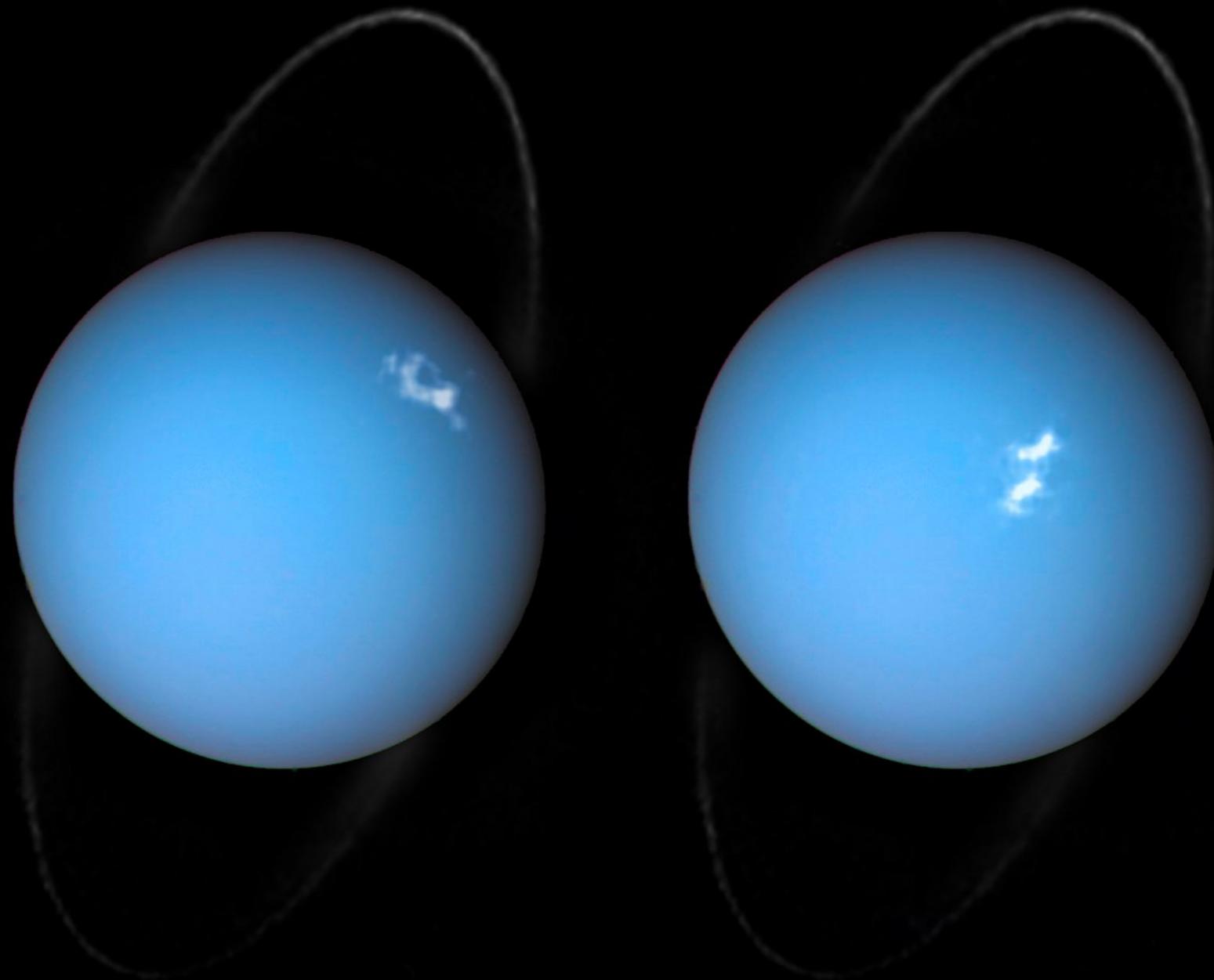


Ice giant aurorae

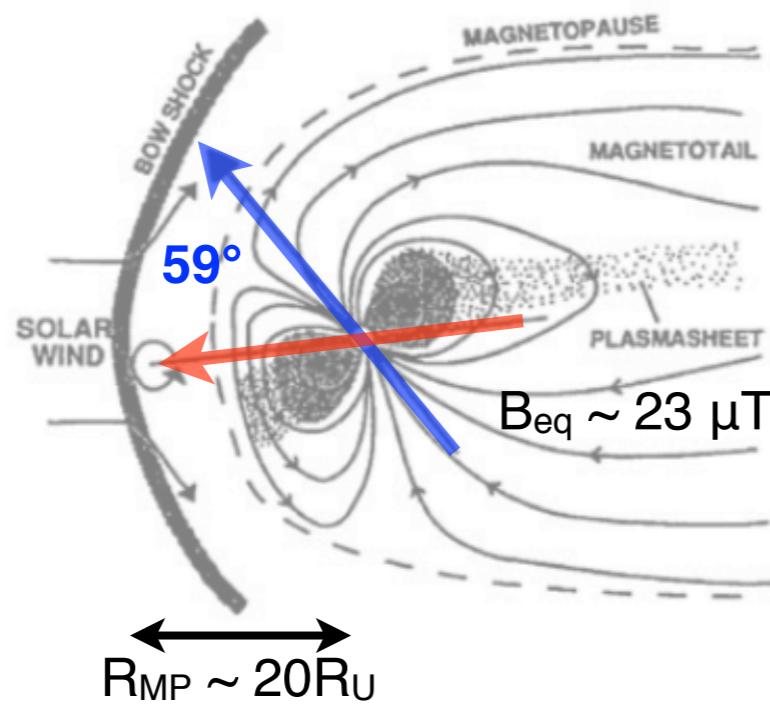


L. Lamy

l'Observatoire
de Paris

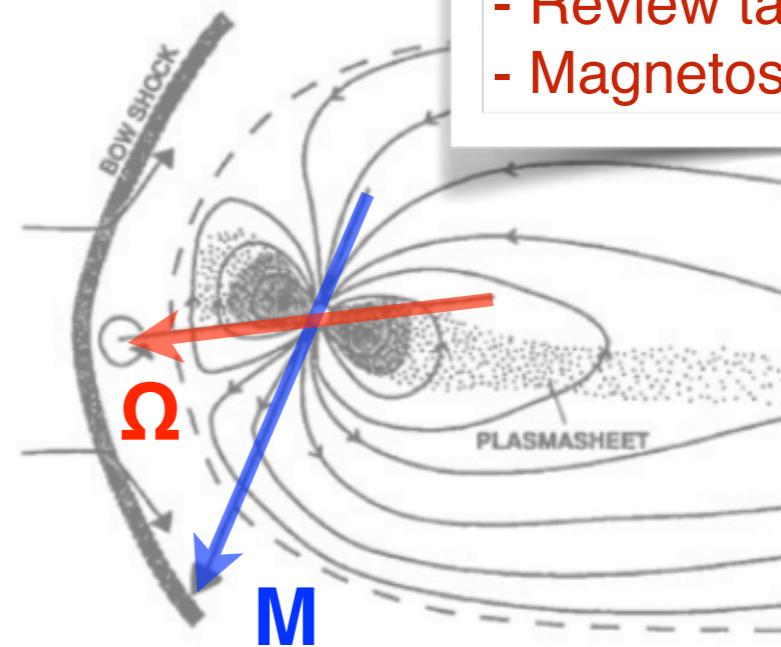
Magnetic « twins »

1986
Solstice



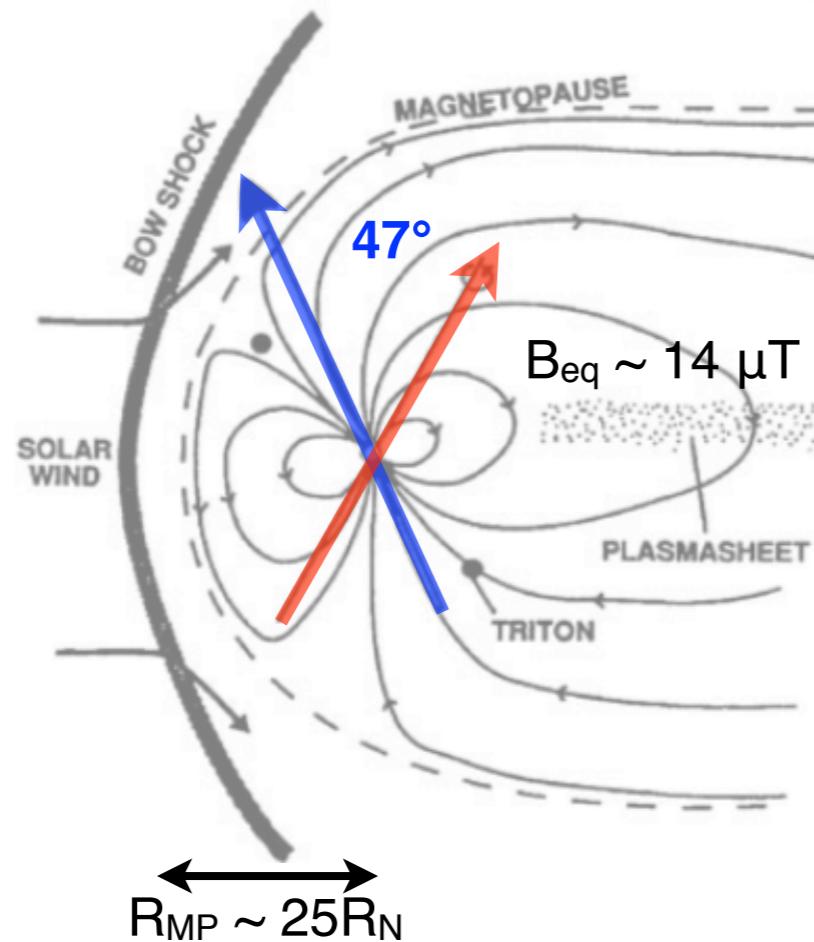
URANUS

- Review talk of C. Paty
- Magnetosphere session

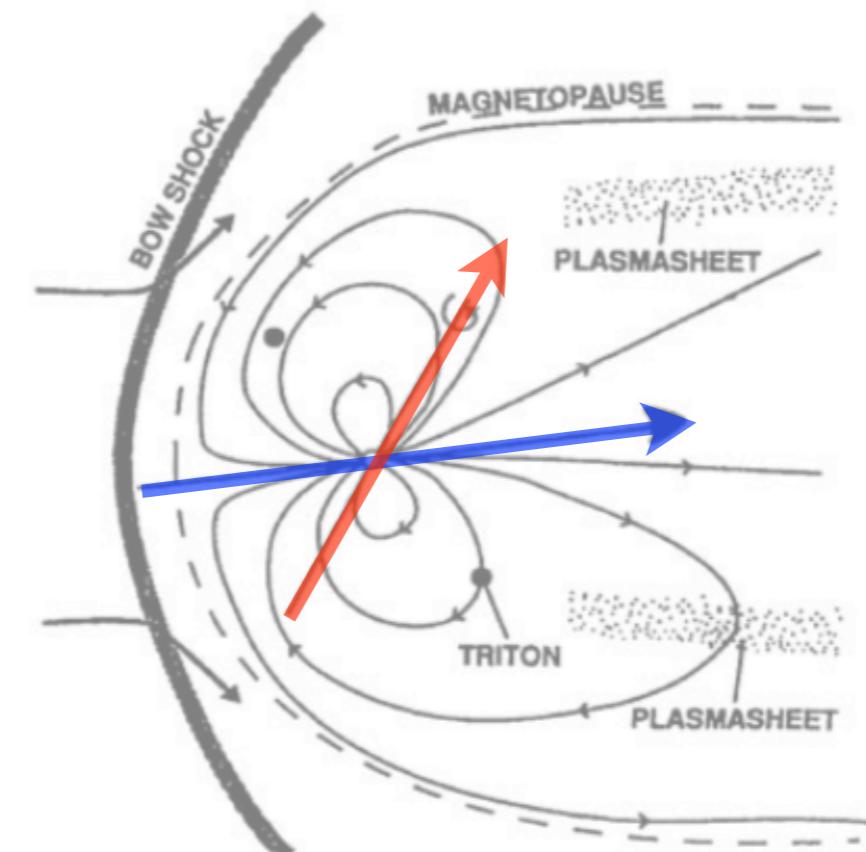


(Bagenal et al., 1992)

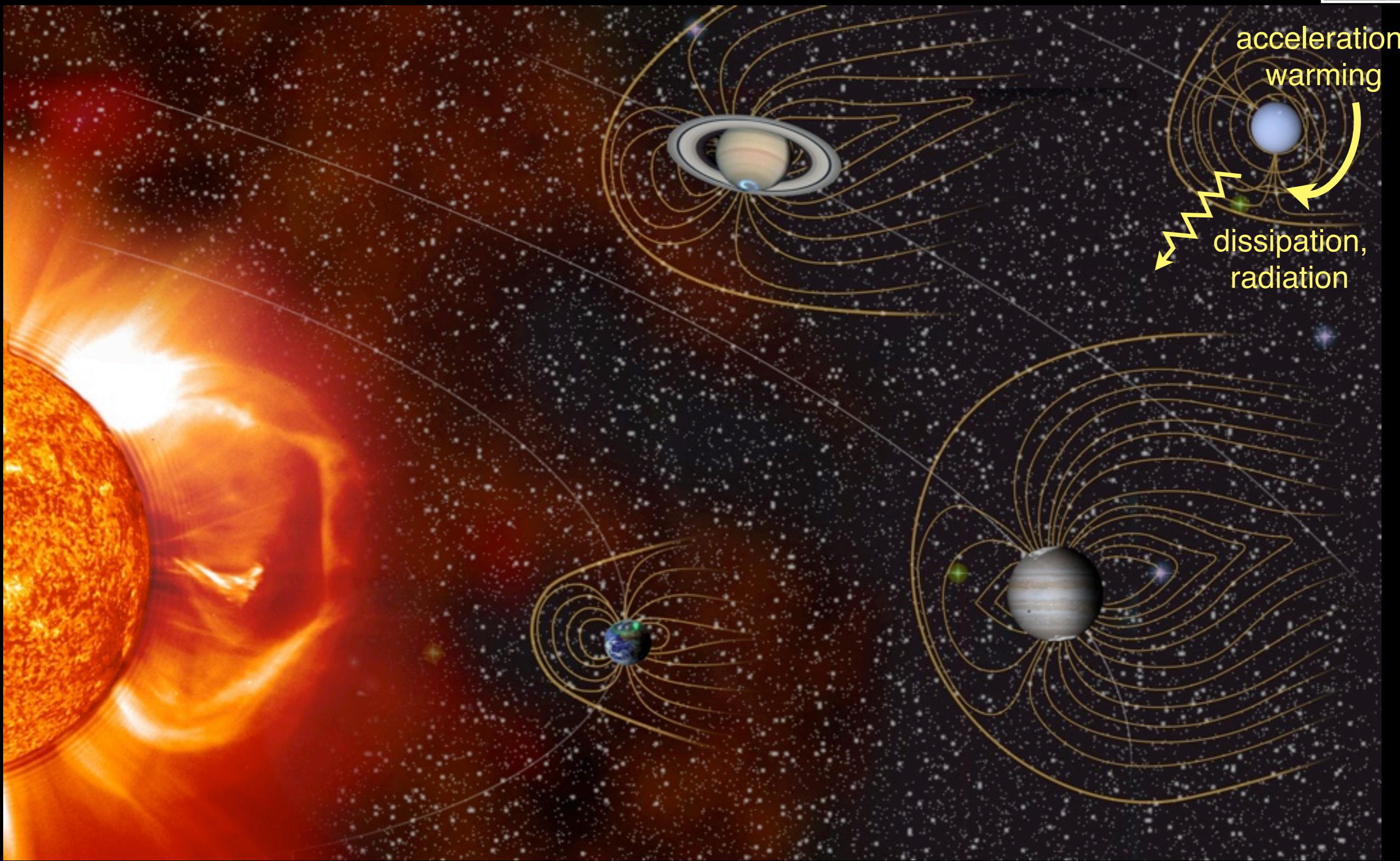
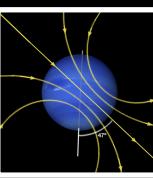
1989



NEPTUNE

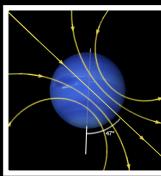


A probe of magnetospheric processes



- Auroral emissions probe a variety of fundamental phenomena : energy transfert/dissipation, magnetospheric dynamics (rotation, solar wind...)

A probe of magnetospheric processes

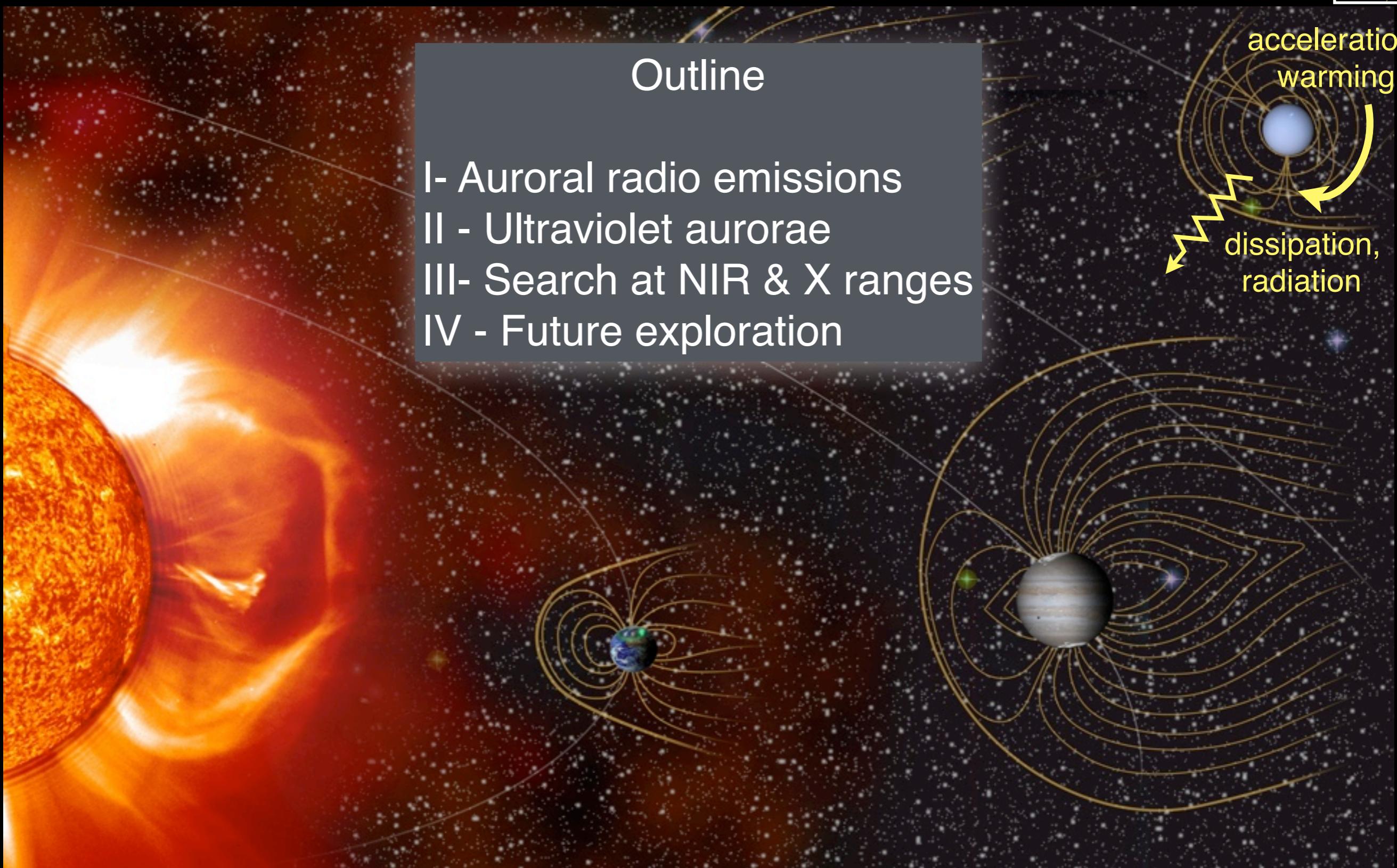


Outline

- I- Auroral radio emissions
- II - Ultraviolet aurorae
- III- Search at NIR & X ranges
- IV - Future exploration

