Radio Wave Emission from the Outer Planets

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All started in 1955 … → decameter emission → cyclotron emission

→ ∃ B Jupiter, |B|~10 G

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OBSERVATIONS OF A VARIABLE RADIO SOURCE ASSOCIATED WITH THE PLANET JUPITER

By B. F. BURKE AND K. L. FRANKLIN

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(Received April 15, 1955)

ABSTRACT

A source of variable 22.2-Mc/sec radiation has been detected with the large "Mills Cross" antenna of the Carnegie Institution of Washington. The source is present on nine records out of a possible 31 obtained during the first quarter of 1955. The appearance of the records of this source resembles that of terrestrial interference, but it lasts no longer than the time necessary for a celestial object to pass through the antenna pattern. The derived position in the sky corresponds to the position of Jupiter and exhibits the geocentric motion of Jupiter. There is no evident correlation between the times of appearance of this phenomenon and the rotational period of the planet Jupiter, or with the occurrence of solar activity. There is evidence that most of the radio energy is concentrated at frequencies lower than 38 Mc/sec.

[Burke and Franklin, 1955]

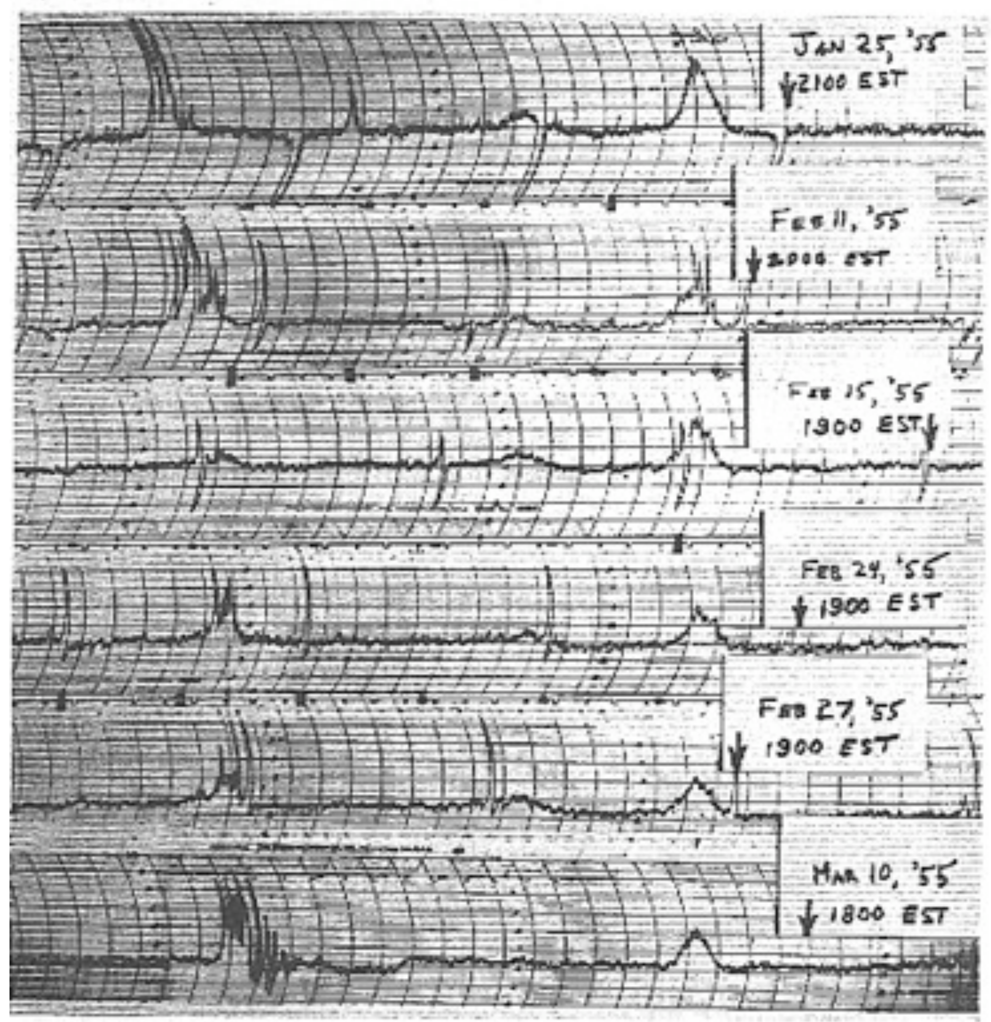


FIG. 2—Phase-switching records showing the appearance of the variable source

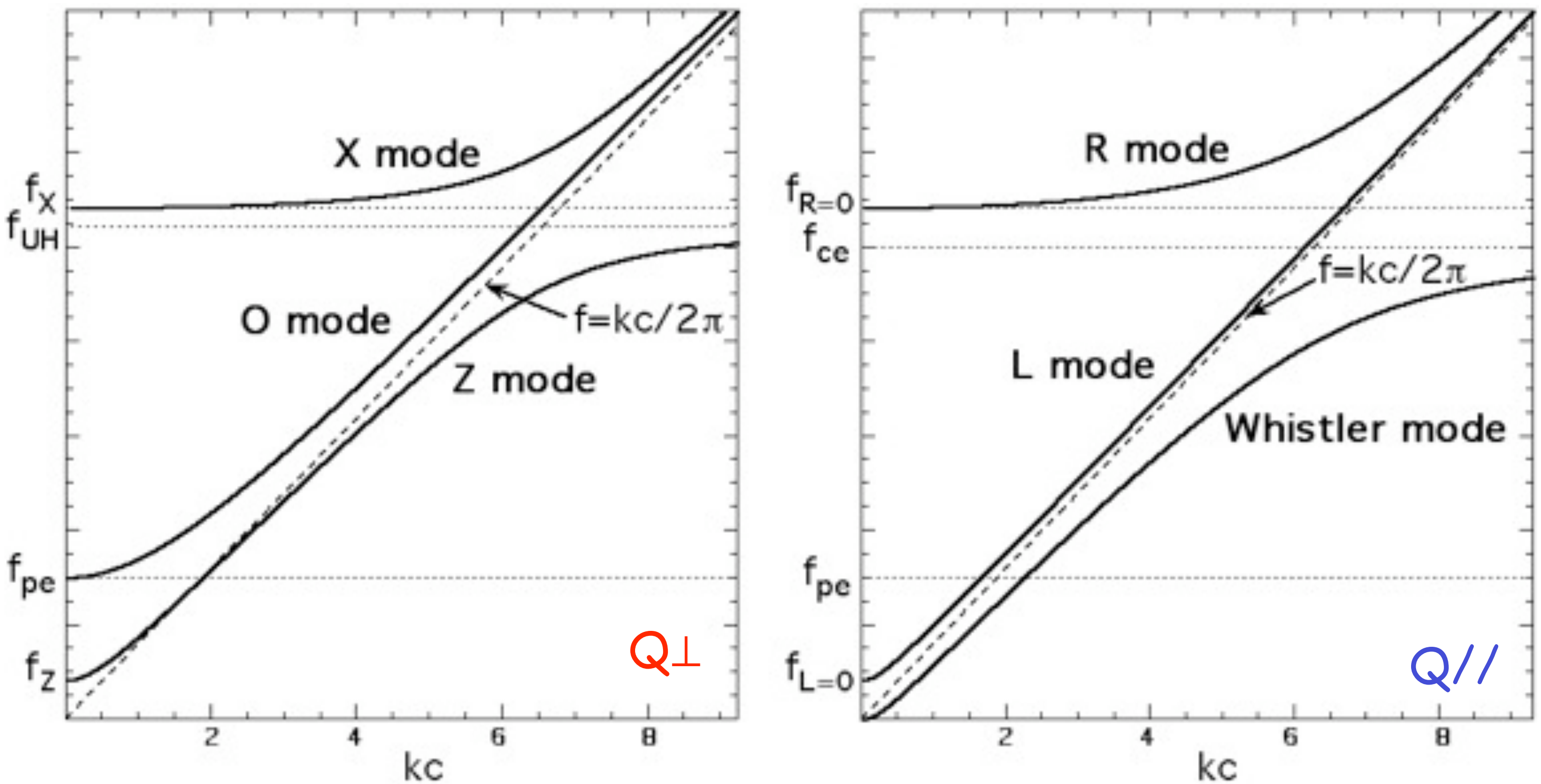
Voyager, Ulysses, Galileo, Ground-Based observations ...

