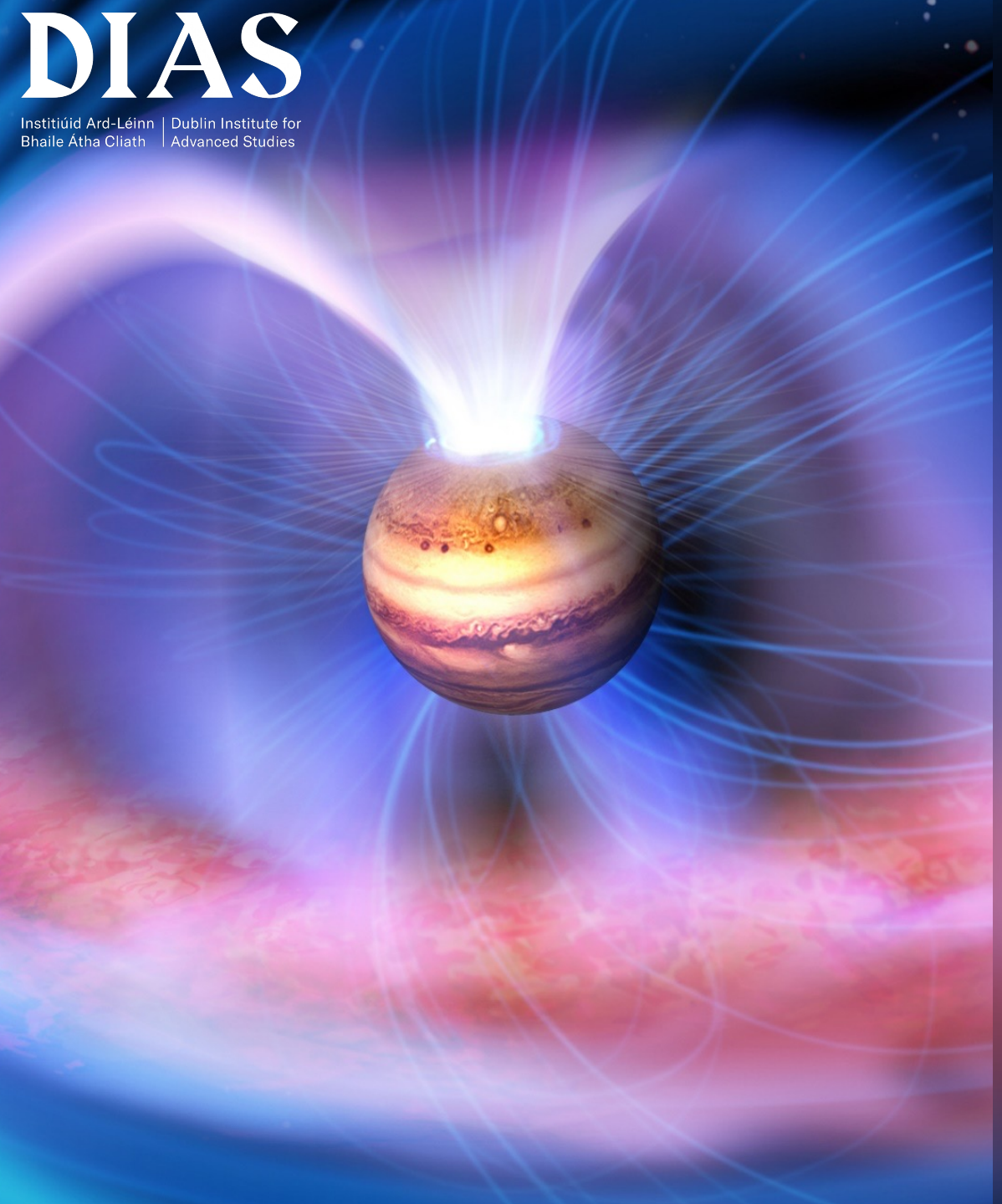

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Bhaile Átha Cliath | Advanced Studies

High Resolution Spectroscopy of Jupiter's X-ray Emissions

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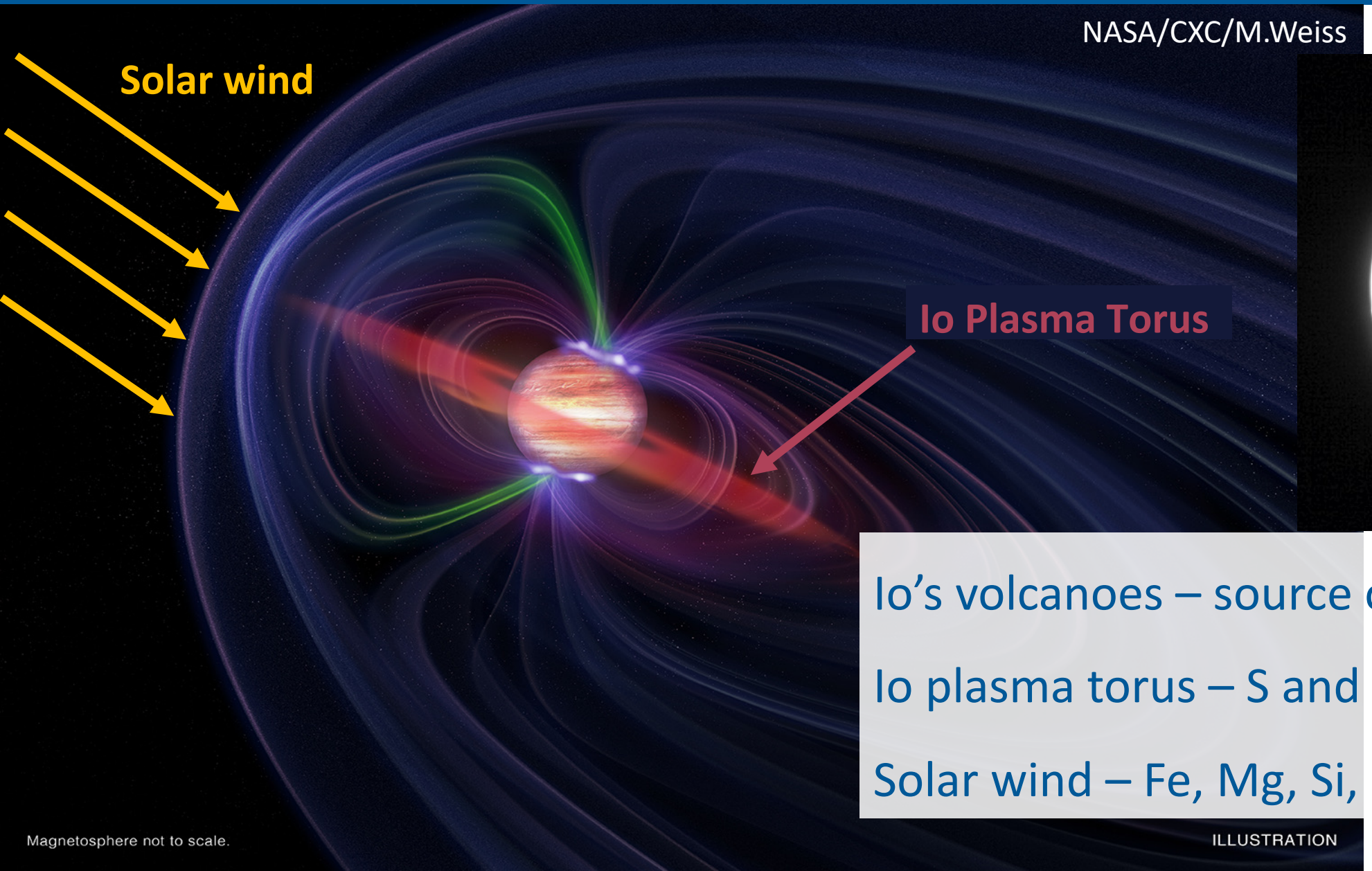
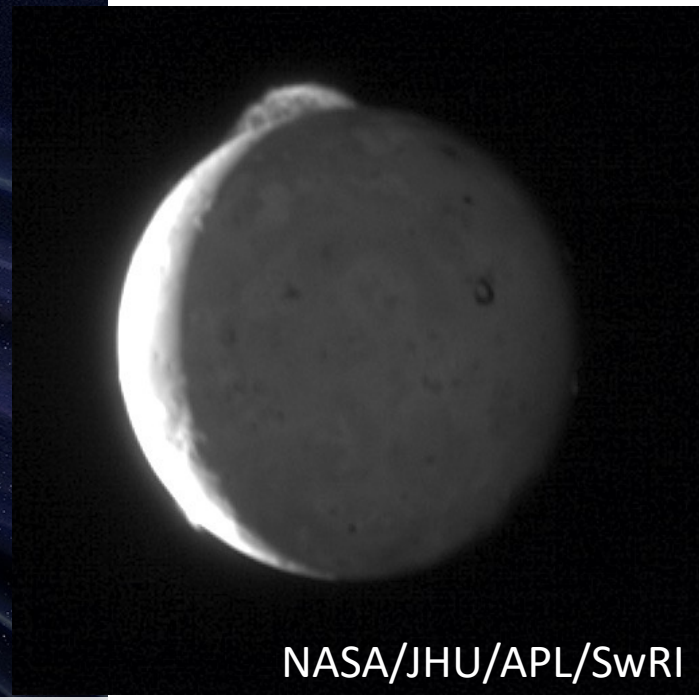
Jupiter's Magnetosphere



