X-ray studies of solar system objects: now and the next decade

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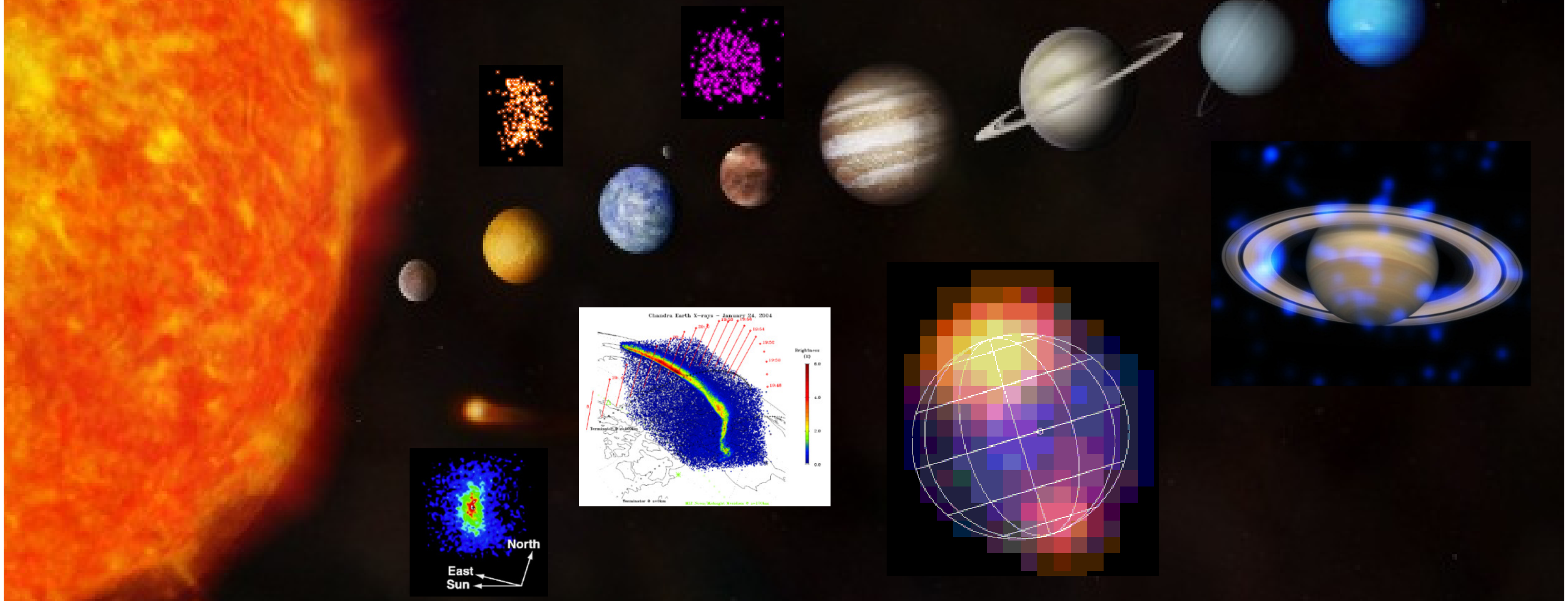


with thanks for their inputs to K. Dennerl, A.Bhardwaj, D. Koutroumpa, S. Wolk and for the contributions by many others over the years!

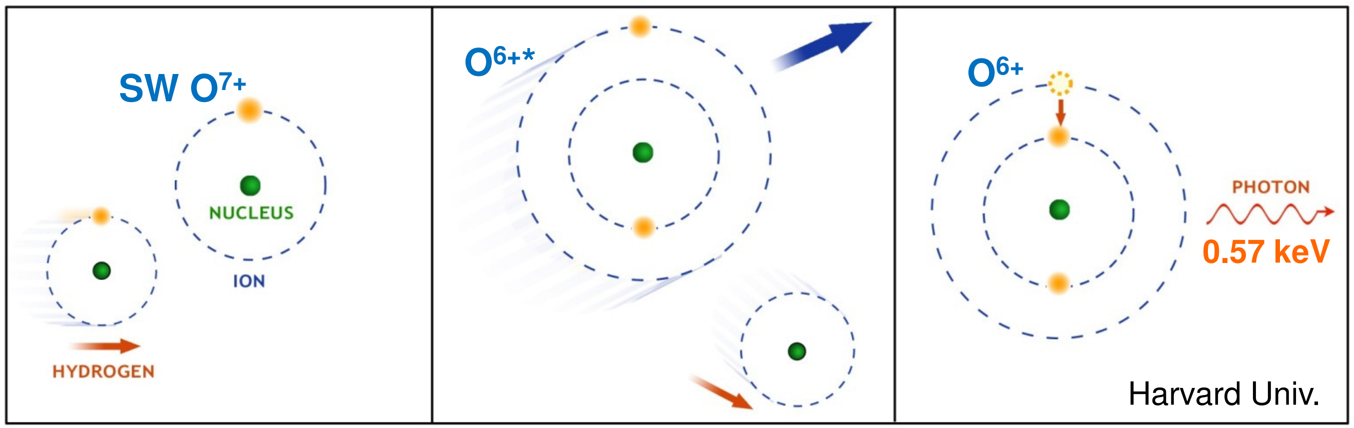
'XMM-Newton: The Next Decade' workshop, ESAC, 9 – 11 May 2016

