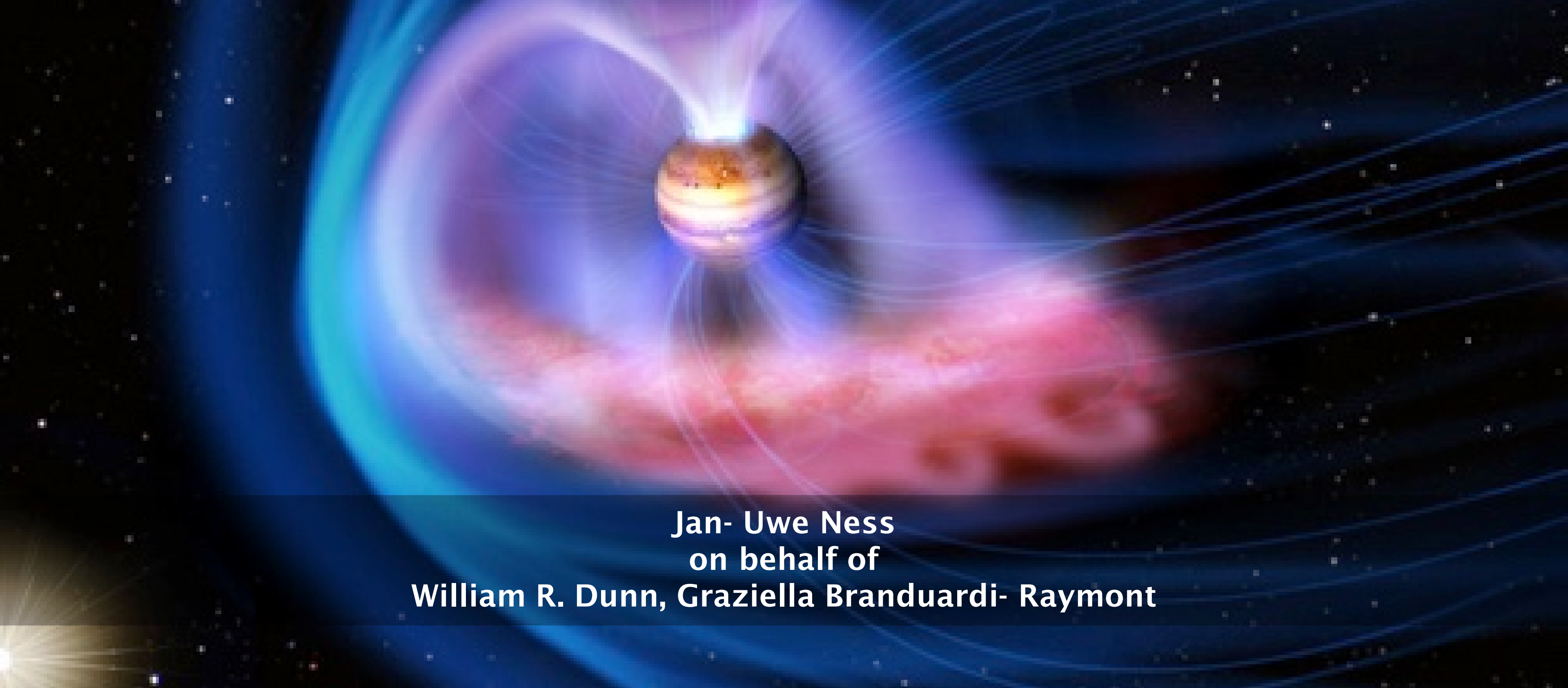
UCL DEPARTMENT OF SPACE AND CLIMATE PHYSICS
MULLARD SPACE SCIENCE LABORATORY

The Auroral Dynamic Duo: Jupiter’s Independently Pulsating X-ray Hot Spots

In-situ: Juno fly through the regions where particles are accelerated and X-rays are produced.
But: No on-board X-ray instrument
==> Remote X-ray measurements with XMM-Newton and Chandra; only dayside



Jan- Uwe Ness
on behalf of
William R. Dunn, Graziella Branduardi- Raymont

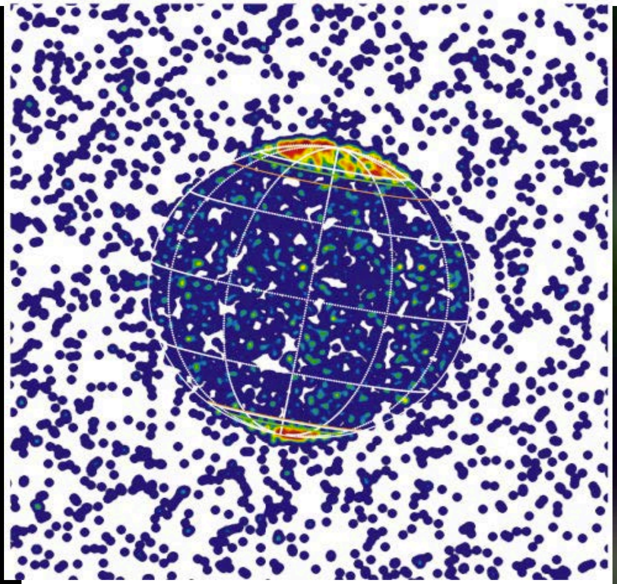
How X- rays Can Contribute To Our Jovian Understanding

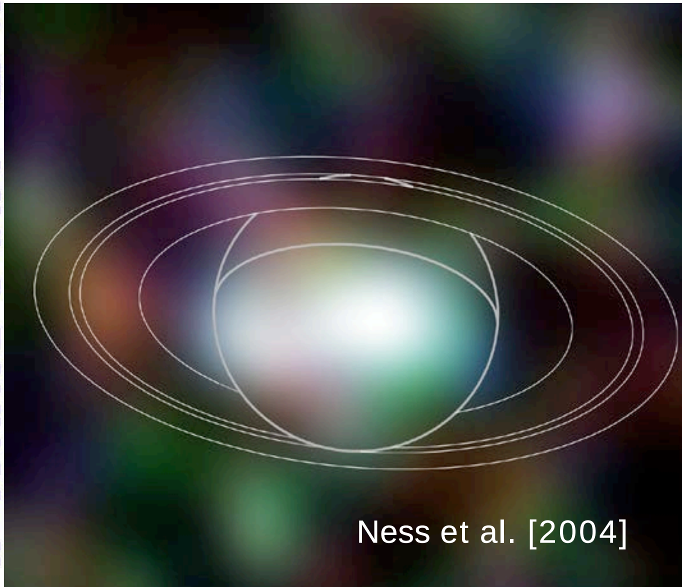
1) **Directly observe precipitating ions in high charge states via spectral lines** Raises question of energisation in rapidly rotating magnetospheres – Jupiter needs to produce ~10s MeV ions (>5×10^3 km/s for oxygen) to explain high charge stages
2) **Long uninterrupted observations allow 10s- hour variability studies**
3) **Solar wind relationship**

Multi- waveband links: X- rays – UV – IR – Radio…

Jupiter has dynamic UV+X- ray aurora; Saturn has a UV aurora but no detectable X- ray emission from the poles

Image Credit: NASA [Dunn + 2016]

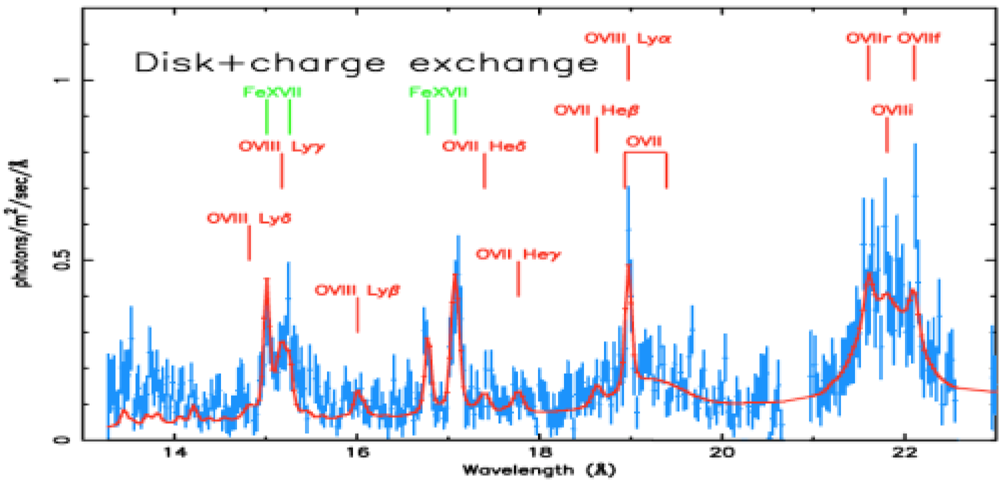




Ness et al. [2004]

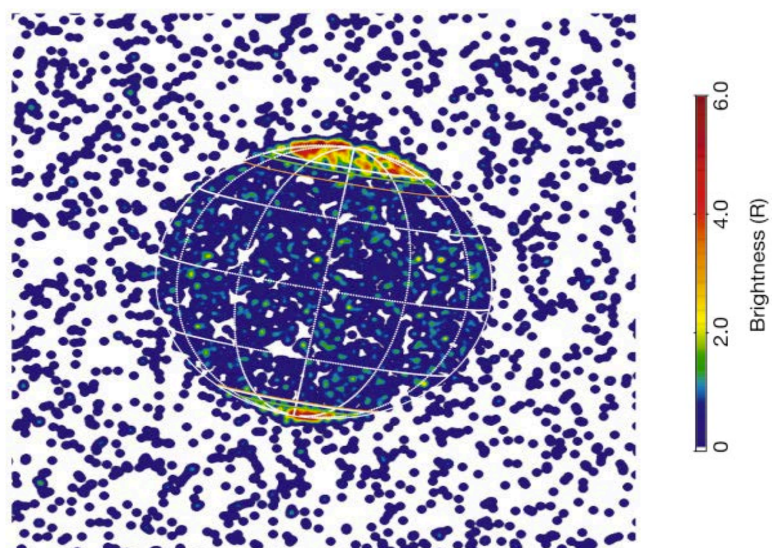
X-ray Observatory Capabilities

XMM- Newton – X- ray Spectrum



Branduardi- Raymont et al. [2017]

Chandra – X- ray Image of Jupiter



Gladstone et al. [2002]

Jupiter's Magnetosphere – An Orientation Tour

	Earth	Jupiter	Saturn
Spin period (hours)	24	9.92	10.56
Magnetic moment (ME)	1	20,000	600
Equatorial magnetic field, B_o (nT)	30,600	430,000	21,400
Plasma source (kg/s)	5	260–1400	12–250
Chapman Ferraro Radius – from balancing planetary dipole magnetic pressure with SW ram pressure	10 RE	46 RJ	20 RS
Observed RMP (RP)	8–12 RE	63 or 92 RJ	22–27 RS

