UCL DEPARTMENT OF SPACE AND CLIMATE PHYSICS
MULLARD SPACE SCIENCE LABORATORY

UCL

Juno Workshop: Jupiter's Aurora

Jupiter's X-rays -- Chandra and XMM-Newton Campaigns

Presenter: William Dunn (w.dunn@ucl.ac.uk)

Investigators: G. R. Gladstone, R. Kraft, C. Jackman, G. Branduardi-Raymont, W. Dunn, J. Nichols, R. Elsner, L. Ray, T. Kimura, Y. Ezoe

Summary

1) Motivations for studying Jupiter's X-rays

2) X-ray Auroral morphology and features

3) Possible connections between Jupiter's X-ray Aurora and the Solar Wind

4) Upcoming X-ray campaigns:
a) Juno approach – Chandra (PI: Kraft and Jackman) & XMM-Newton (PI: Dunn)
b) Juno polar orbits -- Chandra (PI: Gladstone)

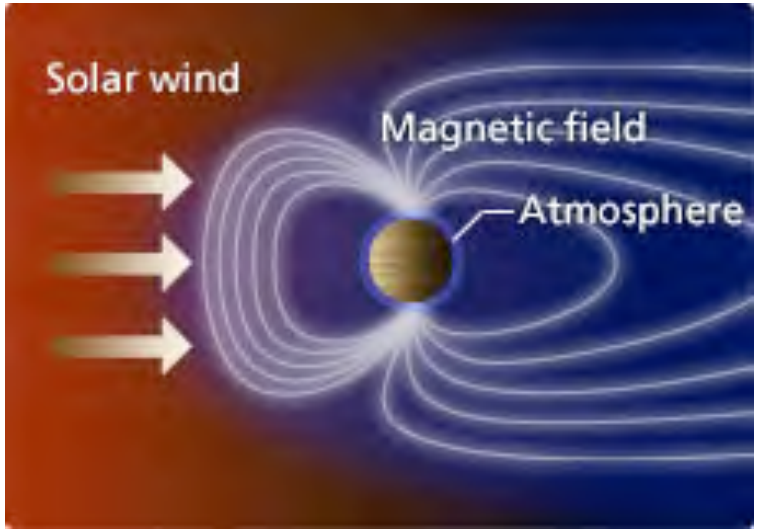
w.dunn@ucl.ac.uk

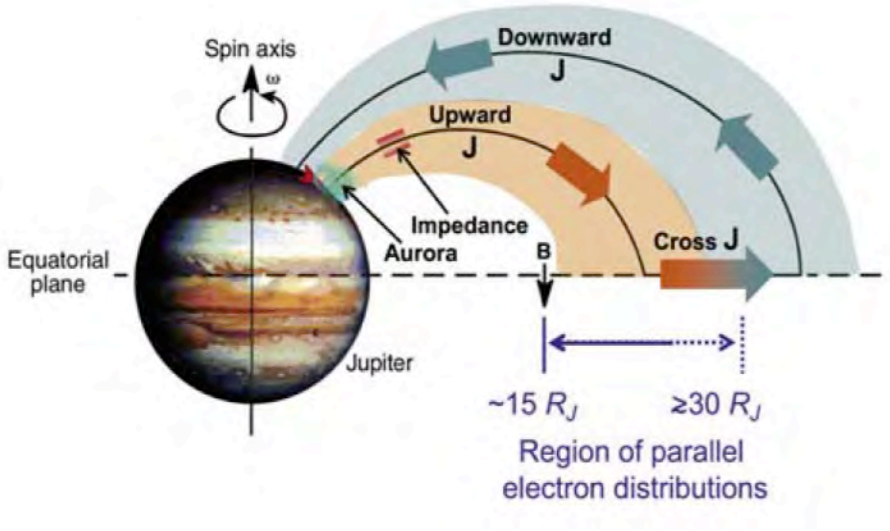
Motivations for Studying Jupiter's X-ray Aurora

1) **Jupiter's X-ray Aurora seems to exhibit relationships to the Solar Wind** -- general trends and distinctive order of magnitude brightening during CMEs. This could help to identify the nature of Jupiter's relationship to the solar wind.

2) **Provide a partial mapping of downward current regions** -- identified through the spectral lines of precipitating ions.

3) **Information about the drivers and acceleration processes in the main oval and polar regions** -- variation in X-ray emission from 10-100 keV electrons and from MeV ions

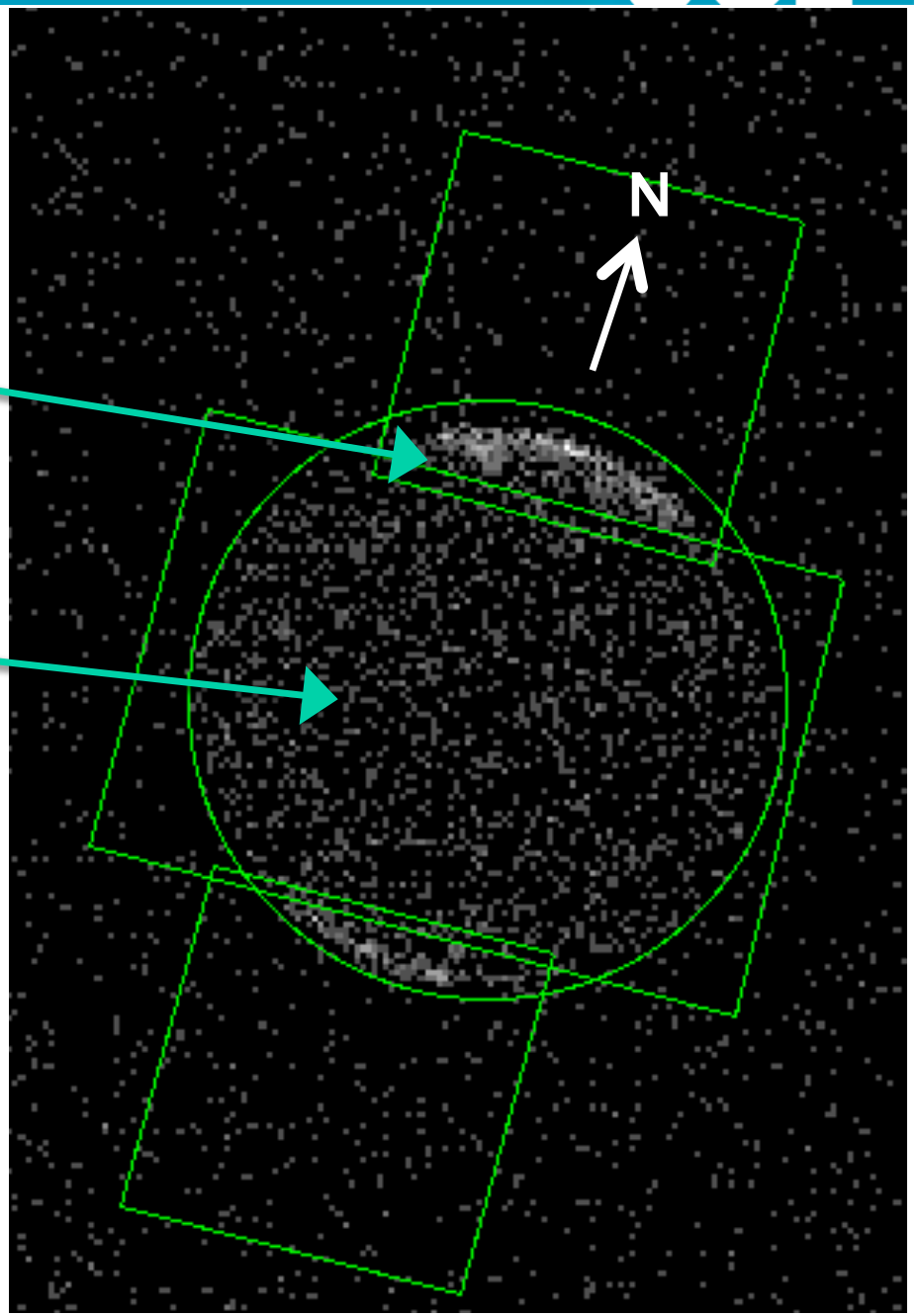




Components of X-ray Emission

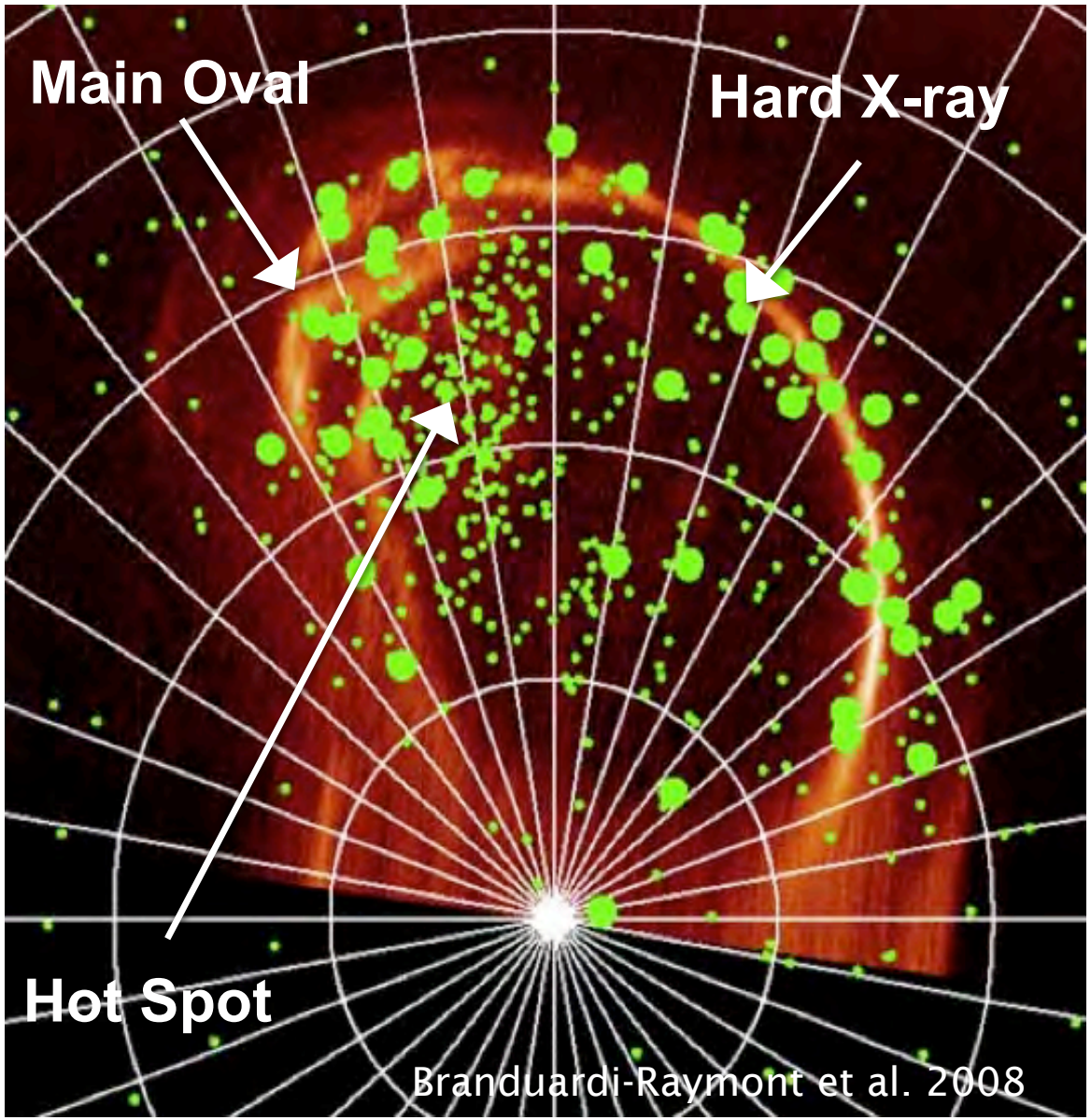
Polar Aurora Component

Equatorial/Disk Component



Disk X-rays are from fluoresced and scattered solar photons – so changes in solar X-ray flux are reflected in Jupiter's disk emission.

