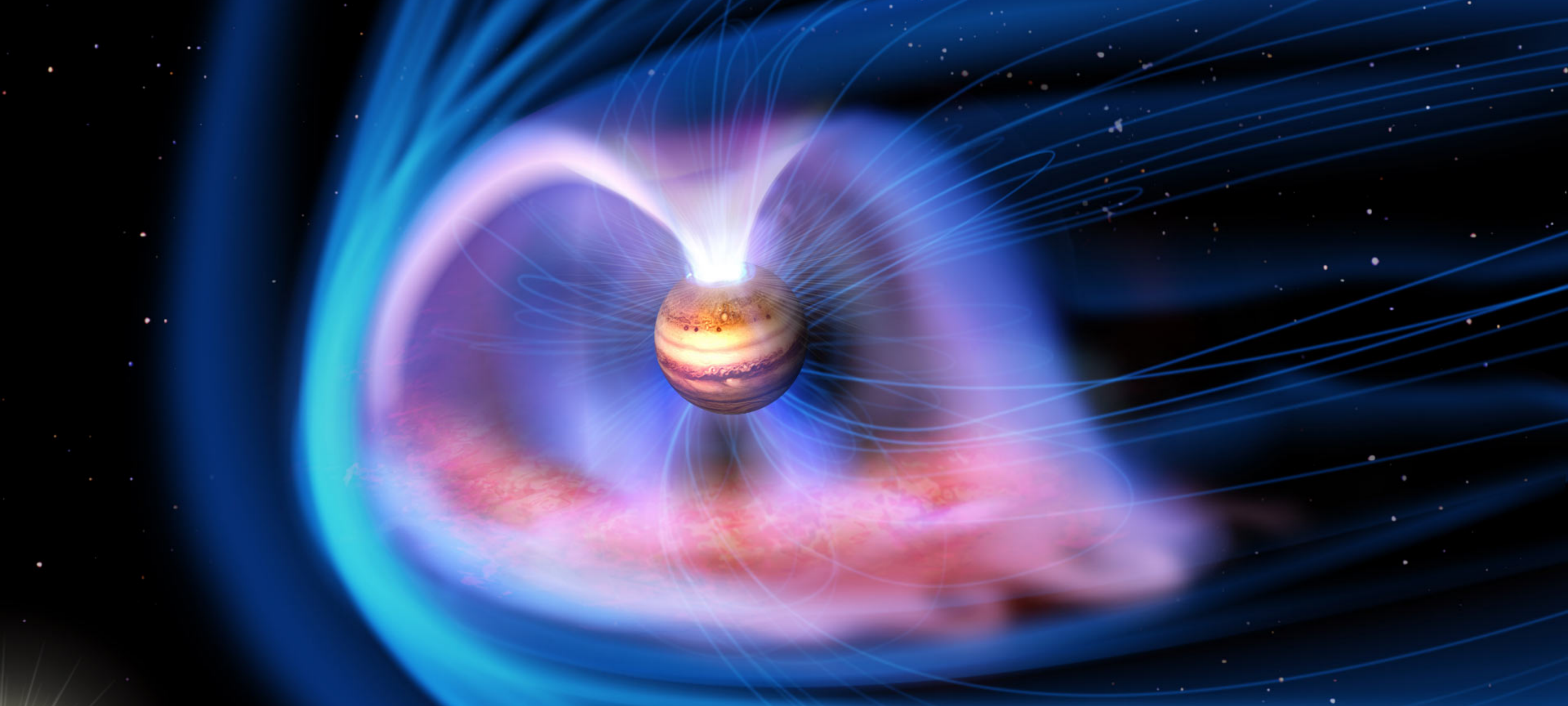
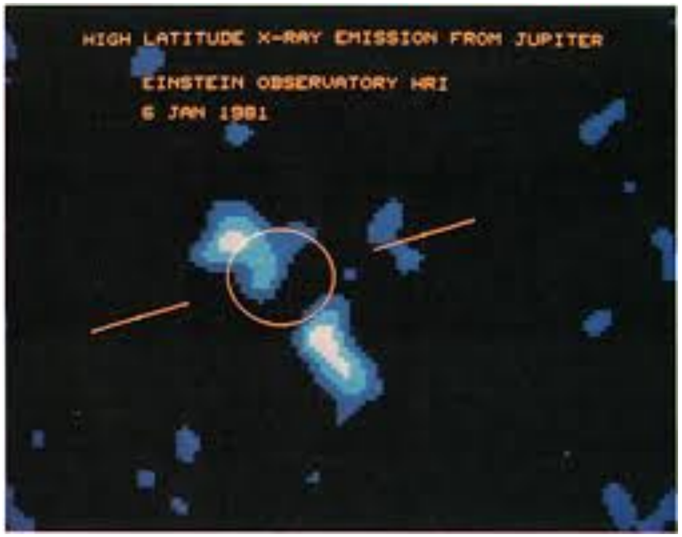
# A New Revolution for Planetary X-ray Emission Through Chandra, XMM and Juno



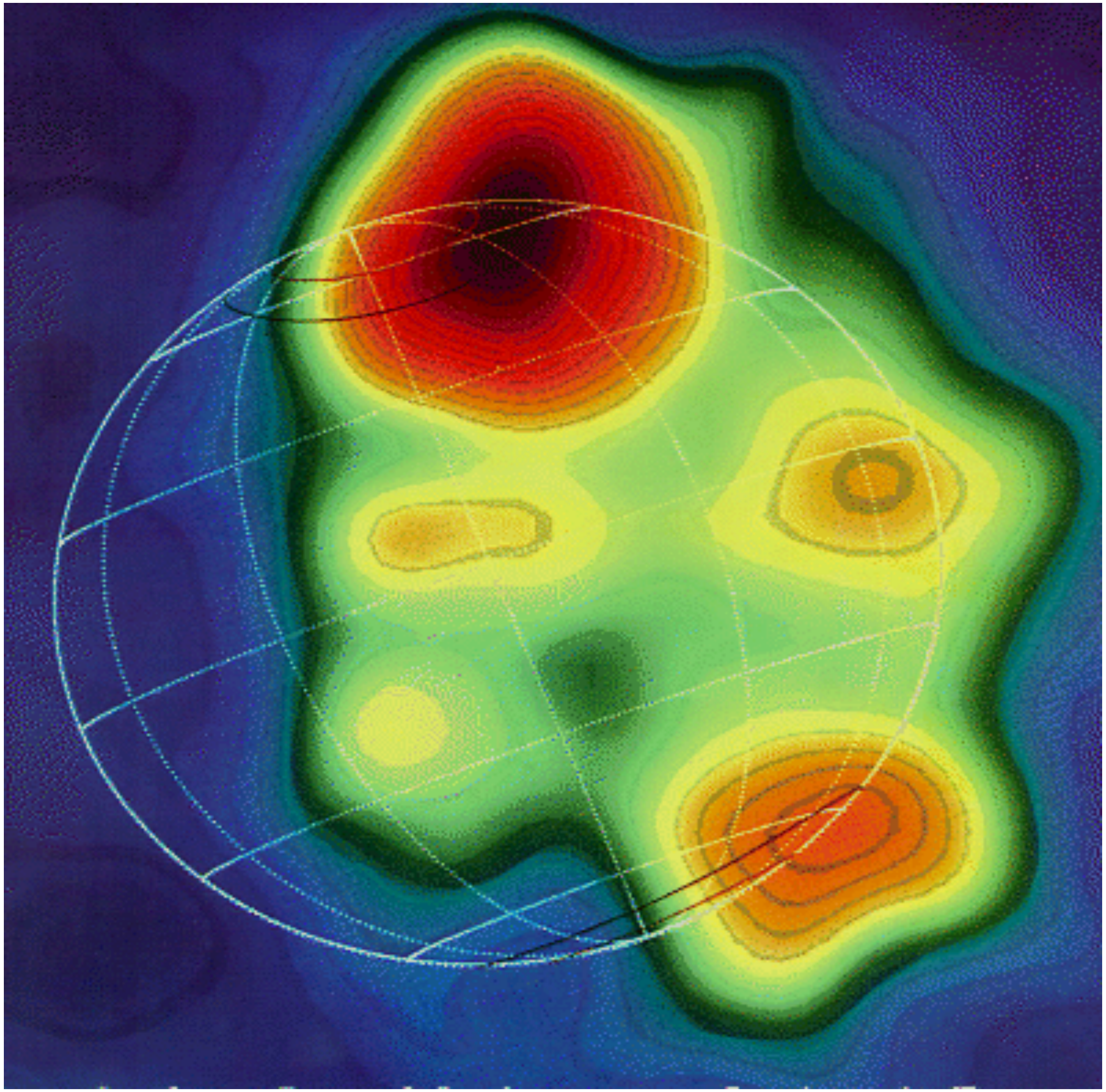
W. Dunn, G. R. Gladstone, Z. Yao, D. Weigt, G. Branduardi-Raymont, D. Grodent J-U. Ness, E. Woodfield, S. Kotsiaros, A. Sulaiman, A. Wibisono, W Kurth, G. Clark, C. Paranicas, B. Mauk, J. Connerney, B. Snios, R. Kraft, E. McClain,

# An Einstein Observatory Jupiter




[Metzger et al. 1983]

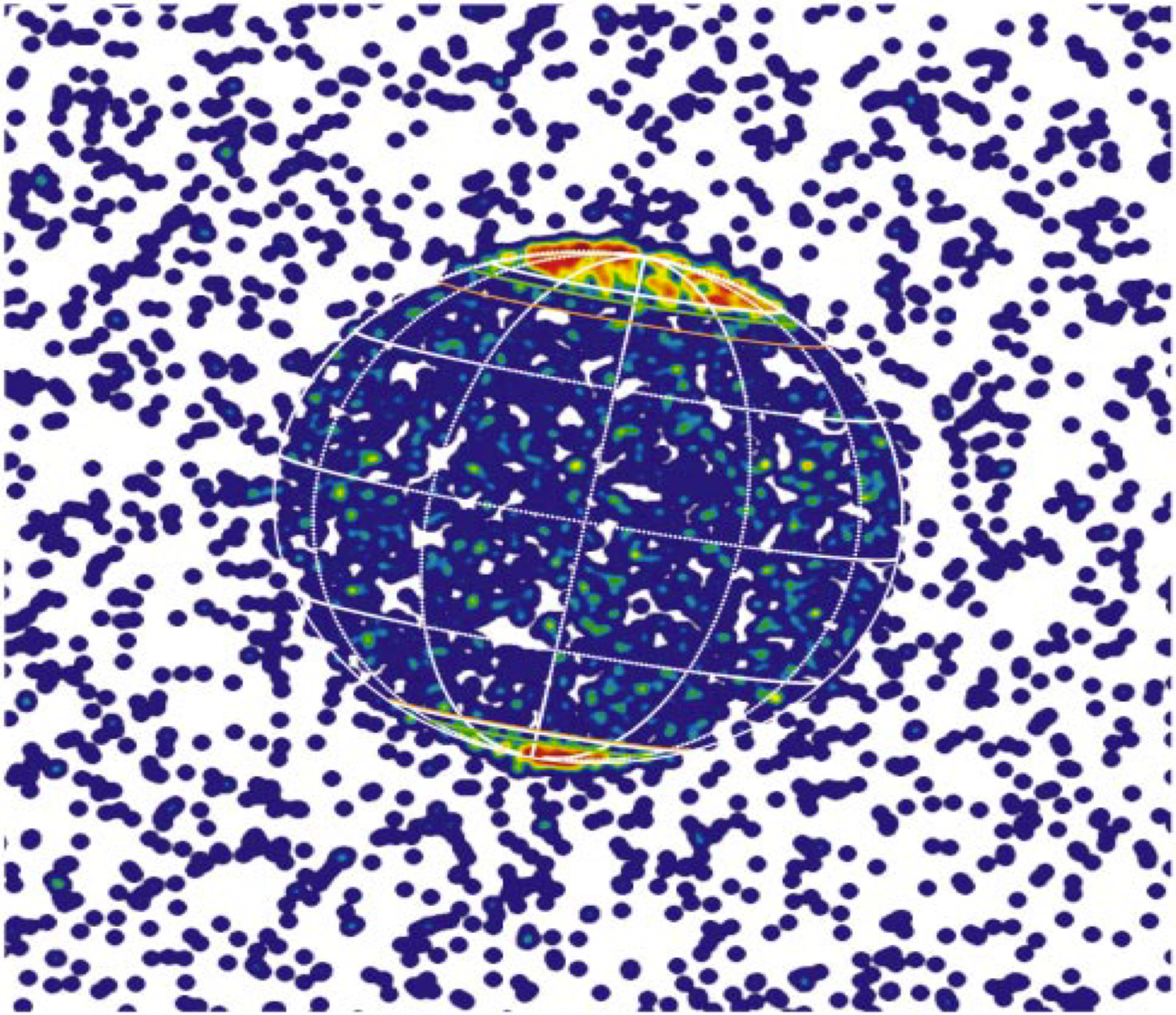
# A ROSAT Jupiter



[Waite & Gladstone 1994]