→ all magnetized planets (including all outer planets) produce intense nonthermal radio emissions

→ potentially interesting remote sensing tool of magnetospheric plasma(s)

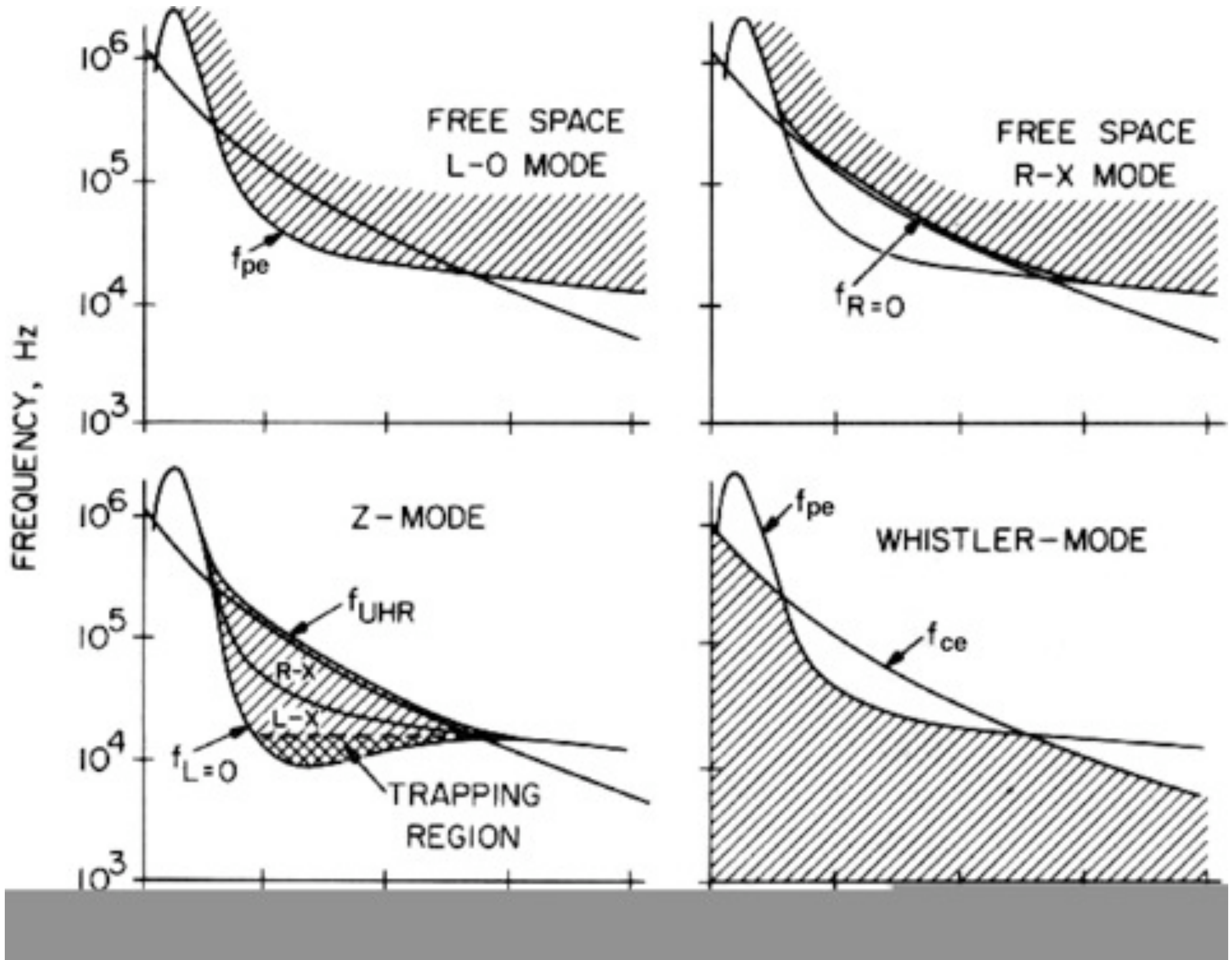
→ we can "see" magnetospheres directly, but do we understand what we see ?