Jupiter's X-ray Morphology

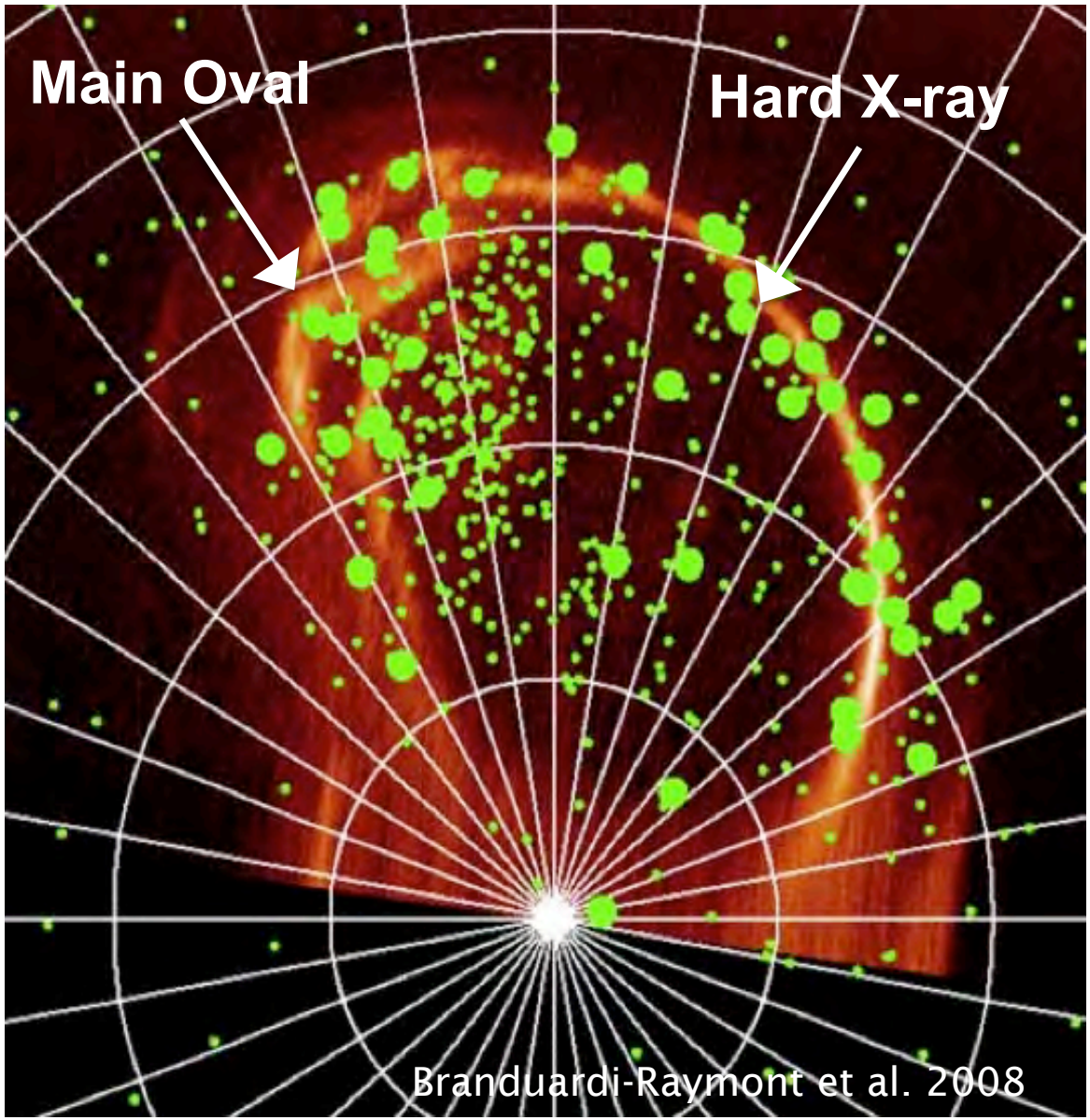


- Big green dots = Hard X-rays (Energies: 2-5 keV)
- Small green dots = Soft X-rays (Energies: 0.2-1.5 keV)

Left figure shows a projection of Jupiter's North Pole from Chandra X-ray observations in 2003 (green dots).

These are superposed on a simultaneous Hubble UV projection (orange).

Jupiter's X-ray Morphology

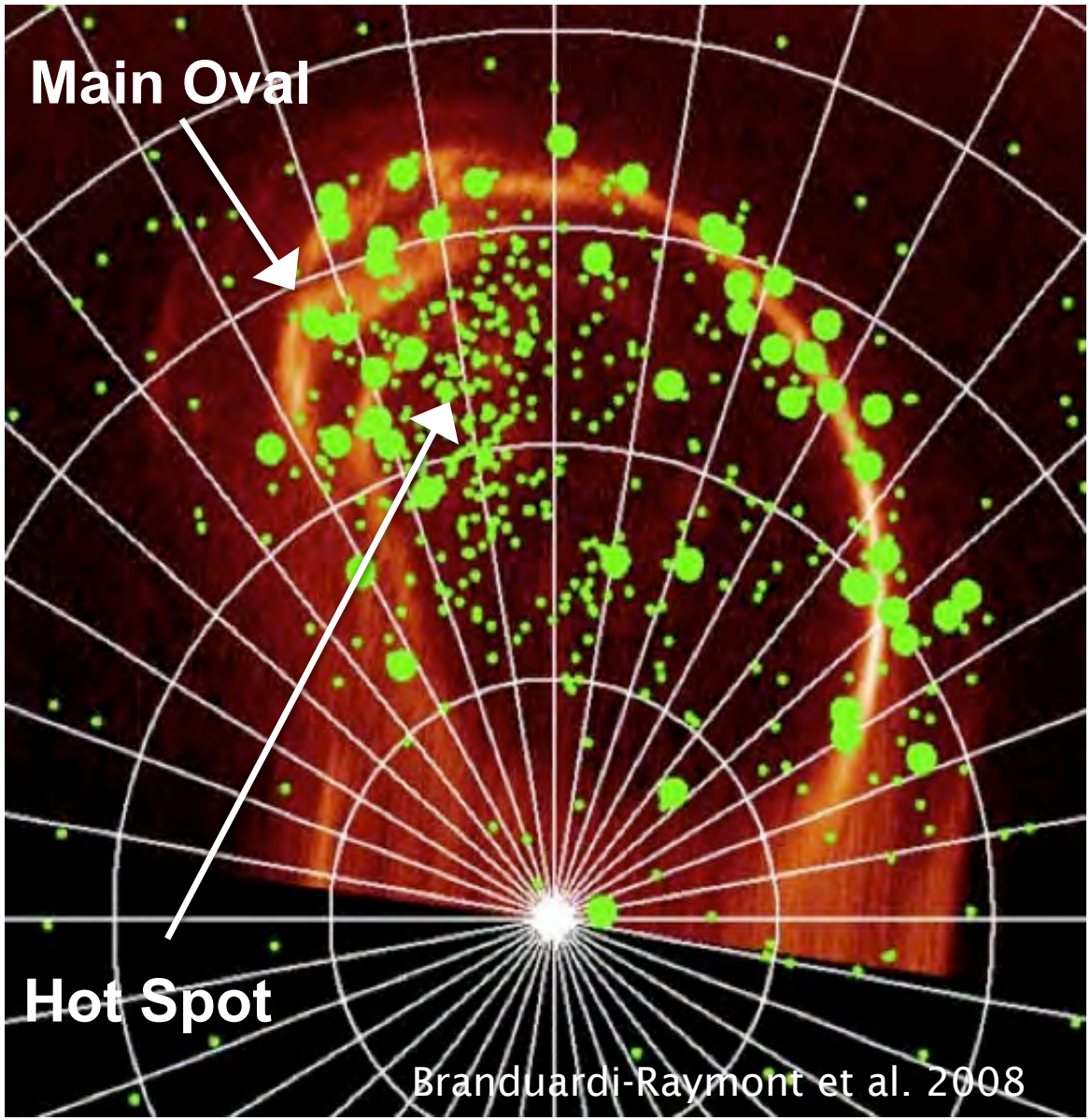


Hard X-rays

- Big green dots
- Brehmsstrahlung –**10s-100s keV electrons**
- **Overlap Main UV oval**
- Significant variation in counts from observation to observation, may relate to solar wind
- May relate to dawn storms

[Branduardi-Raymont et al. 2003, 2004, 2007A, 2008; Dunn et al. 2016]

Jupiter's X-ray Morphology



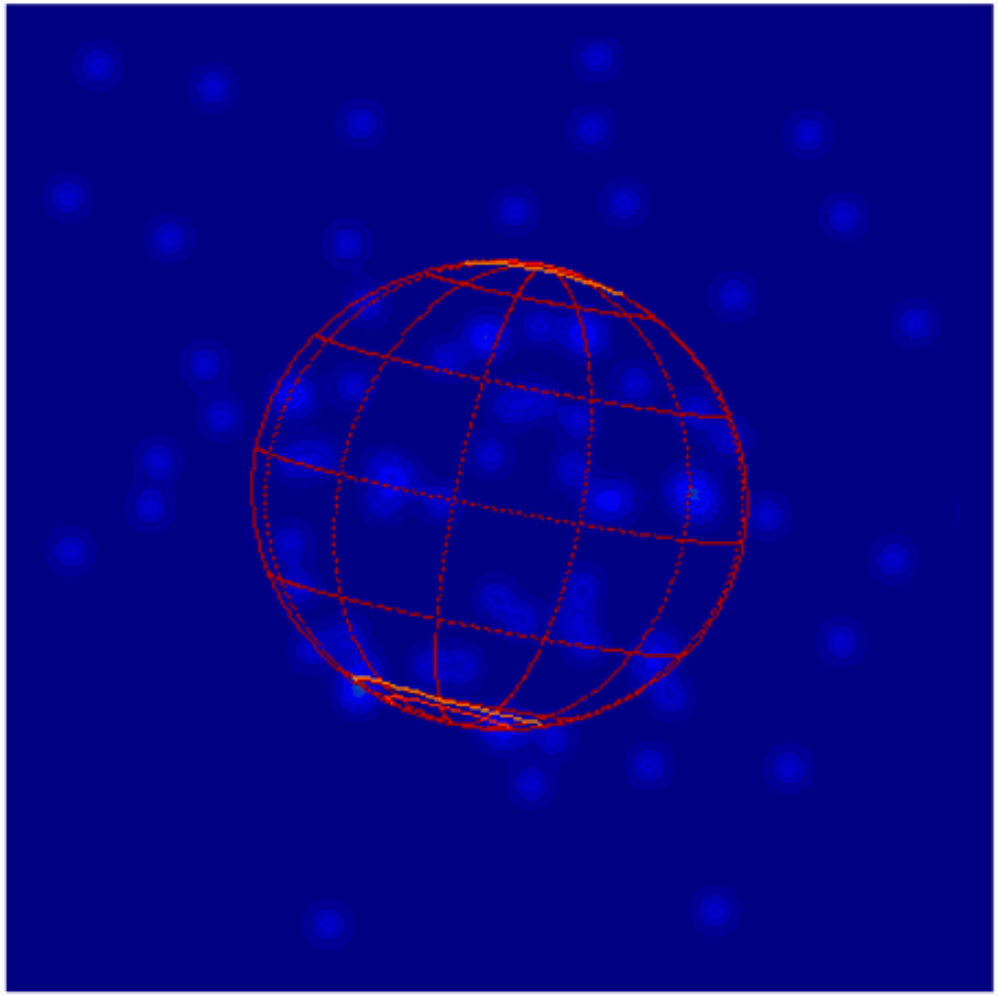
Soft X-rays – the Hot Spot

- Small green dots
- **Hot Spot** – poleward of UV oval – origin beyond middle magnetosphere.
- **MeV ions Charge Exchange**
- Oxygen ($O^{7+,8+}$)
- Sulphur ($S^{7+...16+}$) and/or Carbon ($C^{5+,6+}$) - current spectral resolution cannot distinguish.
- S = magnetospheric origin
- C = solar wind origin
- O = Either

[Branduardi-Raymont et al. 2004, 2007A; Elsner et al. 2005; Gladstone et al. 2002]

Jupiter's X-ray Morphology

The Hot Spot



Rotates with the planet – 65-75° latitude; 160-180° longitude

Quasi-periodic Pulsations:

- 45 min period detected in distinct observations
- 12-26 min period detected during CME
- Period absent in several observations
- Similar periodicity in radio and particle flux data (e.g: Macdowall et al 1993).
- Coincident UV flares (e.g: Elsner et al. 2005)

