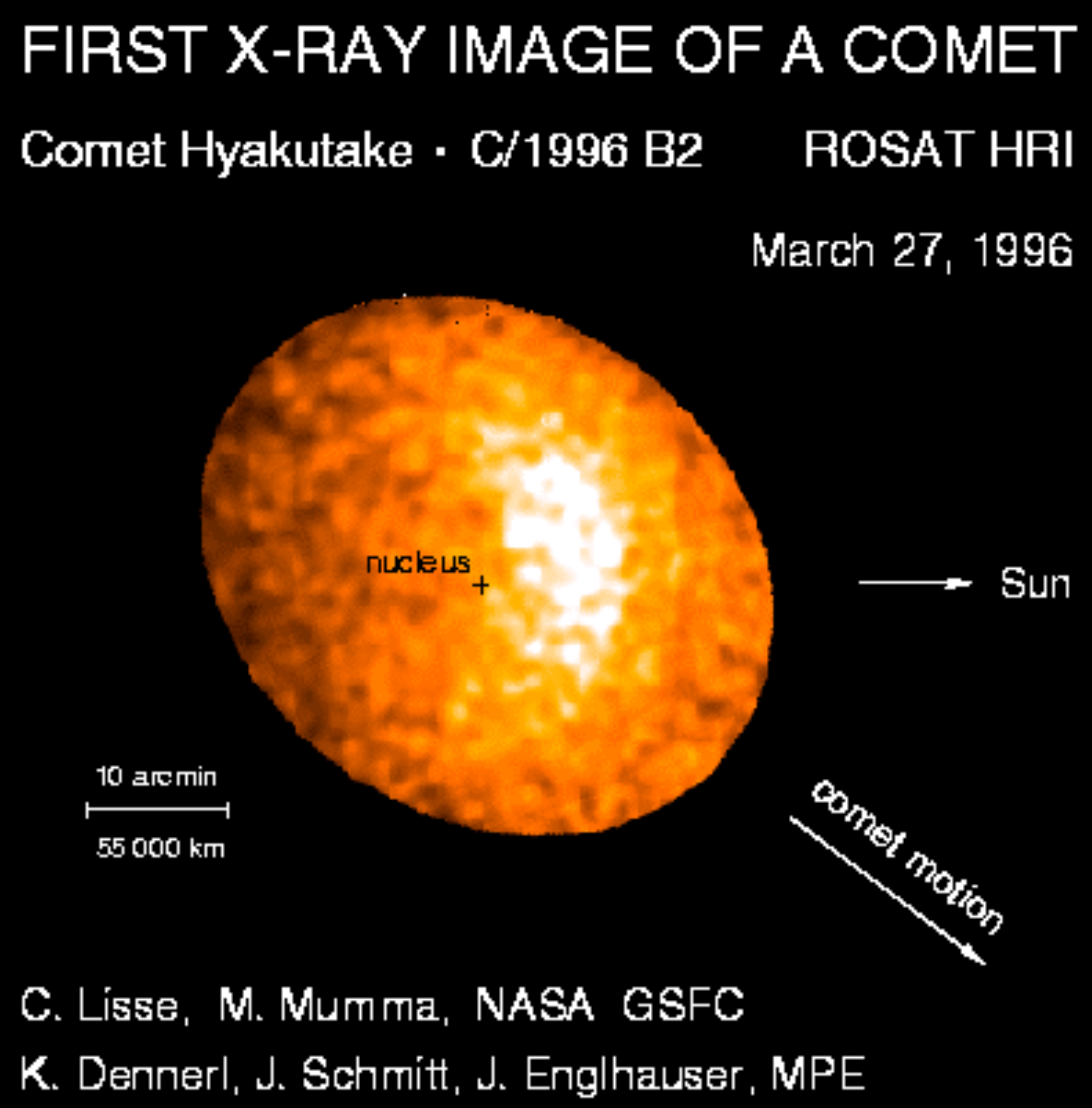
Rosine Lallement
Service d'Aéronomie du CNRS
Verrières-le-Buisson, FRANCE

X-ray emission consecutive to charge-transfer is well known in **laboratories**.
Fusion devices utilize strong neutral beams to transport gases into reactors.

However, its role in **astrophysics** has always been considered **insignificant**.

The main reason is that X-ray emission is associated to **very hot gases and extremely energetic** objects, and **neutrals are absent** from these environments: in other words, charge-transfer X-ray emission is ……

FIRE and ICE ……



FIRST X-RAY IMAGE OF A COMET
Comet Hyakutake · C/1996 B2
ROSAT HRI
March 27, 1996
nucleus
Sun
10 arcmin
55 000 km
comet motion
C. Lisse, M. Mumma, NASA GSFC
K. Dennerl, J. Schmitt, J. Englhauser, MPE

Outline:

SOLAR SYSTEM OBSERVATIONS/MODELS=>SOLAR WIND IONS

-Charge-transfer X-ray emission mecanism: **comets**

-Charge-transfer X-ray emission from **planets**

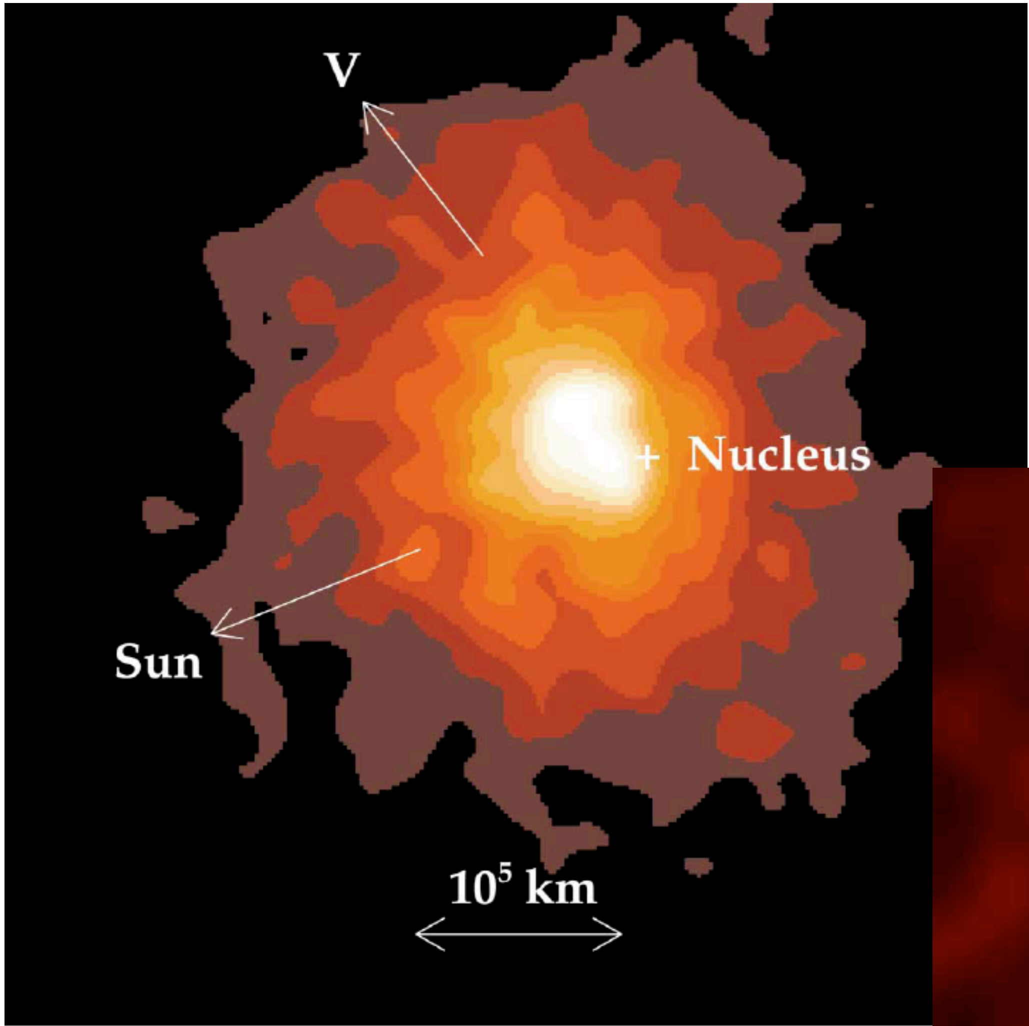
-Full-sky charge-transfer X-ray emission from the **heliosphere**

-The importance of CX emission illustrated by the controversy: Heliosphere vs Local Interstellar Bubble

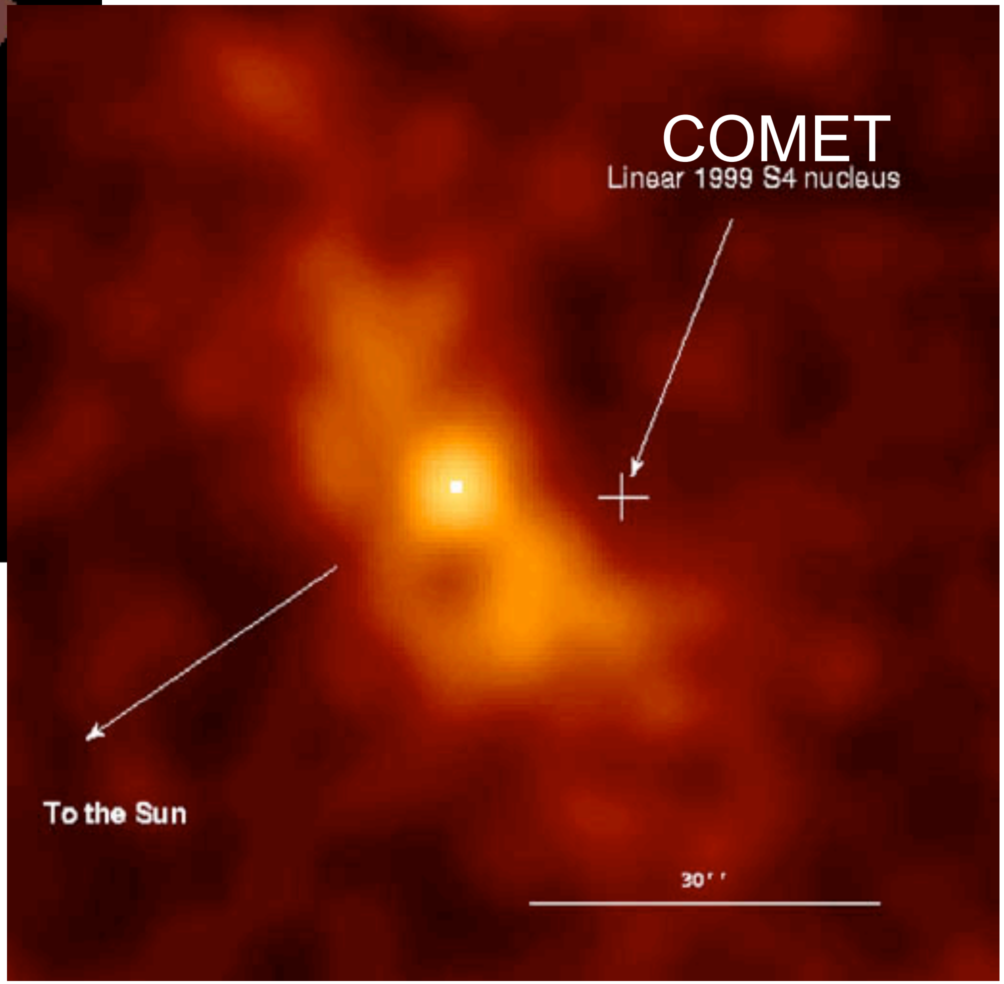
-Needs for experimental and theoretical atomic data

-CX emission in astrophysics

CHANDRA
Soft X-rays
0.2-1.2 keV

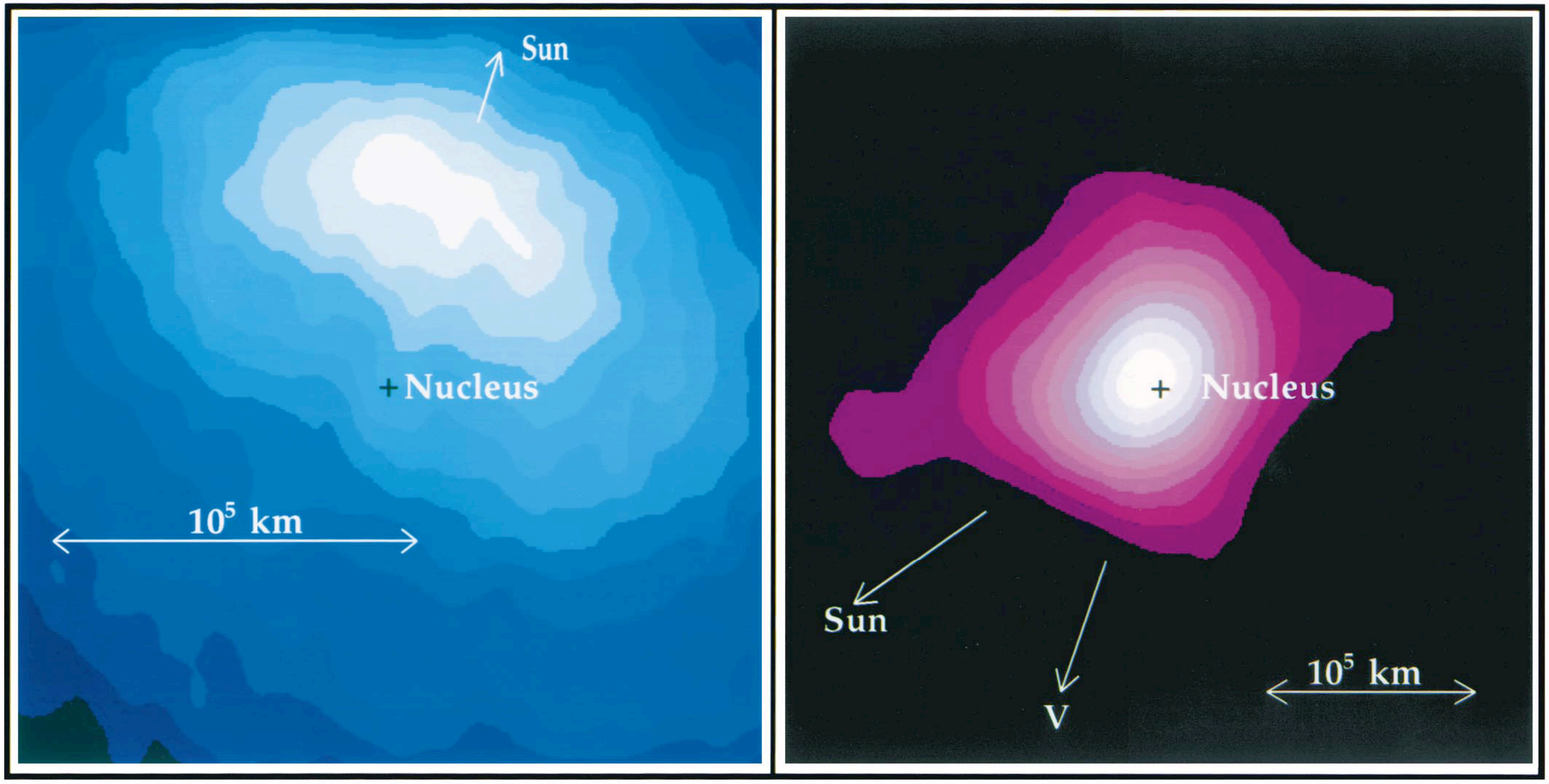


Comet McNaught-Hartley (C/1999T1)



Comet Linear 1999 S4

Ultra-soft X-rays EUVE: 70-180 eV

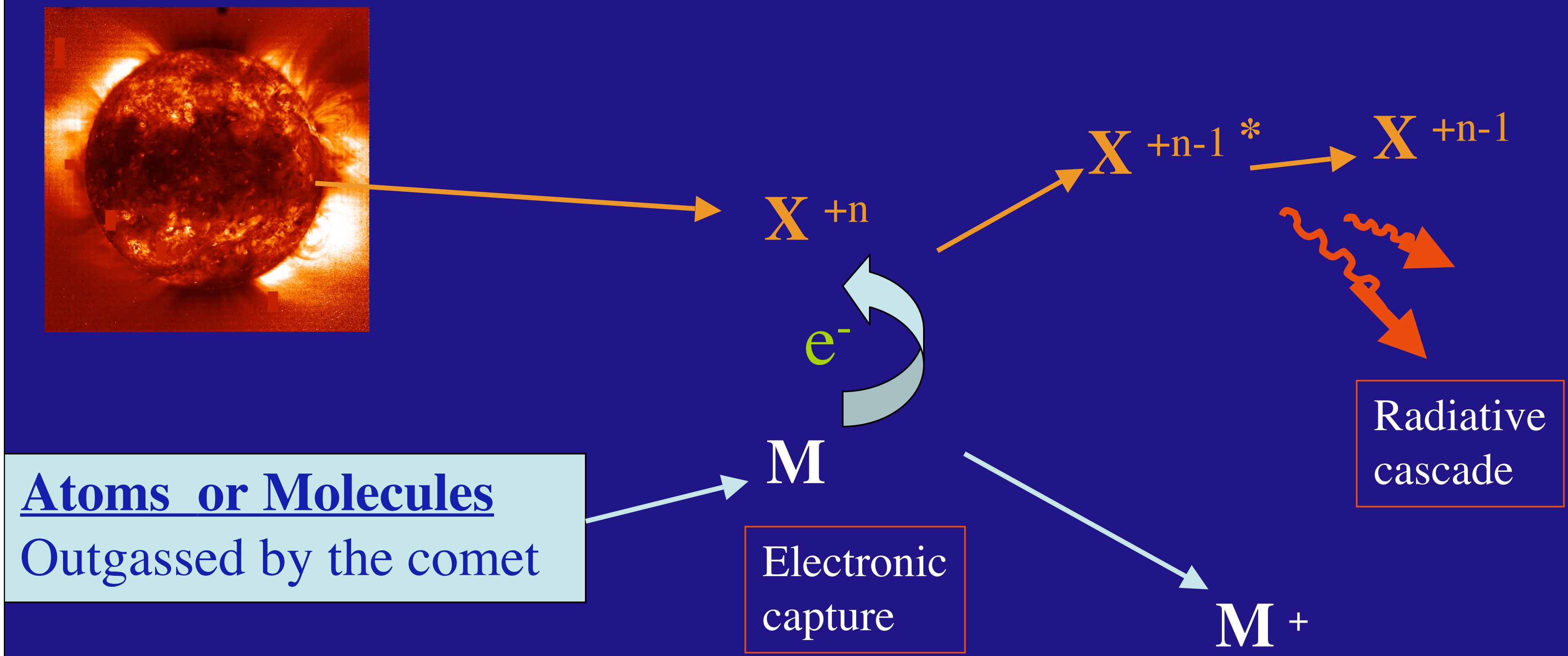


HYAKUTAKE (1996) 6P/d’ARREST (1995)

SOLAR WIND HIGHLY CHARGED IONS,

FROM THE 1-2 MK CORONA

CHARGE STATE « FROZEN » in INTERPLANETARY SPACE

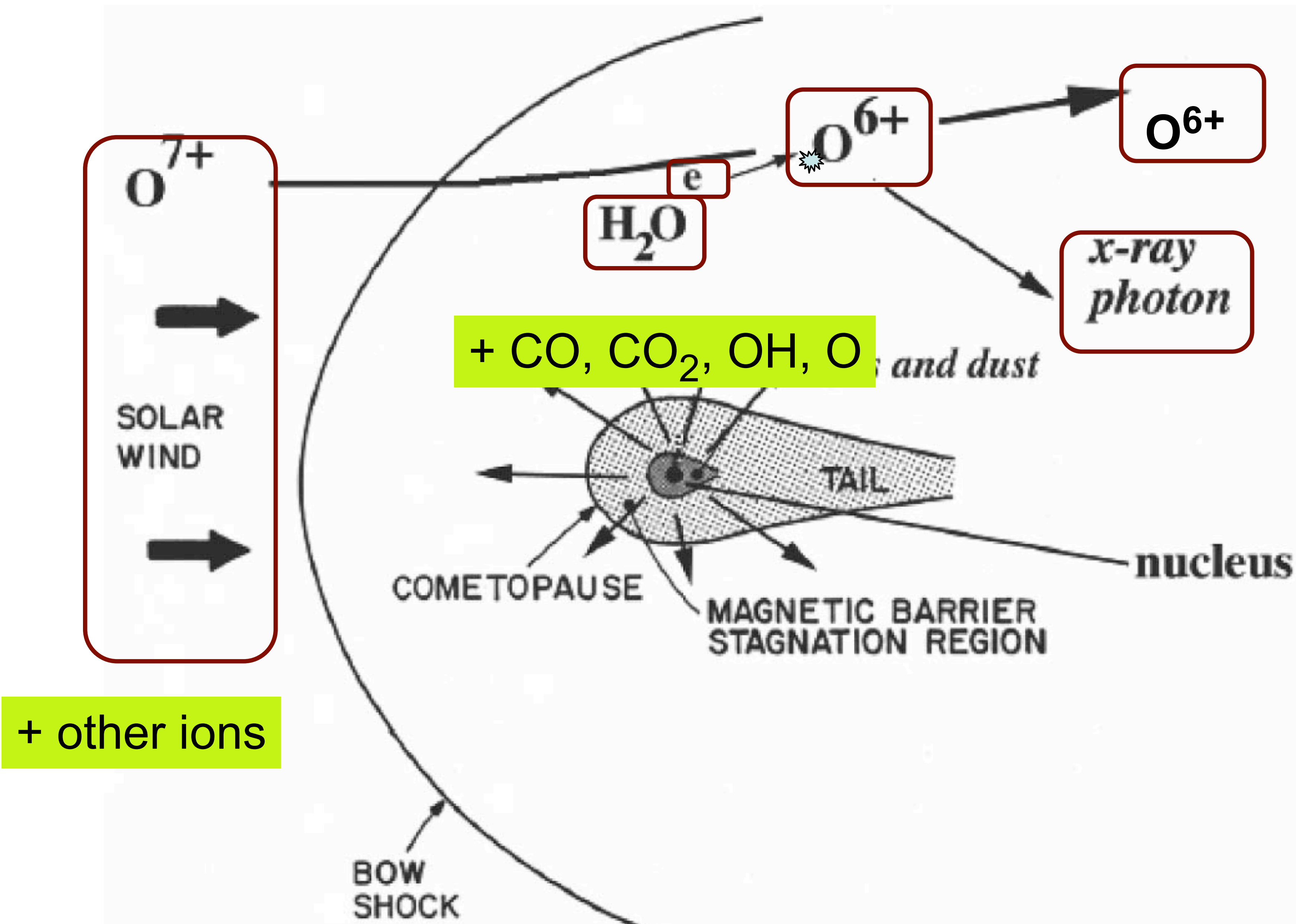


Mechanism devised by Cravens, 1997 (Geophys. Res. Let.)

Proposed mechanisms:

(1) charge transfer of solar wind heavy ions to cometary neutrals followed by X-ray emission (Cravens 1997 Haberli et al. 1997, Krasnopolsky 1997b,Ip & Shemansky 1997)
(2) scattering of solar X-rays by very small (10-19 g) dust particles (Wickramasinghe & Hoyle 1996; Krasnopolsky 1996, 1997a, 1997b)
(3) spectral line radiation from electron impact and recombination excitation (Bingham et al. 1997)
(4) electron bremsstrahlung (Northrop et al. 1997; Northrop 1997).

