Imaging of planetary magnetospheres using Solar Wind Charge Exchange X-rays:

Potential Applications on Mercury's Bepi Colombo mission

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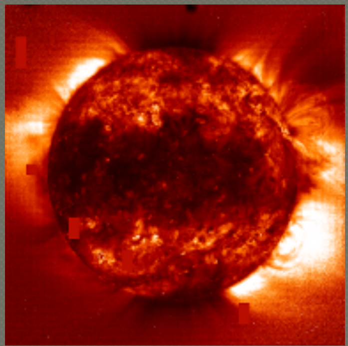
Magnétosphères planétaires comparées
Meudon, 4-6/2/2015

Charge eXchange (CX) X-ray emission mechanism



Highly charged ions from the 1MK solar corona:
Solar Wind Charge eXchange – SWCX

e.g. O^{+8} → $O^{+7\,*}$ → O^{+7}

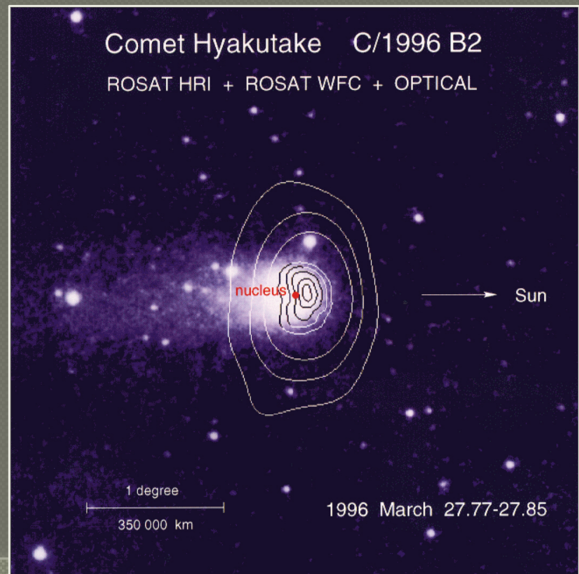
e^-

Radiative cascade
Energies < 1.5 keV

Atom or Molecule:
(e.g., IS, cometary Or exospheric)