acceleration,
warming

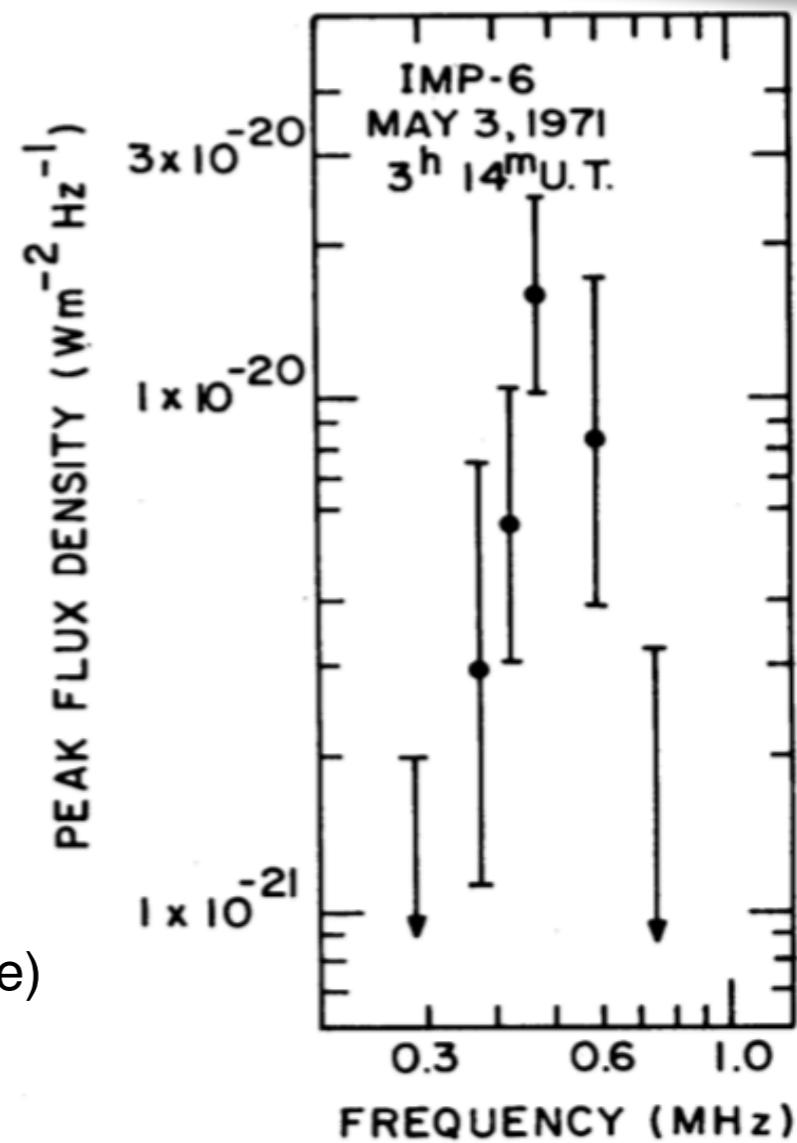
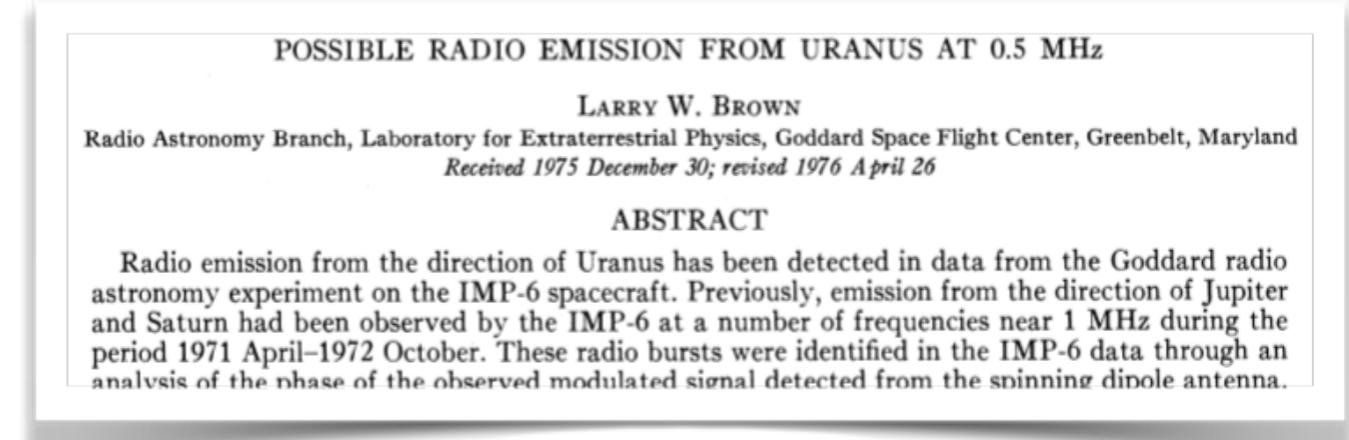
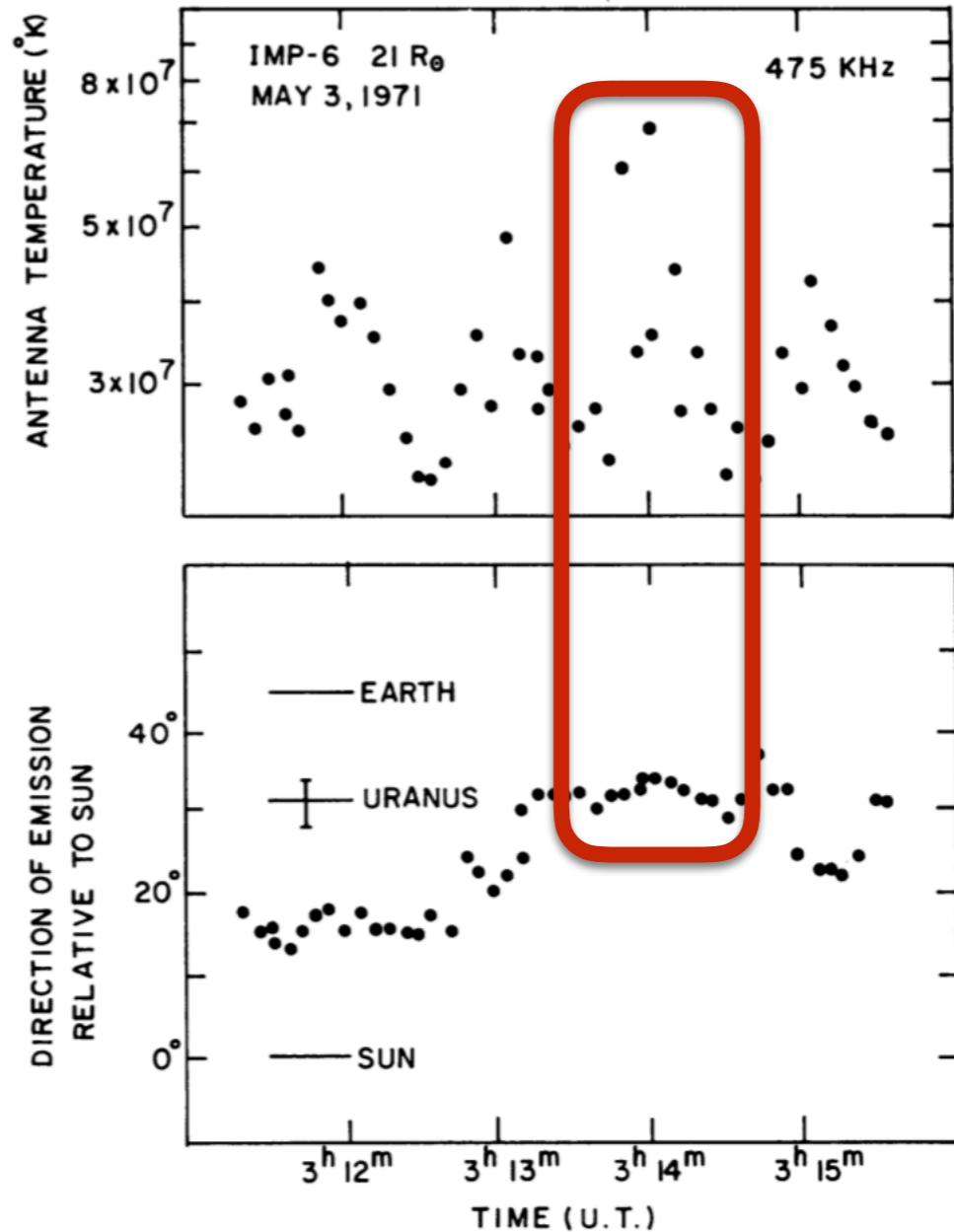
dissipation,
radiation



- Auroral emissions probe a variety of fundamental phenomena : energy transfert/dissipation, magnetospheric dynamics (rotation, solar wind...)

I- Auroral radio emissions

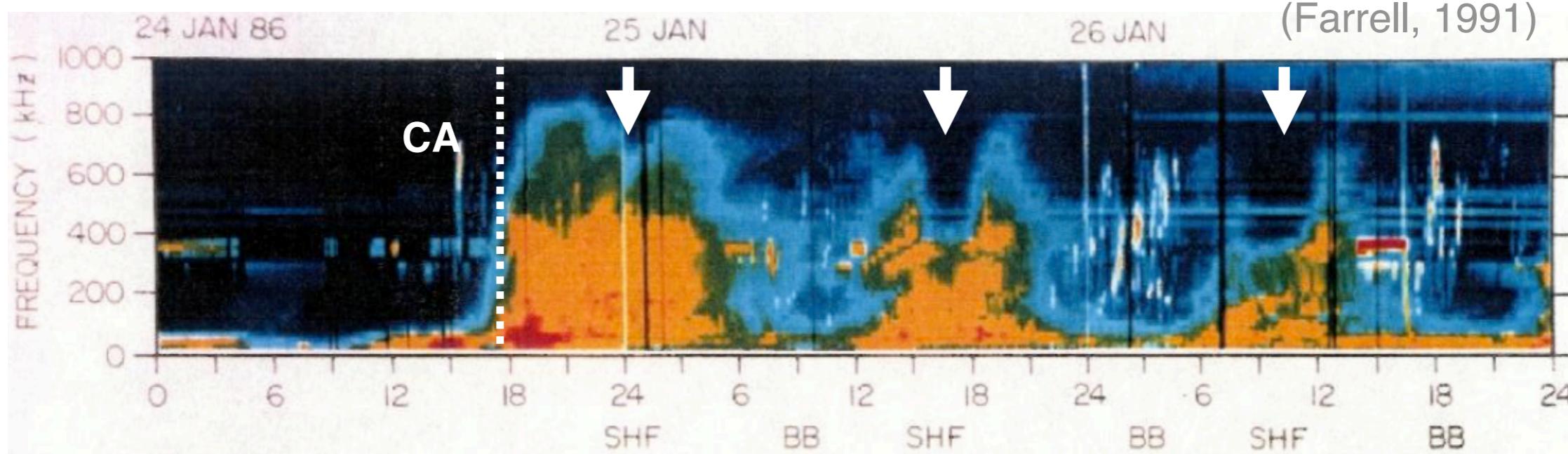
IMP6 / Uranus : 1976



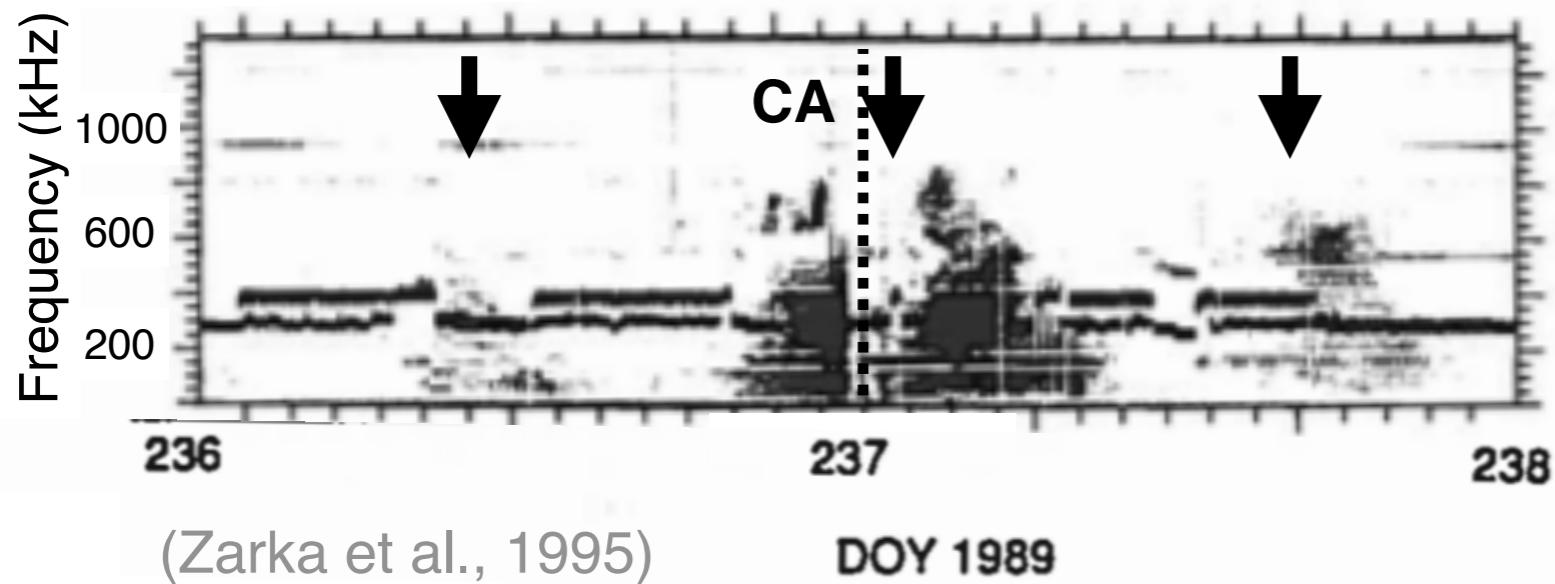
- Tentative distant detection of Uranus (100-m dipole)
- 1971-1972 : 6 bursts @ 500 kHz <3min

I- Auroral radio emissions Voyager 2 flybys : 1986 & 1989

Uranus kilometric Radiation (UKR)



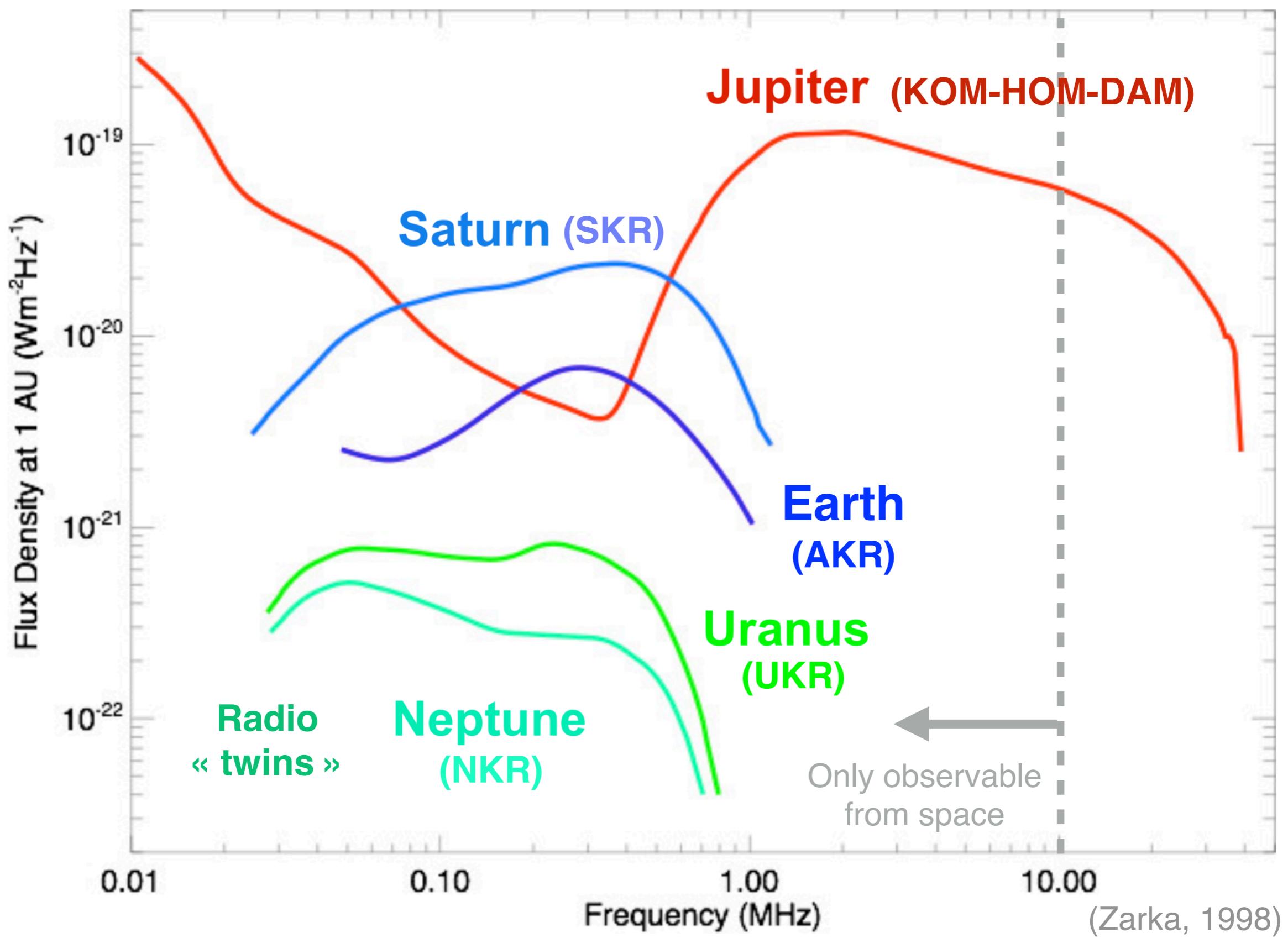
Neptune kilometric Radiation (NKR)



(Zarka et al., 1995)

- Remotely detected within [-10,+30] days from CA
 - auroral radio emissions analog to those of E-J-S
- => *Cyclotron Maser Instability*

I- Auroral radio emissions
Voyager 2 flybys : 1986 & 1989



I- Auroral radio emissions

Voyager 2 flybys : 1986 & 1989

Components	Spectrum	Polar.	Mode	Modulation	Source
UKR - b-smooth	150-900 kHz	LH	R-X	rotation, Ariel ?	S mag. pole
UKR - n-smooth	20-350 kHz	RH/LH	R-X	rotation	Mag. equator
UKR - dayside	100-300 kHz	LH	L-O	rotation	N mag. pole
UKR - b-bursts	200-800 kHz	LH	R-X	rotation, 30Hz	S mag. pole
UKR - n-bursts	16-117 kHz	RH	R-X	period	N cusp ?
NKR - smooth	20-600 kHz	RH/LH	R-X	SW	S/N mag. poles
NKR - smooth HF	600-870 kHz	RH/LH	R-X	rotation	S/N mag. poles
NKR - burst	0.4-1.3 MHz	LH	R-X	rotation, SW	Mag. equator
NKR - anom. burst	10-550 kHz	LH	R-X	rotation	S mag. pole

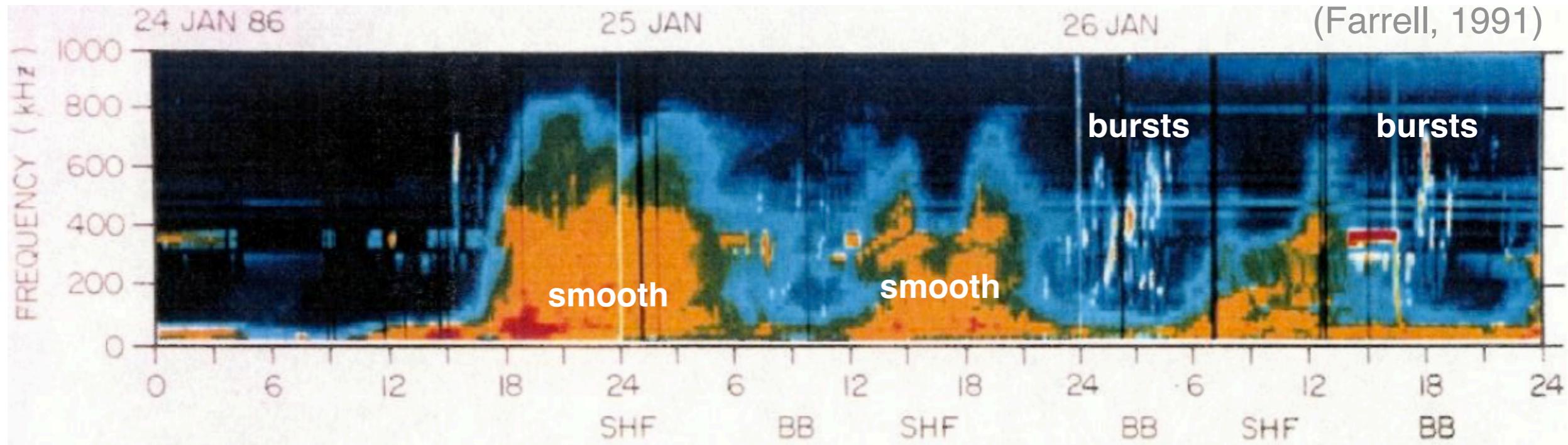
(Desch et al., 1991, Zarka et al., 1995)

Characteristics :

- complex radio spectrum

I- Auroral radio emissions Voyager 2 flybys : 1986 & 1989

Uranus



Characteristics :

- complex radio spectrum

- 2 main categories :