In the case of comets, only (1) passed observational tests and quantitative and detailed comparison between observed and modeled spectra



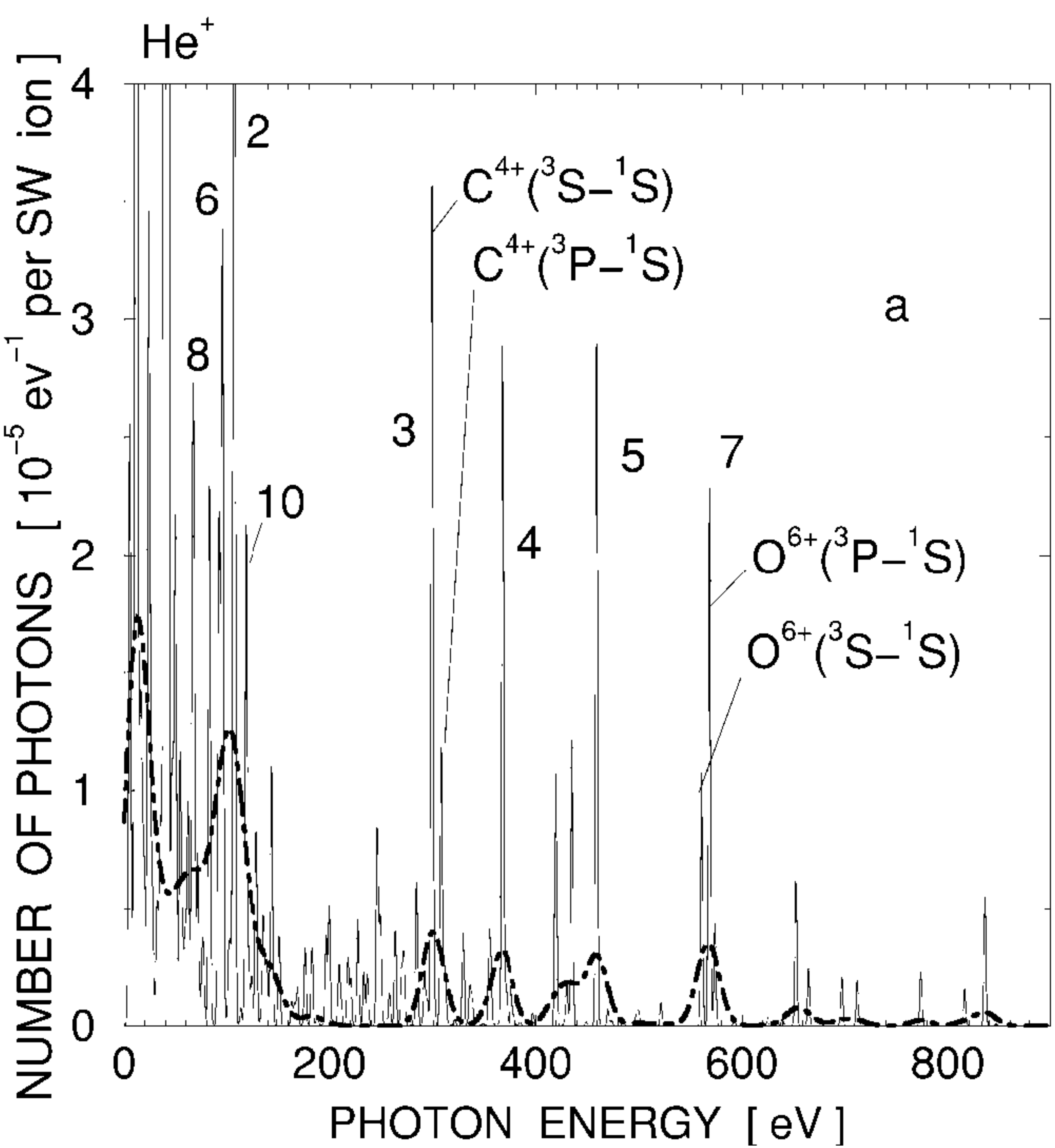
X^{n+} (solar wind) + (H, He, H_2O,..) ---> $X^{(n-1)+**}$ +
(H^+, He^+,..) $X^{(n-1)+**}$ --- > $X^{(n-1)+}$ + $h\nu$ X-ray/EUV

Main high ions in the solar wind:

$C^{4+,\mathbf{5+,6+}}$ $N^{\mathbf{5+,6+},7+}$ $O^{5+,\mathbf{6+,7+,8+}}$ $Ne^{\mathbf{8+},9+,10+}$

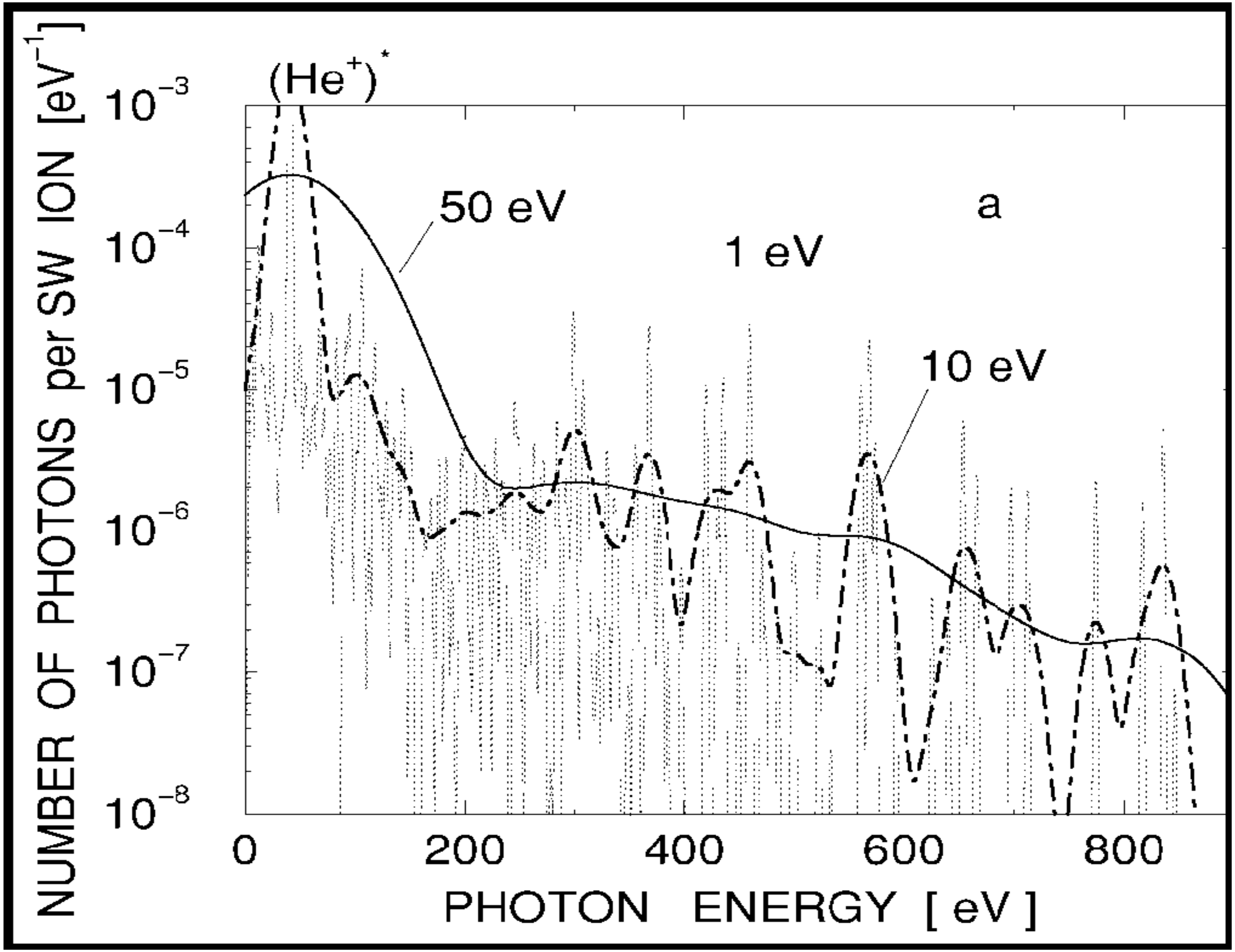
$Mg^{7+,\mathbf{8+,9+,10+}}$ $Si^{\mathbf{8+,9+,10+,11+}}$ $S^{\mathbf{10+,11+},12+,13+,14+}$ $\mathbf{Fe}^{\mathbf{9+,10+,11+},12+,13+,14+}$

Higher charge states during episodic energetic events (solar flares) ==> e.g. $\mathbf{Fe}^{\mathbf{12+,13+,14+}}$, $S^{12+,13+,14+}$

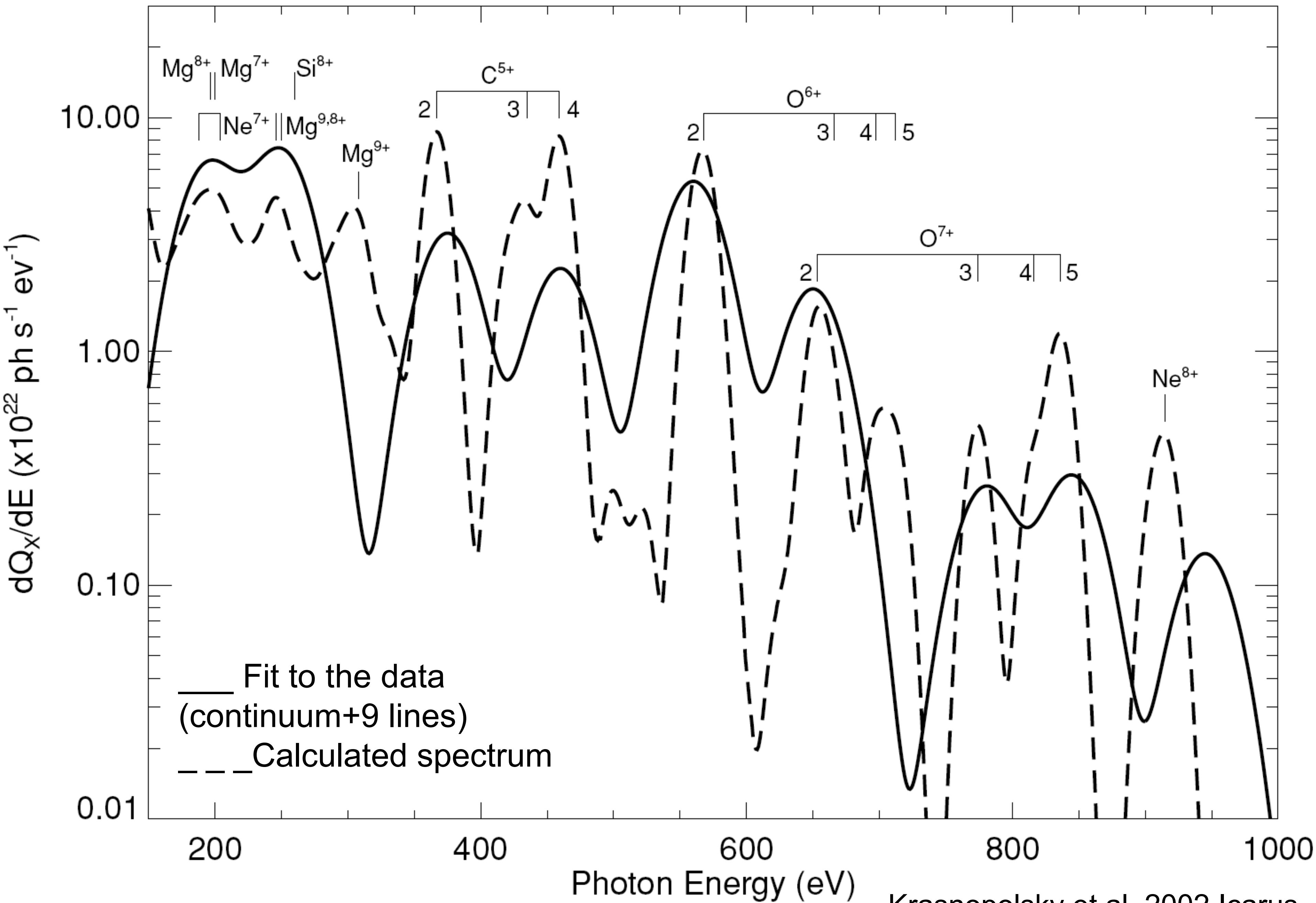


Kharchenko
Dalgarno
2001
Astroph.J.

EFFECT OF SPECTRAL RESOLUTION DEGRADATION

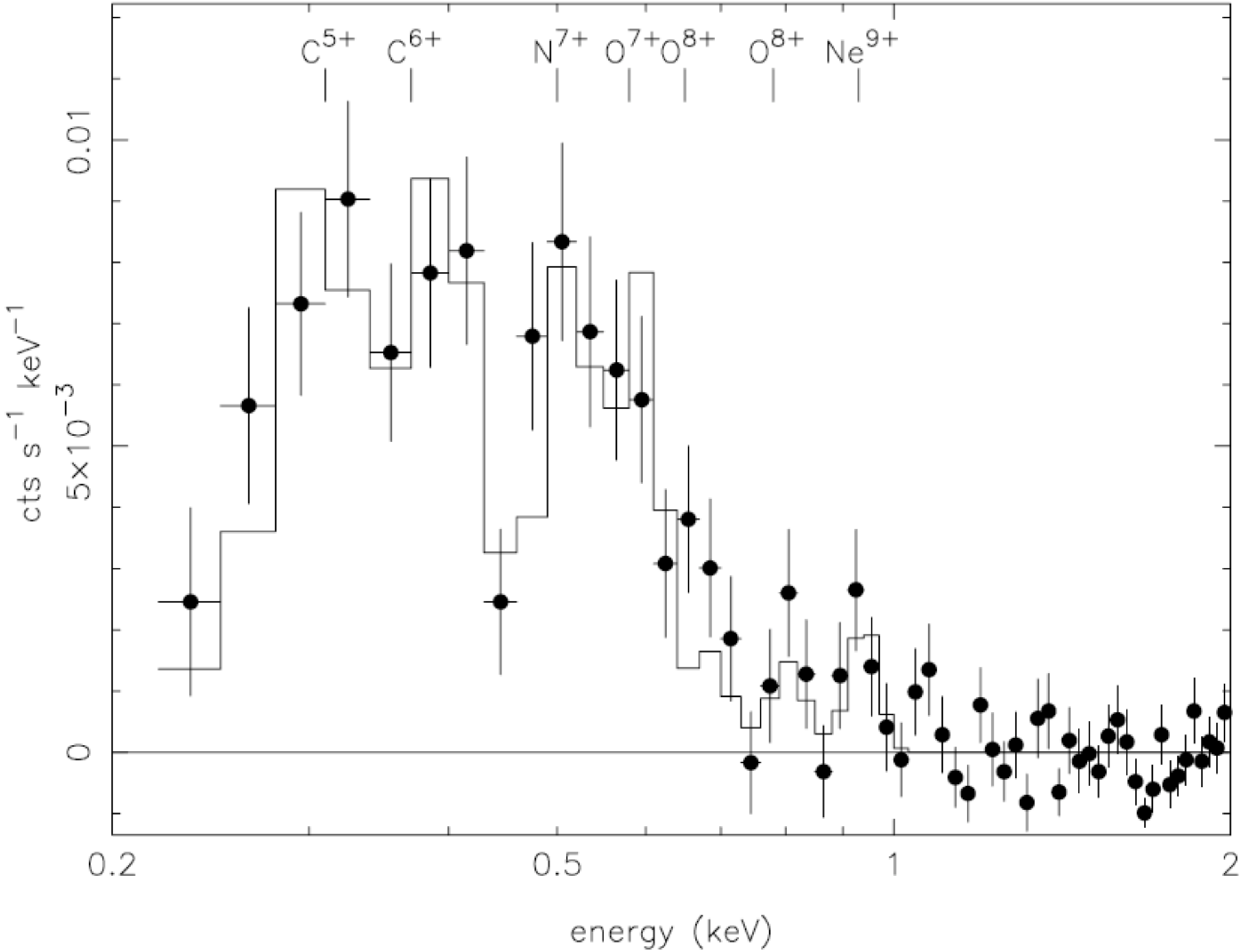


Comet McNaught-Hartley (C/1999 T1) CHANDRA 2001



Krasnopolsky et al, 2002 Icarus

SWIFT- Deep Impact: Comet 9P-Tempel 1



Willingale et al, 2006, Astrophys. J.

Specificities of the charge-transfer spectra

e.g. Kharchenko & Dalgarno, 2000, 2001

-e^- capture populates preferentially **highly excited states**: subsequent cascades controlled by branching ratios

-radiative lifetime of the order of or shorter than **collision time**

-forbidden transitions give rise to **intense emission** lines, not seen in laboratory beam spectra (distances to decay longer than detector dimensions)

-line ratios very **different** from classical electron-ion **recombination spectra**

An exemple: Hydrogen-like ions

$^{**}O^{6+}$, $^{**}N^{5+}$, $^{**}C^{4+}$ formed from O^{7+}, N^{6+}, C^{5+}

radiate preferentially by allowed transitions into

-metastable 2^3S

Magnetic dipole

For C^{4+}
298.89eV, 0.02s
10km at 500km/s

-excited triplet 2^3P

spin-forbidden

Ground state **1^1S**

The **2^3P** --> **1^1S** spin-forbidden of O^{6+} at 568.4 eV
is **2.5 times more intense** than the **2^3S** --> **1^1S** line at 560.9eV
(for comets, also, opposite ratio for C^{4+})

Cometary X-rays are extremely useful for:

-composition
-production rate
-structure of the coma-solar wind interface

Deep Impact crash onto comet 9P/Tempel1:
The X-ray emission increase generated by the impact has been monitored by the SWIFT satellite (Willingale et al, 2006, Astroph. J.)

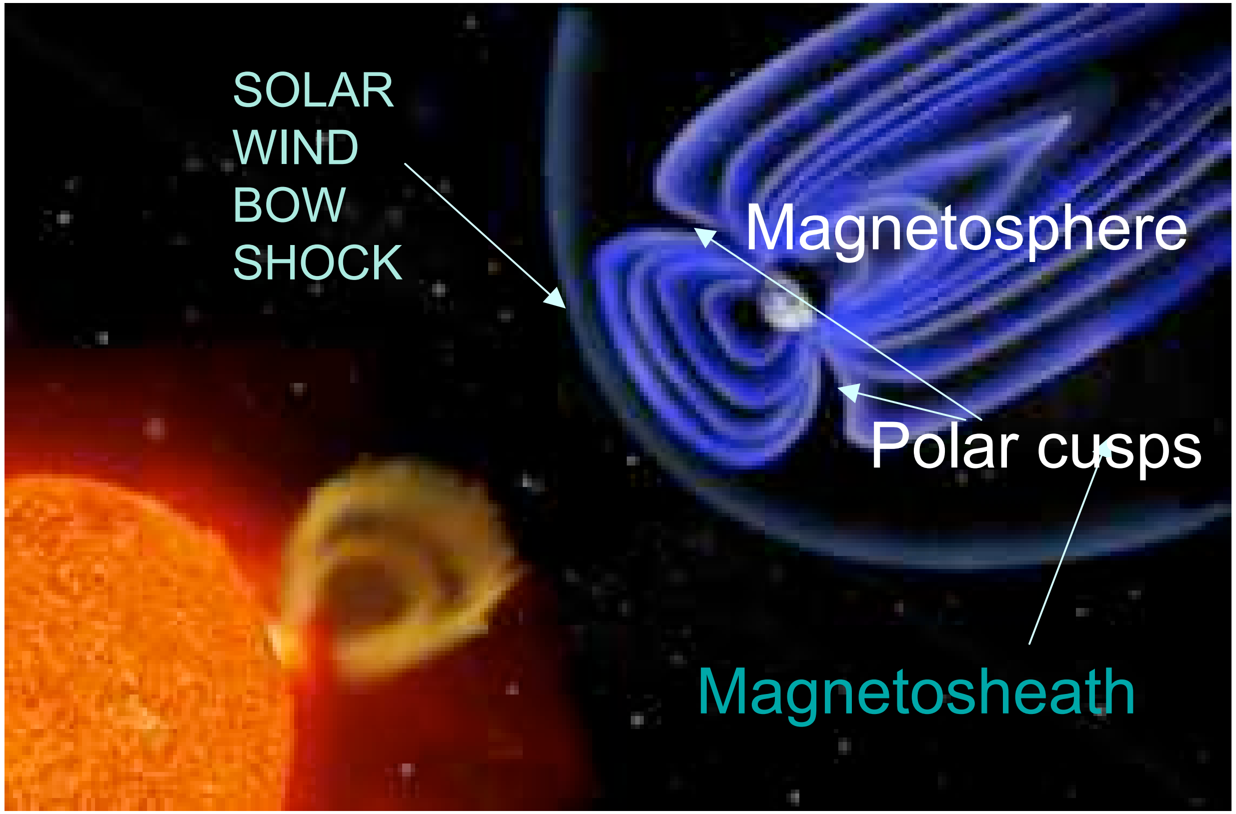
Charge transfer X-ray emission from

PLANETS

In the same way cometary neutrals interact with solar wind high ions, atoms from planetary exospheres also exchange charges with SW ions and are a source of X-ray emission

Magnetized planets are protected by their magnetic field, which deviates the solar wind.

Unmagnetized planets having a dense atmosphere, e.g. MARS, VENUS are the best candidates for X-rays

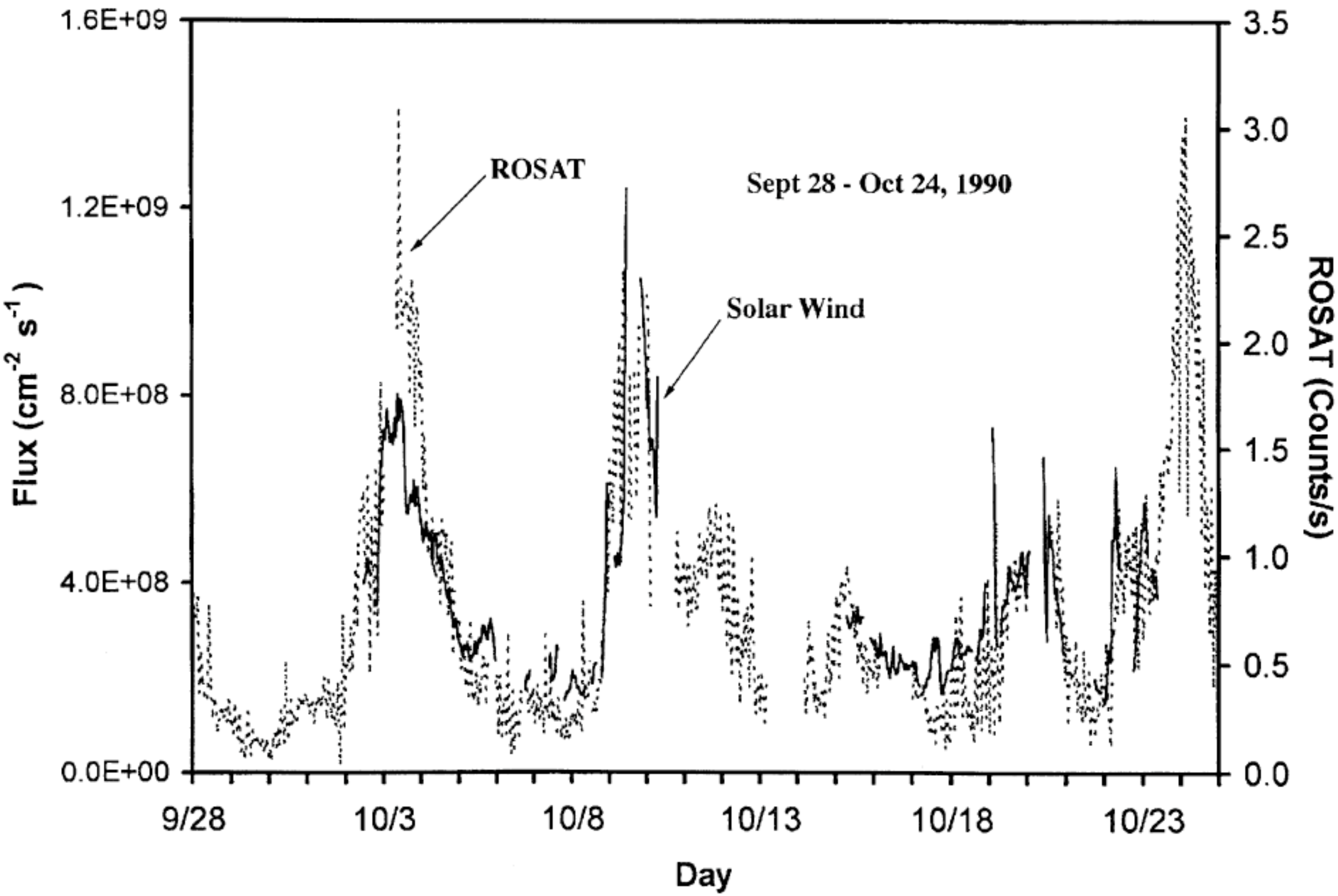


Charge transfer X-ray emission can not occur within the magnetosphere

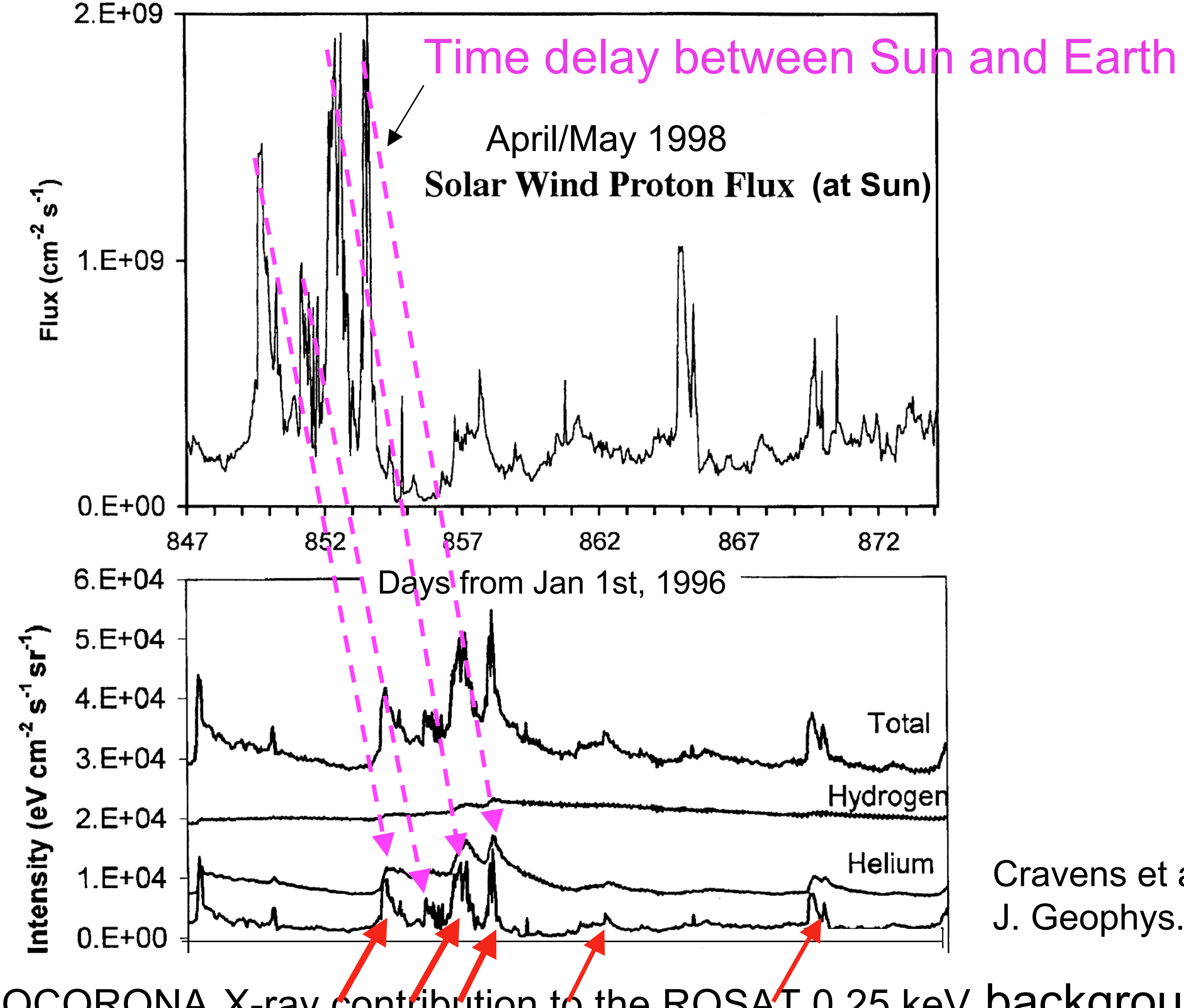
But, the exosphere, (or geocorona) extends far enough to give rise to some interaction