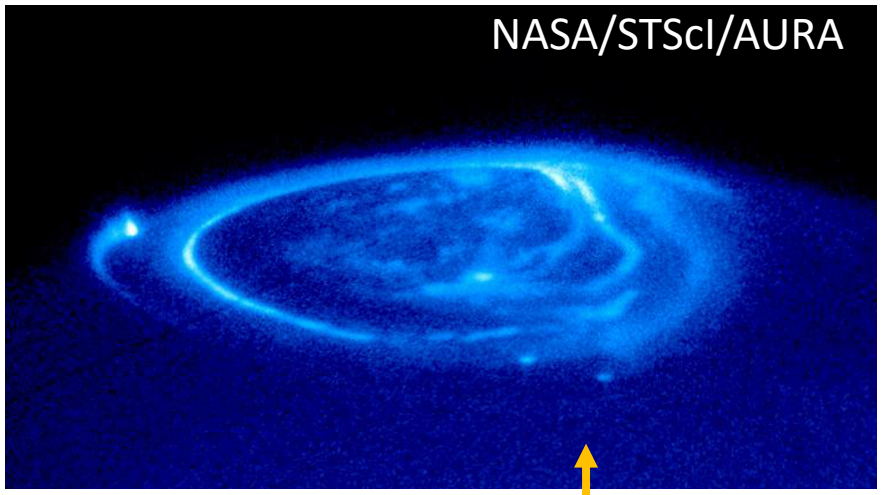


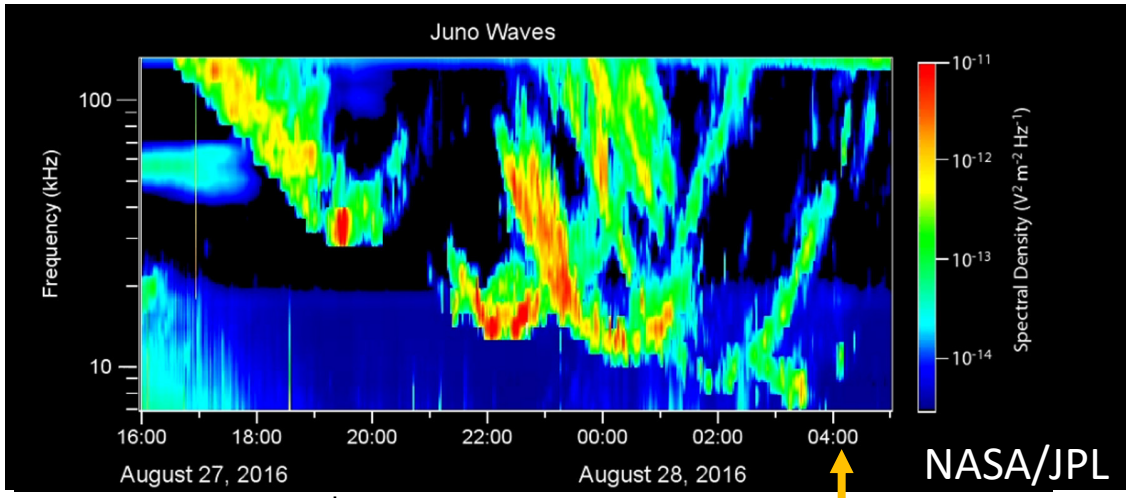
Io's volcanoes – source of neutral SO_2

Io plasma torus – S and O ions

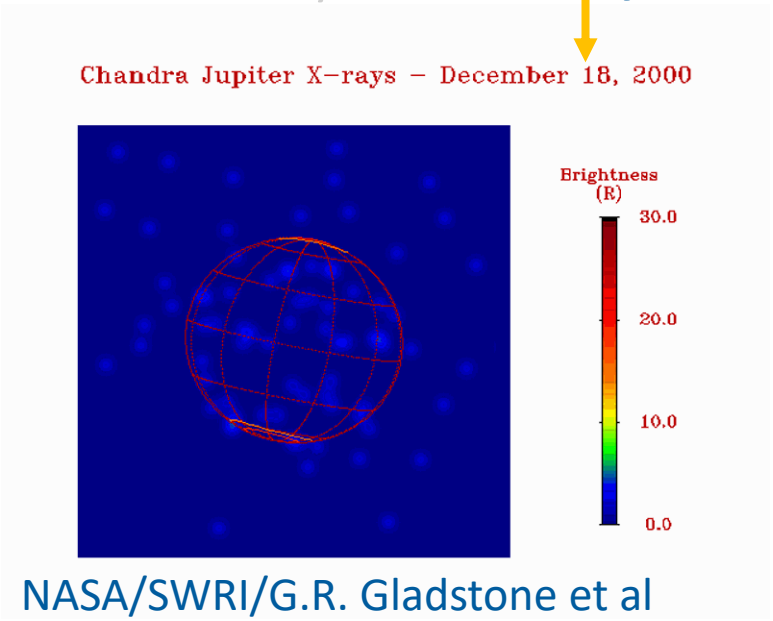
Solar wind – Fe, Mg, Si, N, Ne, O, S, C ions

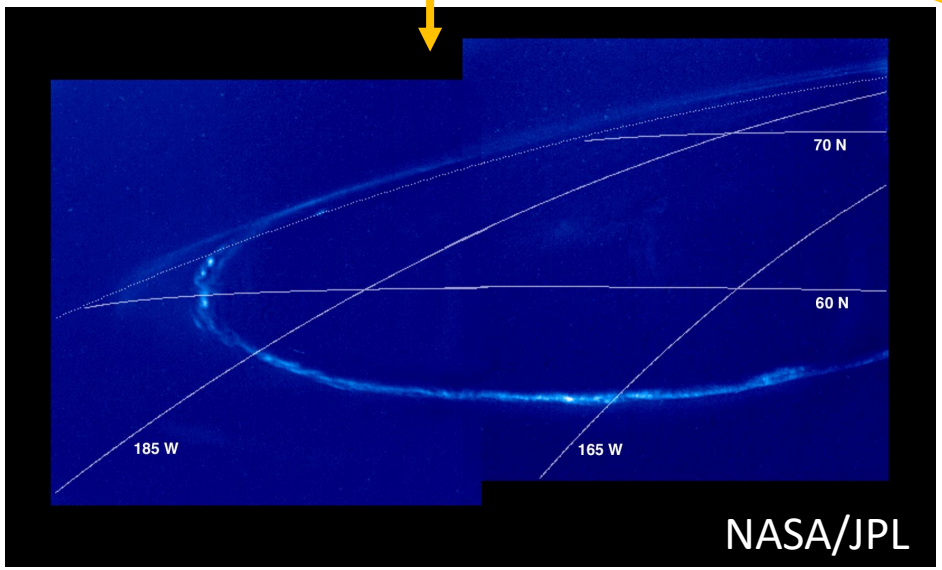
Jupiter's Aurorae

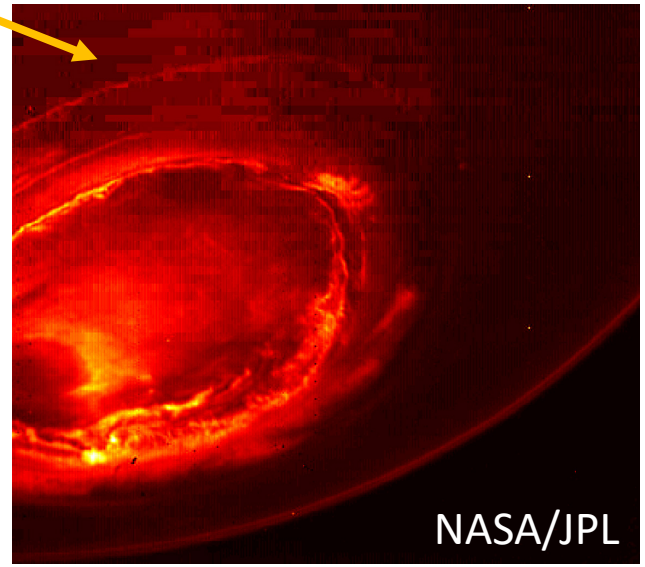




Gamma ray | **X-ray** | **Ultraviolet** | **Optical** | **Infrared** | Microwaves | **Radio**