How it all started

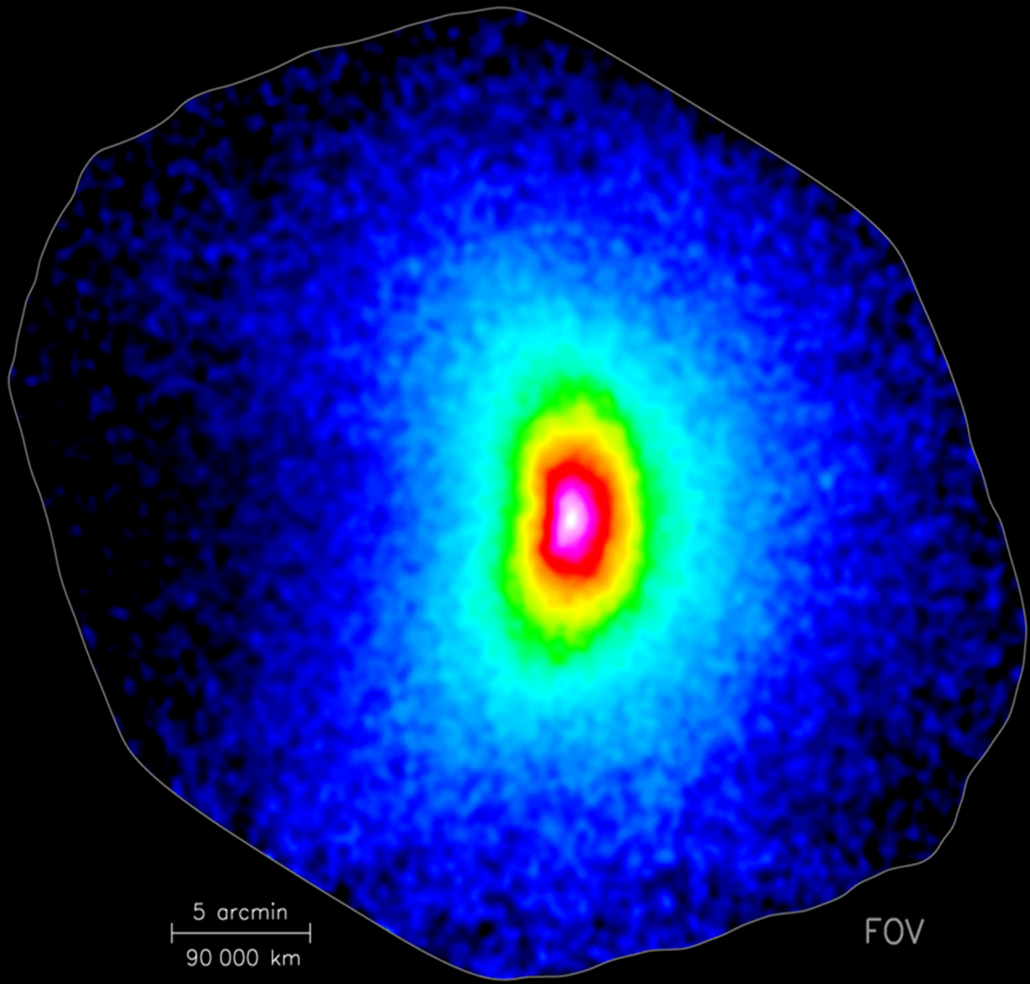
- First detection of Jupiter with the *Einstein Observatory* IPC & HRI (1979, 1981) *Metzger et al. 1983*
- Heavy ion precipitation and 'charge transfer' *Waite et al. 1988* *Horanyi, Cravens & Waite 1988*
- ROSAT discovery of X-rays from comet Hyakutake *Lisse et al. 1996*
- Charge transfer of solar wind heavy ions *Cravens 1997 …* *Snios et al. 2016*
- **Charge eXchange** firmly established as X-ray production mechanism

$P_X \sim n_N \, n_{SW} \, v_{SW}$

Cravens 2000



Comet C/2000 WM1, 2001 Dec. 13 – 14



Optical

XMM-Newton

Dennerl et al. 2003

Soft X-rays (0.2 – 1 keV) from Jupiter's aurorae

- Ionic CX process thought to lead to soft X-rays

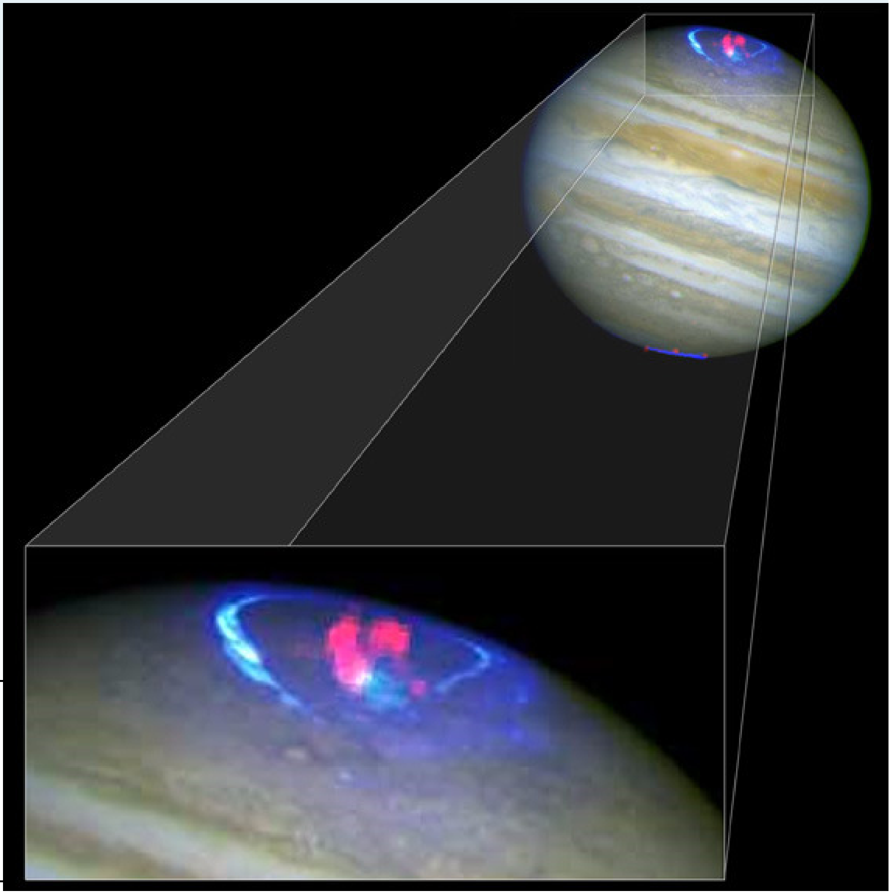
- Ions first thought to originate in the inner magnetosphere (8–12R_J) but *Chandra* data point to origin at >30 R_J ***Gladstone et al. 2002***

- What are the ion species (C or S) and thus their origin (solar wind / magnetosphere)?