e.g. H, He → H^+, He^+

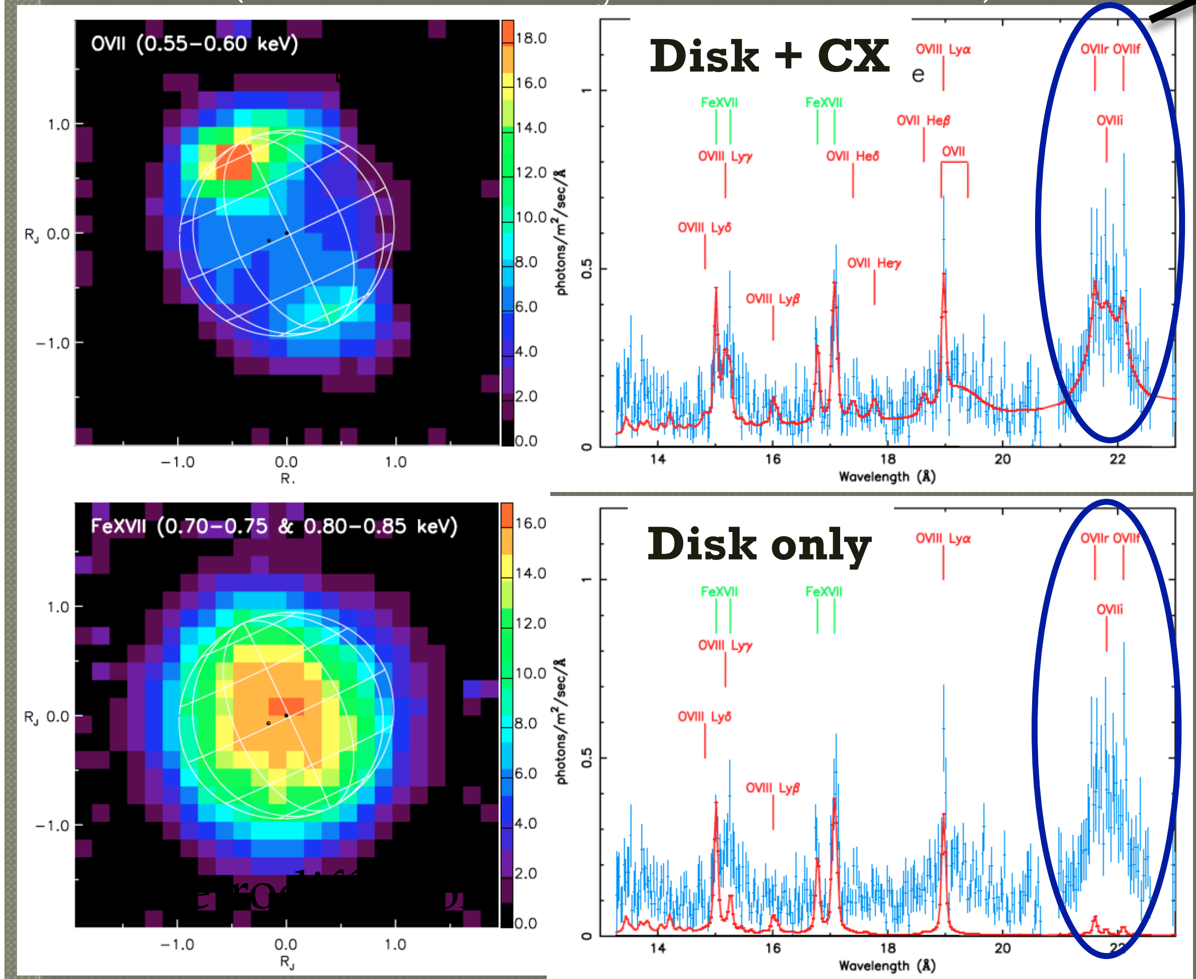
Electron capture



-First discovered in space from cometary observations (Lisse et al., 1996)

Applications to X-ray imaging of planetary environments (1)

Jupiter seen by XMM-Newton
(Branduardi-Raymont et al 2007)



OVII triplet ~0.57 keV

Spectral diagnostics:

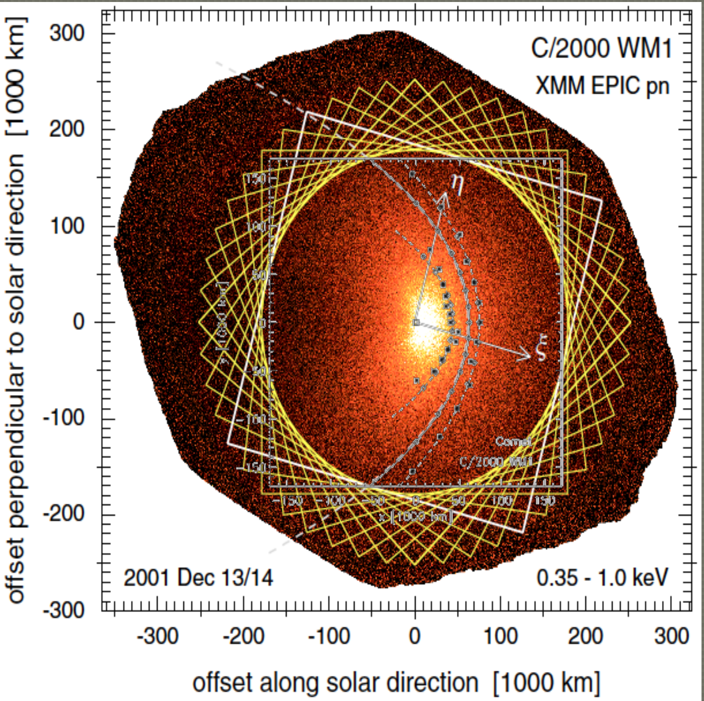
-Characteristic spectral lines of the SW ions

-Proportional to SW ion flux and planetary neutral densities

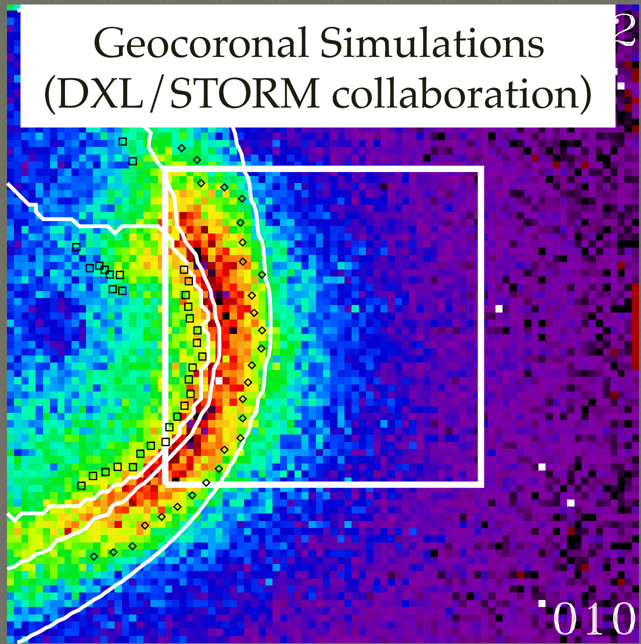
-Study of precipitating ions (e.g. Jupiter's polar cusps)