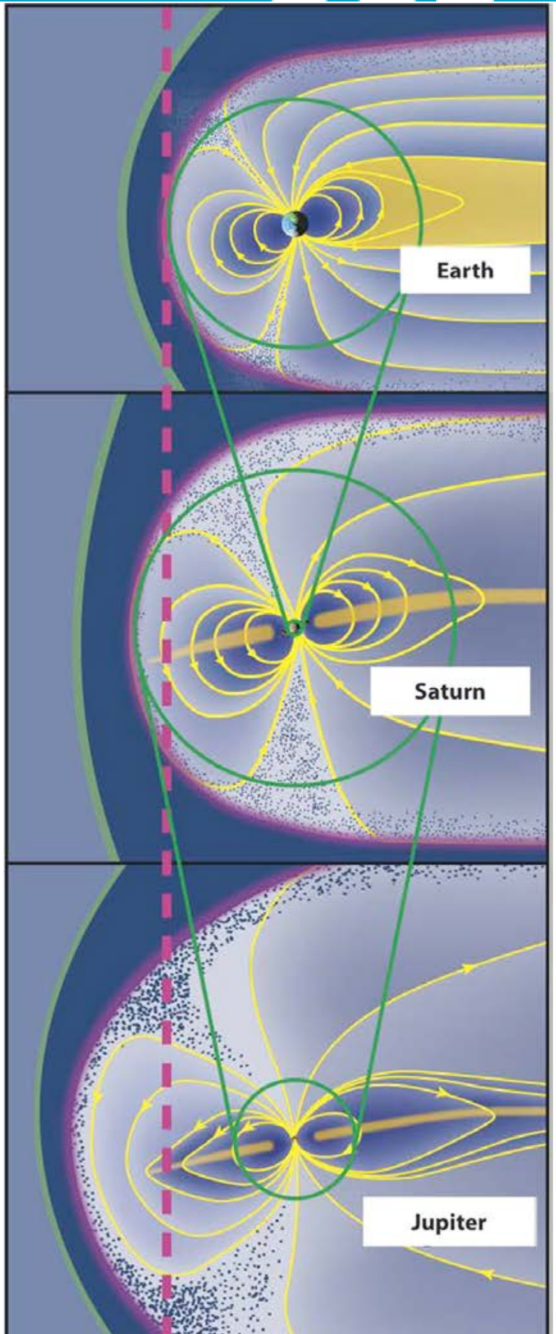


Figure: Comparison of Earth-Saturn-Jupiter magnetospheres. Pink dashed line shows Chapman Ferraro predicted magnetopause accounting only for dipole magnetic pressure.

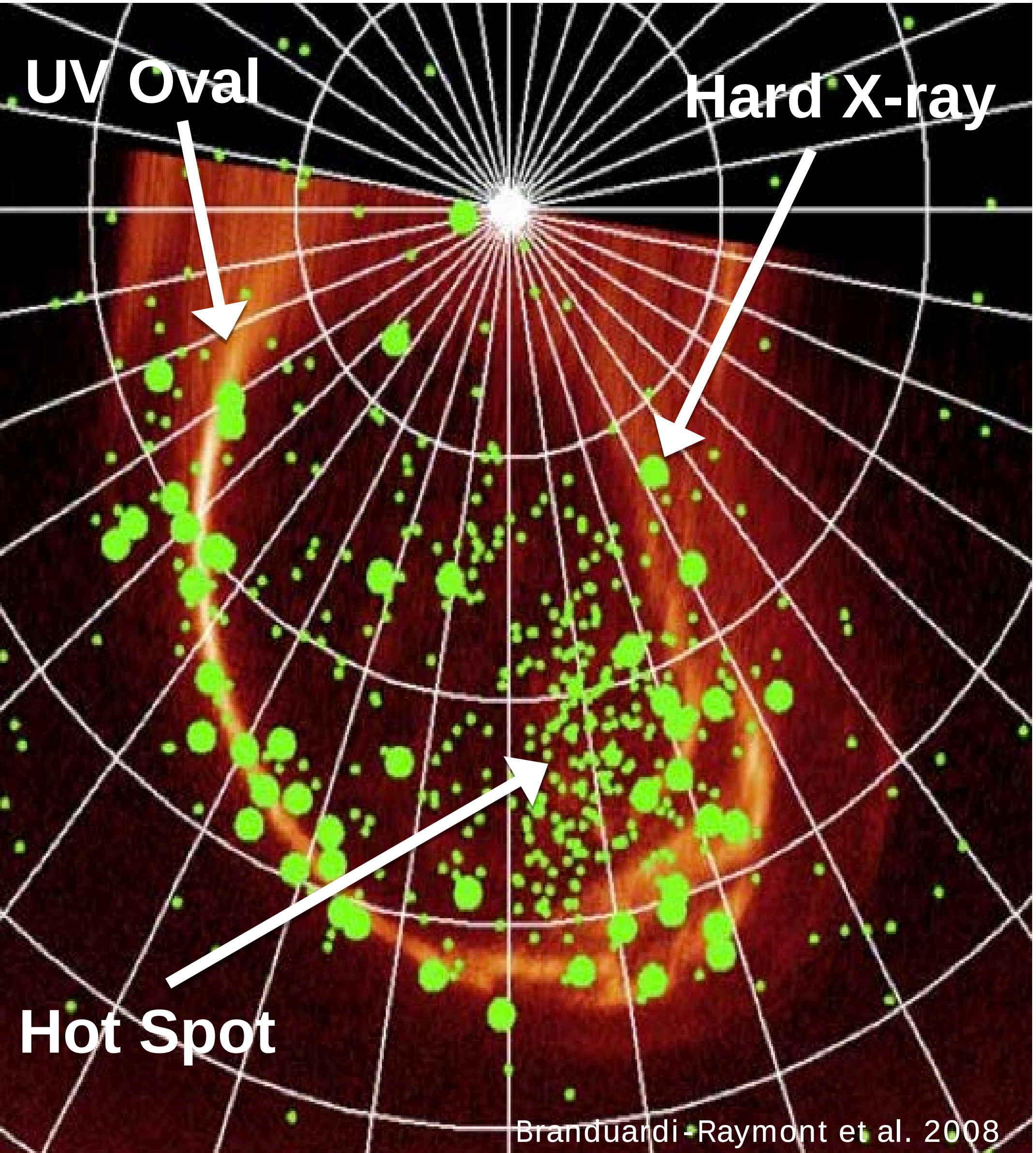
=> Prediction works for Earth while Saturn and Jupiter have additional thermal pressure adding to the magnetic pressure, thus magnetopause further out

Also the whole magnetospere dynamics changes with

- **fast rotation**
- **strong magnetic fields**
- **the presence of an internal plasma source**

Figure and Table from Bagenal et al. [2014]

Jupiter's X- ray Aurora Morphology

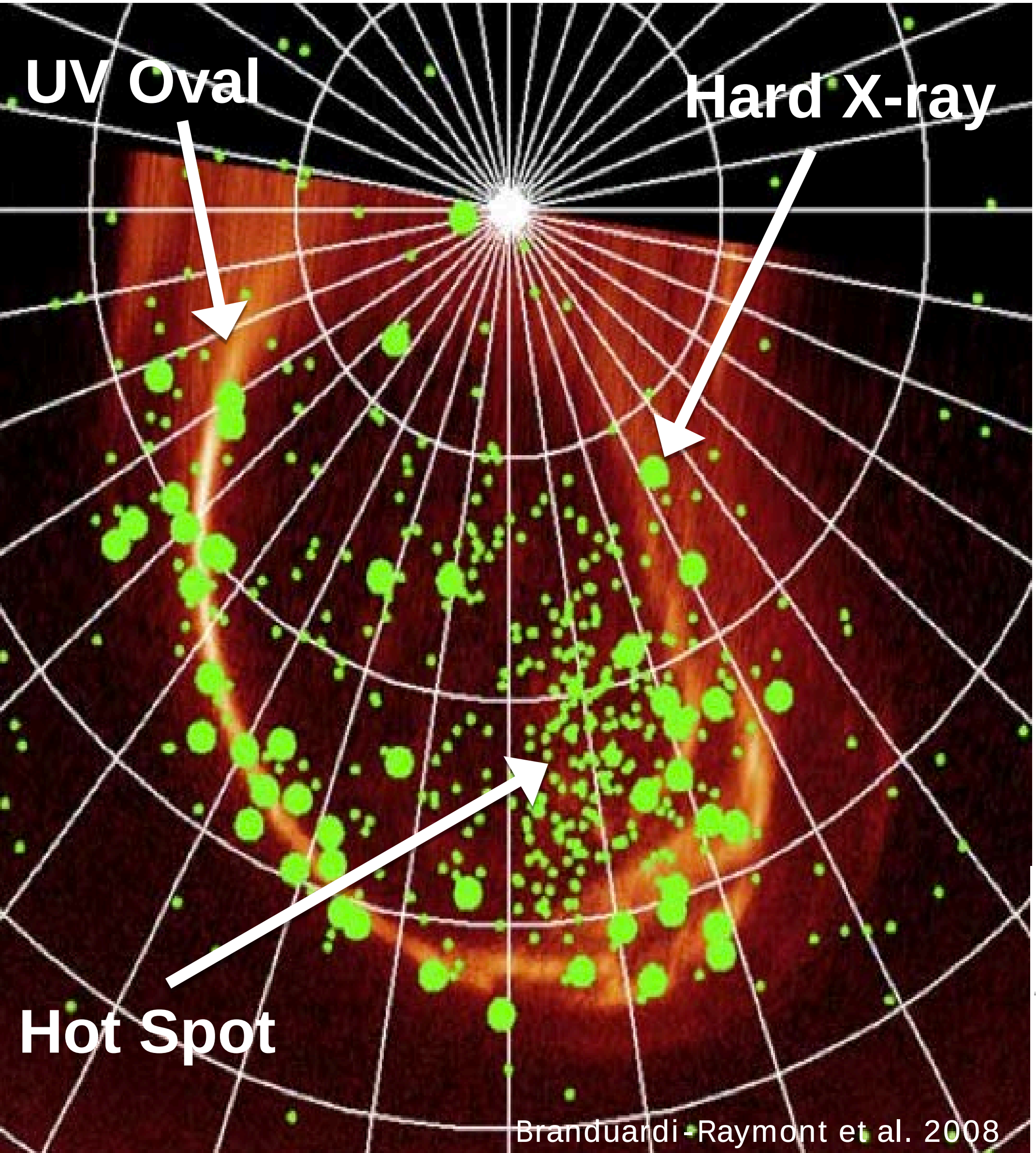


Hard X- rays (Big Green Dots)

- **Aligns with UV main oval**
- Bremsstrahlung e^- ~10^1-10^2 keV

[Branduardi-Raymont+ 2007, 2008; Cravens+ 2003; Elsner+ 2005; Gladstone+ 2002; Kimura+ 2016]

Jupiter's X- ray Aurora Morphology



Hard X- rays (Big Green Dots)

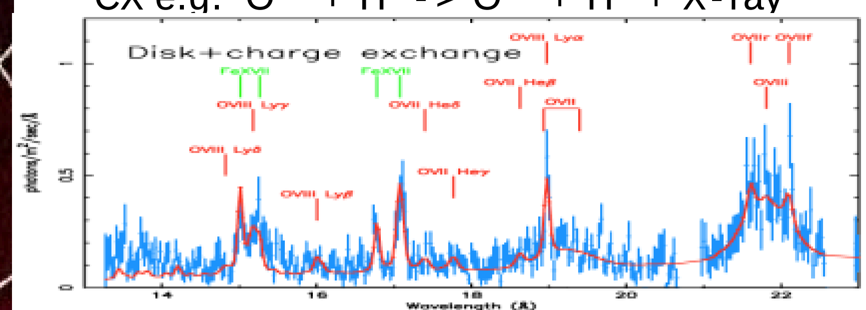
- **Aligns with UV main oval**
- Bremsstrahlung e^- ~10^1-10^2 keV

Soft X- rays (Small Green Dots)