- (i) « bursts » = E-S-J

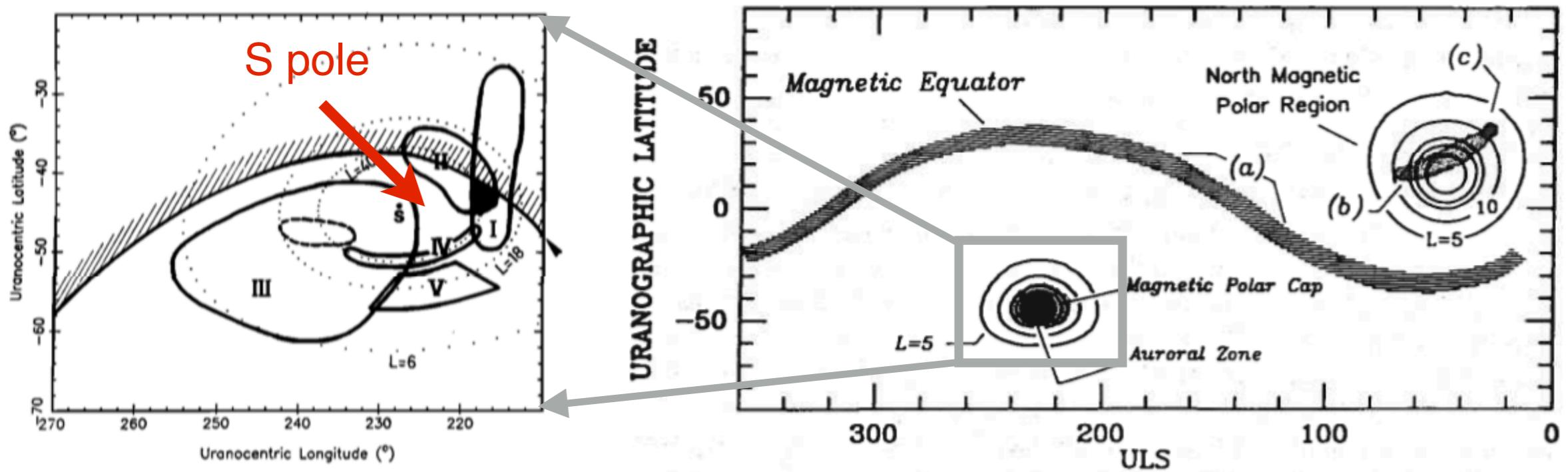
- (ii) « smooth » **≠ E-S-J**

=> Unknown time-stationary source of free energy

I- Auroral radio emissions

Voyager 2 flybys : 1986 & 1989

Uranus



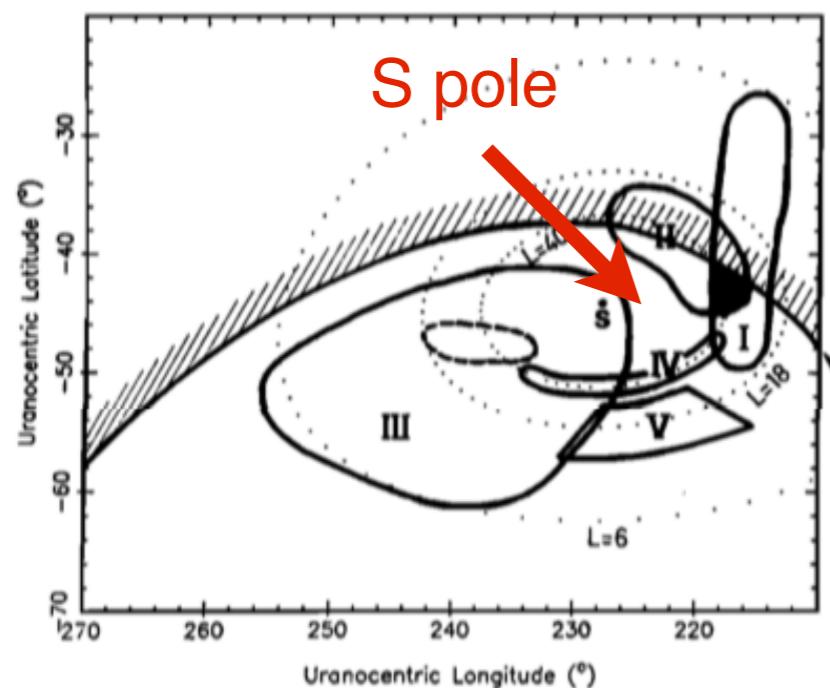
Characteristics :

- complex radio spectrum
- 2 main categories :
 - (i) « bursts » = E-S-J
 - (ii) « smooth » **≠ E-S-J**
 - => Unknown time-stationary source of free energy**
- sources located around both mag. poles => linked to aurora = E-S-J

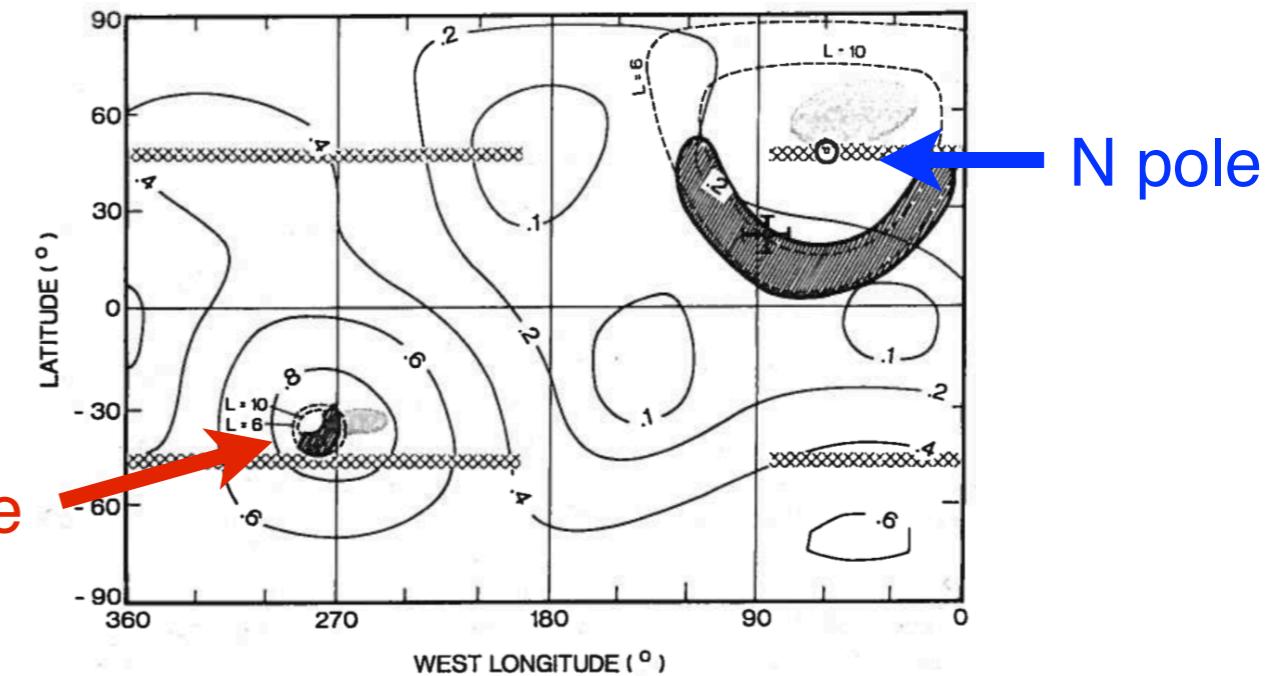
(Zarka et al., 1987, Lecacheux & Ortega-Molina, 1987; Kaiser et al., 1987, 1989, Leblanc et al. 1987, Gulkis & Carr, 1987, Barbosa, 1987, Romig et al., 1987)

I- Auroral radio emissions Voyager 2 flybys : 1986 & 1989

Uranus



Neptune



(Farrell et al., 1990, Desch et al., 1991, Boischot, 1995)

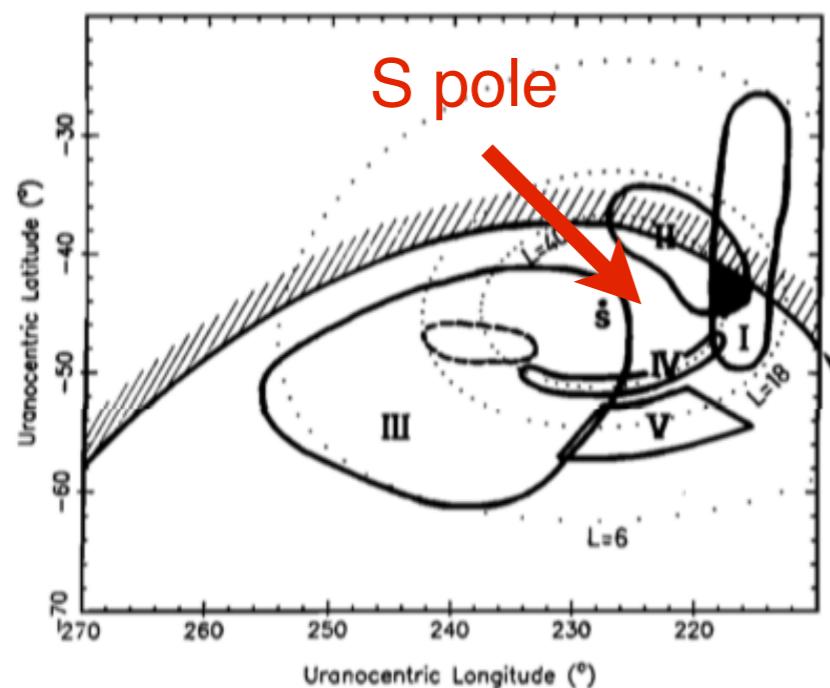
Characteristics :

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- 2 main categories :
 - (i) « bursts » = E-S-J
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I- Auroral radio emissions

Voyager 2 flybys : 1986 & 1989

Uranus



Characteristics :

- complex radio spectrum

- 2 main categories :

- (i) « bursts »

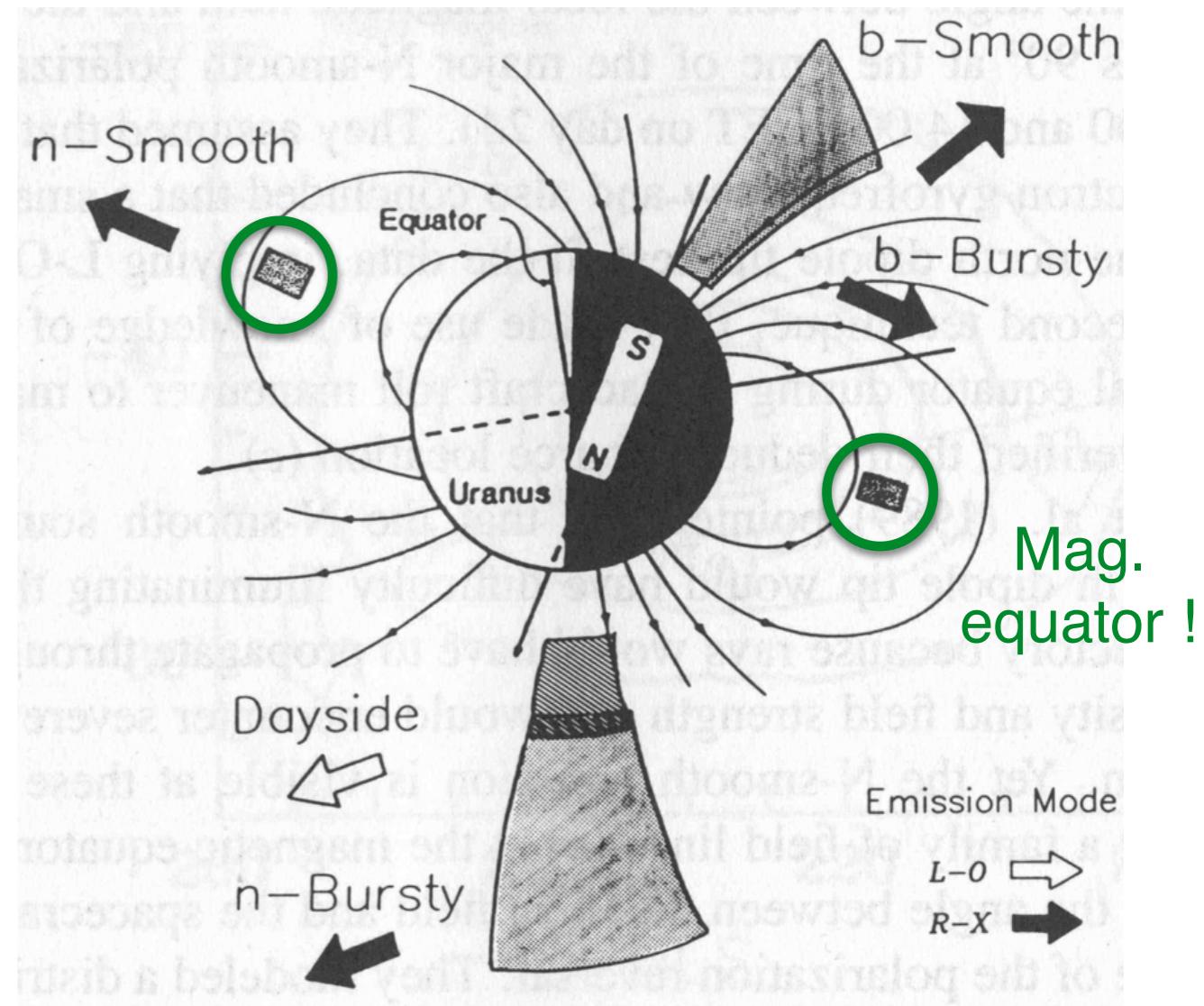
- (ii) « smooth » **≠ E-S-J**

=> Unknown time-stationary source of free energy

- sources located around both mag. poles => linked to aurora

- + near magnetic equator **≠ E-S-J**

=> How can ‘auroral’ radio amplification develop there ?

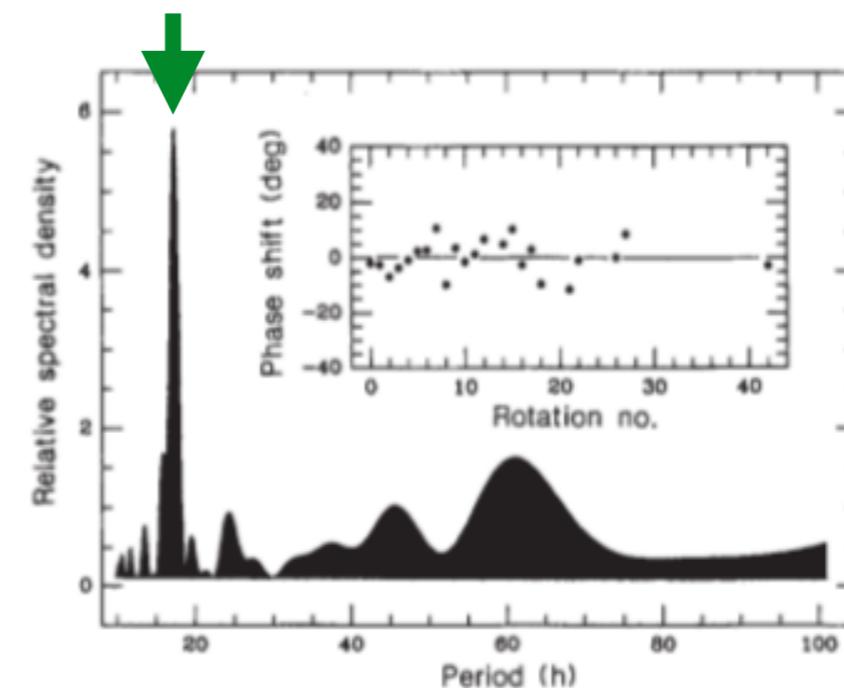
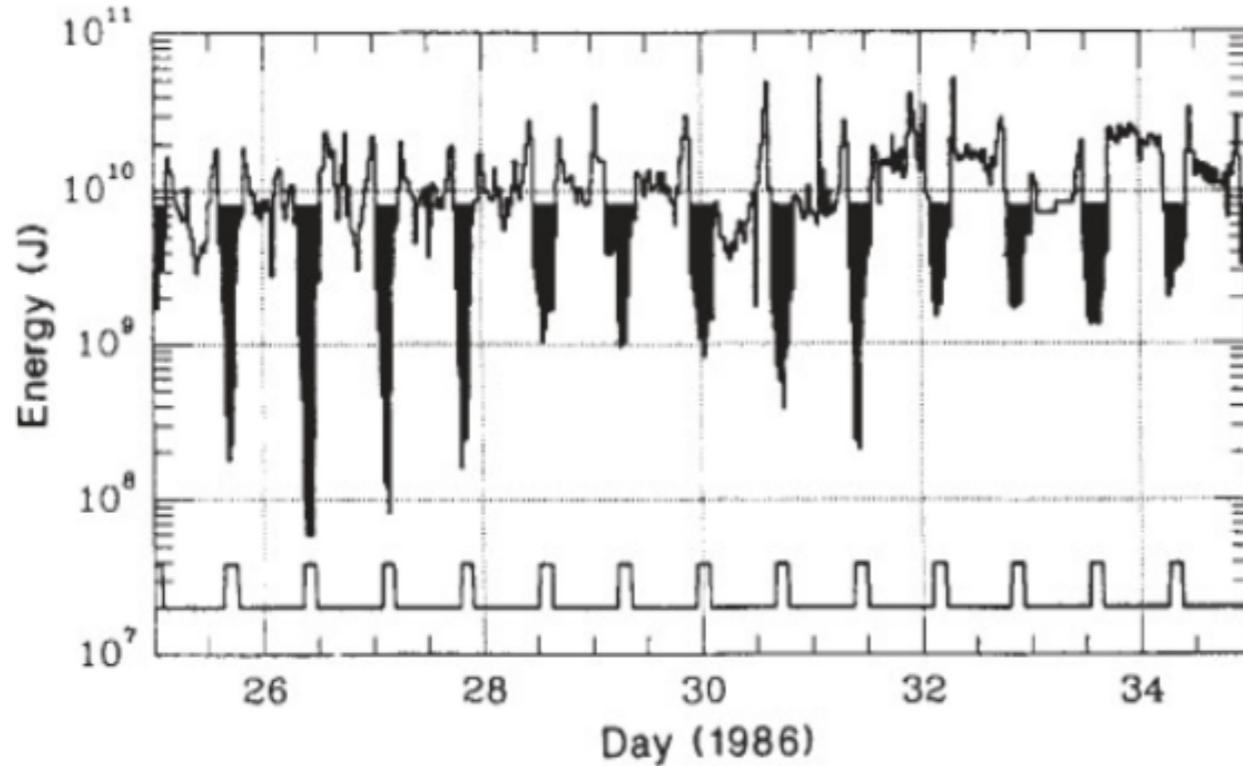


(Desch et al., 1991)

I- Auroral radio emissions Voyager 2 flybys : 1986 & 1989

Dynamics : rotation period

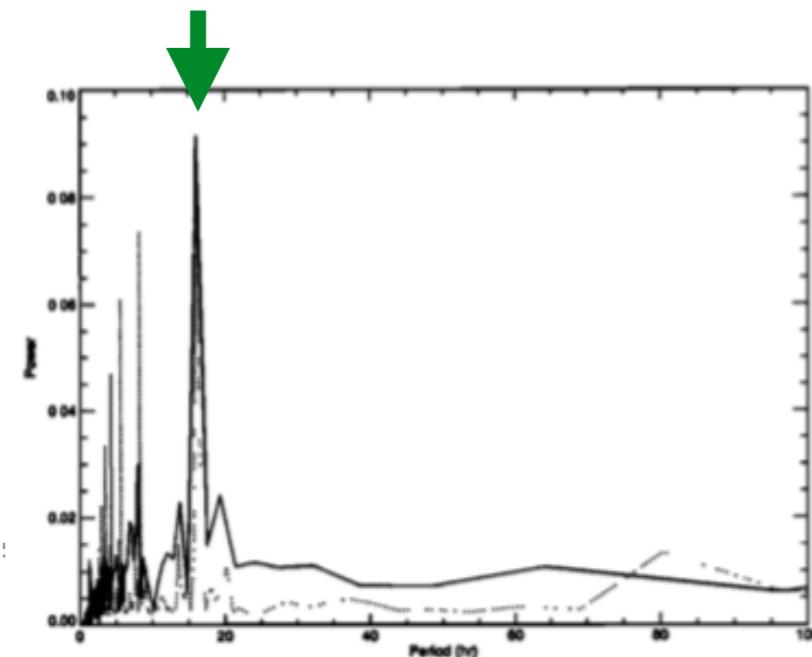
Uranus



(Desh et al., 1986)

$P_U = 17.24 \pm 0.01\text{h}$
 \Rightarrow Uranian Longitude System (ULS)

Neptune



$P_N = 16.108 \pm 0.006\text{h}$
 \Rightarrow Neptunian Longitude System (NLS)

(Warwick et al., 1989,
Lecacheux et al., 1993,
Zarka et al., 1995)

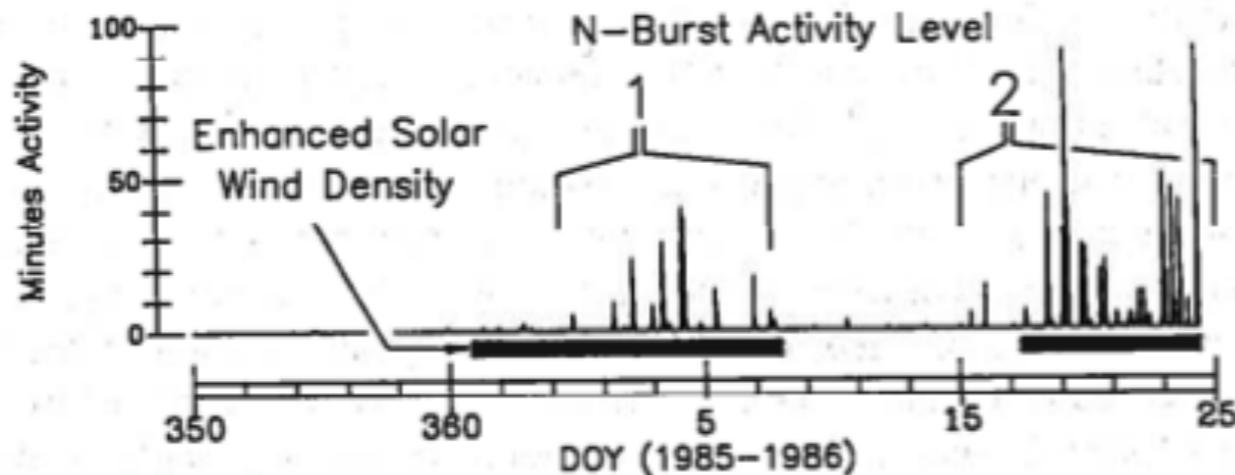
Both SIII systems are now over-dated
 \Rightarrow **Longitude of N/S poles is lost**