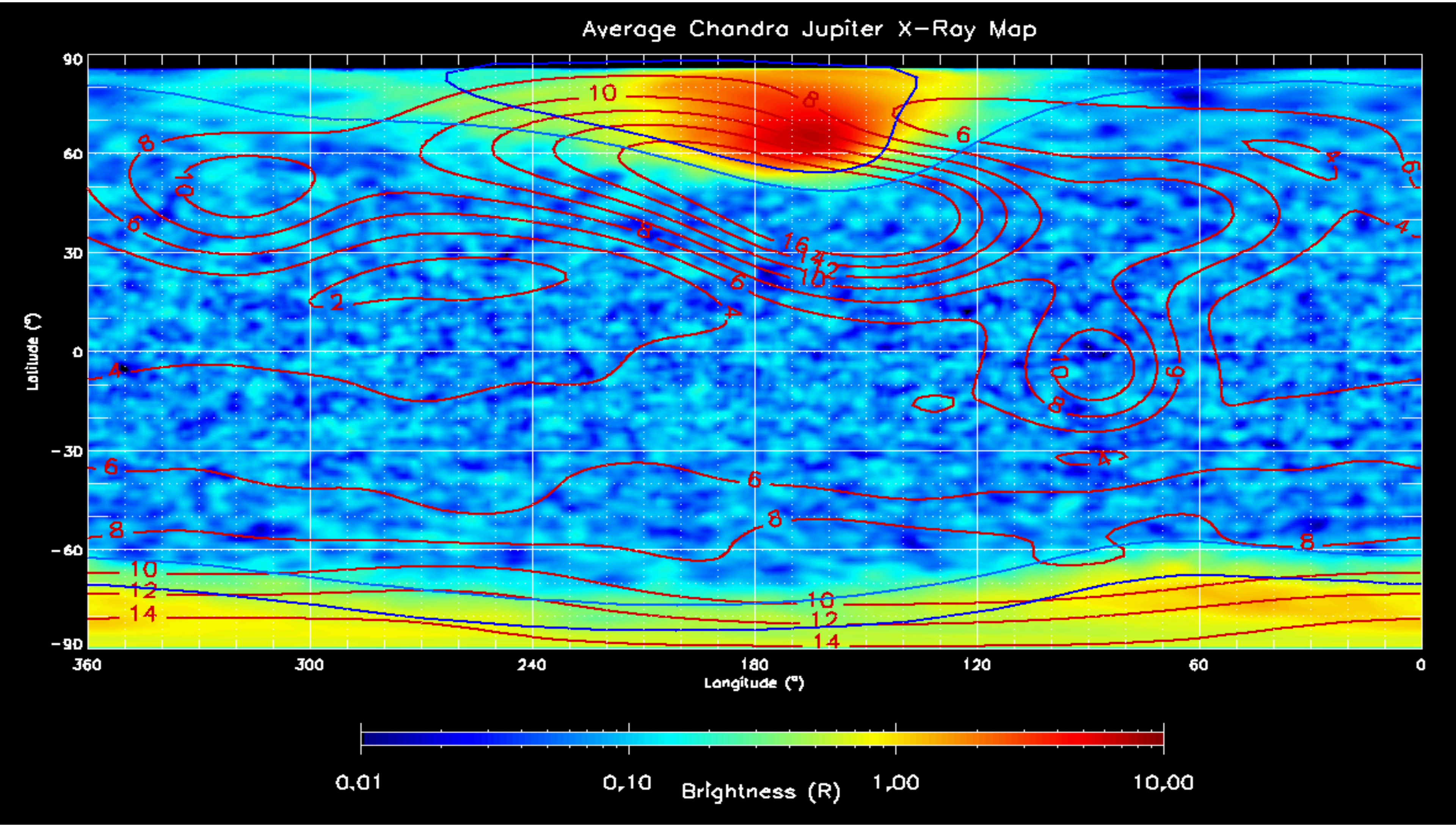
# The First Planetary X-ray Revolution

# A Chandra Jupiter



Gladstone et al. Nature, 2002

# An X-ray Map of Jupiter

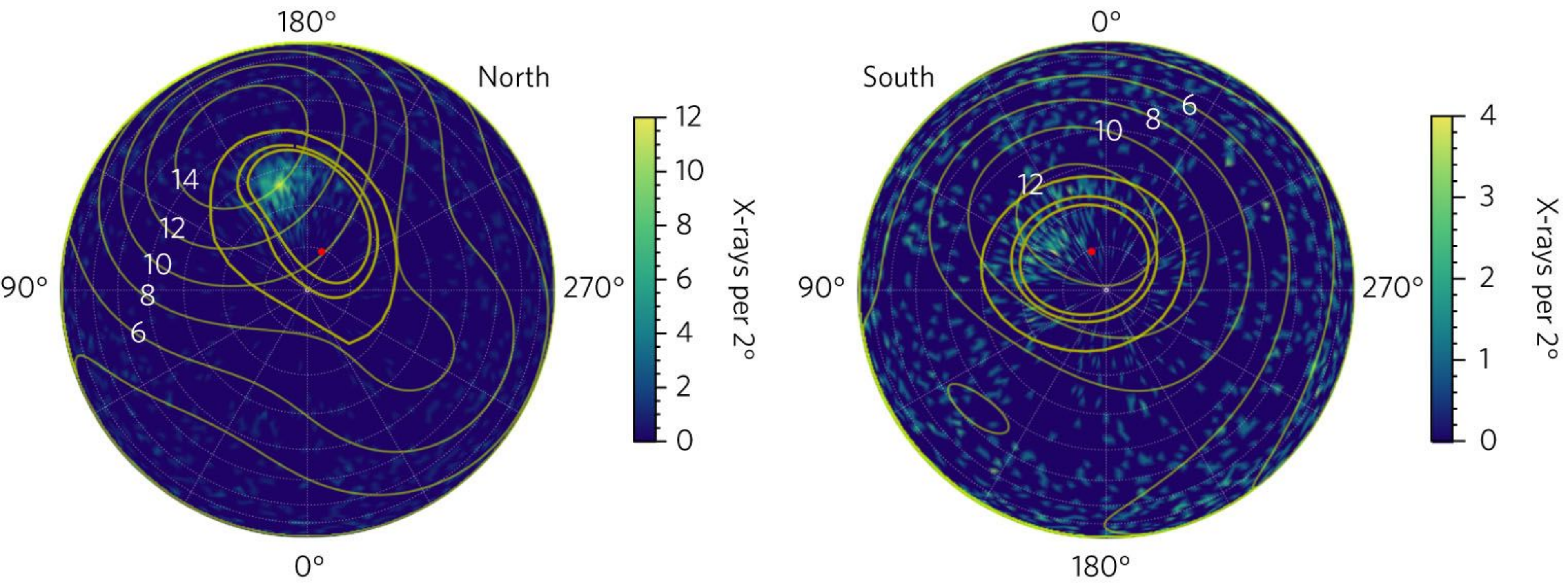



X-ray Heat Map

Red Contours are Magnetic Field Strength

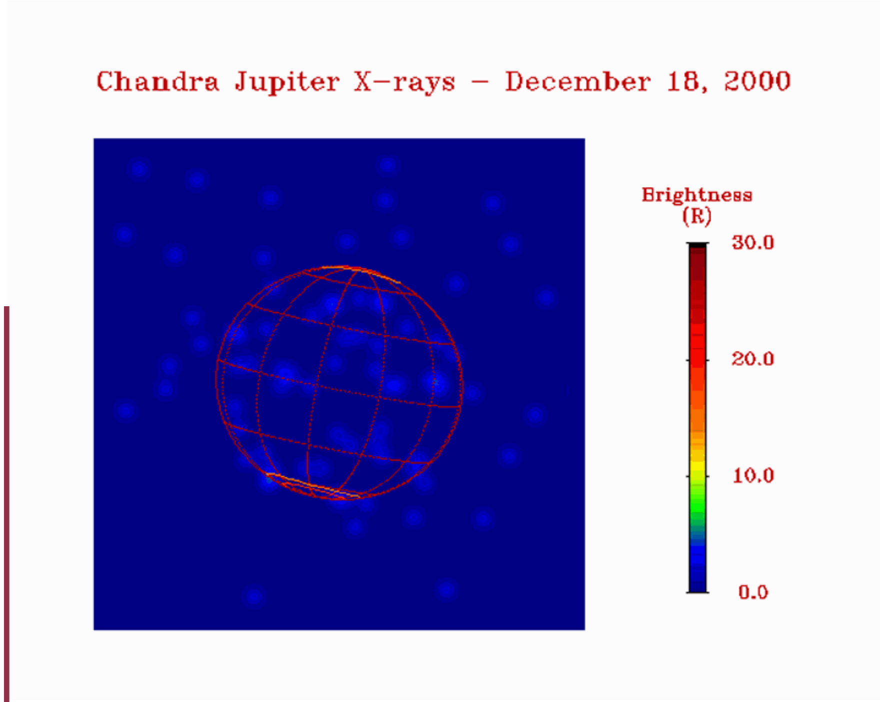
Blue contours show the footprints of Io and the UV main auroral oval.

# X-ray Hot Spots at Each of Jupiter Poles



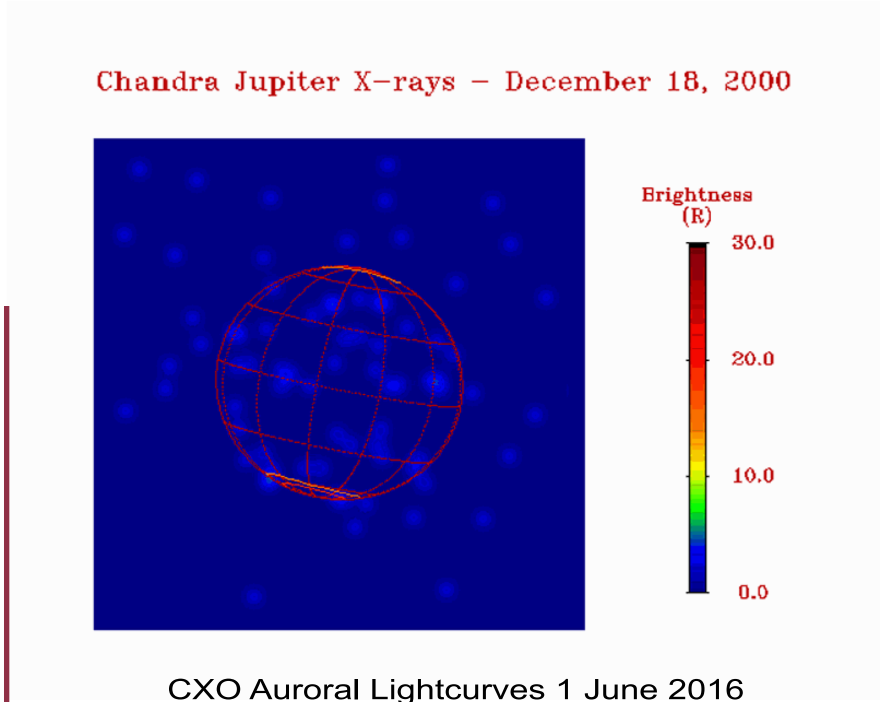

Dunn et al. Nature Astro, 2017

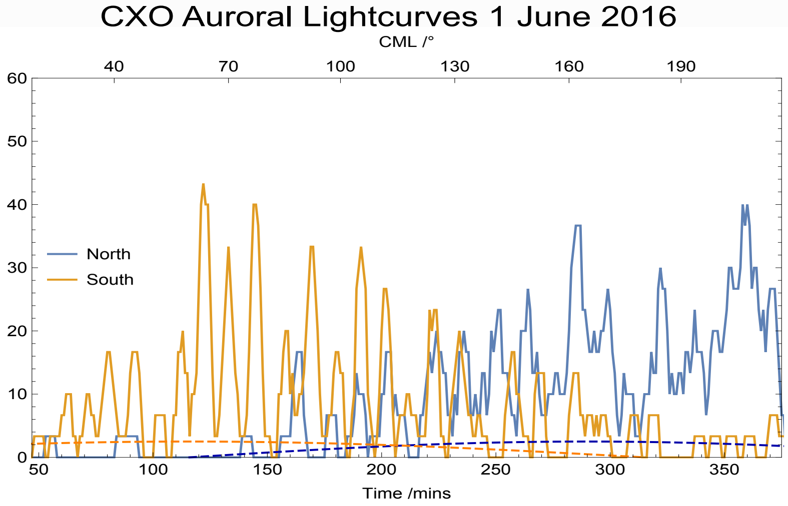
# Quasi-Periodic X-ray Aurora




[Gladstone et al. 2002; Dunn et al. 2017]

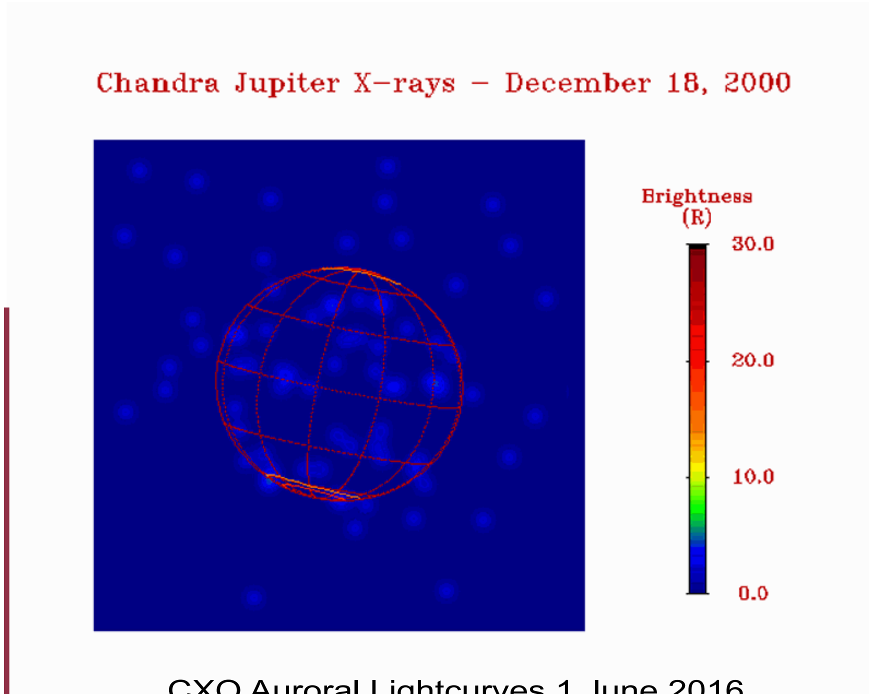
# Quasi-Periodic X-ray Aurora

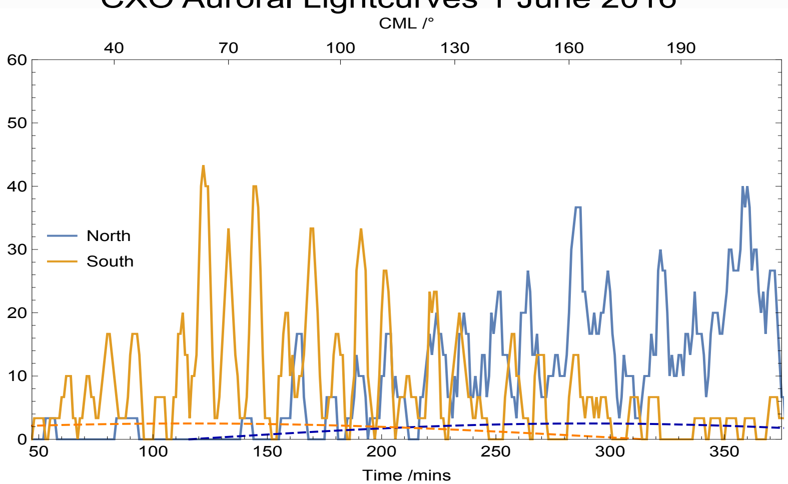


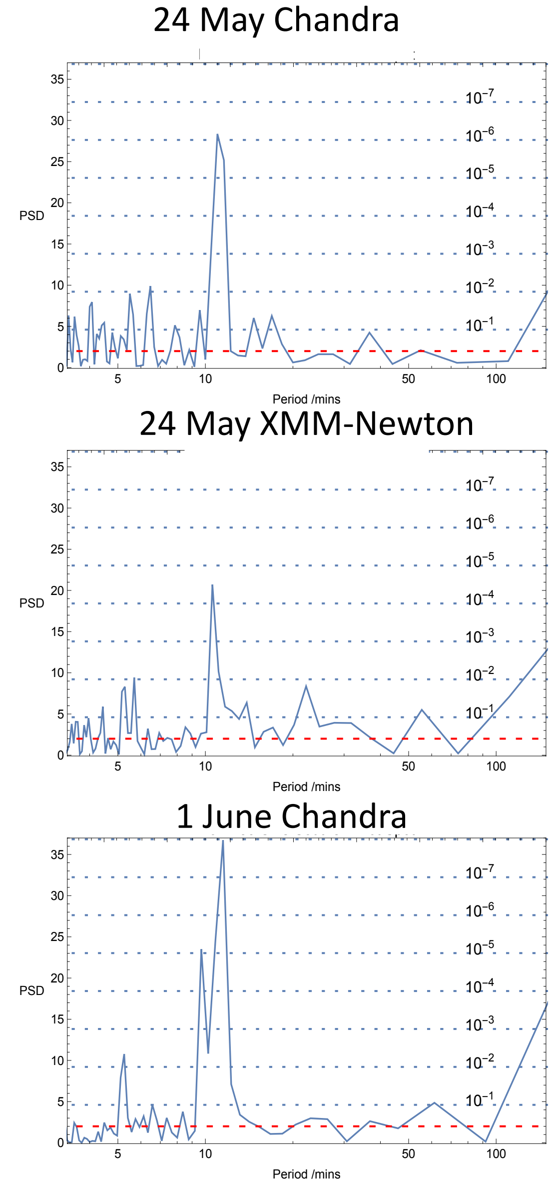

[Gladstone et al. 2002; Dunn et al. 2017]

# Quasi-Periodic X-ray Aurora



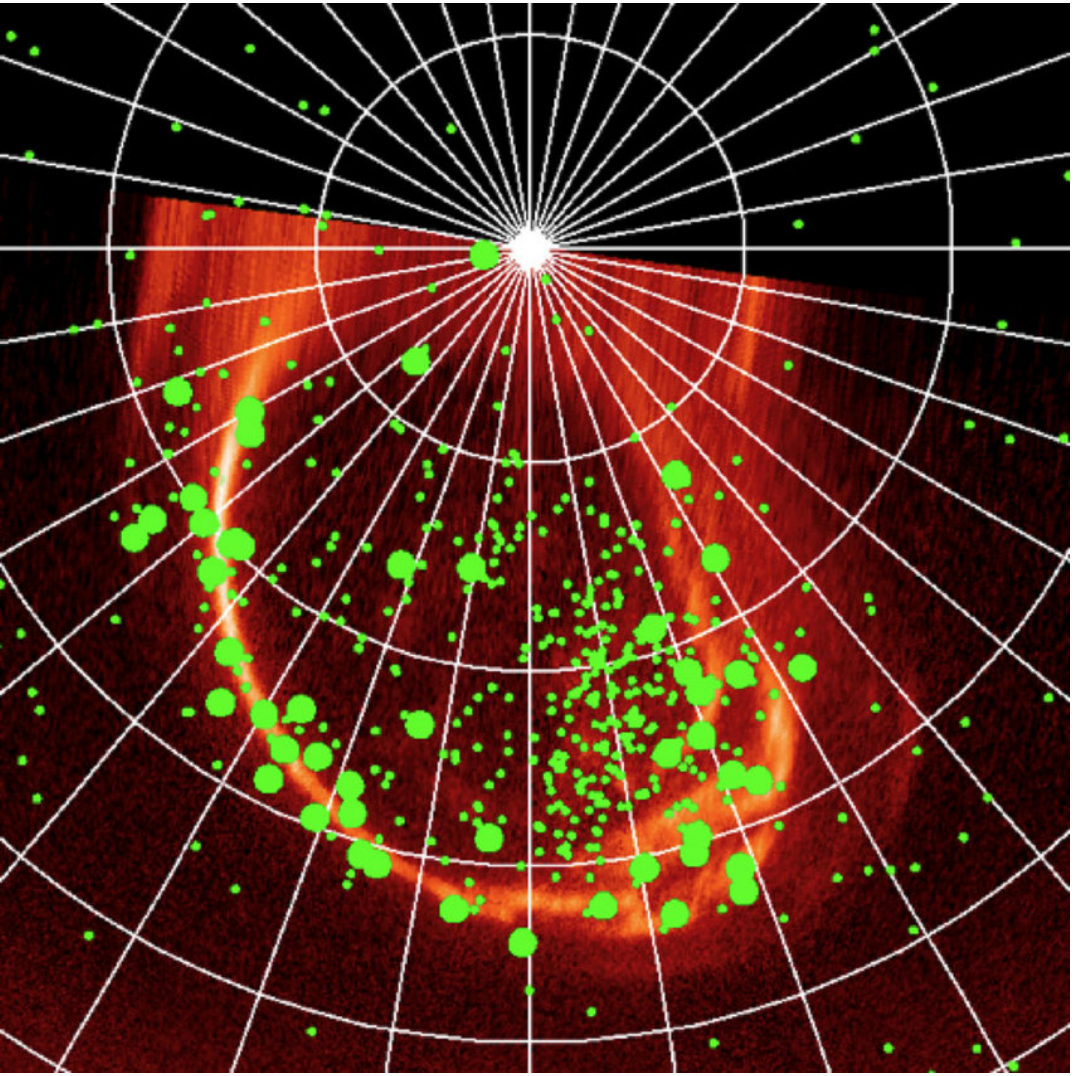




Southern Aurora Fourier Transform PSDs 2016




[Gladstone et al. 2002; Dunn et al. 2017]

# X-ray Aurora Morphology



Branduardi-Raymont et al. (2004; 2008); Cravens et al. (2003); Gladstone et al. (2002)

## Electron Aurora (Big Dots)

Hard X-rays (E> 2keV)

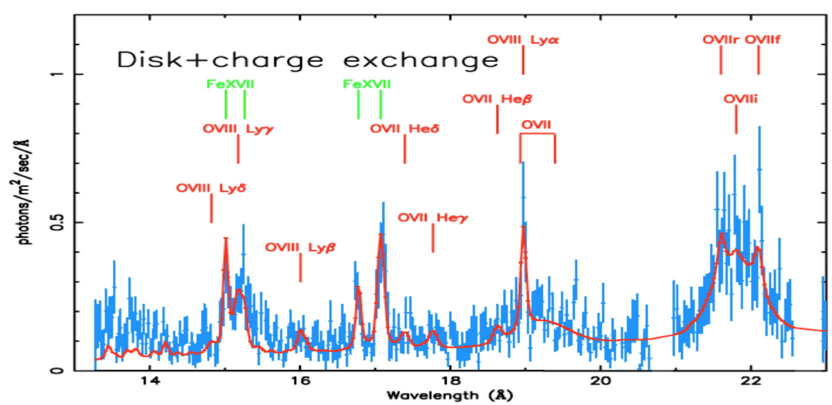
Bremsstrahlung from precipitating electrons along the main UV oval

## Ion Aurora (Small Dots)

Soft X-rays (E< 2keV)

Charge Exchange lines from precipitating ions

Map beyond 50 RJ



# The Juno-Chandra-XMM Revolution

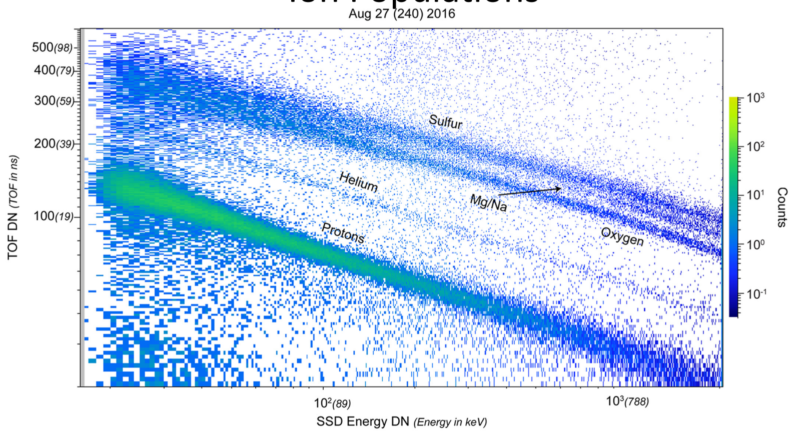
Image: NASA Juno/CXC N. Wolk/W. Dunn

# X-ray Comparisons with Particle Data

Juno measures ion (and electron) populations.