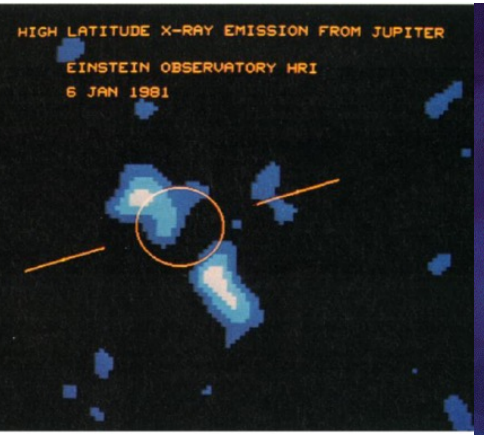






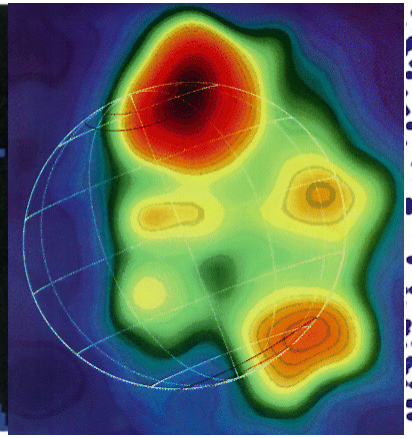
Jupiter X-ray Studies

Einstein Observatory



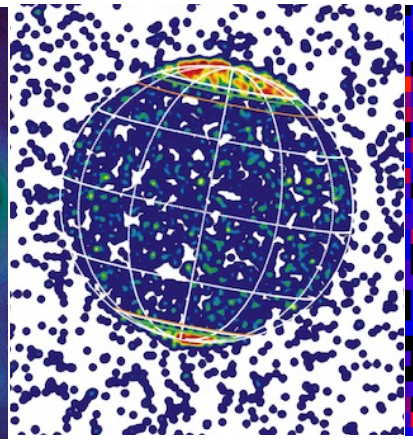
Metzger et al., 1983

ROSAT



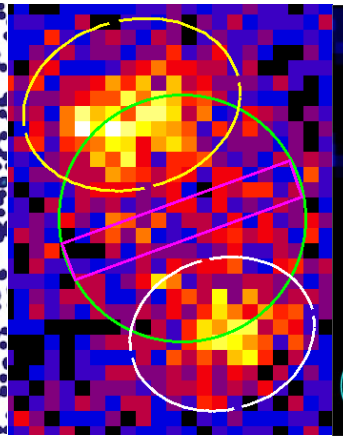
SWRI/H. Waite/G.R. Gladstone

Chandra



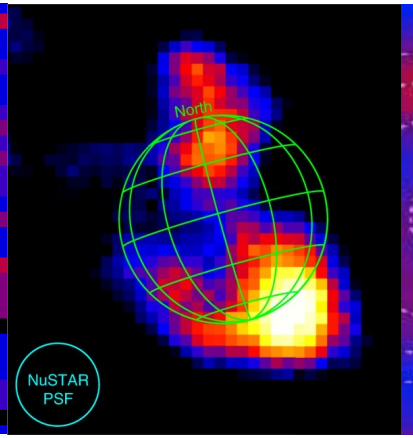
Gladstone et al., 2002

XMM-Newton



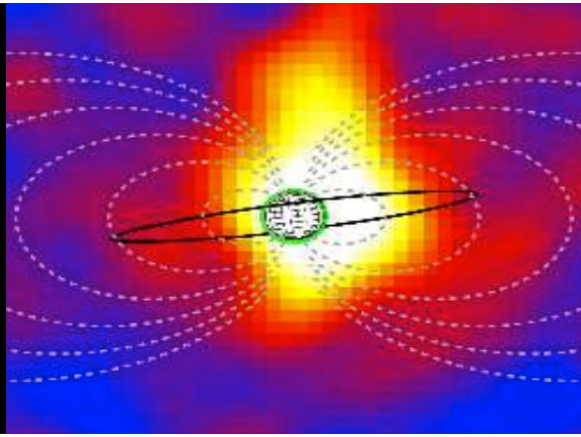
Wibisono et al., 2020

NuSTAR



Mori et al., 2022

Suzaku

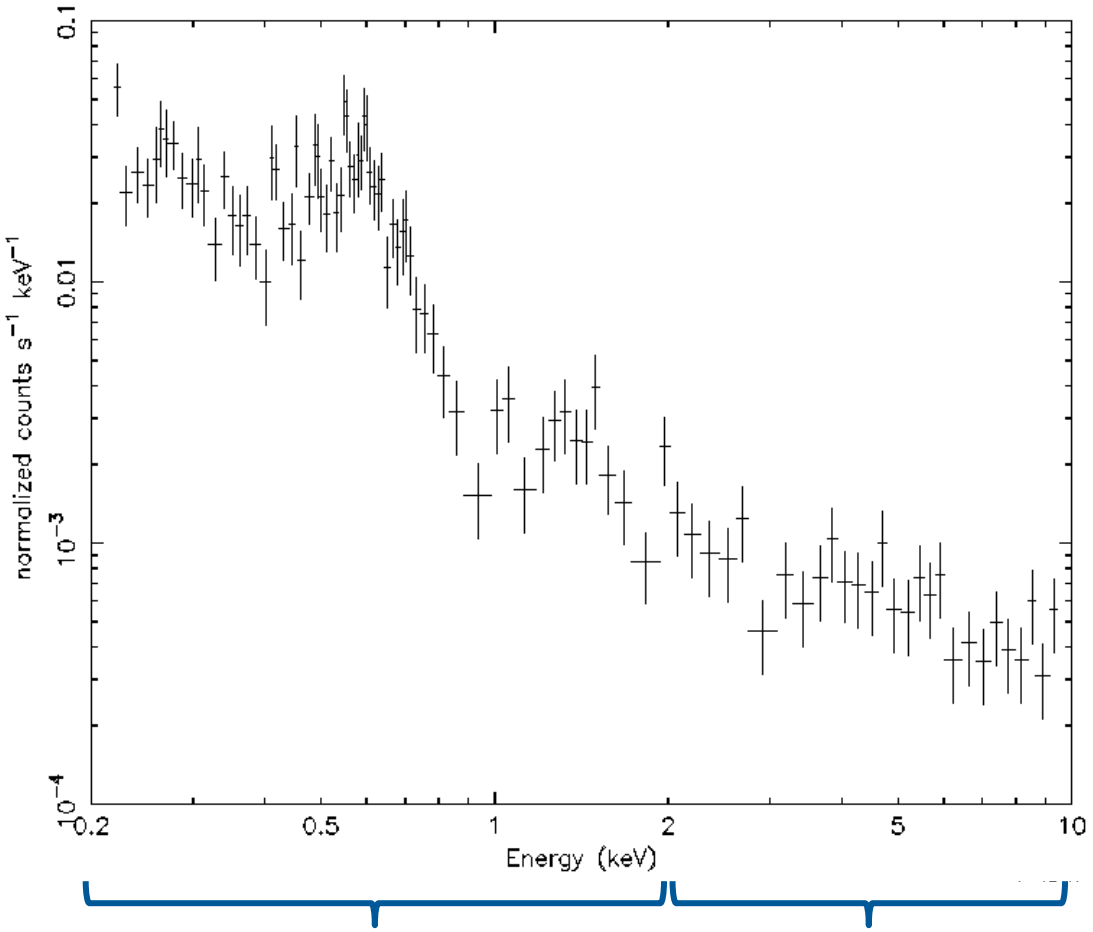


Numazawa et al., 2019

- X-ray auroral emissions at the poles
- Elastically scattered solar X-rays (+some fluorescence) off the disk
- Radiation belts also scatters solar X-rays
- Fluorescence from Galilean moons & Io Plasma Torus