- Some *XMM-Newton* & *Chandra* spectra appear to favour a magnetospheric origin

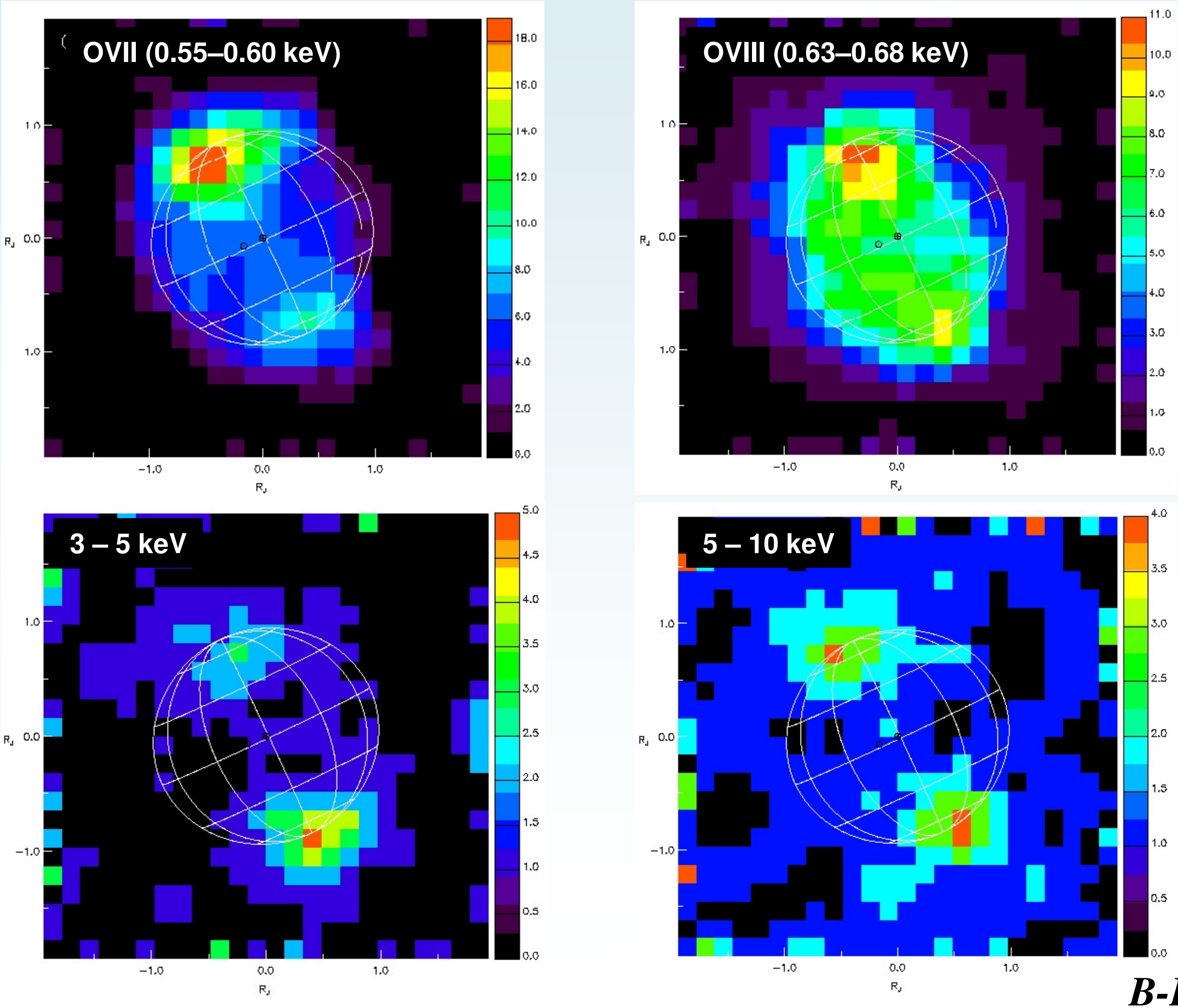
B-R et al. 2007, Hui et al. 2009, 2010

- Relative roles?



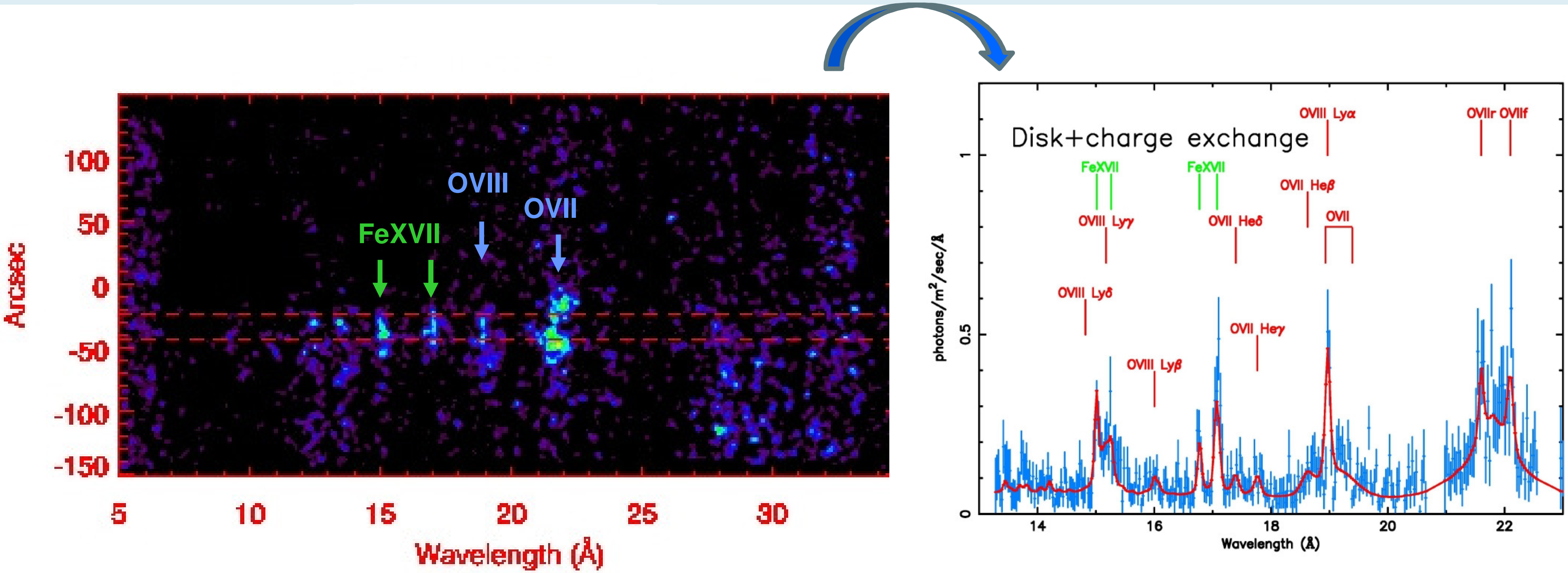
X-ray: Chandra HRC (*Gladstone et al.*)
UV: HST STIS (*Clarke et al.*)
Optical: HST (*Beebe et al.)*