During solar wind enhancements or simply strong variations, the magnetosphere suffers reconfigurations and solar wind enters + role of polar cups

Temporal variability of the 0.25 keV background: ROSAT data



Cravens,Robertson, 2001



Cravens et al,2001,
J. Geophys. Res

GEOCORONA X-ray contribution to the ROSAT 0.25 keV background
About 1/10 of the average measured background

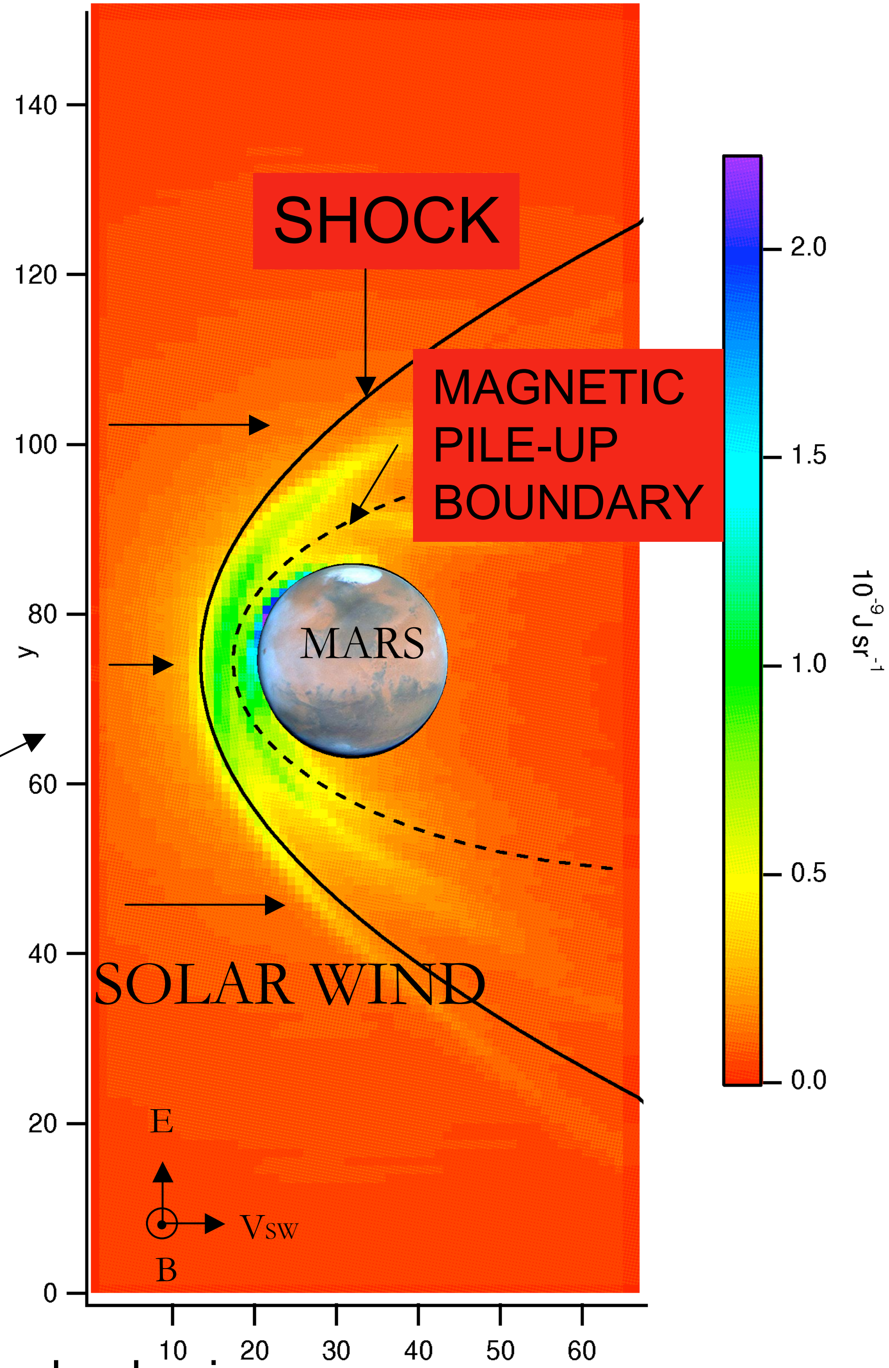
MARS

The Solar wind interacts directly with atoms and photo-ions of the Mars exosphere

The wind is first decelerated by a shock and beyond by a magnetic barrier

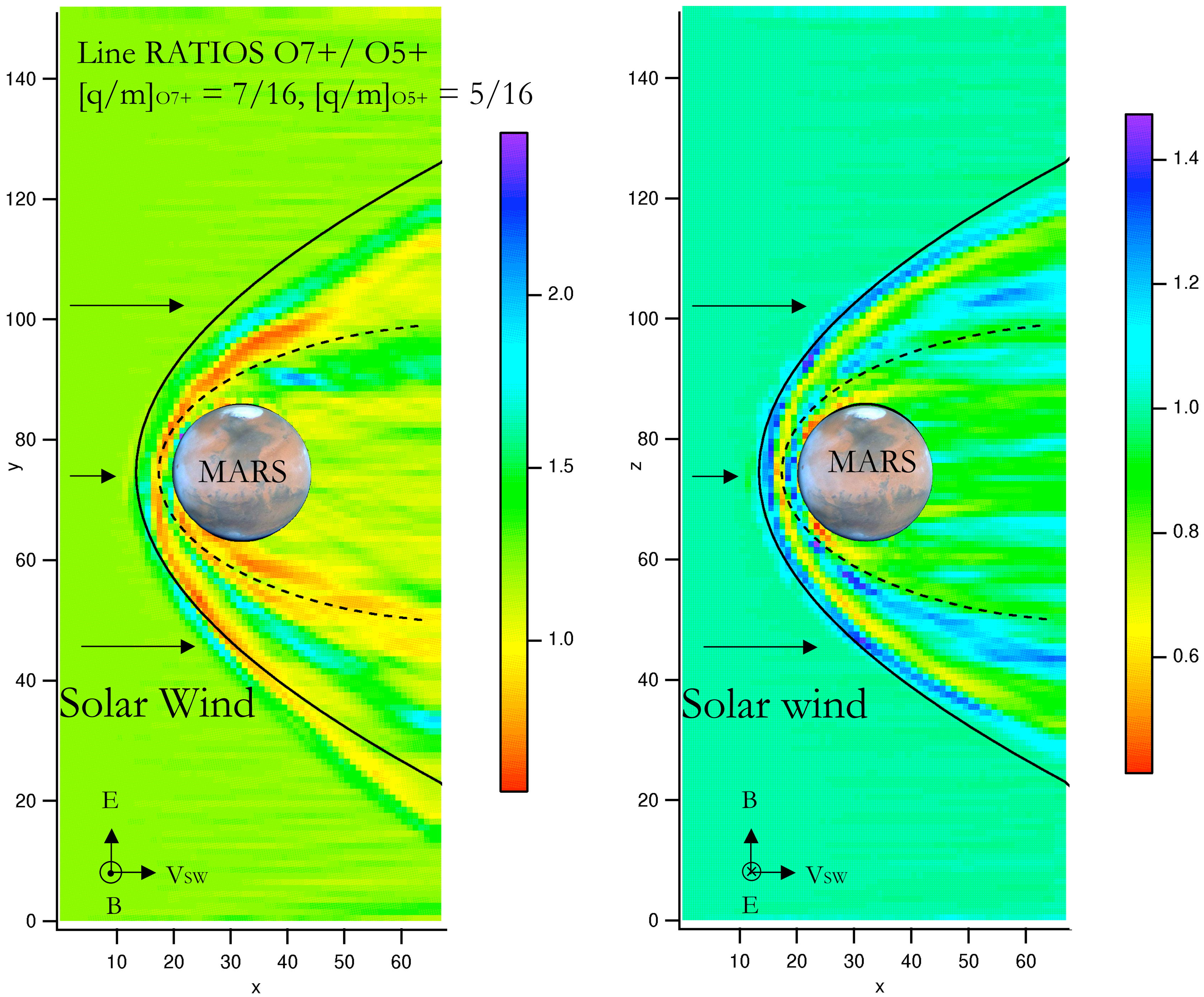
High ions propagate inside this structure, charge-transfer with H and O, or escape

Xray emission between 0.3 and 1 keV

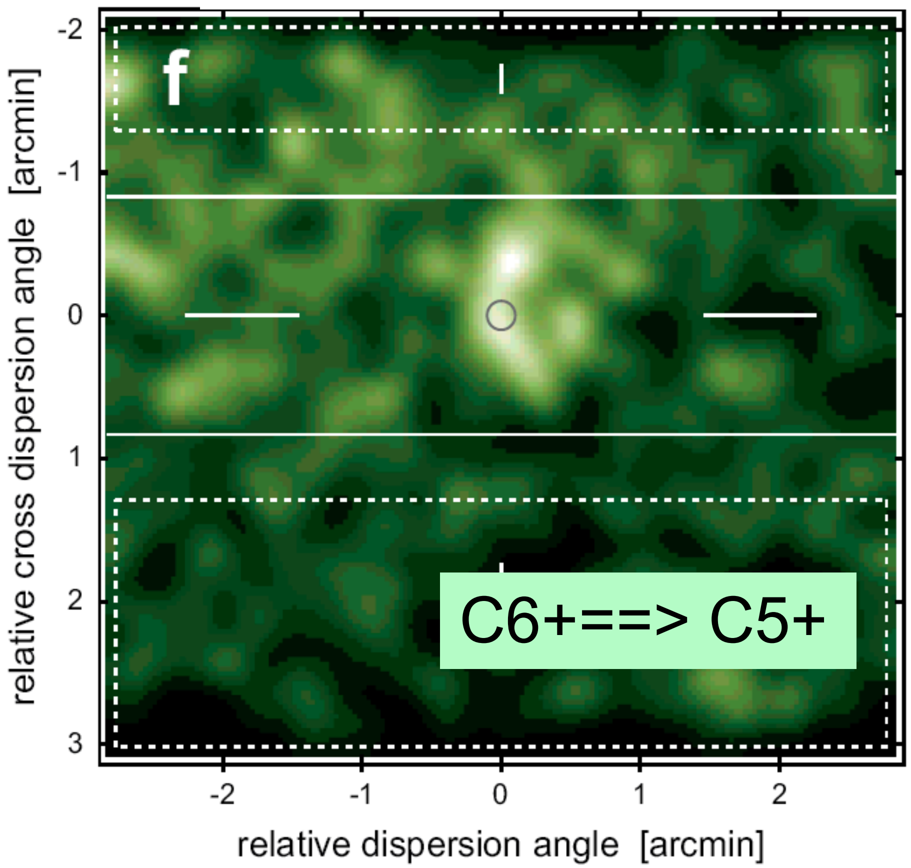


X-ray images are an excellent tracer of the solar wind shock and the magnetic structure of the Mars exosphere-Solar Wind interface

Koutroumpa, Modolo, Lallement, Chanteur, Kharchenko, in prep.

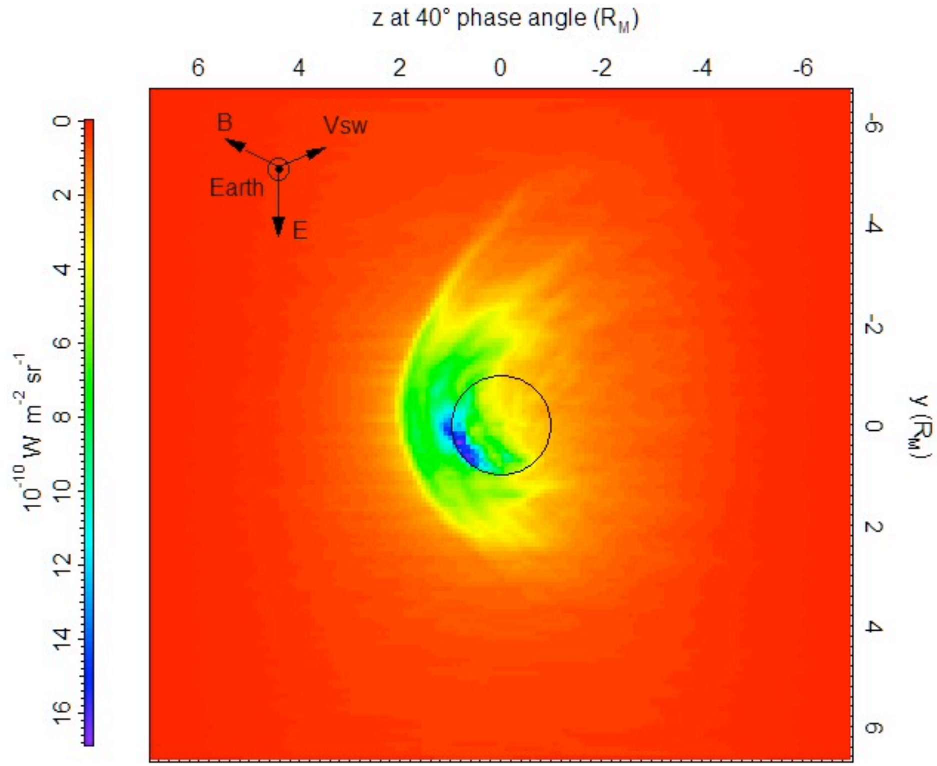

Line RATIOS O7+/ O5+
[q/m]O7+ = 7/16, [q/m]O5+ = 5/16
MARS
Solar Wind
E
B
VSW
y
x
MARS
Solar wind
B
E
VSW
z
x

MARS XMM-NEWTON monochromatic map



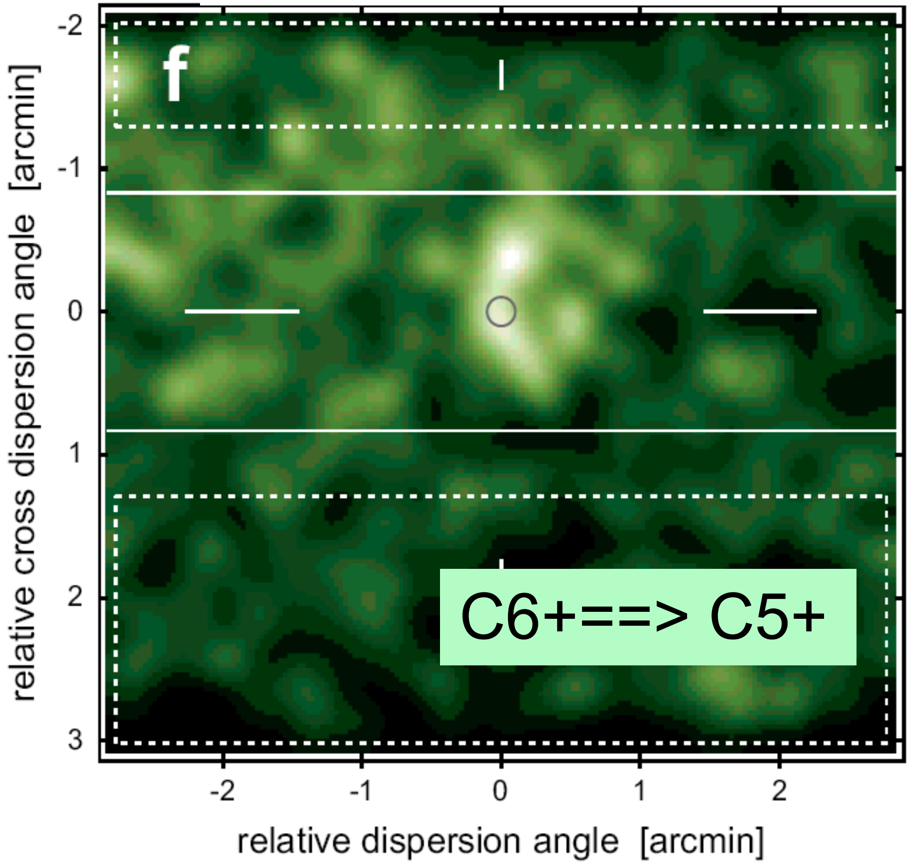
Dennerl et al, 2006, Astron. Astrophys.

Model emission



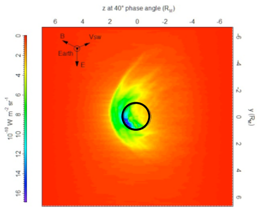
Koutroumpa et al, in prep.

MARS XMM-NEWTON
monochromatic map



Dennerl et al, 2006, Astron. Astrophys.

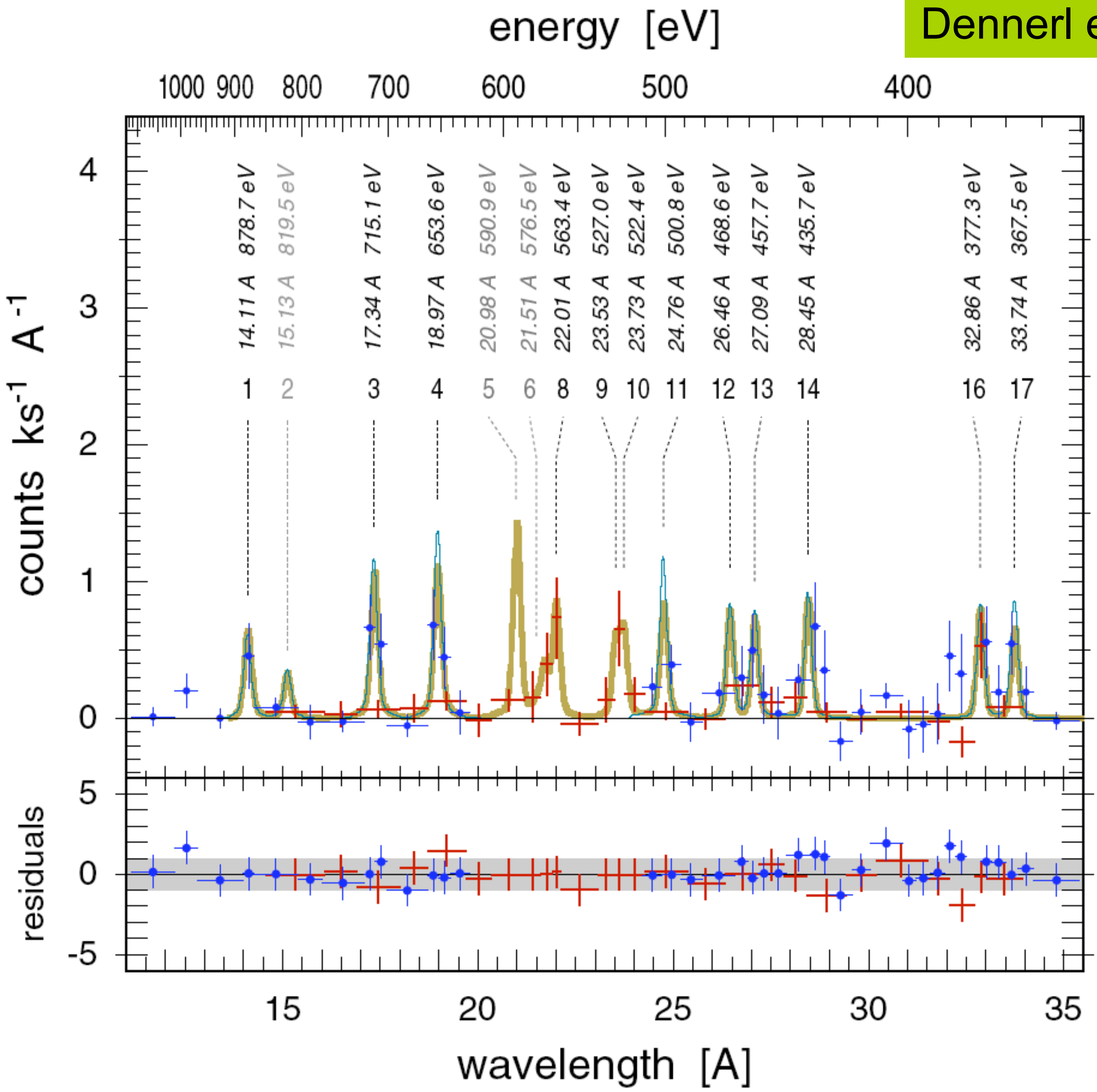
Model emission



Koutroumpa et al, in prep.

PLANET MARS CHARGE-EXCHANGE EMISSION:XMM DATA

Dennerl et al, 2006



The He-like O^{6+} multiplet

2^1P_1 --> 1^1S_0 574.0 eV O6r (resonance)

2^3P_1 --> 1^1S_0 568.5 eV O6i (intercombination)

2^3S_1 --> 1^1S_0 560.9 eV O6f (forbidden)

G= (O6f+06i) / O6r

Mars HALO XMM spectrum
observed ==> **G ≈ 5-6**

computed (Kharchenko 2005) **G= 6.7**

collisional-radiative
hot plasmas **G <1**
(e.g. Smith et al, 2001
Astroph. J)

==> a good spectral diagnostic of charge-transfer

A NUMBER OF MODEL-DATA disagreements:

-unexpected lines: e.g. O^{7+} 4p->1s 0.817 keV (from O8+ neutralisation)

-unexpected morphology

-unexpected differential morpology from one line to the other

Potential explanations?