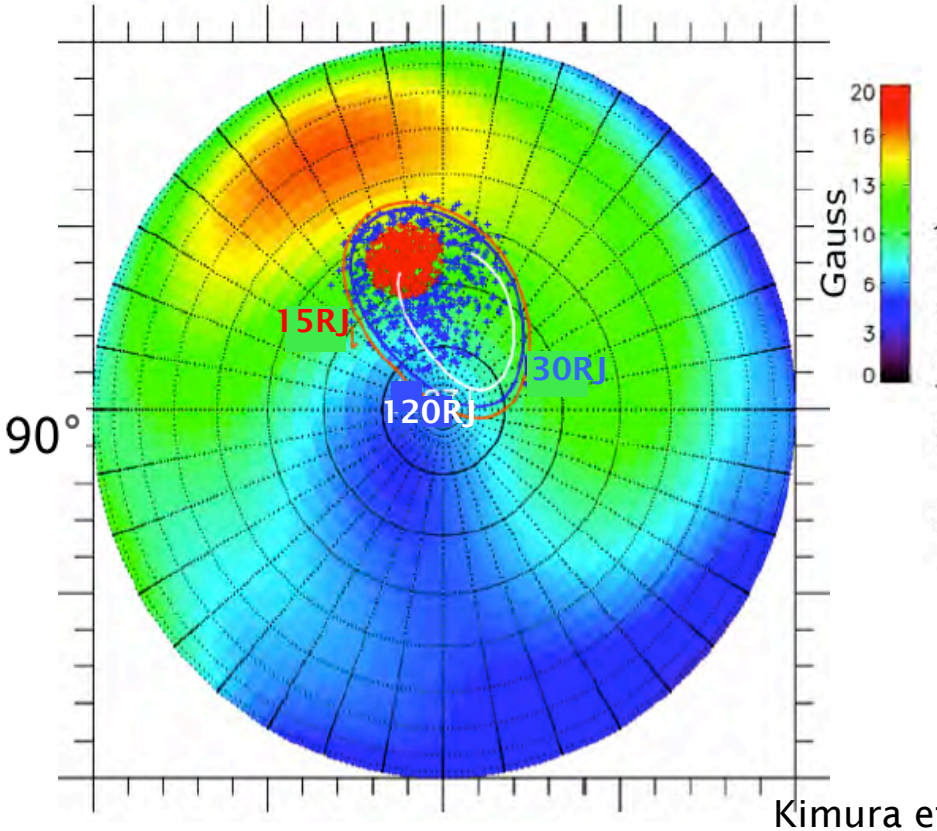
[Branduardi-Raymont et al. 2004; 2007A, 2008; Gladtstone et al. 2002; Elsner et al. 2005; Dunn et al. 2016]

X-ray Aurora Source

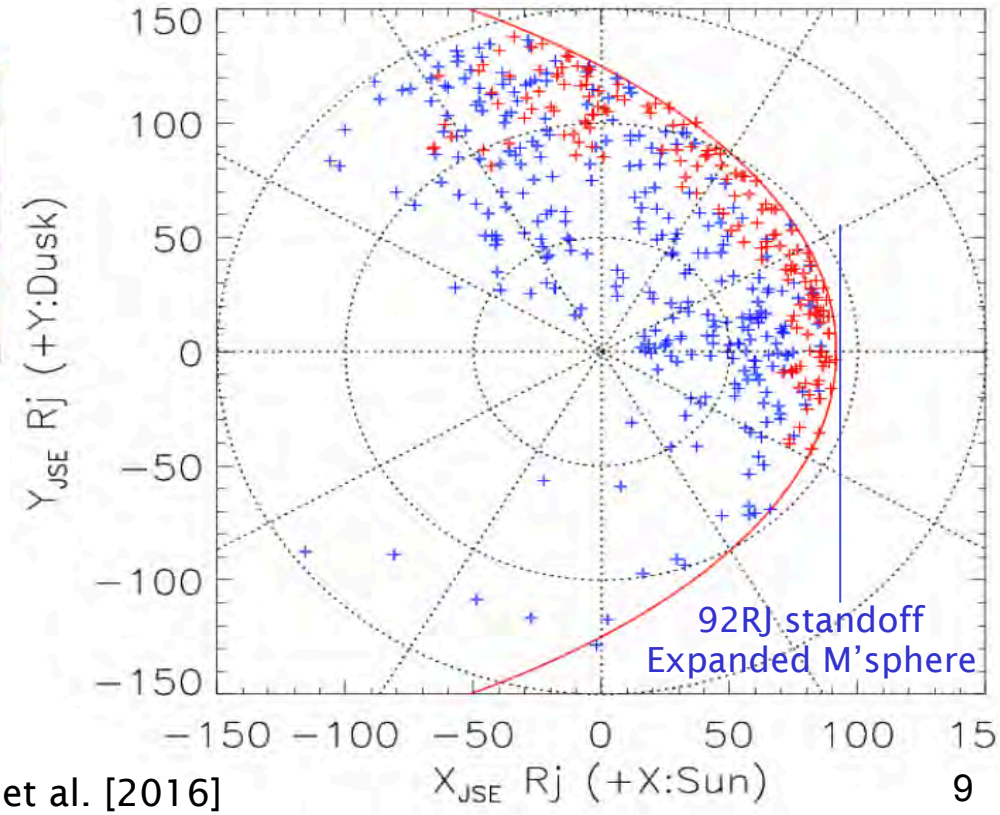
- Hot Spot Core (red) maps to near magnetopause
- Emission shows a ~50/50 mapping to closed and open field lines
- 'Halo' (blue) maps to several origins

- Magnetopause mapping implies that Jupiter's X-ray aurora may provide a diagnostic of Jupiter-Solar Wind interactions.

S3 Polar Projection



Source



Kimura et al. [2016]

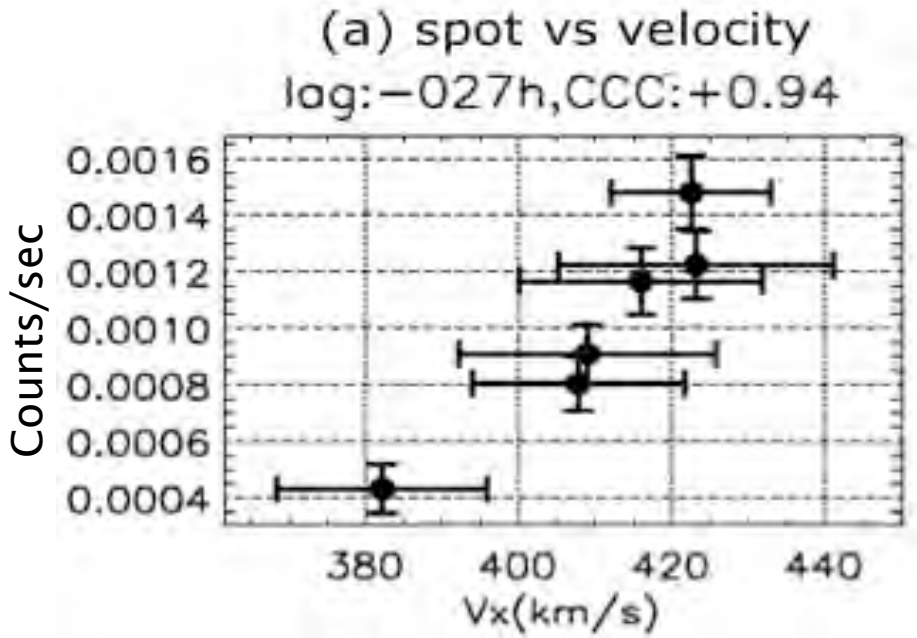
Jupiter's X-ray Solar Wind Relationship

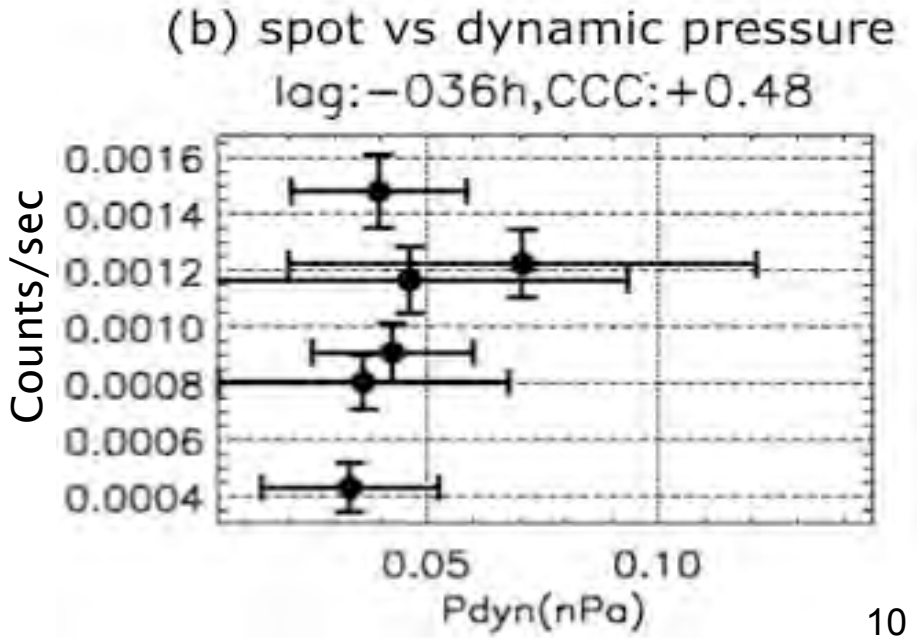
Branduardi-Raymont et al. [2004, 2007A] :

- Hard and Soft X-ray Emission increased around the time of the 2003 Halloween storms.

Kimura et al. 2016 (figure):

- X-ray emission correlated to SW Velocity
- X-ray emission not correlated to SW density
- During generally quieter solar wind conditions

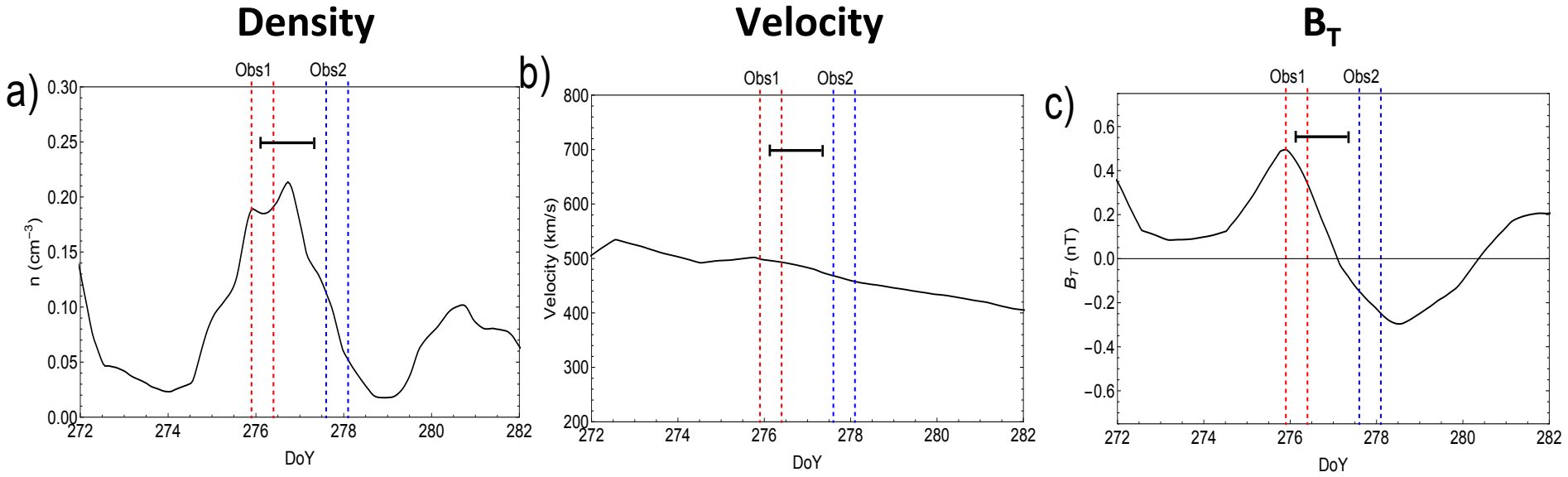




w.dunn@ucl.ac.uk

What does an ICME do to Jupiter's X-ray Aurora?