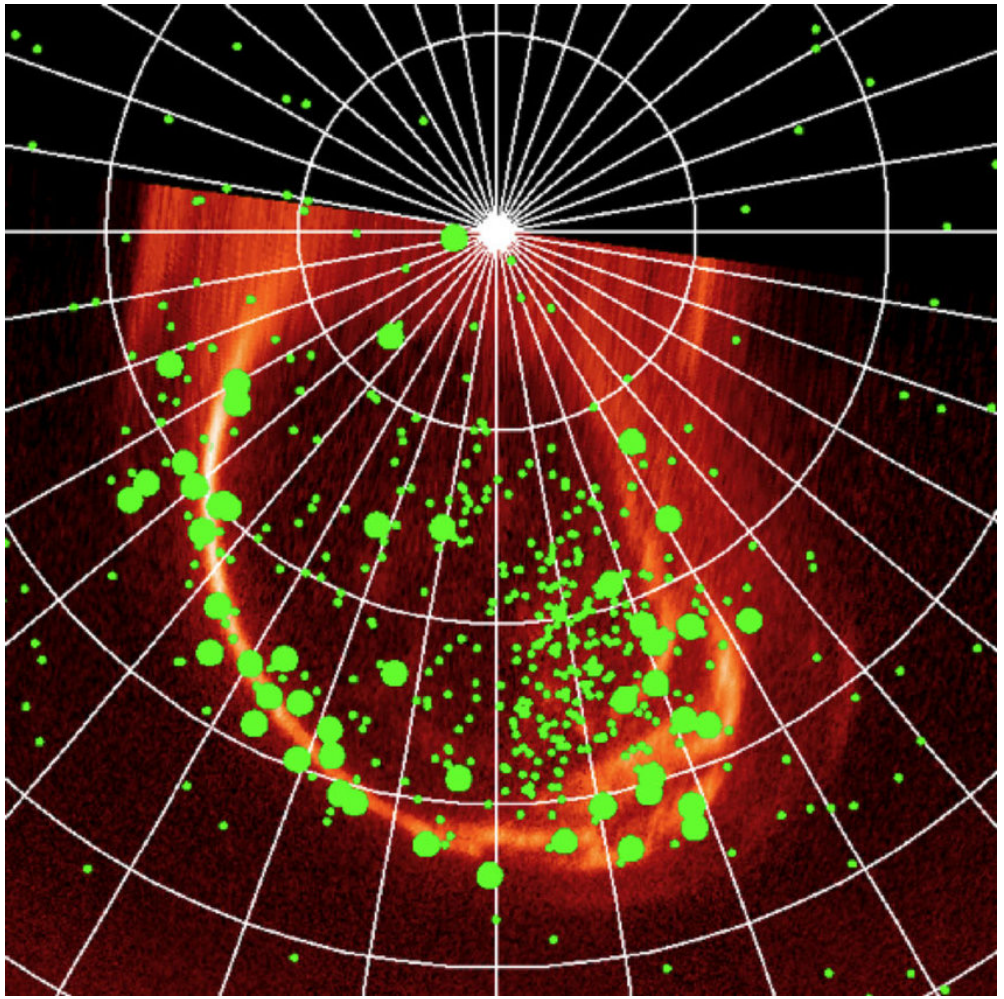
The X-ray Aurora

EPIC-pn Jupiter Northern Aurora Spectrum



Soft X-rays
Ion charge exchange

Hard X-rays
Electron bremsstrahlung



Soft X-rays

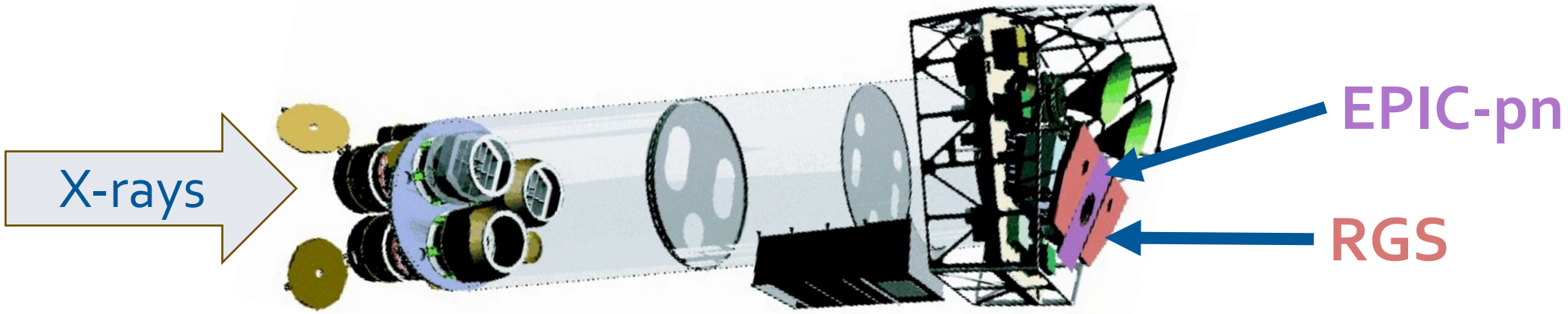
Hard X-rays

UV aurora

Branduardi-Raymont et al., 2008

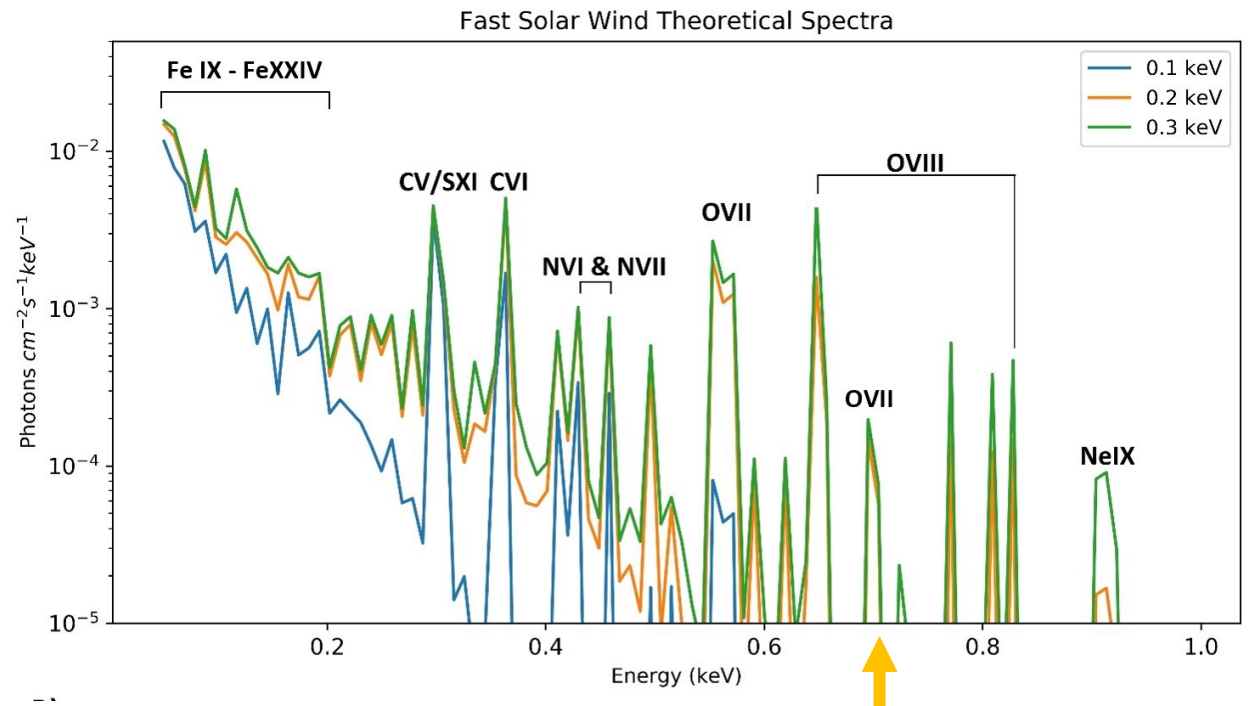
The EPIC-pn and RGS detectors

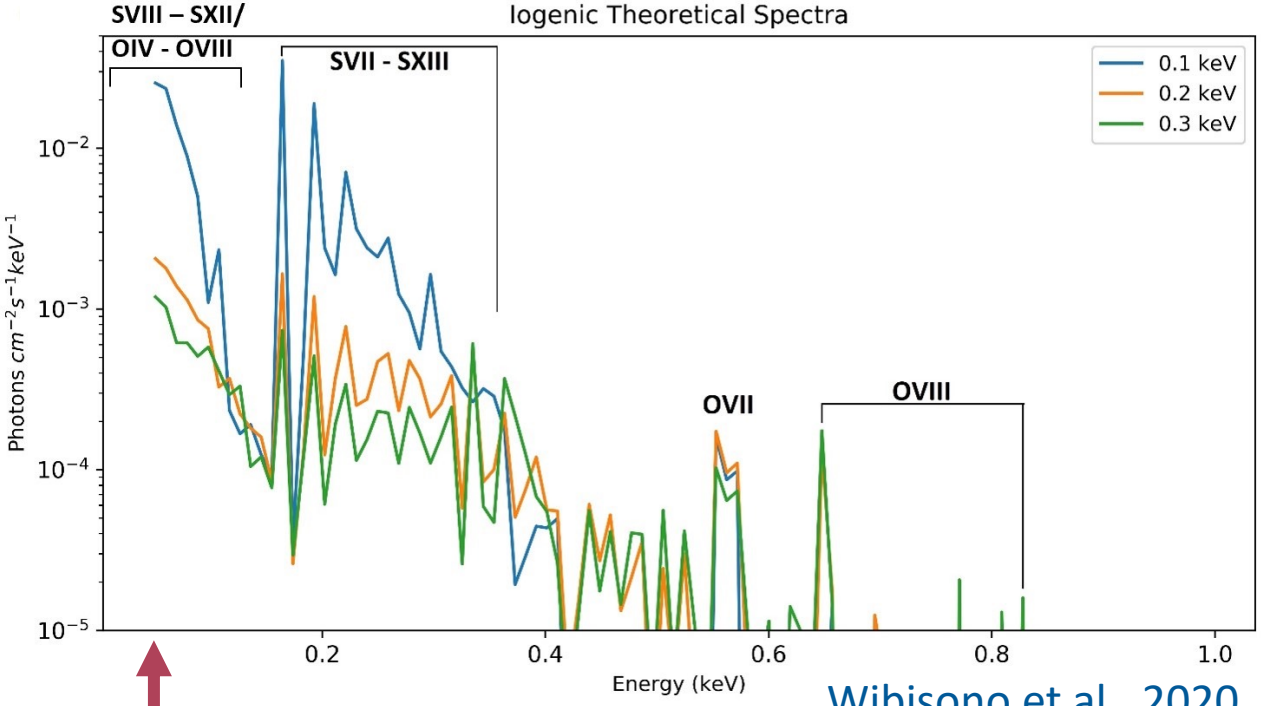
EPIC-pn	RGS
0.2 – 10 keV (62 – 1.24 Å)	0.54 – 0.95 keV (23 – 13 Å) (for Jupiter studies)
Larger effective area	Smaller effective area
Lower spectral resolution	Higher spectral resolution
X-ray imaging, moderate resolution spectroscopy	High resolution spectroscopy
The energy, time and position on the detector is recorded for every photon	Dispersive spectrometer