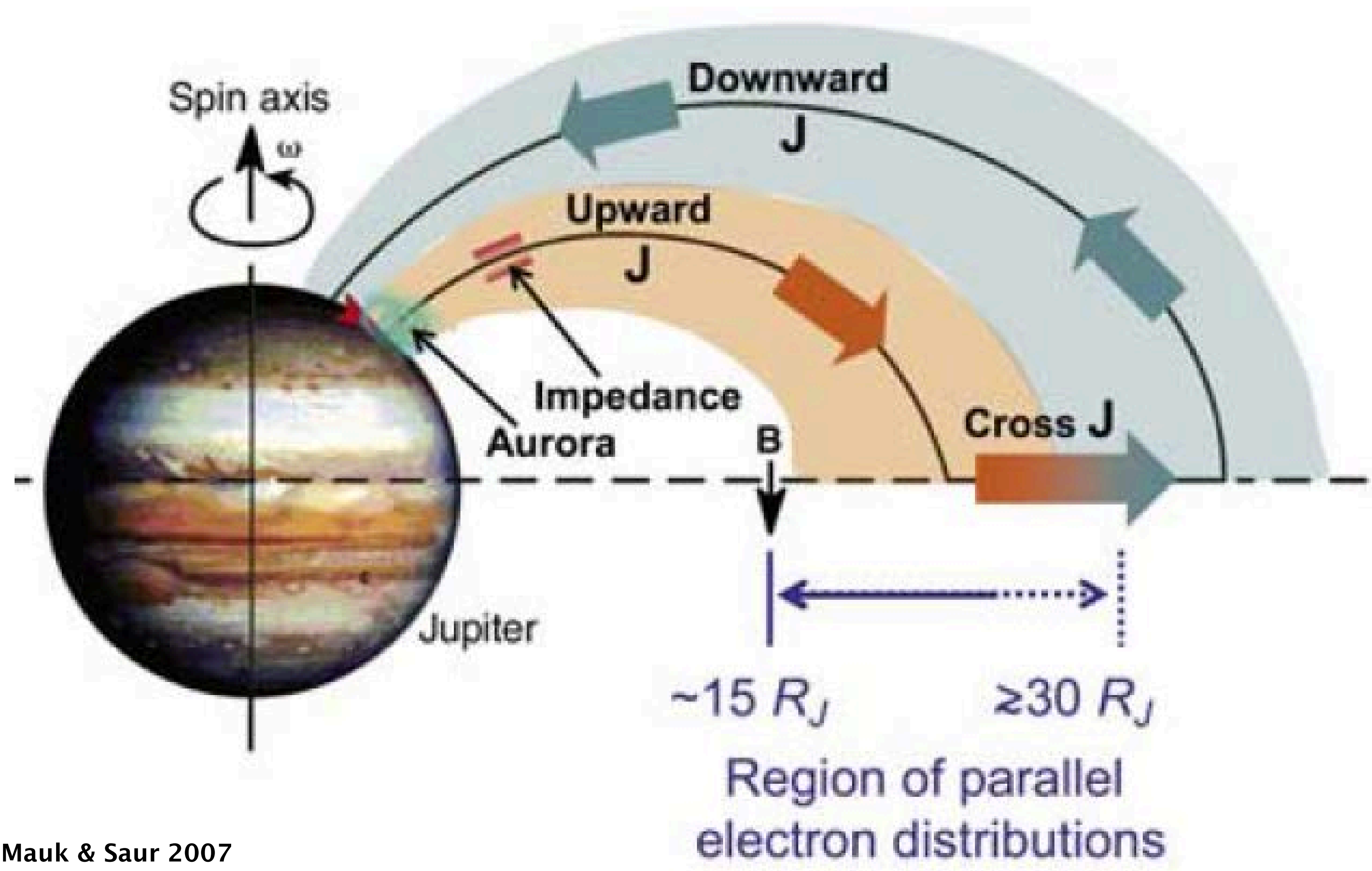
- **Hot Spot**
- MeV/amu Ions Charge Exchange
- Oxygen ($O^{7+,8+}$)
- Sulphur ($S^{7+...16+}$) and/or Carbon ($C^{5+,6+}$)

-

CX e.g. $O^{7+} + H \rightarrow O^{6+} + H^+ +$ X-ray

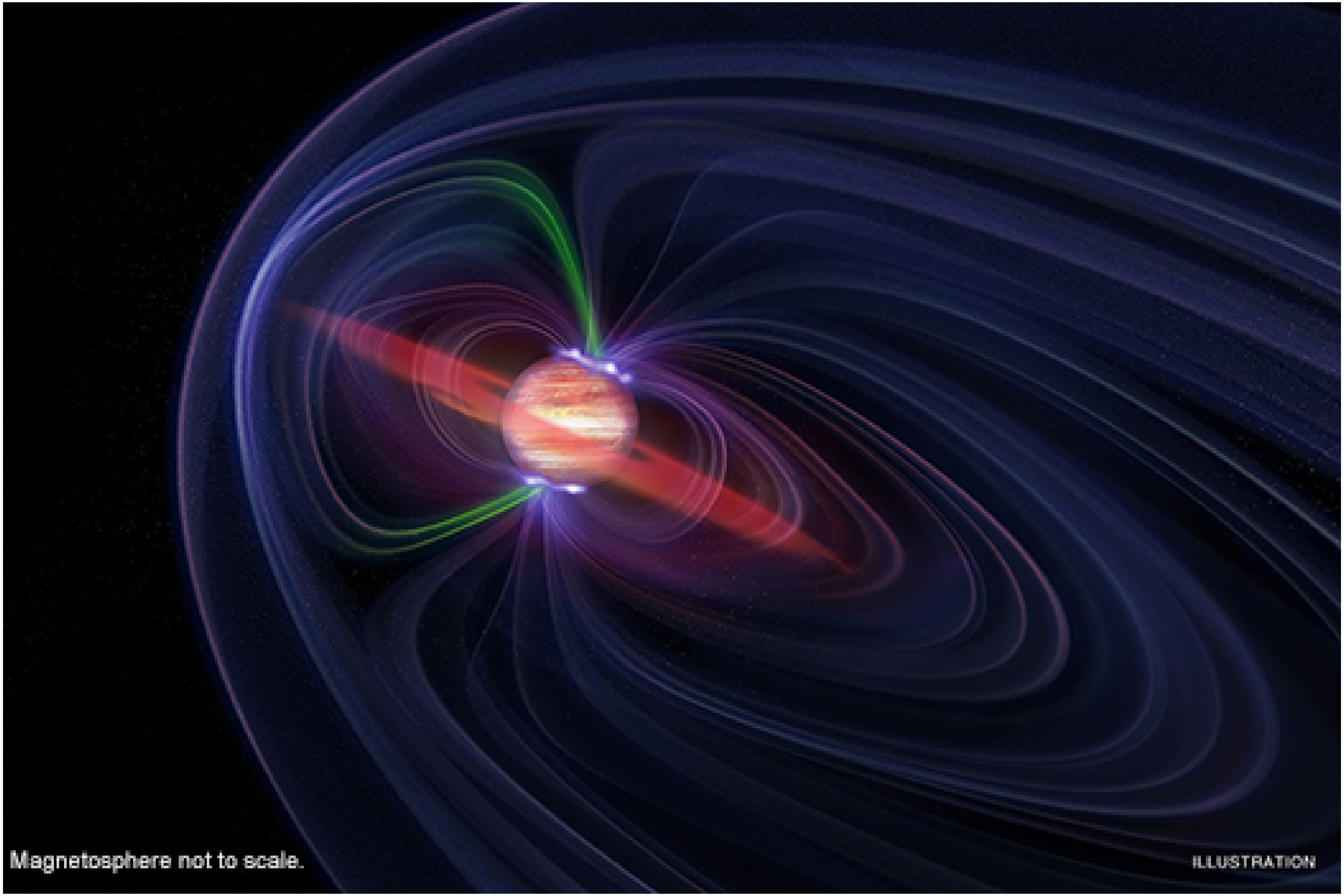


Suggested Drivers for Jupiter's high velocities in X- ray Aurora

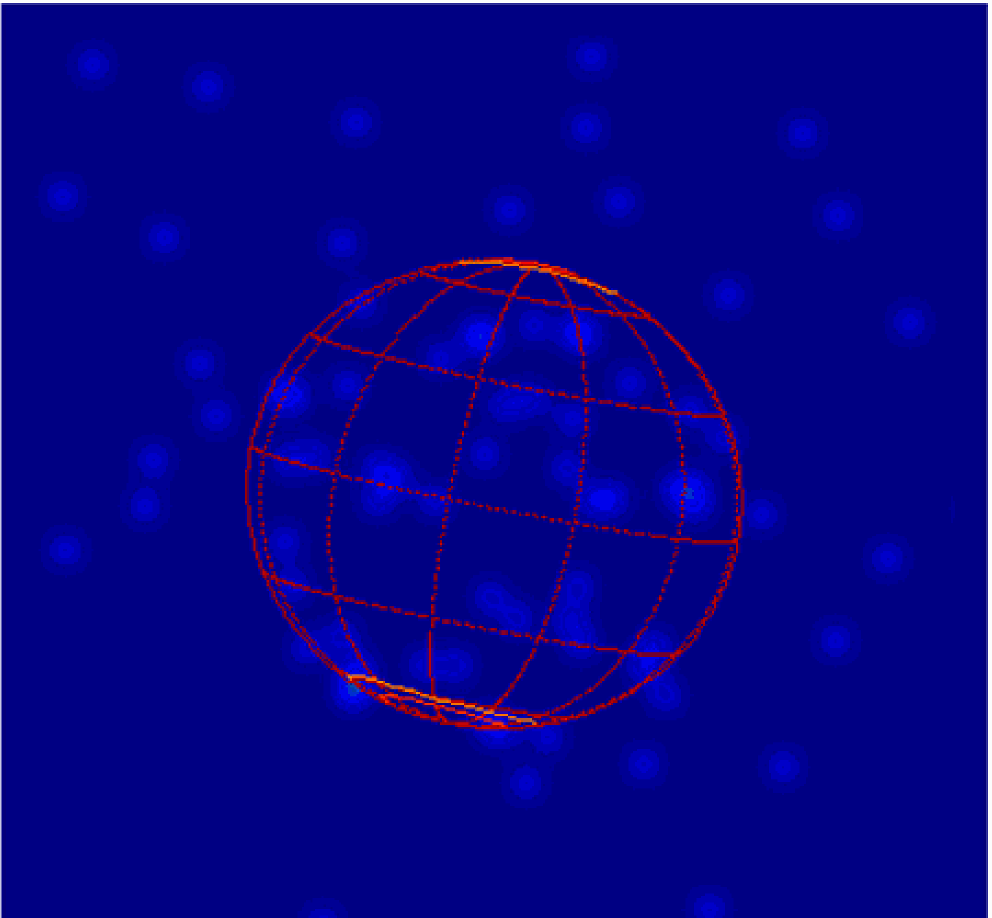


Mauk & Saur 2007

Suggested Drivers for Jupiter's high velocities in X- ray Aurora



Jupiter's Pulsing X- ray Hot Spot


[Gladstone et al. 2002]

Quasi-periodic Pulsations

- Regular ~40-45 min periodic enhancements [Gladstone+ 2002; Dunn+ 2016]
- Regular several 10s of mins periodic enhancements [Dunn+2016]
- Irregular pulsations [Elsner+ 2005; Branduardi-Raymont+ 2007; Kimura+2016]
- Radio and energetic particles also seen to exhibit similar 20-40 min Quasi-periodicity

Suggested Drivers for Jupiter's high velocities in X- ray Aurora

Outer Magnetosphere Downward Current with MV potential drops [Cravens+ 2003]
=> Does not necessarily explain pulsations