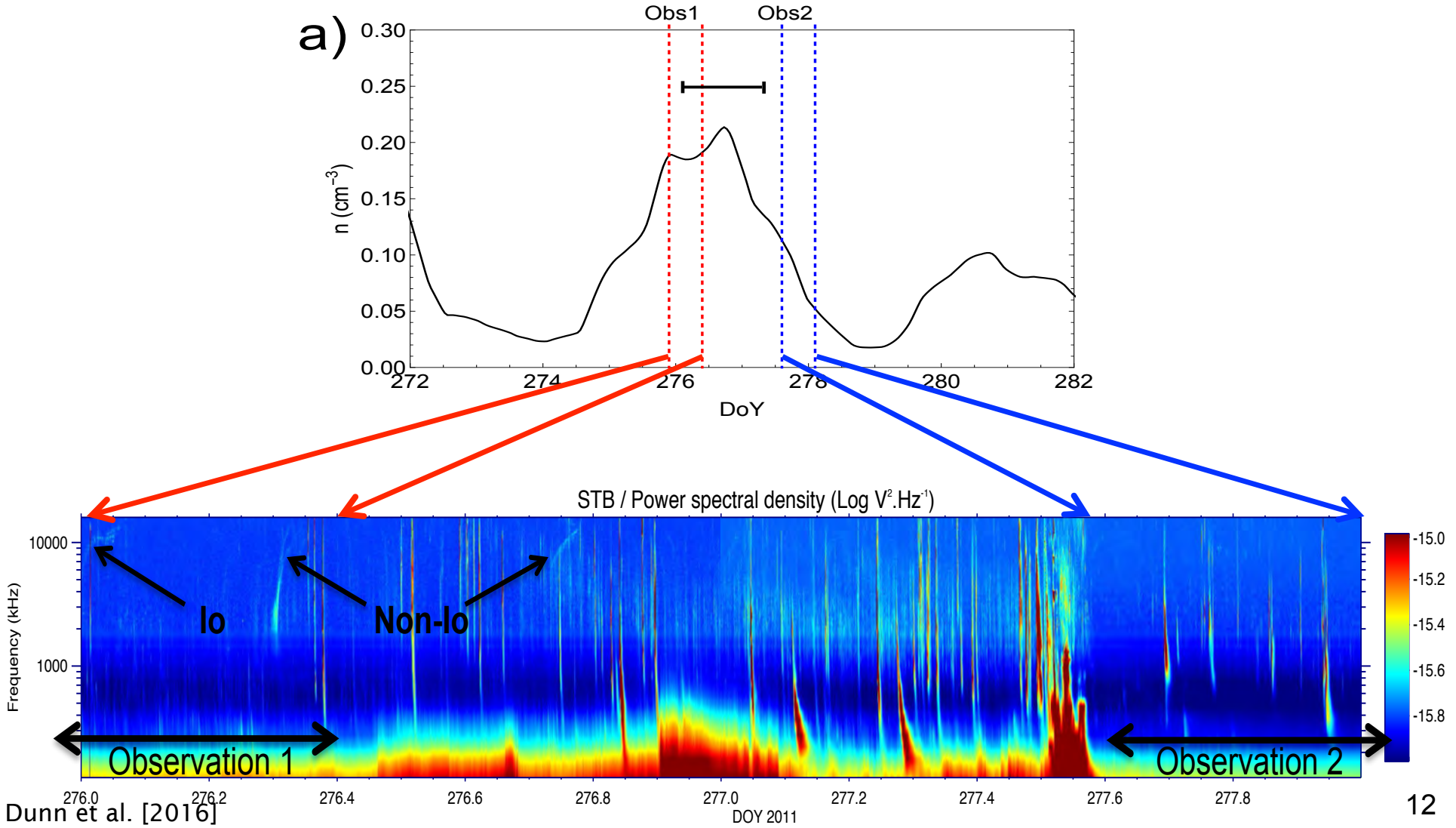
The Michigan Solar Wind propagation Model (upper figures) predicts the arrival of an ICME during an X-ray observation in 2011.



Dunn et al. [2016]

What does an ICME do to Jupiter's X-ray Aurora?

Radio observations show non-Io decametric bursts (lower figure) during the same X-ray observation, which suggest an ICME-induced forward shock arrived [e.g: Hess et al. 2012; 2014; Lamy et al. 2012; Gurnett et al 2002]



Dunn et al. [2016]

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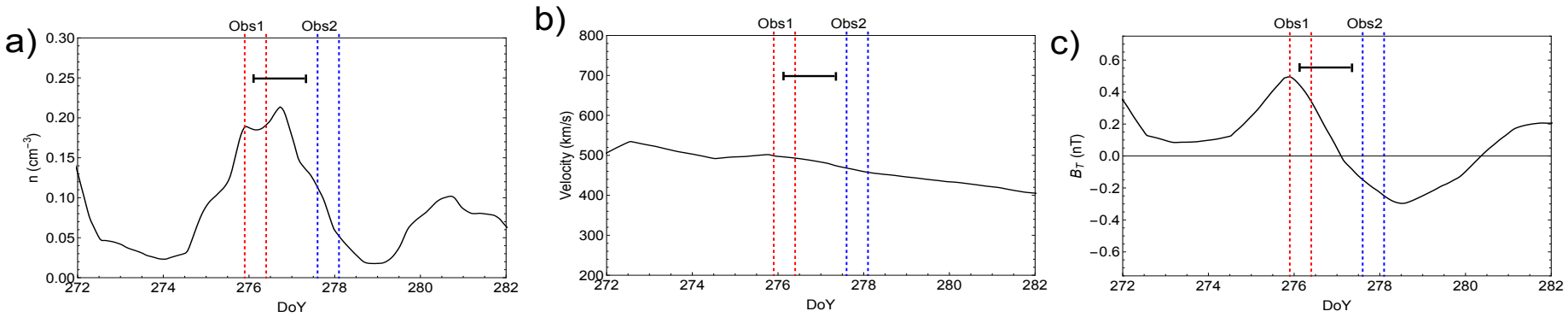

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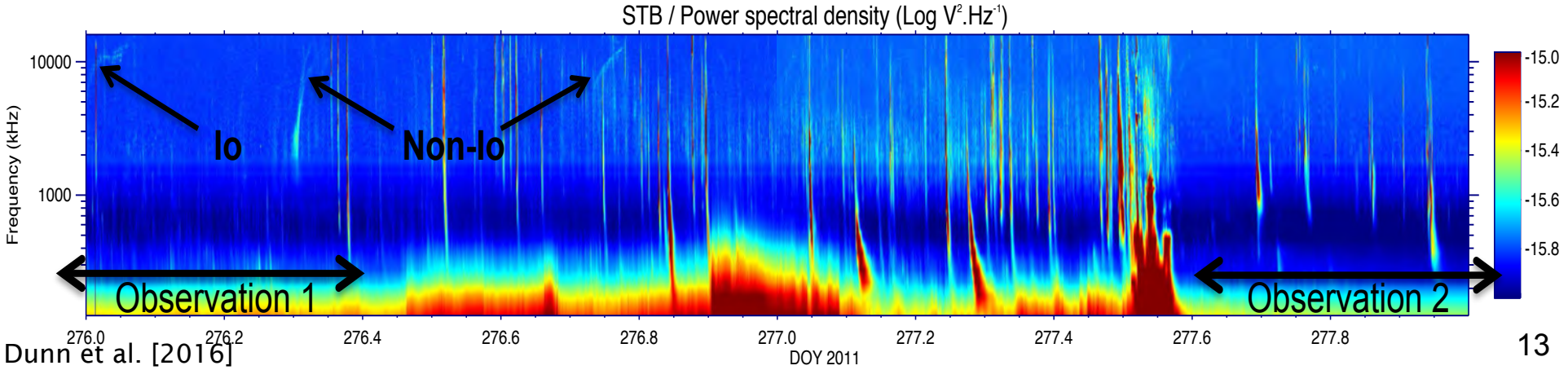
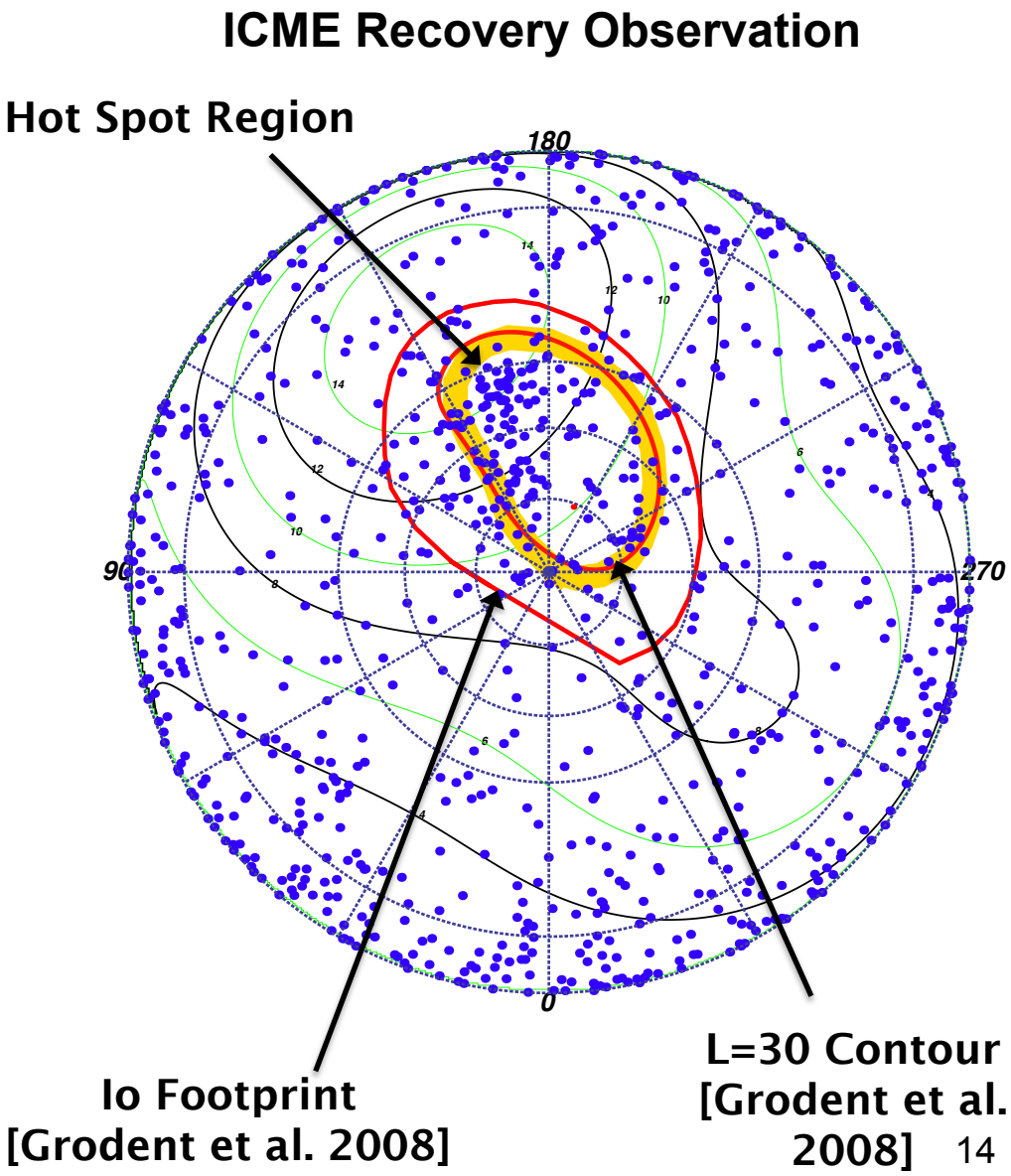


Dunn et al. [2016]