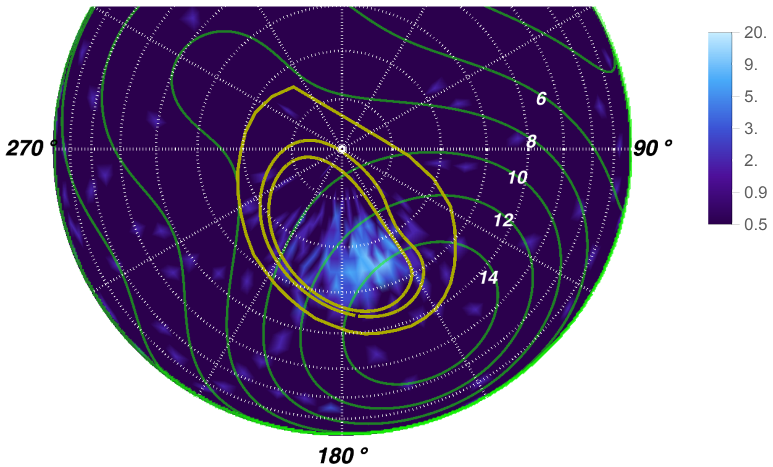
Chandra ACIS Observations of Oxygen line locations are remotely tracing these ion precipitations.

Ion Populations

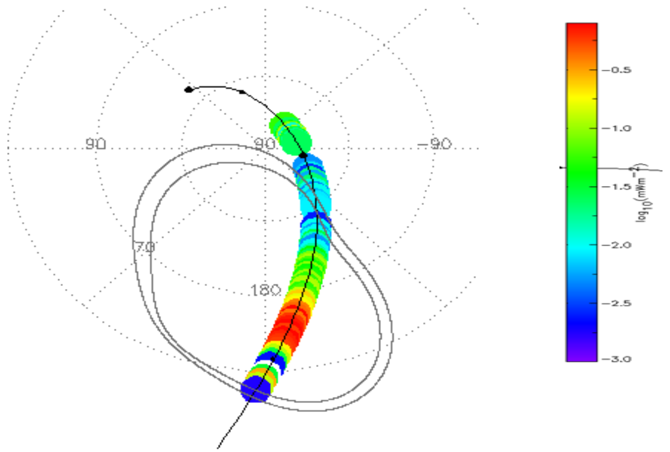



Dunn + Rymer (prep)

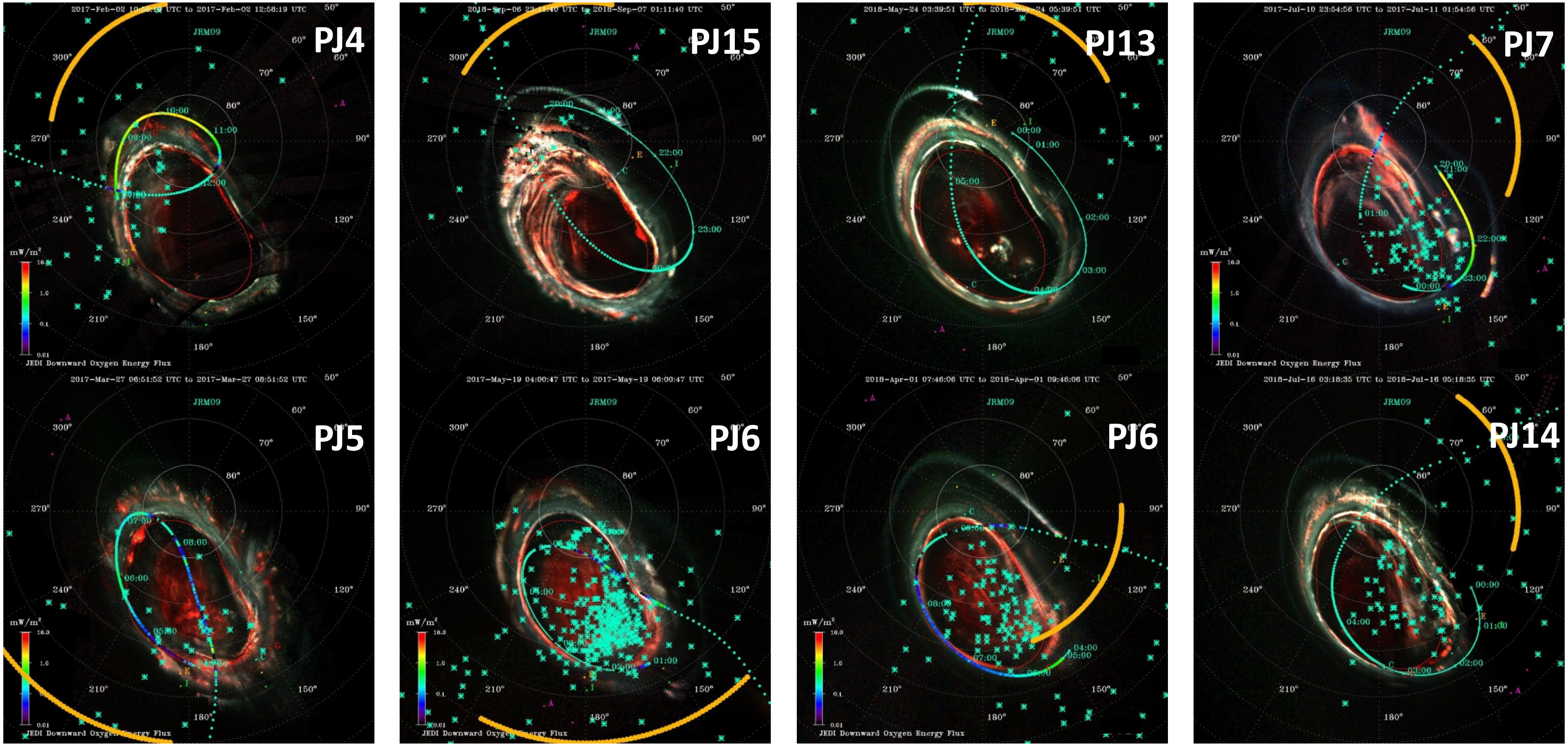
Chandra ACIS North Pole Projection of 0.5-0.9 keV Charge Exchange Lines from Oxygen




Juno JEDI PJ 11 Measurements of the North Pole Oxygen Ion Energy Fluxes

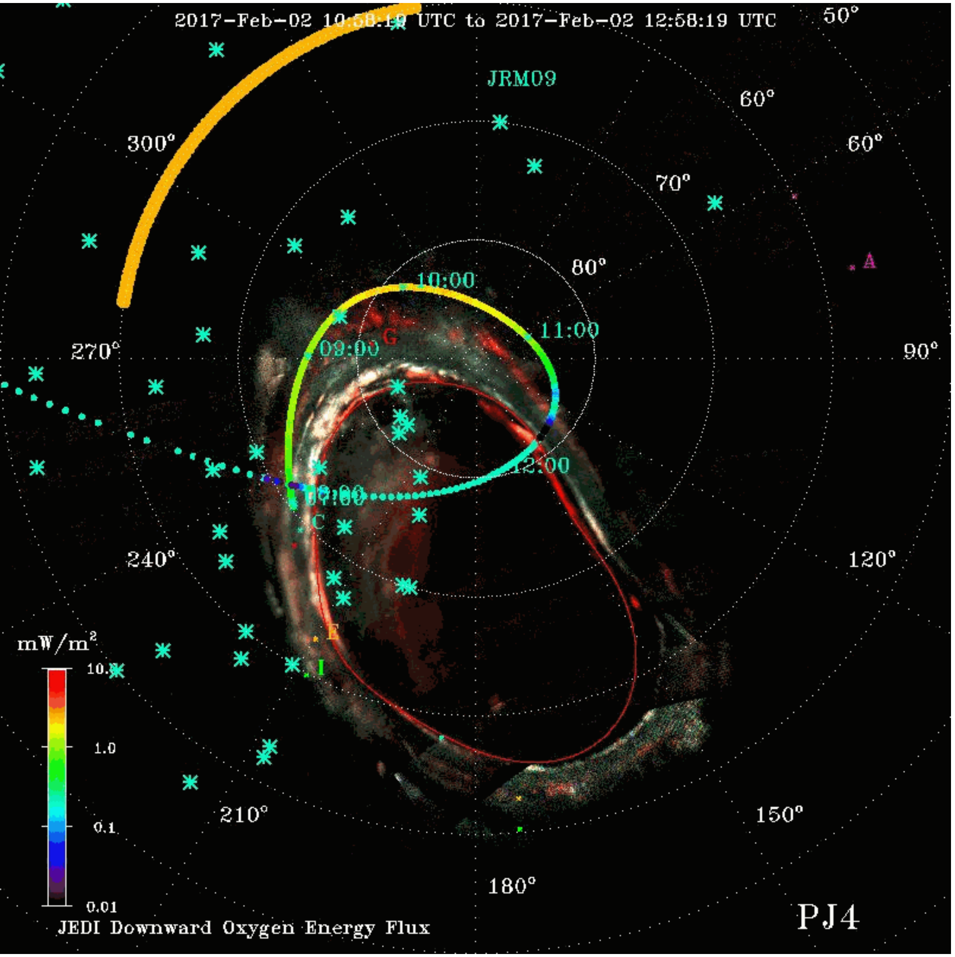


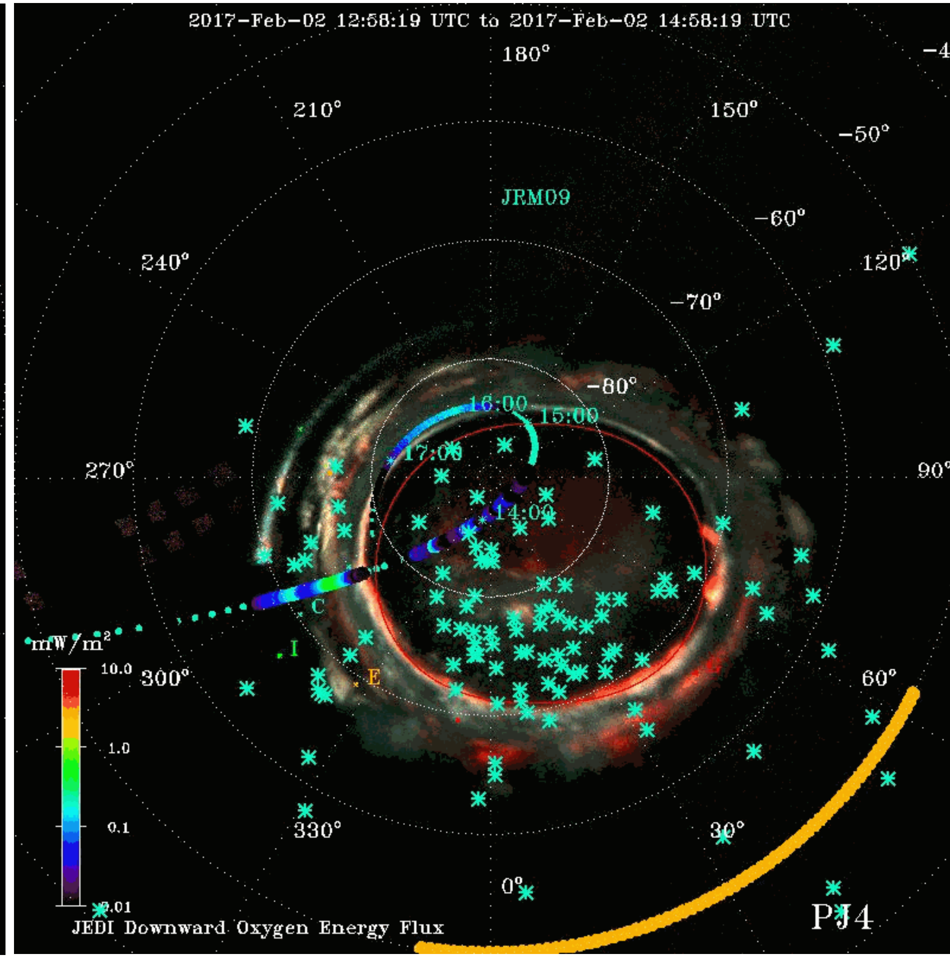
# Juno UVS – Chandra Overlays




Gladstone [prep]

# Juno UVS – Chandra Overlays

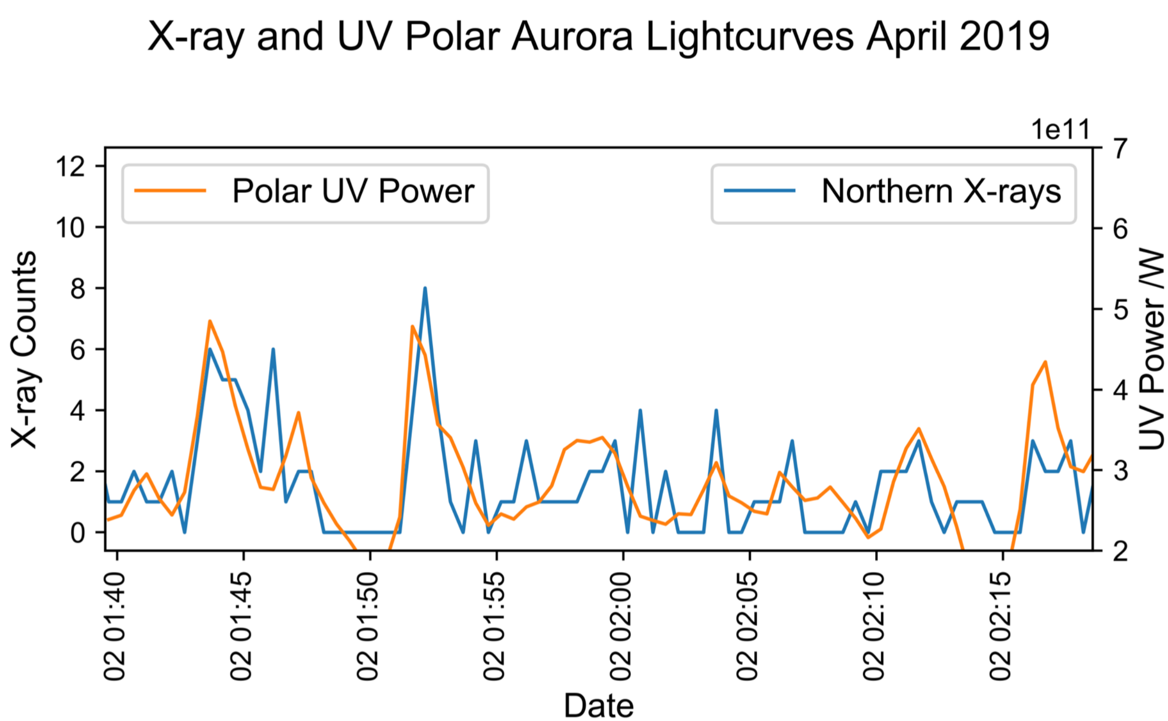



Gladstone [prep]

# Synchronised X-ray-UV Polar Pulsations

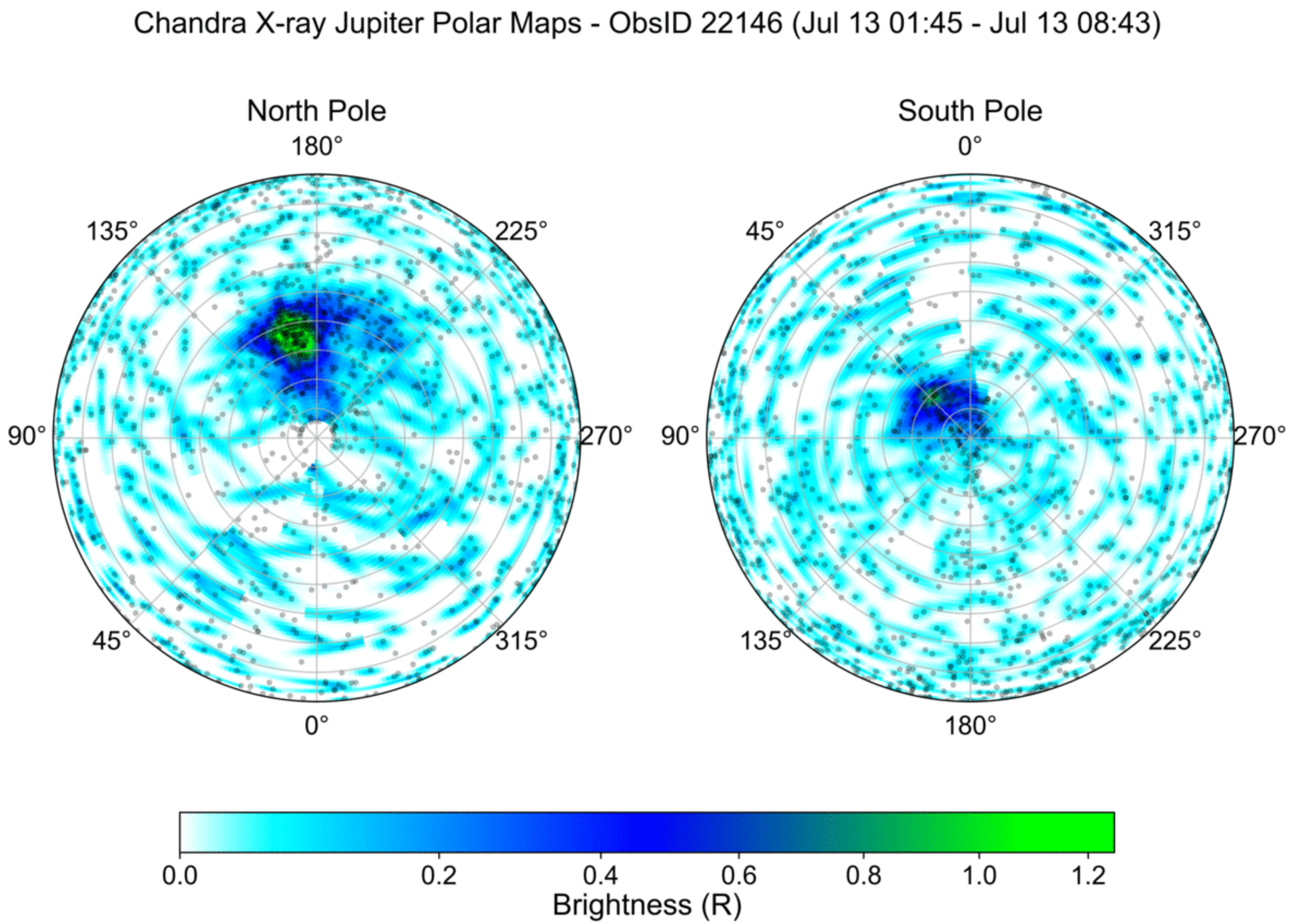
*Lower lightcurve shows coincident XMM-Newton Northern X-ray and HST UV polar emissions from 2nd April 2019 (HST data from D. Grodent) - Pearson Correlation Coefficient = 0.72*