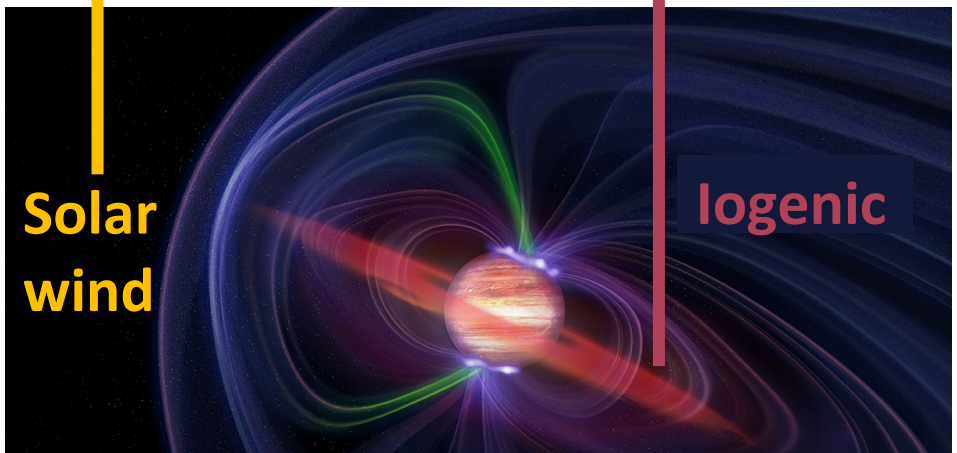
Jansen et al., 2001

Internal and External Plasma Population Spectral Models



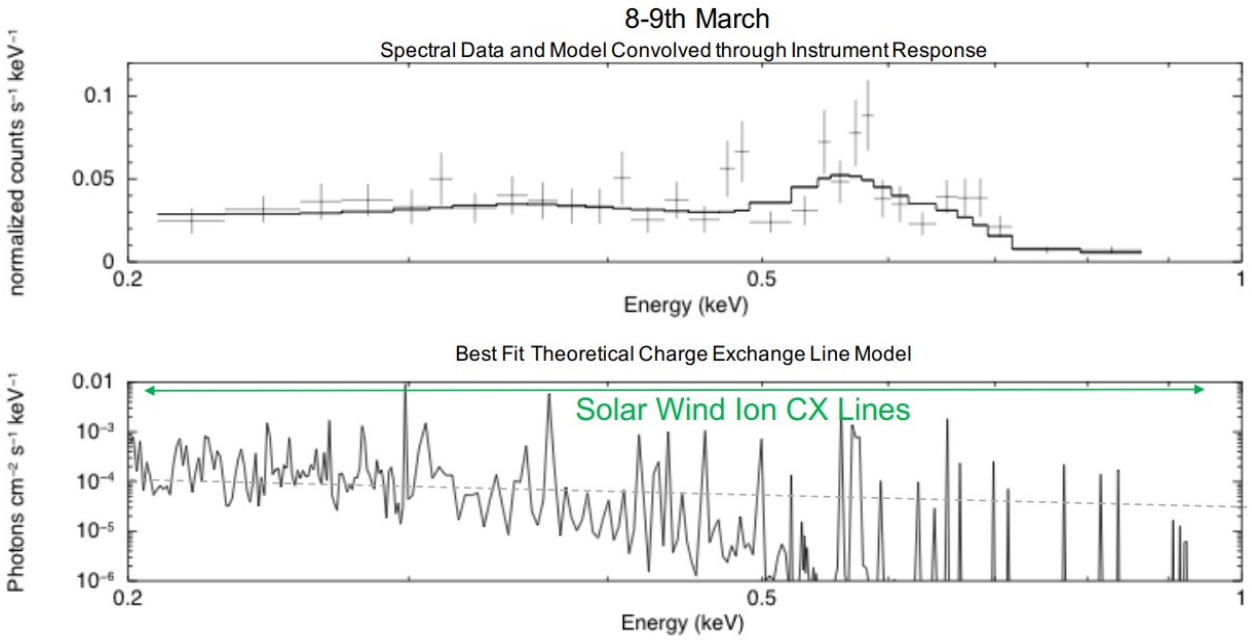


Wibisono et al., 2020

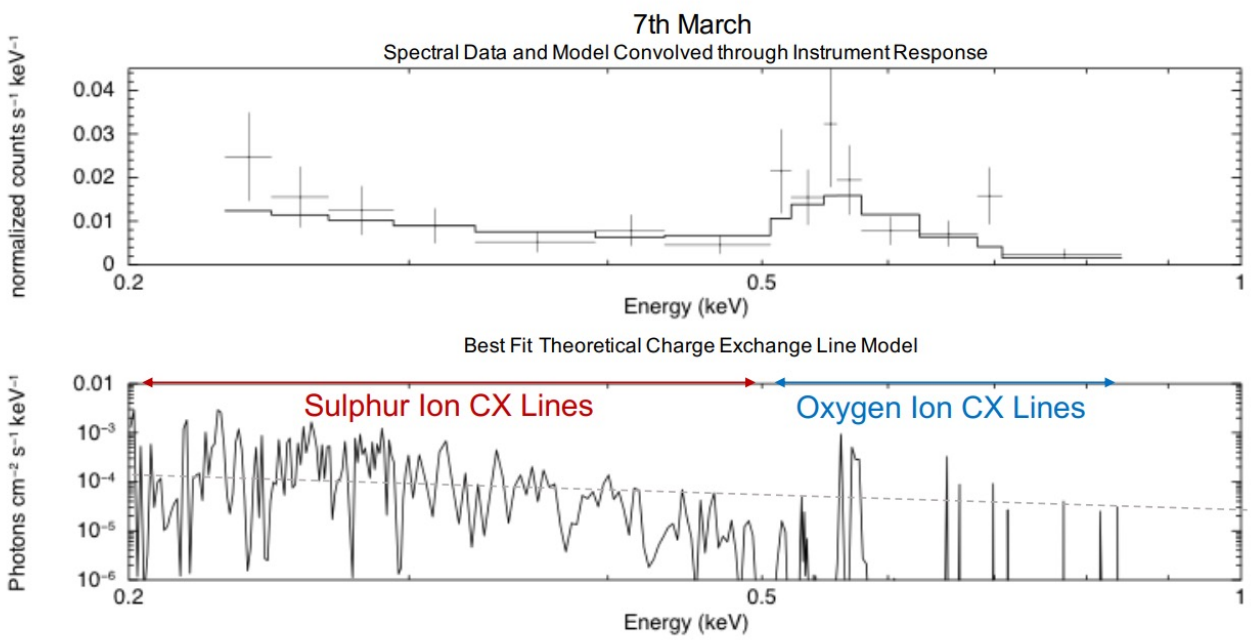


Sources of Jupiter's Aurorae – External and Internal Sources

Solar wind fit

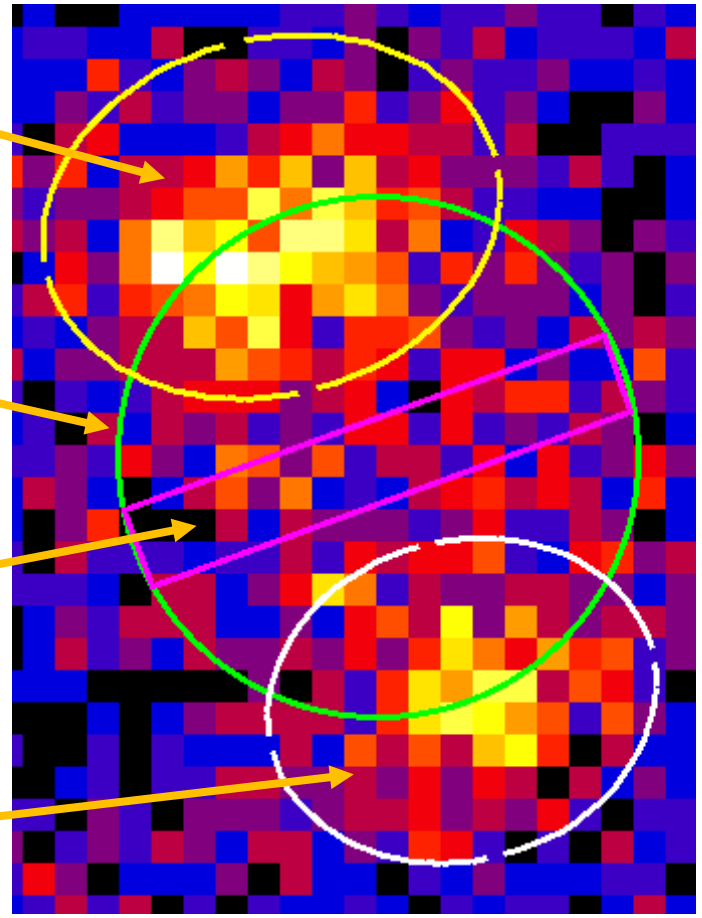


Iogenic fit

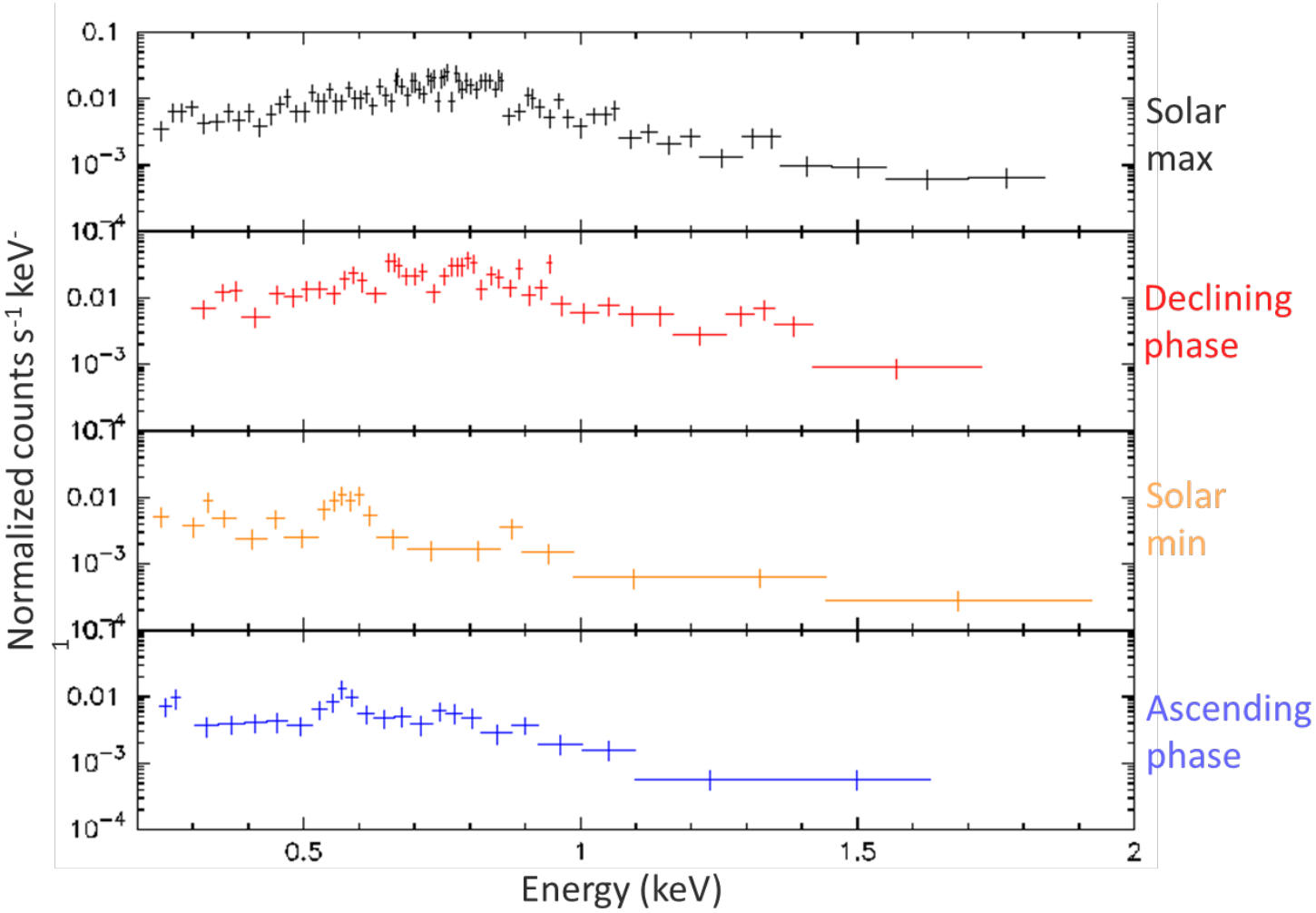


Dunn et al., 2020

Jupiter Equatorial Emissions

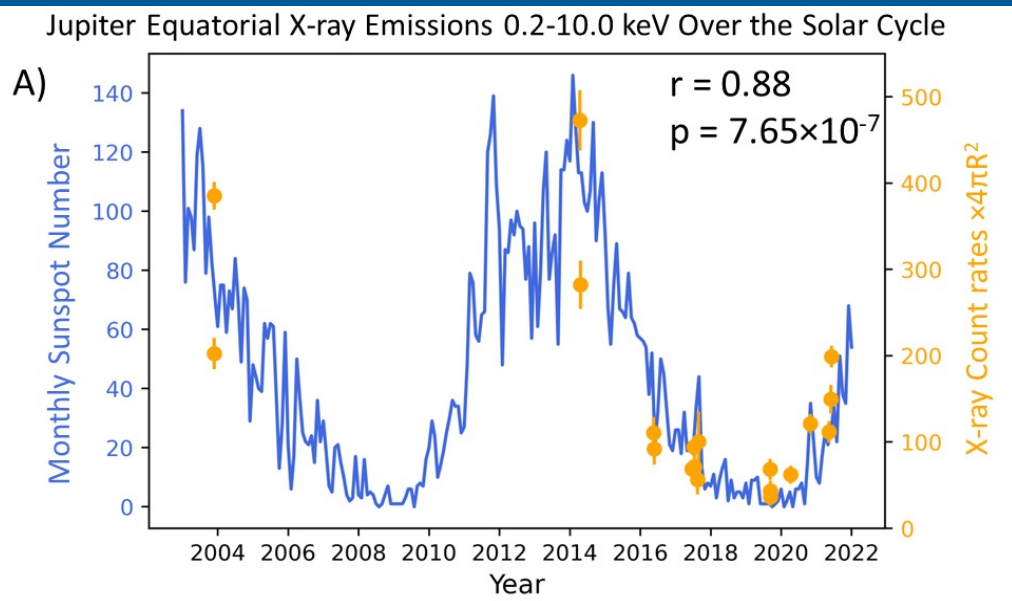


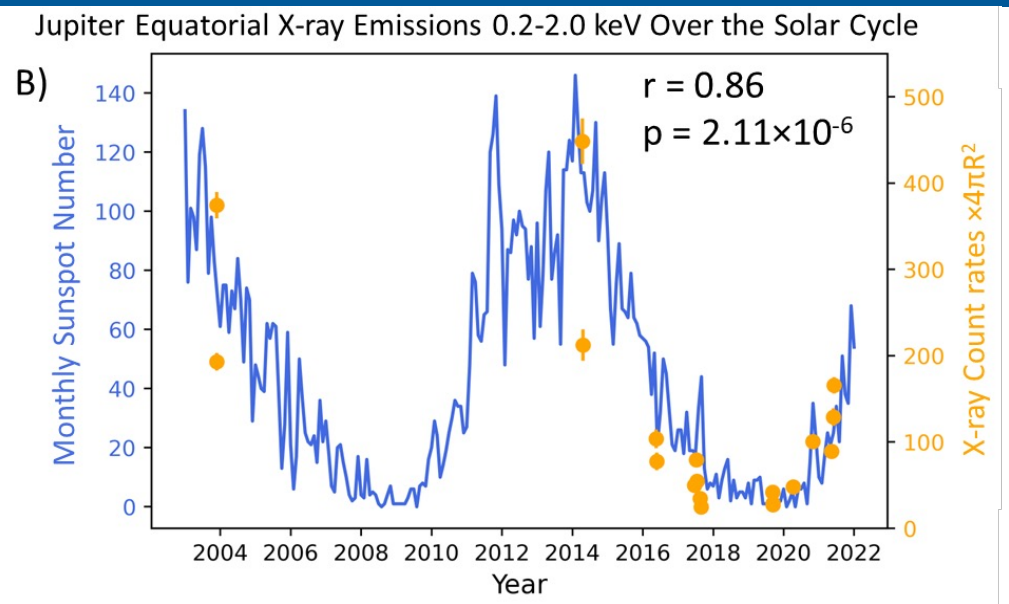
Wibisono et al., 2020



Jupiter As A Solar Monitor