I- Auroral radio emissions Voyager 2 flybys : 1986 & 1989

Dynamics : solar wind

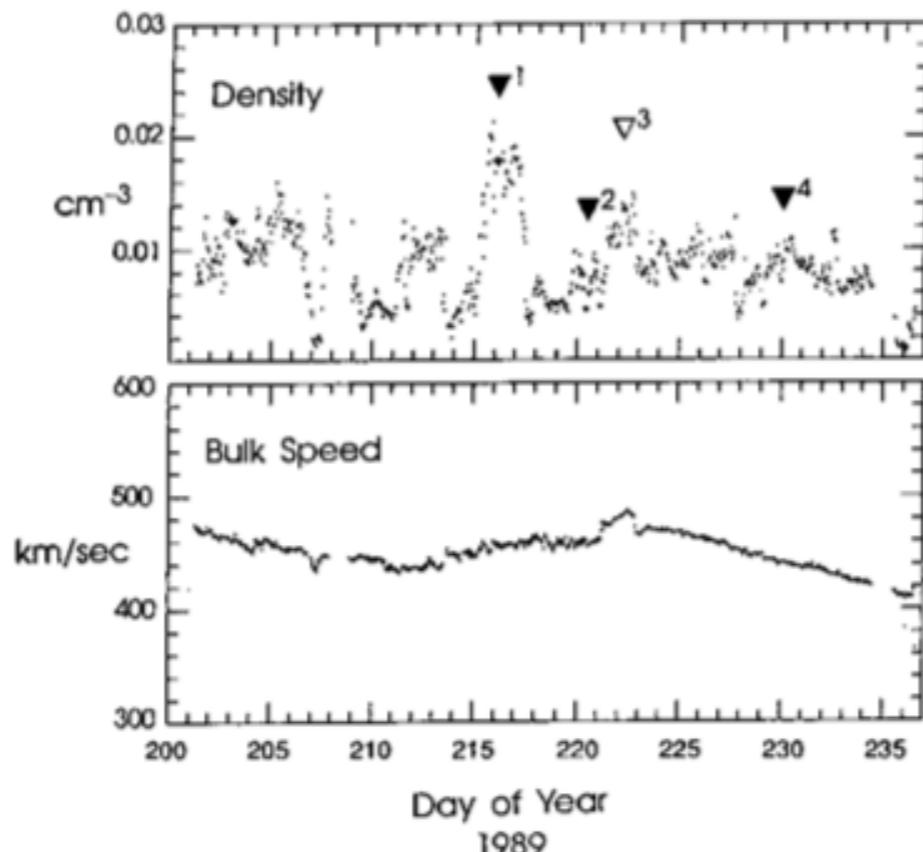
Uranus

(Desh et al., 1989)



Neptune

(Desh et al., 1991)



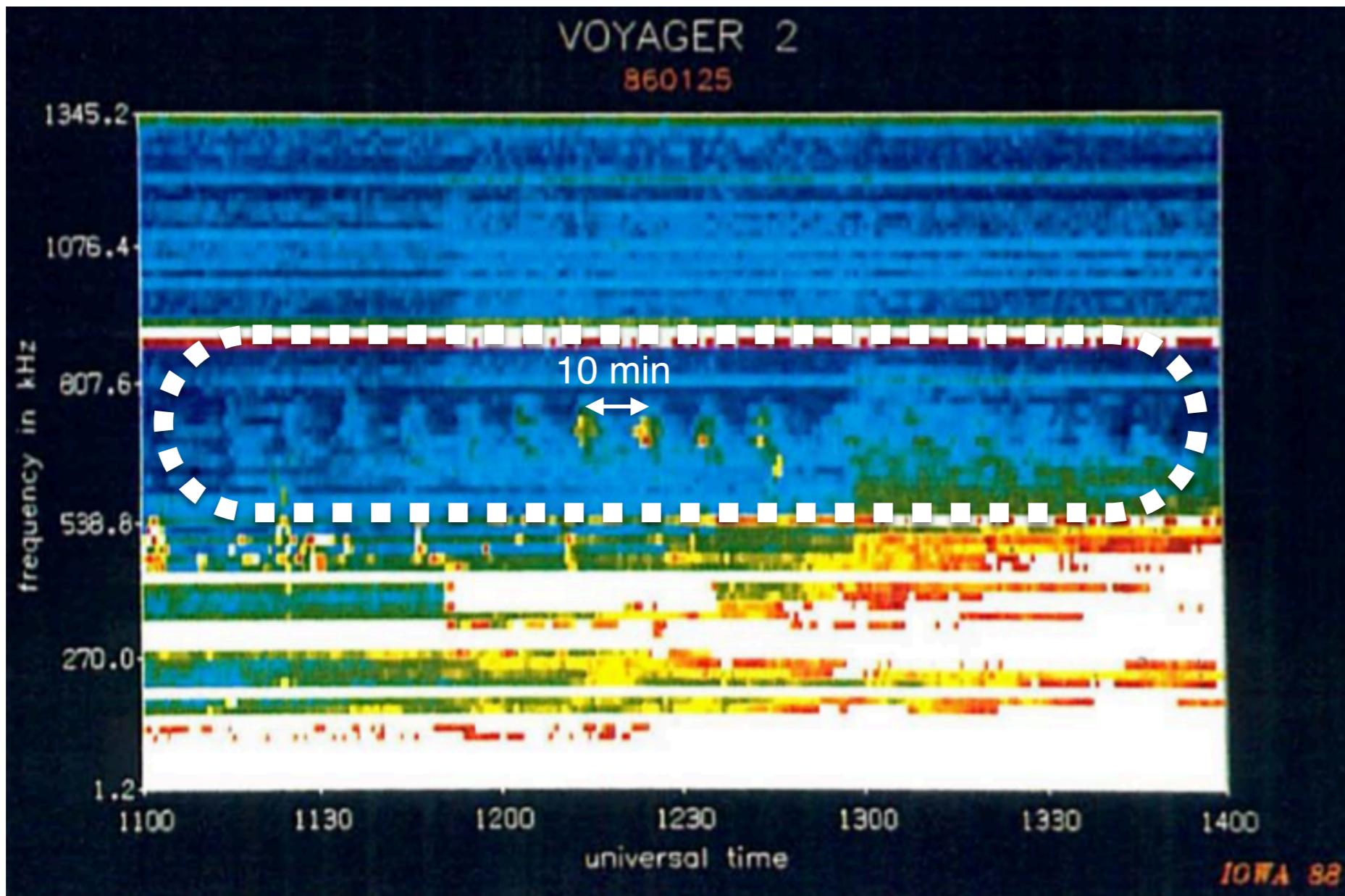
- weaker solar wind control
than at E-S : **why ?**

I- Auroral radio emissions Voyager 2 flybys : 1986 & 1989

Dynamics : moon/planet interactions ?

Uranus

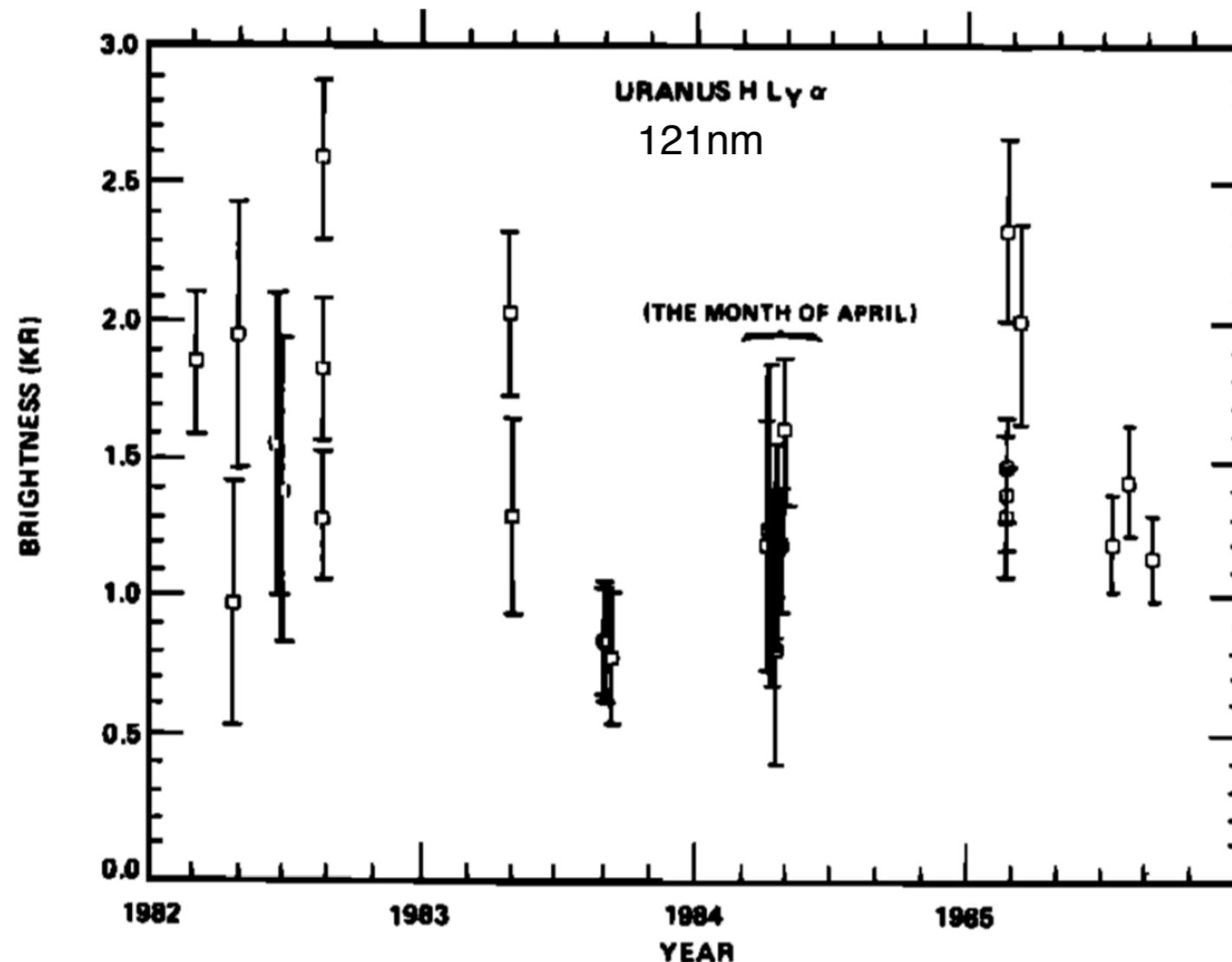
(Kistler, 1988)



=> tentative identification of periodic UKR arcs induced by Ariel : **active moon ?**

II- Ultraviolet aurorae

IUE / Uranus : 1982-1986



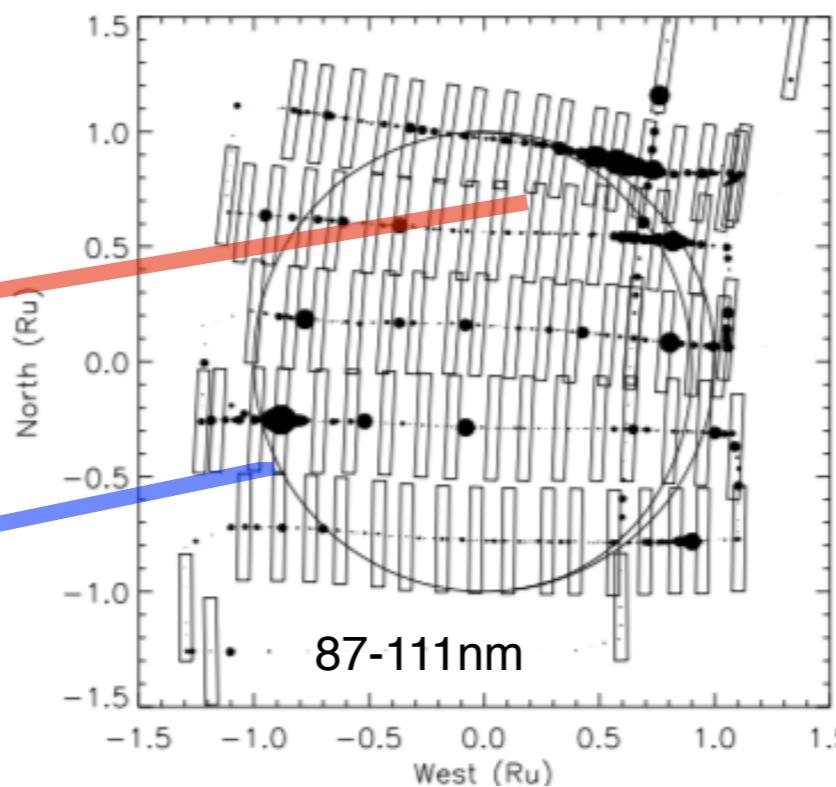
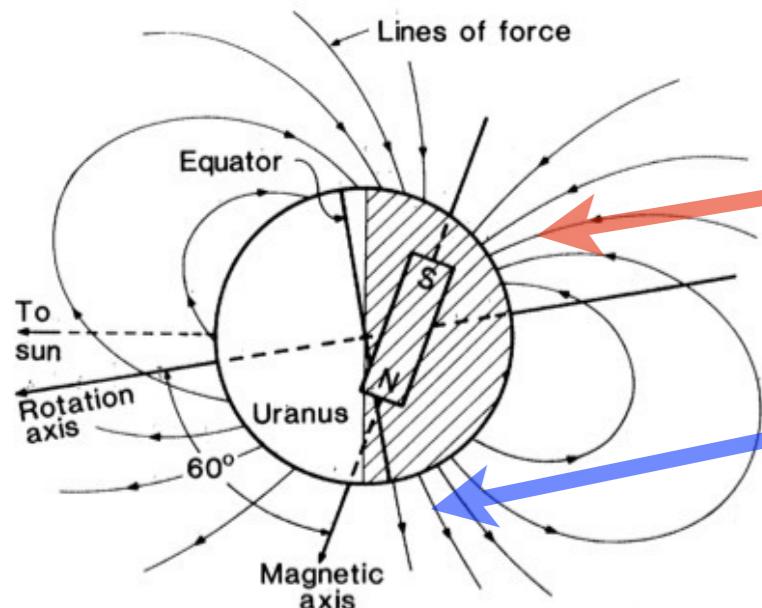
(Clarke et al.,
1982, 1986)

- unexpectedly high and time-variable emission from H-Lya line => aurora ?

II- Ultraviolet aurorae

Voyager 2 flybys : 1986 & 1986

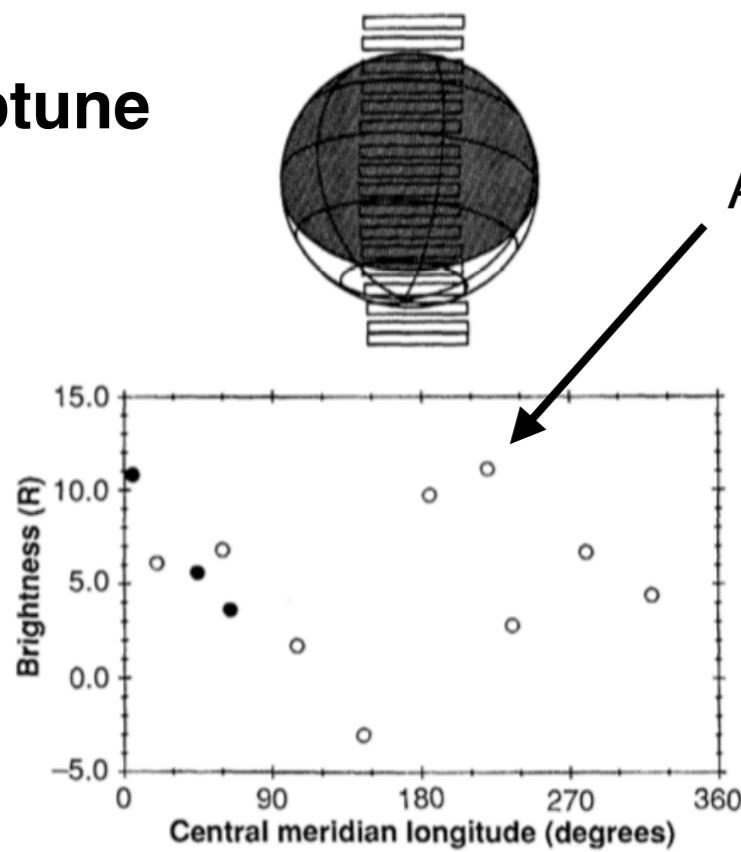
Uranus



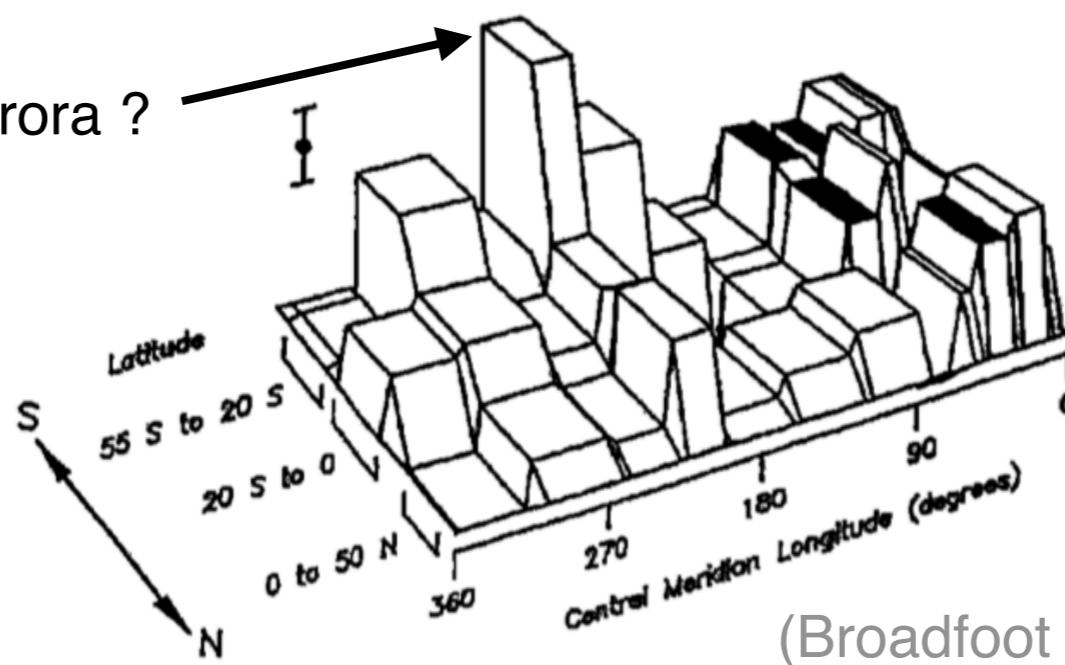
=> patchy emission of a few kR in the H₂ bands

(Broadfoot et al., 1986,
Herbert et al., 1994)

Neptune



Aurora ?



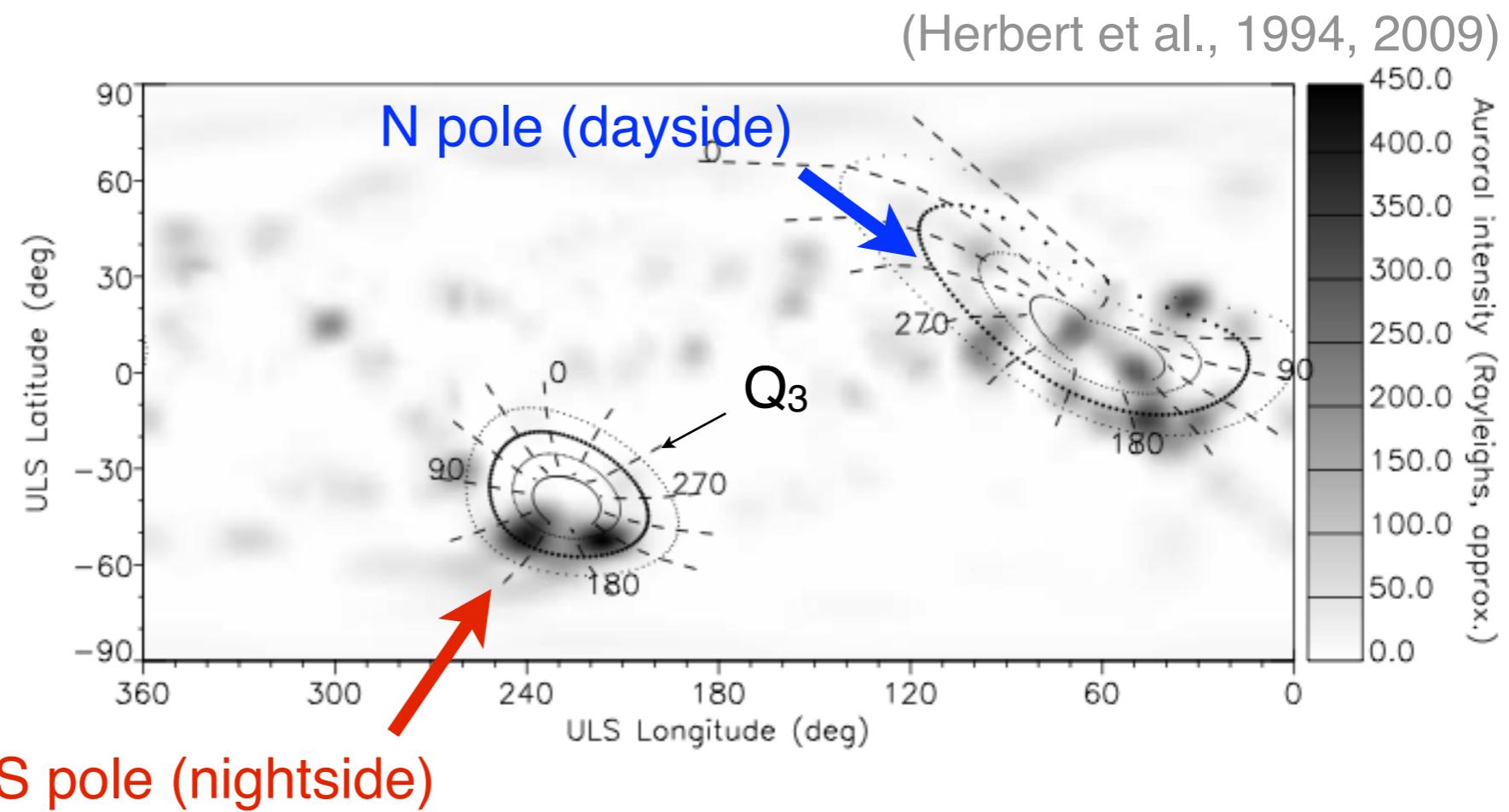
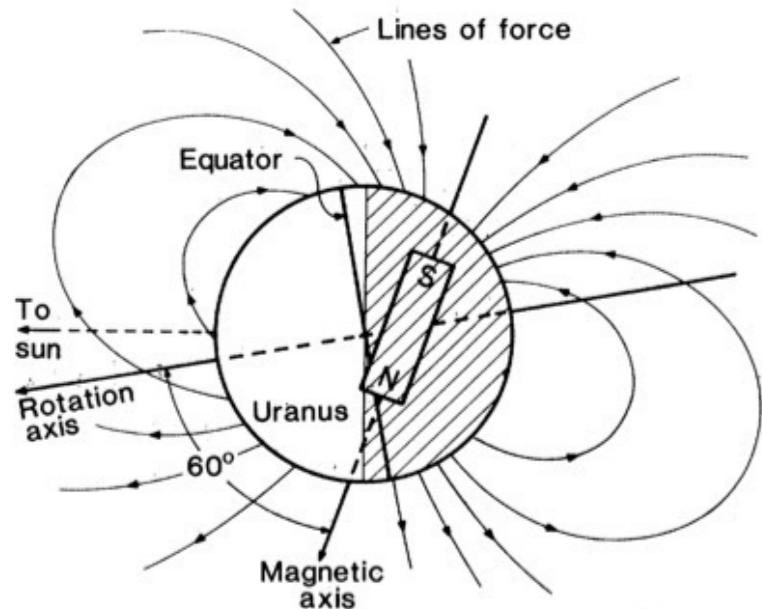
=> faint (5R),
ambiguous
detection