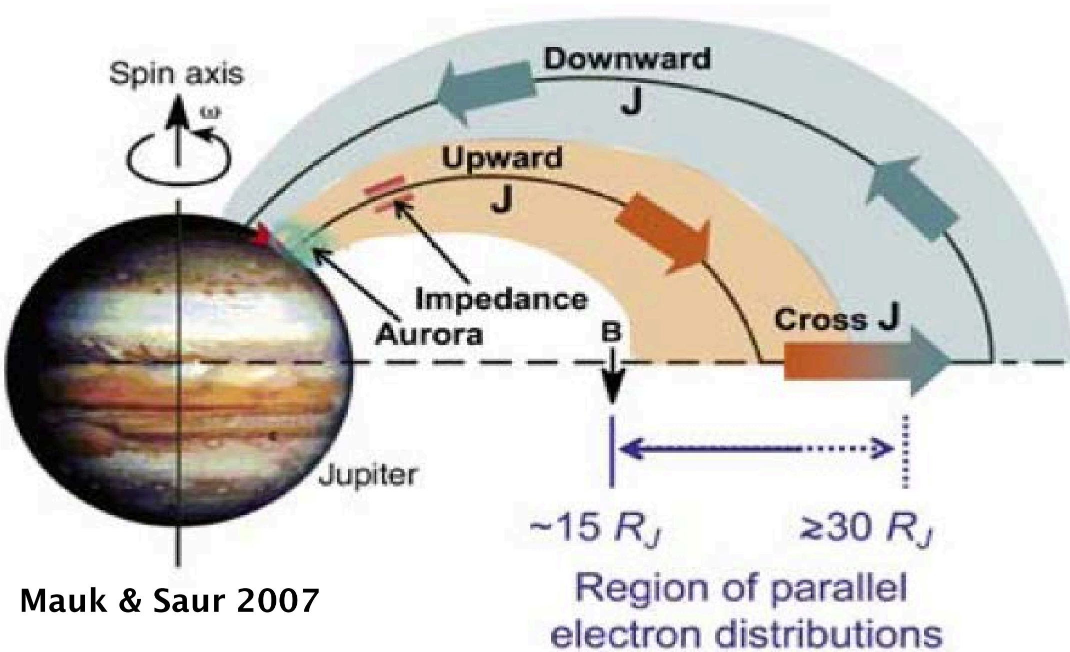
Pulsed Dayside Reconnection [Bunce+ 2004]:

- Direct solar wind precipitation: ions already in correct charge state, and reconnection with SW and magnetopause can theoretically cause pulsations at obs. frequencies

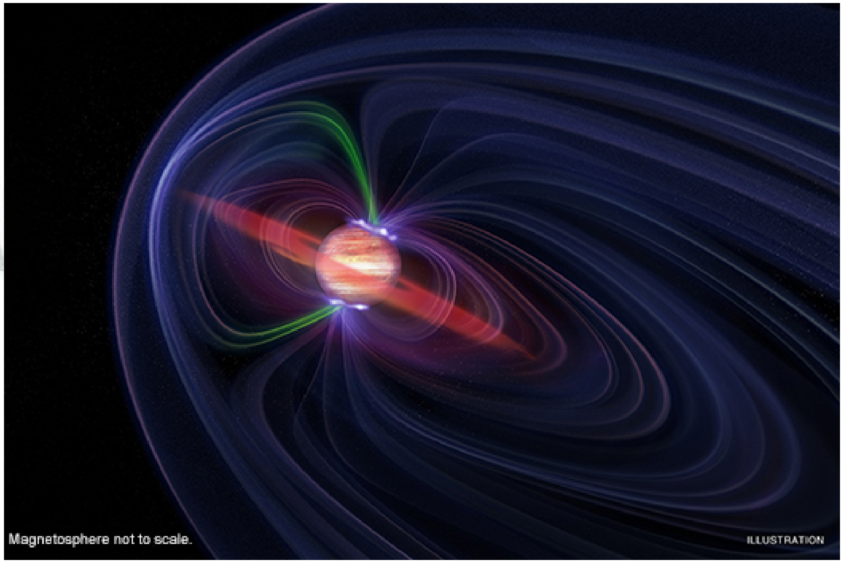
HOWEVER: SW densities too low, only explain fraction (<10%) of observed X-rays

- Perturbations from Pulsed Reconnection Vortical Flows Chapman-Ferraro Magnetopause Currents could produce the observed emission and explain pulsations.

Kelvin Helmholtz Instabilities [Kimura et al. 2016] between solar wind and magnetospheric plasma



Mauk & Saur 2007



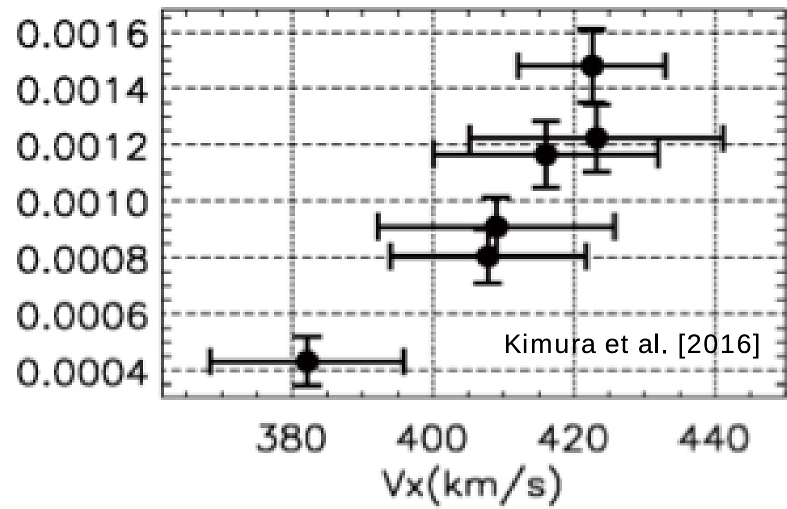
X- ray Aurora Solar Wind Relationships

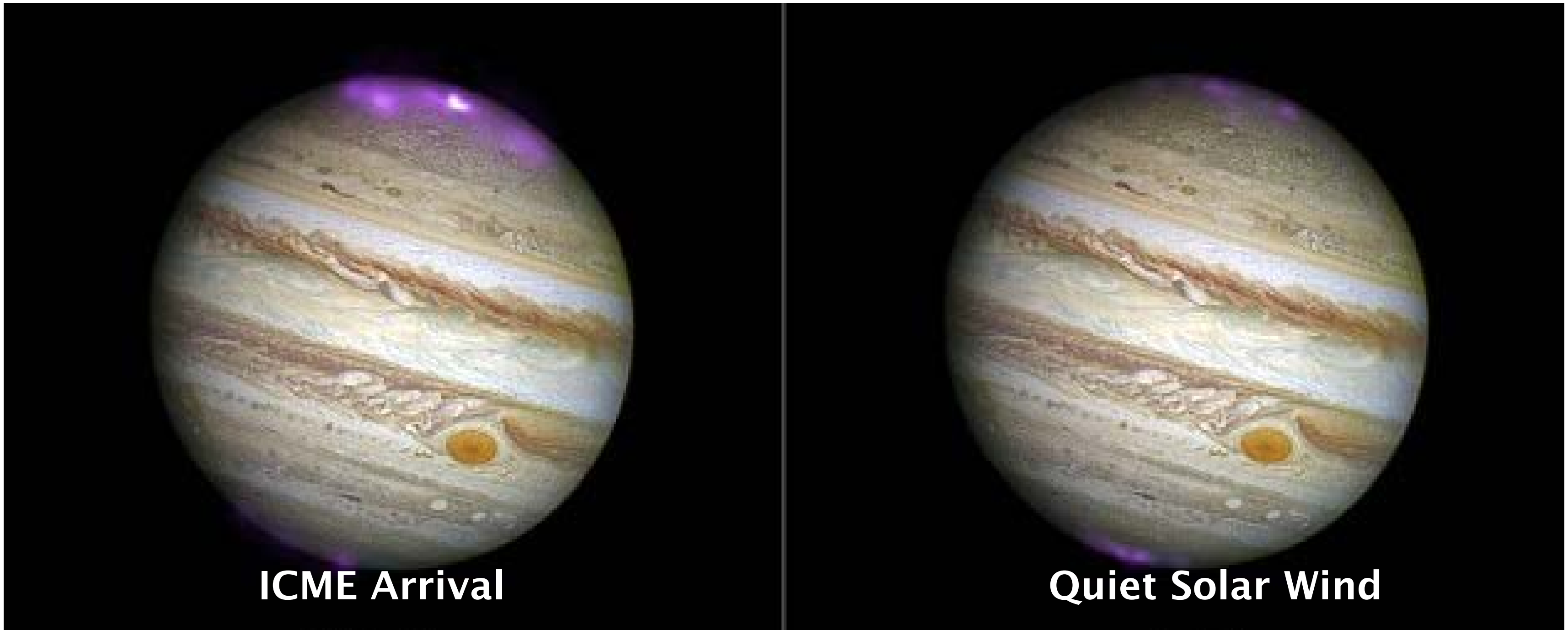
X-ray aurora correlated with solar wind velocity (right [Kimura+ 2016])?
Indicators:
During an ICME Jupiter's X-ray aurora [Dunn et al. 2016]:

1. Significantly brightened (below)
2. Expanded spatially
3. Changed precipitating particle populations (different spectra)
4. Changed pulsations timescale (10s min Vs 45 min 'normally')
5. Coincided with bursts of non-Io decametric radio emission (previously correlated to solar wind P [e.g. Hess + 2014])

Studies used solar wind propagations from 1AU (uncertainties of +/- 10s hrs) because of absence of in-situ upstream measurements.

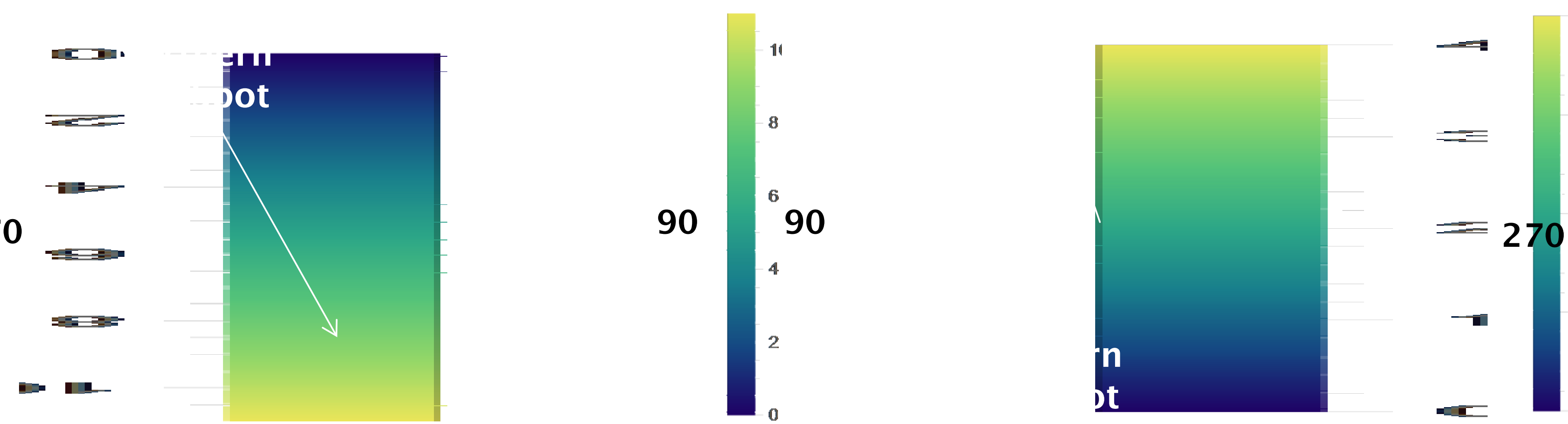
Hot Spot Counts/sec Vs Solar Wind Velocity