Jupiter – *XMM-Newton*, 2003: EPIC



B-R et al. 2007

Jupiter – *XMM-Newton*, 2003: RGS



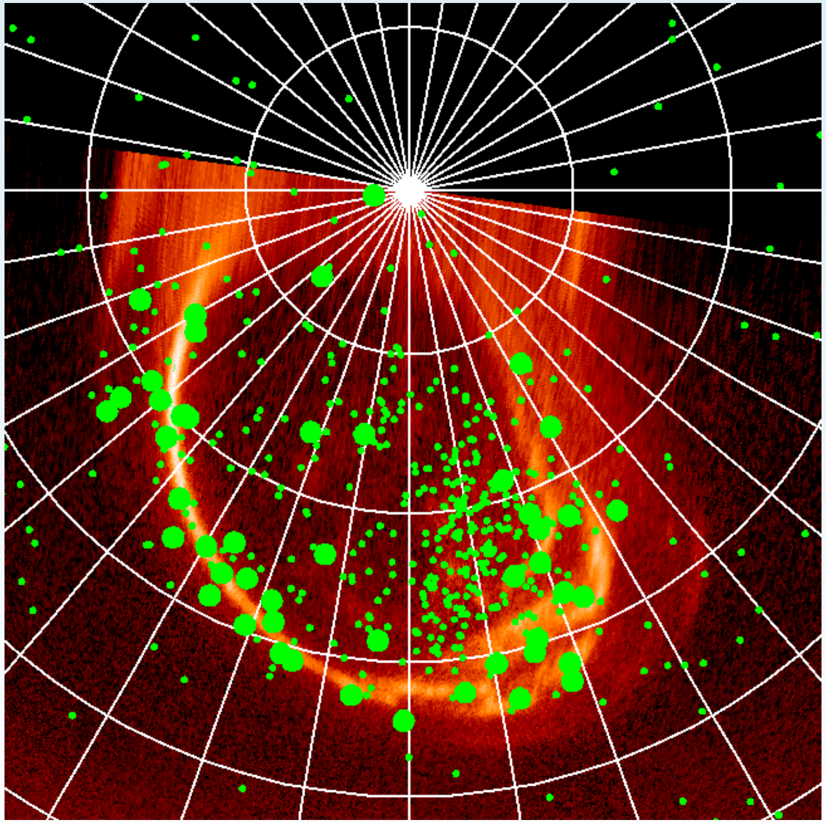
- RGS clearly resolves auroral CX from disk soft X-ray emission lines
- Width of OVII and OVIII lines corresponds to velocities of +/- 5000 km s^{-1} or energies of few MeV for O ions

Jupiter – *Chandra* and *Hubble* STIS – 2003

Chandra ACIS reveals different spatial morphology of soft (< 2 keV, ion CX) and hard (> 2 keV, electron bremsstrahlung) X-ray events

→ CX X-ray events map far out from the planet

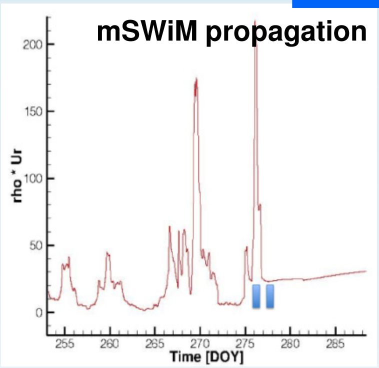
Simultaneous Hubble STIS images show > 2 keV events coincide with FUV auroral oval and bright features (FUV from excitation of atmospheric H_2 and H by 10 - 100 keV electrons)



B-R et al. 2008

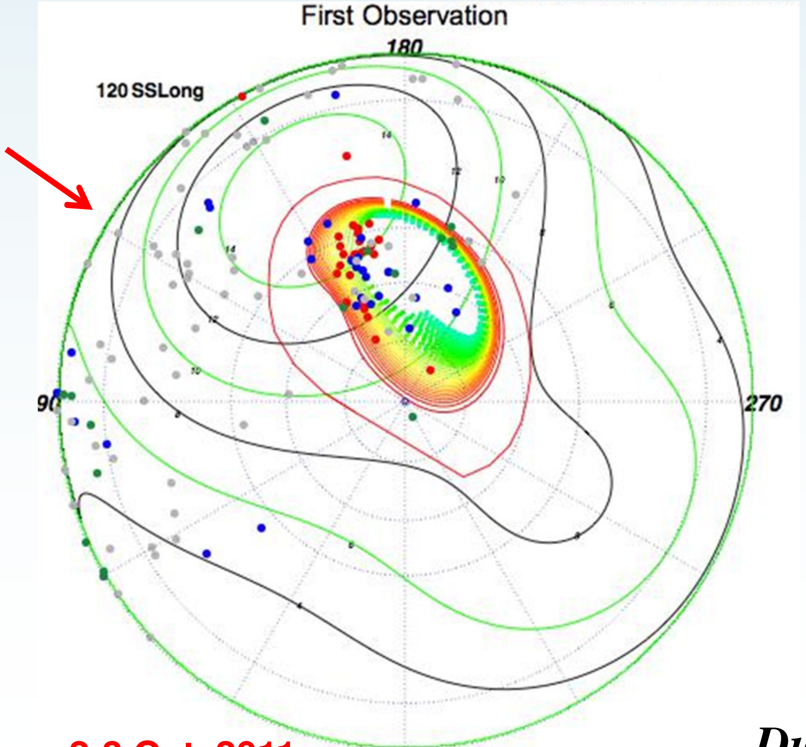
→ Same energetic electrons responsible for both, UV and X-rays