- role of the velocity field (**via the velocity-dependent cross-section) ?**

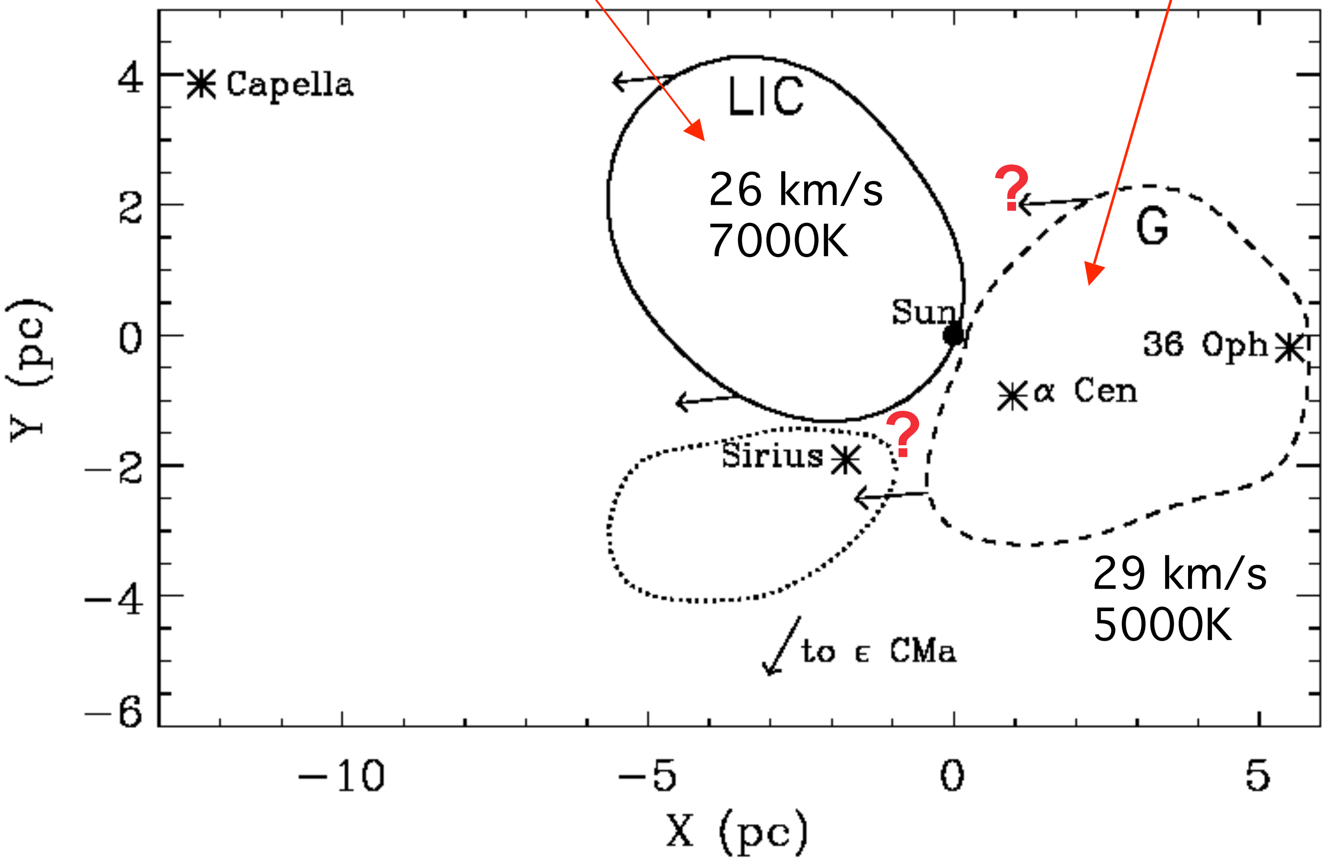
-other effects ? energetic electrons?

-more extended martian exosphere?

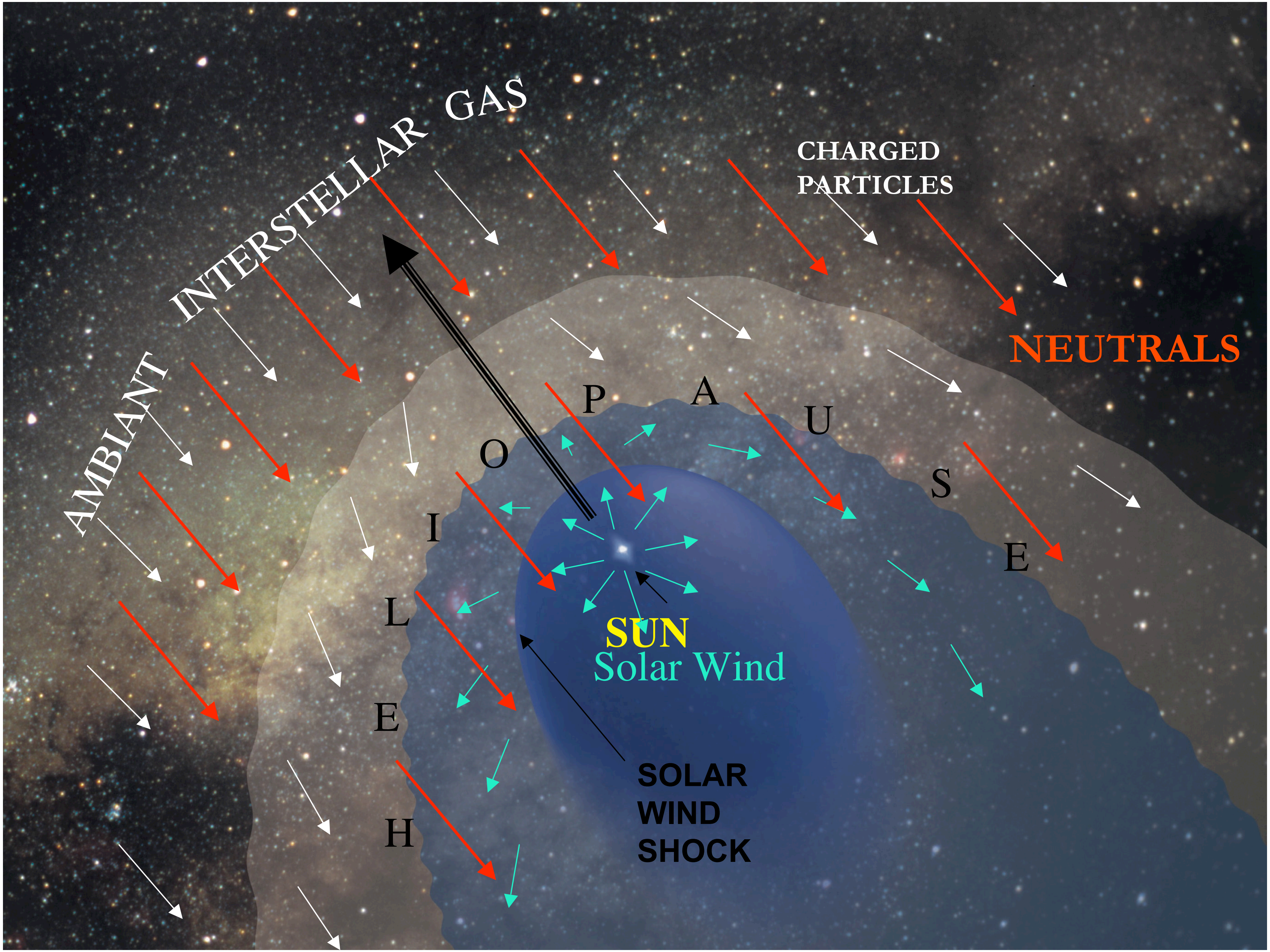
SOLAR WIND IONS and INTERSTELLAR NEUTRALS

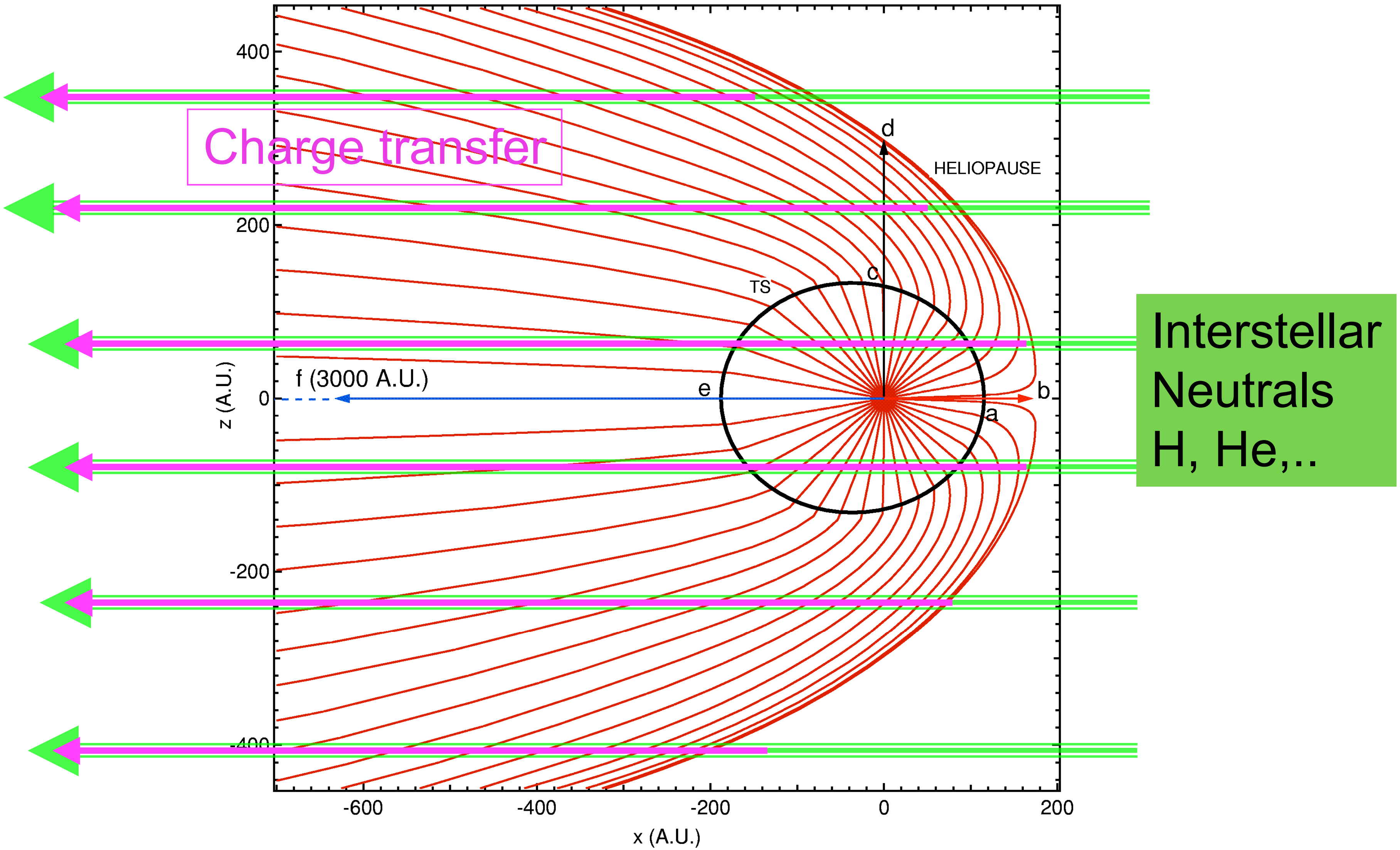
LOCAL INTERSTELLAR CLOUD

FUTURE LOCAL CLOUD



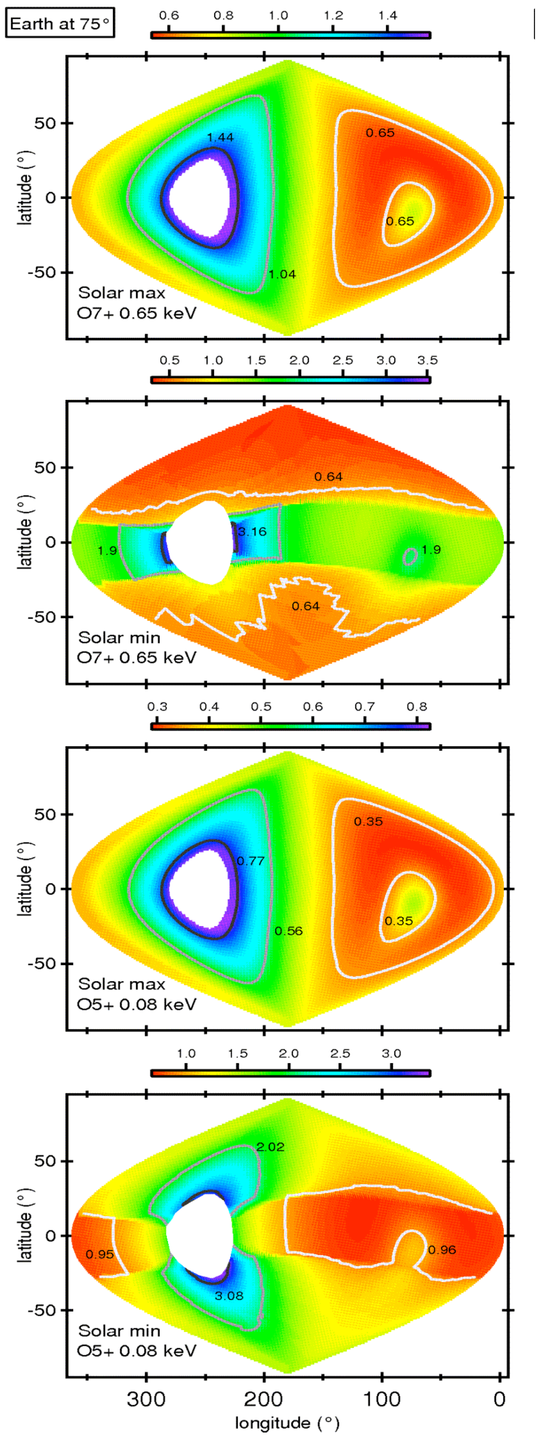
Redfield&Linsky, 2002,2004, Lallement et al, 1995


AMBIANT INTERSTELLAR GAS
CHARGED PARTICLES
NEUTRALS
HELIOPAUSE
SUN
Solar Wind
SOLAR WIND SHOCK



Along a given line-of-sight the contribution to the emission ends:

- either at the heliopause
- in the downwind direction where the particular solar ion has been entirely neutralized



HELIOSPHERIC SOLAR WIND CHARGE TRANSFER X-RAY EMISSION

Neutral H and He distributions

+

Solar Wind density, velocity

Composition,

Charge states

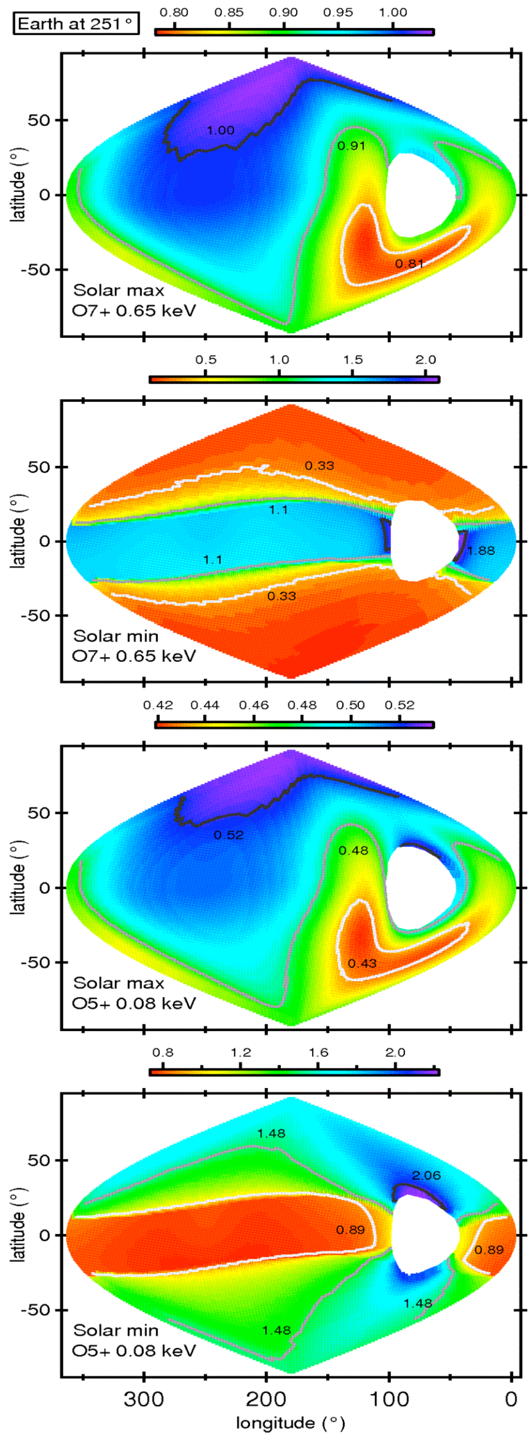
Latitudinal dependence: Fast and Slow wind