"Radio" emissions = e.m. free-space modes O & X (or R & L)
polarized circularly near their cutoff



Dispersion of e.m. electronic modes in a magnetized cold plasma with f_{pe}/f_{ce}=0.3

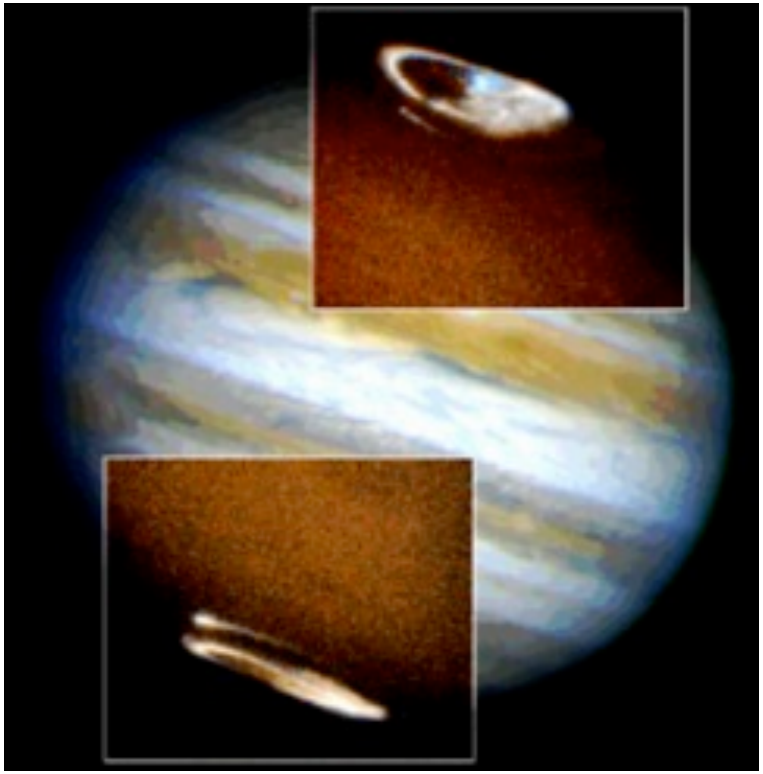
O & X modes can propagating to 'infinity'



[Gurnett et al., 1983]