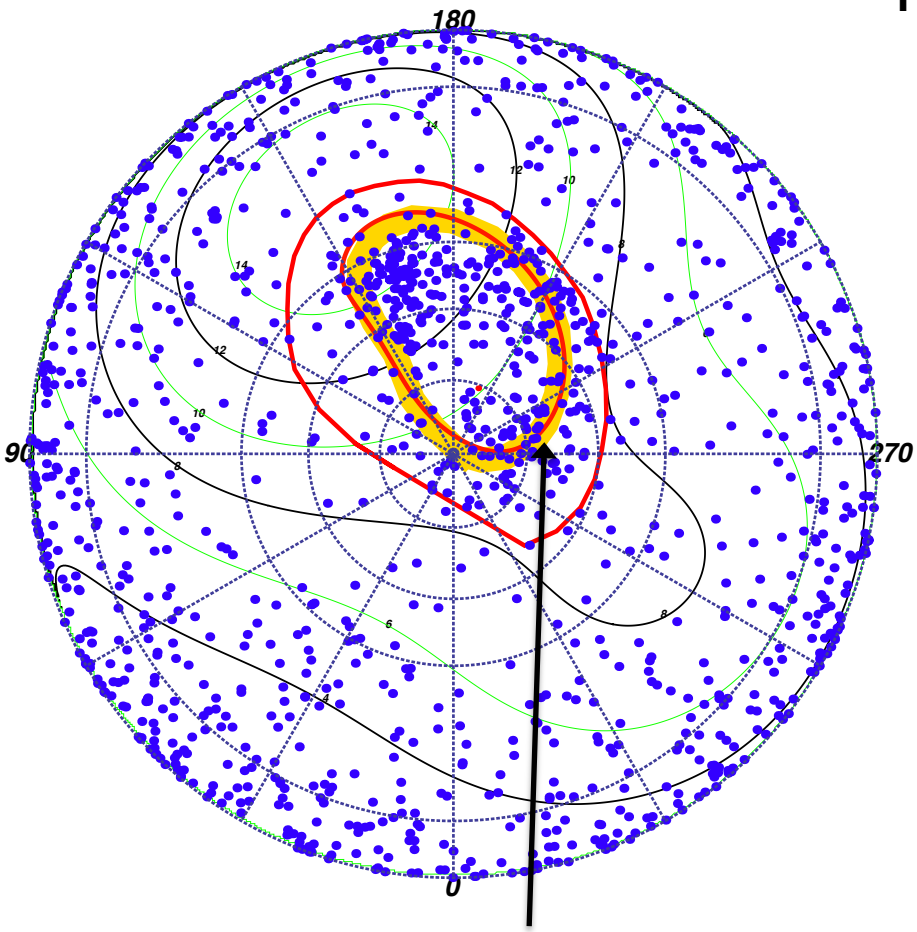
X-ray Observations: S3 Polar Projections



Dunn et al. [2016]

ICME Triggers New X-ray Aurora

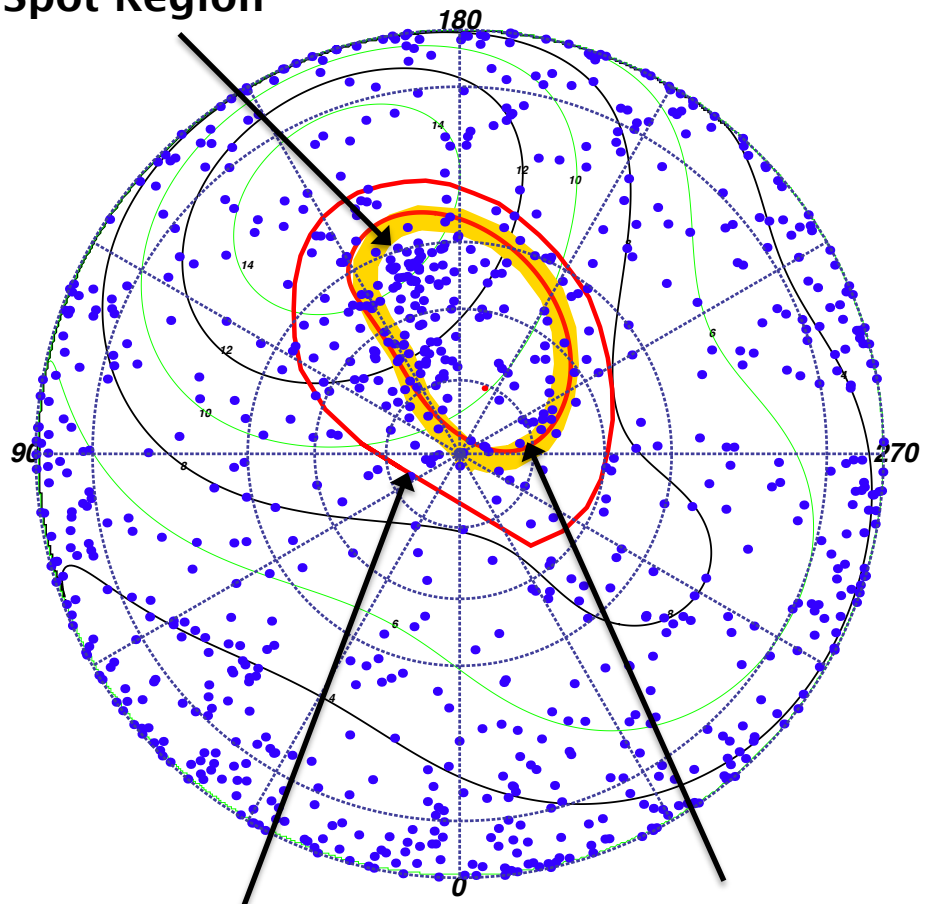
ICME Arrival Observation



New Emission Quadrant: Auroral Enhancement

ICME Recovery Observation

Hot Spot Region



Io Footprint [Grodent et al. 2008]

L=30 Contour [Grodent et al. 2008]

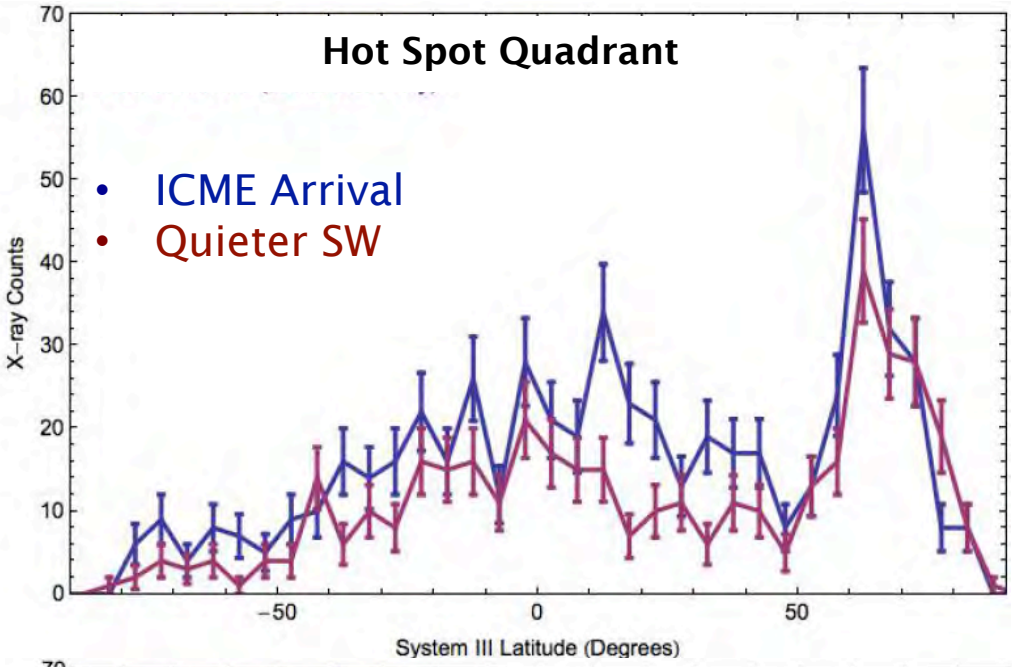
Dunn et al. [2016]

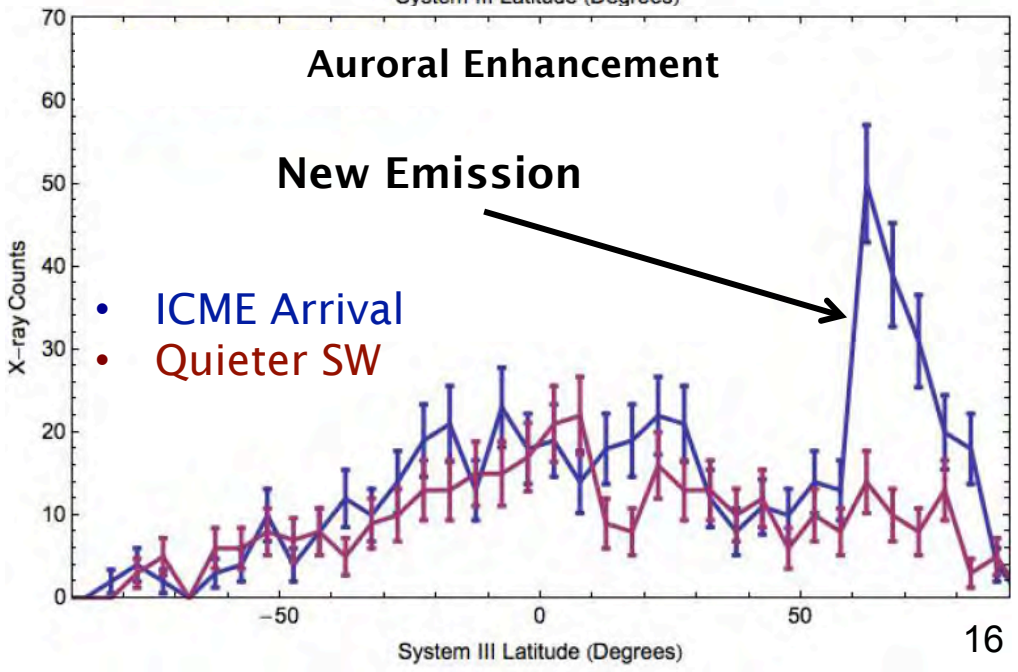
ICME Triggers New X-ray Aurora

Splitting the 2 quadrants quantifies the difference between the two observations for:

Upper Figure: Hot Spot Quadrant
(S3 Longitude 90-180º)

Lower Figure: Auroral Enhancement Quadrant
(S3 Longitude 180-270º)

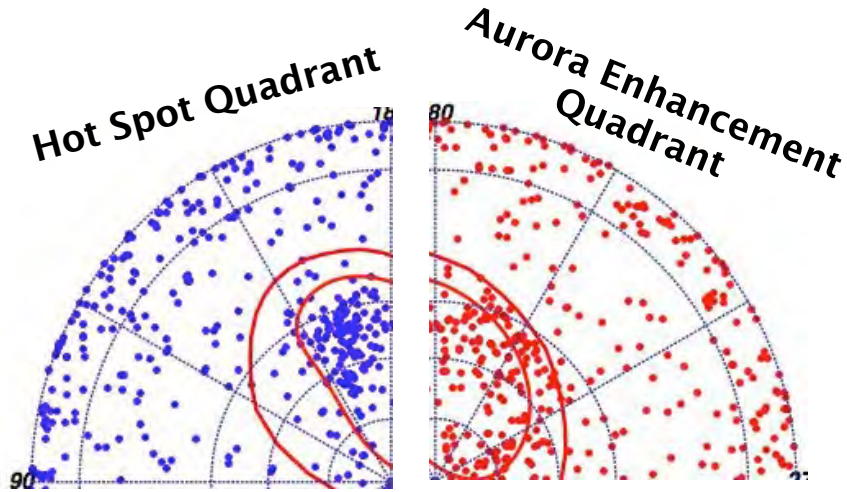


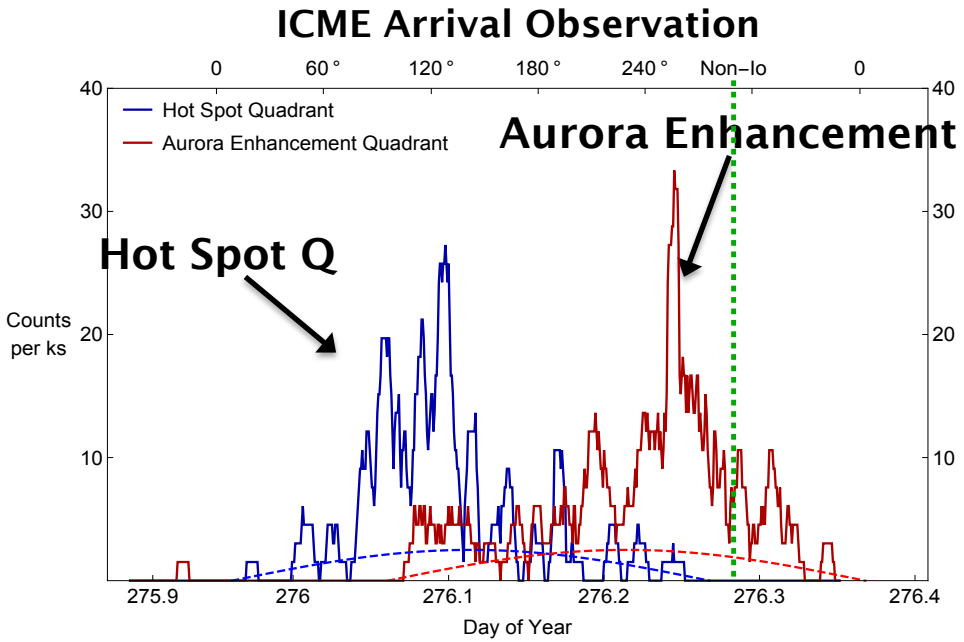


Dunn et al. [2016]