(Broadfoot et al., 1989,
Sandel et al. 1990)

II- Ultraviolet aurorae

Voyager 2 flyby : 1986

Uranus



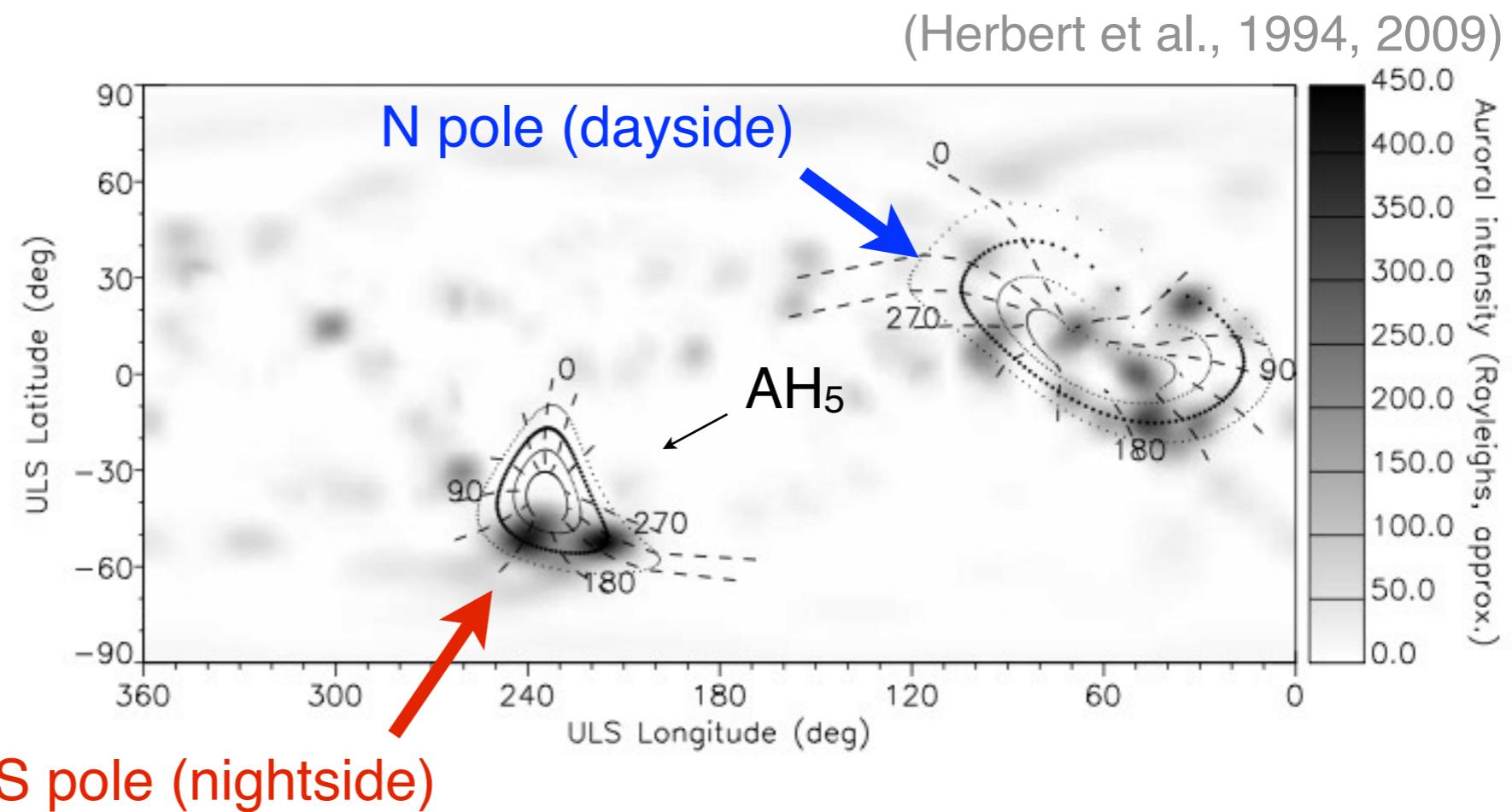
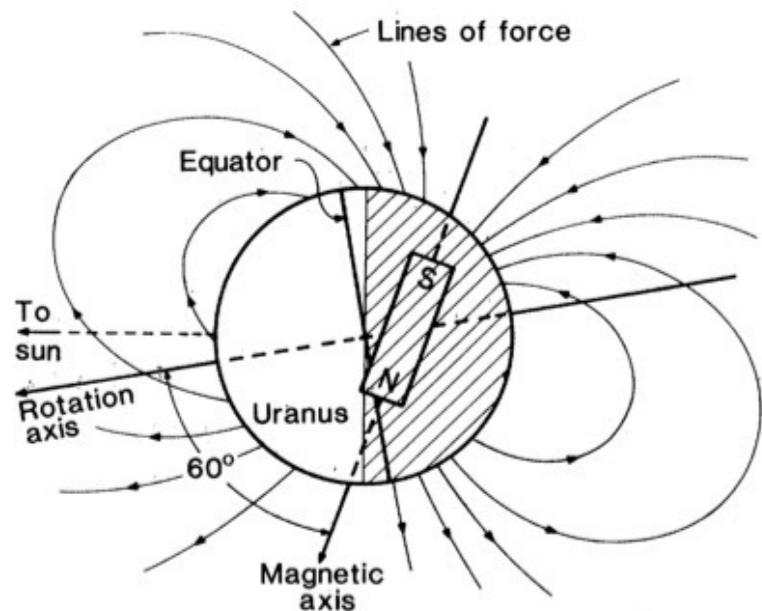
Aurorae at solstice :

- radiated power : N = 3 GW / S = 7 GW => input power < 10^{11} W
- N / S aurora magnetically conjugate at $\sim 60\text{--}65^\circ$ latitude ($L = 5\text{--}10$) => AH5 model

II- Ultraviolet aurorae

Voyager 2 flyby : 1986

Uranus



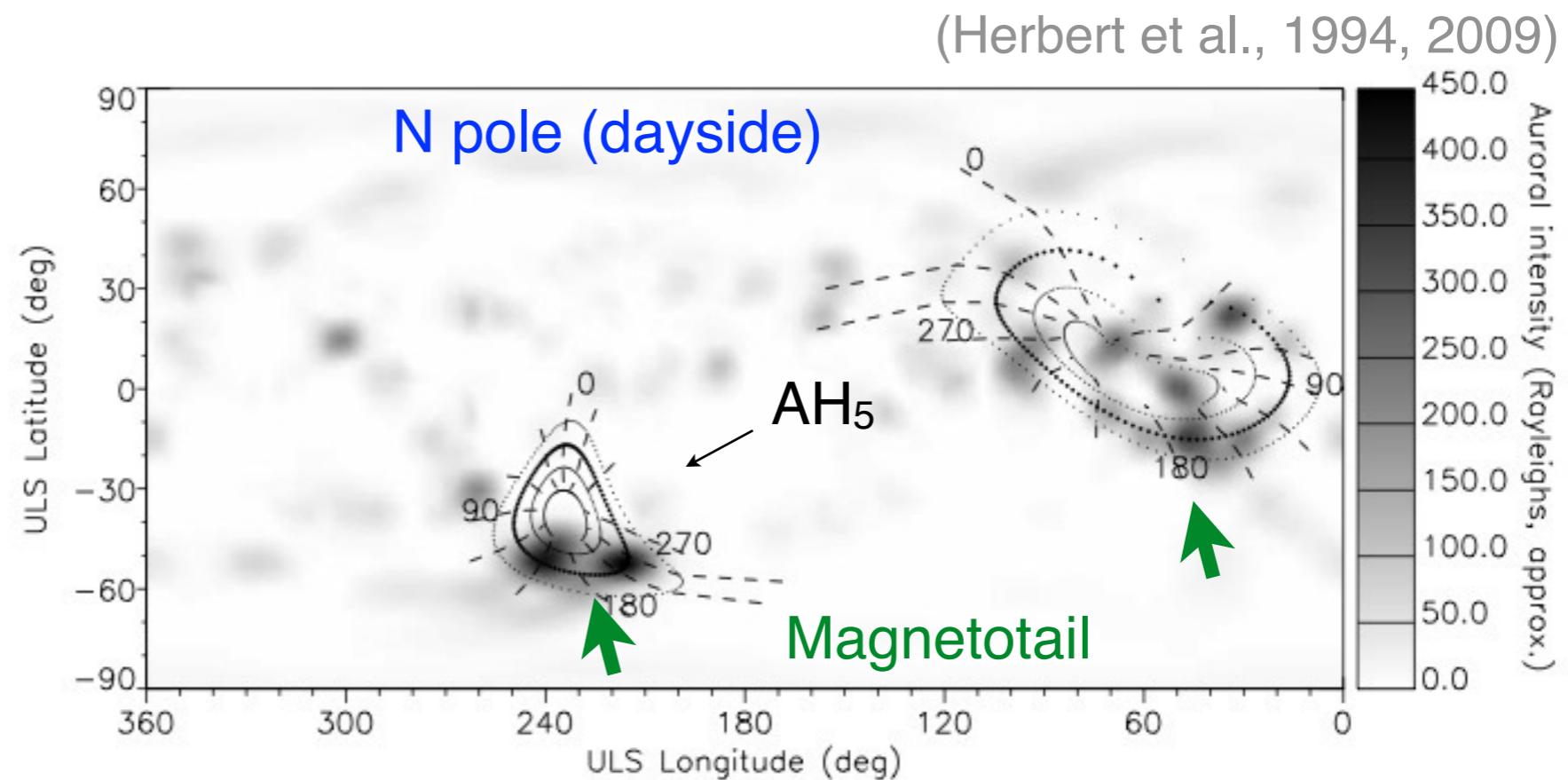
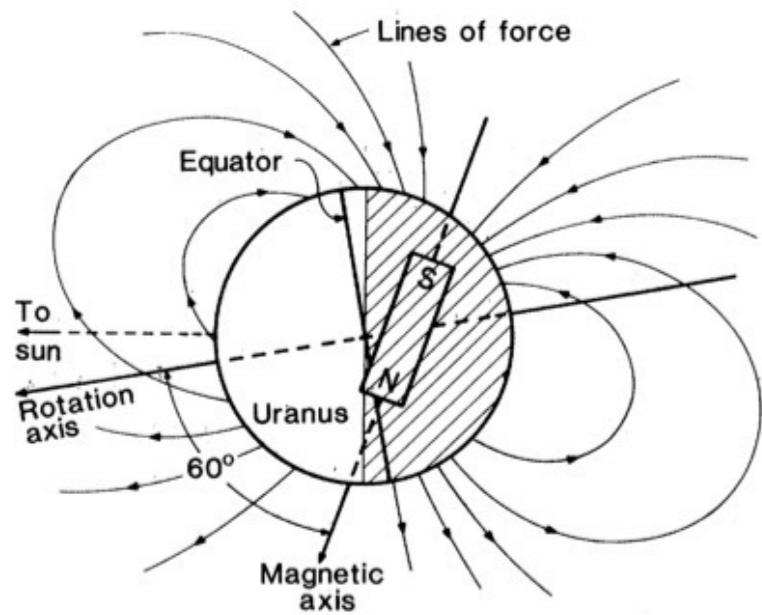
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II- Ultraviolet aurorae

Voyager 2 flyby : 1986

Uranus

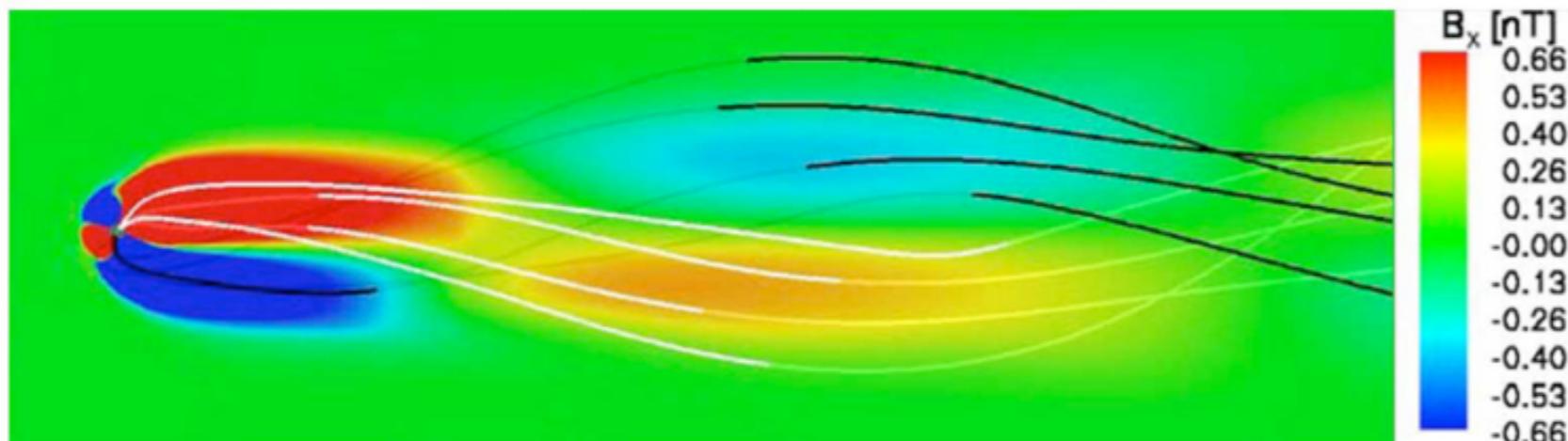


Aurorae at solstice :

- radiated power : N = 3 GW / S = 7 GW => input power < 10^{11} W
- N / S aurora magnetically conjugate at $\sim 60\text{-}65^\circ$ latitude ($L = 5\text{-}10$) => AH₅ model
- enhanced along the nightside direction ($\sim 180^\circ$ long.)

II- Ultraviolet aurorae Voyager 2 flyby : 1986

Uranus



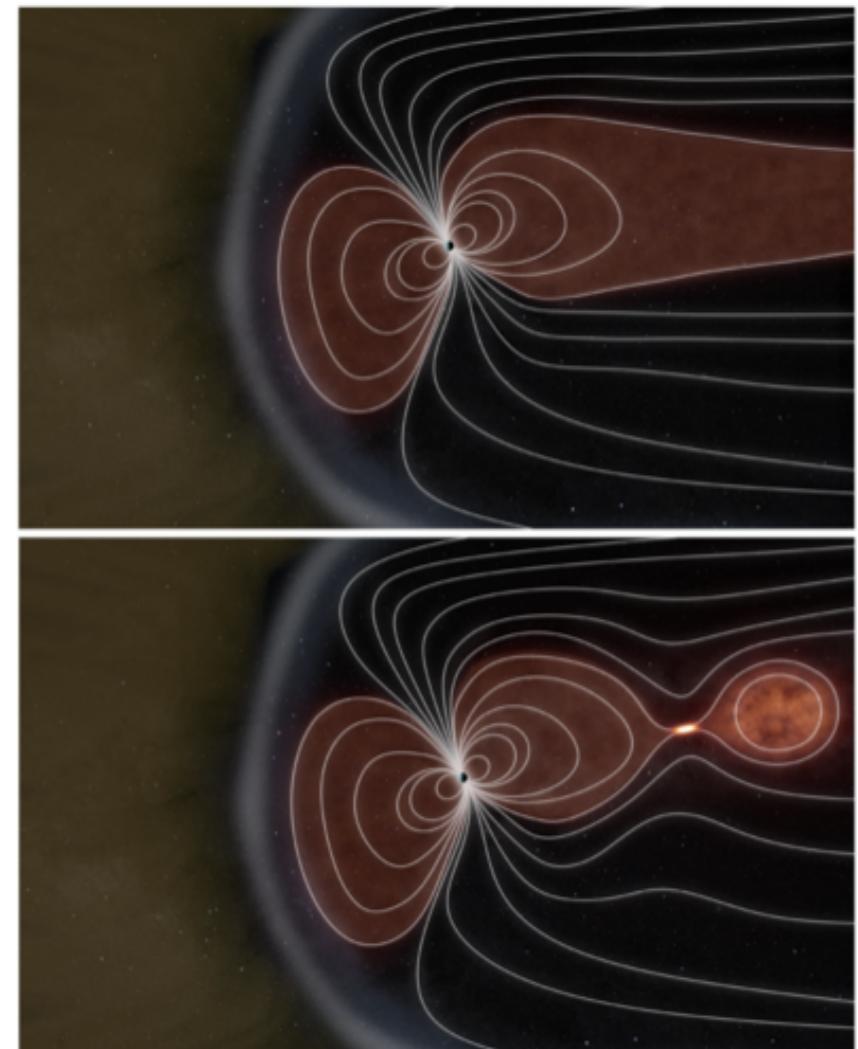
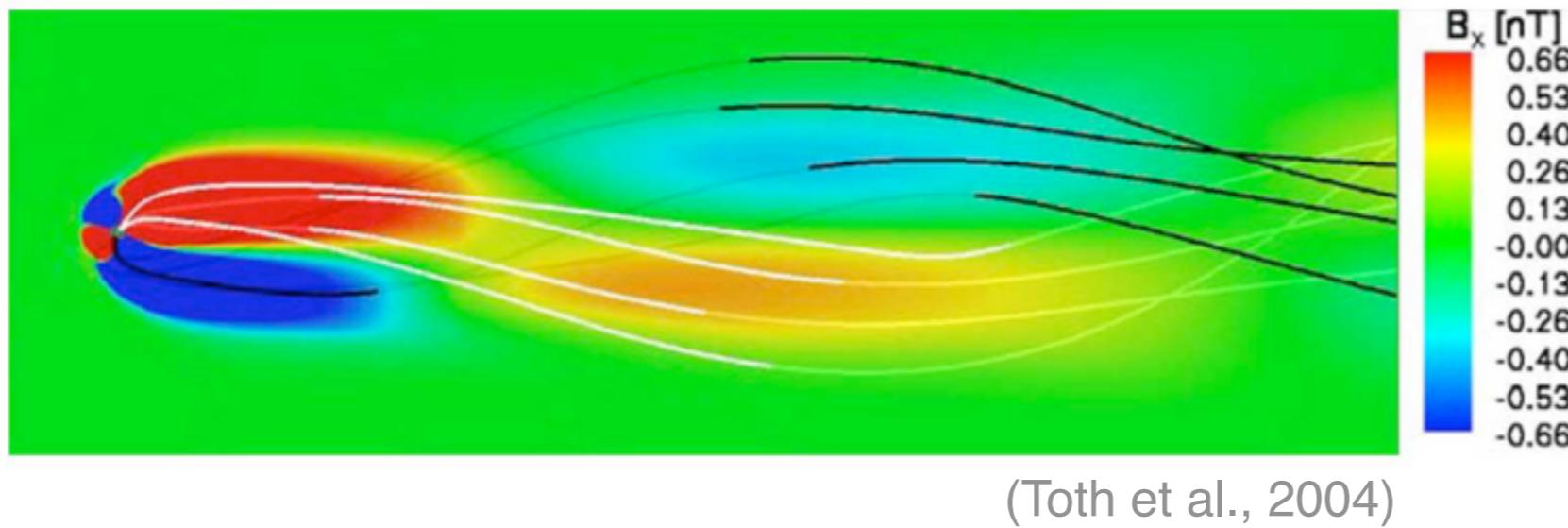
(Toth et al., 2004)

Aurorae at solstice :

- radiated power : $N = 3 \text{ GW} / S = 7 \text{ GW} \Rightarrow \text{input power} < 10^{11} \text{ W}$
- N / S aurora magnetically conjugate at $\sim 60\text{-}65^\circ$ latitude ($L = 5\text{-}10$) \Rightarrow AH5 model
- enhanced along the nightside direction ($\sim 180^\circ$ long.) \Rightarrow Earth-like solar wind convection