X- rays During Juno Approach – Detection of the Twin Southern Spot

- ~11-14 hr X-ray observations in Summer 2016 on: **18 May (XMM), 24 May (Chandra and XMM) and 1 June 2016 (Chandra)**
- **2016 campaign reveals that South also has an X-ray hot spot [Dunn et al., 2017]**
- Southern Spot also in same location in 2007 – only other X-ray observation with visibility of S pole



Projections centered on Jupiter's North (left) and South (right) pole for two Chandra X-ray observations. X-rays binned into 1.5° by 1.5° of S3 latitude-longitude. Thick gold contours: magnetic field footprints of Io at 5.9 RJ and 15 RJ and 50 RJ moving polewards. Red Dot: Magnetic pole. Alternating Green/Black contours: VIP4 surface field strength (innermost: 14G, outermost 4G)

Independent X- ray Spot Behaviour

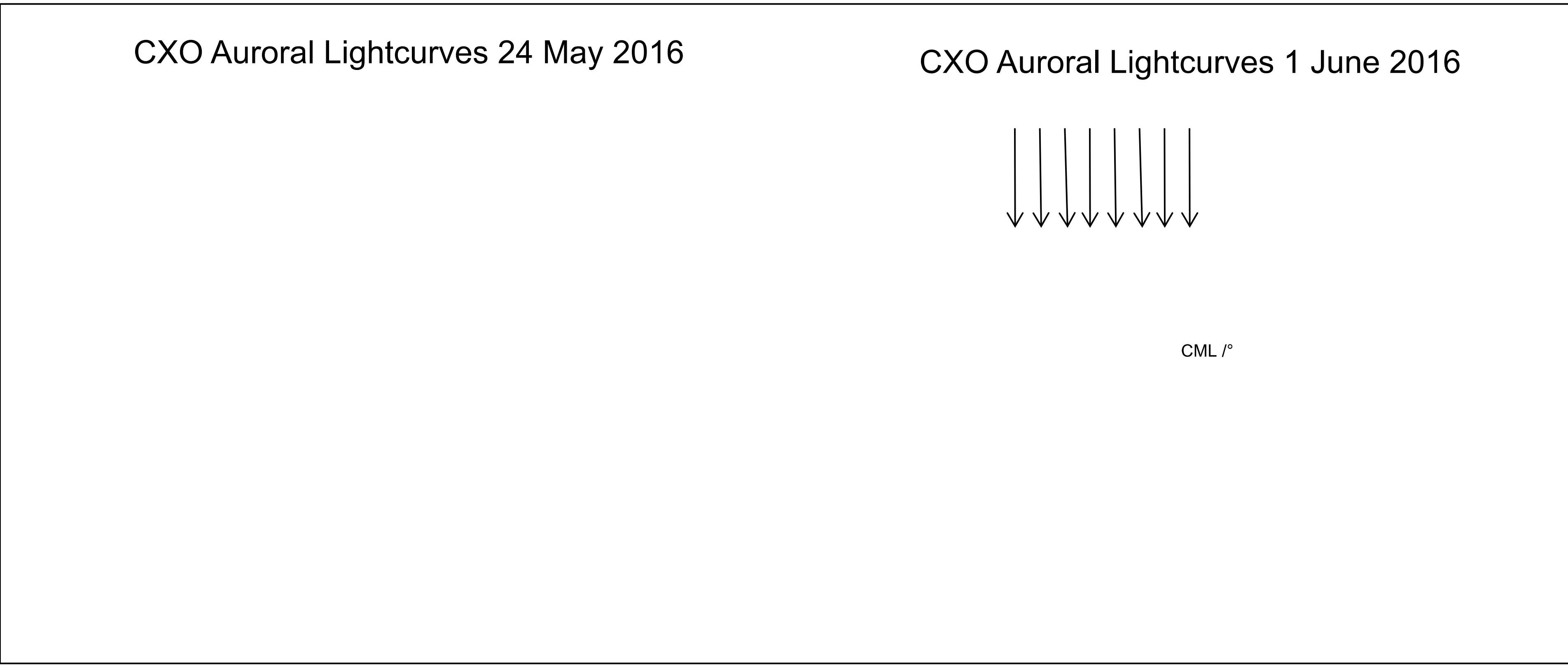
CXO Auroral Lightcurves 24 May 2016

CXO Auroral Lightcurves 1 June 2016

CML /°

Independent X- ray Spot Behaviour

- **Regular Pulsations in the South**



X-ray Spot Periodic Behaviour

Fourier transforms of the lightcurves provide power spectral density plots to identify any regularity in the pulsations.

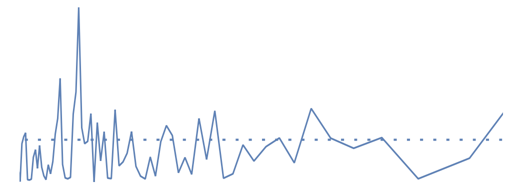
- Southern spot is dominated by pulsations with regular 9-11 min period in both observations and detected in both instruments.
- Northern spot is not dominated by this same period.