Applications to X-ray imaging of planetary environments (2)

X-ray tomography of comet C/2000 WM1
(Wegmann & Dennerl 2005)



Geocoronal Simulations
(DXL/STORM collaboration)



<u>Extracting E-M structure boundaries:</u>
SWCX emission traces planetary/cometary shocks because of SW ion compression in regions of increased neutral density

Applications in remote imaging of EM boundaries and plasma-neutral interaction

SWCX emission from Mars. Simulation in 3 steps

1. Hybrid model for E/M interface (130km resolution) Modolo et al, 2005, 2006, 2012

2. Test-particle simulation for SW species X^{+q} with E & B in equilibrium

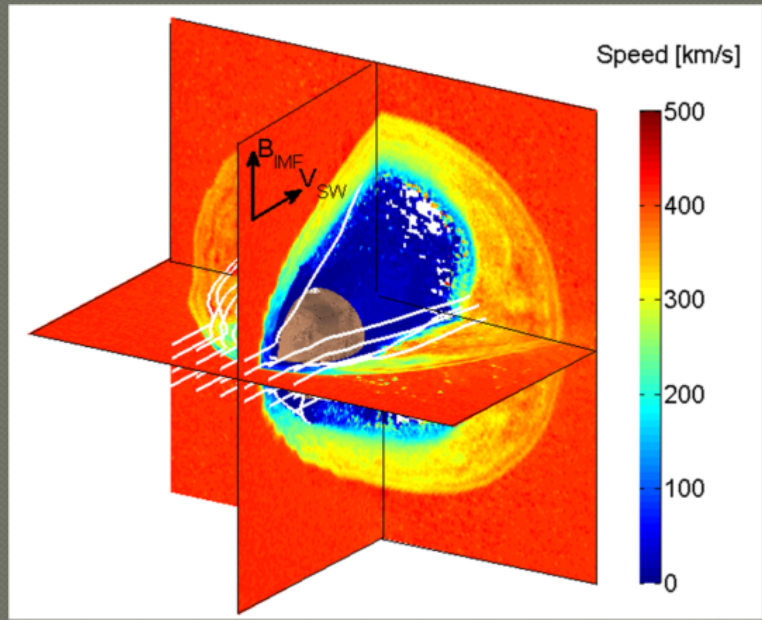
$X^{+q} + M \longrightarrow X^{+(q-1)*} + M^{+}$

- calculating CX production rates for each ion species $X^{+(q-1)}$

3. Application of CX transition probabilites to calculate the Mars SWCX spectrum and total luminosities

Koutroumpa et al. A&A 2012

SW input parameters appropriate to period of XMM-Newton 2003 observations of Mars