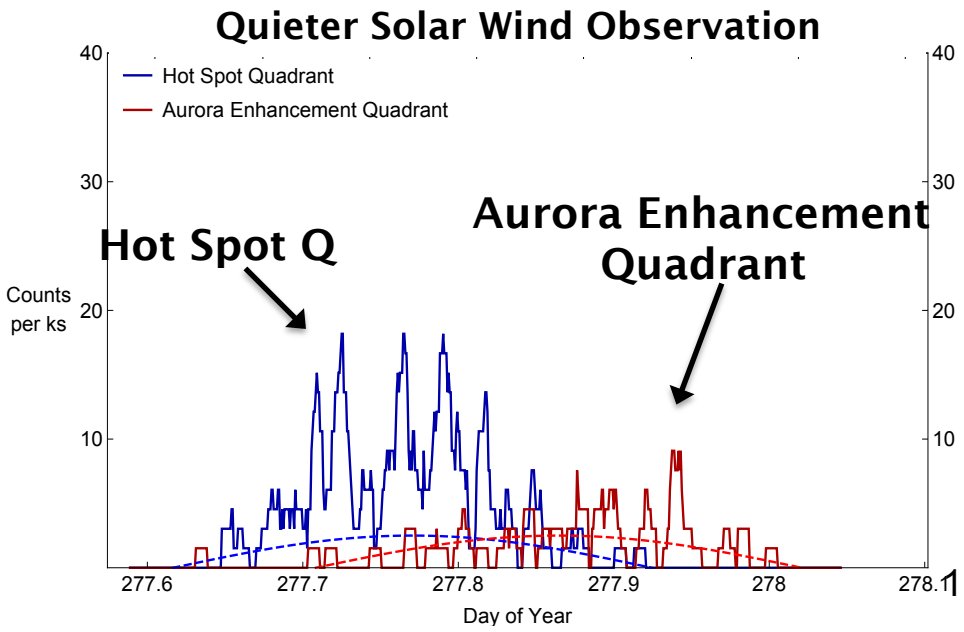
w.dunn@ucl.ac.uk

X-ray Lightcurves and Radio Bursts





- **Order of Magnitude 'Flare' Enhancement triggered by ICME**
- ~1.5 hours before the non-Io radio burst
- Heightened Emission throughout
- Hot Spot periodicity shifts: ~45 min in second obs (like Gladstone et al. 2002); 12 and 26 min period during ICME



Dunn et al. [2016]

Jupiter's X-ray - Solar Wind Relationship and the Upcoming Observations

Is there a solar wind parameter connected to the X-ray aurora and, if so, how does it link to the drivers of emission?

- IMF direction? -- Pulsed Dayside reconnection [Bunce et al. 2004] ?
- SW Density/Dynamic Pressure? -- Magnetosphere Compression [Dunn et al. 2016] ?
- SW Velocity? -- Kelvin Helmholtz [Kimura et al. 2016] ?
- Internally Driven? -- MV Potentials on down FACs [Cravens et al. 2003]

To help identify SW driver -> X-ray obs during Juno approach (PI: Kraft & Jackman;PI: Dunn)

- **May 20: XMM 10 hour Observation**
- **May 26: Simultaneous XMM and Chandra 10 hour Observations**
- **June 1: Chandra 10 hour Observation**

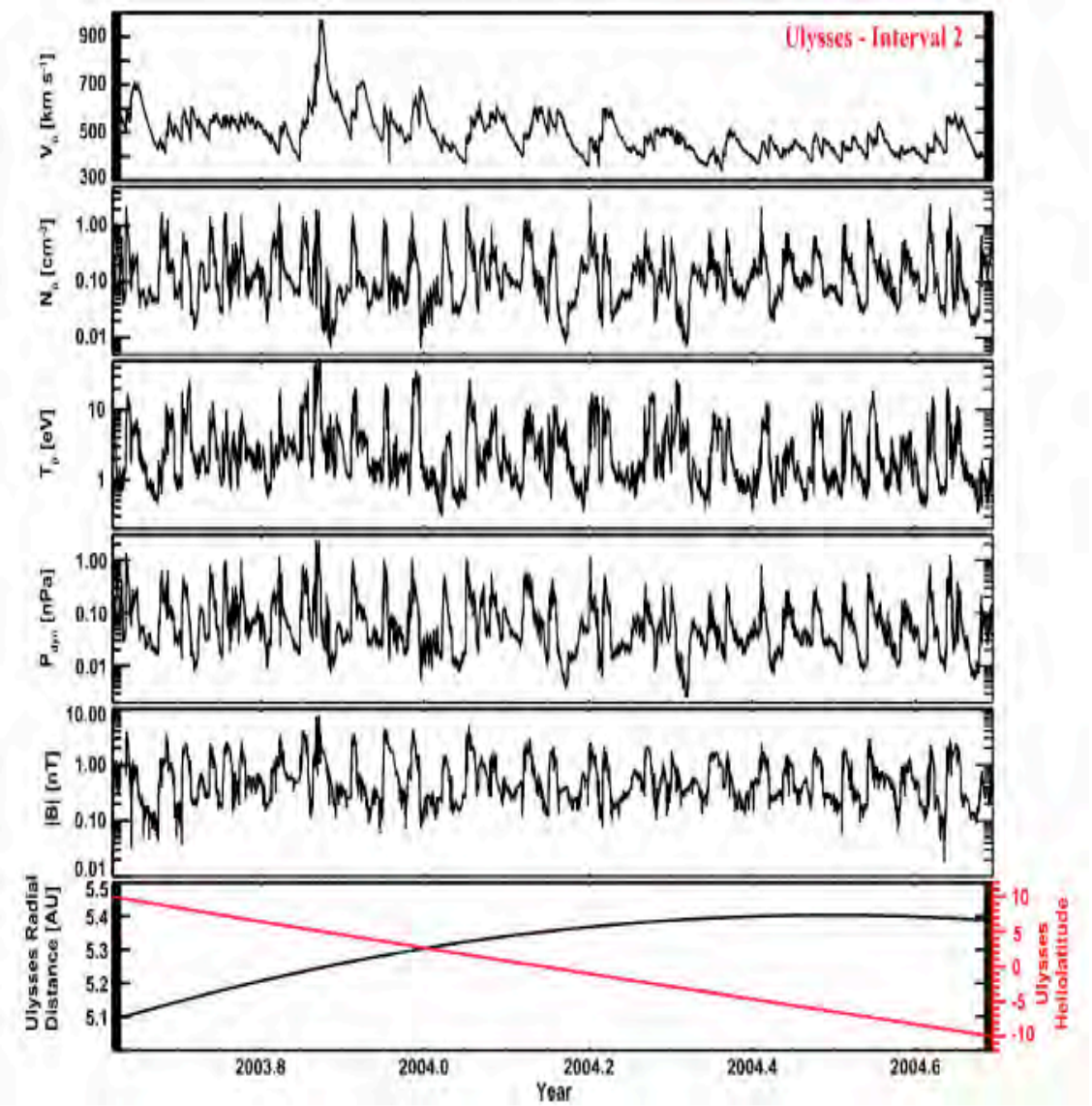
Also simultaneous with HST observations (PI J. Nichols) which helps connect features and identify global current systems (UV = mostly upward ; X-ray = mostly downward)

Jupiter's X-ray - Solar Wind Relationship and the Upcoming Observations

- Ebert et al. 2014 used Ulysses data from an analogous point in the solar cycle.
- More structured
- ~1 week between compression and rarefaction.

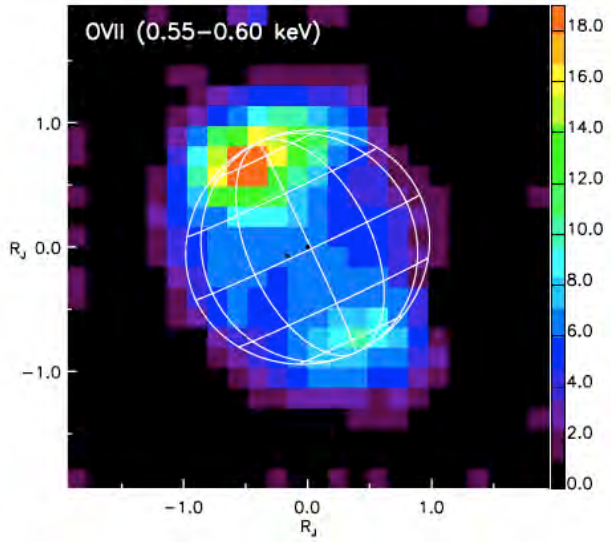
For X-ray observations:

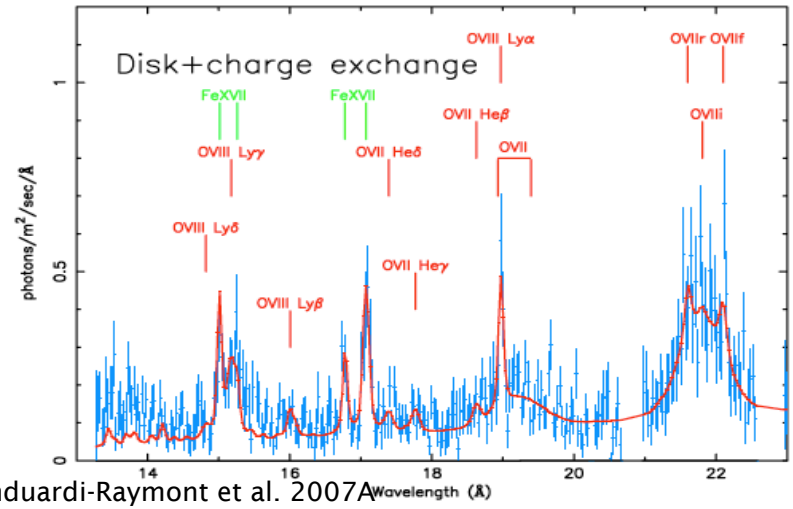
- Appropriate separation to increase chance of alternating SW conditions
- Simultaneous with HST



XMM- Newton –EPIC and RGS

High Spectral Resolution – poor spatial resolution

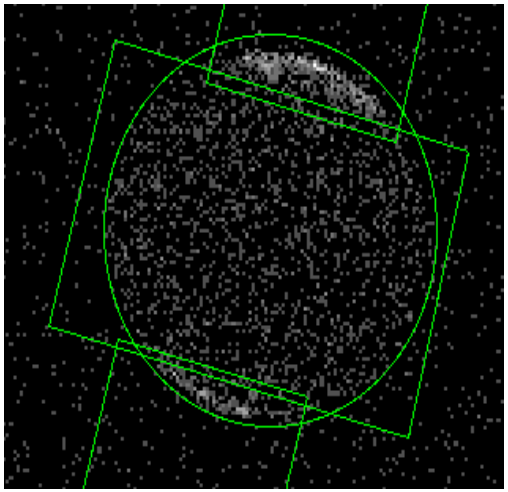


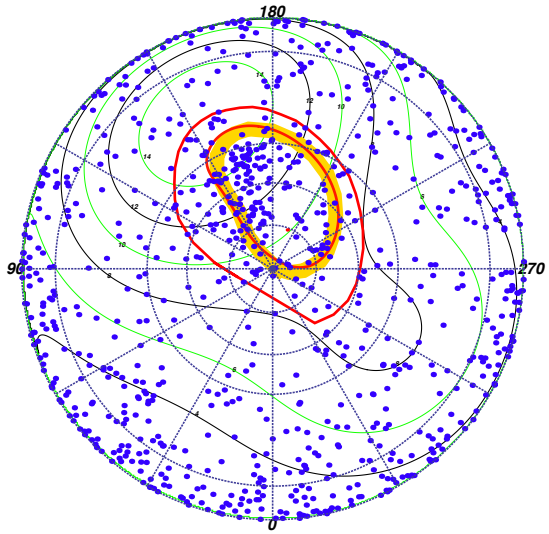


Branduardi-Raymont et al. 2007A

Chandra – High Resolution Camera

High Spatial Resolution – no spectral resolution





CXO Campaign During Juno Orbits

Juno presents the unique opportunity to study the X-ray emission from the hot spot, while traversing the field lines producing it.