Dunn & Yao et al. [prep]

# So what causes Jupiter’s X-ray Aurora?

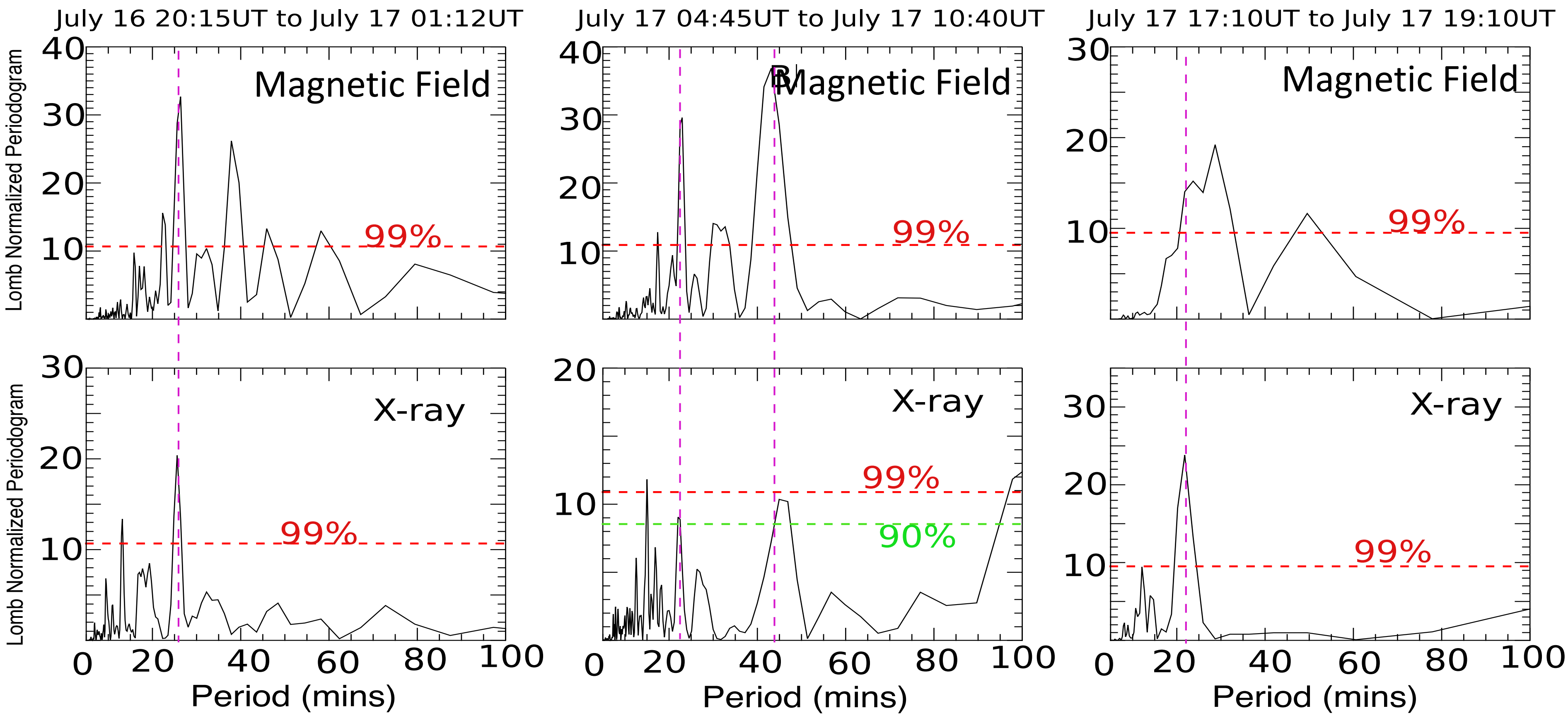
# X-ray Aurora Variability Over 1 Week (July 2019)



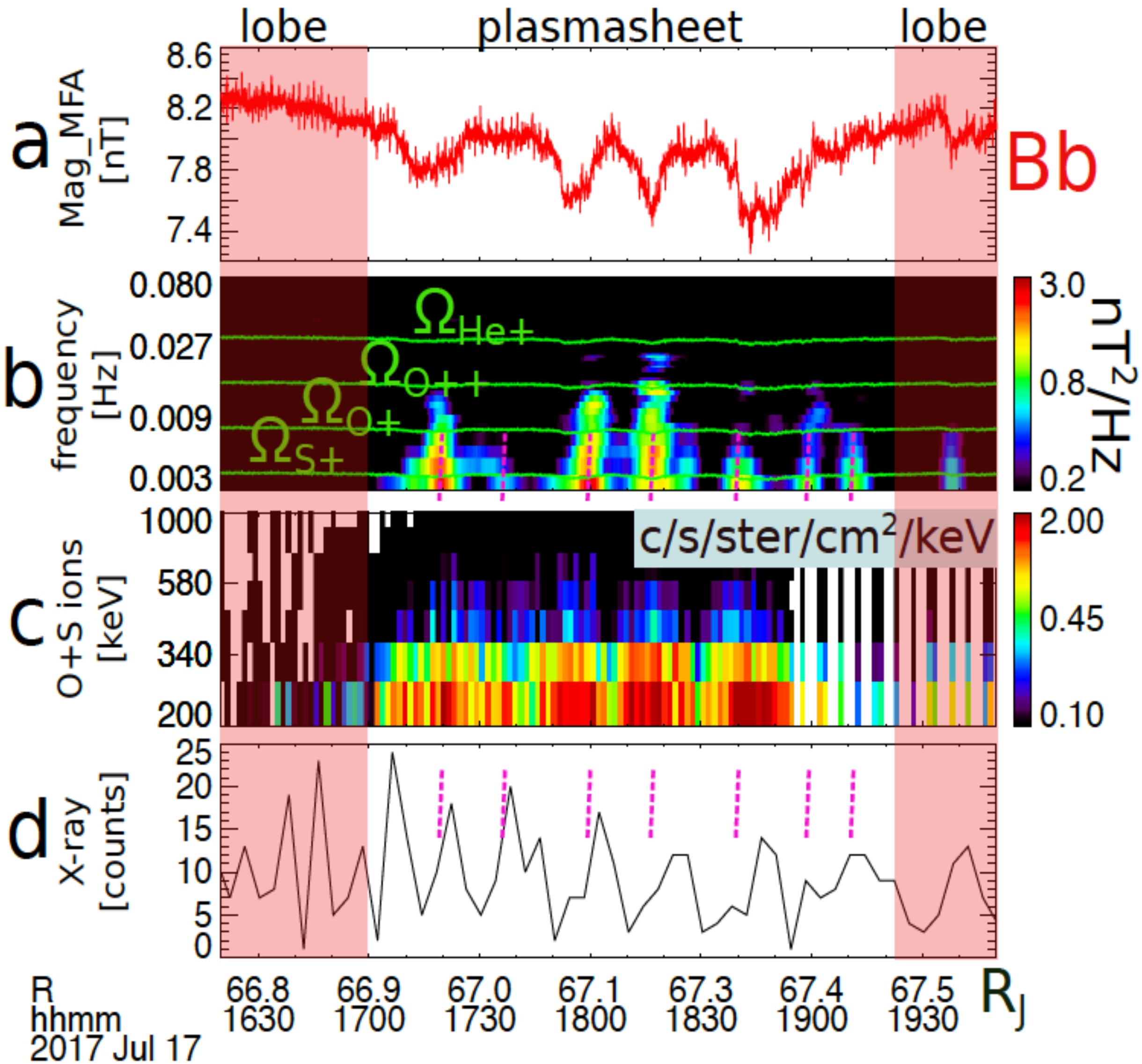

Dunn & Weigt [prep]

# The Drivers of X-ray Auroral Flares

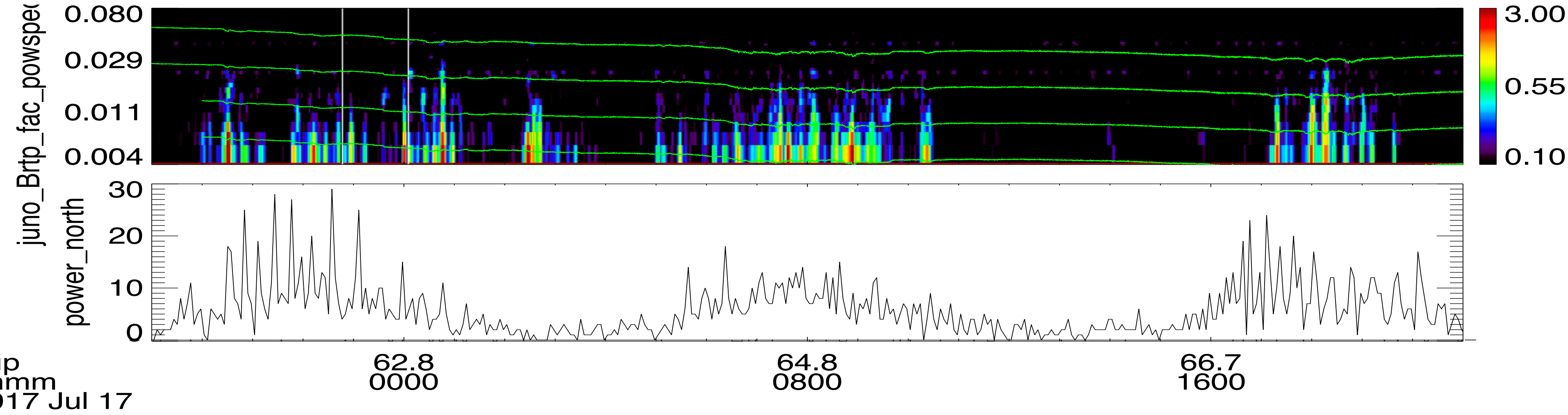
Lomb-Scargle's show that the magnetic field and X-ray aurora pulse with the same periodicity [Yao & Dunn et al. in prep]



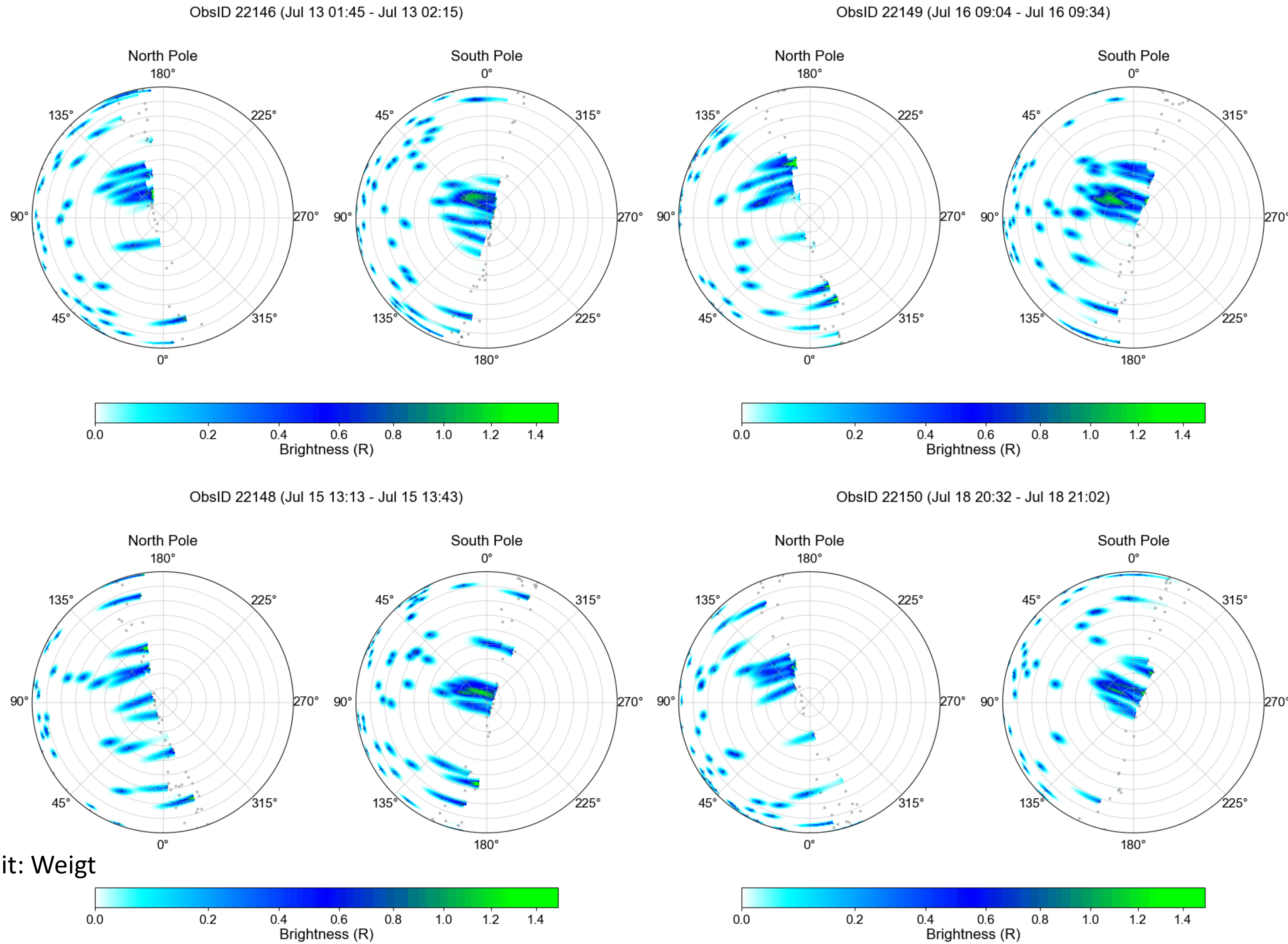
# The Drivers of X-ray Auroral Flares



# EMIC Waves at X-ray Auroral Pulsation Rates (Expanded)

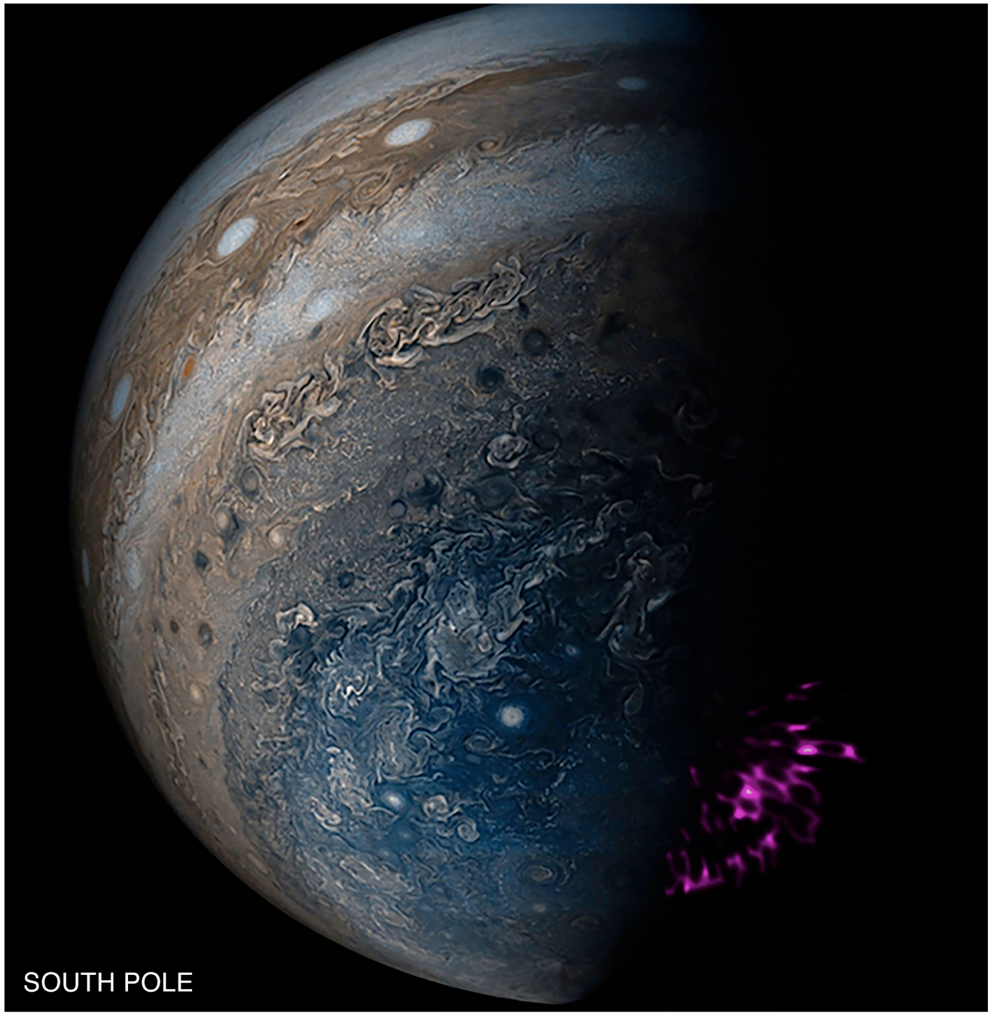


# A BIG THANK YOU to Ed, Jan and the CXO planning team




Credit: Weigt

# Summary

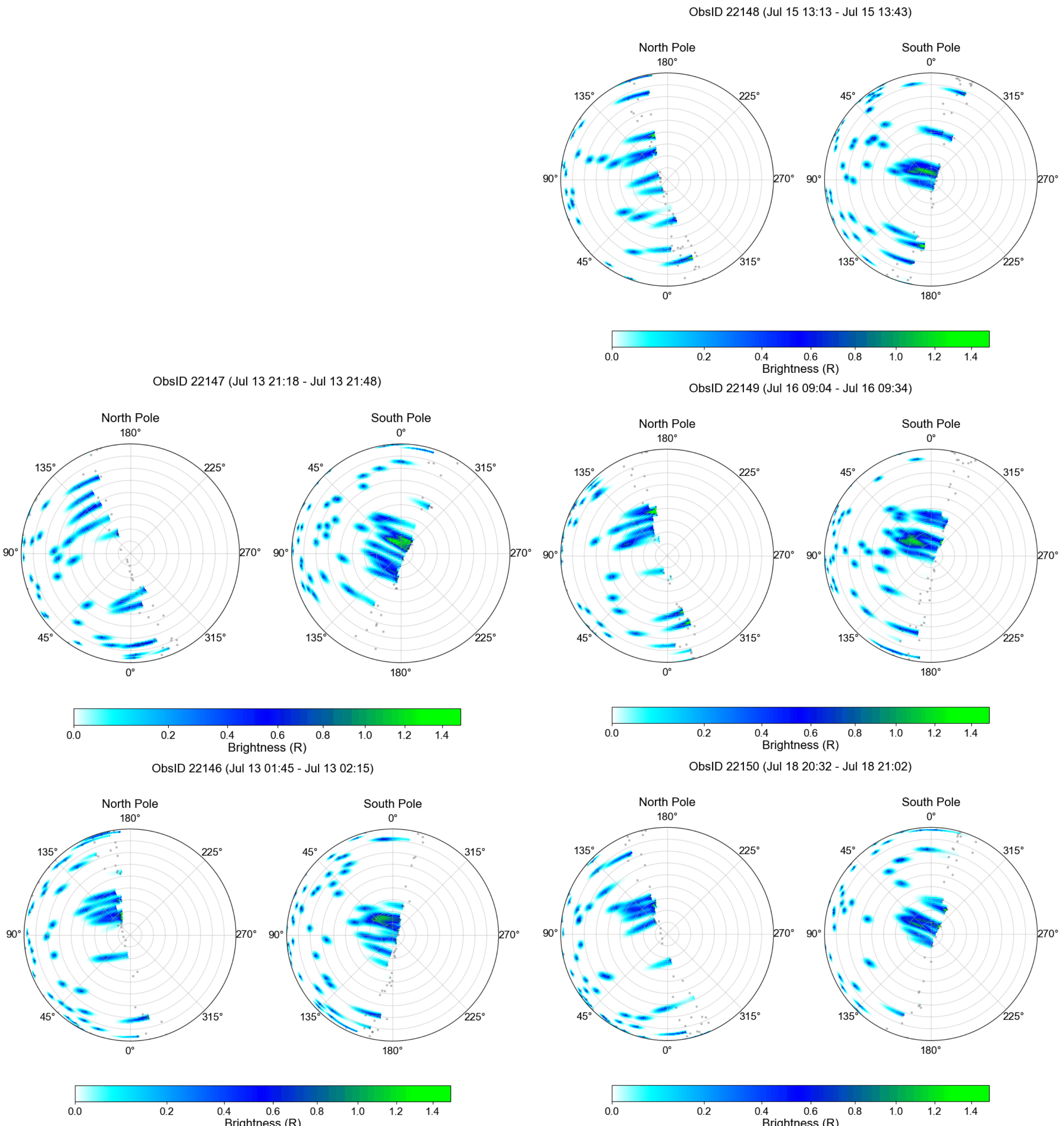



**Chandra and XMM have revolutionized our understanding of the high energy environments of the outer planets**

The Juno-Chandra-XMM campaigns are providing a treasure trove of planetary and X-ray astronomy science revealing precisely how X-ray signatures connect with in-situ processes and UV, radio and IR emissions.