Jupiter – *Chandra* TOO Oct. 2011

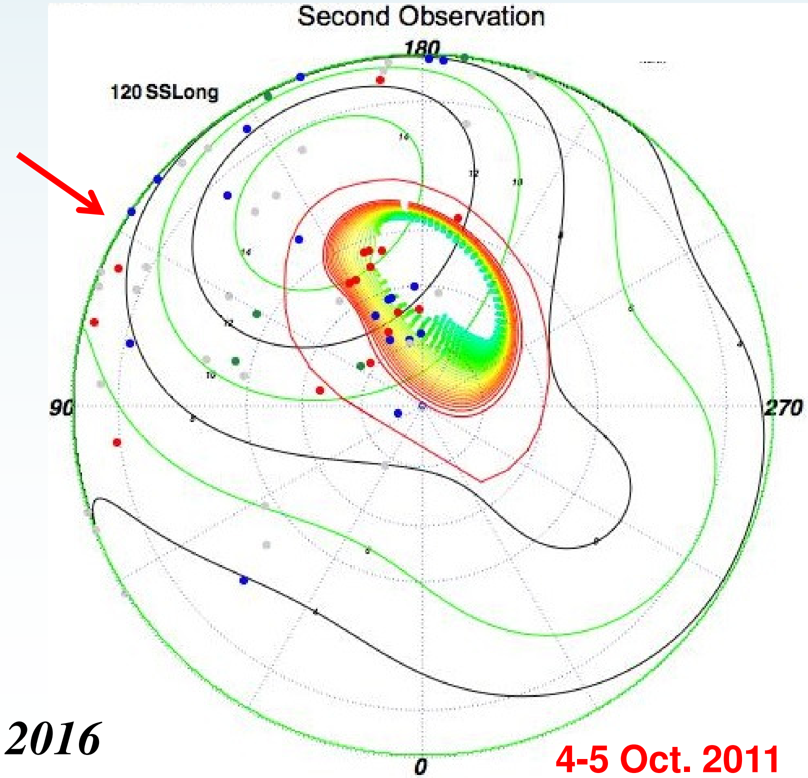


Chandra ACIS polar projections in System III:

Red	0.2 – 0.5 keV	(C/S)
Blue	0.5 – 0.8 keV	(O)
Grey	0.8 – 1.5 keV	(solar)
Green	> 1.5 keV	(bremss.)



2-3 Oct. 2011



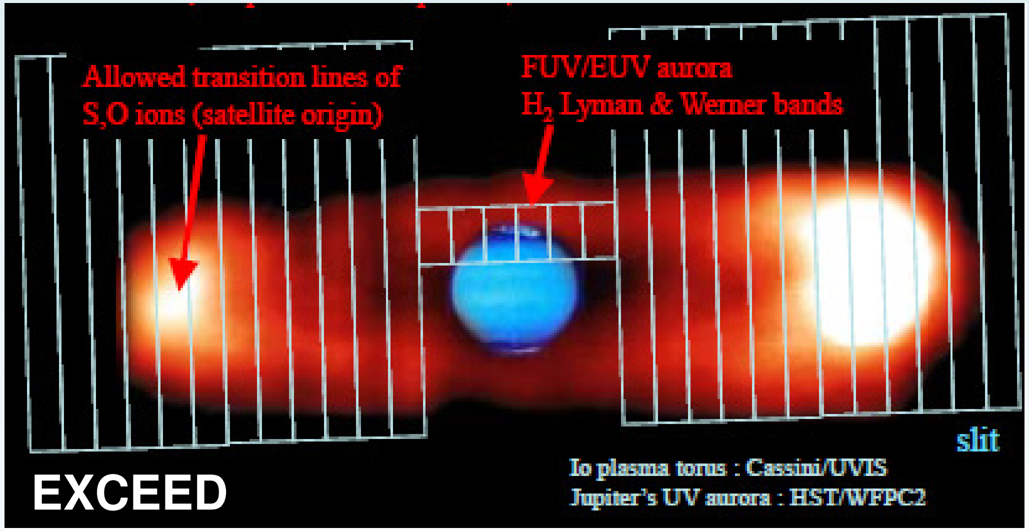
4-5 Oct. 2011

Dunn et al. 2016

Jupiter observing campaigns: *Hisaki* / EXCEED +

- Evidence of solar wind impact on X-ray aurora

Kimura et al. 2016



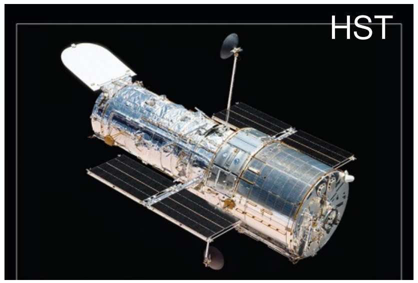
Tsuchiya et al. 2011

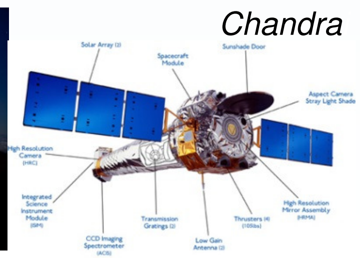
Nov. 2013 - Feb. 2014
HST (FUV)

1-14 Jan. 2014
HST (FUV)
Gemini & IRTF (IR)
Kitt Peak (Visible)