II- Ultraviolet aurorae Voyager 2 flyby : 1986

Uranus



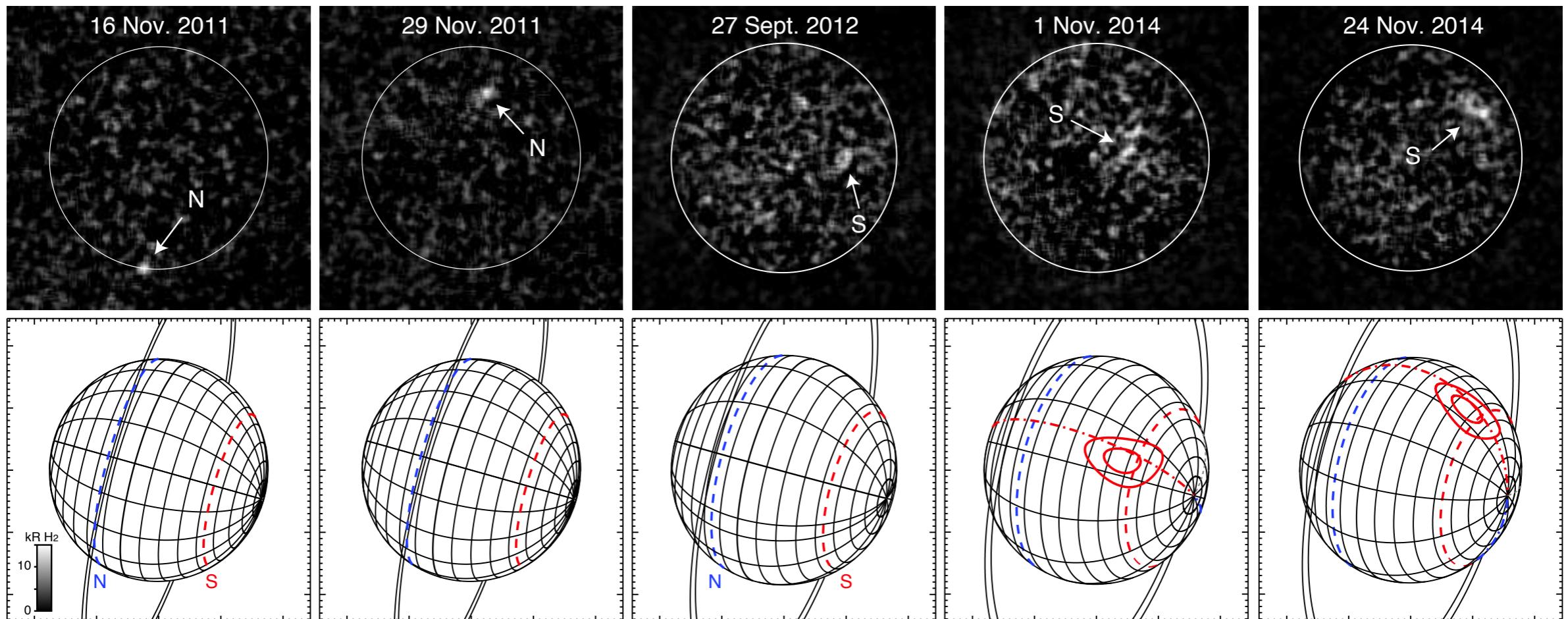
Aurorae at solstice :

- radiated power : $N = 3 \text{ GW} / S = 7 \text{ GW} \Rightarrow \text{input power} < 10^{11} \text{ W}$
- N / S aurora magnetically conjugate at $\sim 60\text{-}65^\circ$ latitude ($L = 5\text{-}10$) \Rightarrow AH5 model
- enhanced along the nightside direction ($\sim 180^\circ$ long.) \Rightarrow Earth-like solar wind convection
- substorm-like activity inferred from in situ tail measurements (Mauk et al., 1987, Cheng et al., 1987, Richardson et al., 1988, Dibraccio et al., 2019)

II- Ultraviolet aurorae

HST : 2011-2014

Uranus



(Lamy et al, 2012, 2017, Barthélémy et al., 2014)

Aurorae near equinox :

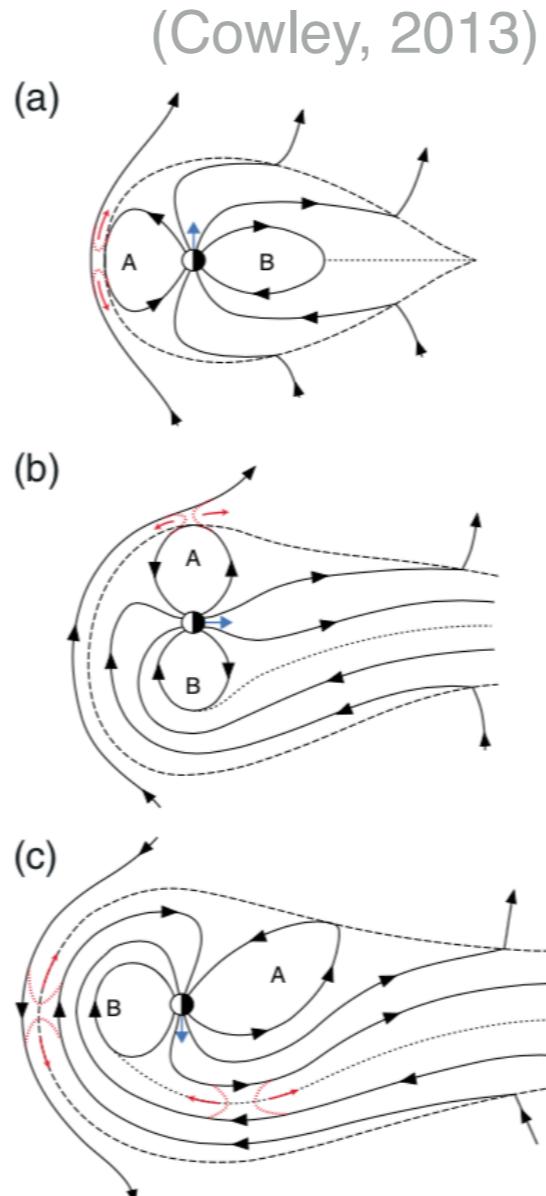
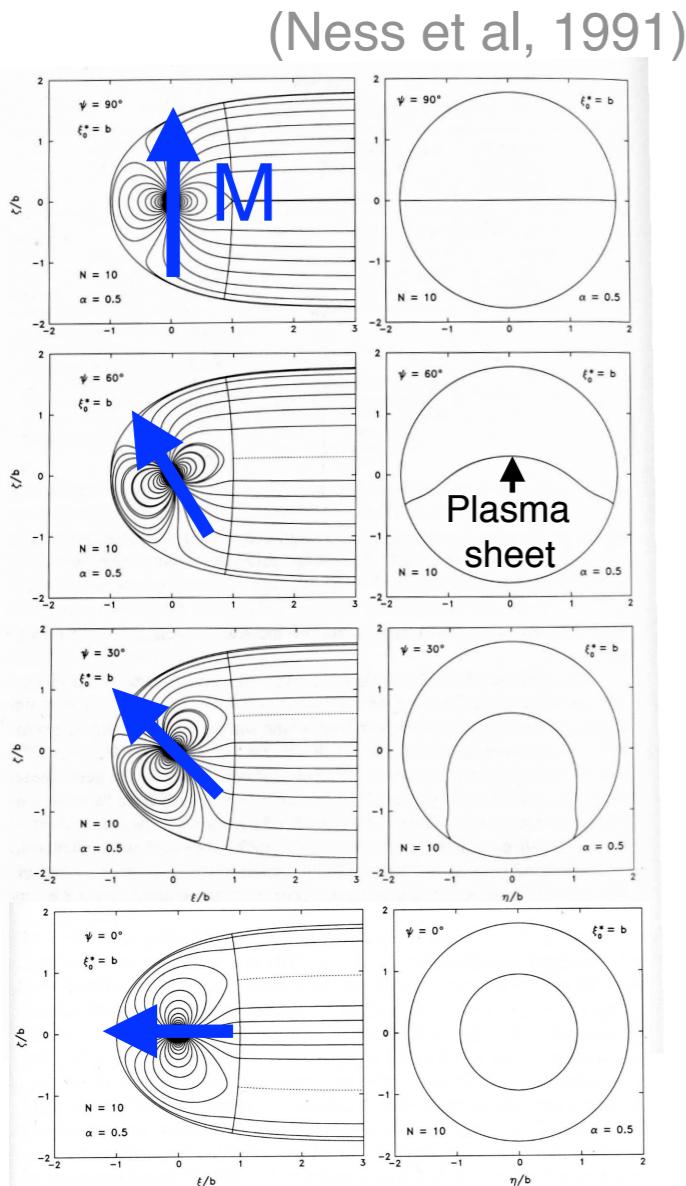
- Faint (few GW) UV aurorae observed with HST during active solar wind conditions
- Dayside, short-lived (few min), N/S spots => **≠ Voyager 2 picture**
- **rotationally phased !** => active rotating region
=> polar cusp aurora

II- Ultraviolet aurorae

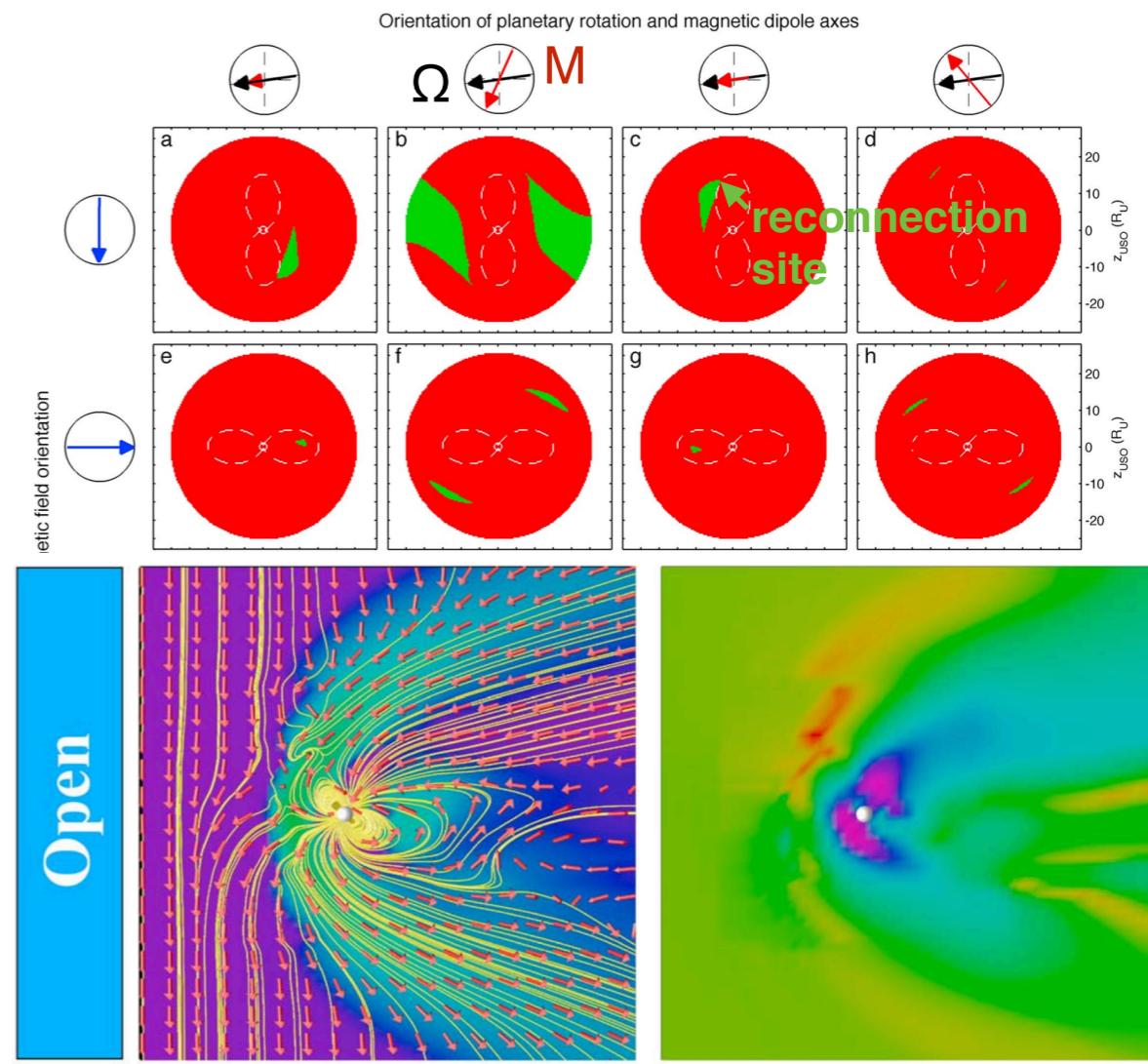
HST : 2011-2014

- See talks of A.
Masters and L. Griton

Uranus



(Masters, 2014, Cao et al., 2017)

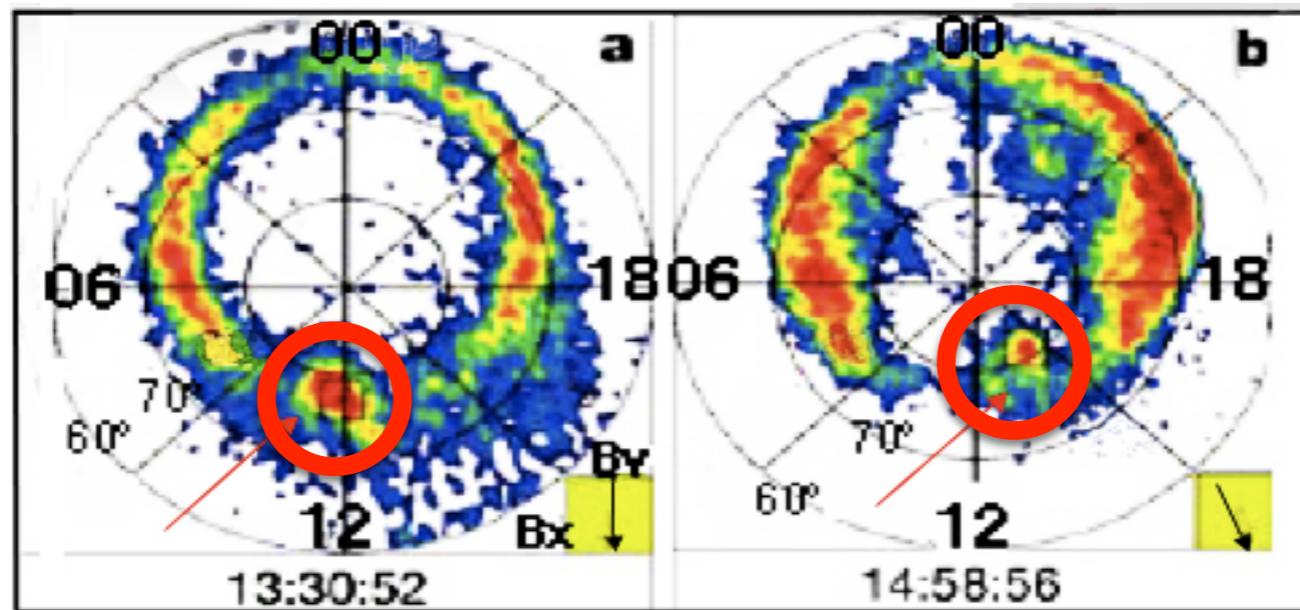


Near equinox : extreme SW/MS configurations succeed within each rotation

- short lifetime plasma sheet = no major auroral storm \neq E-S-J
- highly dynamical dayside magnetic reconnection

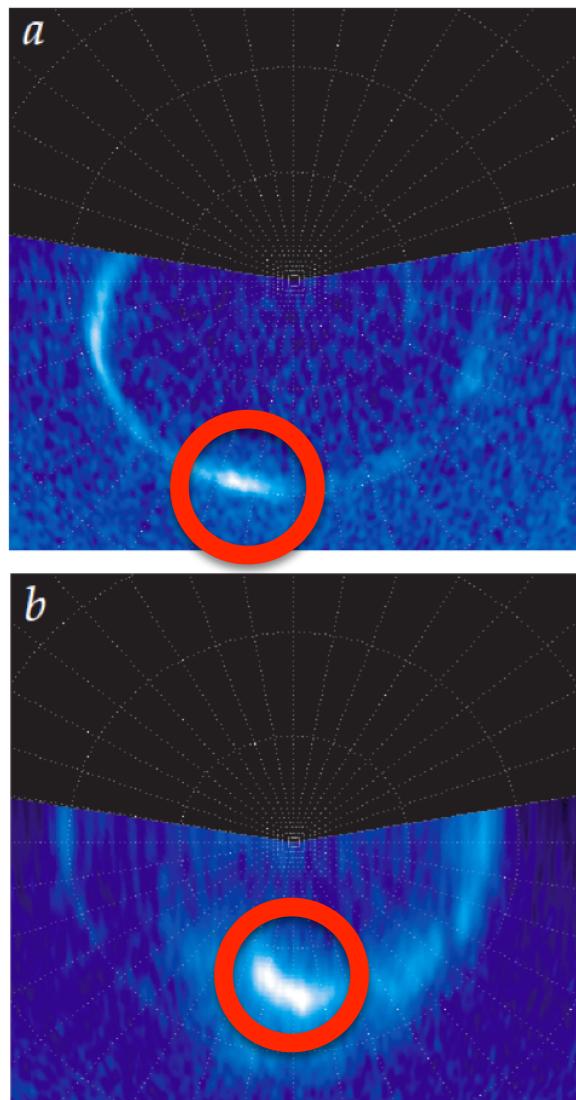
(Gérard et al, 2005,
Kinrade et al., 2017,
Lamy et al., 2018)

Earth

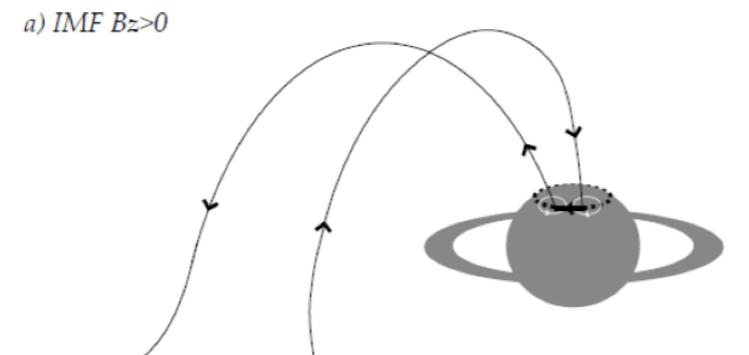


(Sandholt et al., 1994,
Fuselier et al, 2007,
Trattner et al., 2008,
Mende et al., 2016,
Reidy et al., 2017)