South

24 May Chandra

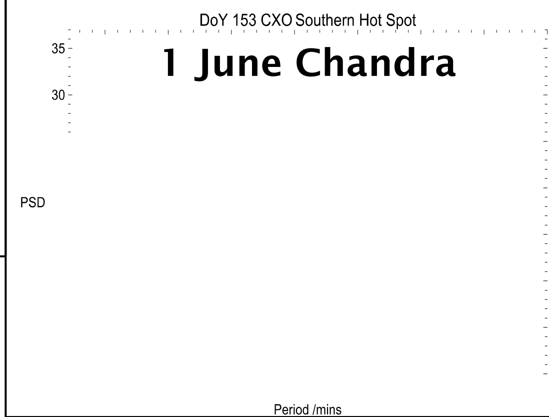
North

24 May Chandra



24 May XMM- Newton

24 May XMM- Newton

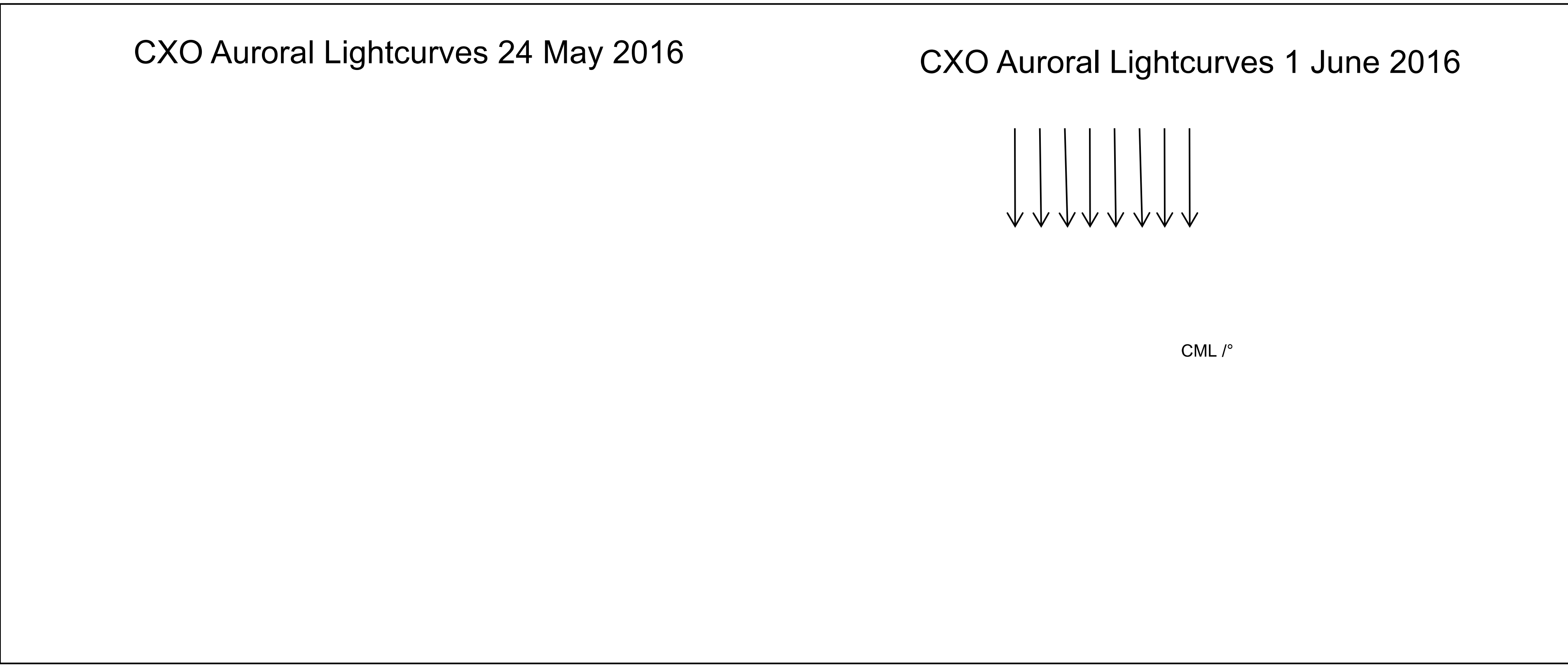


1 June Chandra

1 June Chandra

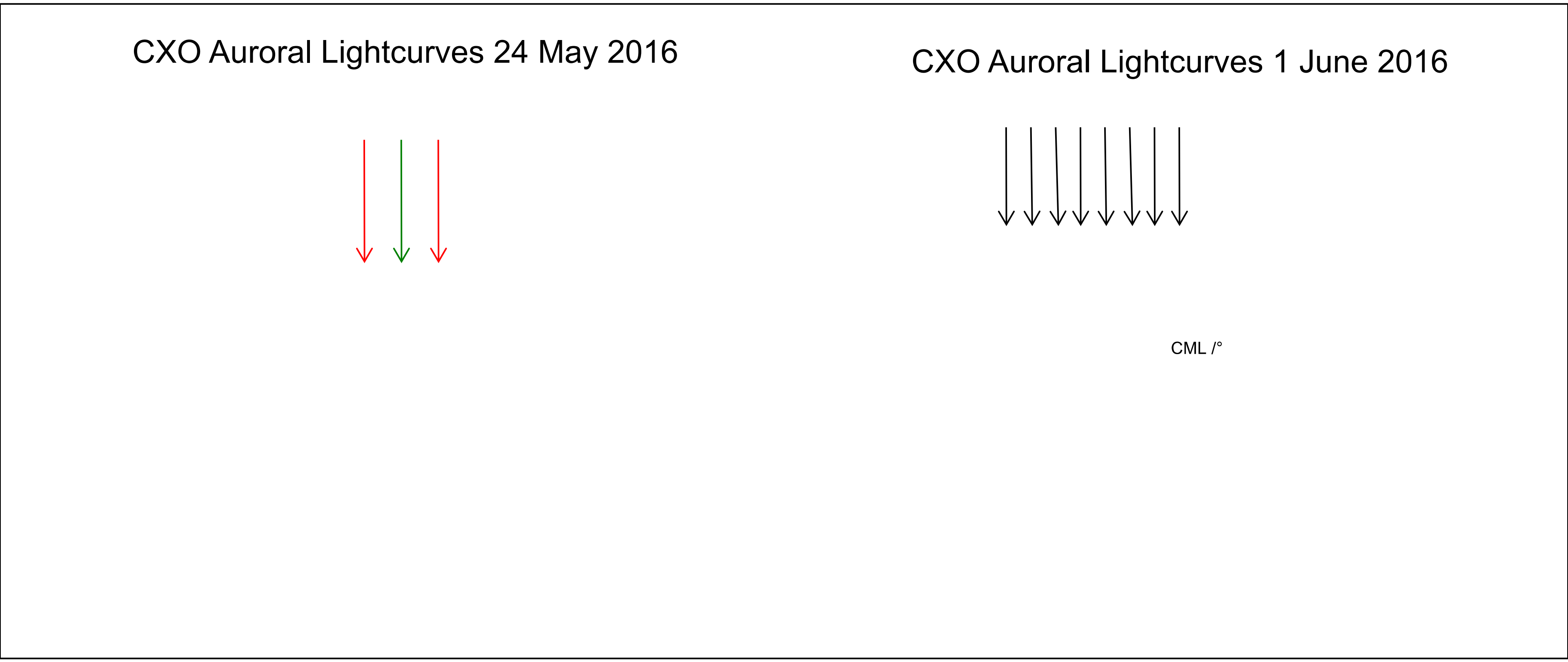
Independent X- ray Spot Behaviour

- **Regular Pulsations in the South**



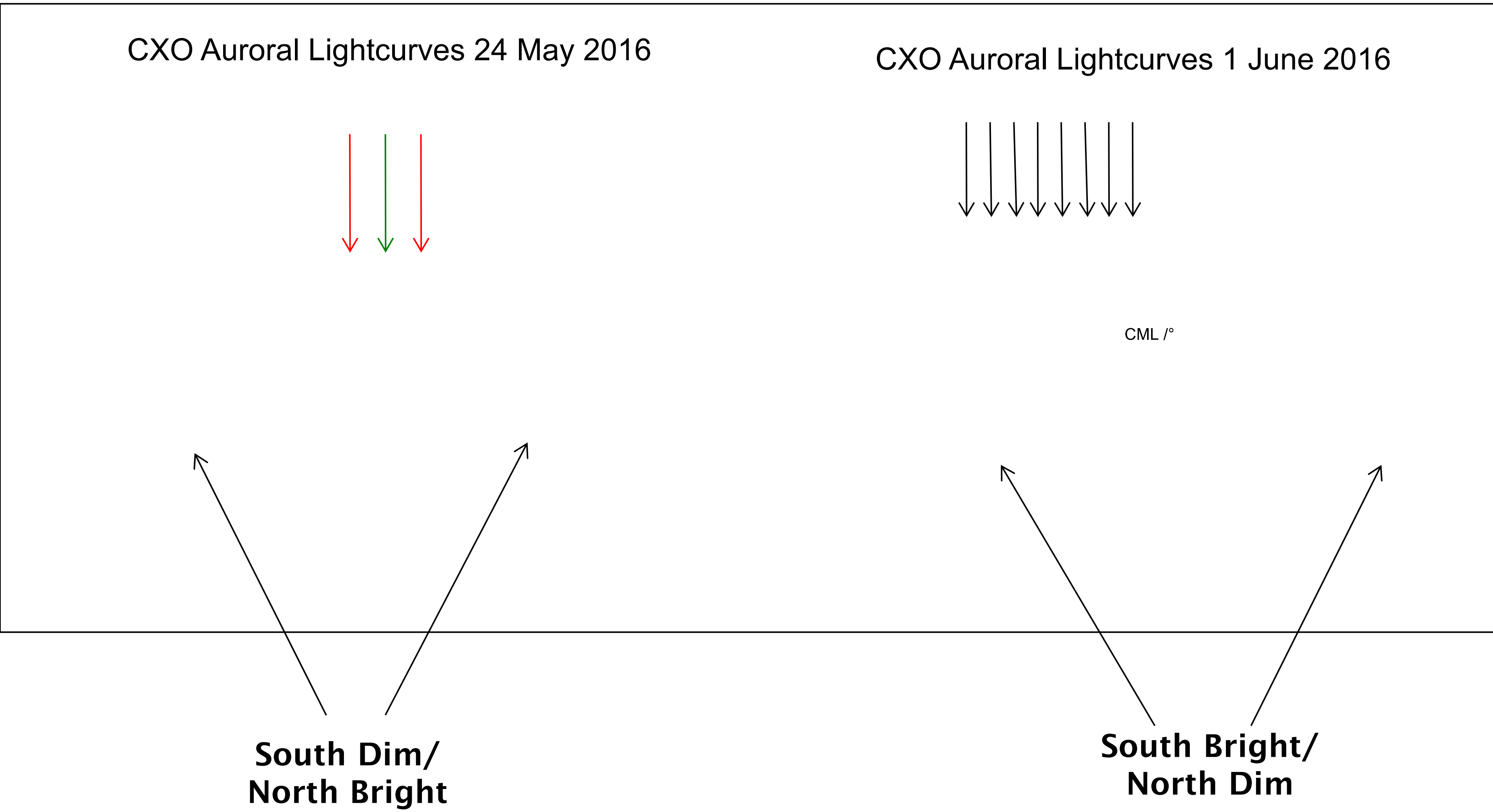
Independent X- ray Spot Behaviour

- **Regular Pulsations in the South**
- **Conjugate and Non-conjugate Polar Emissions**



Independent X- ray Spot Behaviour

- **Regular Pulsations in the South**
- **Conjugate and Non-conjugate Polar Emissions**
- **General Brightening of one pole is not correlated to the other**

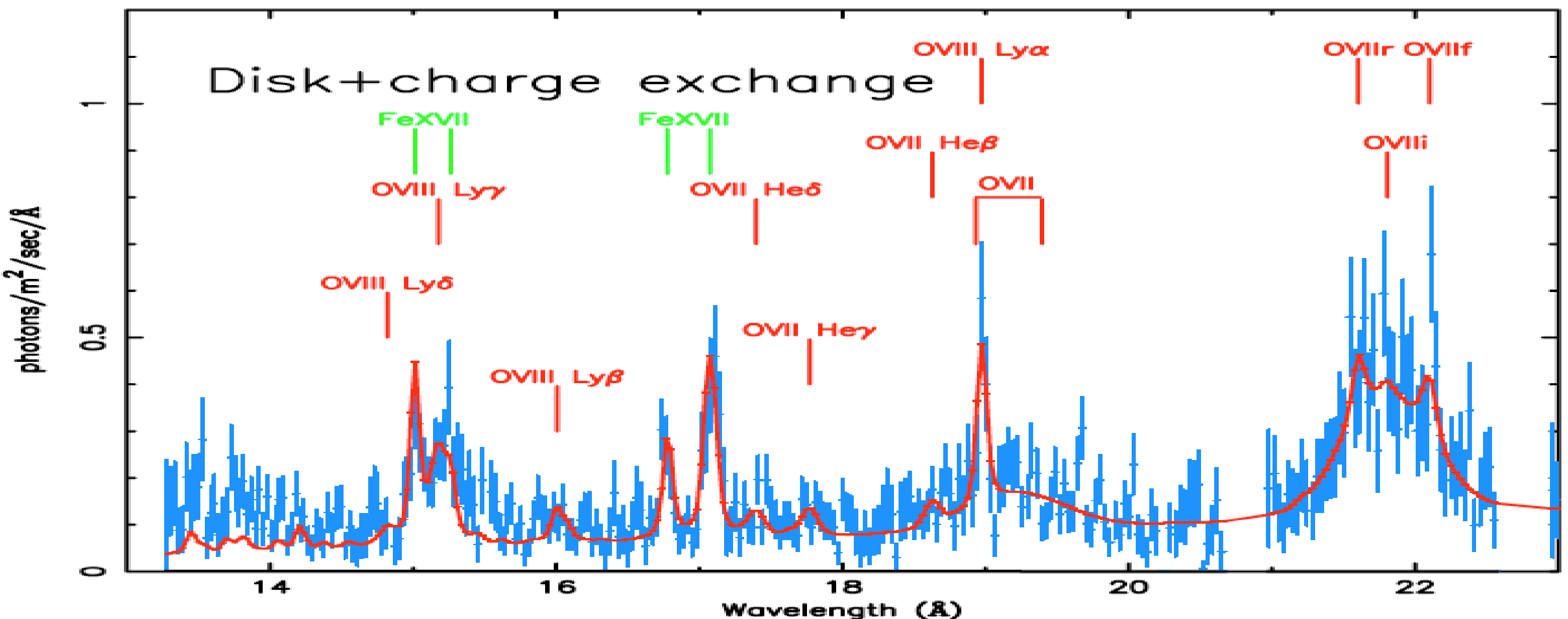


Future Opportunities: Juno

What is the X- ray Driver?

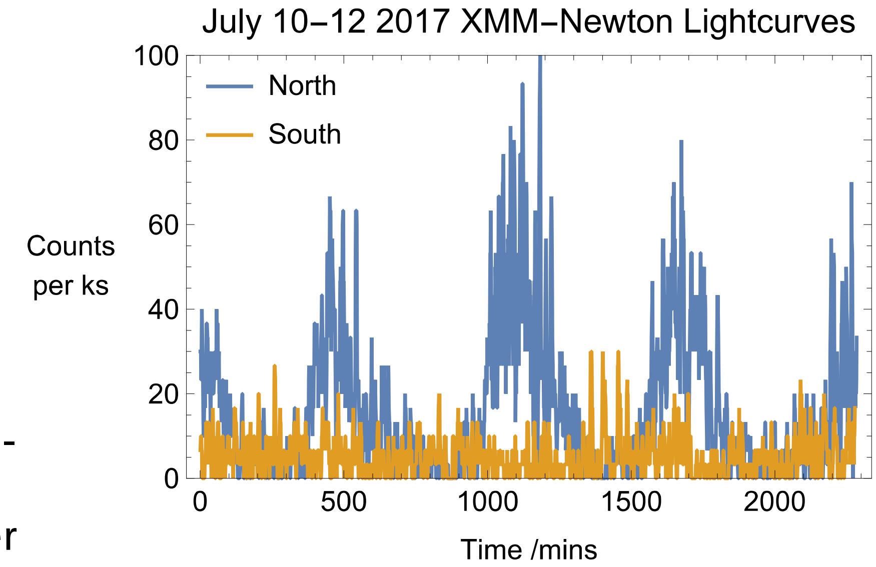
Compare Juno precipitating ions with X-ray spectra doppler broadening to quantify acceleration between magnetosphere and atmosphere [e.g. Branduardi-Raymont+2007]

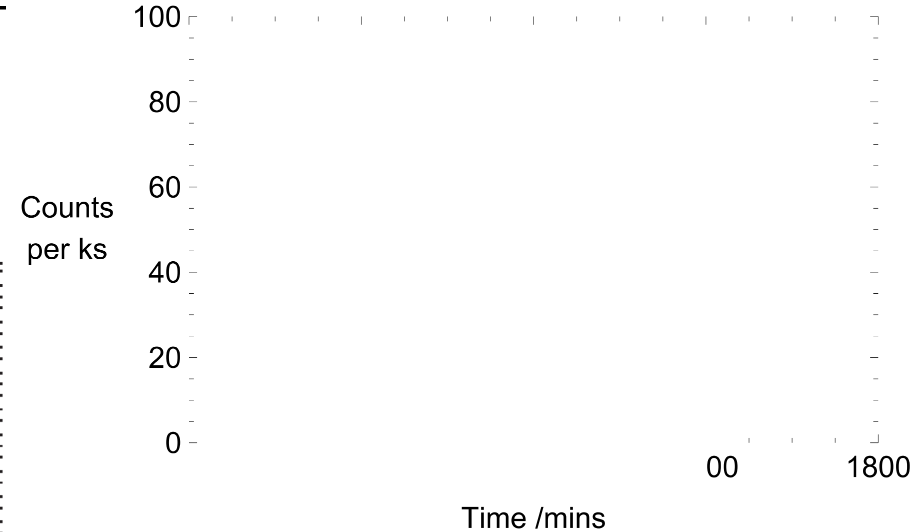
How else can we complement Juno's amazing data: Radio/WAVEs relationship? High energy electrons? Magnetic field drivers?