Feb.-March 2014
Subaru

9-20 April 2014
Chandra/XMM-Newton
Suzaku
IRTF

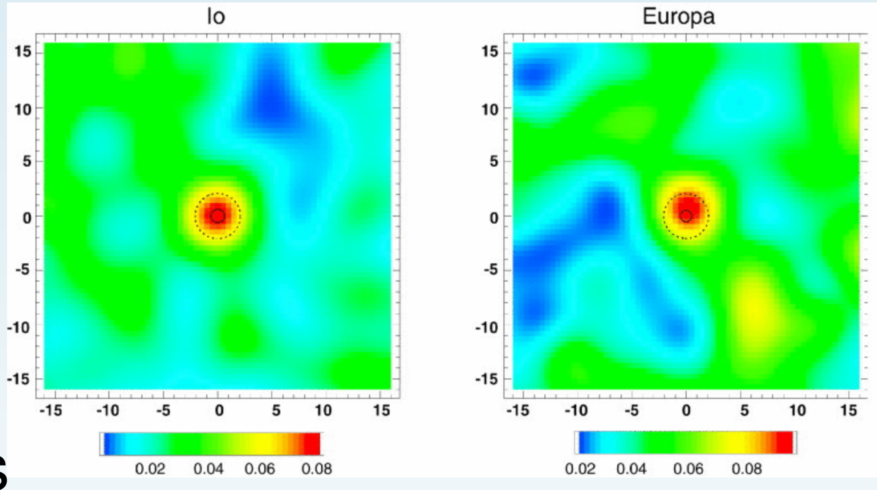


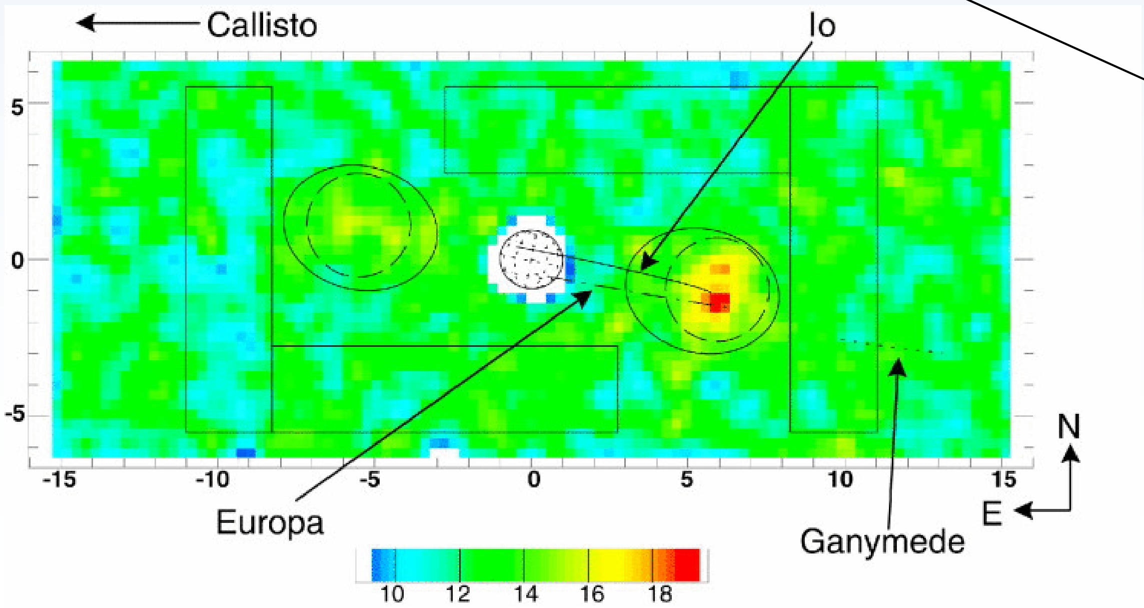


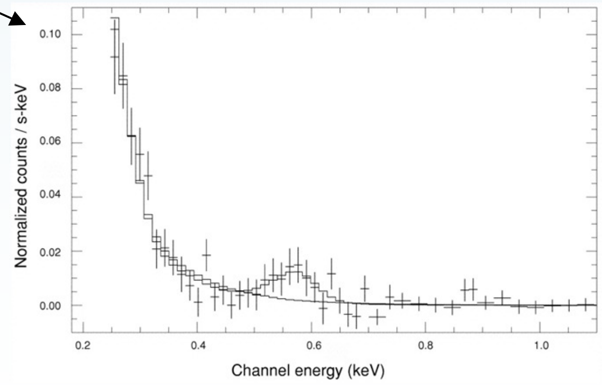
X-rays from the Galilean satellites and the IPT

Io and Europa X-rays (*Chandra* ACIS) from energetic H, O and S ion impacts → fluorescence

Non-thermal electron bremsstr. + OVII em. from Io Plasma Torus



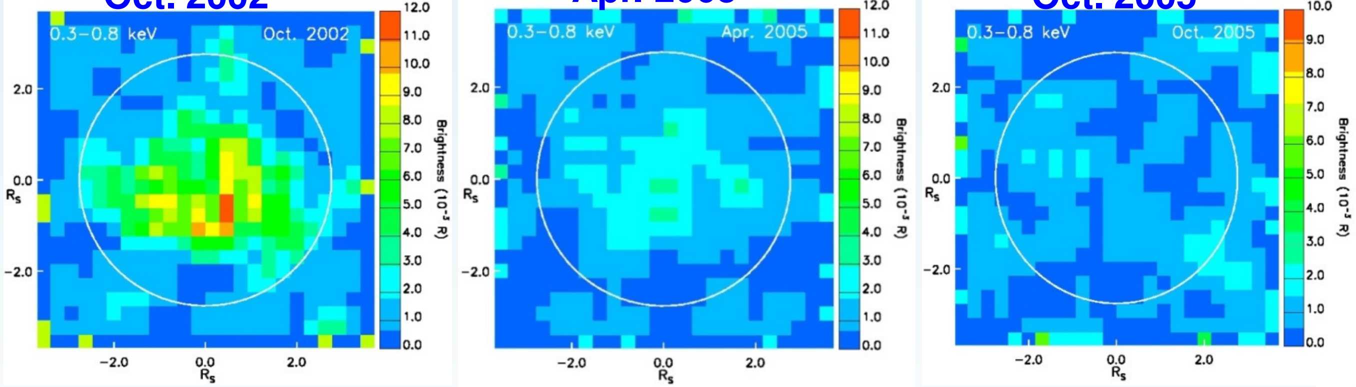




Elsner et al. 2002

On Saturn …

- Disk and polar cap X-ray emissions (unlike Jupiter) have similar coronal-type spectra *Bhardwaj et al. 2005a*
- Flux variability suggests X-ray emission is controlled by the Sun

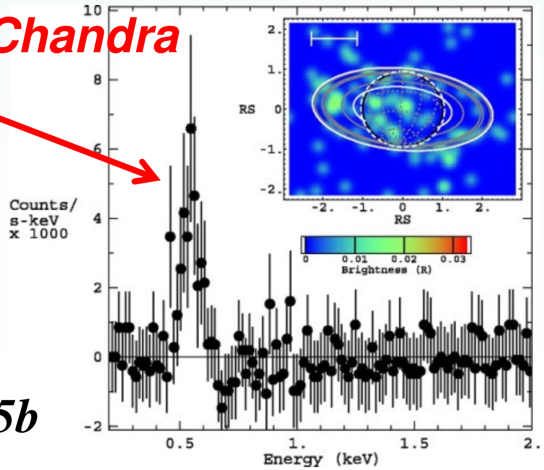


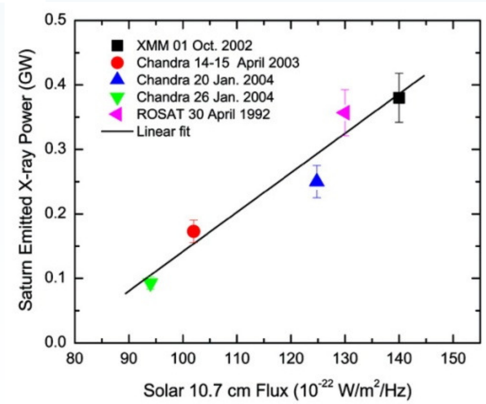
XMM-Newton

B-R et al. 2010

- Fluorescent O-Kα line
- Scattering of solar X-rays on atomic oxygen in H_2O icy ring material