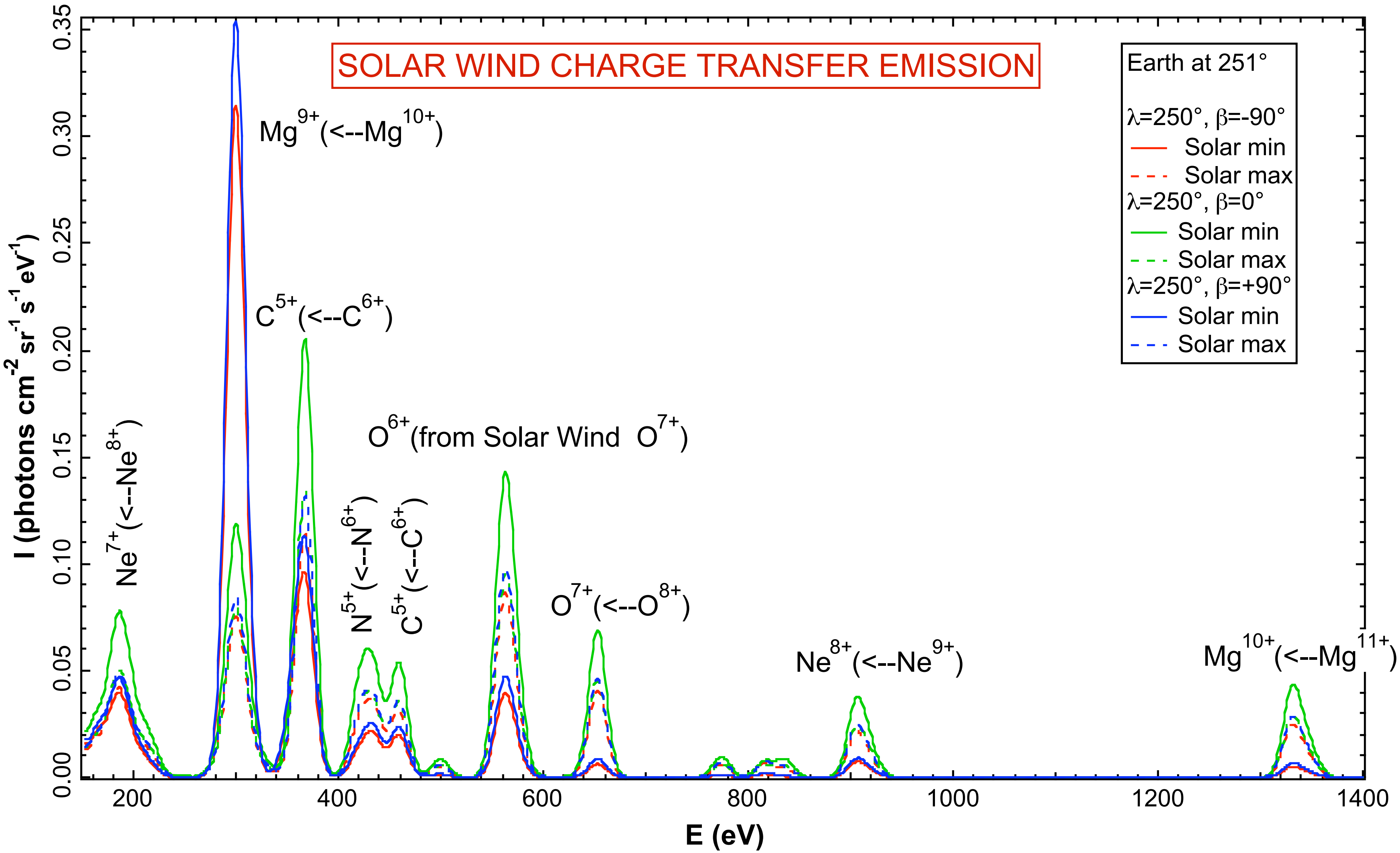
+

Atomic data

Cross-sections

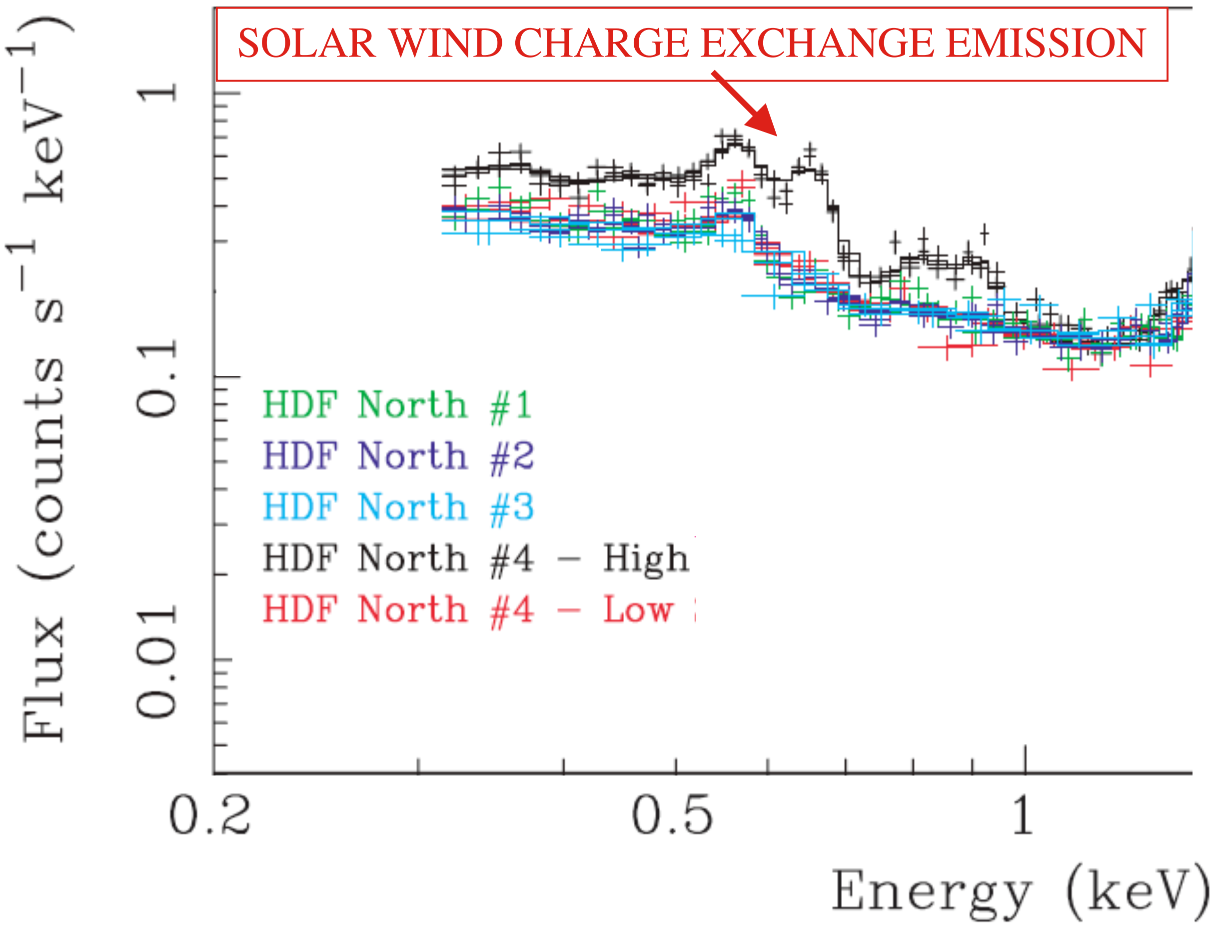
Photon yields





Koutroumpa,Lallement, Kharchenko, Dalgarno, Izmodenov, in press

Hubble Deep Field North: XMM-Newton spectra

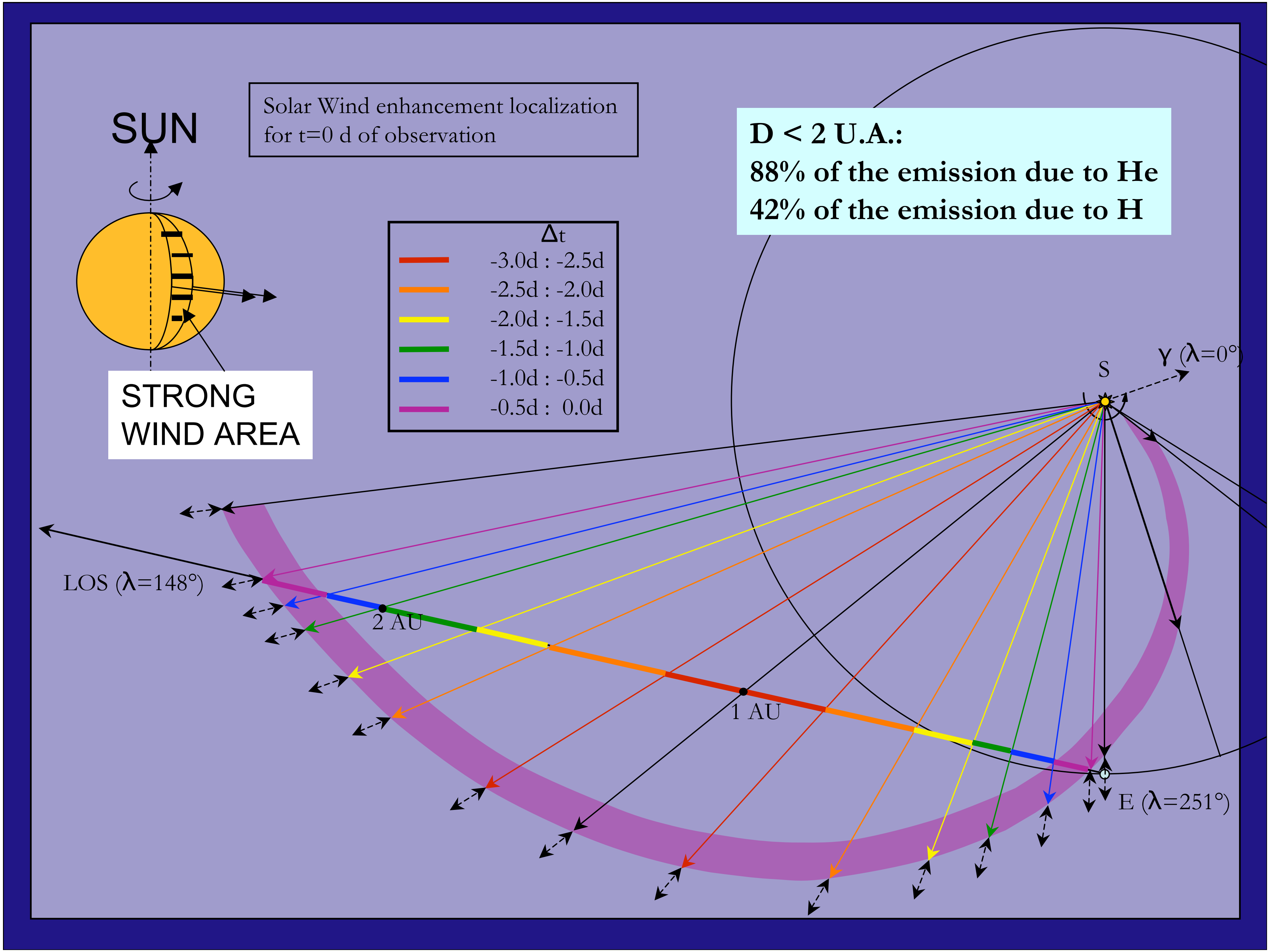


Snowden et al, 2004

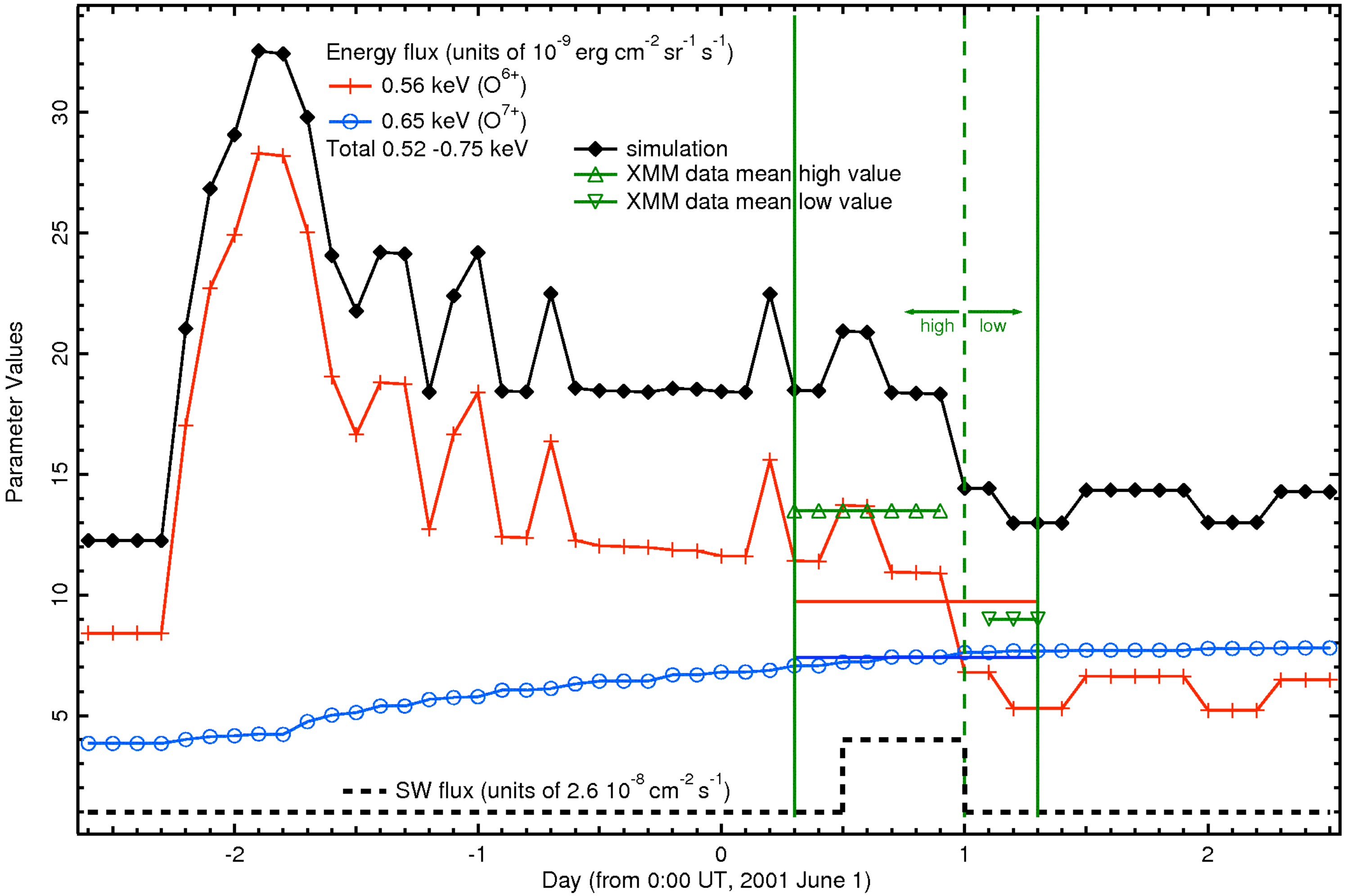
Consecutive exposures towards the same field

- first half of exposure 4 exhibits a very different spectrum (in black)

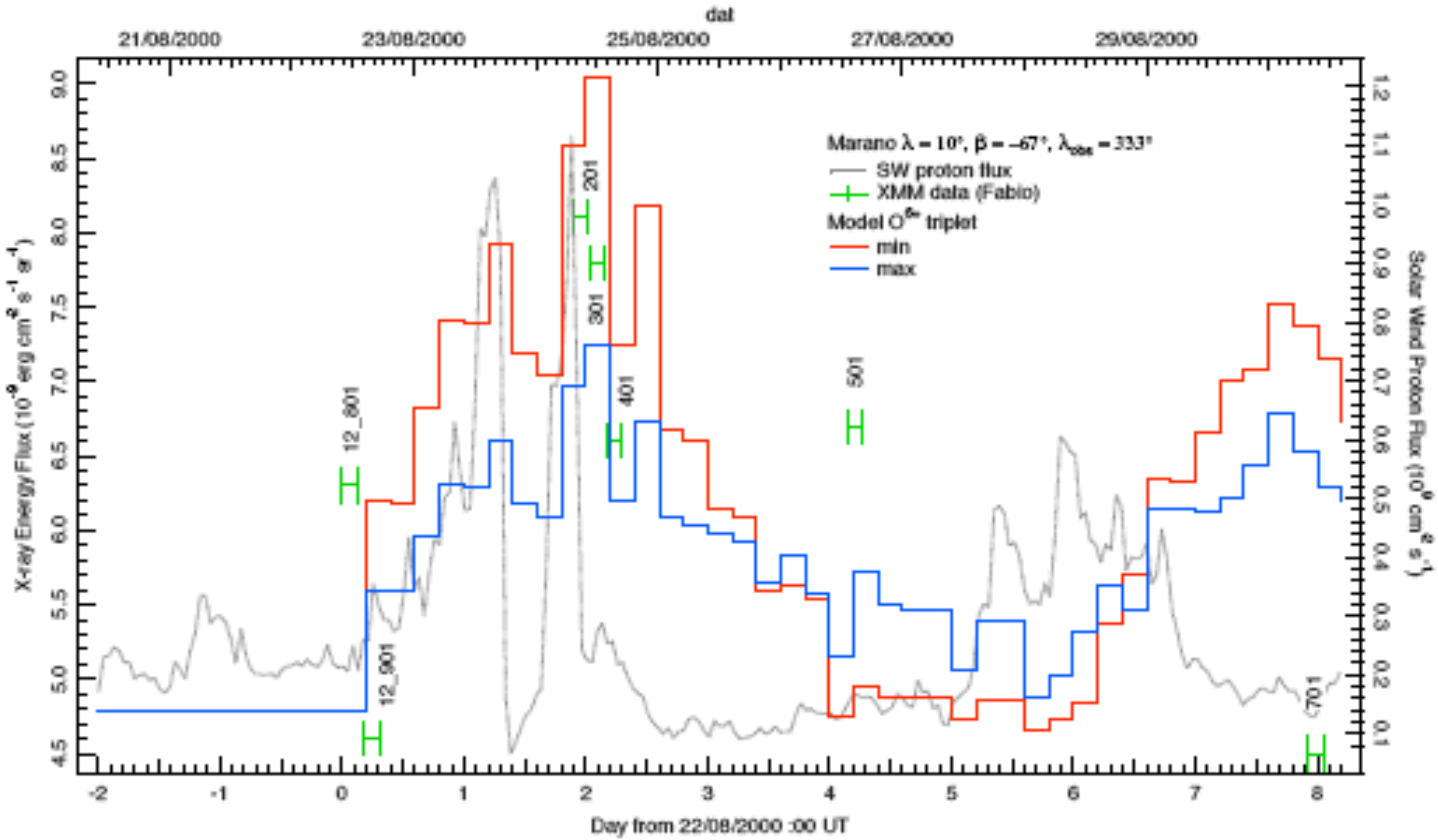
-corresponds to a strong solar wind event



SUN
Solar Wind enhancement localization
for t=0 d of observation
D < 2 U.A.:
88% of the emission due to He
42% of the emission due to H
Δt
-3.0d : -2.5d
-2.5d : -2.0d
-2.0d : -1.5d
-1.5d : -1.0d
-1.0d : -0.5d
-0.5d : 0.0d
STRONG WIND AREA
S
γ (λ=0°)
LOS (λ=148°)
2 AU
1 AU
E (λ=251°)



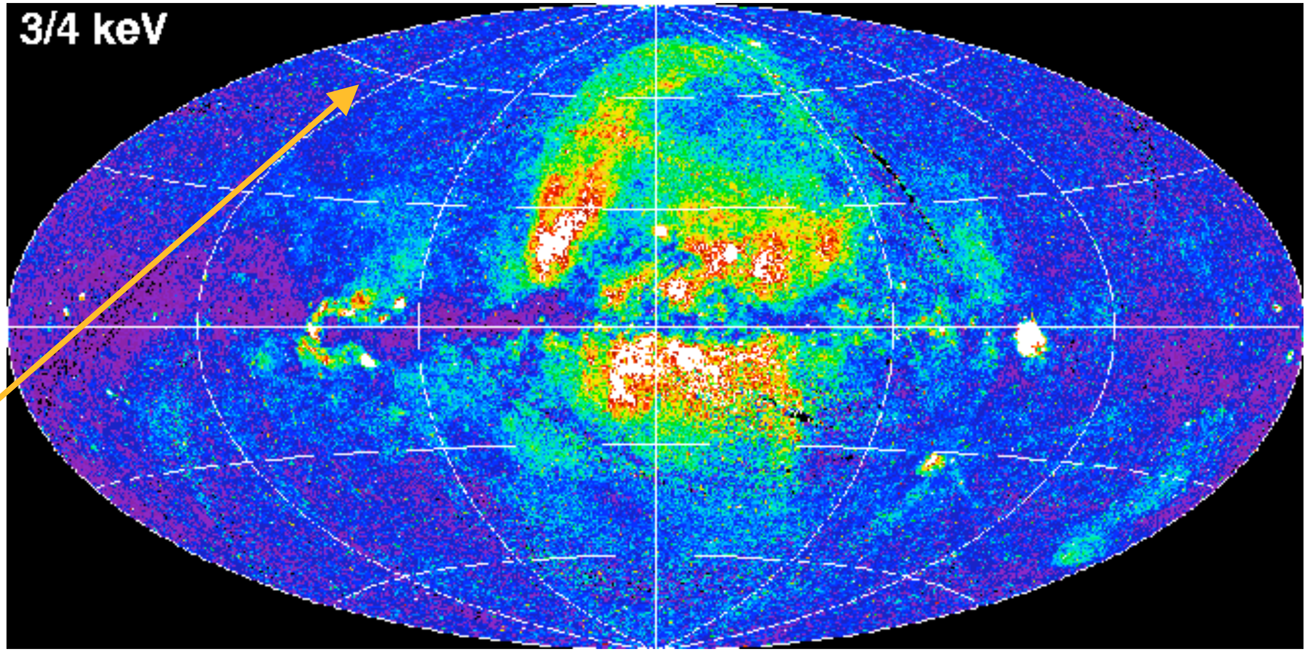
Energy flux (units of 10^-9 erg cm^-2 sr^-1 s^-1)
0.56 keV (O6+)
0.65 keV (O7+)
Total 0.52 -0.75 keV
simulation
XMM data mean high value
XMM data mean low value
high
low
SW flux (units of 2.6 10^-8 cm^-2 s^-1)
Parameter Values
Day (from 0:00 UT, 2001 June 1)
5
10
15
20
25
30
-2
-1
0
1
2



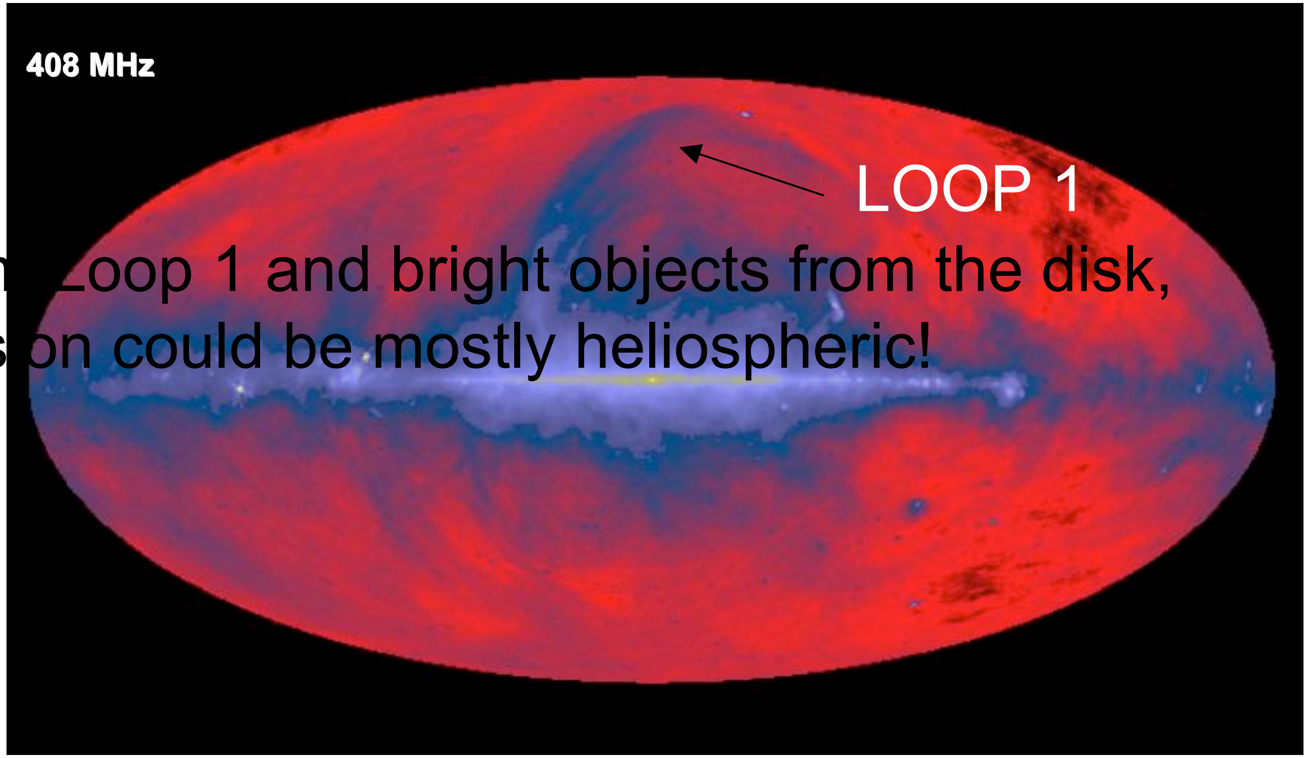
It is possible to reproduce both the intensity level and the relative variations of the signal for the two main O lines

SOFT X-RAYS
ROSAT
0.75keV band

Snowden et al. 1997



Hubble Deep Field North



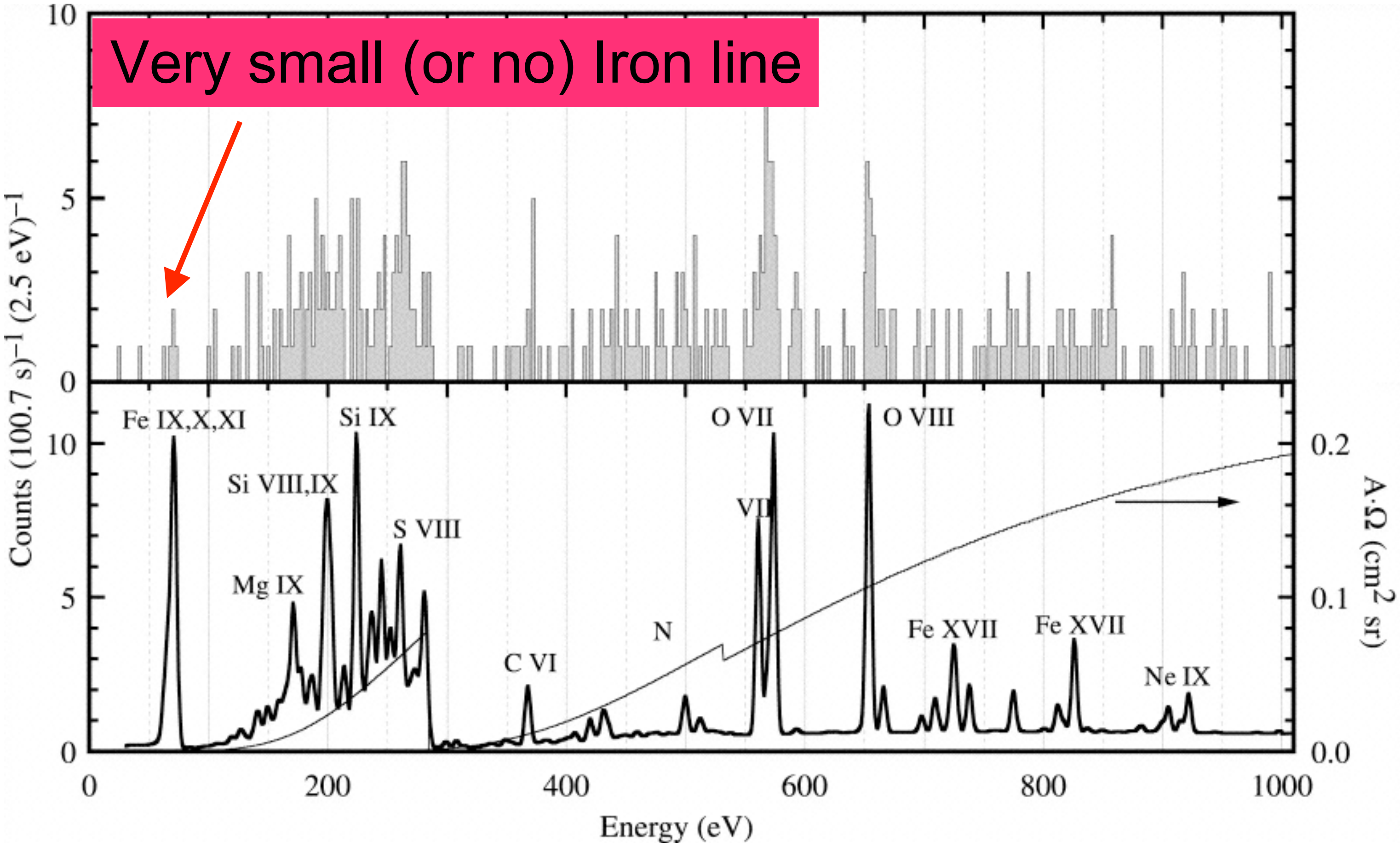
Apart from Loop 1 and bright objects from the disk, the emission could be mostly heliospheric!