Typical profiles of characteristic frequencies in a planetary magnetosphere

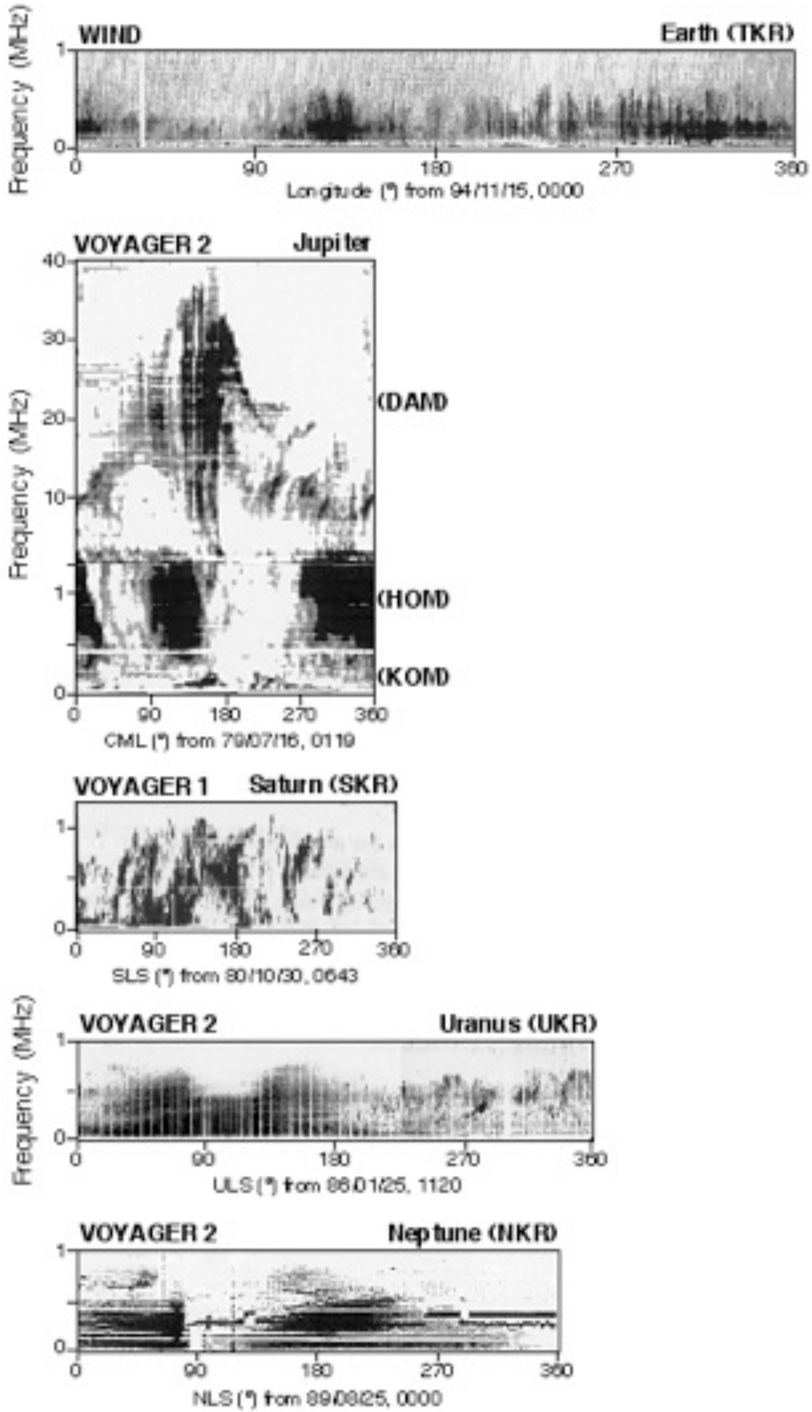
λ/D generally ~ 1 or > 1 → no angular resolution



UV eyes

Radio eyes (optimistic)

→ dynamic spectra !



Radiotelescopes and Spacecraft having made observations of Outer Planets Radio Emissions