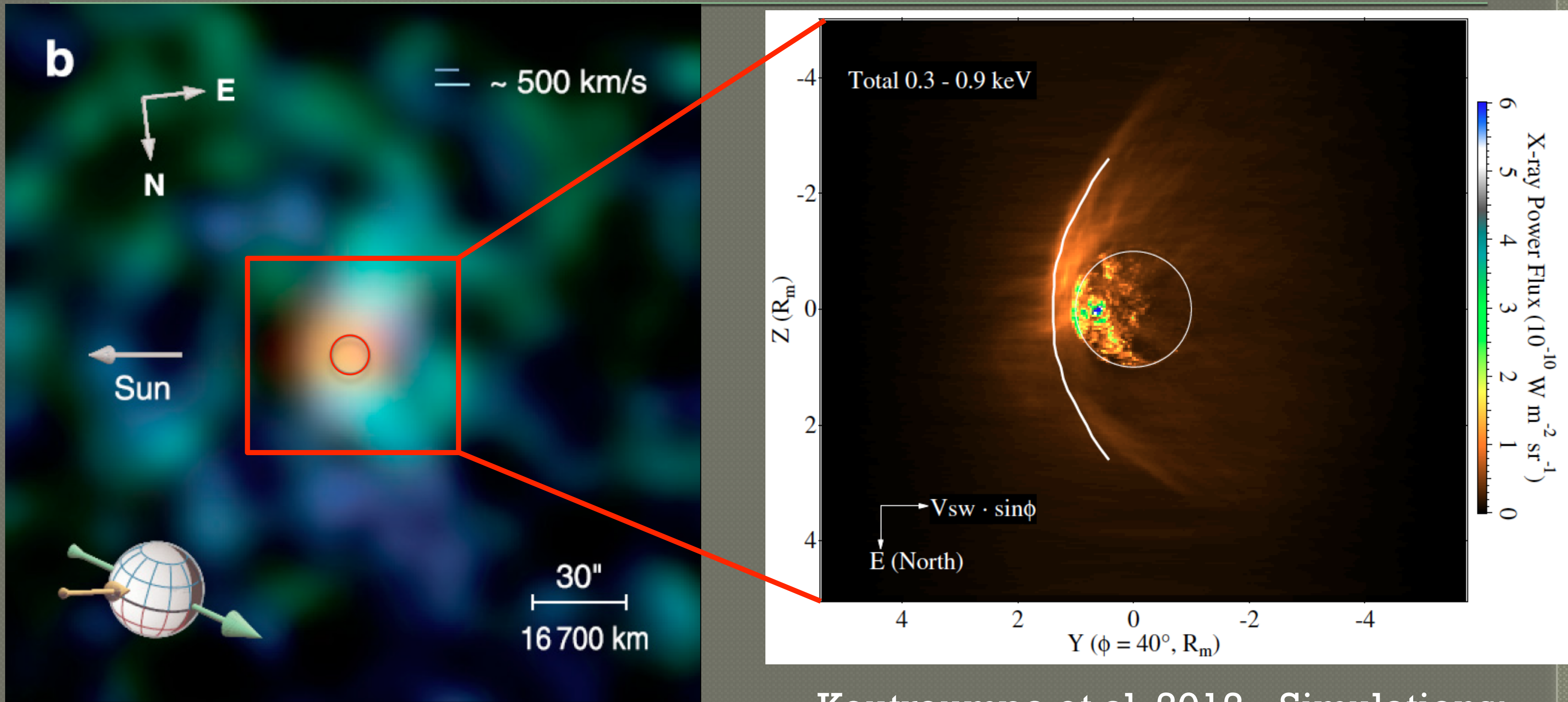


Spectral Line Intensity:

$$I(h\nu) = \frac{1}{4\pi} \int \underbrace{n_n}_{\text{Neutral density}} \cdot \overbrace{n_i \cdot V_i}^{\text{SW ion flux}} \cdot \underbrace{\sigma_{ni} \cdot Y_{ni}(h\nu)}_{\text{Atomic data}} \cdot ds$$

Mars SWCX emission maps

Morphology similar, imaging of Bow shock (position consistent with MGS)
BUT, major quantitative differences:



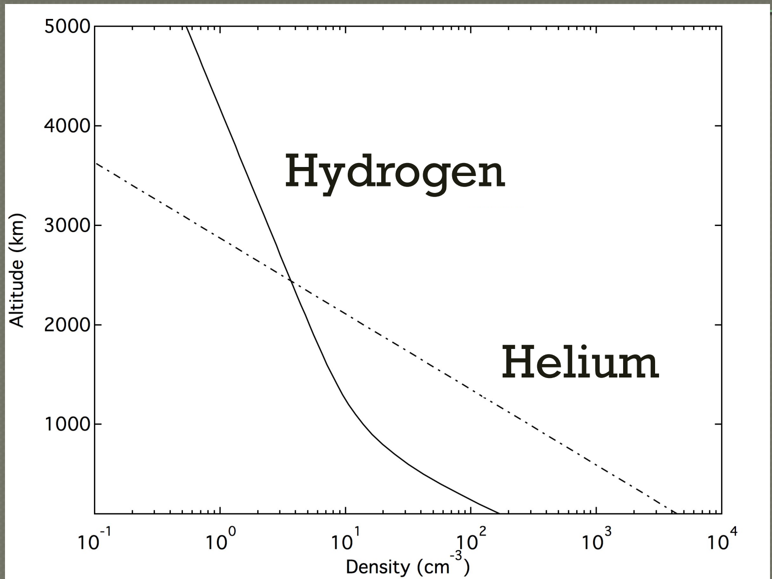
Dennerl et al. 2006 – XMM Data:

Total Luminosity: **11.8 MW**
(numbers never reproduced by any subsequent observation)

Koutroumpa et al. 2012 - Simulations:

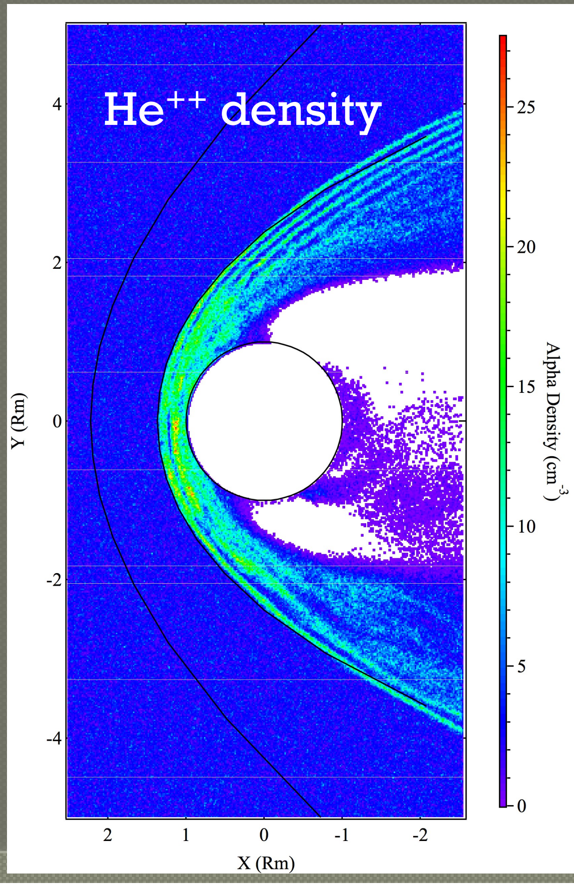
Total luminosity: **0.23 MW**
(similar to Chandra 2001 obs.)

SWCX emission from Mercury. Input



Spherically symmetric neutral coronas:
$n_H(z) = 23 * \exp(-z/1330) + 230 * \exp(-z/230)$

$n_{He}(z) = 6000 * \exp(-z/330)$

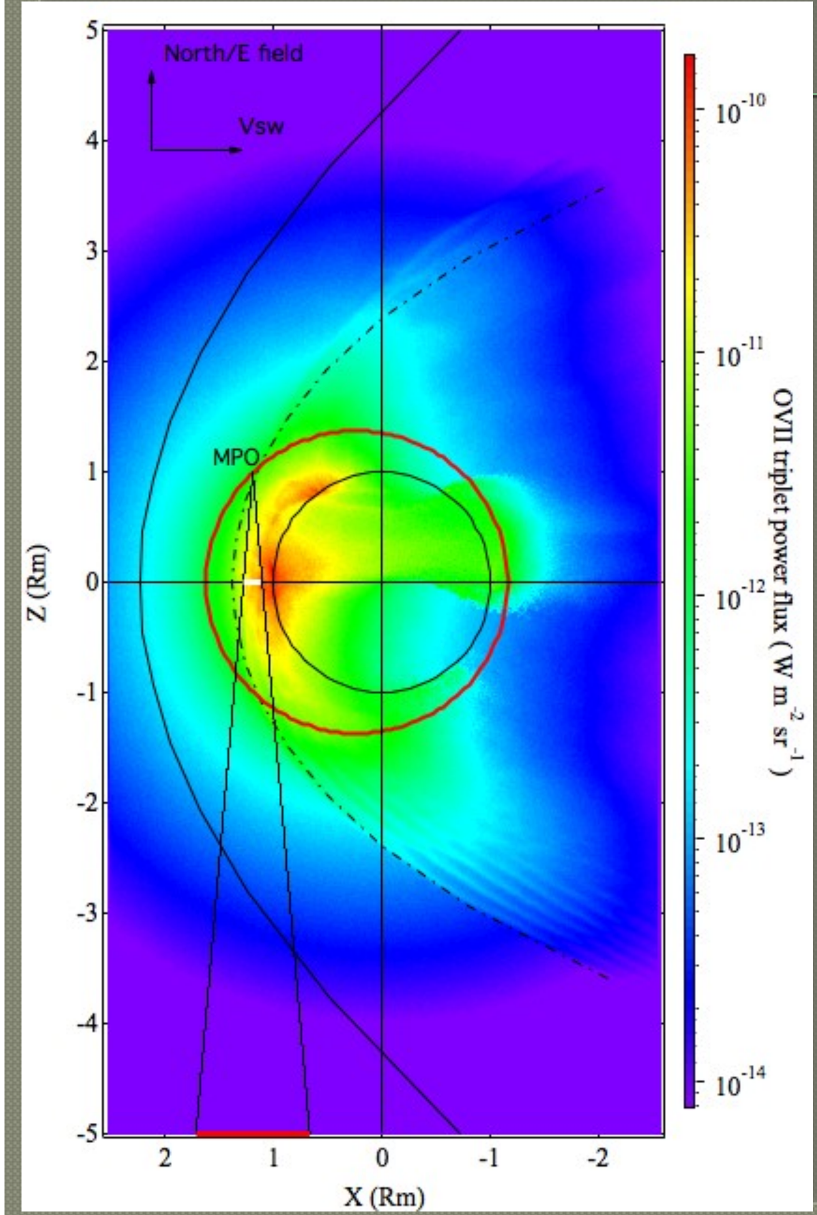


O^{7+} distribution:
Adjusted to hybrid model He^{++} distribution

$n_{He++} = 1.6\ cm^{-3}$, V = 500 km/s, B = 21 nT, $\phi_B = 35.53°$

$n_{O7+} = [O^{7+}/O] * [O/He^{++}] * n_{He++} = 4\text{x}10^{-3}\ cm^{-3}$
For slow SW