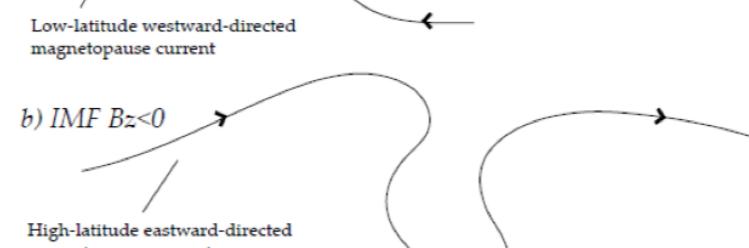
Saturn



Subsolar reconnection

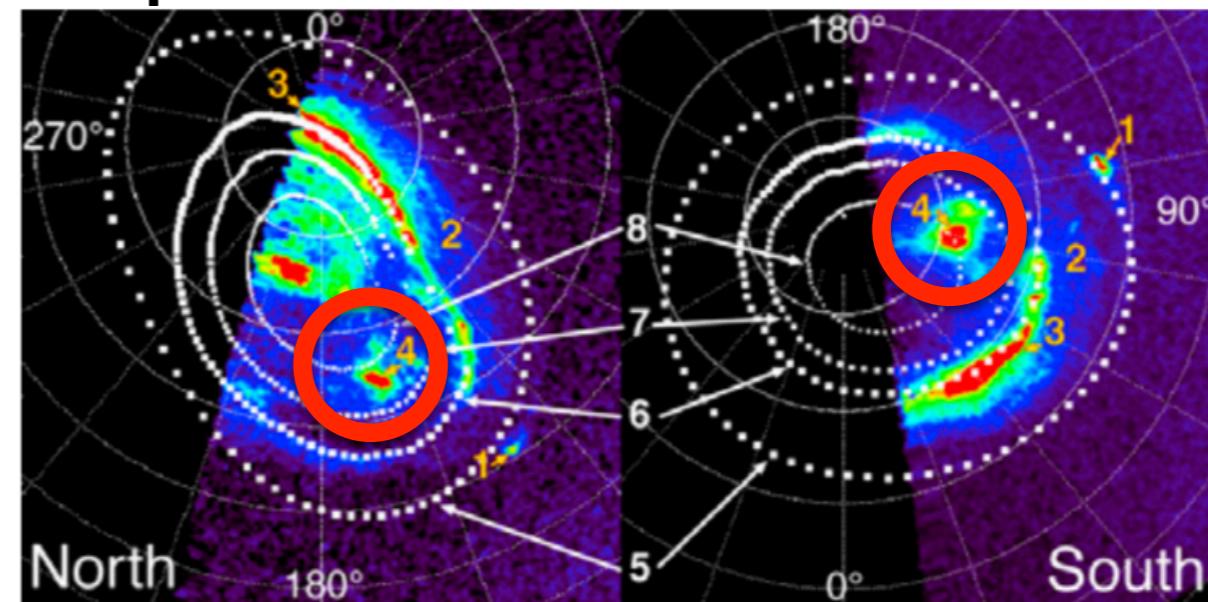


a) IMF $B_z > 0$



High latitude reconnection

Jupiter



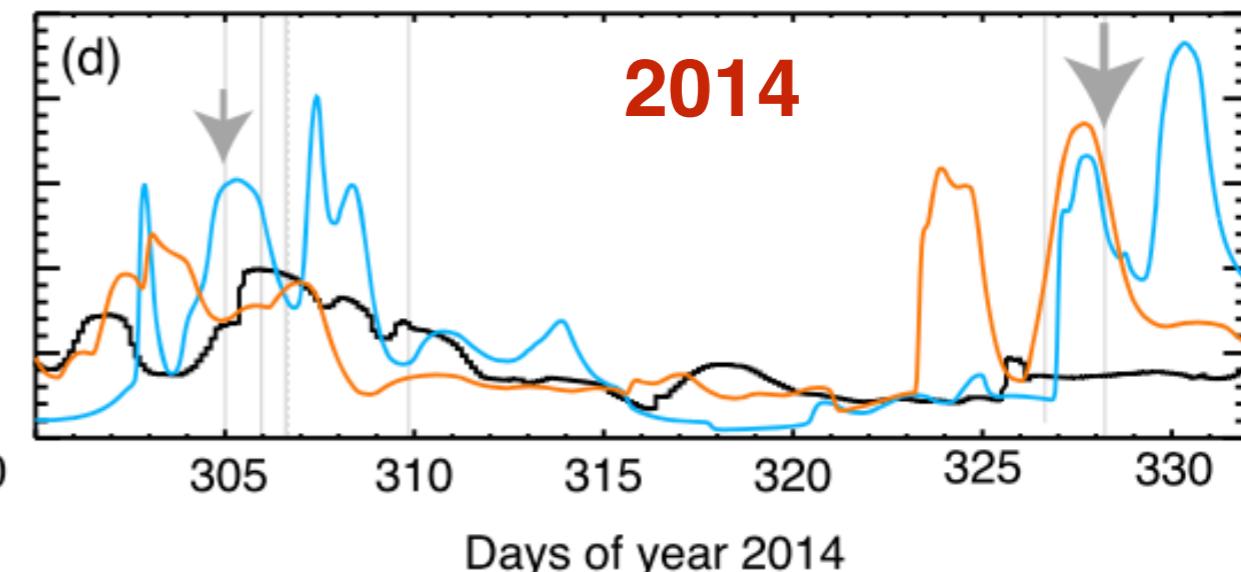
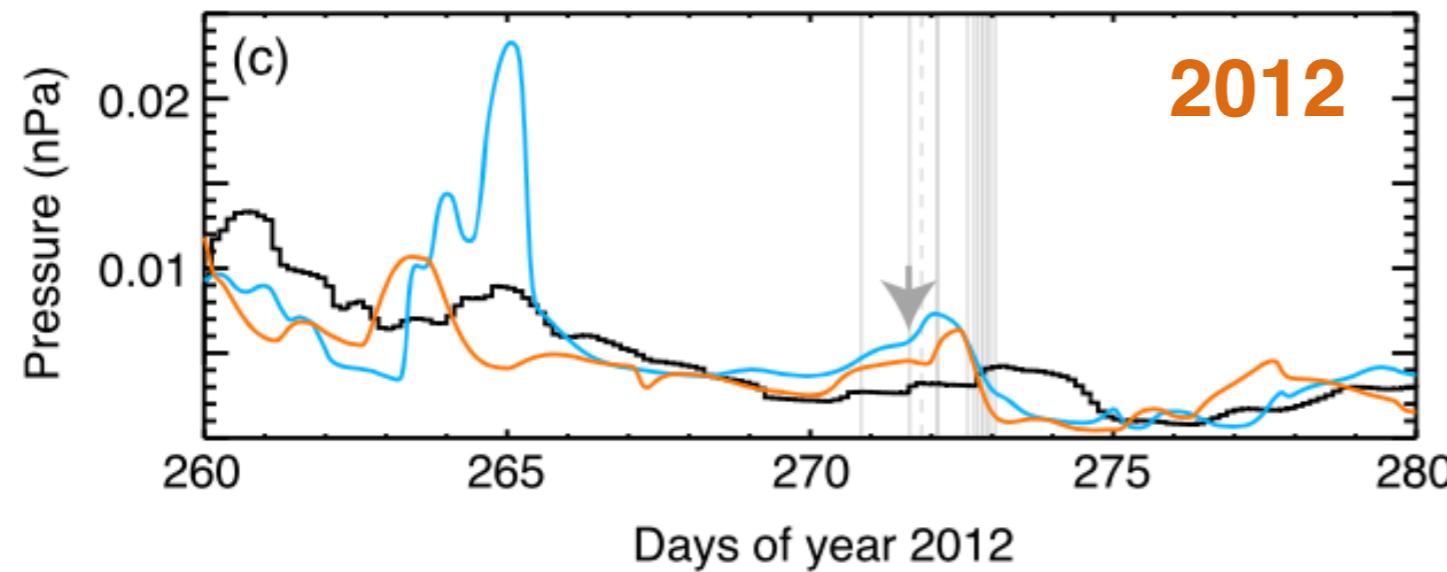
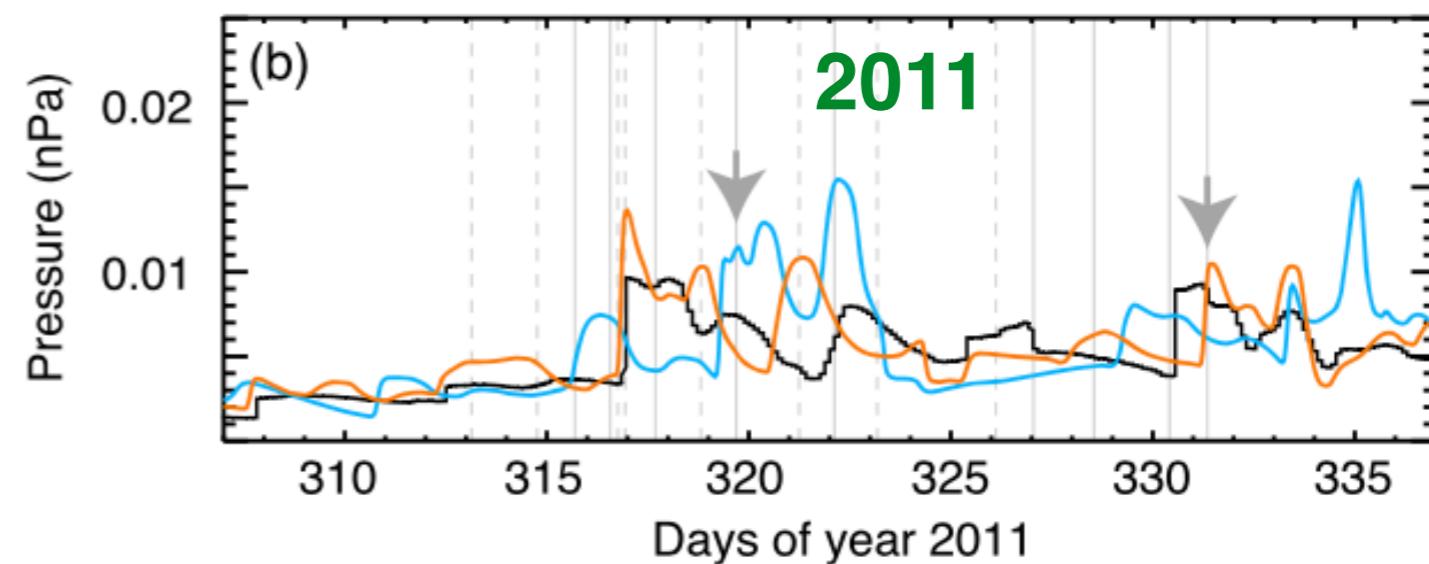
(Pallier et al., 2001, Pallier & Prangé
2004, Waite et al., 2001)

II- Ultraviolet aurorae

HST : 2011-2014

Uranus

Solar wind role ?

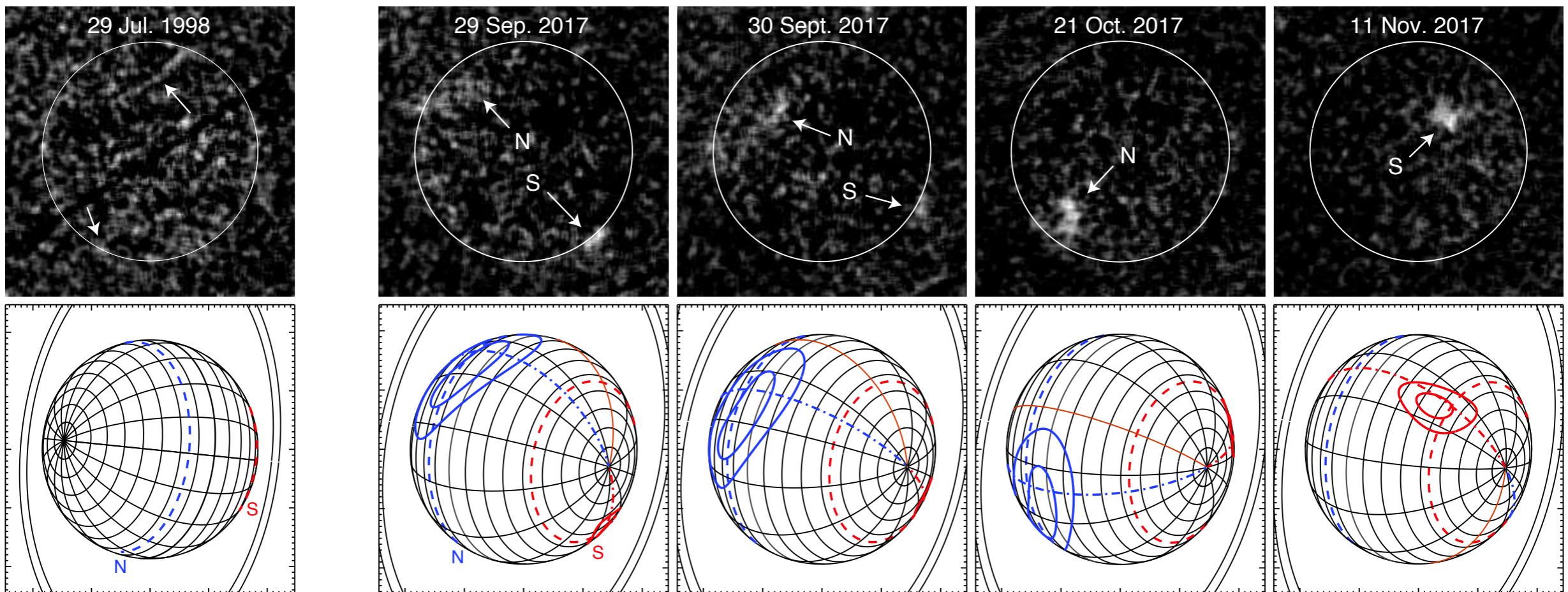


Aurorae near equinox :

- brightest events occur closer to SW shocks => prominent role of solar wind
- => compression-induced cusp aurora

II- Ultraviolet aurorae HST : 1998 and 2017

Uranus



(Lamy et al, 2012, in prep.)

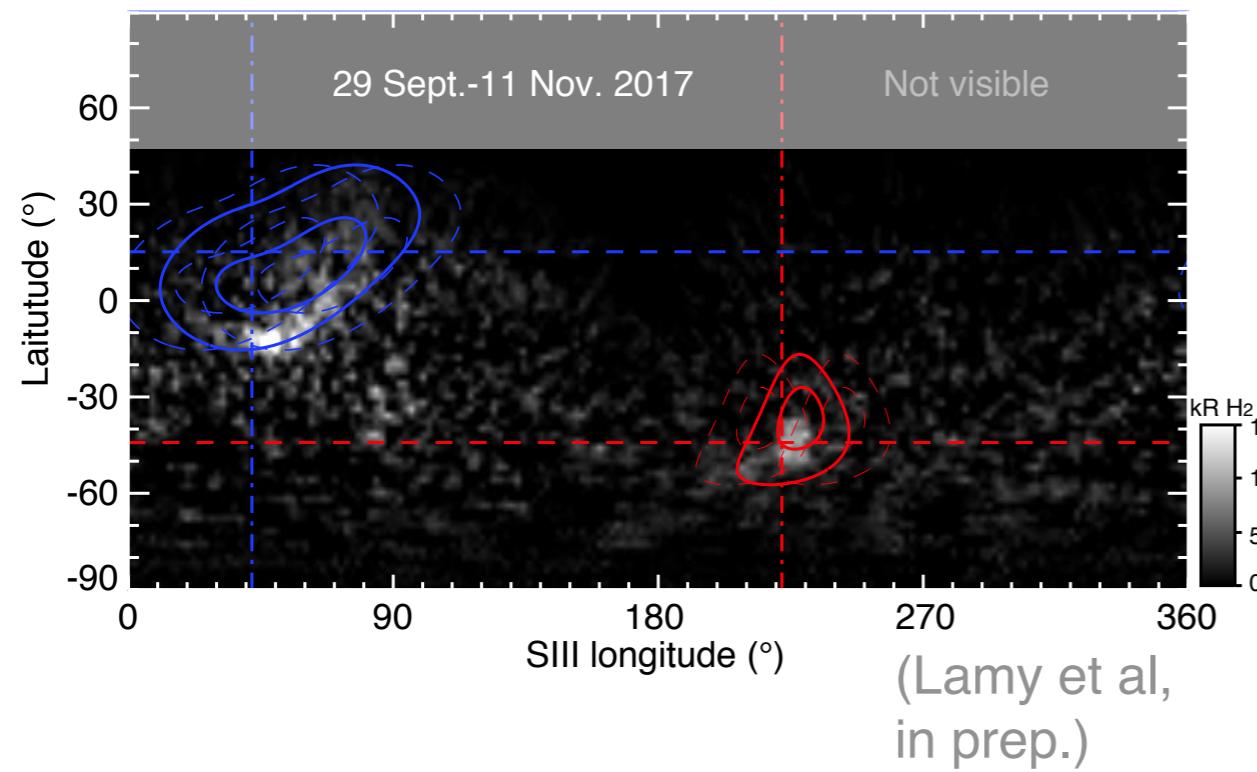
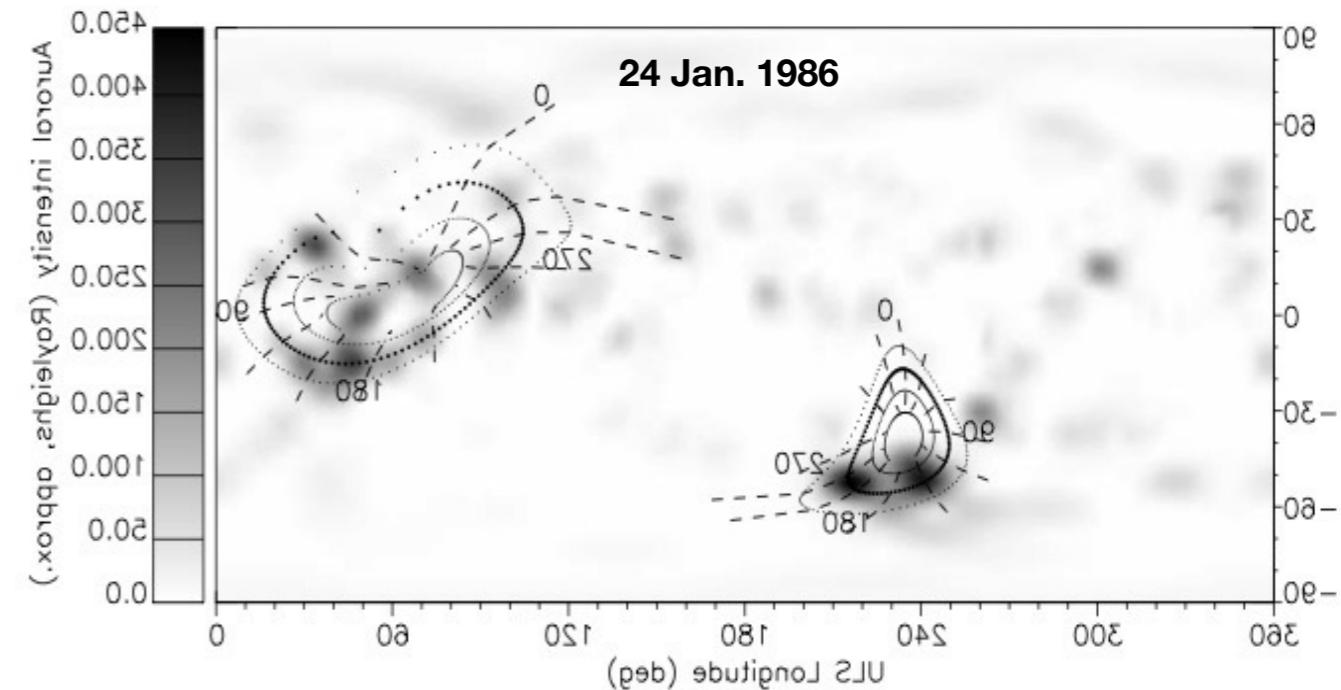
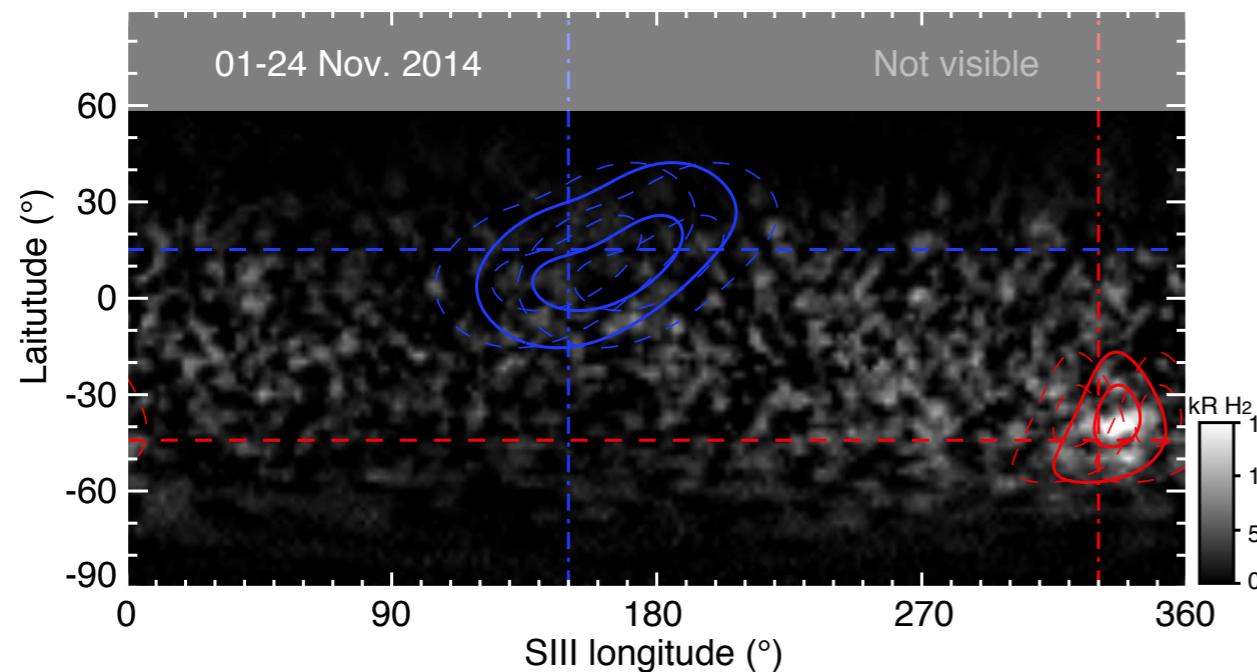
Aurorae between solstice and equinox :

- 1998 : quiet SW, faint rings of emission => **Unknown driver**
- 2017 : active SW, dayside extended regions => **Prominent dayside reconnection ?**

II- Ultraviolet aurorae

HST : 2014 and 2017

Uranus : constraints on *rotation period and SIII longitude system ?*

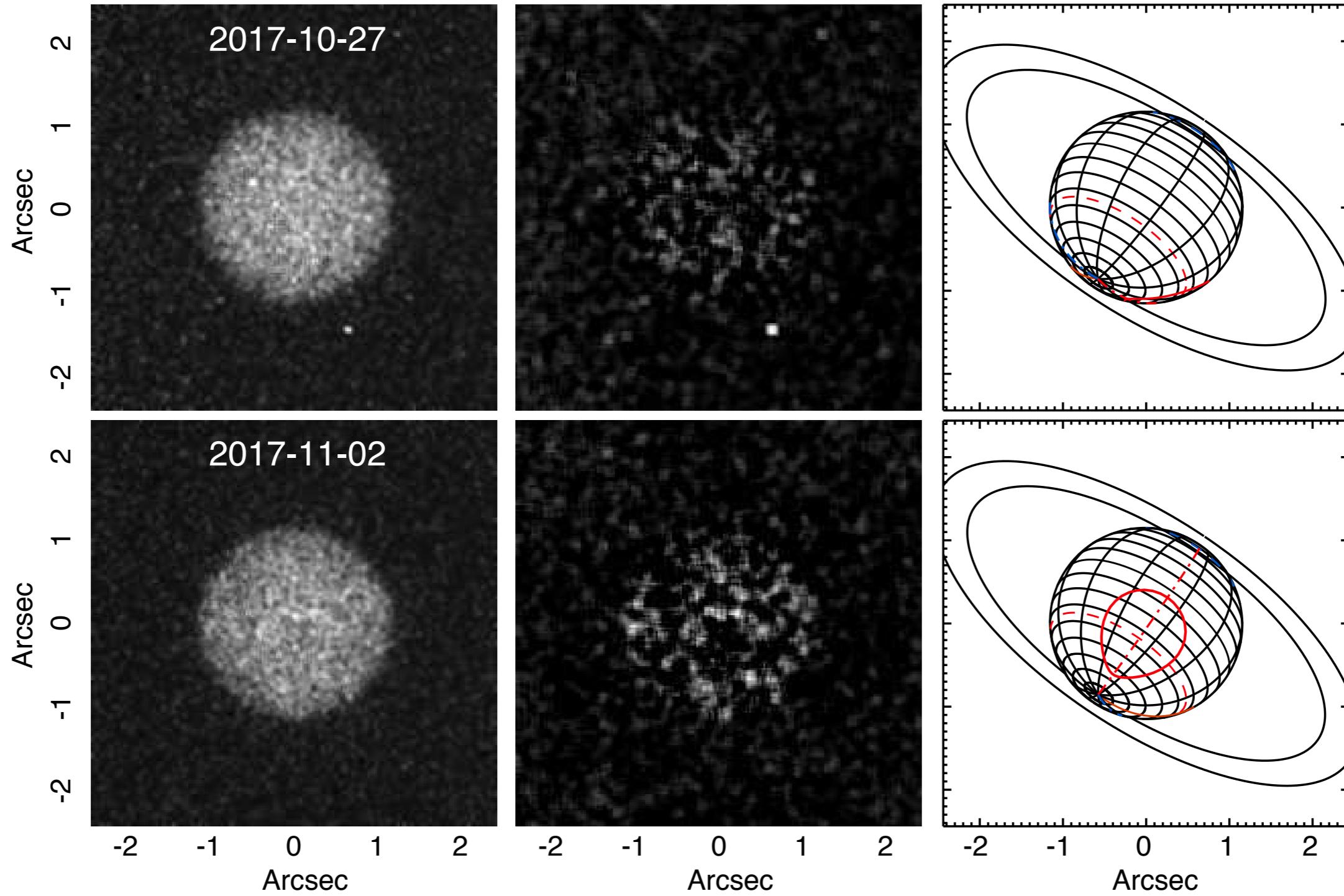


- HST data of 2014 and 2017 fitted by model ovals = new longitude references => only valid for ± 6 months
- 2017 dataset => $P_U = 17.247 \pm 0.020\text{h}$
- Next step : update the rotation period and SIII system => **crucial for the design of any future Uranus mission**