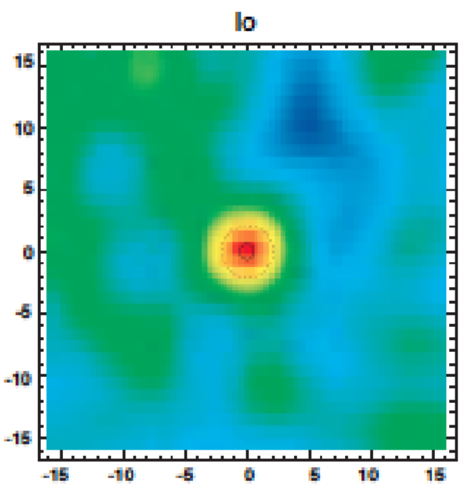


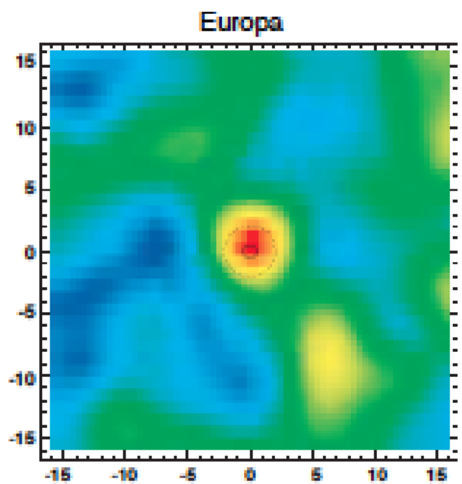
Summary

- X-ray Aurora from ion precipitation has only been detected at Jupiter
- Jupiter's Northern and Southern X-ray Aurora Behave Independently
- Juno presents unique opportunity to connect in-situ measurements of physics with the X-ray signatures observed by XMM and CXO so Jupiter can be used as an analogue for more distant X-ray sources
- Other opportunities (moons (below), IPT, Uranus...)









Summary of Jovian X- rays

- Hot spot pulsations from precipitation of highly charged 10s MeV ions that originate near magnetopause
- Jupiter's X-ray aurora change temporal, spectral and spatial emissions with solar wind conditions
- Northern and Southern hot spots sometimes behave independently
- Possible connections with UV flares, non-Io Decametric Radio Emissions and with IR hot spots
- Lots of X-hilirating observations ahead!

Just Scratching the Surface - a few of the Open Questions:

- How does Jupiter's outer magnetosphere/pole produce pulsating 10s MeV precipitating ions?
- How does the X-ray emission relate to the IR, UV, Radio and why?
- Why are the hard X-rays transient?
- Why do the North and South Pole Hot Spots seem to behave independently?
- How does the solar wind drive/modulate the emissions?

Why else may we care about Jupiter's X- rays?

1) Jupiter is a laboratory in our back yard to learn for understanding of more exotic astrophysical bodies Involving astrophysical rotationally-dominated magnetospheres e.g.

- Pulsars
- Rapidly Rotating Brown Dwarfs
- Exoplanets

2) **Holistic view to magnetospheric physics:** How do processes vary with different magnetospheric conditions and what are the auroral signatures of these?

Are processes and signatures ubiquitous across magnetospheres? For instance, do all planets interact with the solar wind in the same way? Can we even learn about interactions with the Interstellar Medium?

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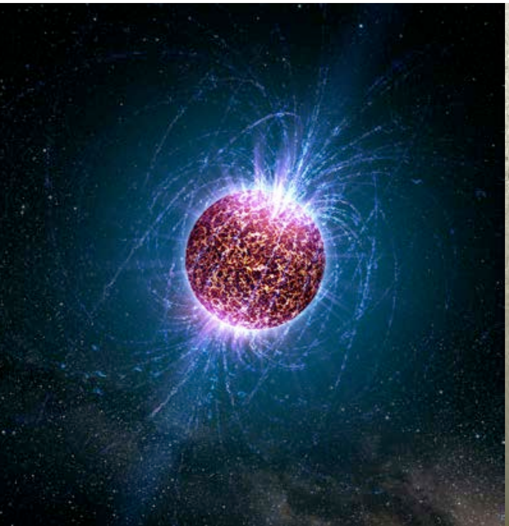
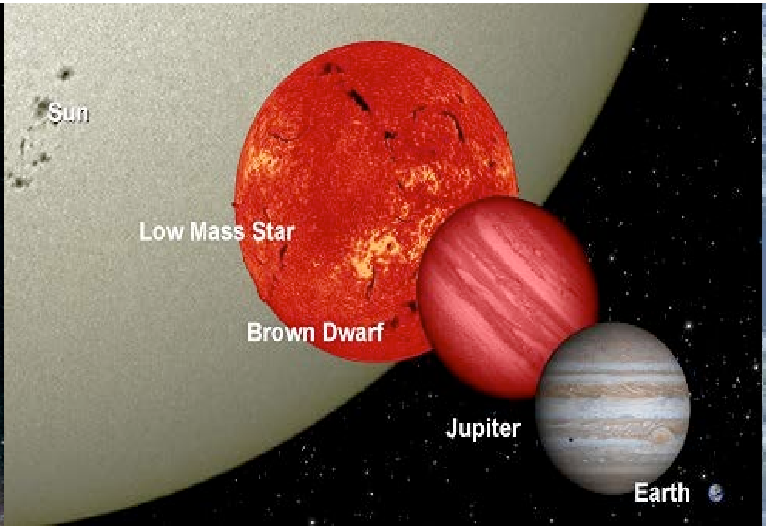
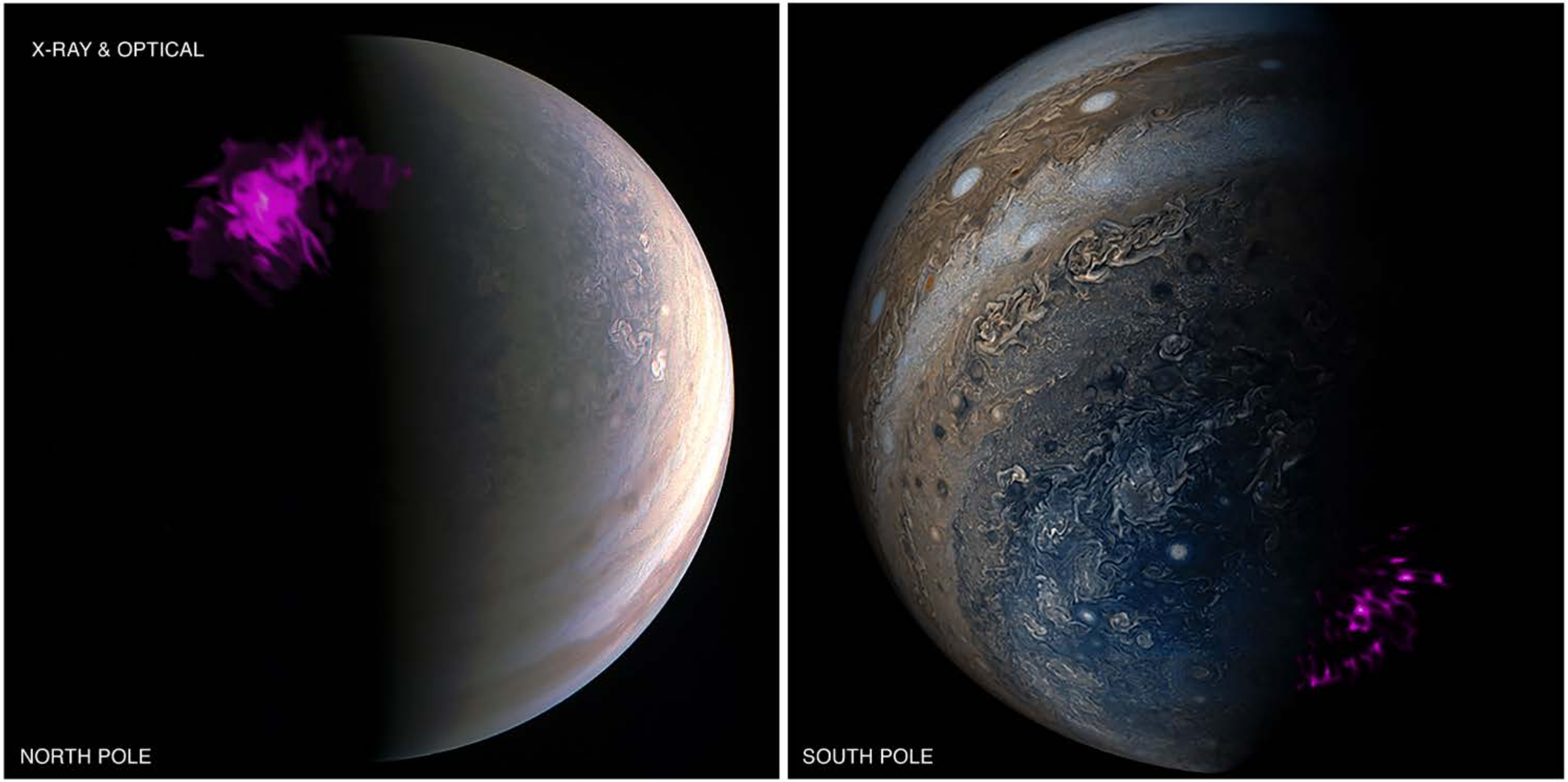
Juno will fly through the regions where particles are accelerated and X-rays are produced.
But: No on-board X-ray instrument: Thus remote X-ray measurements necessary