Chandra

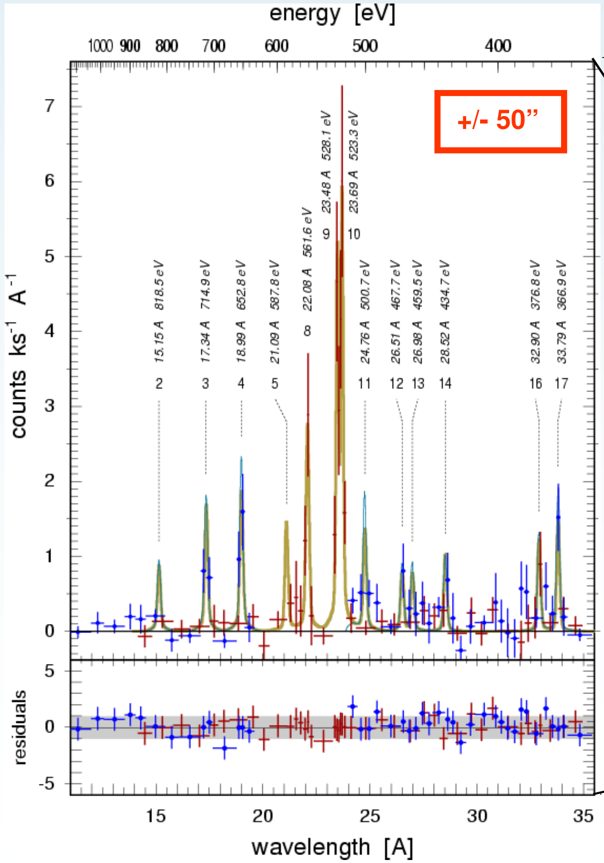




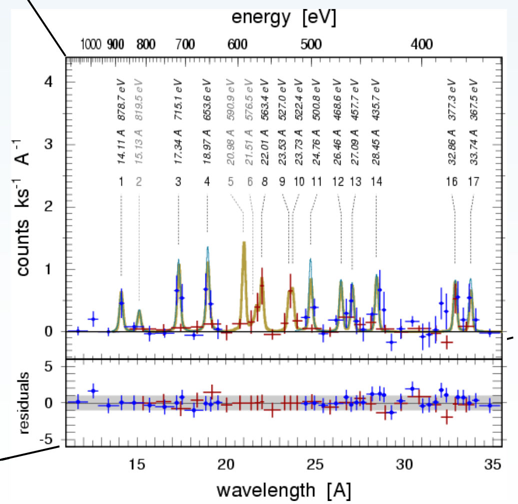
Bhardwaj et al. 2005b

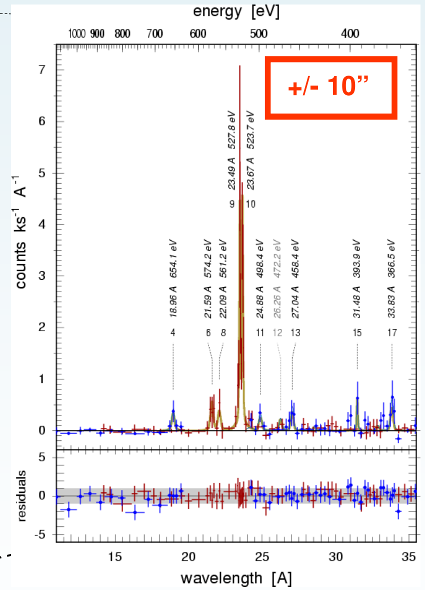
Mars disk and exosphere (halo): *XMM-Newton* RGS

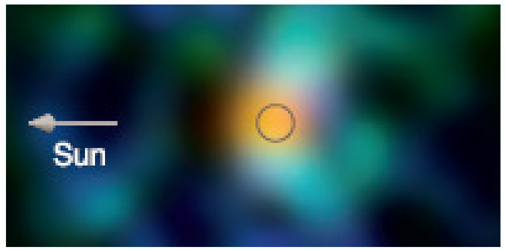
- <u>Fluorescent scattering</u> of solar X-rays in CO_2 atmosphere
- <u>Solar wind charge exchange</u> (SWCX) in the exosphere



- 50” to - 15” and + 15” to + 50”







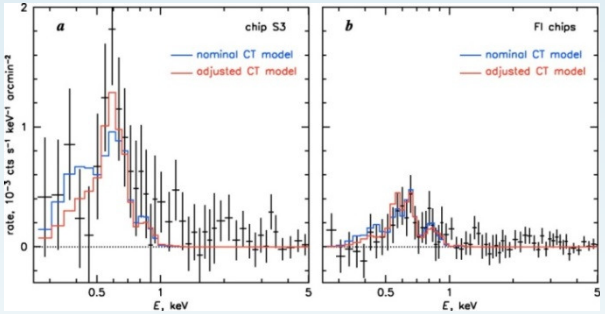
Dennerl et al. 2006

The Earth's geocorona and the heliosphere

- LTE of the *ROSAT* All Sky Survey ¼ keV background ***Snowden et al. 1995***

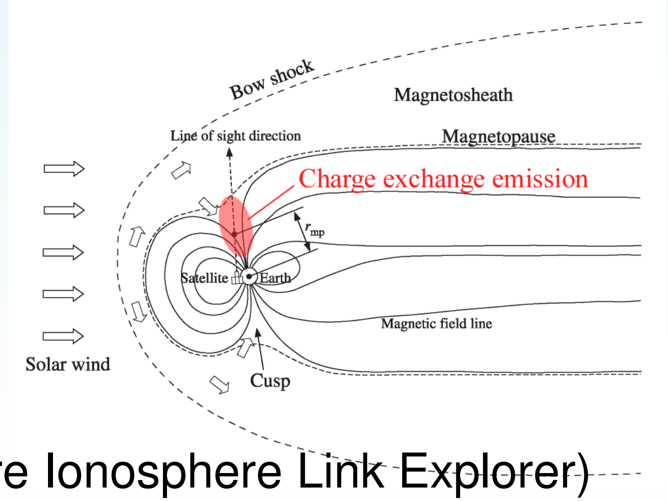
- Time variable O emission lines on the dark side of the Moon