-> 80 hour Chandra campaign (PI: Gladstone). Observations during:

Northern Aurora: GRAV orbits 5, 13, 22, & 34
Southern Aurora: MWR orbit 6 and GRAV orbits 11, 20, & 36

This will also help:

- Identify further connections between UV polar flares and X-rays [E.g: Elsner et al. 2005]
- Assess the source of the quasi-periodicity
- Identify hot spot drivers (Dayside reconnection [Bunce et al. 2004] Vs Kelvin Helmholtz [Kimura et al. 2016] Vs MV Potentials on down FACs [Cravens et al. 2003])
- Test various mapping models VIPAL, VIP4, Grodent Anomaly….
- Identify possible X-ray emission from the Galilean moons and Io Plasma Torus.

Conclusions

Juno presents a unique opportunity to probe the sources of Jupiter's X-ray Aurora:

Science Questions for Approach Campaign (CXO PI: Kraft and Jackman; XMM PI: Dunn)

1. Which solar wind parameter (if any) is connected with the X-ray aurora?
2. What is the nature of the X-ray producing Jupiter-Solar wind interaction?
3. How does X-ray emission connect with UV features (HST) and other wavebands?

Juno instruments ware very important for us to be able to connect SW with X-ray aurora - we are very keen to collaborate. We are also keen to collaborate with other EM wavebands.

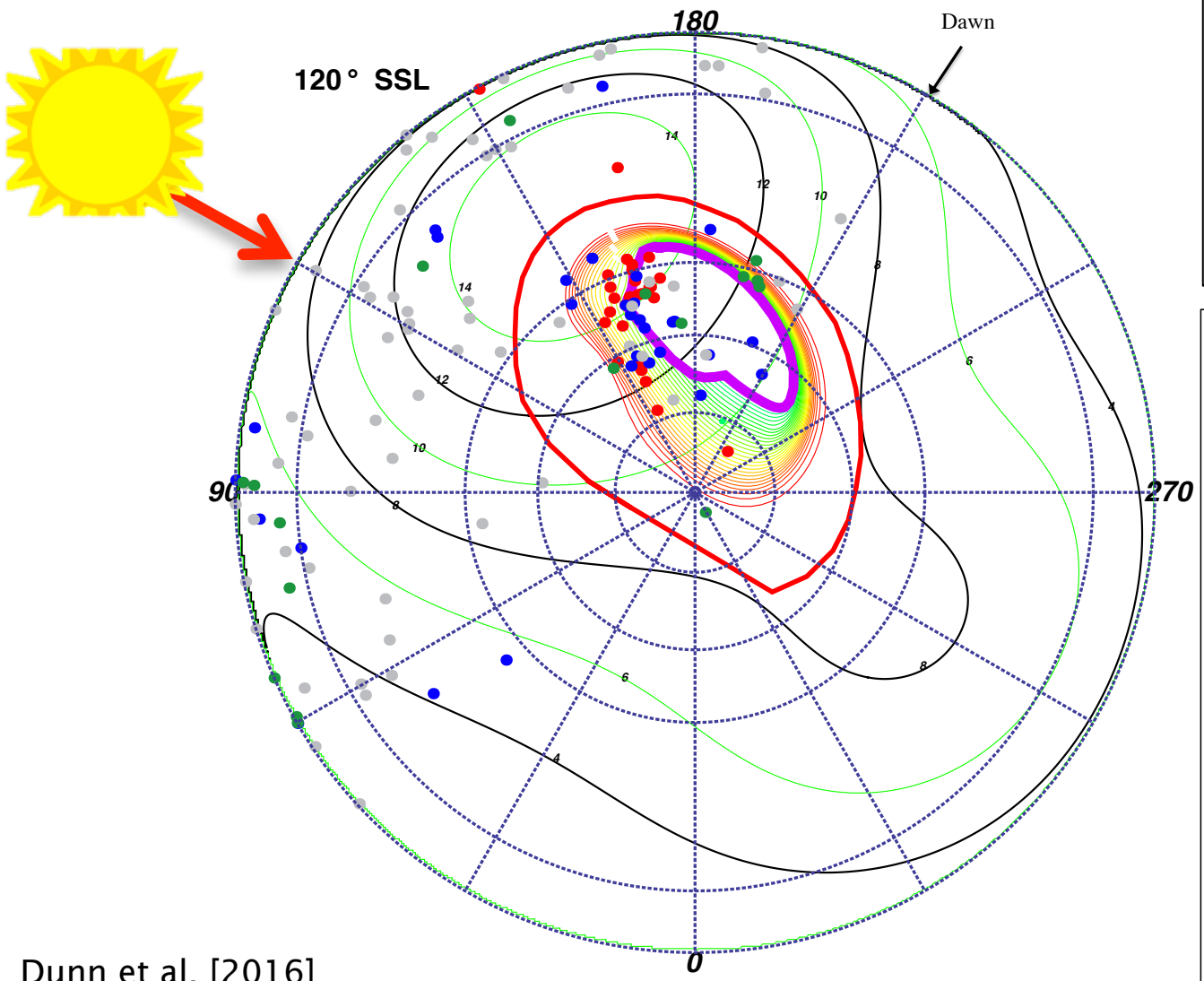
Science Goals for Polar Orbit Campaign (CXO PI: Gladstone)

1. Test theories [e.g., Cravens et al. 2003; Bunce et al. 2004] on the source of emissions by comparing 'cusp' measurements with X-ray (Chandra) and UV emissions (Juno UVS).
2. Identify which conditions produce the ~45 min quasi-periodic X-ray intensity oscillations and how these correlate with energetic particle fluxes and radio emission.
3. To constrain mapping models (e.g., VIP4 [Connerney et al., 1998], VIPAL [Hess et al., 2011]) with a high-quality map of X-ray emission topology
4. Search for X-ray emission from the Galilean moons and Io Plasma Torus (IPT).

Back-Up Slides

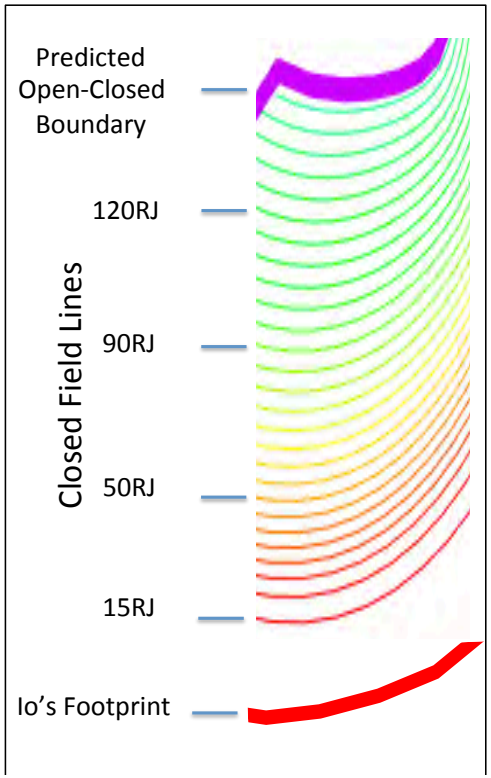
Sub-structure within the Hot Spot?

Vogt Models (2011): balance equatorial magnetic flux with ionospheric magnetic flux to map beyond 30 RJ.



Emission From:

- Sulphur/Carbon Ions
- Oxygen Ions
- Electrons
- Scattered Solar Photons



Dunn et al. [2016]

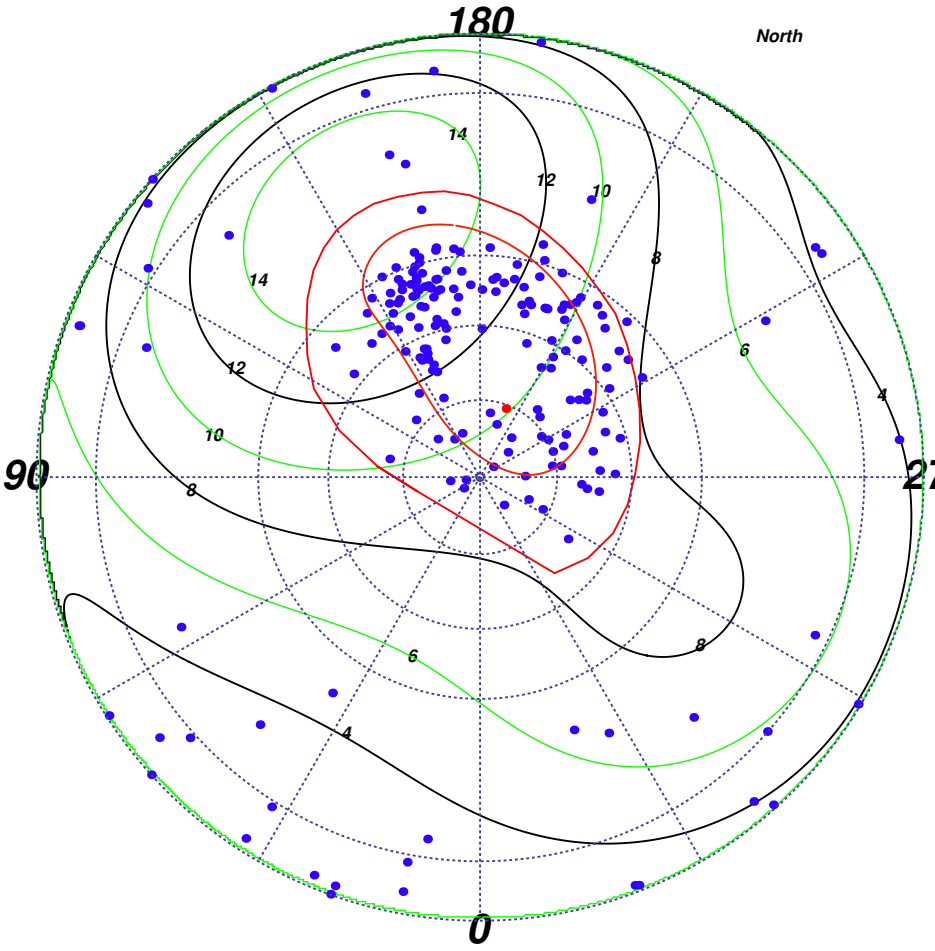
Mapping the X-ray Hot Spot Source

Particle Species	Magnetospheric Local Time	Equatorial Origin
Carbon and/or Sulphur	10:30 – 18:30	60 - 120 R_J and Open Flux
Oxygen	10:30 -- 18:30	80 - 120 R_J and Open Flux
High Energy Electrons	02:00 – 06:00	Middle Magnetosphere

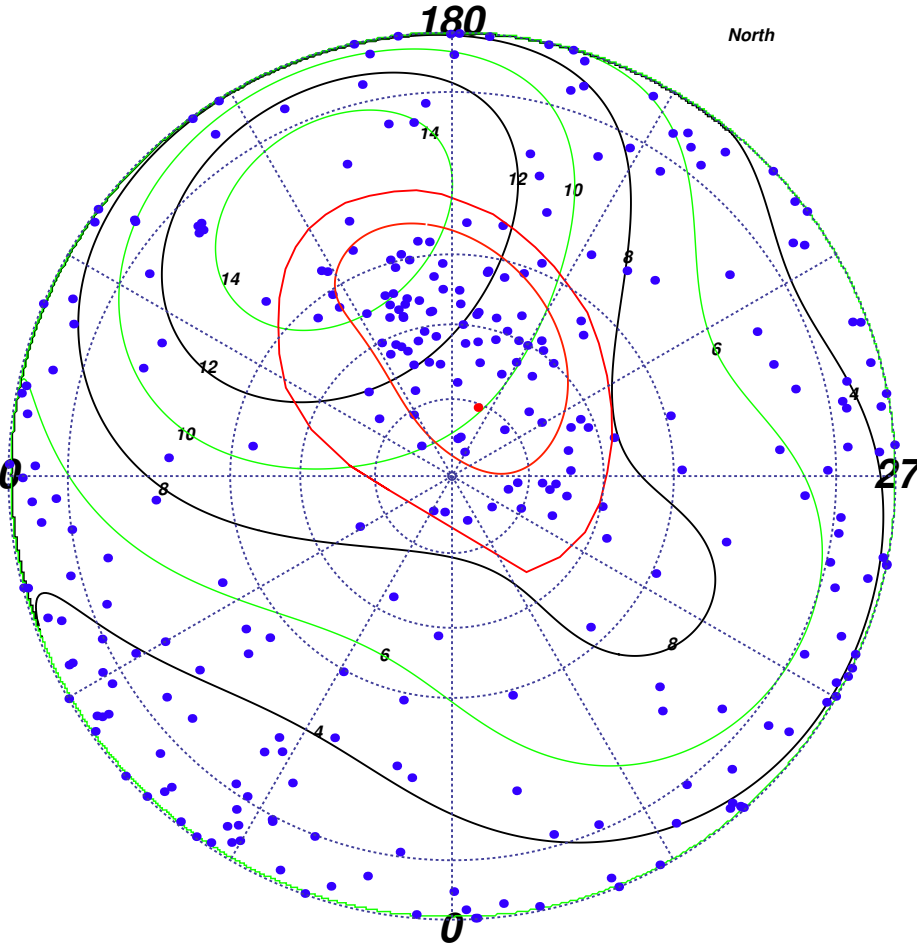
- Sulphur has a lower ionisation potential than oxygen.
- So it may be that one region energises sulphur sufficiently for X-ray production, but does not inject enough energy to do the same for oxygen.