RADIO

Haslam et al. 1982

HIGH RESOLUTION SPECTRA OF THE X RAY DIFFUSE BACKGROUND

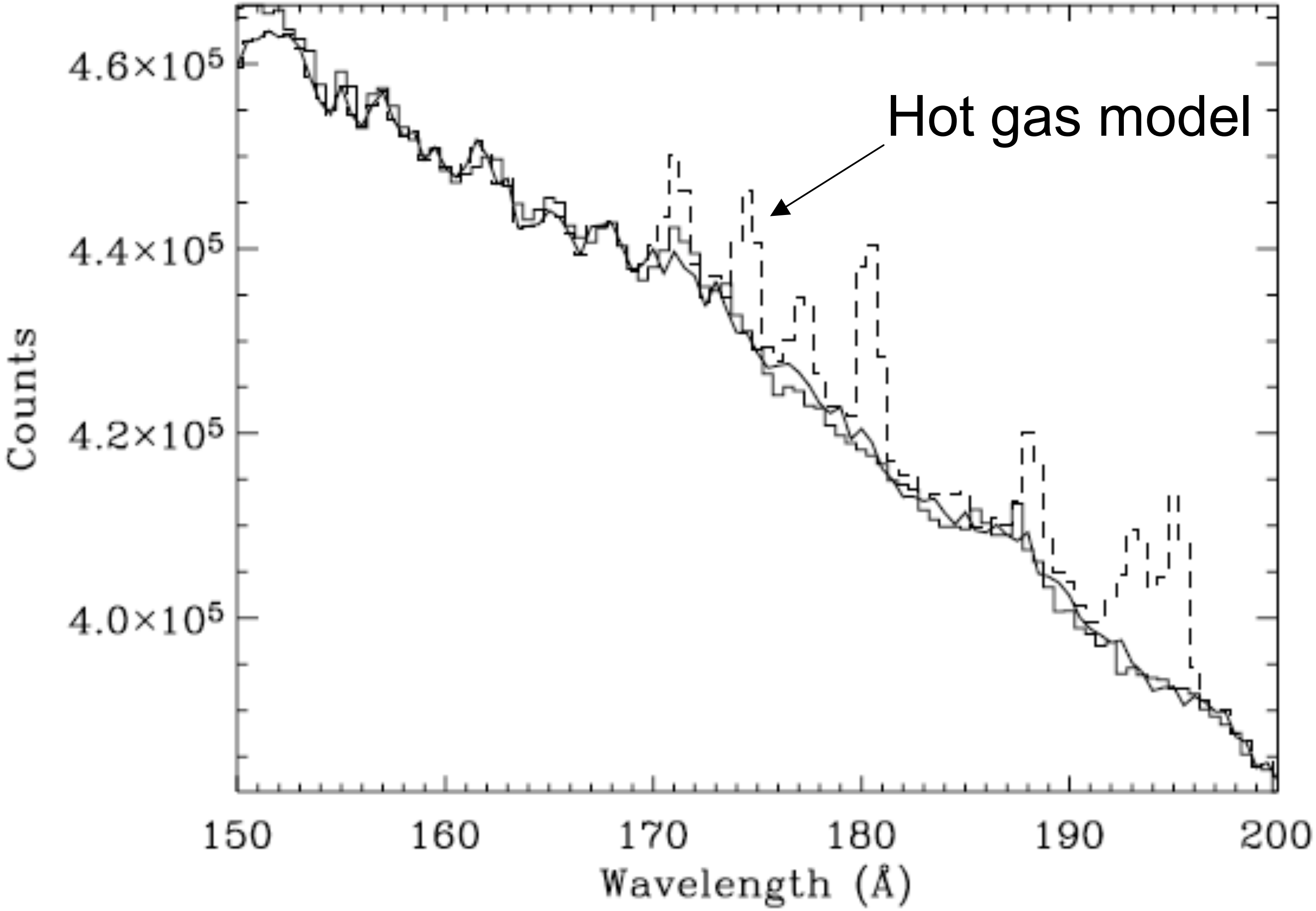
X-ray calorimeter on sounding rocket



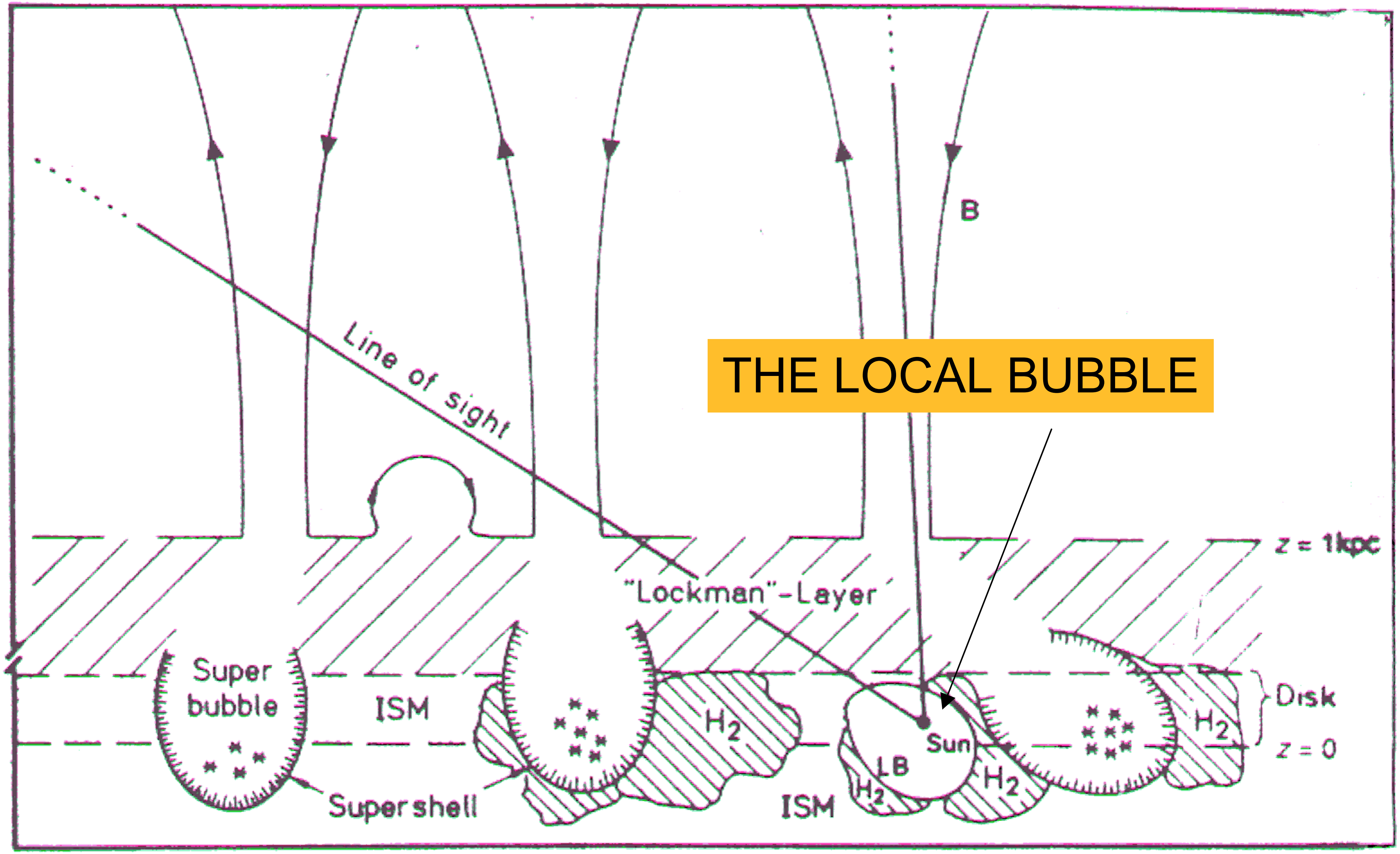
Within a few minutes==> promising tool

McCammon et al (2002) -

EXTREME UV CHIPS RESULTS

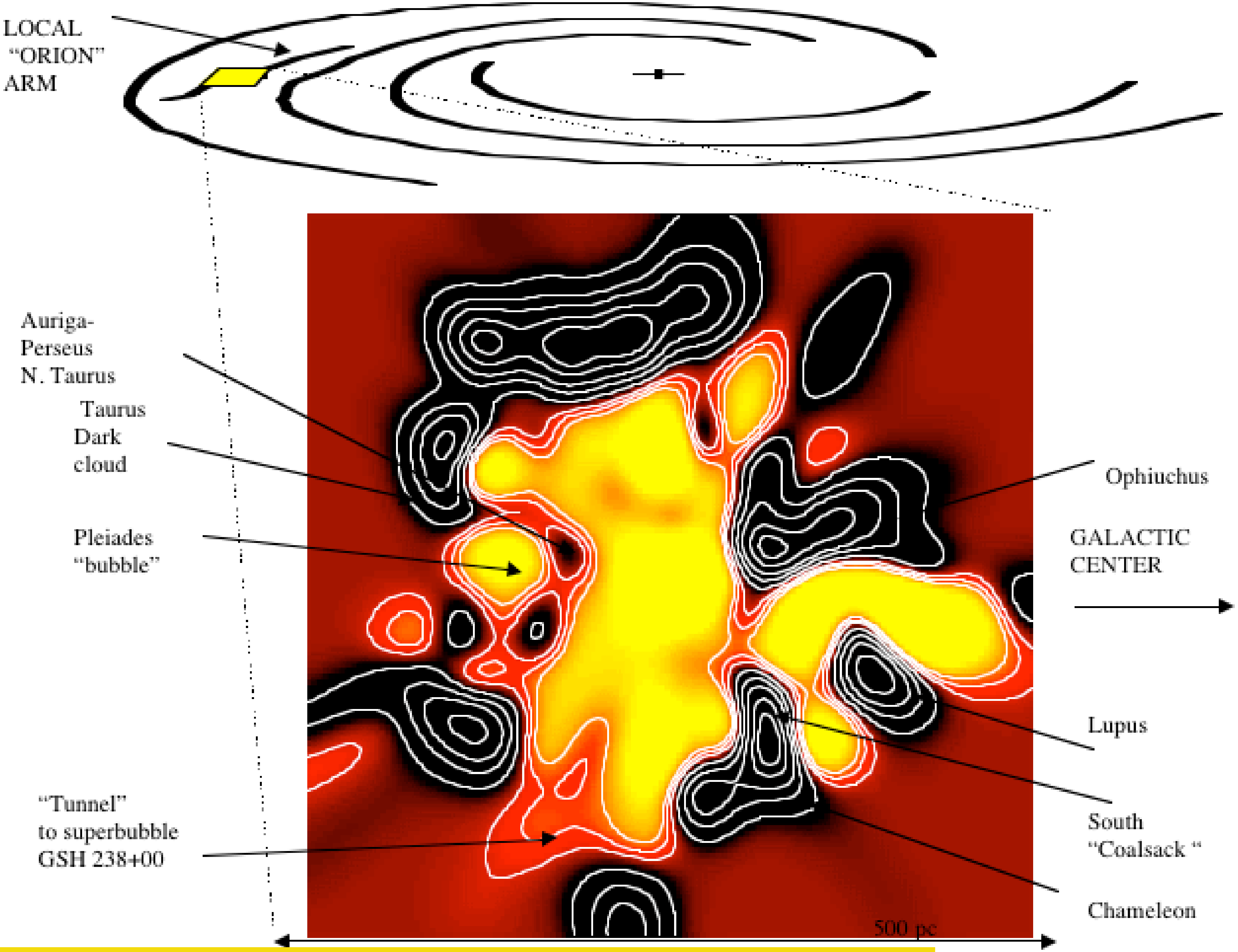


Hurwitz et al, 2005



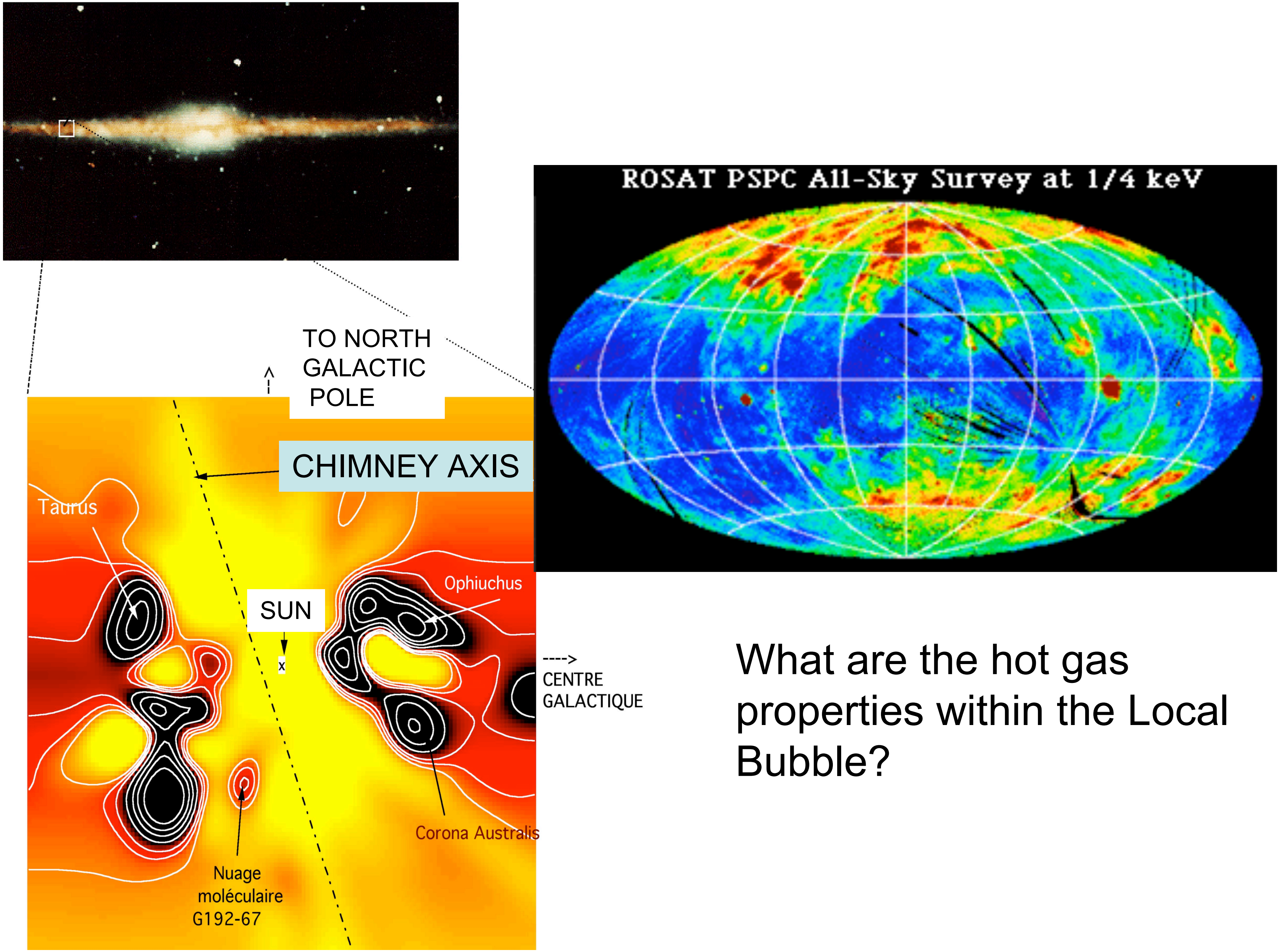
THE LOCAL BUBBLE
B
Line of sight
z = 1kpc
"Lockman"-Layer
Super
bubble
ISM
H2
Sun
LB
H2
H2
H2
Disk
z = 0
Supershell
ISM

THE LOCAL BUBBLE: ABSENCE OF DENSE GAS



Inversion of 1005 lines-of-sight : correlation length 25 pc

Lallement et al, 2003



What are the hot gas properties within the Local Bubble?

From intensity level and intensity variations, we conclude that the main part of the diffuse soft X-ray emission between 0.3 and 1 keV originates in the heliosphere!!

This emission was previously attributed to the X-ray background:
-from the so-called Local Bubble at low energies
-from the galactic halo at higher energies

CAUTION

The heliospheric emission contaminates all X-ray observations of distant objects: -adds lines at zero redshift e.g. O^{6+} and O^{7+} which are often used for temperature diagnostics -should be carefully removed or estimated

Needs:

Accurate **charge-transfer cross-sections**, and **photon yields** for **subsequent cascades**

Influence of **neutral target** ?: H, He (IS) + O (planets), + H_2O, H_2, CO, CO_2,Ne, Ar, (comets) etc……

Influence of **collisional energy**?:

-on **cross-sections**?

-on spectral lines relative **strengths**? (Beiersdorfer et al ,2005)

Influence of Multiple capture and Auger autoionization?

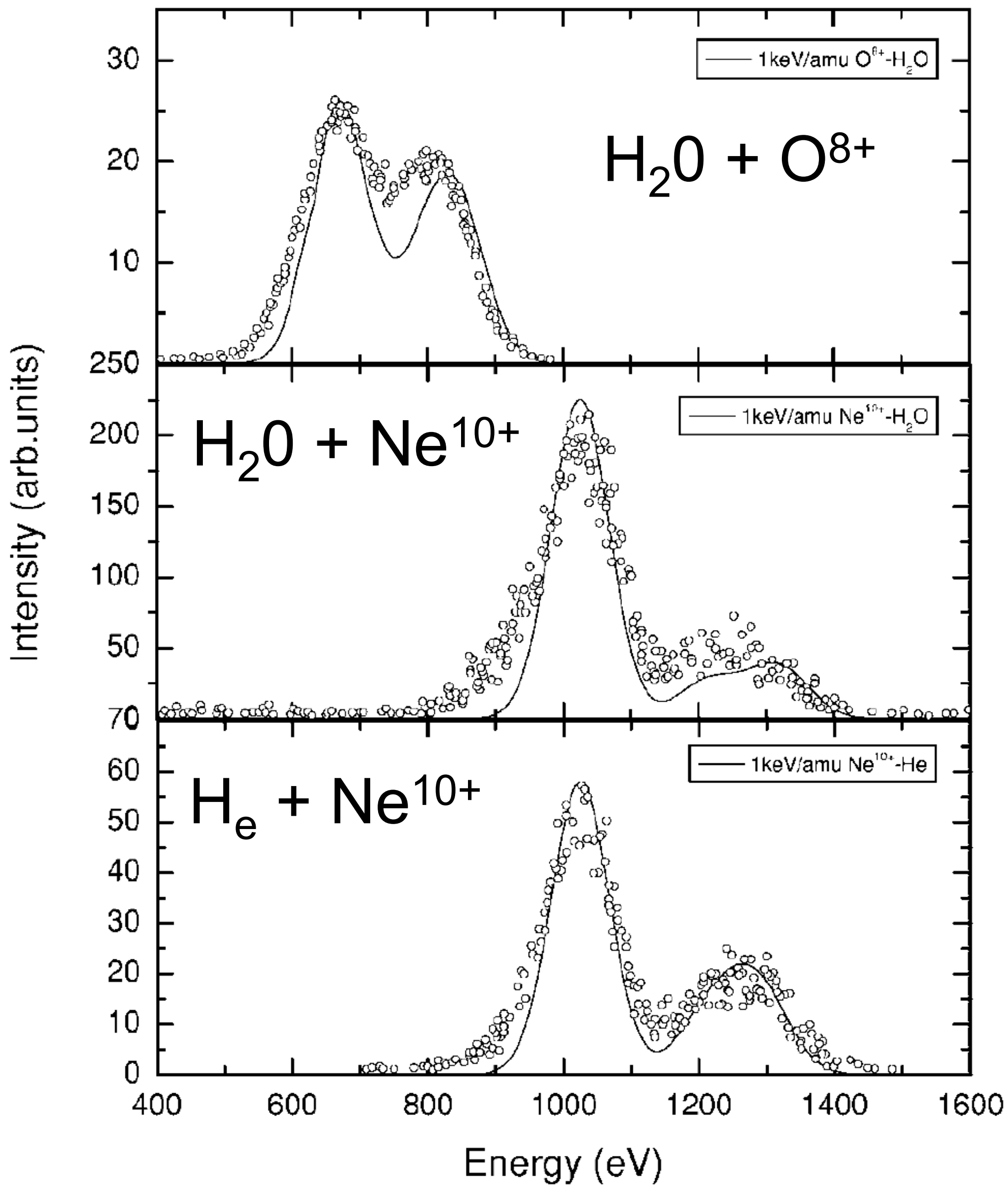
Extension to higher energies : up to 10 MK

WHY?

Increased sensitivity, spatial, and spectral resolution of X-ray satellites (+ New microcalorimeters)

Lines are detected which were not previously resolved

Comparison with high spatial resolution UV data is now possible



Influence of
ion and neutral
species

Otranto et al
Phys Rev A 2006

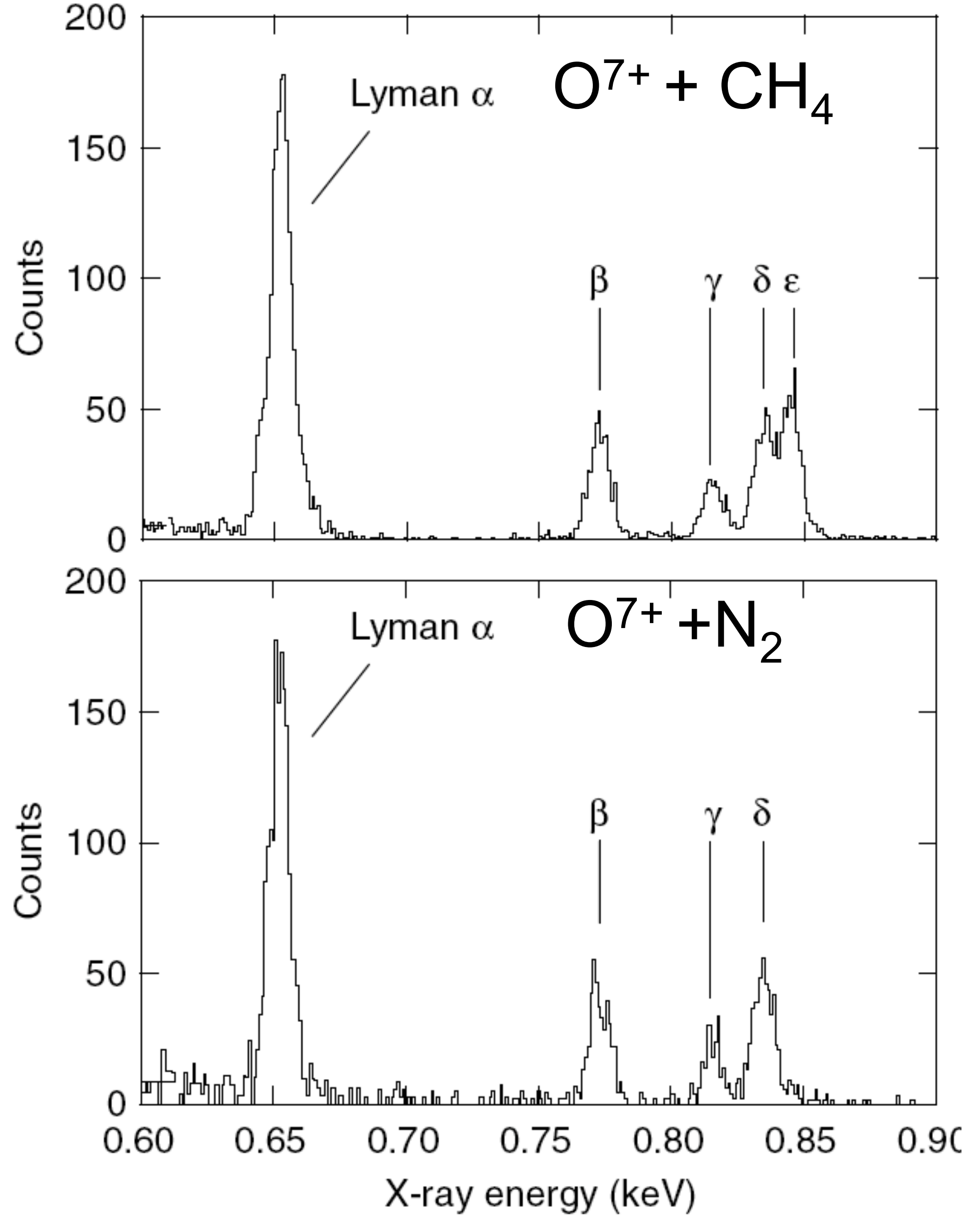


Fig. 2. K-shell emission of H-like O^{7+} produced by charg exchange with CH_4 (top) and N_2 (bottom). Note changes in th ratio of Lyman-δ emanating from $n = 5$ and Lyman-ϵ fror $n = 6$.