II- Ultraviolet aurorae

HST : 2017

Neptune



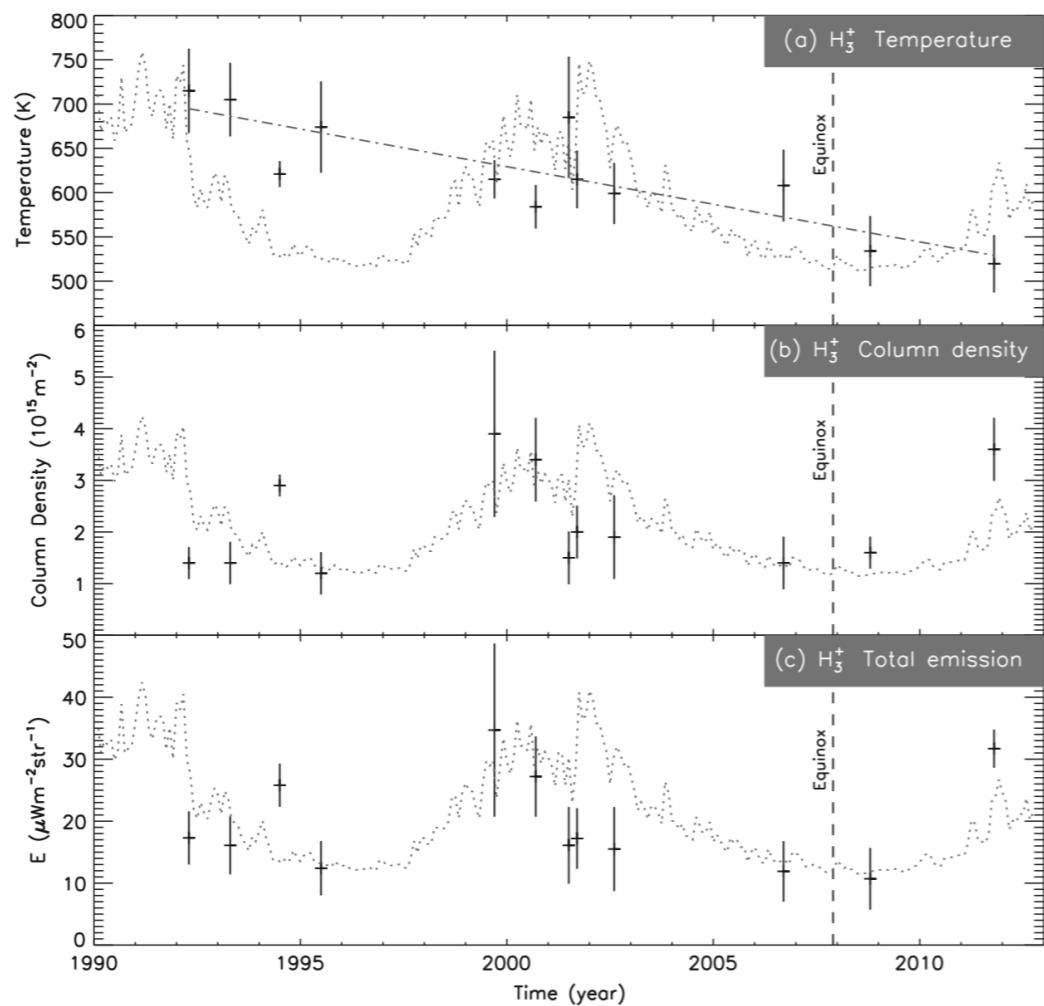
- Search for UV H_2 aurorae => ?

III- Search for NIR/X-ray auroral signatures

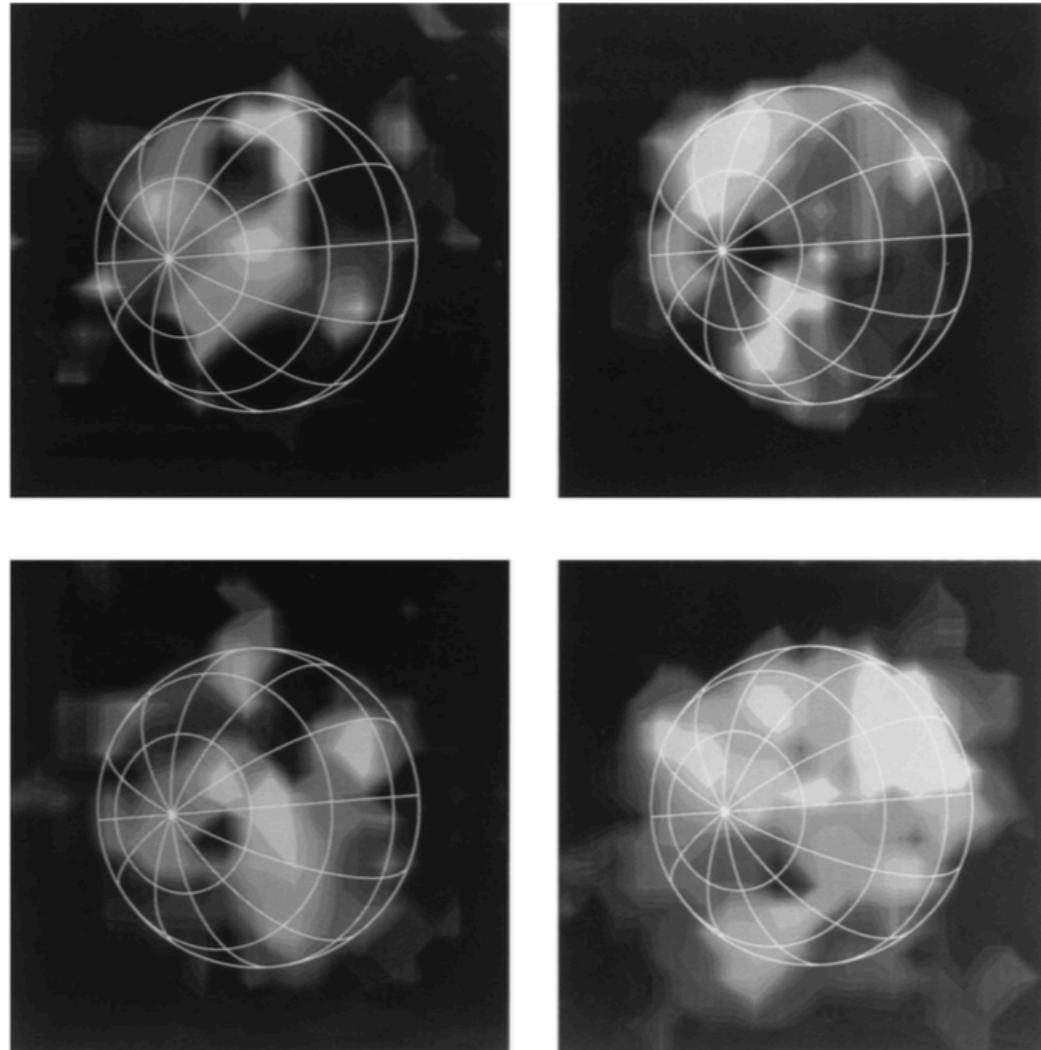
Ground-based telescopes/NIR : >1992

Uranus

(Trafton et al., 1993,
Melin et al., 2011, 2013, 2019)



(Lam et al., 1997)



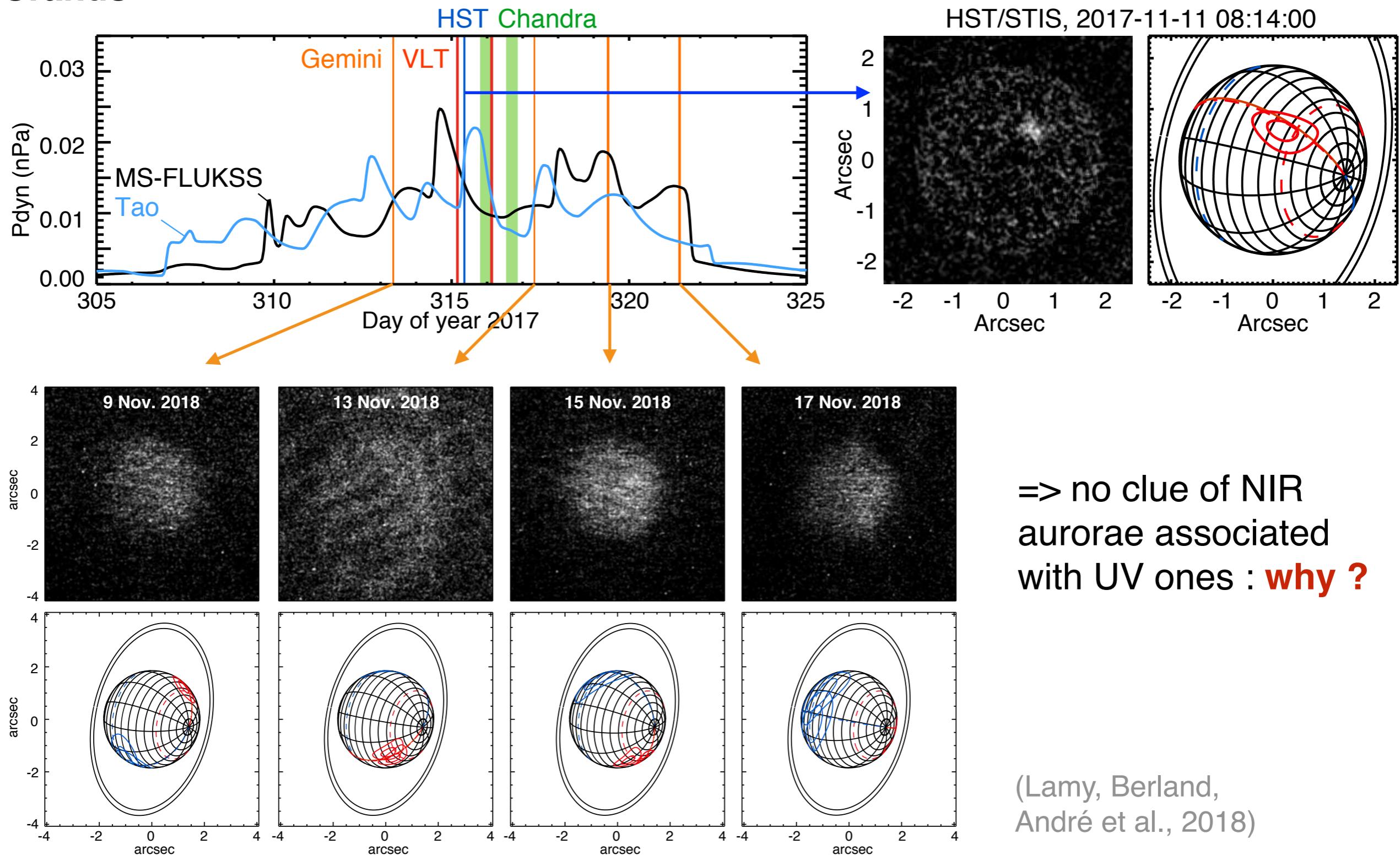
Review talk
of H. Melin

- permanent, inhomogeneous, H_3^+ emission from the whole disc (not seen at Neptune !)
- temporal/spatial variations tentatively attributed to auroral precipitations

III- Search for NIR/X-ray auroral signatures

Ground-based telescopes/NIR : 2017

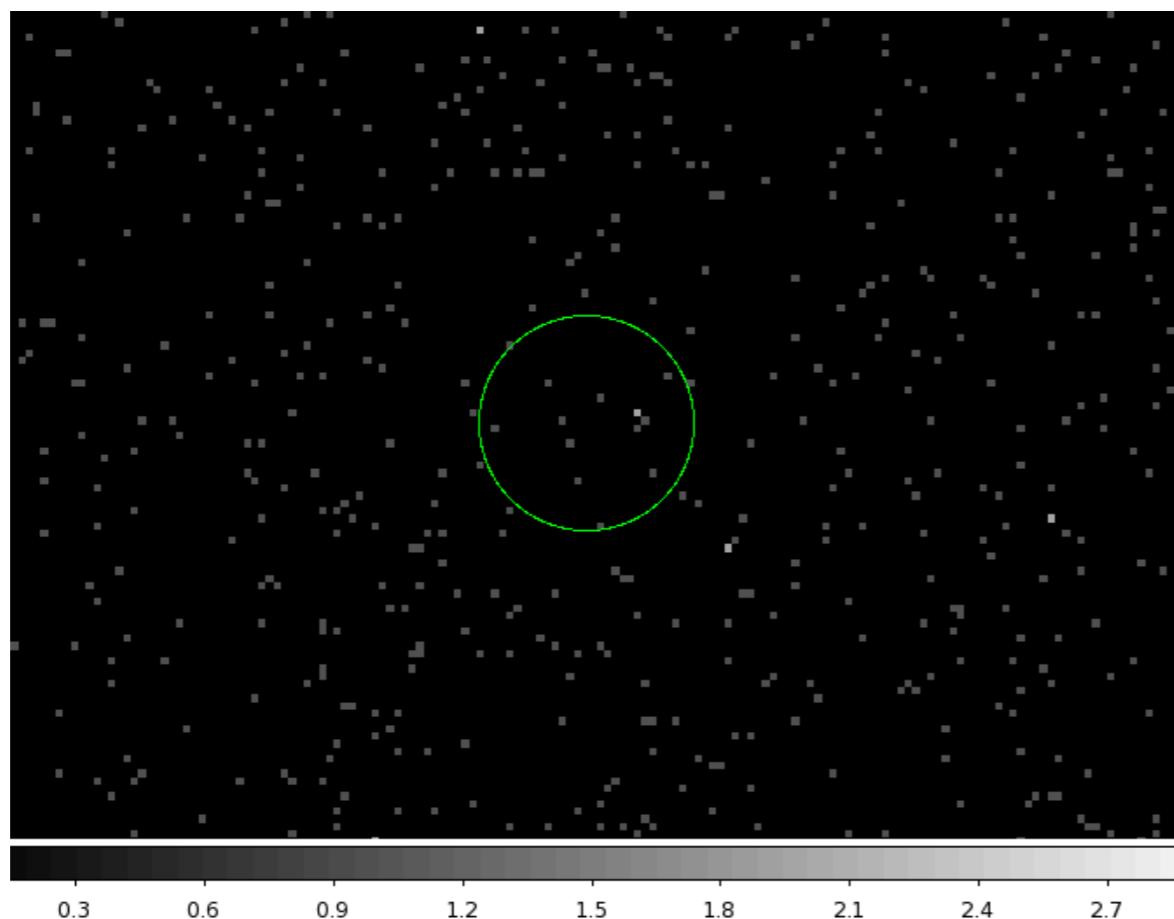
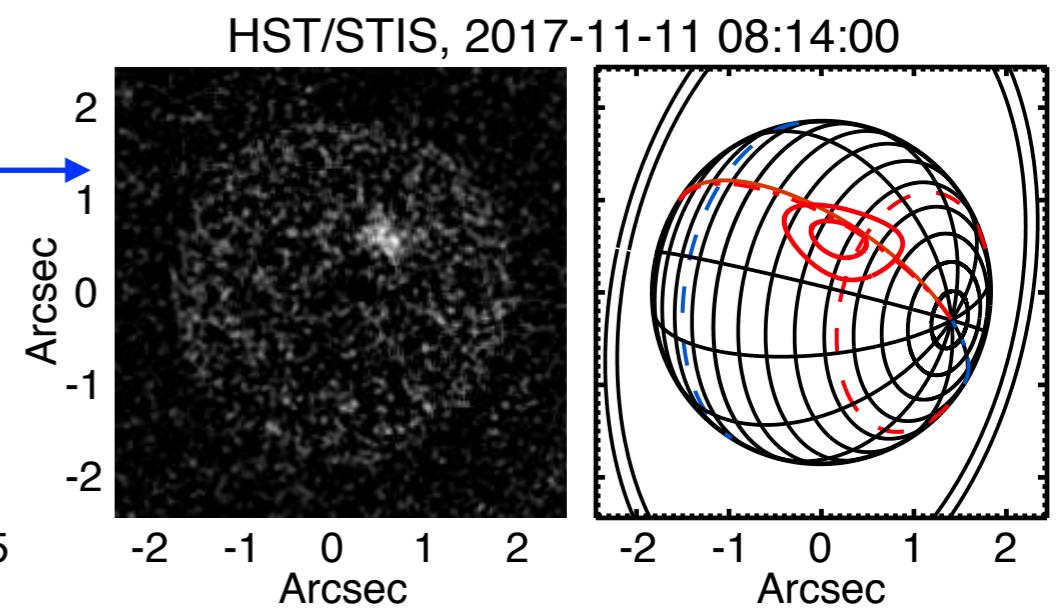
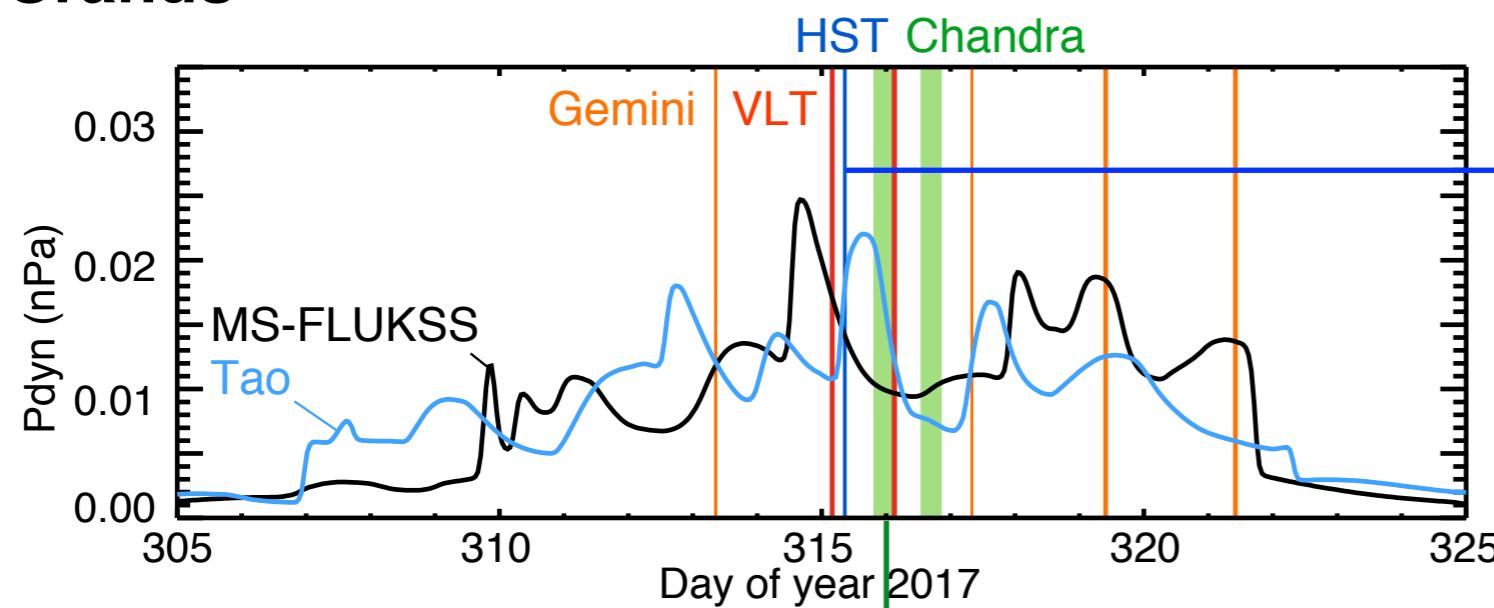
Uranus



III- Search for NIR/X-ray auroral signatures

Chandra/X-ray : 2017

Uranus



=> no detectable X-ray neither

Credits : W. Dunn

Future exploration

- Uranus/Neptune auroral emissions : **rich proxy** of ice giant magnetospheres
=> essential goal for any future exploration probe with adequate payload

- (i) U/N are ‘twin’ radiosources **unique in the solar system, mostly ununderstood**
=> implications for the ongoing radio search for exoplanets

See contributions of Andrews et al., Sulaiman et al.,
Morooka et al., Lamy et al.

- (ii) UV aurorae do not compare at all, while those of Uranus reveal **complex magnetospheric processes** evolving with the planetary revolution around the Sun

See the contribution of Greathouse et al.

- (ii) NIR/X-ray aurorae still to be detected

See the contributions of Melin et al., Moore et al., Dunn et al.



7 years ago ...
on the other side of the « channel »