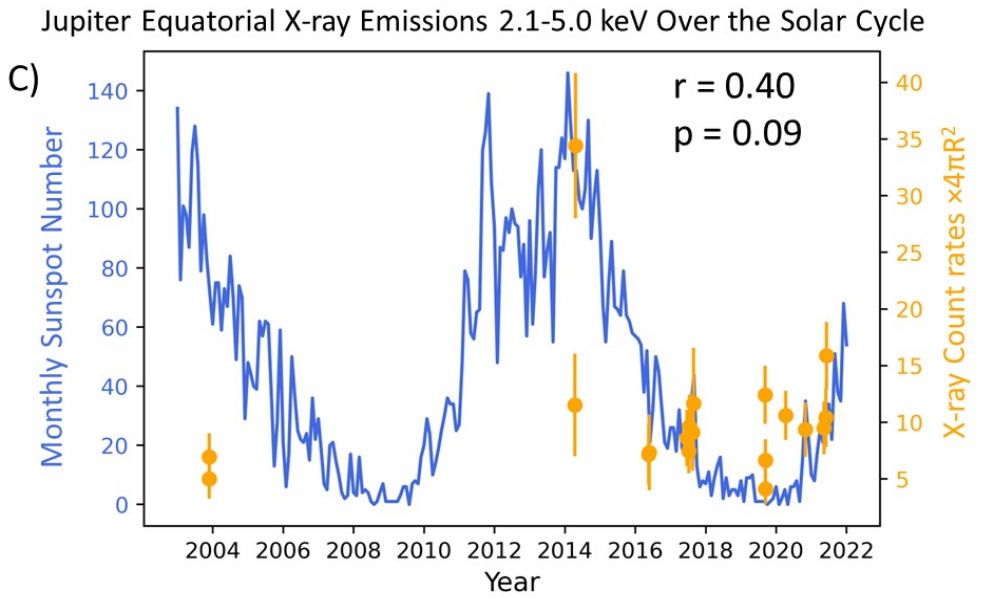
All Jupiter X-ray energies

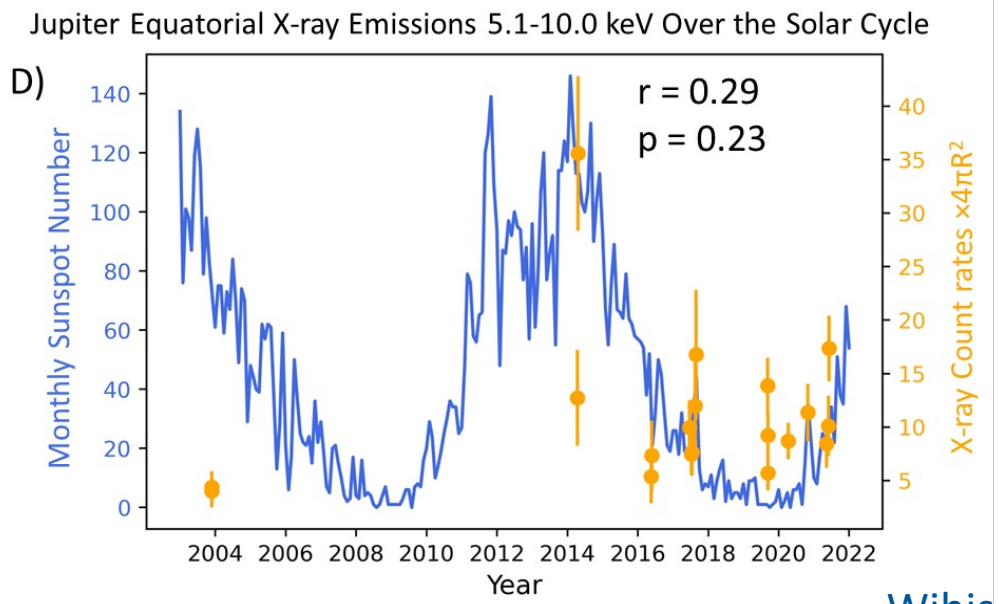




Low energies

Mid energies

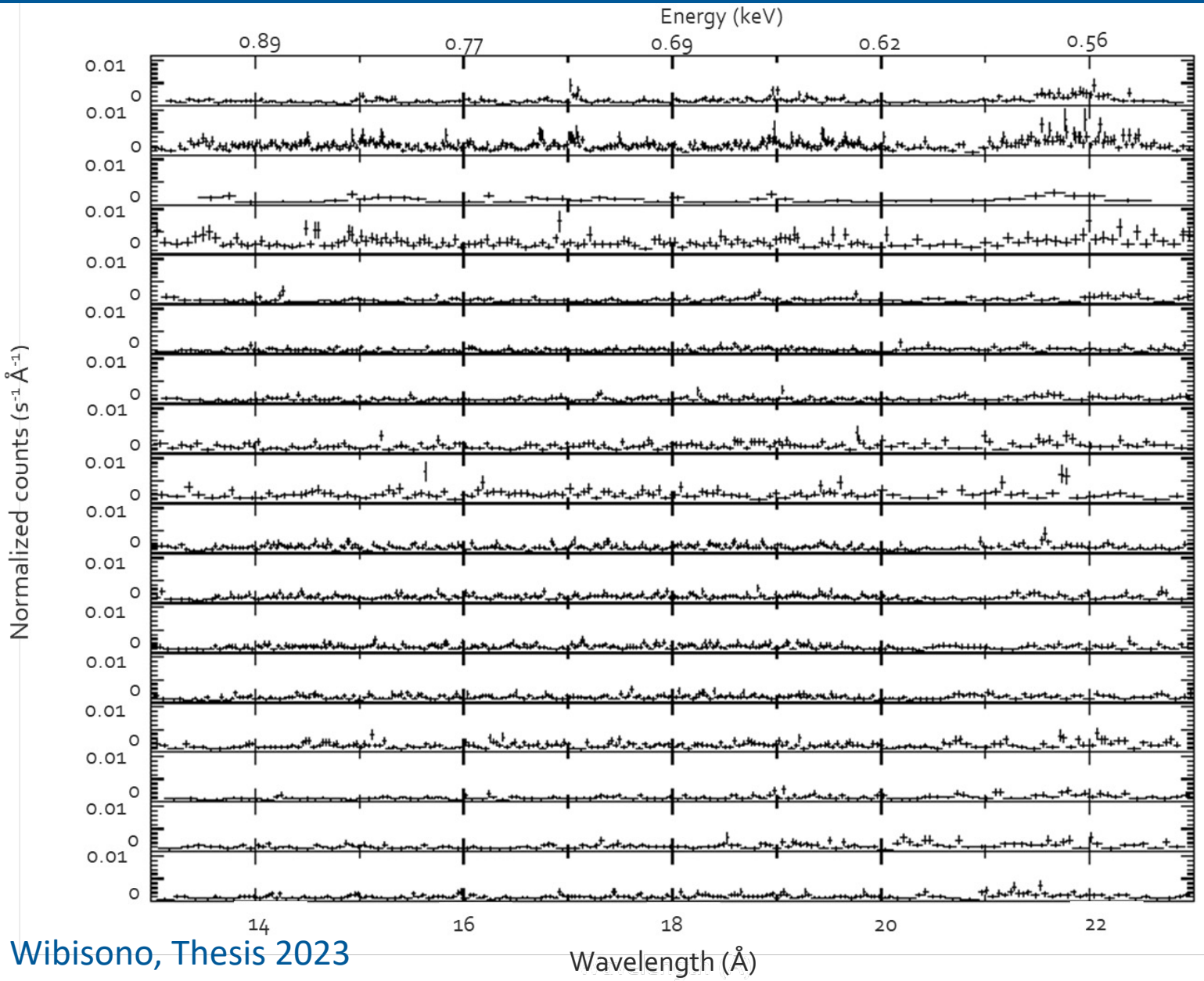




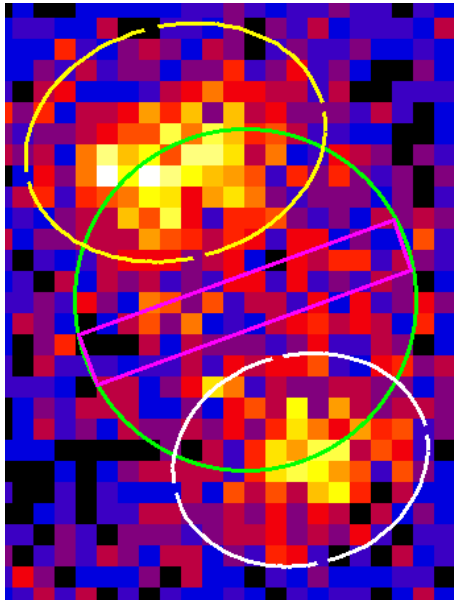
High energies

Wibisono et al., 2023

Jupiter RGS spectra



Date	Exposure time (ks)
25 Nov 2003	122
27 Nov 2003	134
15 Apr 2014	44
20 Apr 2014	46
19 Jun 2017	101
10 Jul 2017	140
16 Jul 2017	100
16 Jul 2018	22
27 Aug 2018	48
08 Sep 2019	135
10 Sep 2019	135
12 Sep 2019	136
08 Apr 2020	140
31 Oct 2020	135
10 May 2021	127
02 Jun 2021	79
07 Jun 2021	131