Back-Up Slides – C/S and O separation

First Observation: 200−500eV

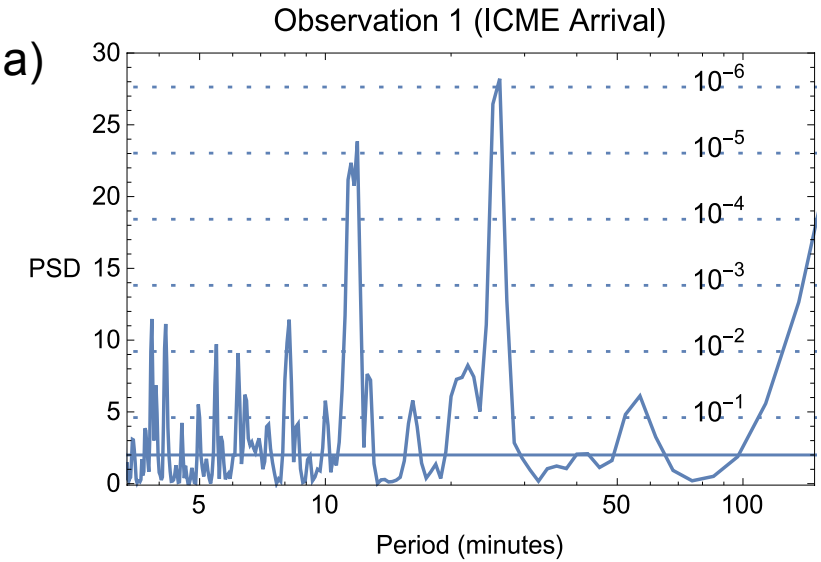


First Observation: 500−800eV



Back-Up Slides – PSDs from 2011 observations

a)



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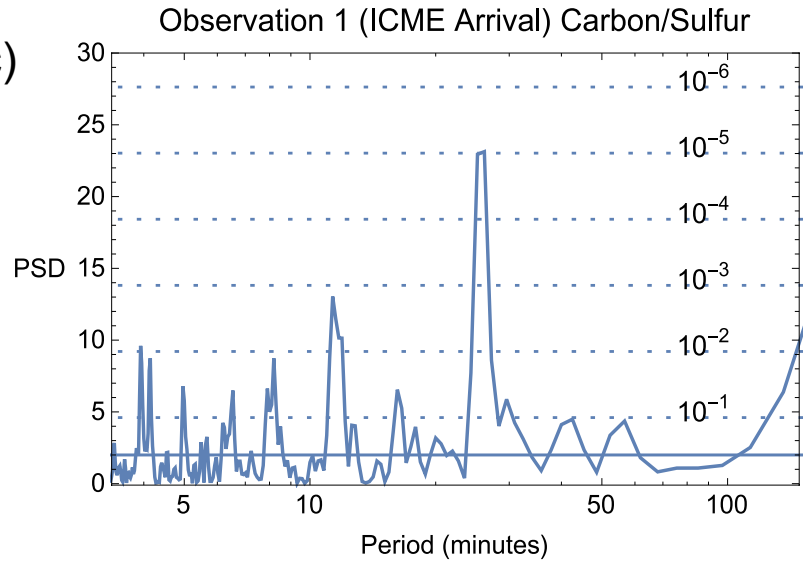
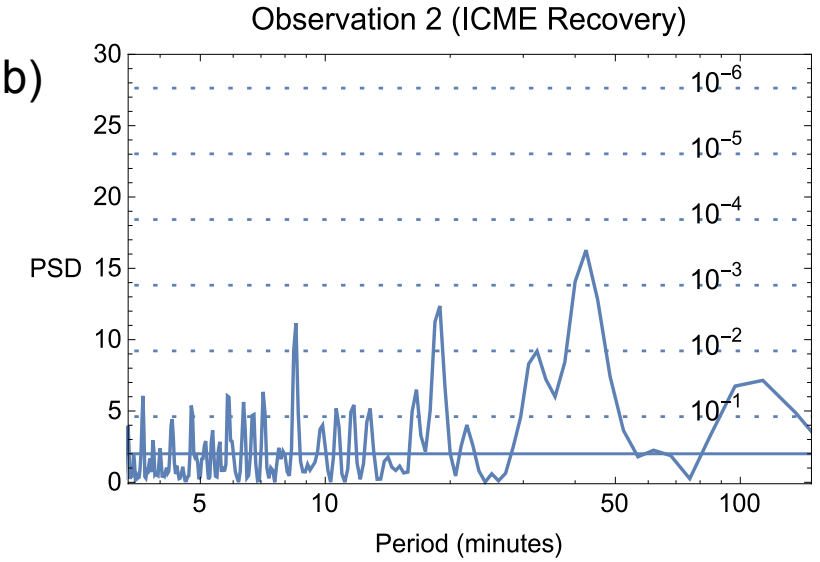
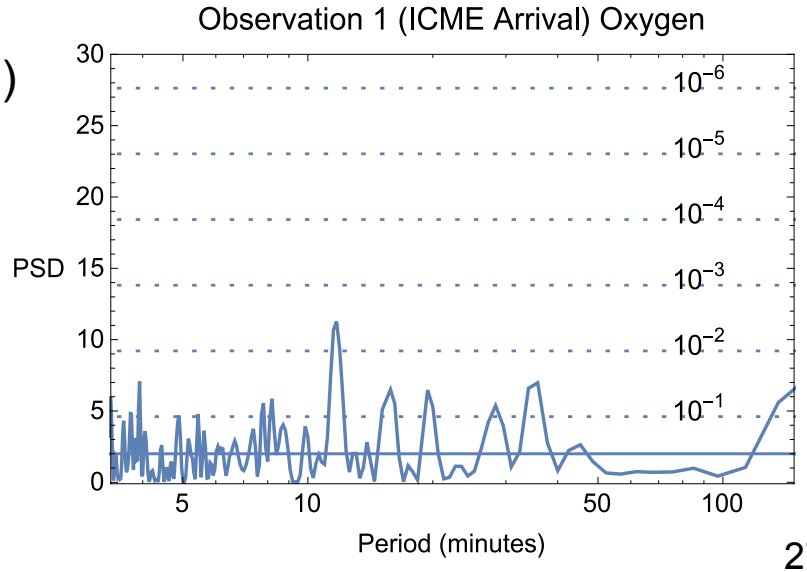


b)



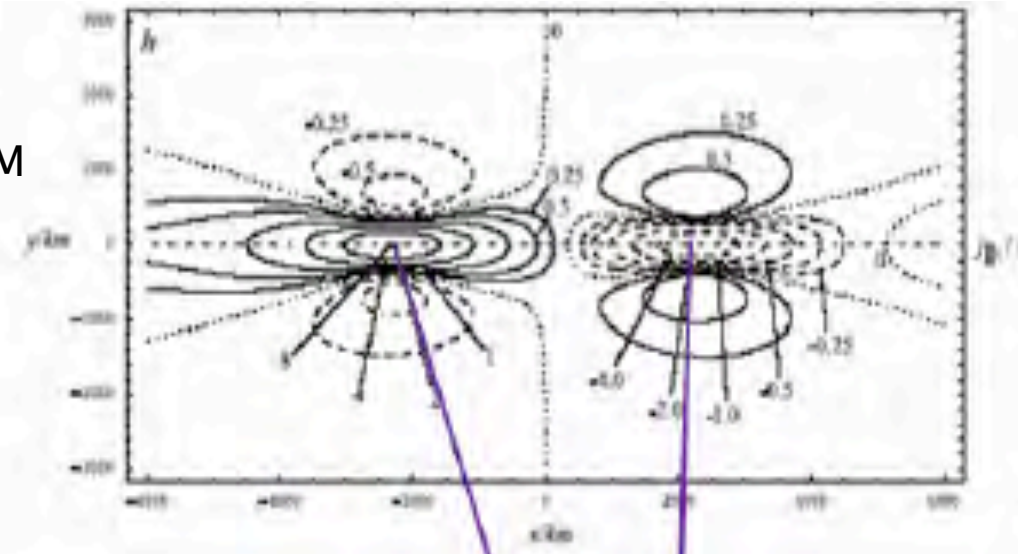
d)

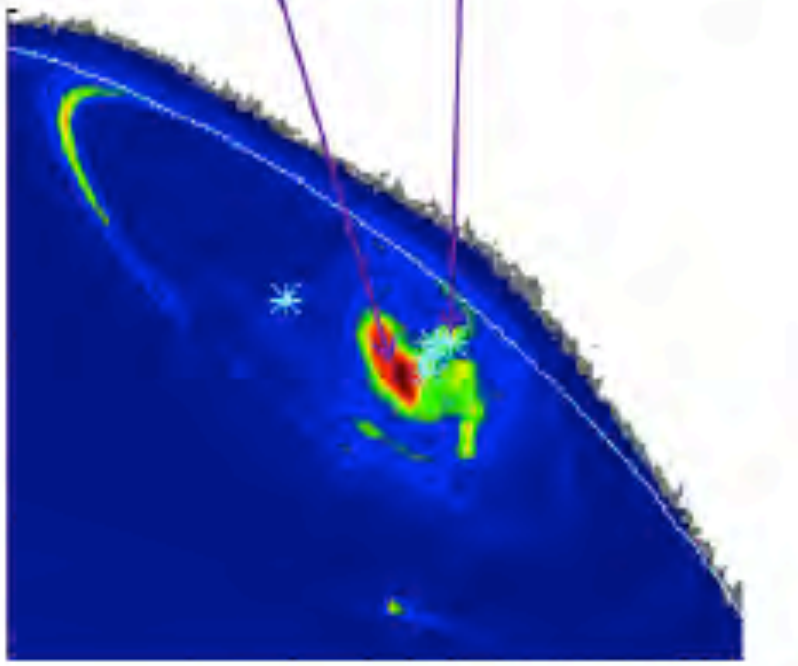


Connecting Wavelengths - UV

Juno UVS alongside HST, Chandra and XMM observations will help to identify connections between UV polar flares [e.g: Bonfond et al. 2011] and X-ray events that are found in similar locations at similar times [Elsner et al. 2005].

Providing richer datasets to study the drivers of features with similar origins.





Connecting Wavebands - Radio

Radio events have been noted to share similar periodicity to the X-ray events [e.g: Macdowall et al. 1993; Gladstone et al. 2002].

Bursts of Jovian non-Io decametric emission coincident with strong solar activity have also been found to occur at similar times to significant brightening of the X-ray aurora, suggesting similar origins. Although the X-ray events were associated with downward moving ions, while the radio emission is thought to be associated with upward moving electrons.