SWCX emission from Mercury. Preliminary Results



Total luminosity of OVII triplet: 4 mW (for standard slow SW)

For comparison, Mars simulations: 3 mW with less favourable SW conditions: n_{He++} = 0.08 cm^{-3}, V = 675 km/s, B = 3 nT and ϕ_B =-56°, n_{O7+} = 3x10^{-5} cm^{-3}

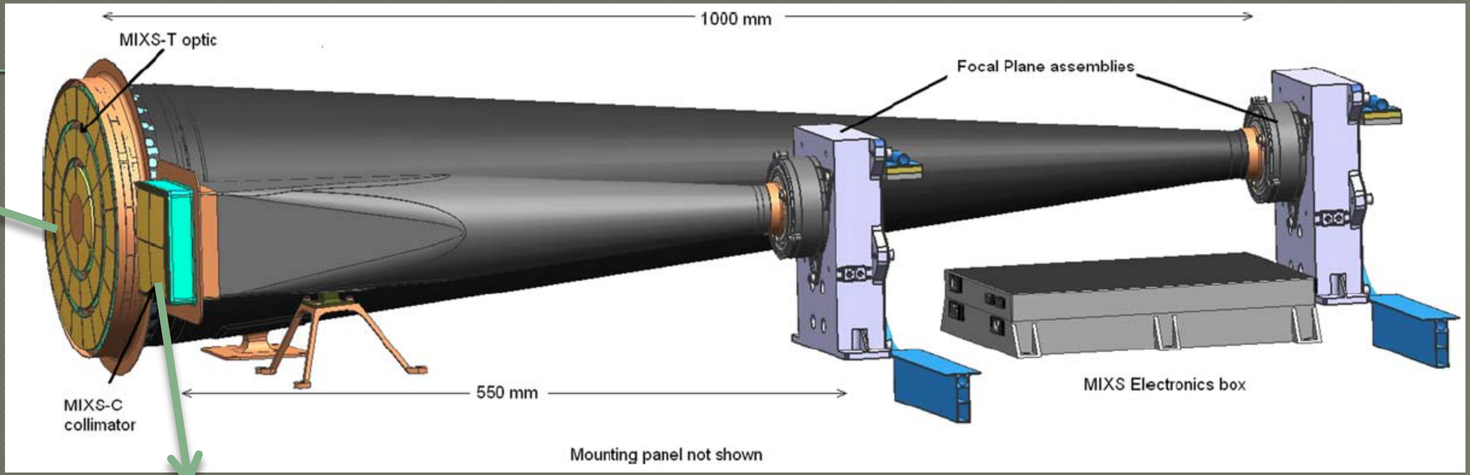
CAN WE OBSERVE IT?

-Remote observations impossible for Earth-bound satellites, due to the Sun's visual proximity

-In situ imaging/measurements possible with BepiColombo MPO/MIXS-C X-ray detector

Mercury X-ray Imaging Spectrometer (MIXS) on MPO
Conceived for surface fluorescence (0.5-7.5 keV) studies

MIXS-T:
10km spatial resolution



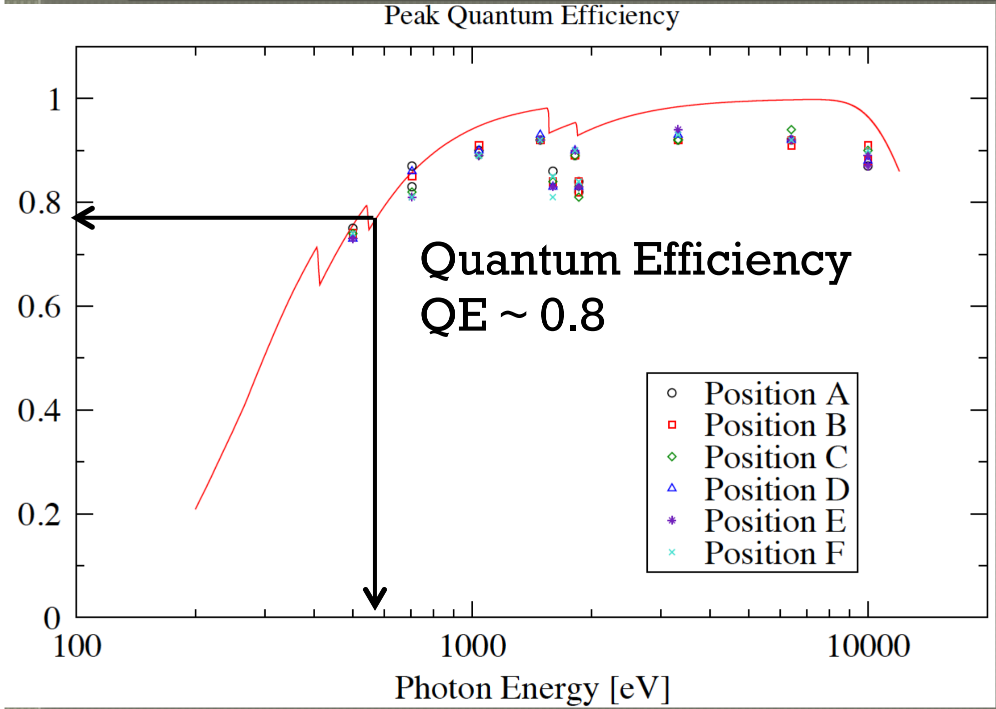
MIXS-C: (micropore reflectors, equivalent to STORM tested on the DXL flight in Dec. 2012)