Jupiter's X- ray Aurora Morphology



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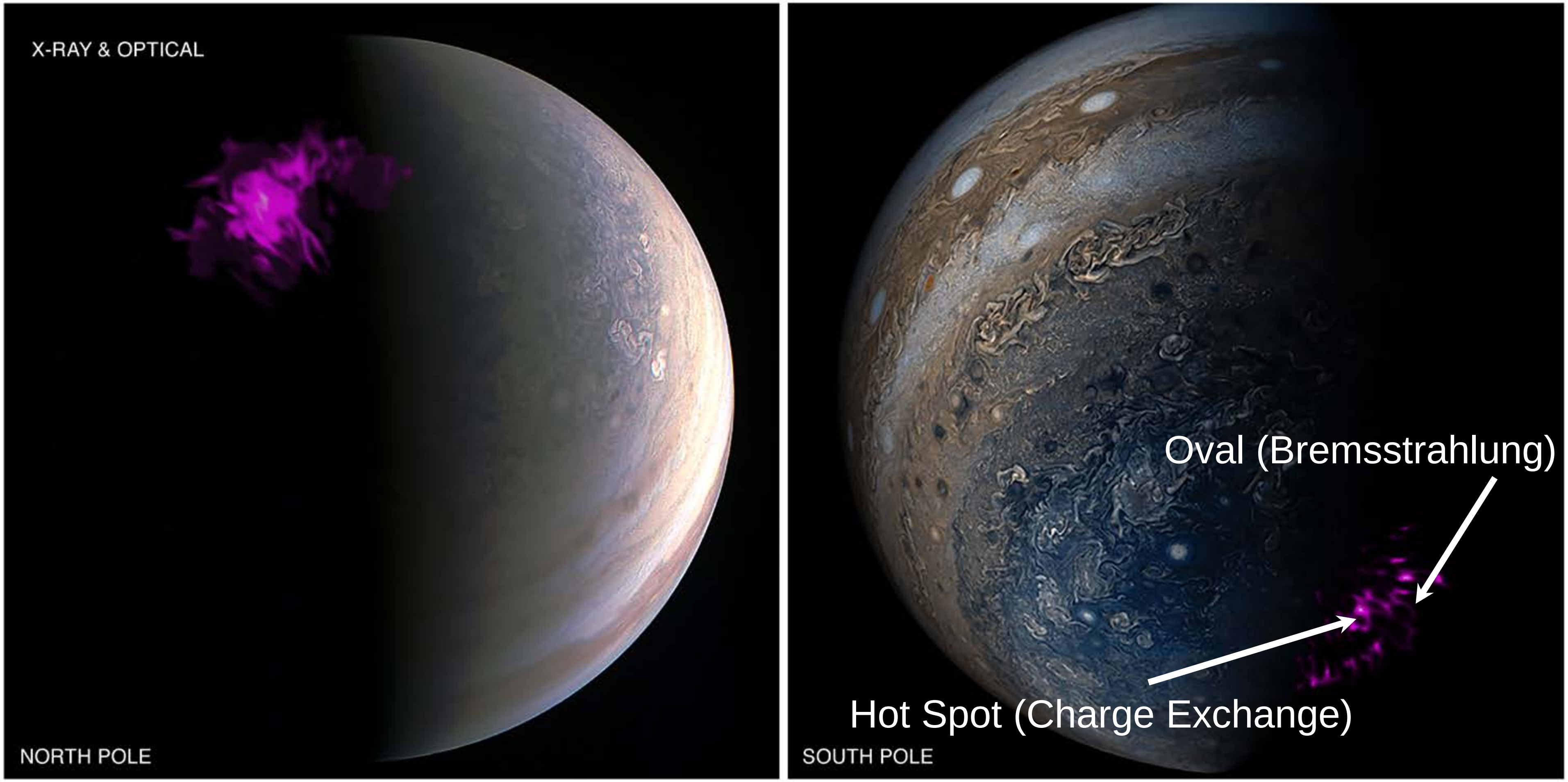
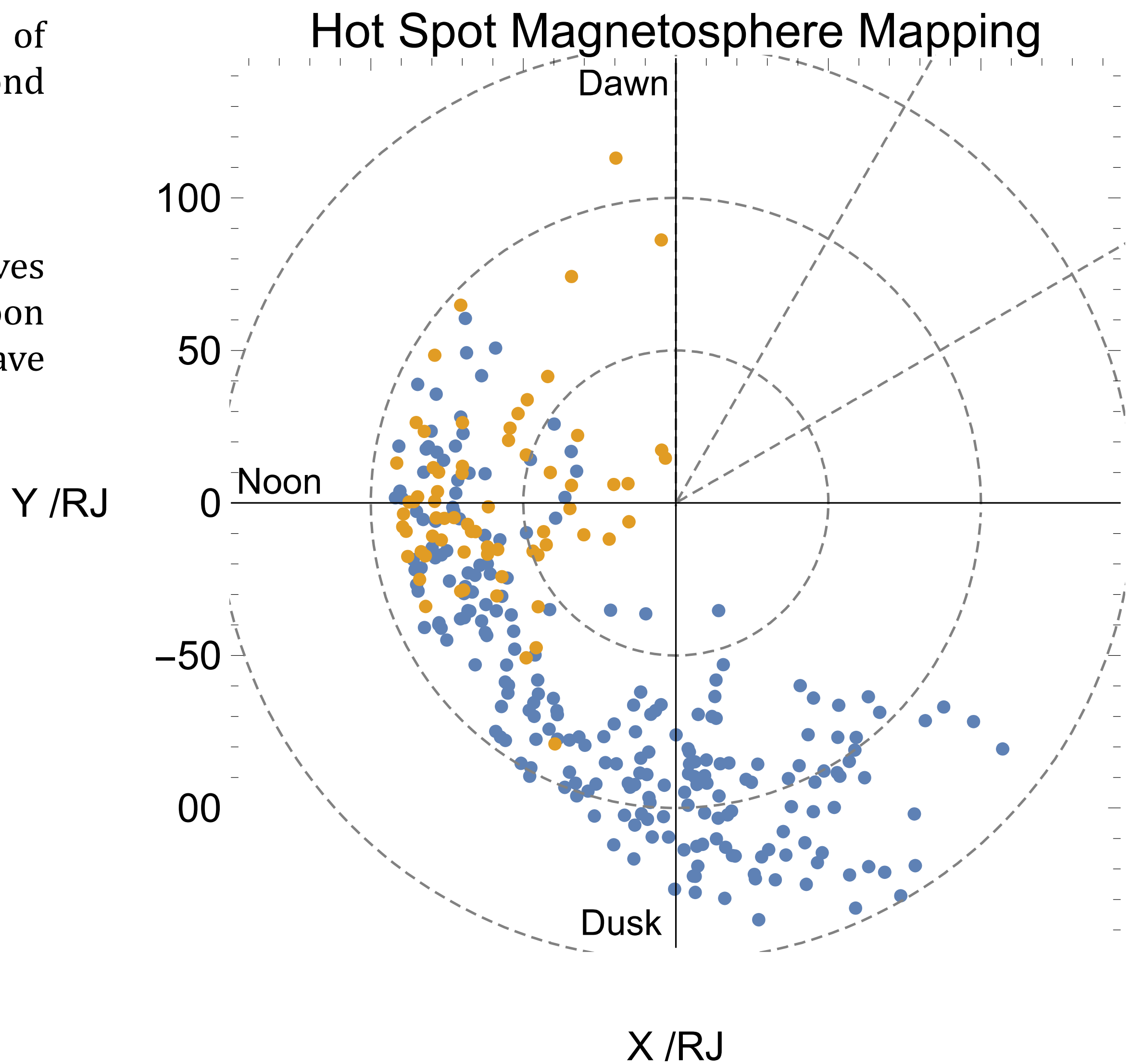


Magnetospheric Mapping and Possible Local drivers?

- Using Vogt model mapping, 30-60% of emission from each spot maps beyond the magnetopause to open field lines.

- Maybe the distinctive behaviour derives from the different source regions (noon vs dusk?) and associated different wave transit times or different FLRs?

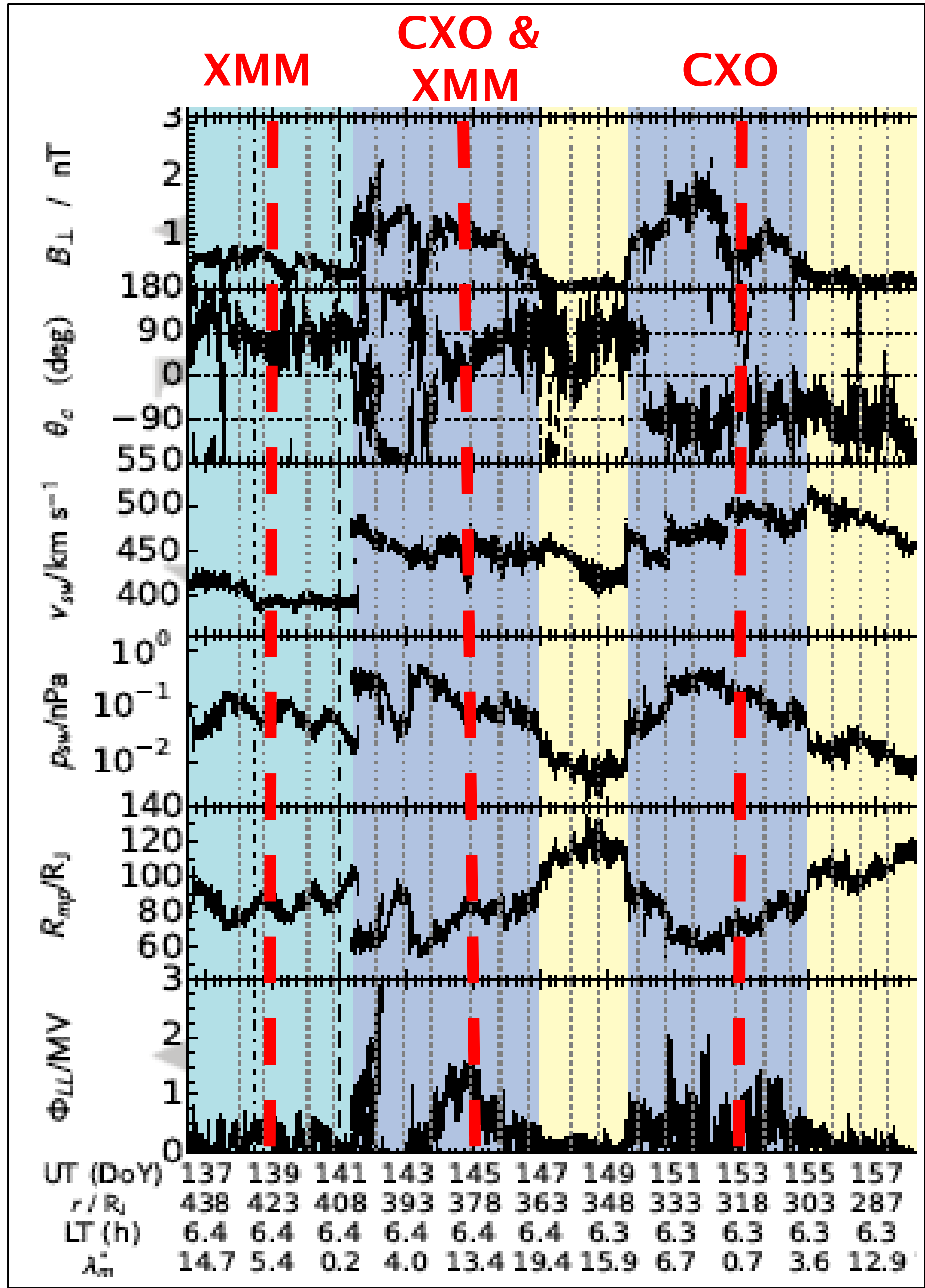


Juno Upstream Comparison

- 40 hrs of time-tagged X-ray observations while Juno was Upstream

- Delighted to work with anyone with expertise with the upstream data to test whether there are correlations between the X-ray emissions and Solar wind conditions.

==> Will Dunn will be at ESAC Nov.20-Dec1



An X- citing Time for X- ray Observations of Jupiter: 2017

Date	Observatory	Obs Duration /hr	Juno Location	PI
2-Feb	Chandra	10	PJ 4	Gladstone
28-Feb	Chandra	20	AJ	Jackman
27-Mar	Chandra	10	PJ 5	Gladstone
19-May	Chandra	10	PJ 6	Gladstone
18-Jun	Chandra	10	AJ	Jackman
18-Jun	XMM-Newton	20	AJ	Dunn
18-Jun	NuSTAR	28	AJ	Jackman
11-July	NuSTAR	40	PJ 7	Mori
11-July	Chandra	10	PJ 7	Gladstone
10-12 July	XMM-Newton	40	PJ 7	Dunn
17-July	XMM-Newton	20	Mid->Outer m'sphere	Dunn
6-August	Chandra	10	AJ	Jackman

Very happy to collaborate on observations with any other wavebands or with Juno teams.

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