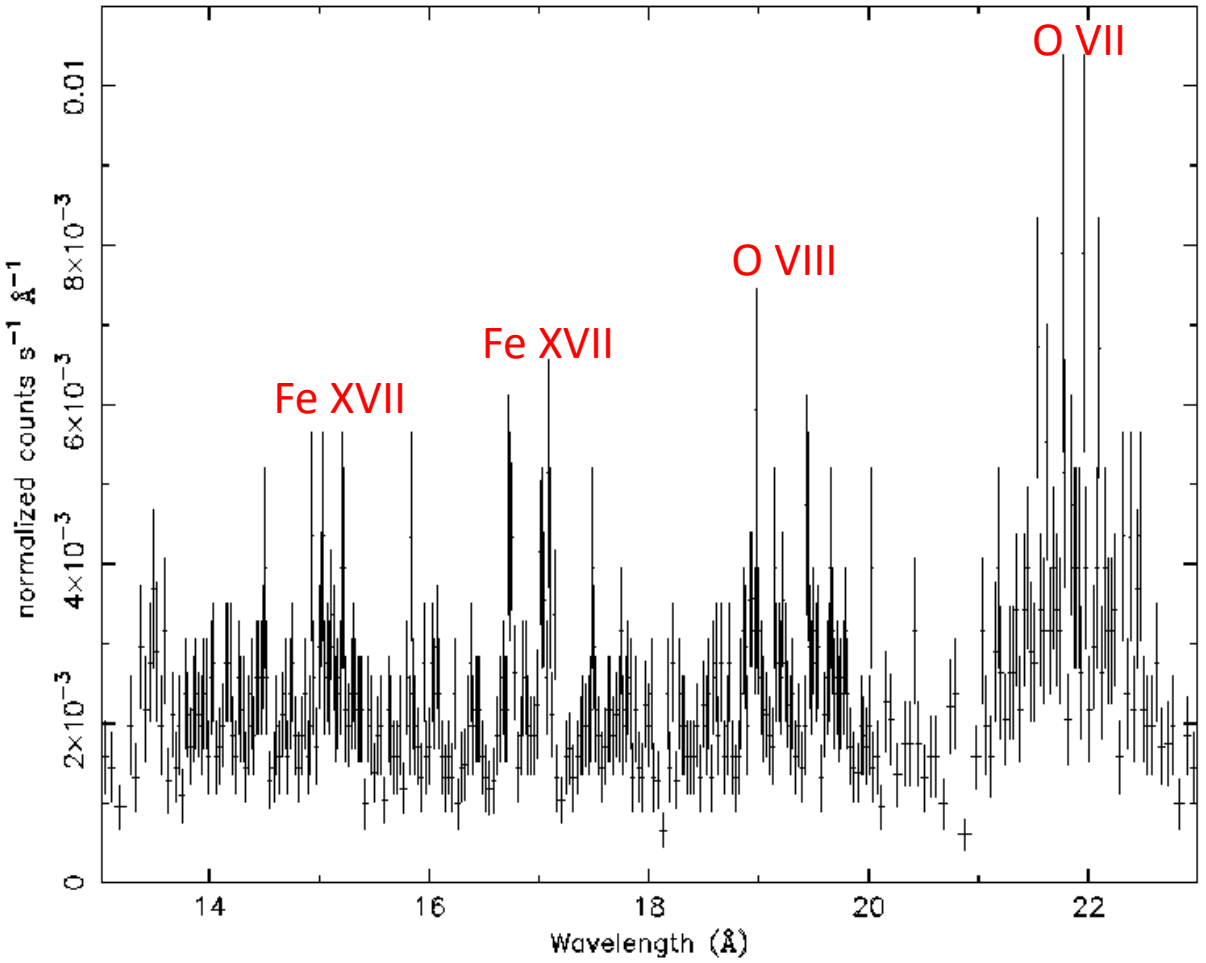
Wibisono et al., 2020

RGS spectra extracted from entire disk

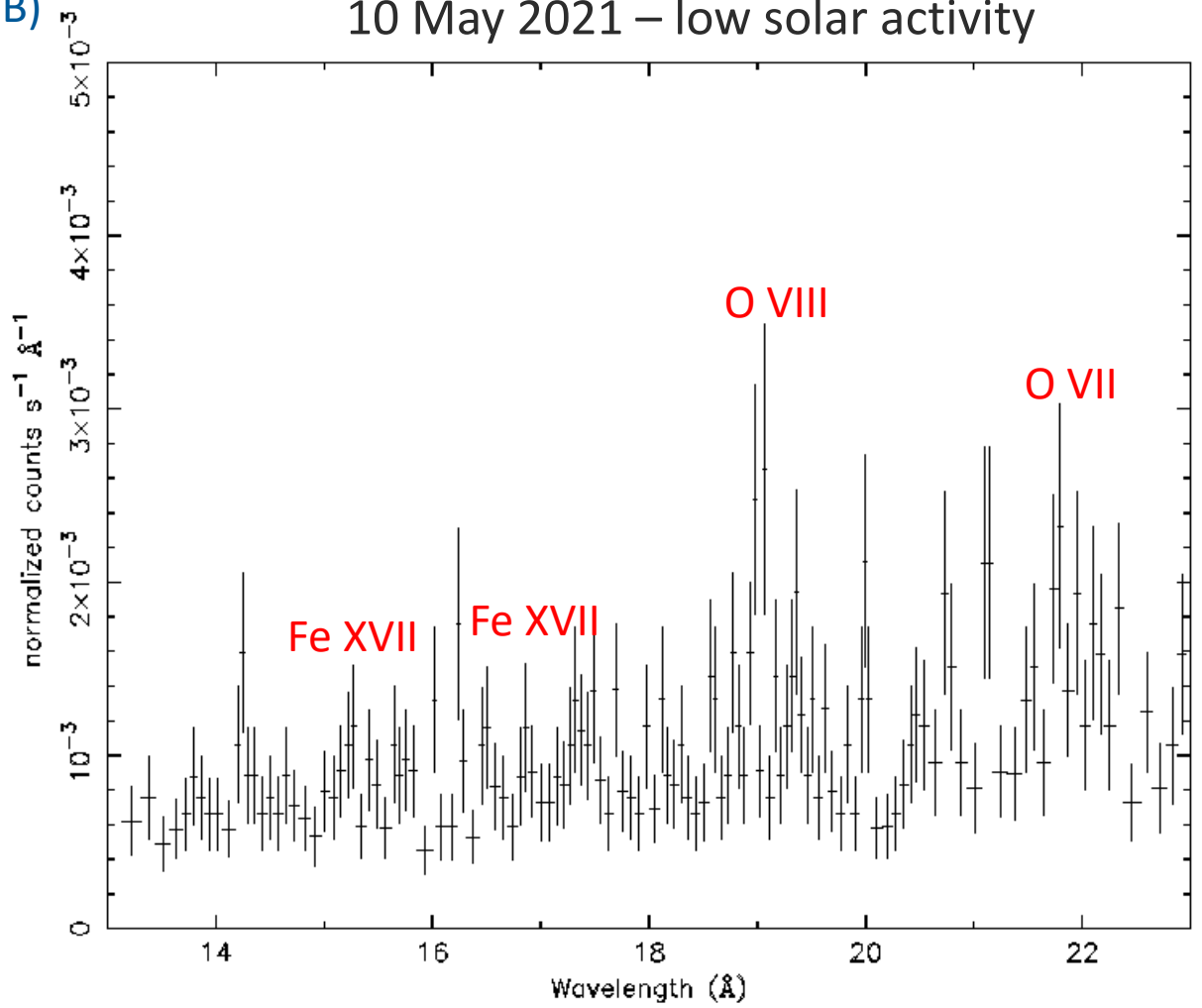
Wibisono, Thesis 2023

Jupiter RGS spectra

A) 27 Nov 2003 – increased solar activity



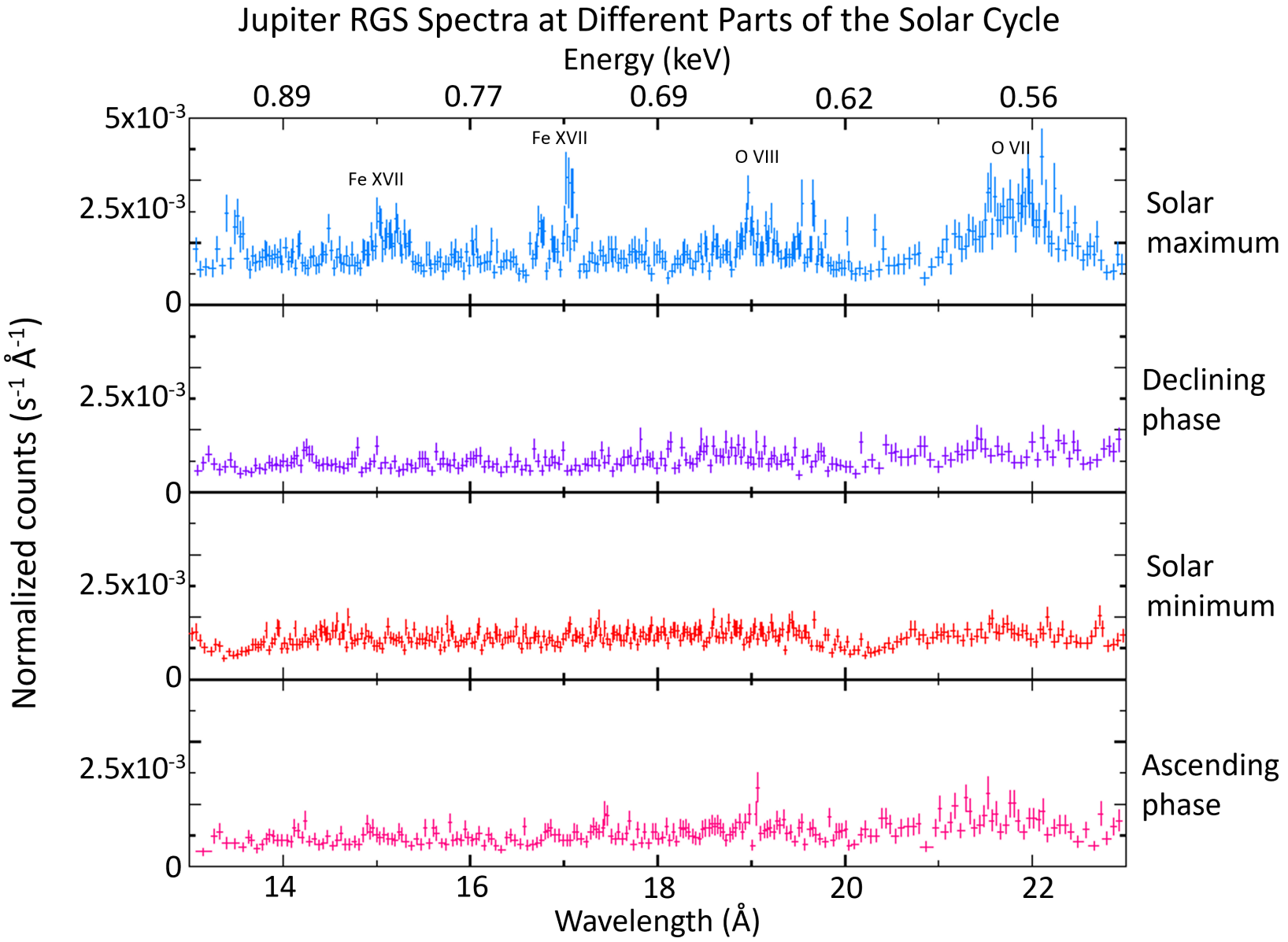
B) 10 May 2021 – low solar activity



Wibisono, Thesis 2023

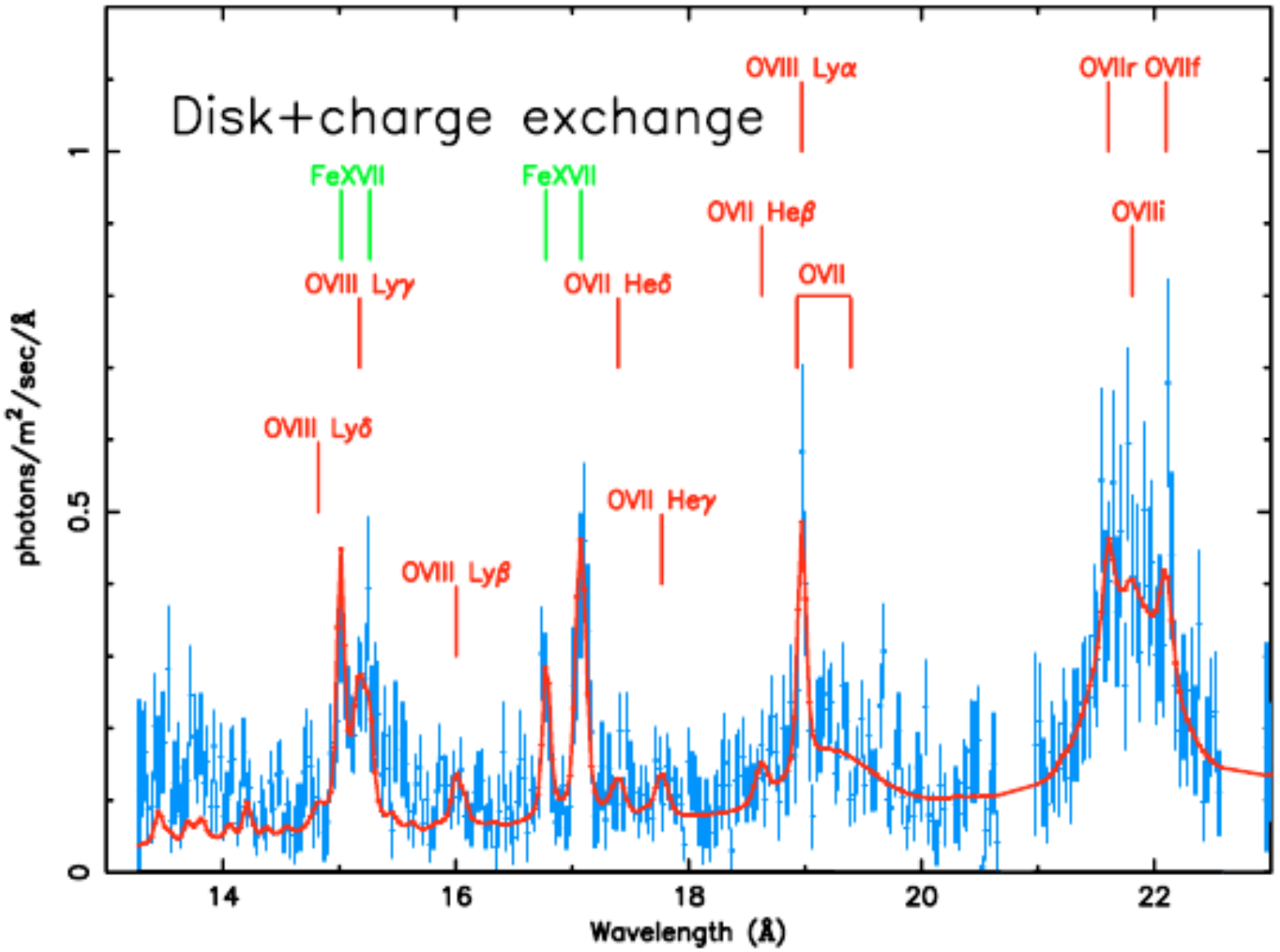
O VII and O VIII are from the aurorae; Fe XVII is from the disk