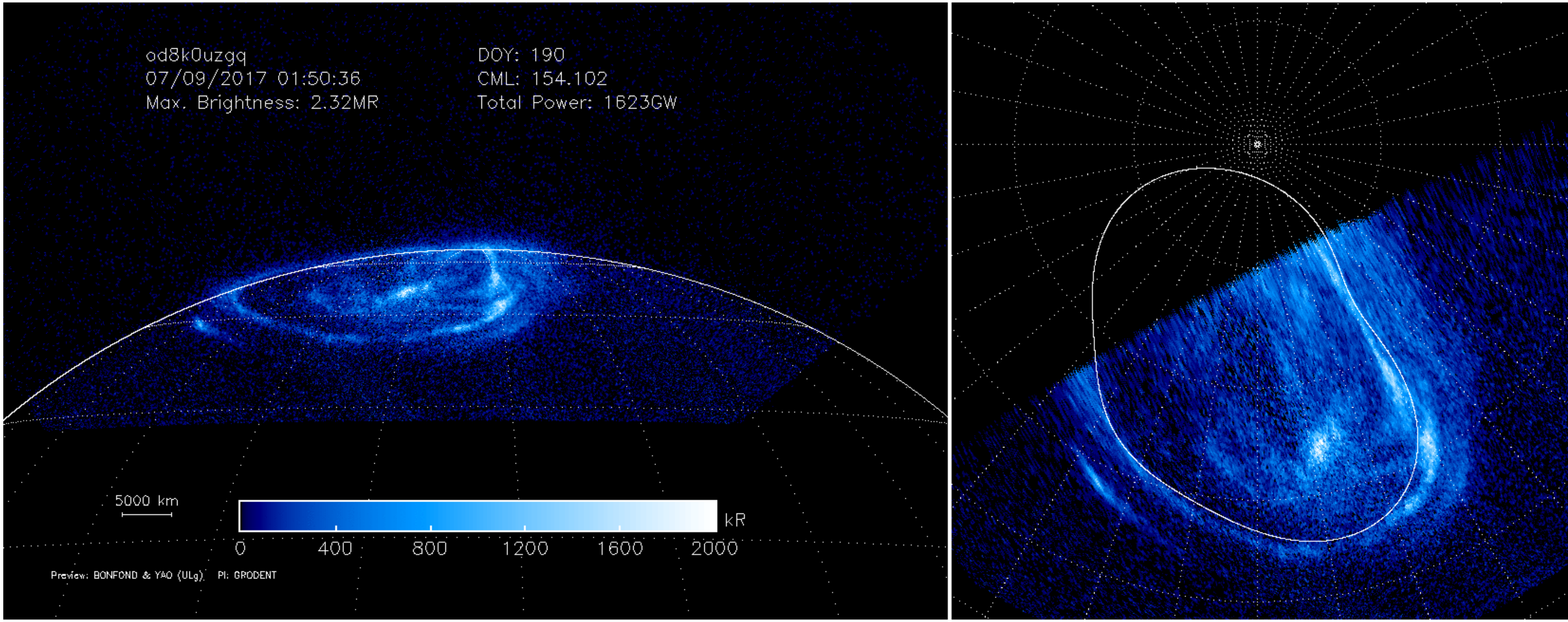
Quasi-Periodic Planetary X-ray flares/ are produced by wave-particle interactions, which are critical for driving the movement of energy (and its explosive release) in these plasma regimes

Contact William Dunn: w.dunn@ucl.ac.uk,
Twitter: @astro__will



ObsID 22148 (Jul 15 13:13 - Jul 15 13:43)
North Pole
South Pole
Brightness (R)
ObsID 22147 (Jul 13 21:18 - Jul 13 21:48)
North Pole
South Pole
Brightness (R)
ObsID 22149 (Jul 16 09:04 - Jul 16 09:34)
North Pole
South Pole
Brightness (R)
ObsID 22146 (Jul 13 01:45 - Jul 13 02:15)
North Pole
South Pole
Brightness (R)
ObsID 22150 (Jul 18 20:32 - Jul 18 21:02)
North Pole
South Pole
Brightness (R)

# UV Aurora Context

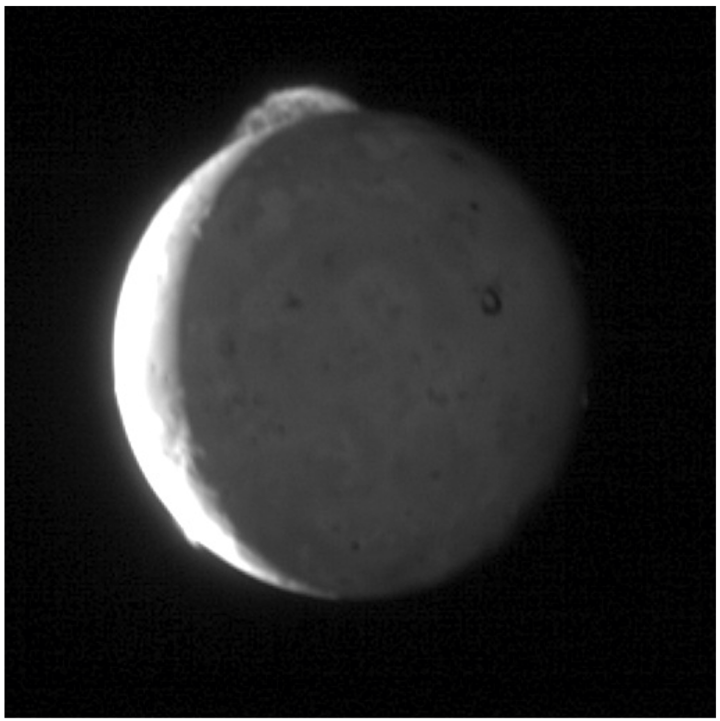


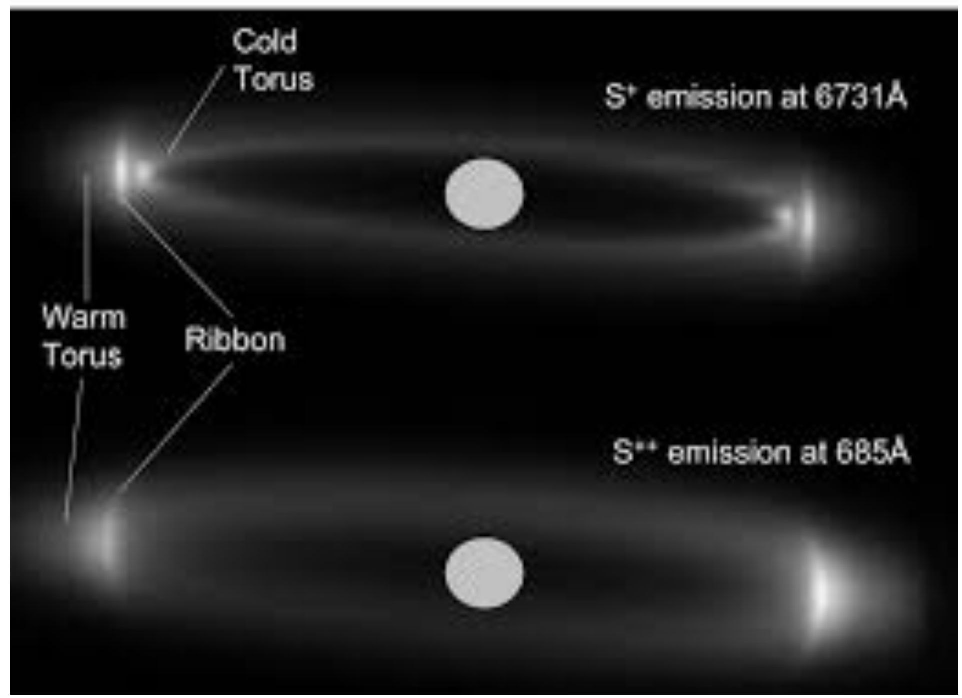

Credit: D Grodent

# Io and the Plasma Torus

Io's volcanoes eject ~1 ton/s, producing a torus of plasma and neutrals around Jupiter

Schneider & Bagenal [2007]; Image: NASA New Horizons





# Jupiter is Hotter, Faster, Stronger

1 **Hot Plasma + Injections**

Io injects > 1000 kg/s,,

2 **Fast Rotation**

Jupiter rotates every 10 hours, forcing plasma to rotate quicker than Keplerian motion

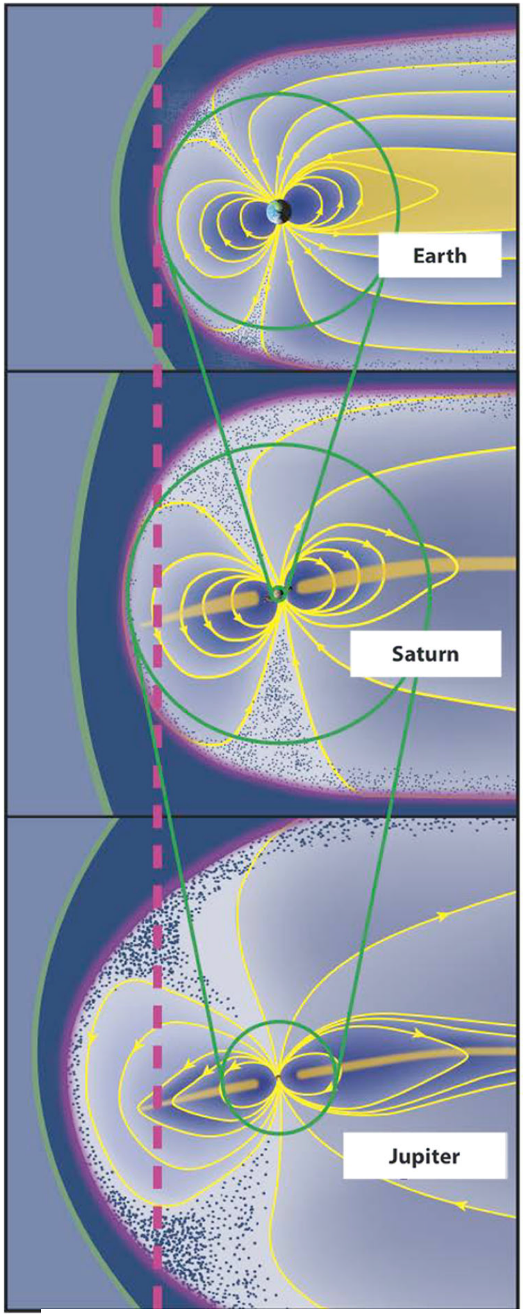
3 **Strong Magnetic Field**

Jupiter's magnetic moment is 20,000 times that of Earth. Jupiter's surface field at the poles is ~10s G.

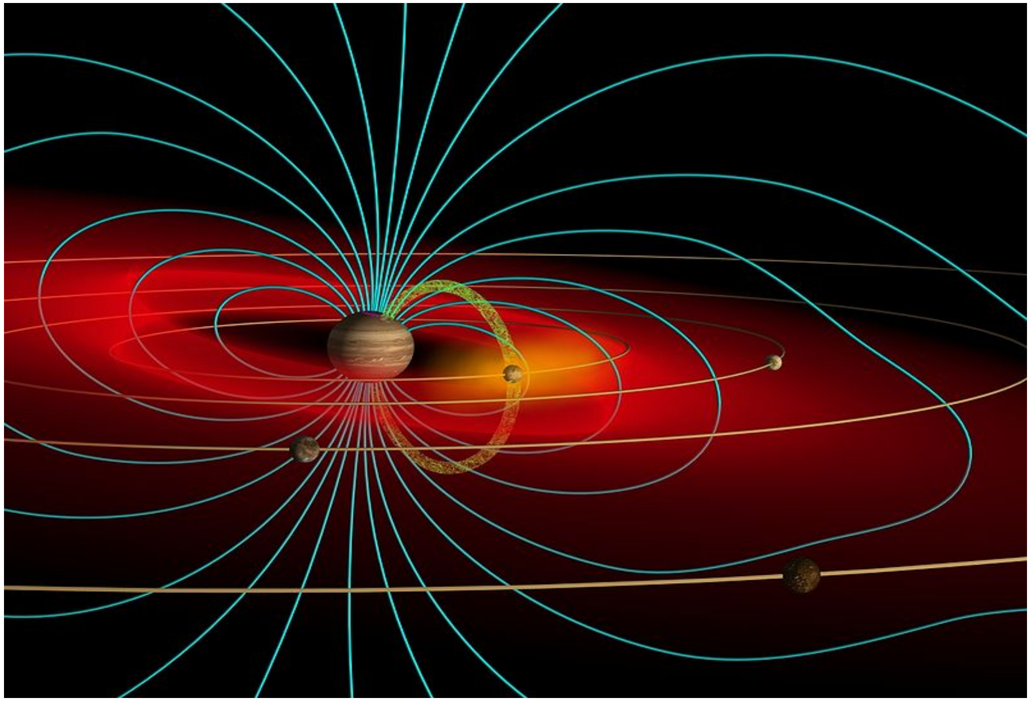
4 **Resulting Magnetosphere**

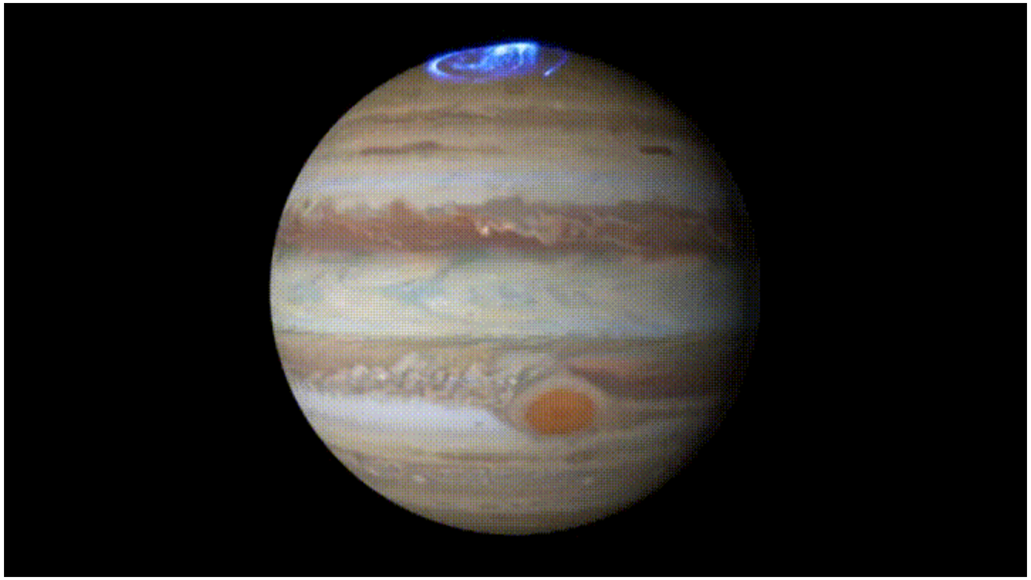
Jupiter's substantial thermal plasma pressure (beta ~100) leads the magnetosphere to be twice the size it would be from magnetic pressure alone. Its rapid rotation centrifugally confines the plasma to a disk

In Jupiter's outer magnetosphere
T~keV, $n \sim 0.02 cm^{-3}$, Plasma beta~10-100, B~nT




Bagenal et al. [2014]





# Aurora

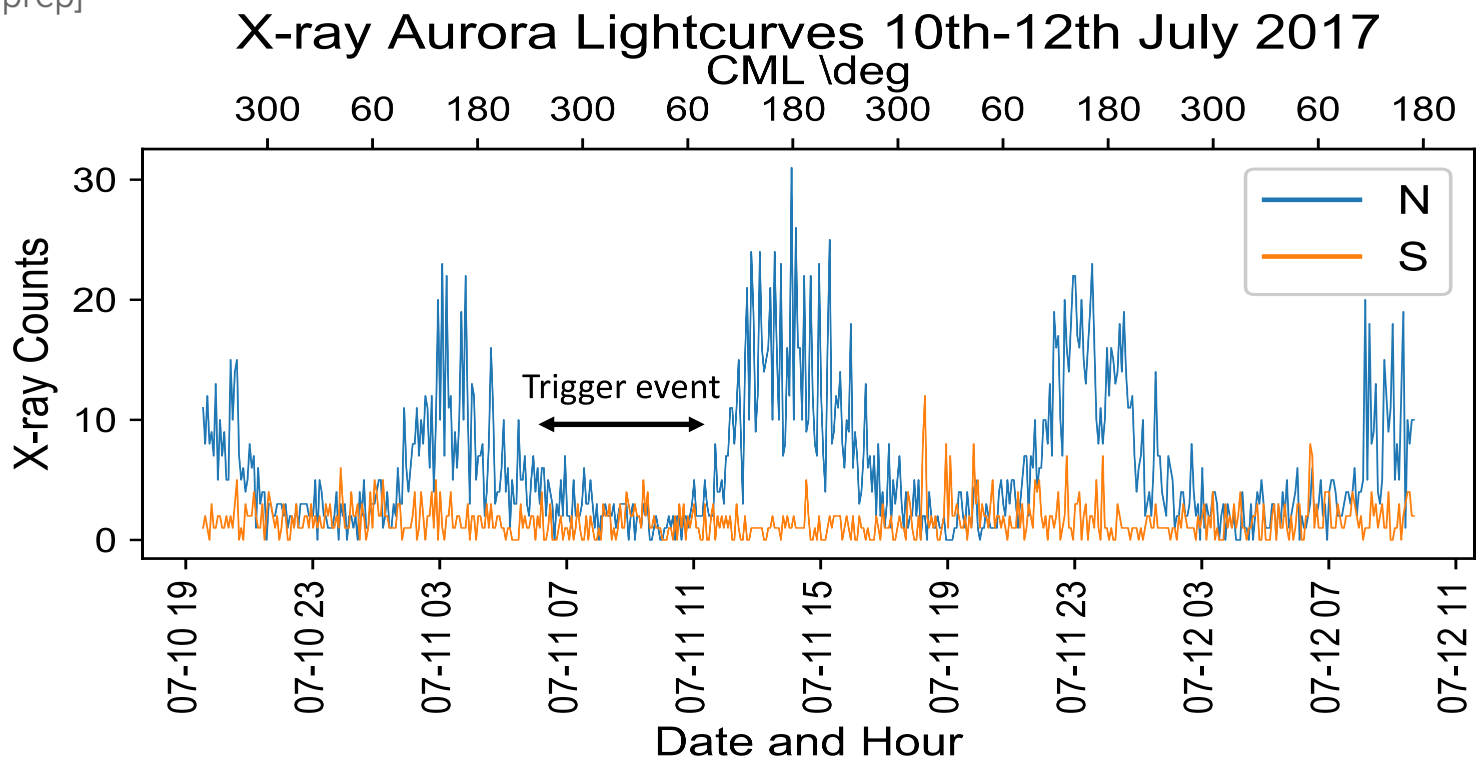
How do we go about understanding the processes in Jupiter's outer magnetosphere?