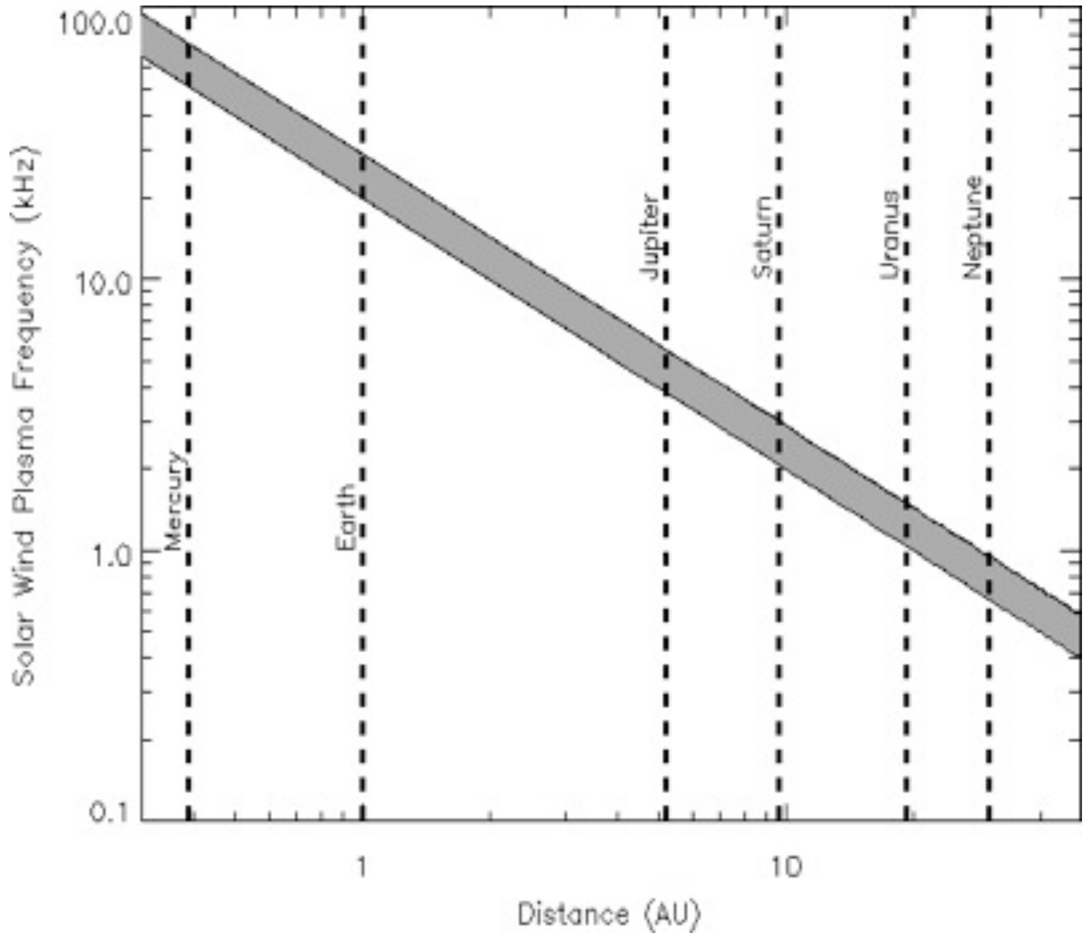
Radiotelescope or Spacecraft	Planet	Measurement Capabilities
Ground-based radiotelescopes ($\geq$ 1955) (Boulder, Nançay, Florida, Kharkov...)	J	I, Q, U, V
RAE (Radio Astronomy Explorers) 1–2	E J	I, 2D-DF
Geos 1–2, Hawkeye, Imp 6–8, ISEE 1–2 ISIS 1–2, Viking, AMPTE	E	I, 1D-DF
DE (Dynamic Explorer) A	E	I, V, 1D-DF
ISEE 3	E	I, Q, U, V, 2D-DF
Voyager 1–2	E J S U N	I, V
Ulysses	J (S)	I, Q, U, V, 2D-DF
Wind (Polar, Geotail)	E J (S)	I, Q, U, V, 2D-DF
Galileo	(V) E J	I

polarisation

direction-finding (spinning s/c)

Propagation is permitted only for $f \geq f_{pe}/\cos\theta$

- Earth's ionosphere → reflection below $f_{pe\text{-}max}$~10 MHz
- SW → a few kHz for outer planets (~100 kHz for Mercury)