Jupiter RGS spectra and the solar cycle



Wibisono, Thesis 2023

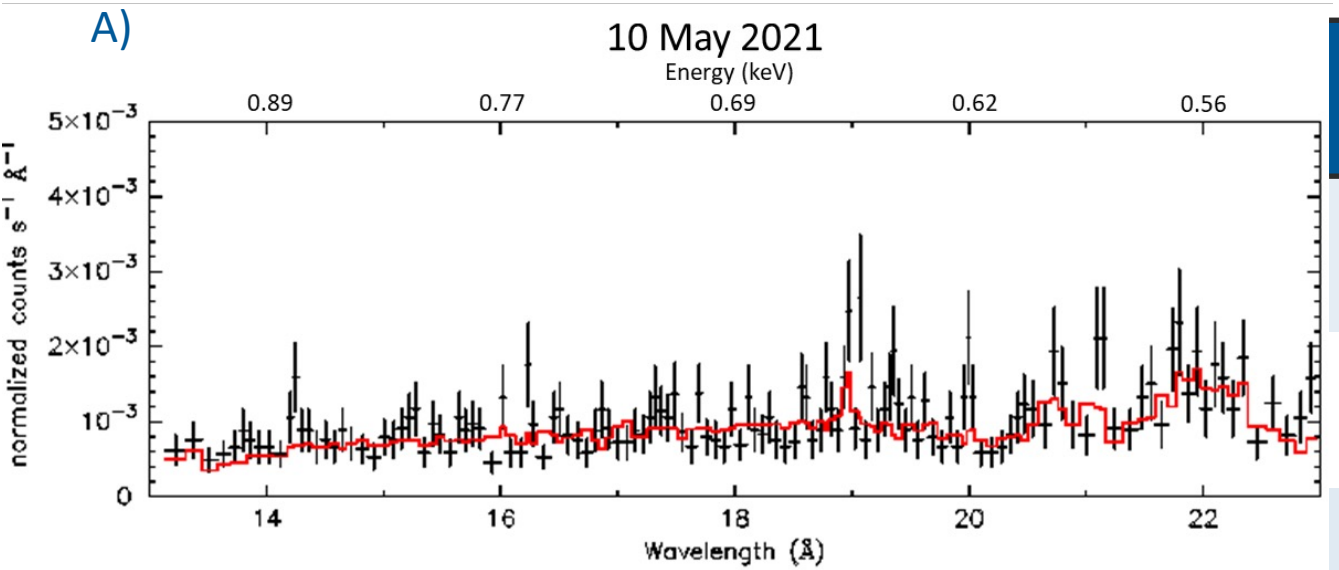
Fitting Jupiter RGS spectra



- Models to fit disk and auroral CX emissions
- Widths of broad OVII and OVIII lines indicate O ions had speeds of +/- 5000 km s^{-1} and energies of 2.5 MeV

Branduardi-Raymont et al., 2007

2021 Jupiter RGS spectra



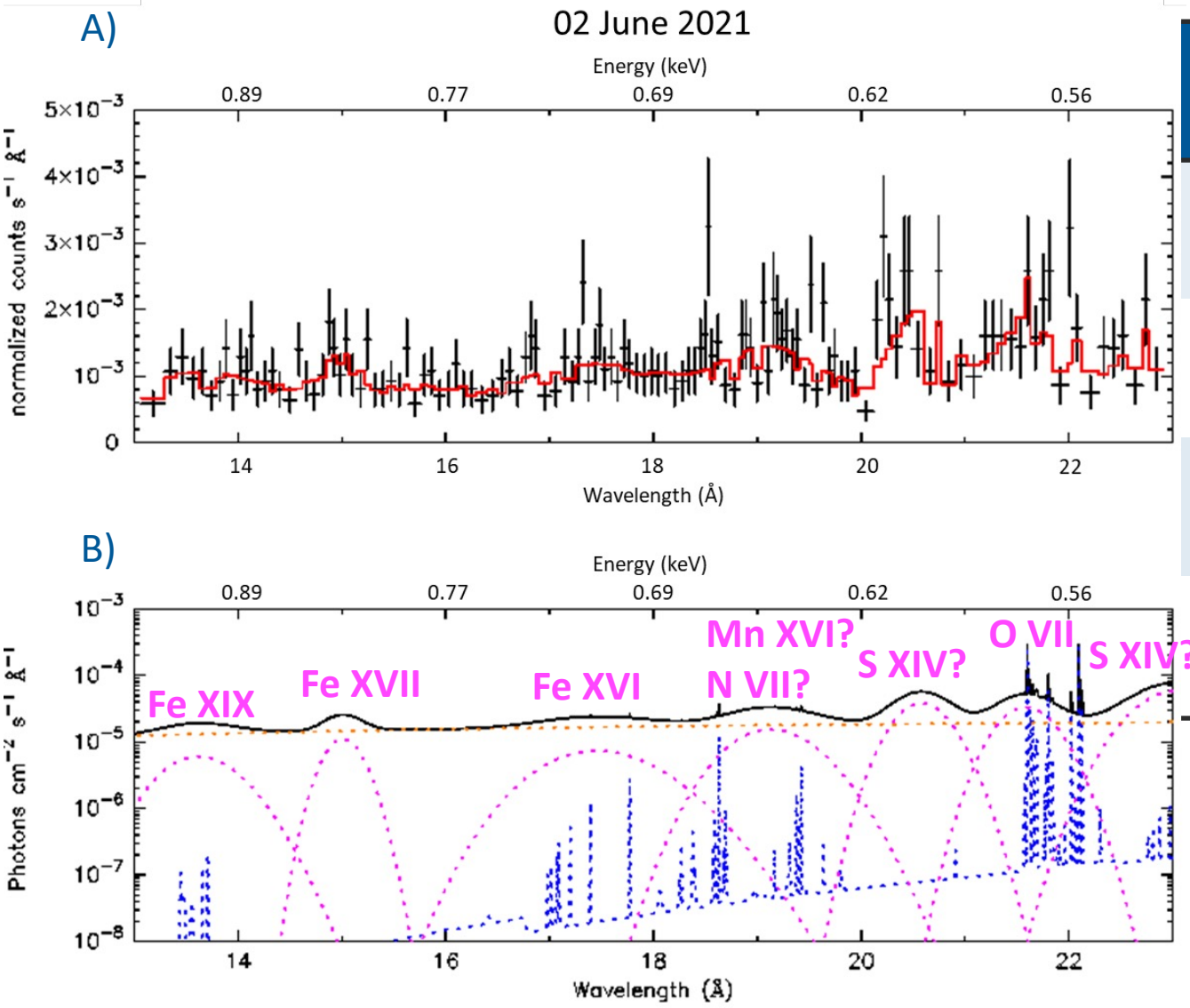
Model	Parameter value
APEC kT (keV) - - - - - (Solar scattering)	0.21 +0.04/-0.05
APEC normalization	(7.28 +/- 4.26)x10^{-6}
Bremsstrahlung kT (keV) - - - - - (Underlying continuum)	0.27 +/- 0.01
Bremsstrahlung normalization	(1.95 +/- 0.01)x10^{-3}

Reduced χ^2 = 1.03 for 122 degrees of freedom

Model Flux 2.40x10^{-13} ergs cm^{-2} s^{-1}

Wibisono, Thesis 2023

2021 Jupiter RGS spectra



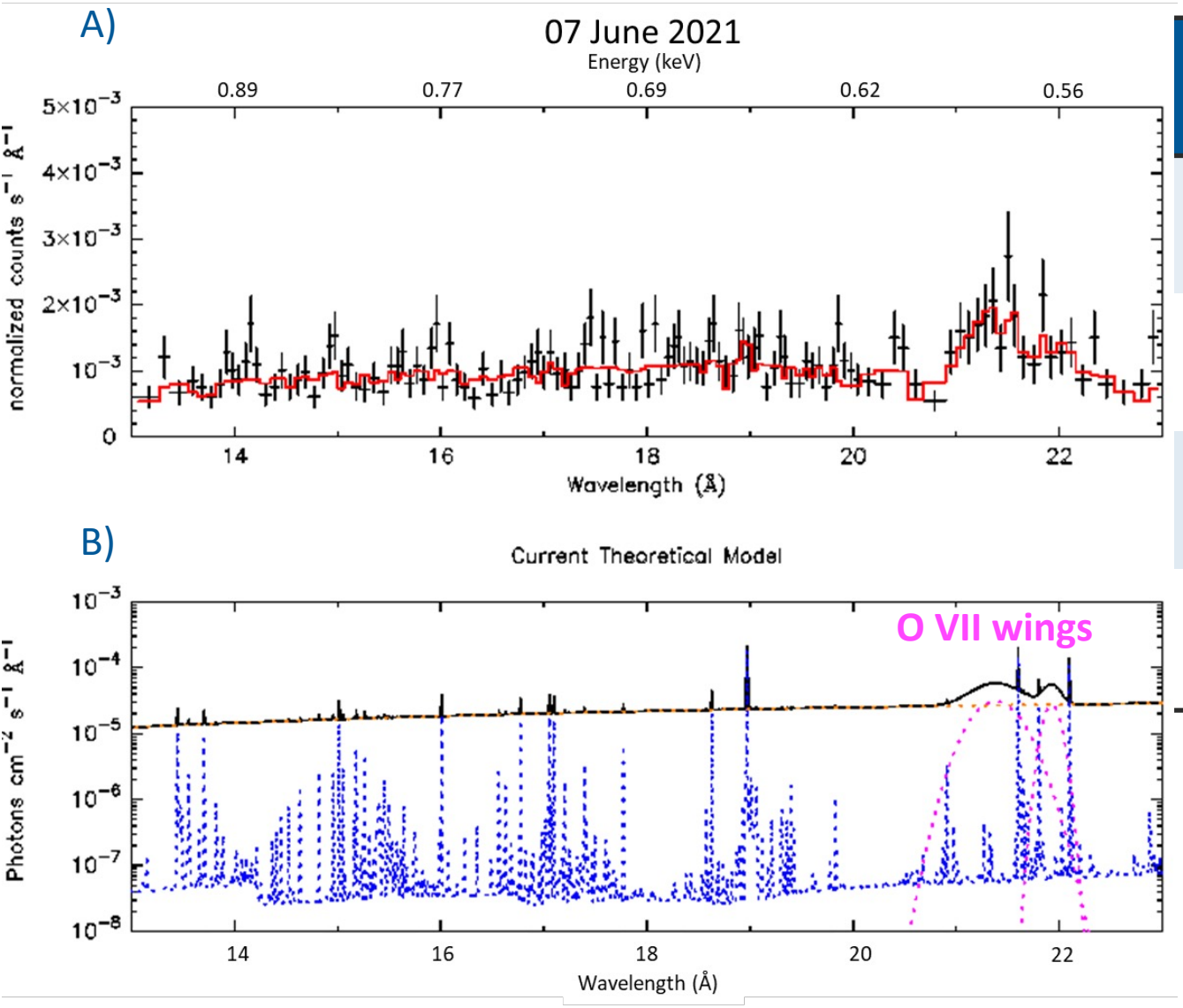
Model	Parameter value
APEC kT (keV)	0.06 +/- 0.01
APEC normalization	$(6.59 \pm 0.6) \times 10^{-4}$
Bremsstrahlung kT (keV)	0.48 +0.03/- 0.02
Bremsstrahlung normalization	$(0.69 \pm 0.04) \times 10^{-3}$

Reduced χ^2 = 0.92 for 107 degrees of freedom

Model Flux 2.94×10^{-13} ergs cm^{-2} s^{-1}

Wibisono, Thesis 2023

2021 Jupiter RGS spectra



Model	Parameter value
APEC kT (keV)	0.22 +0.1/- 0.07
APEC normalization	(5.38 +/- 3.50)x10^{-6}
Bremsstrahlung kT (keV)	0.33 +/- 0.01
Bremsstrahlung normalization	(1.49 +/- 0.06)x10^{-3}

Reduced χ^2 = 1.03 for 118 degrees of freedom

Model Flux 2.63x10^{-13} ergs cm^{-2} s^{-1}

Wibisono, Thesis 2023

Summary

- Jupiter's X-ray emissions are highly variable between observations and even planetary rotations
- Analysing Jupiter RGS spectra requires exposures of at least 100 ks (or for Jupiter to be hit by intense solar activity)
- Stacking spectra can wash out unique details from individual spectra
- EPIC-pn and RGS spectra show sulfur ion emission lines – Iogenic in origin

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