Aurora provides a video of the processes occurring in a magnetosphere

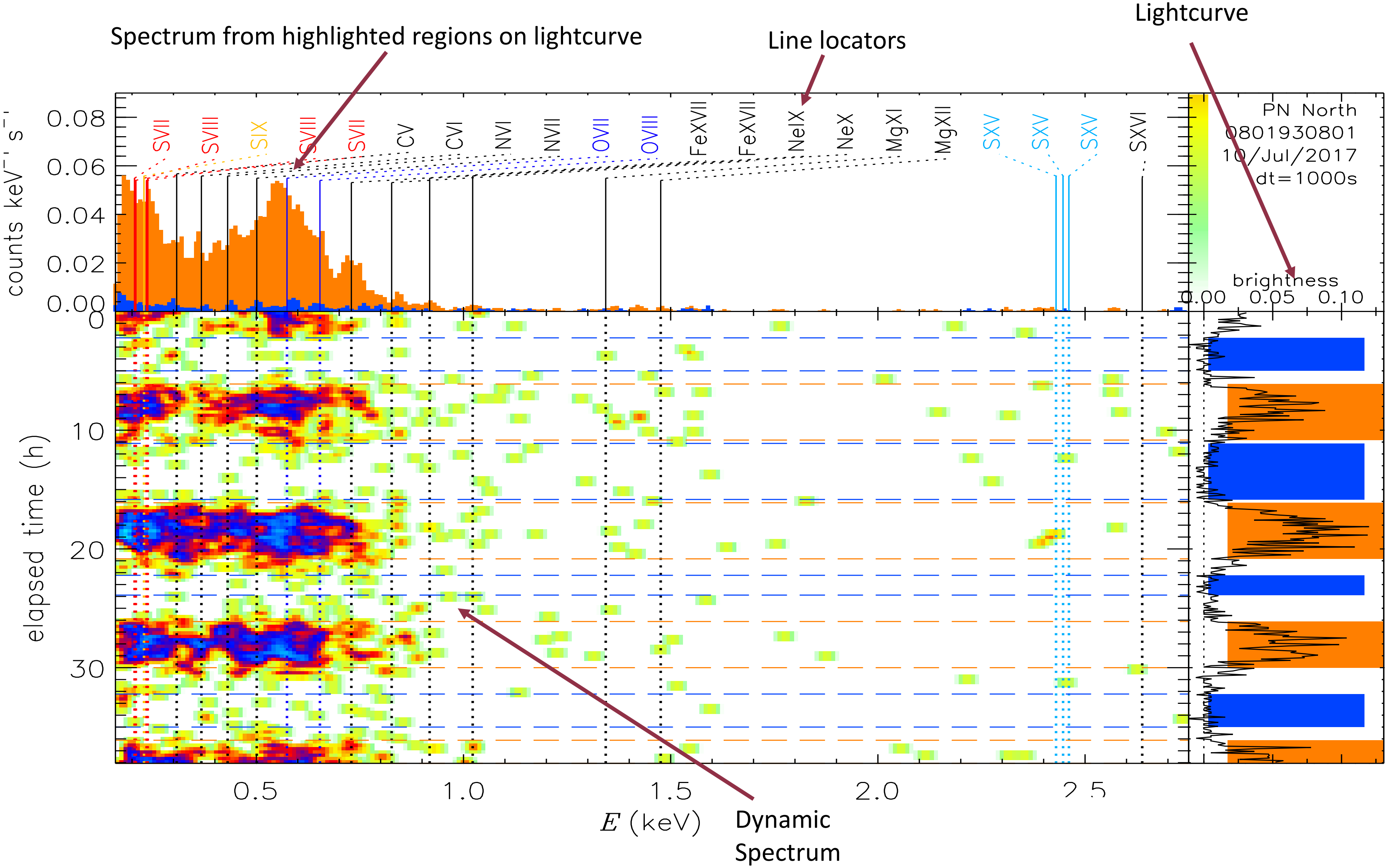
# Juno Era Results – Identifying the Auroral Drivers 2: Trigger Events

# Auroral Triggers

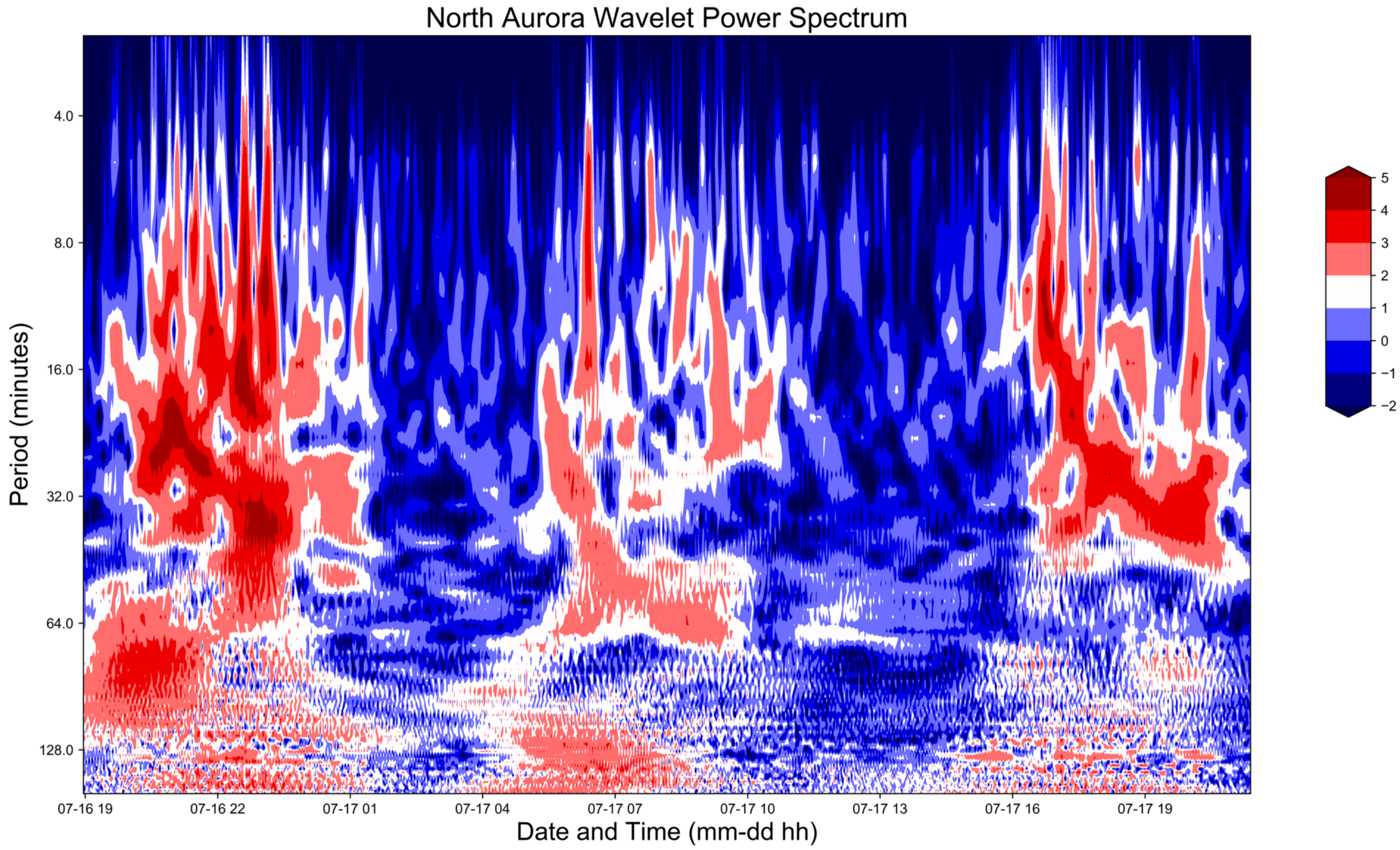
> Comparing changes in auroral behaviour with simultaneous *in-situ* data allows us to identify the physical processes that drive rapidly rotating magnetospheres and aurora [Dunn + Ness, prep]



# Dynamic Spectra: Energisation with Brightening



# Wavelet of Jovian Aurora

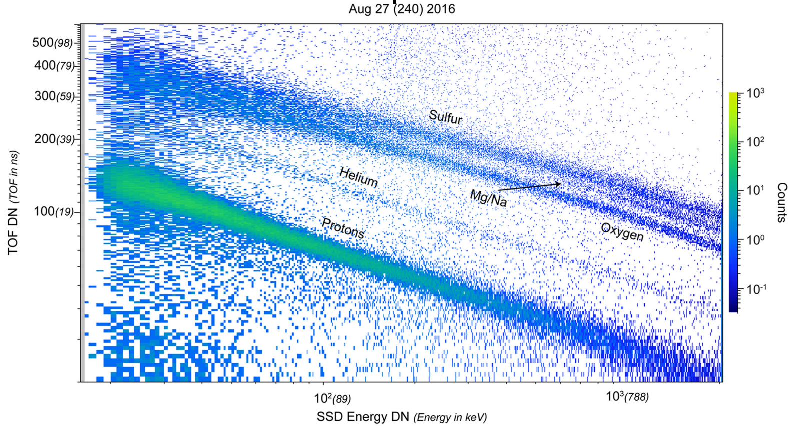


# Juno JEDI Energetic Particles Vs X-ray Observations

Juno measures ion (and electron) populations.

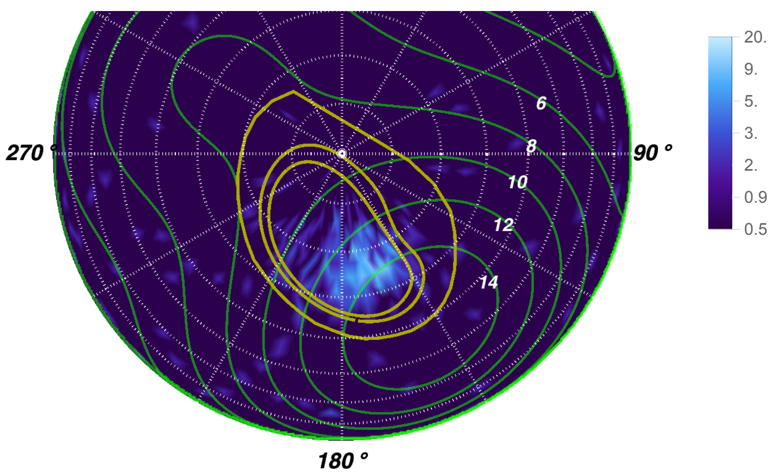
Chandra ACIS Observations of Oxygen line locations are remotely tracing these ion precipitations.

Ion Populations

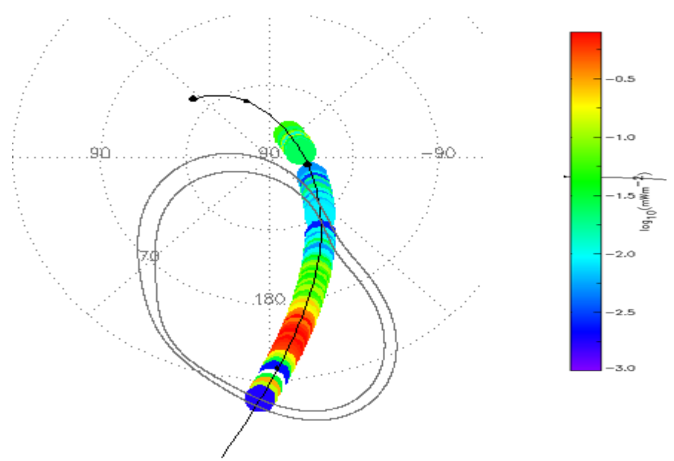



Rymer + Dunn (prep)

Chandra ACIS North Pole Projection of 0.5-0.9 keV Charge Exchange Lines from Oxygen