Beiersdorfer et al, 2005 NIMB

$O^{8+} + H_2O$

Influence of collisional energy on final state quantum number

0.001keV/amu

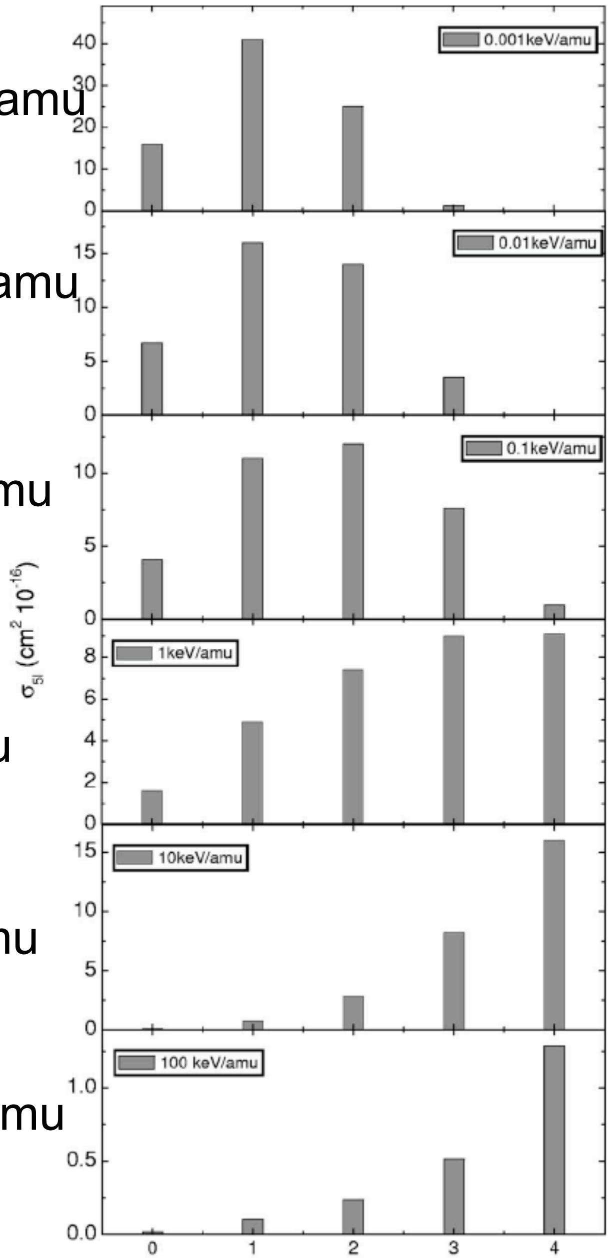
0.01keV/amu

0.1keV/amu

1keV/amu

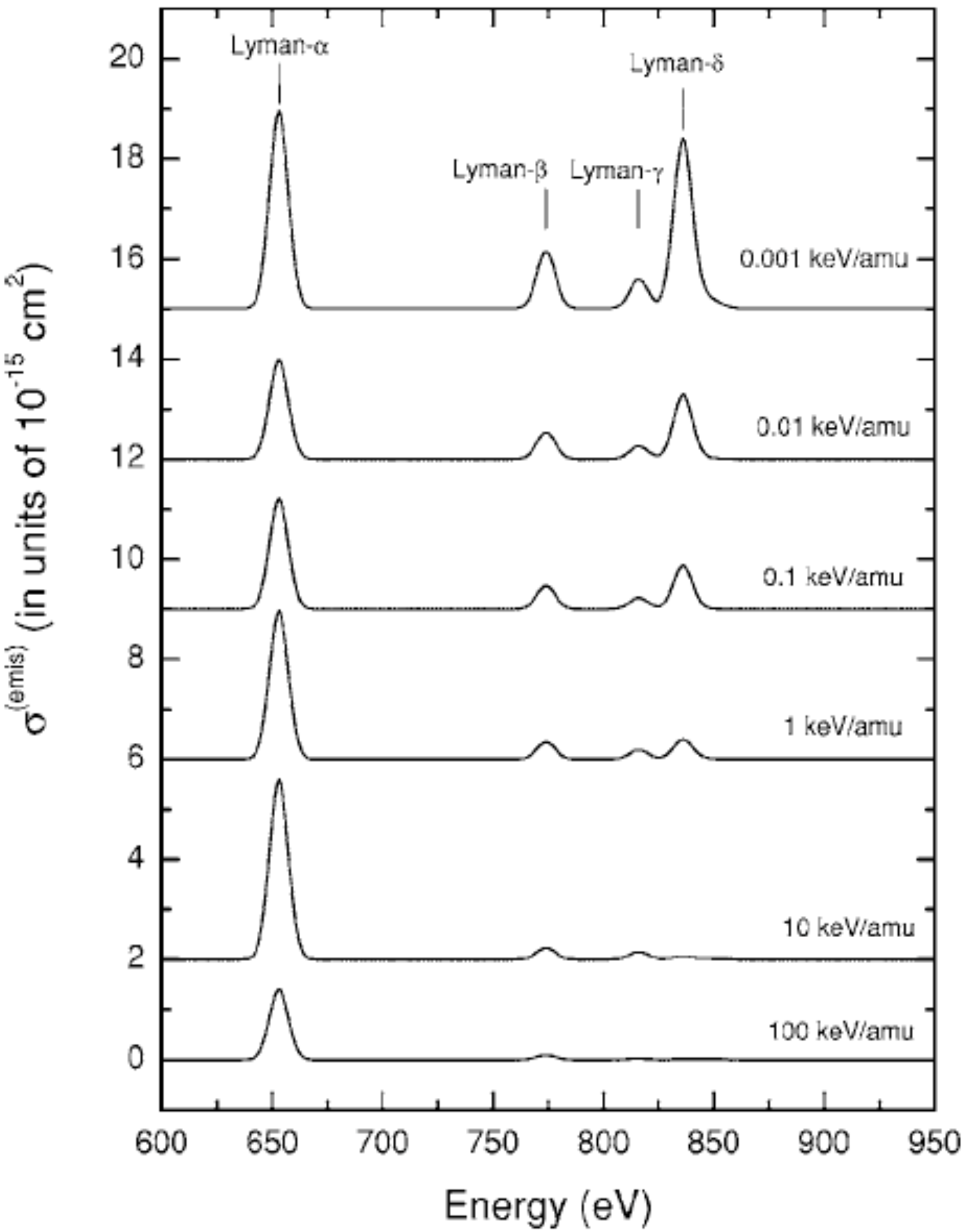
10keV/amu

100keV/amu



final state quantum number

Otranto et al
Phys Rev A
2006



$O^{8+} + H_2O$

Otranto et al
Phys Rev A
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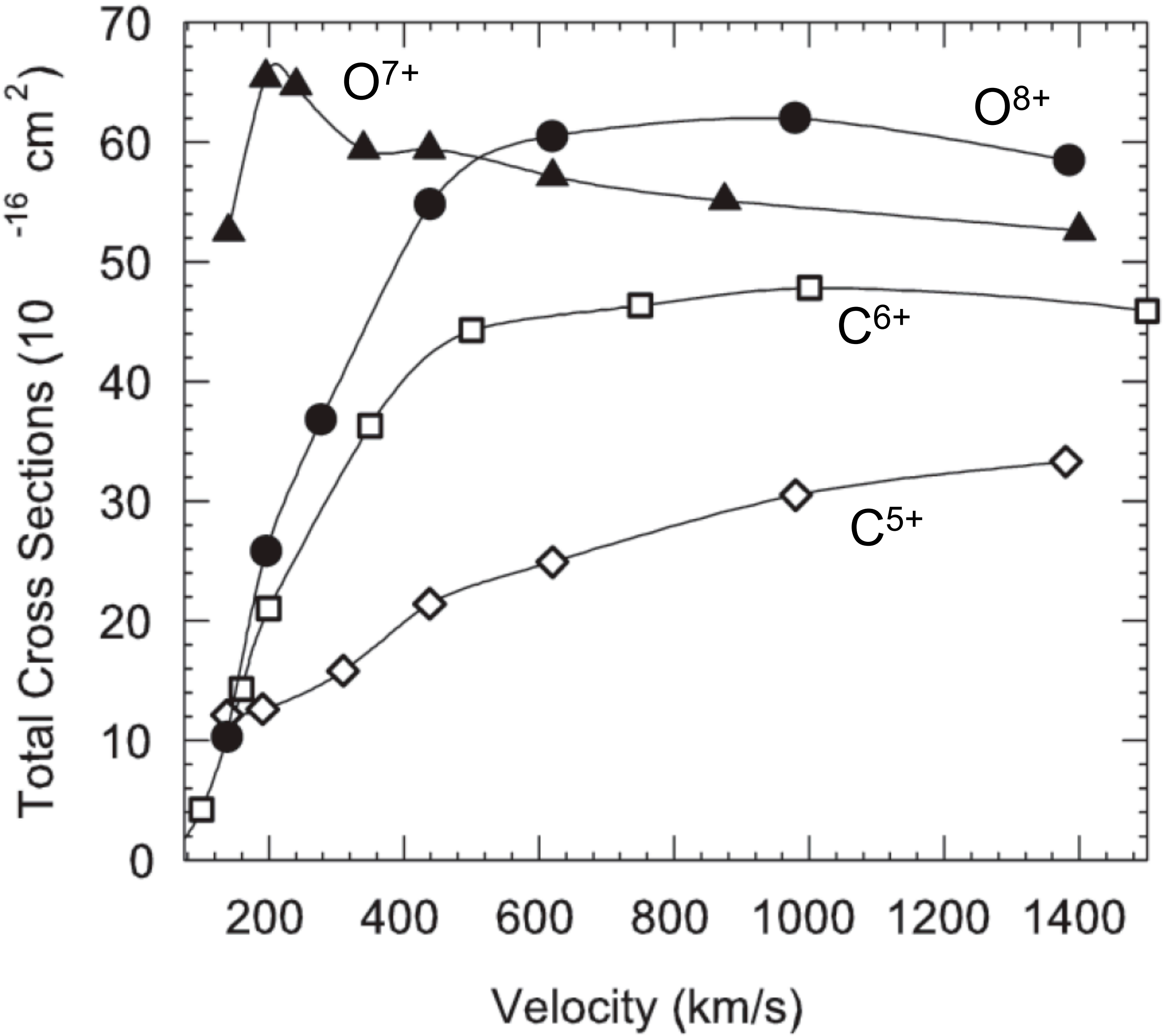
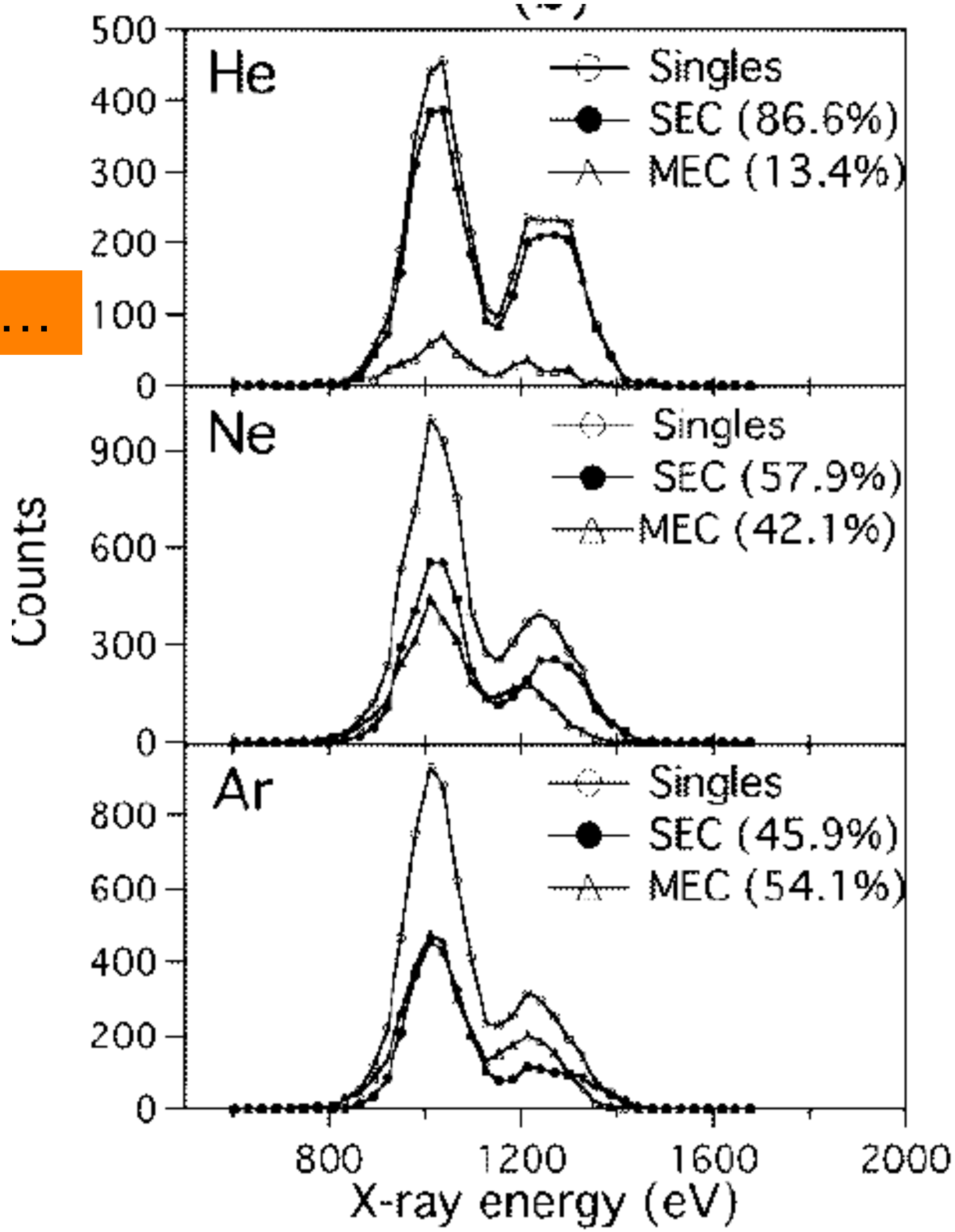


Shipsey et al, 1983, Phys Rev A, Fritsch& Lin, 1984, J. Phys. B

Ne^{10+} +…



Ali et al, 2005, Astroph. J.

Multiple
vs
single
electron
capture

-The soft X-ray surface brightness of solar wind/interstellar neutrals CX diffuse emission generated over 50 A.U. path-length is of the same order than 100 parsecs wide Local Bubble hot gas emission !!!!
==> 5-6 orders of magnitude in volumic emission

A potential role of charge-transfer outside the solar system?

The heliospheric emission is generated :

-because **neutrals do not feel** the plasma-plasma interface

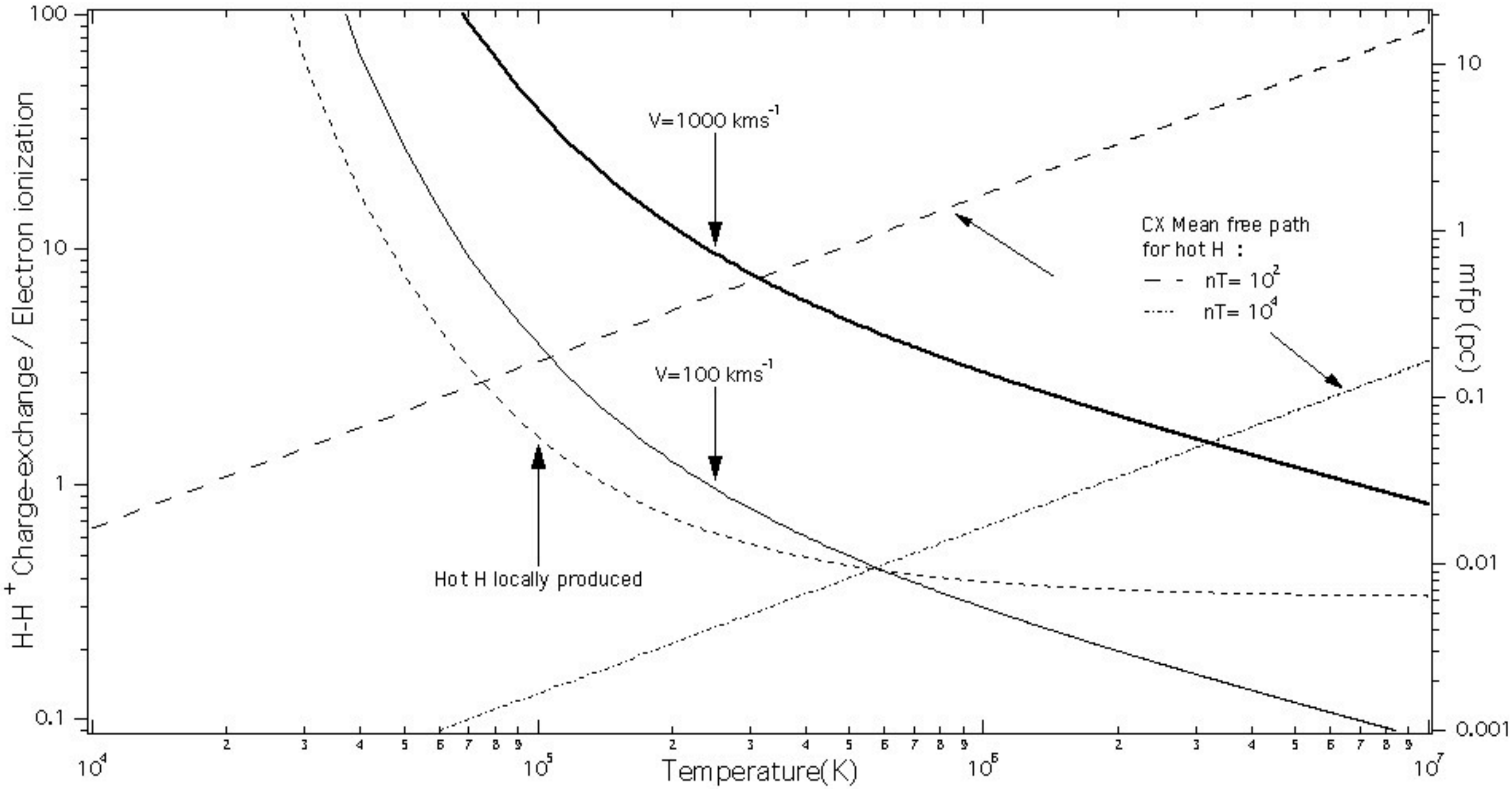
-within the small (x100 A.U.) pathlength of interstellar neutrals through the solar wind

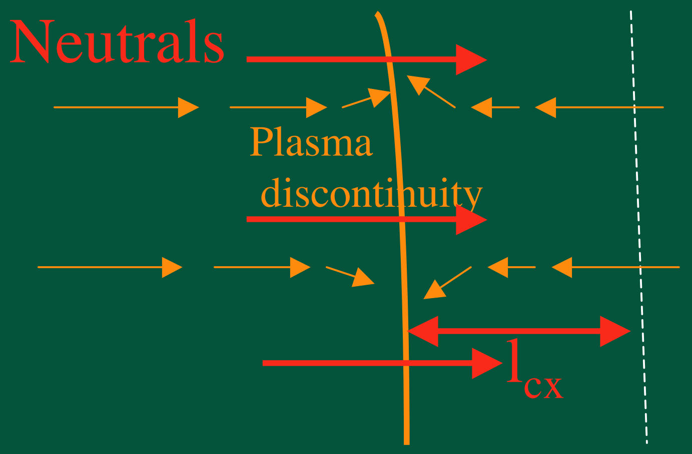
Neutral H atom injected in hot gas:

-charge-transfer with H+

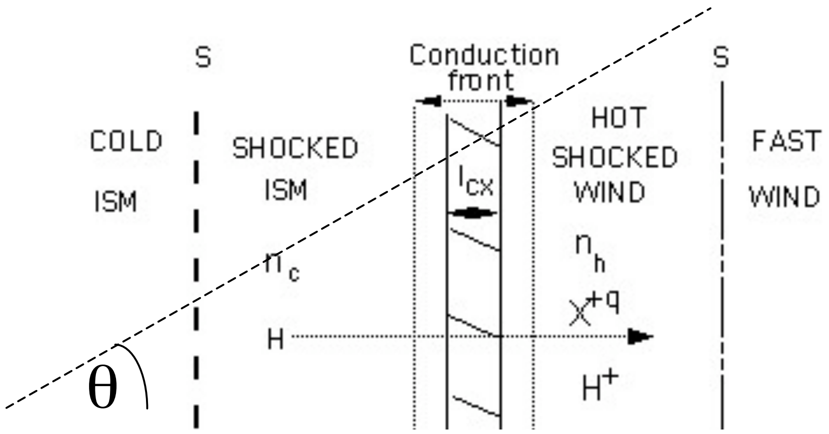
-electron-impact ionization

RATIO of CX / e- ionization





L_{cx} mean free path through the hot gas before collisional ionization



Estimates of the potential emission measure of the narrow neutral penetration layer

EM (cm^{-6} pc)$= 0.06\ n_c\ V_{100}\ (\ \varepsilon\ \ \chi(T, a)^{-1})\ (\cos\theta)^{-1}$

Terms of order unity

The diffuse emission from the narrow layer of thickness lcx (neutral mfp) is equivalent to thermal hot gas emission generated over a pathlength

$L\ (\text{parsec}) = 0.06\ \ n_c\ n_e^{-2}\ V_{100}\ (\ \varepsilon\ \ \chi(T, a)^{-1})\ \ \ (\cos\theta)^{-1}$

Lallement, 2004,A&A

In most cases the CX emission from the narrow interface Is equivalent to thermal emission from extremely large pathlengths through hot gas, thus potentially contributing

A test case: High velocity clouds falling into the halo:

Evidence has have been found by Kerp et al (1999) using ROSAT that they emit soft X-ray with EM = 0.02 cm^{-6} pc

Our crude estimate gives EM = 0.006 cm^{-6} pc for one interface (normal incidence) with V_{100}= 1, n_c= 1 cm^{-3} and n_e= 0.01 cm^{-3}

With new generation X-ray instruments and required atomic data

Spectral diagnostics

-Lower than EIE Lyα/Lyβ, Lyβ/Lyγ, Heα/Heβ, Heβ/Heγ ratios

-Temperature deduced from helium-like triplets largely above the maximum emission for each ion ==> overestimate of temperature

-Anomalous abundances deduced from fits to thermal models

Morphological diagnostics

- Tight spatial correlations with optical (esp. H-alpha broad lines)

- Highly structured emission pattern (tangential LOS)

- Correlations with relative motions of neutral/dense gas wrt hot plasma

Conclusion:

Charge transfer X-ray emission is generated throughout the solar system (comets, planets, interstellar gas)

Heliospheric emission contaminates X-ray spectra

CX emission is potentially important in many astrophysical objects

With the new-generation X-ray satellites, spectral diagnostics will be the clue to a number of unsolved questions

Atomic data are CRUCIALLY needed.

Charge transfer X-ray emission: potential observational tests

Spatial:

- Tight spatial correlations with optical (esp. H-alpha broad lines)
- Highly structured emission pattern (tangential LOS)
- Correlations with relative motions of neutral/dense gas wrt hot plasma

Spectral:

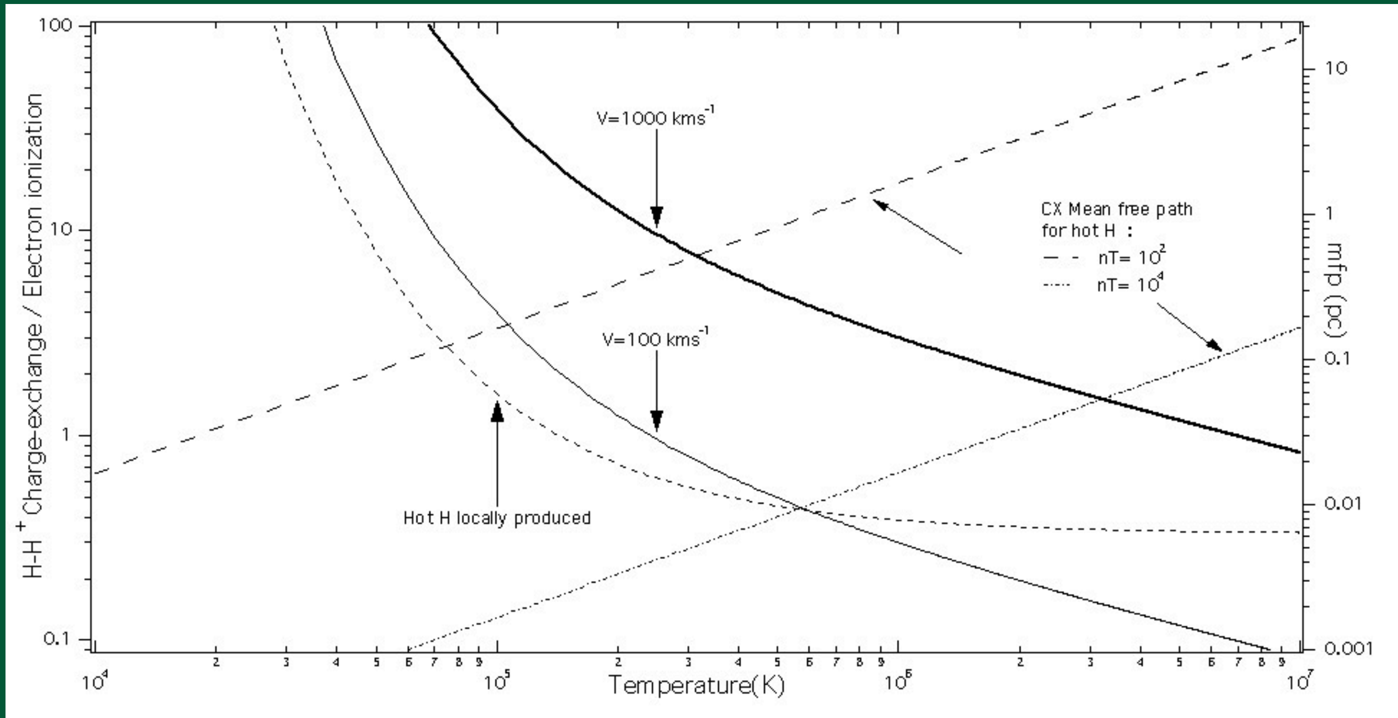
-Lower than EIE Lyα/Lyβ, Lyβ/Lyγ, Heα/Heβ, Heβ/Heγ ratios
-T from helium-like triplets largely above the maximum emission for each ion ==> overestimate of temperature
-Anomalous abundances deduced from fits to thermal models

A renewed interest for charge-transfer (CT) emission:
-Spectra measured by ROSAT, Chandra, XMM
-Laboratory Simulation of Charge Exchange-Produced X-ray Emission
-Theoretical calculations of spectral lines (Kharchenko & Dalgarno, 2000)

- soft X-ray surface brightness of solar wind/interstellar neutrals CX diffuse emission generated over **5 A.U.** path-length is of the same order than **100 pc** wide Local Bubble emission

- surface brigthness from ONLY **10,000 Km** of solar wind/martian exospheric neutrals CT diffuse emission is about **5 times the LHB soft X-ray SB**

Does the charge-transfer emission contribute to the diffuse X-ray emission in other astrophysical cases in the ISM/ICM?



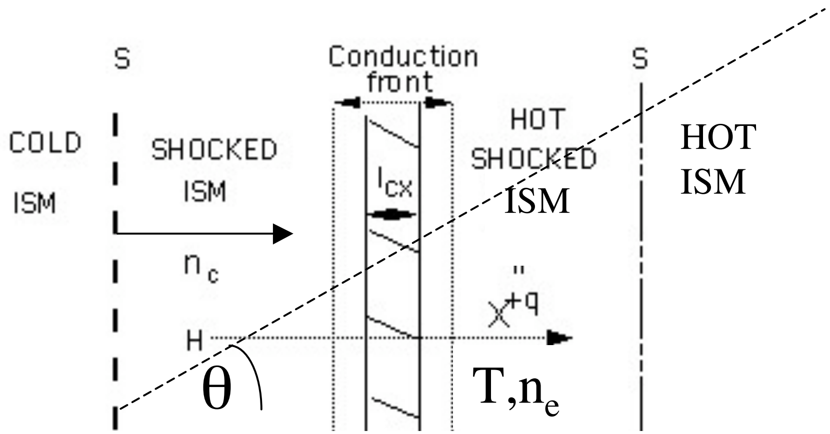
Charge transfer/ electron impact ionization ratio for neutral H atoms entering an isobaric conduction front

A potential test case: High velocity clouds falling into the halo:

Evidence has have been found by Kerp et al (1999) using ROSAT that they emit soft X-ray with EM = 0.02 cm^{-6} pc

Our crude estimate gives EM = 0.006 cm^{-6} pc for one interface (normal incidence) with V_{100}= 1, n_c= 1 cm^{-3} and n_e= 0.01 cm^{-3}

Neutral diffusion and charge-transfer along stationnary or expanding contact discontinuities: dense gas moving wrt hot plasma



Estimates of the potential CT emission from the interface: if n_c is the density of neutrals reaching the discontinuity, the diffuse emission from the narrow layer of thickness lcx (neutral mfp) is equivalent to thermal hot gas emission generated over a pathlength

$$L\ (pc) = 0.06\quad n_c\, n_e^{-2}\, V_{100} \qquad (\varepsilon\ \chi(T, a)^{-1}) \qquad (\cos\theta)^{-1}$$

V_{100} : front velocity or cloud velocity wrt ambient hot gas in units of 100kms^{-1}

$\chi(T, a)$ hot gas thermal emissivity / 1MK gas with solar abundance emissivity(of the order of unity

ε fraction of neutrals experiencing charge transfer before getting collisionally ionized : $\varepsilon= 0.2$

Equivalently: the interface hot gas equivalent emission measure i s

EM (cm^{-6} pc)= $0.06\, n_c\, V_{100}\, (\varepsilon\ \chi(T, a)^{-1})\, (\cos\theta)^{-1}$ EM= 6 10^{-3}

==>for n_c = 1 cm^{-3} , n_c =10^{-3} cm^{-3} , V_{100}=0.5 L= 6kpc and EM= 6 10^{-3} cm^{-6} pc at right incidence

The more tenuous the ambient hot gas, the stronger the potential contribution of a CX interface to the total emission. This is due to the « constancy » of the interface emission, to be compared with the $n_e^2 L_H$ dependence of the electronic excitation emission (L_H hot gas extent)

e.g the equivalent path length L can potentially reach 10^5 pc and the equivalent EM (lines only) reach 0.5 10^{-3} in the case of dense gas with $n_c = 0.1$ cm^{-3} moving in an ICM type hot gas with .$n_e = 10^{-4}$ cm^{-3} .