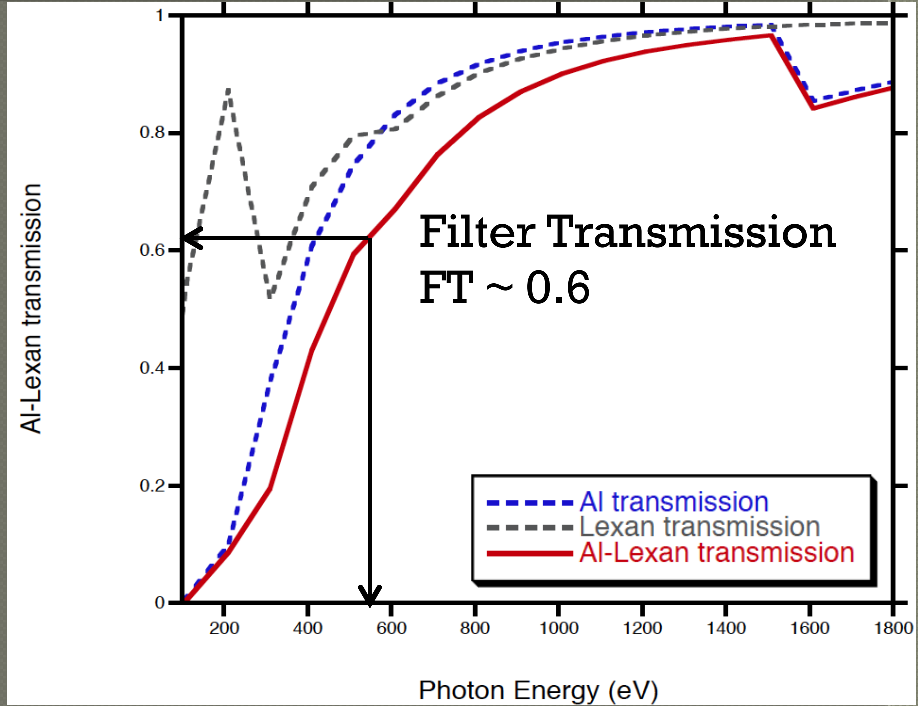
-Spatial resolution @70-270km – not very important for first SWCX detection

-Larger effective area, and 11°x11° FOV – crucial, because SWCX emission is faint

'In the current mission configuration, it is in principle possible to observe grazing the exosphere, while avoiding the much brighter surface'
(communication with S. Sembay and the MIXS team at Leicester University)
BUT, can we detect SWCX?

MIXS-C Effective Area @0.57keV (OVII triplet)





Figures curtesy of K. Dennerl and MPE MIXS team

MIXS C optics: 11 deg x 11 deg FoV (10°x10° to account for vignetting), 21 cm diameter ~ 346 cm^2

-effective collecting area: about 60% (Microchannel plate optics)