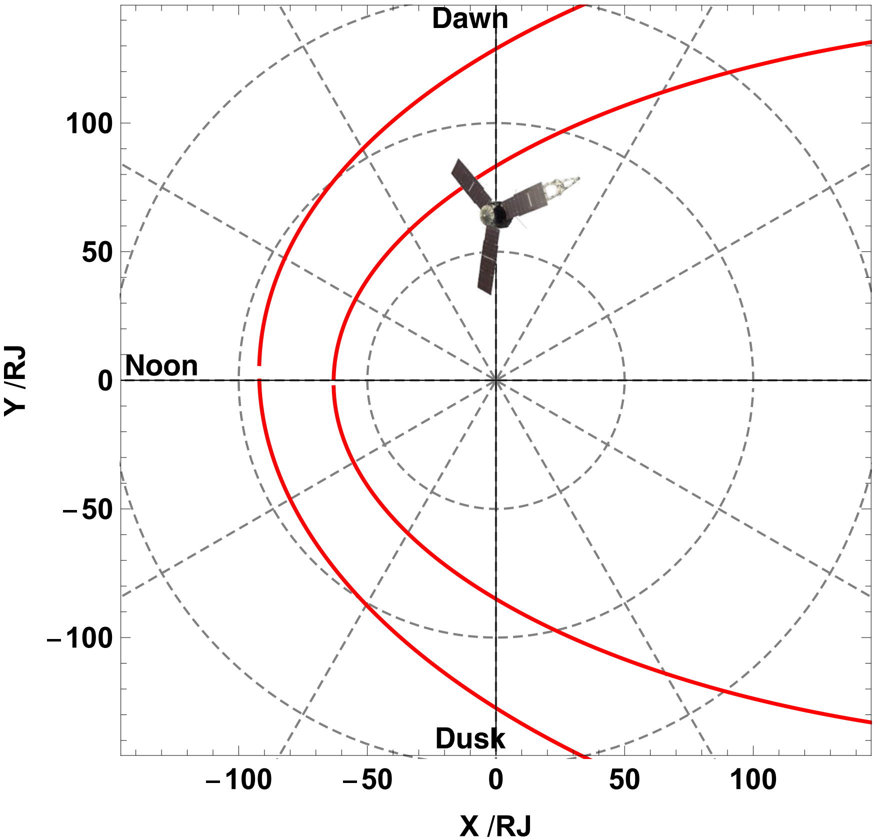


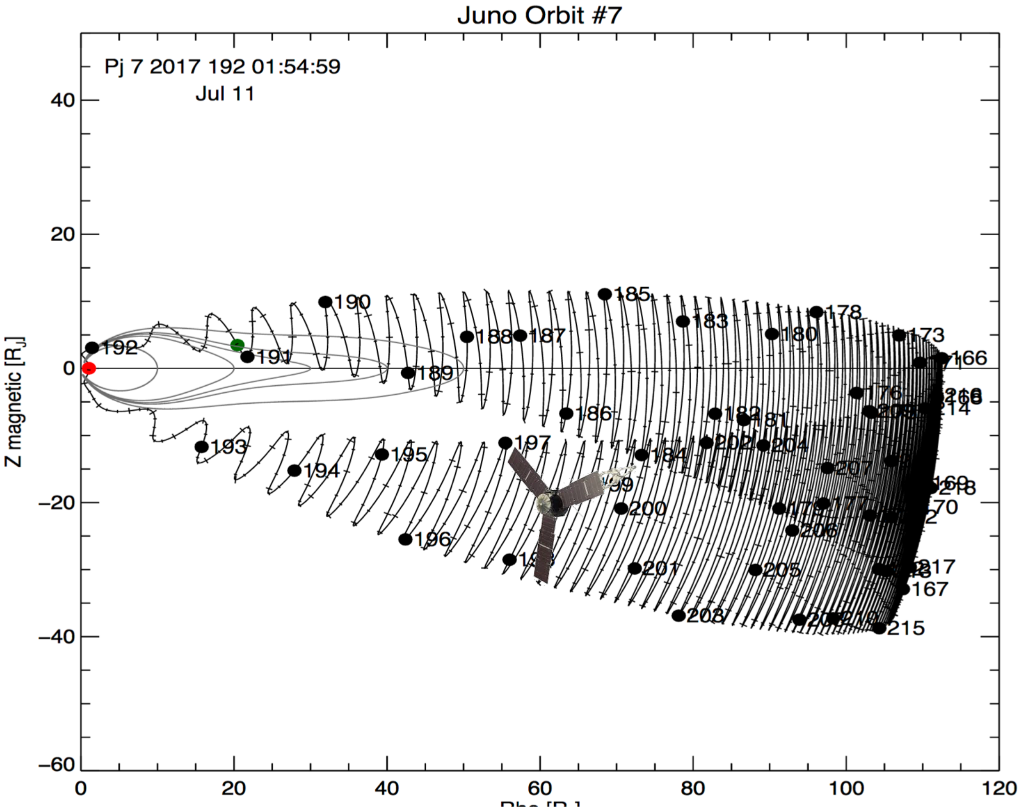

Juno JEDI PJ 11 Measurements of the North Pole Oxygen Ion Energy Fluxes



# Juno July 16-17 2017

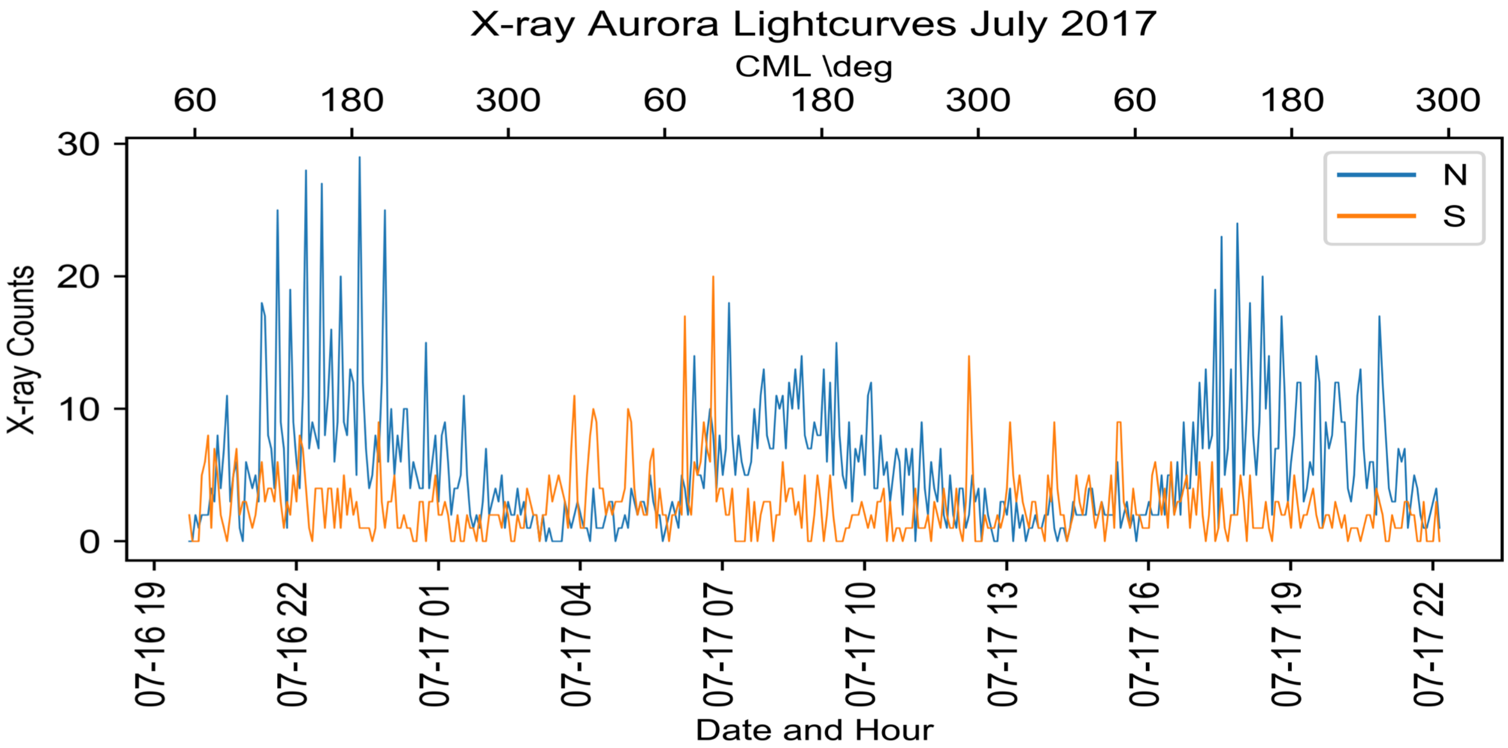
- *Juno was at 58-68 RJ*
- *Southern lobes <-> plasma sheet.*
- *first opportunity to connect magnetospheric conditions with X-ray auroral emissions.*



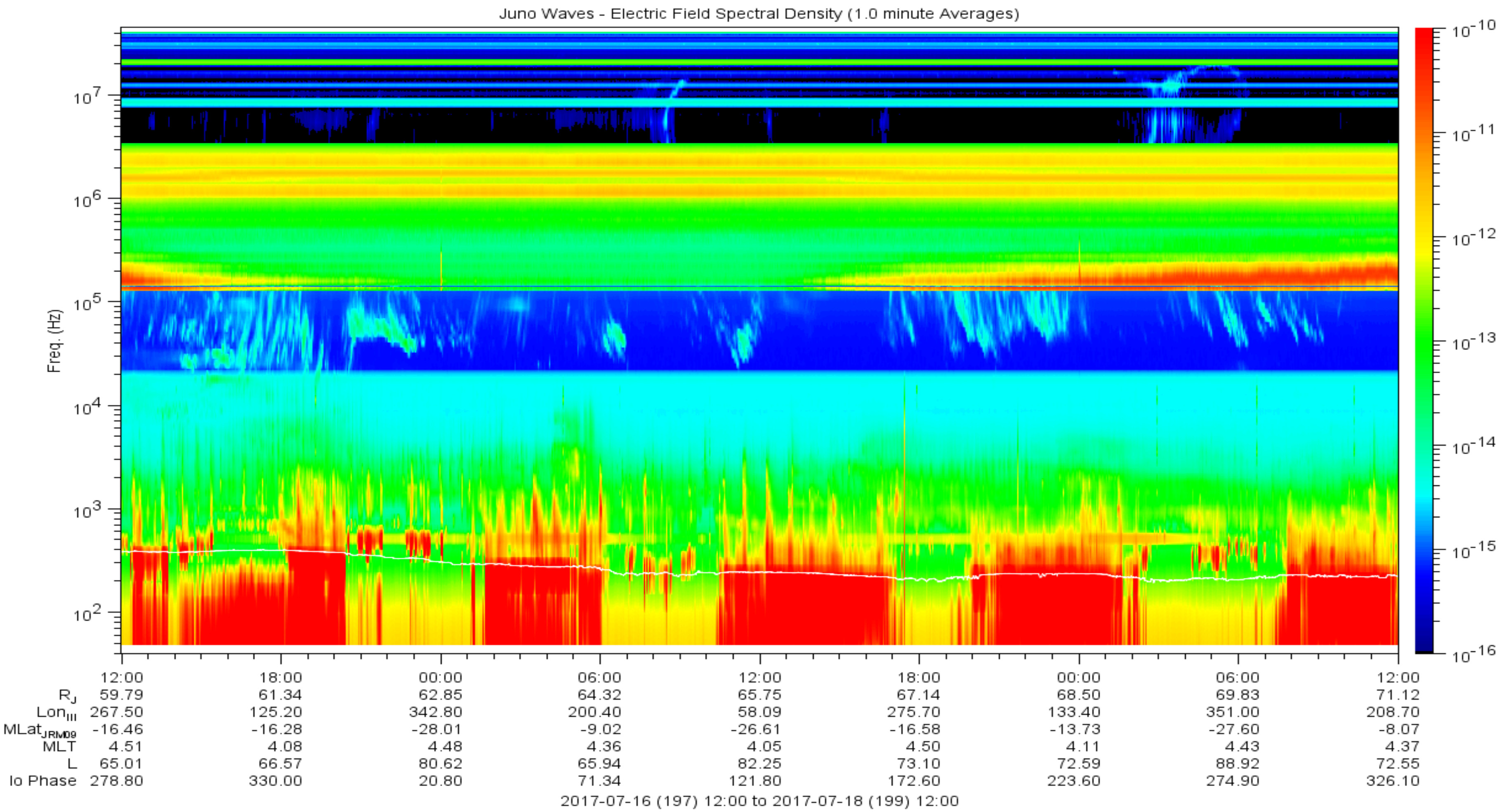
# XMM Observation July 16-17 2017

- *26 Hour XMM Observation*
- *Highly Pulsed Auroral Emission*

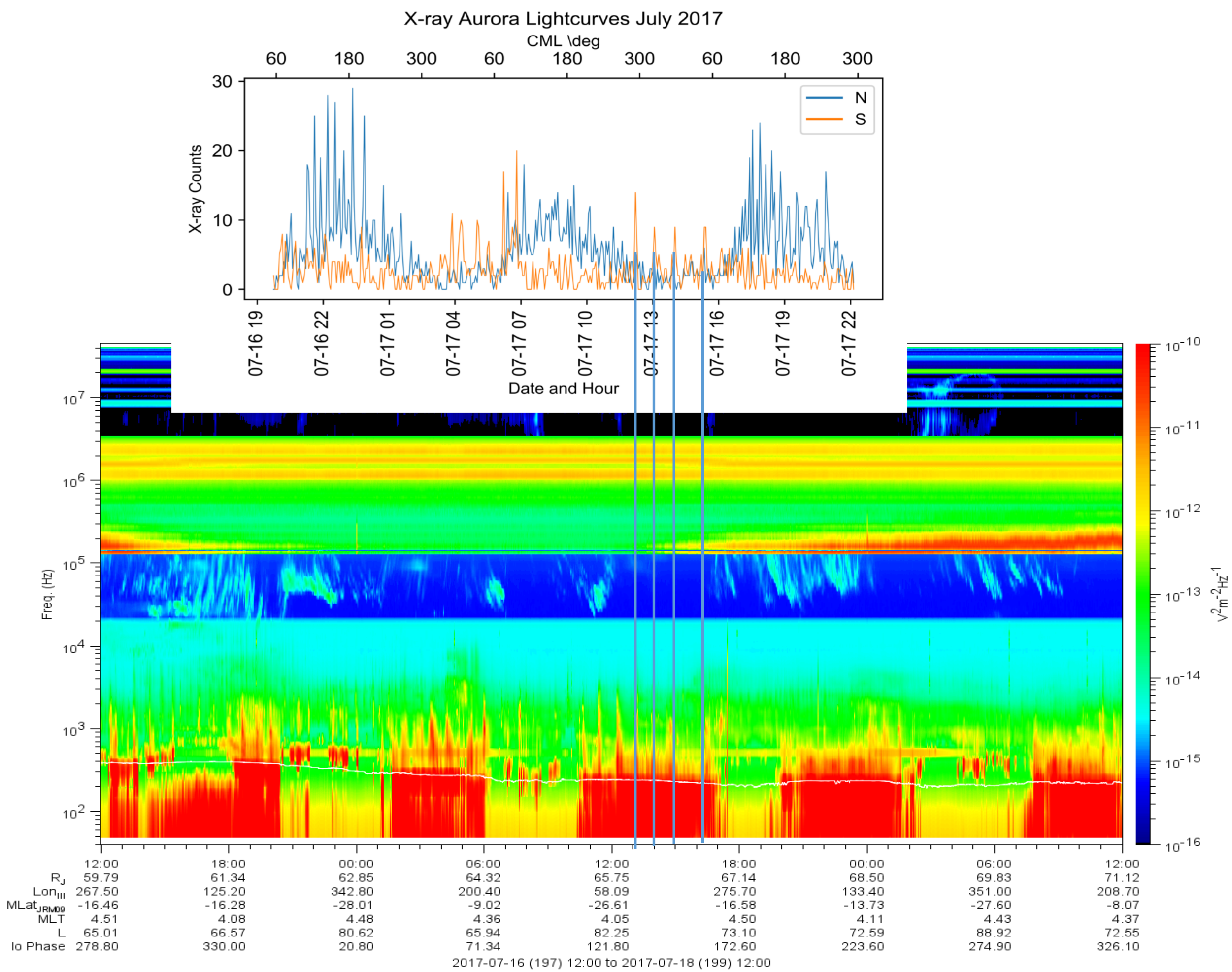


# Juno WAVES Radio data also pulses at 1kHz

*WAVES data from A. Sulaiman and W. Kurth*



# Synchronised X-ray-Radio Pulsations



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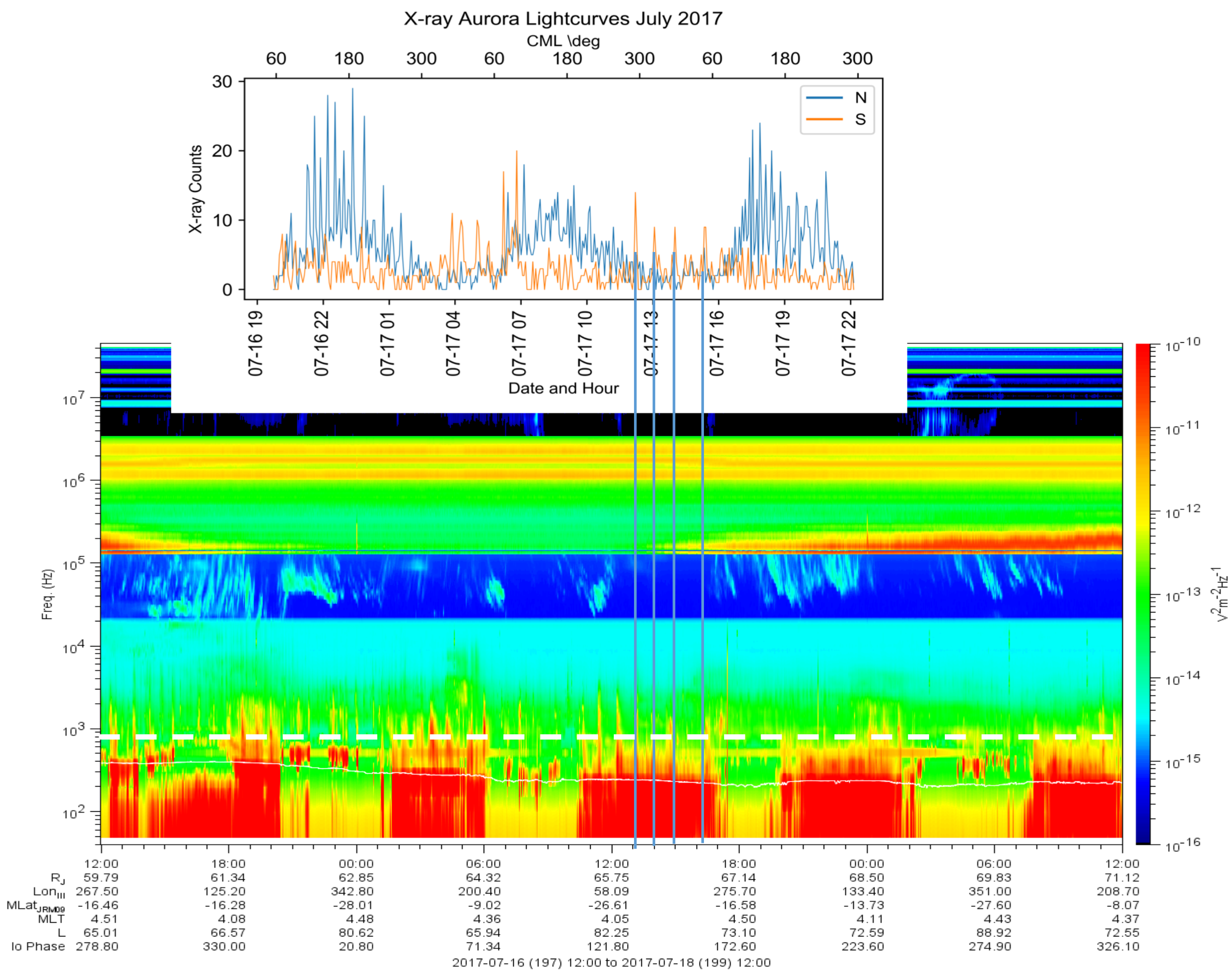
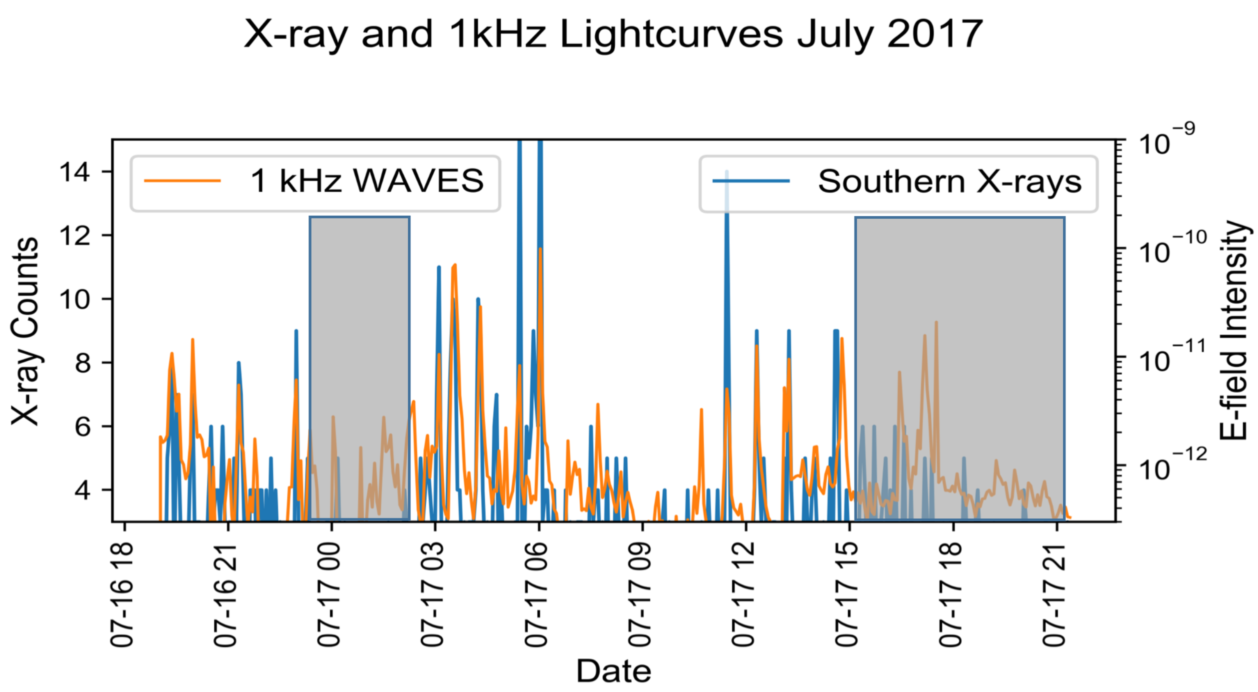
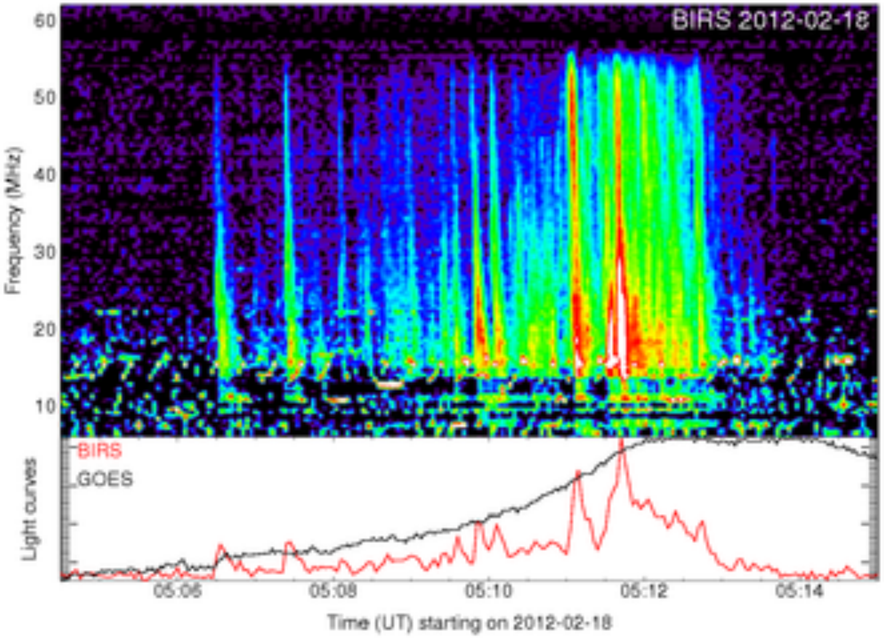