  Correlation with solar wind flux
  → SWCX in Earth's geocorona



***Chandra* ACIS**
Wargelin et al. 2004

- *Suzaku* observations of the NEP:
  Increase in soft X-ray lines correlated with solar wind proton flux ***Fujimoto et al. 2007***

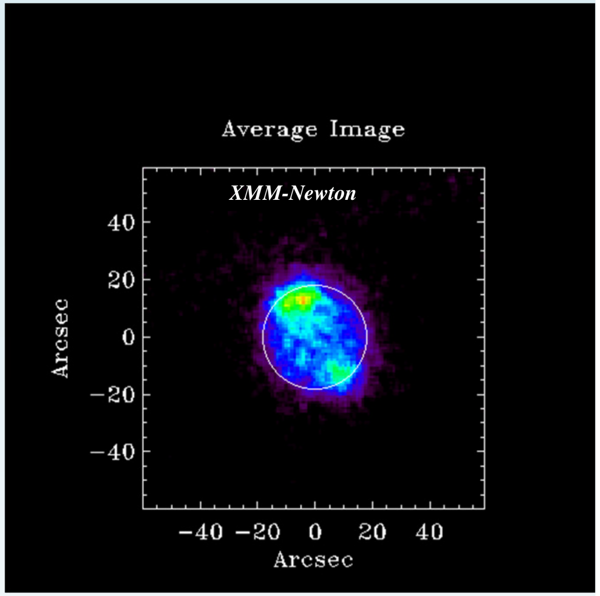


- Systematic study with *XMM-Newton*
  Carter et al. 2008, 2010 (CME), 2011

  Now leading to *SMILE* (Solar wind Magnetosphere Ionosphere Link Explorer)

- Firm measurement (up to 40%) of heliospheric SWCX signal contribution to diffuse X-ray background ***Galeazzi et al. 2014***

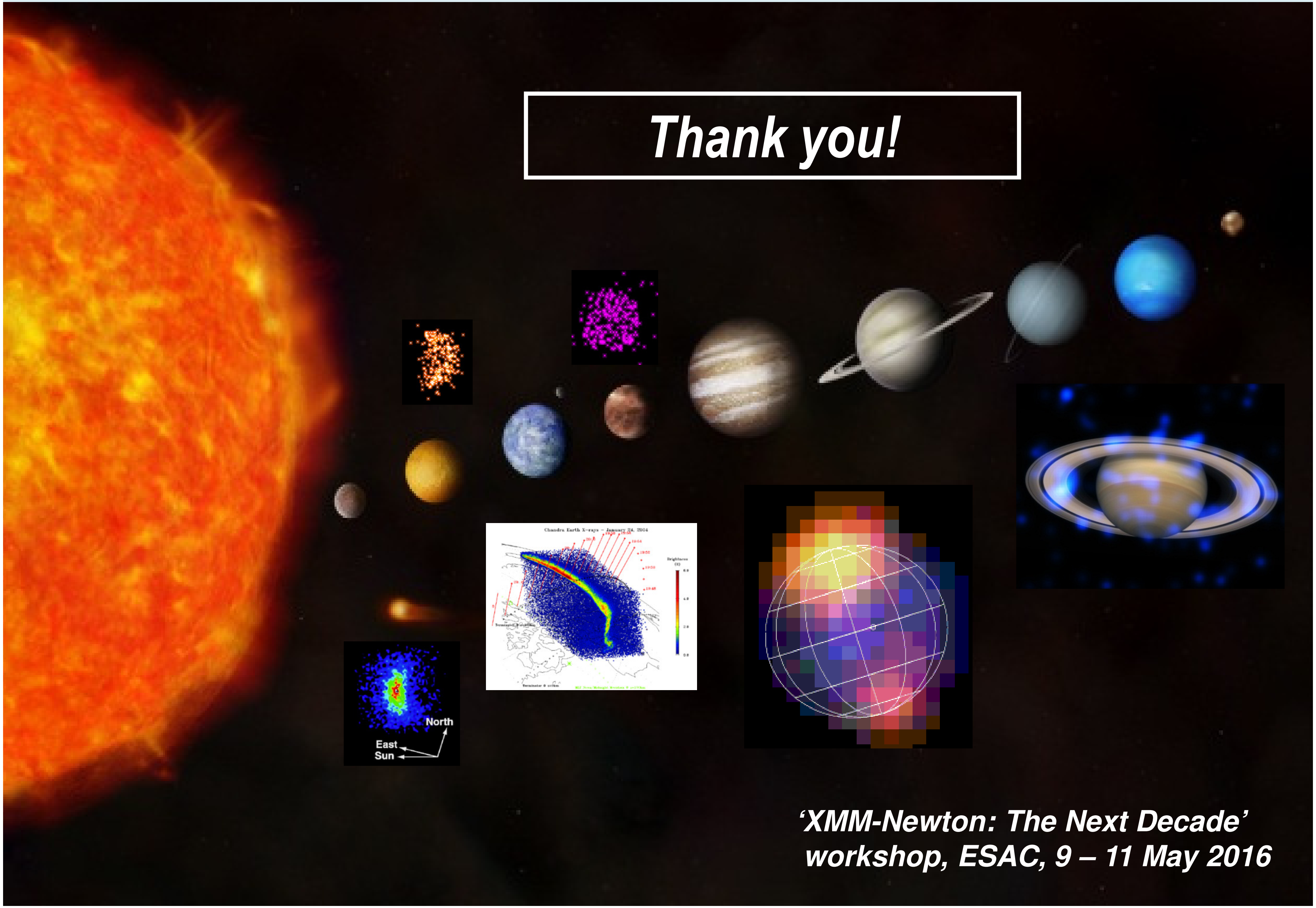
Looking ahead with *XMM-Newton* ...



- Observations at times of enhanced solar activity & simultaneous observations with other facilities (e.g. in situ) return most science
- Establish how solar wind interacts with planetary magnetospheres and exospheres, and comets, at different times in the solar cycle
- Uniqueness of coincidence with JUNO's operations makes next couple of years of *XMM-Newton* Jovian spectra invaluable
- Mars observations while MAVEN orbits the planet give insights in outflowing exosphere under changing solar wind conditions
- Synergy with measurements of SWCX contributions to diffuse soft X-ray background

UCL

Thank you!



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