Conclusion:

Rough estimates of the CT emission show that despite the extremely small size of the emitting volume this process is a potential contributor to the X-ray/EUV emission, i.e. in some favorable cases it could be non negligible with respect to the emission from the hot gas itself,

Multi-fluid (plasma and neutrals) detailed modeling is necessary for each type of interface.

A potential role in galaxy clusters ?

In very tenuous ICM hot gas, hot/cool gas interfaces in moving clouds and mixing layers are potential contributors to the overall emission.
Multi-fluid (MHD,hydrodynamic) models are needed to quantify their contributions.

CX emission is converting into X-rays the potential energy stored in the high ions in narrow layers of ambient hot gas around the dense clouds moving through it.
It may be seen as **localized accelerated cooling once cold gas has started to condense in cluster cores.** In this case **extrapolation back in time of the emission leads to overestimates of the time-integrated cooling**.

CXE spectra differ from EIE ones. Thermal emission interpretations of spectra with CXE contributions may alter temperature and abundances.

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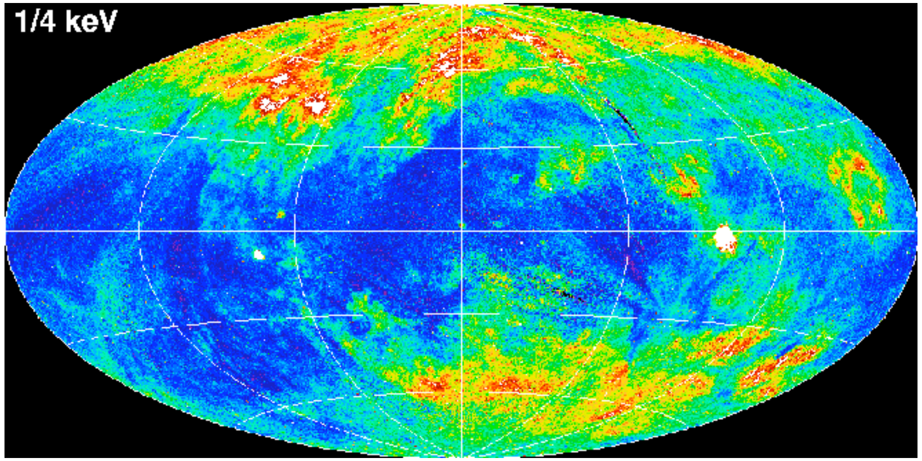
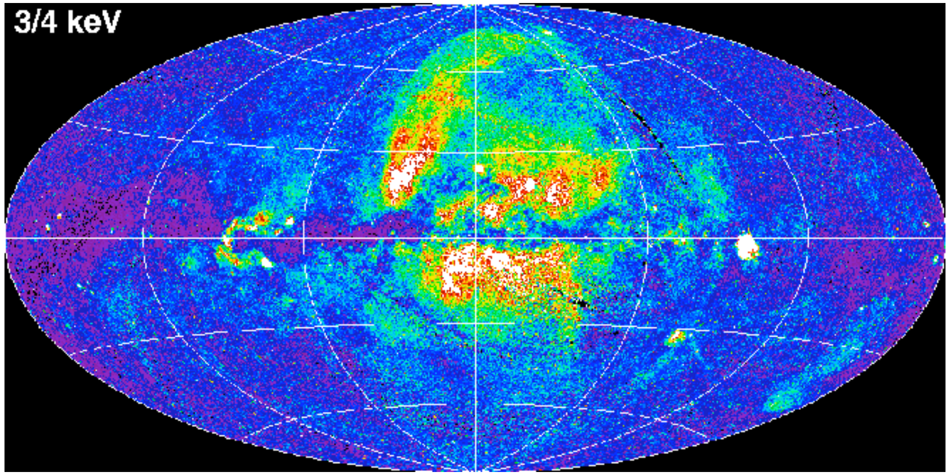
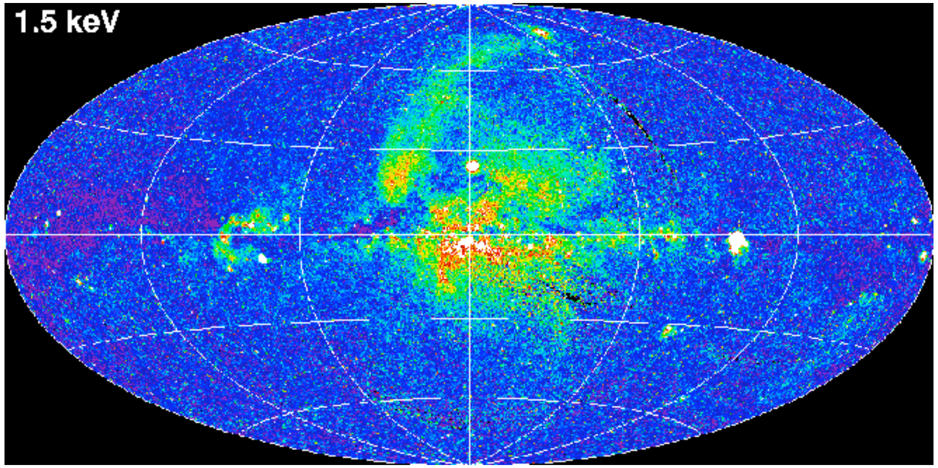
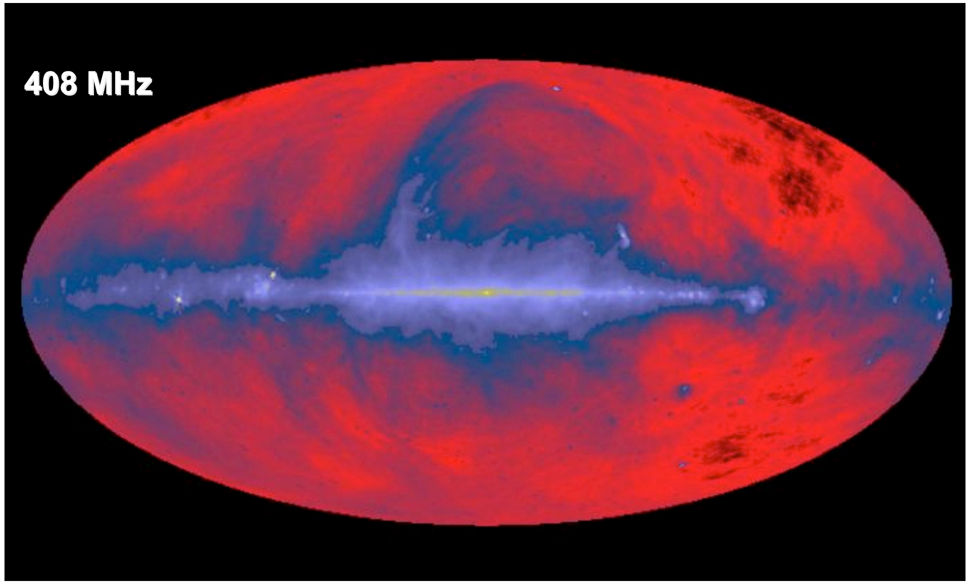


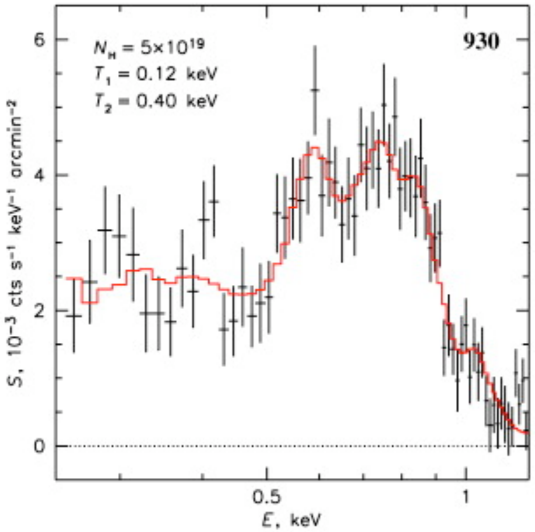


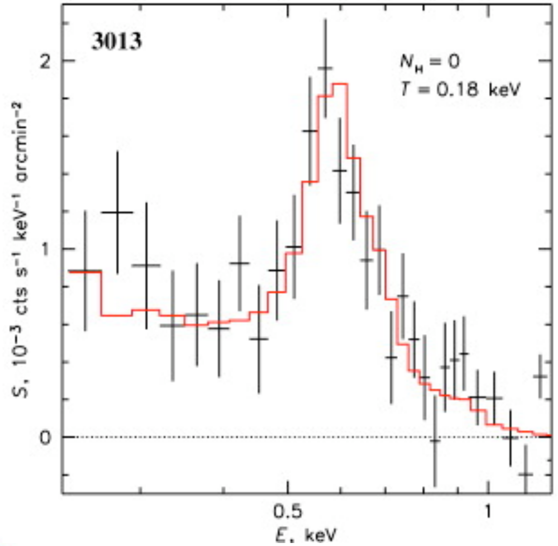




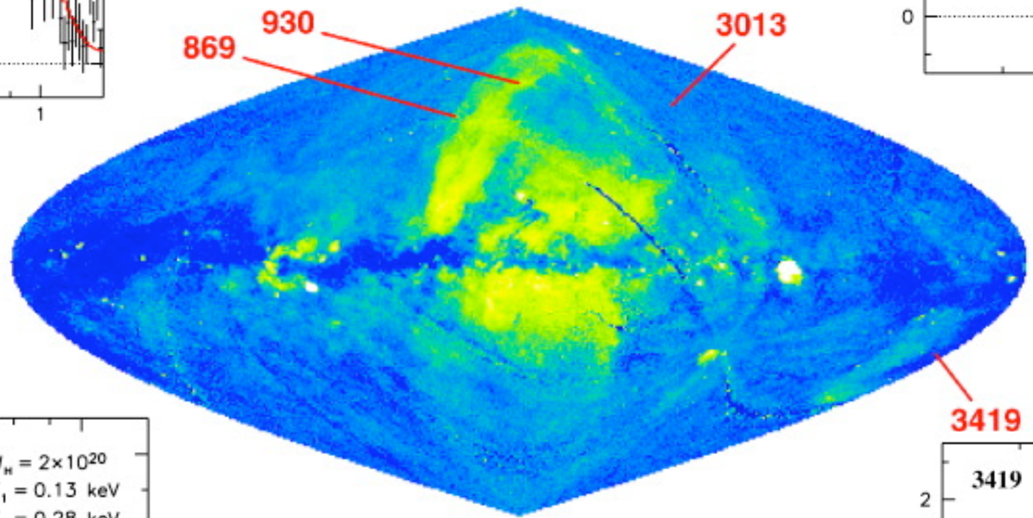
Snowden et al. 1997

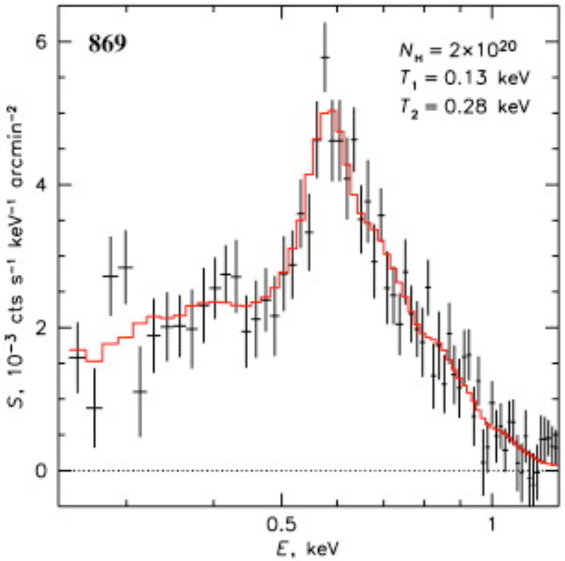
Haslam et al. 1982

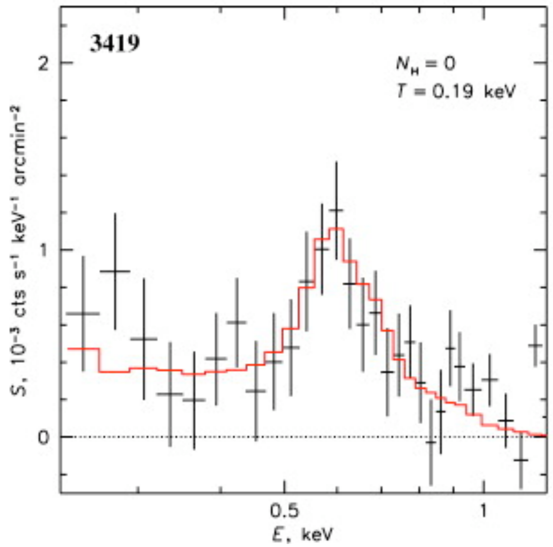




ROSAT map0.75keV



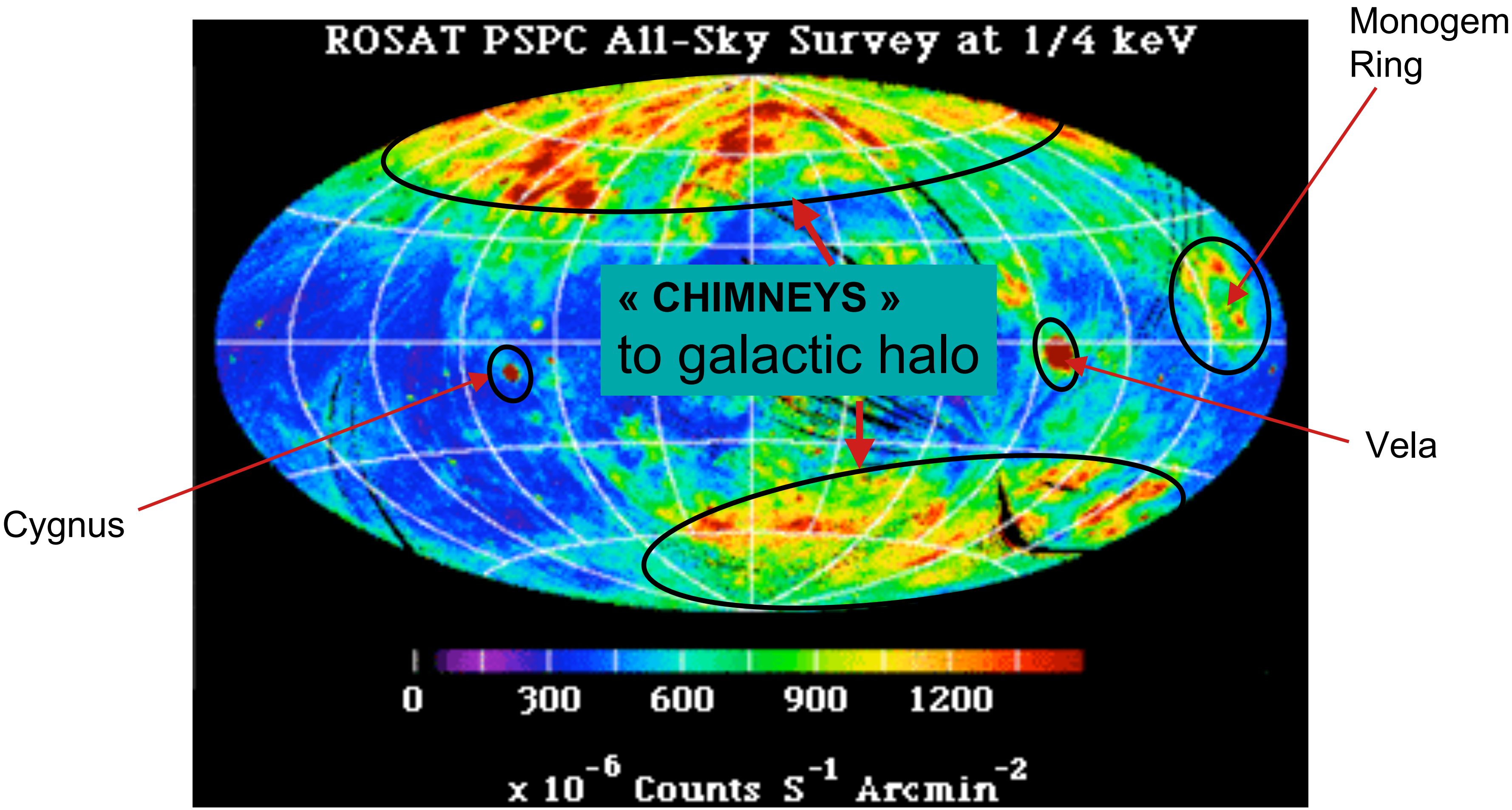




Markevitch et al, 2003

THE 0.25keV BACKGROUND

- ROSAT 0.25keV sky-survey revealed an extensive diffuse emission signal: (Snowden et al 1998).



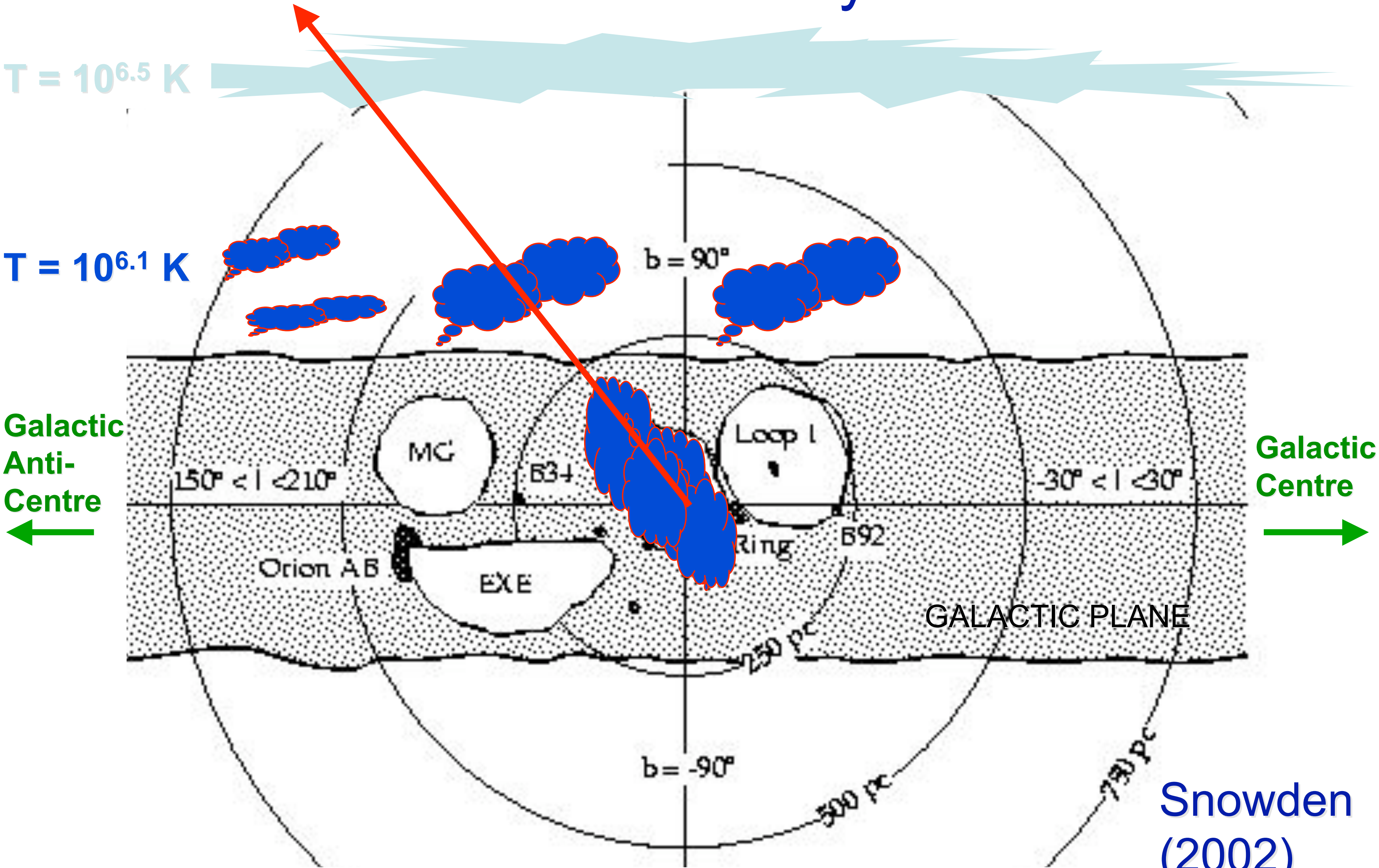
- The Local Bubble: A cavity surrounding the Sun, devoid of dense, cold gas(size: boundary at 40 to 250 pc according to direction)

- Its existence has been inferred from the soft X-ray background emission
- discovered and mapped by ROSAT (Snowden et al, 1997,1998, ApJ)

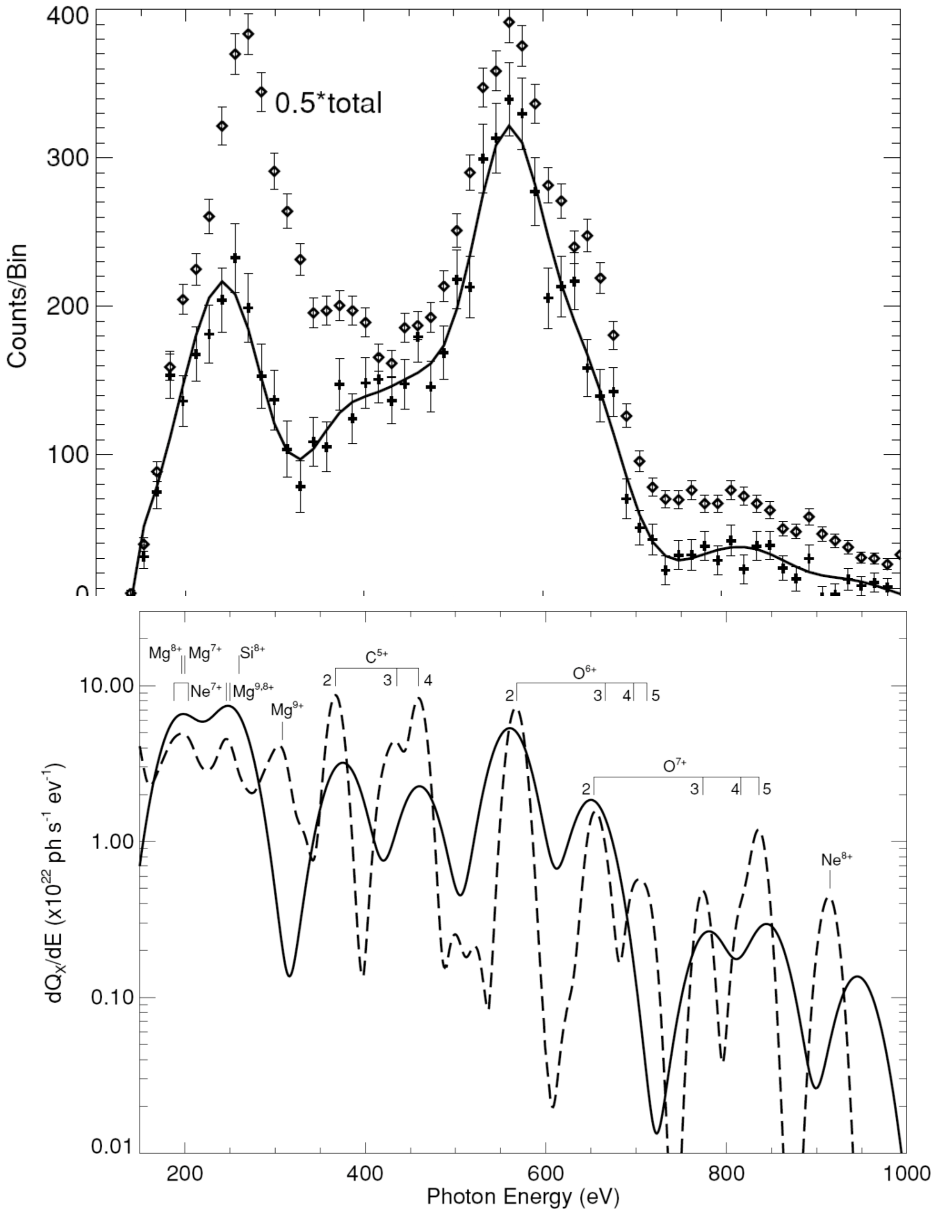
- Band ratios imply T=10^6 K

- Probably carved in the local galactic disk by a series of supernovae

Distribution of ~ 10^6 K Plasma in the Local Galaxy



Snowden (2002)



Counts/Bin
0.5*total
Mg8+ Mg7+ Si8+
Ne7+ Mg9,8+
Mg9+
C5+
O6+
O7+
Ne8+
dQX/dE (x10^22 ph s-1 ev-1)
Photon Energy (eV)