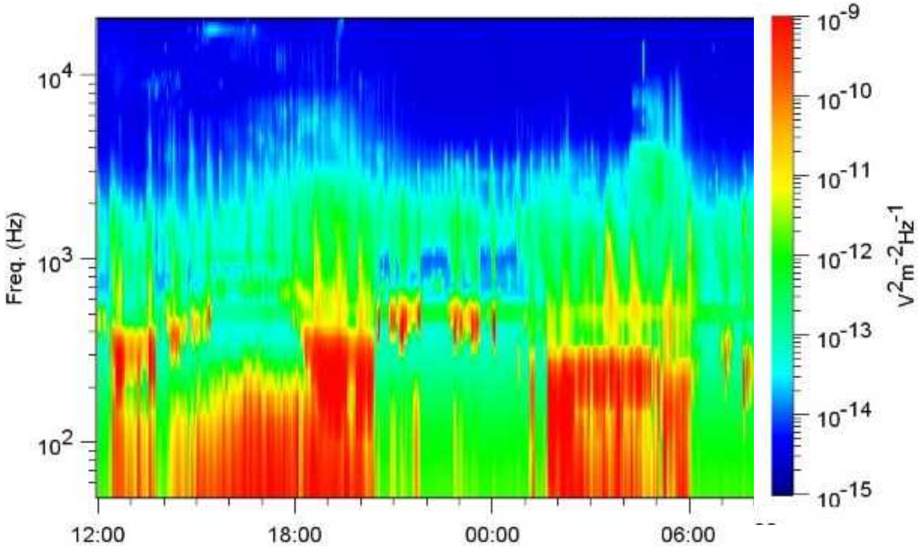
# Synchronised X-ray-Radio Pulsations

> *Overlaid 1 kHz radio and light-travel shifted X-ray time series shows that they seem to be synchronized. Pearson Correlation Coefficients of 0.55-0.7.*
> *Grey boxes = intervals when aurora was not in view for one instrument*

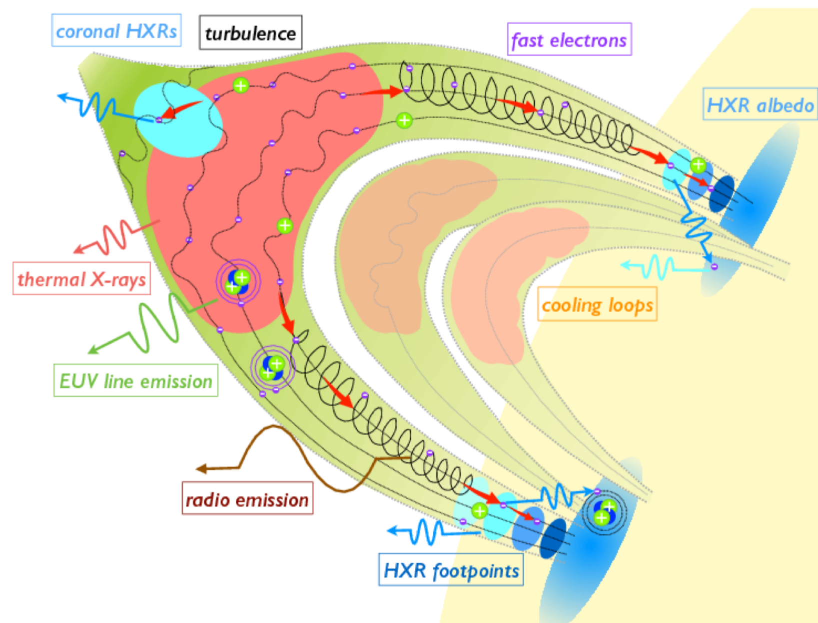


# Jupiter-Stellar Flare Parallels? (with plenty of caution)

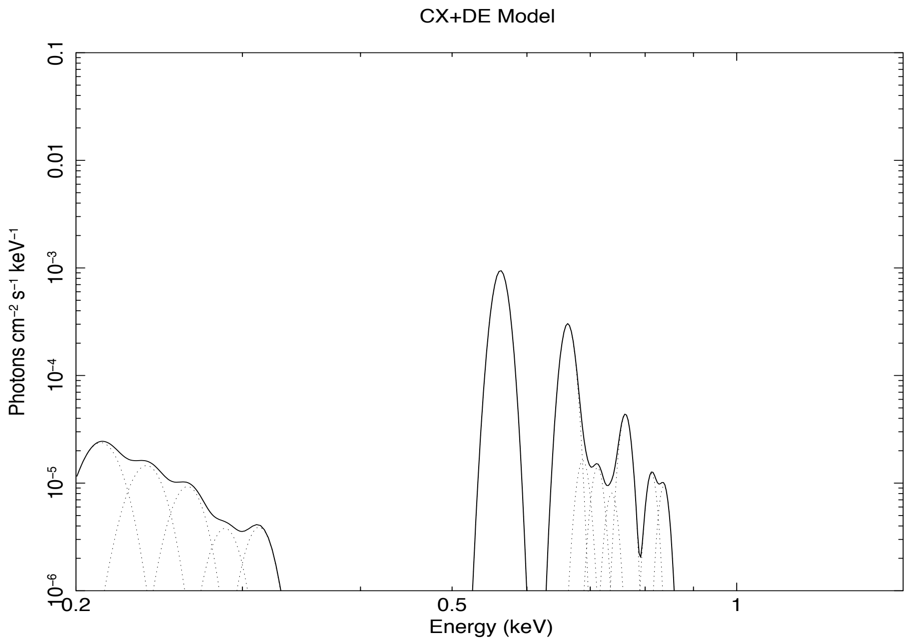


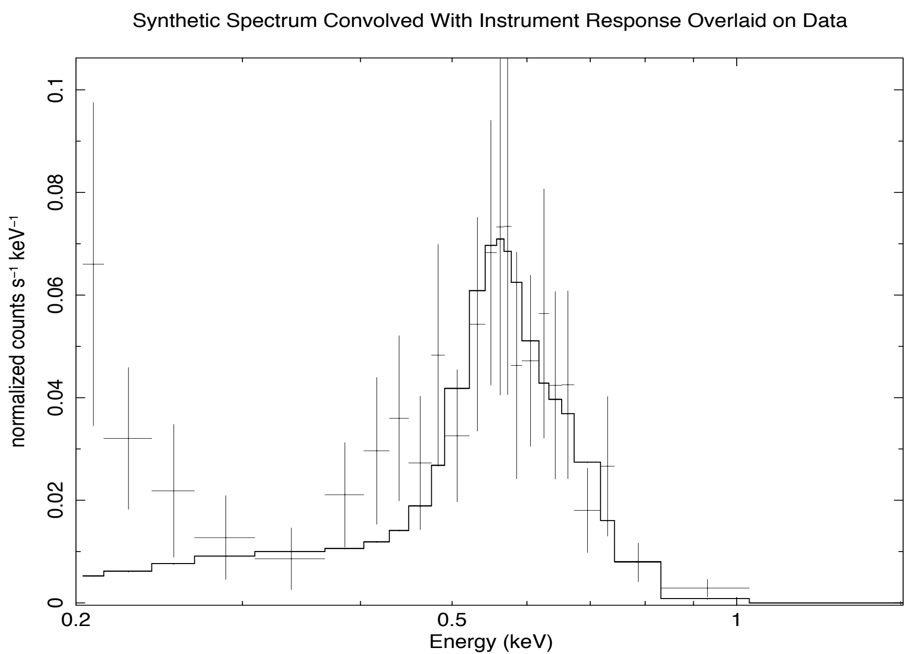




- *Top left : Solar Synchronised Type III Radio and X-ray Flares (e.g. Doddamani et al 2012)*
- *Lower Left: Jupiter Type III (also synchronized with X-ray flares)*
- *Below: Schematic for Solar production (Kontar et al. 2017)*



Synthetic Spectrum from Juno data



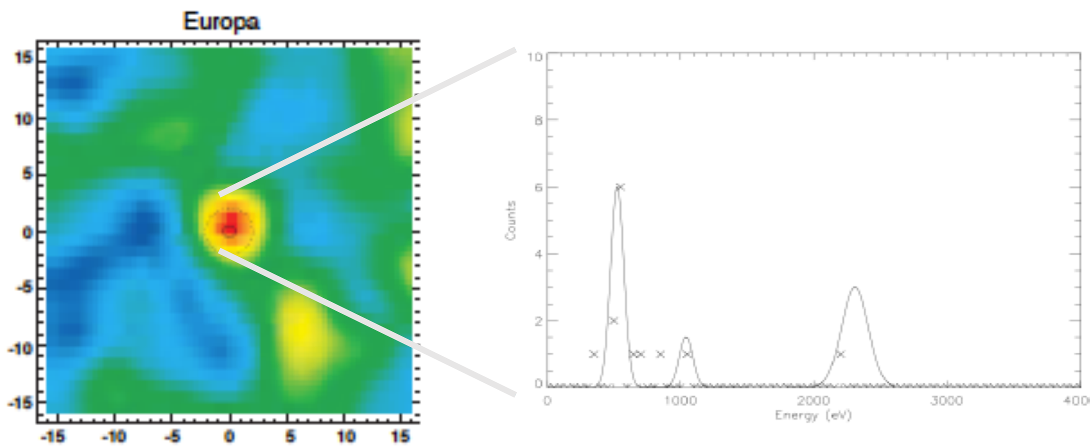




# *In-Situ* Ion Flux Simulated Spectrum Vs XMM Observation

Houston et al. simulate an X-ray spectrum through Monte Carlo simulations of ion precipitation into the Jovian atmosphere.

They take Juno JEDI ion measurements from PJ7.

We compare this with XMM observations from PJ7



Europa
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
Counts
Energy (eV)
0
1000
2000
3000
4000
10
8
6
4
2
0

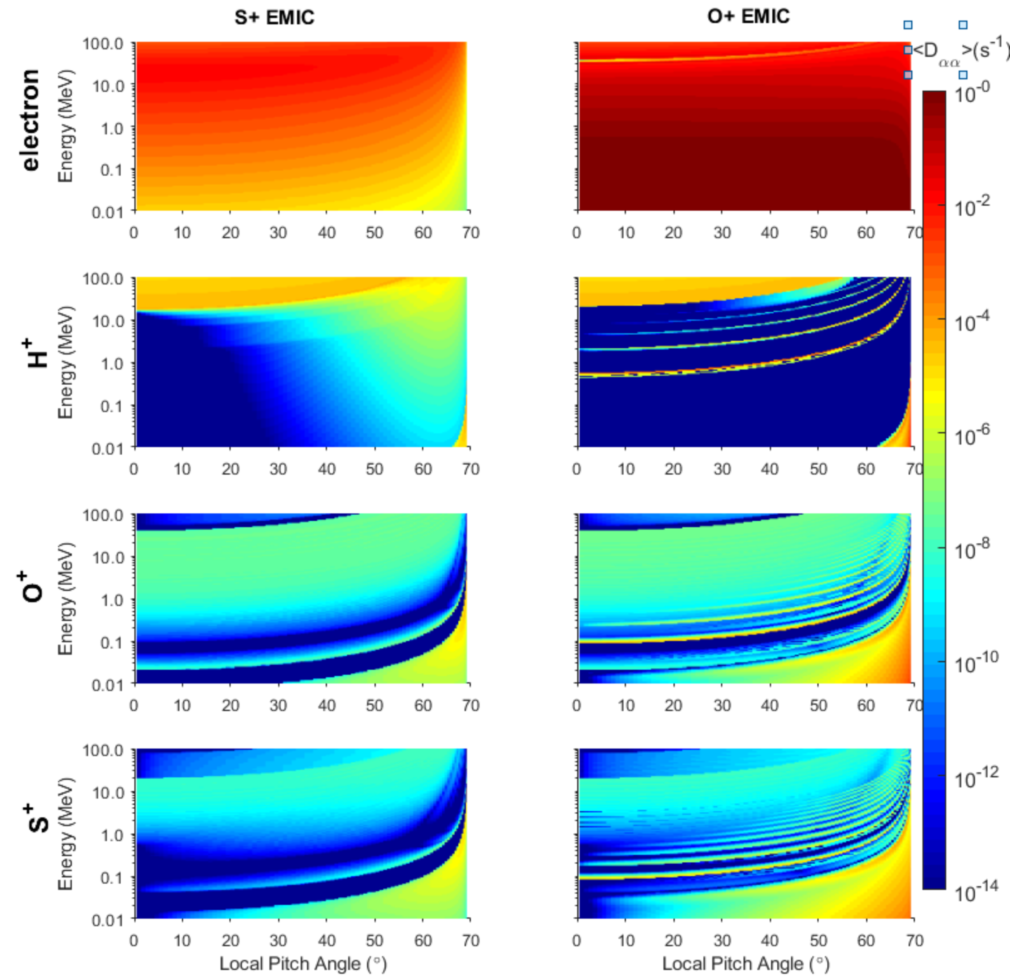
# EMIC waves also lead to Electron precipitation

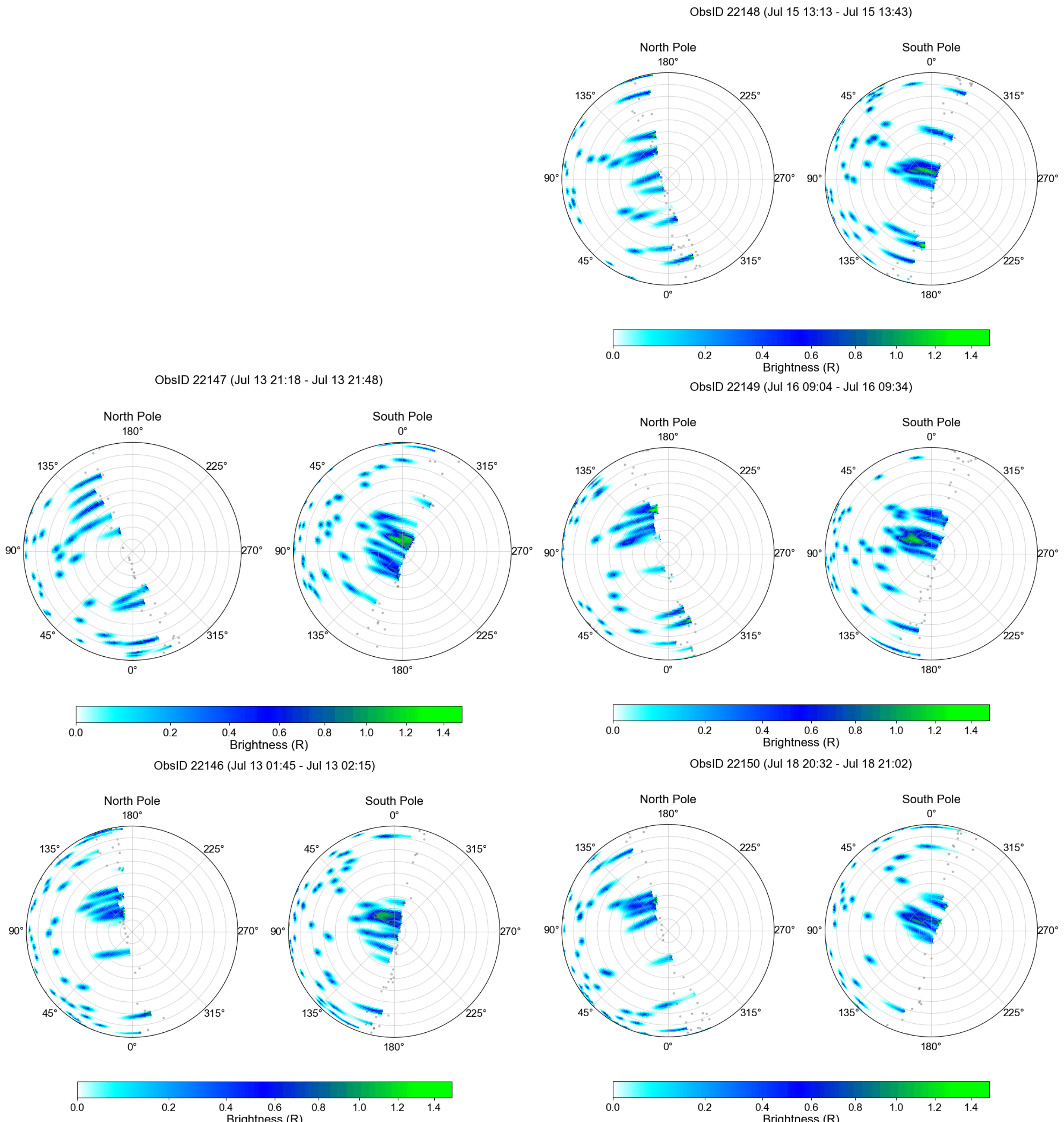
Sulphur and Oxygen Ion Cyclotron waves couple well to energetic (>100keV) S+ and O+

Surprisingly, they also couple very strongly to the full energy range of electrons.

This allows them to drive both ion and electron precipitation into the pole of Jupiter.

[work by Emma Woodfield]




ObsID 22148 (Jul 15 13:13 - Jul 15 13:43)
North Pole
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