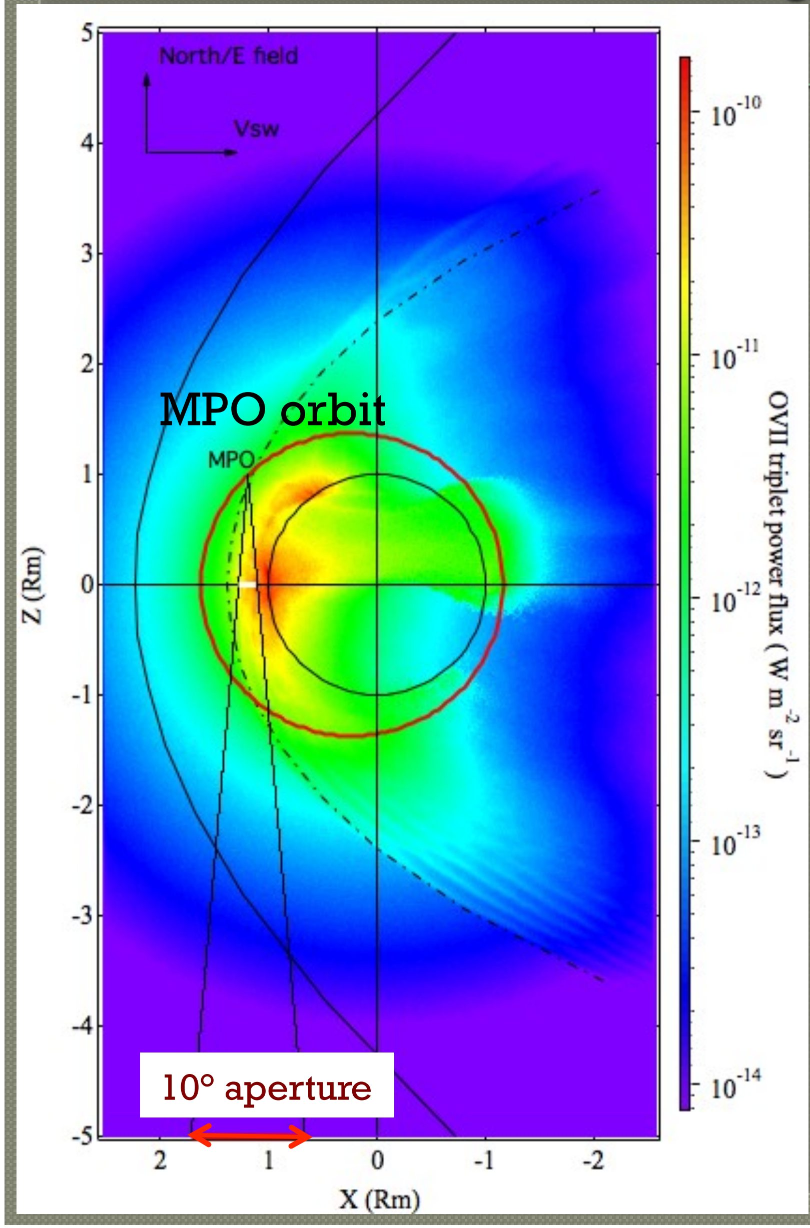
-reflection efficiency at 500 eV: about 50%

-Effective FoV, {FoV} = 103.8 cm^2

Total Effective Area:

E.A. = QE * FT * {FoV} ~ 50 cm^2

Possible observation geometry: 90° through the subsolar point



Compromise between:
-scanning the highest SWCX emissivity region
-minimum deviation from standard nadir observations
-avoiding the bright fluorescent surface

First order estimate:
-MIXS-C detector has a 10°x10° aperture FoV with one single 50 cm^2 pixel (not true, but good enough for first estimate)

Photon Flux :

$$F = \int_0^Z \frac{\langle \varepsilon(z) \rangle \cdot \Delta X(z) \cdot \Delta Y(z)}{4\pi z^2} dz = 0.98 \left[ph\ cm^{-2}\ s^{-1} \right]$$

where $\langle \varepsilon(z) \rangle$ is the average emissivity per layer at distance **z** from the detector, and $\Delta X \cdot \Delta Y$ the total surface of the layer within the 10°x10° FoV

Comparison to fluorescence photon rates

Table 6
Counts detected by MIXS-C in 9000 s during solar quiet.

Fraser et al. PSS 2010

Element	Line	Number of counts	% error
O	K	6.1×10^6	0.03
Na	K	6500	1
Mg	K	3.4×10^4	0.5
Al	K	8700	1
Si	K	1.1×10^4	1
Fe	L_α	7.6×10^5	0.1
Fe	L_β	6.6×10^5	0.1

SWCX OVII Photon rate: Flux * detector E.A. = 0.98* 50 = 49 ph. counts s^{-1}

So, in 9000s, SWCX OVII would give 4.4 x10^5 counts (ideal case)

Detectable well within the order of magnitude for fluorescence lines!
BUT it is only first order, and we should not get as much signal

Conclusions & Perspectives

- SWCX simulations and X-ray data prove that:
  - SWCX spectroscopy can provide insight to SW-planetary neutral interaction
  - SWCX imaging is promising for magnetospheric studies
- MPO/MIXS-C should be able to detect SWCX emission from the Hermean exosphere in the right geometry configuration and SW conditions
- More detailed calculations are needed to account for:
  - The expected SWCX emission level (test-particle simulations)
  - The S/N ratio (background & noise level estimates, scattered solar X-rays)
  - The detector optics detailed configuration (number of pixels, vignetting etc.)