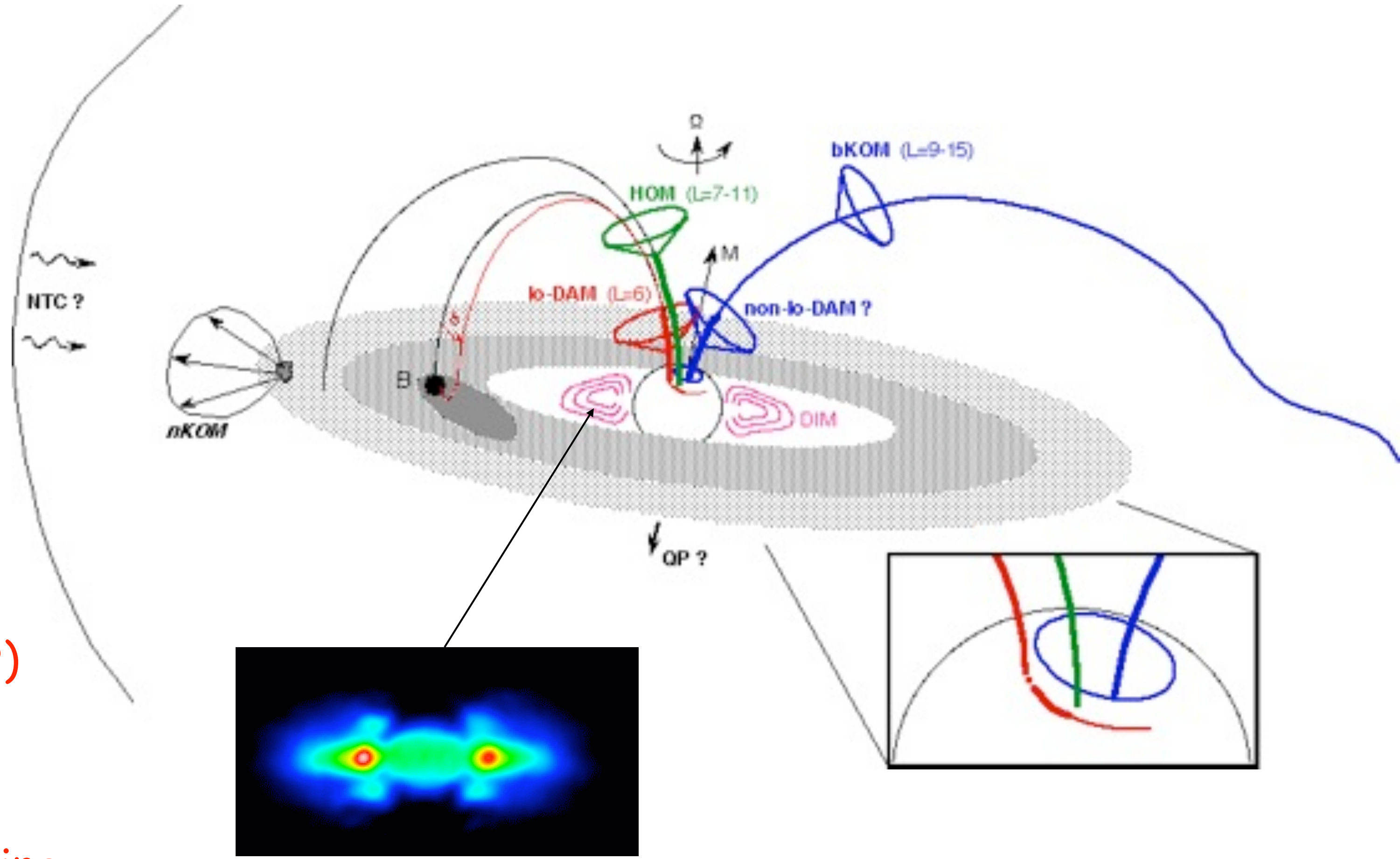
<u>NB</u>: in a metal, 1e-/(2Å)^3 → $N_e \sim 10^{29}$ m^{-3}→ $f_{pe} \sim 3\times10^{15}$ Hz, $\lambda \approx 100$ nm (UV)

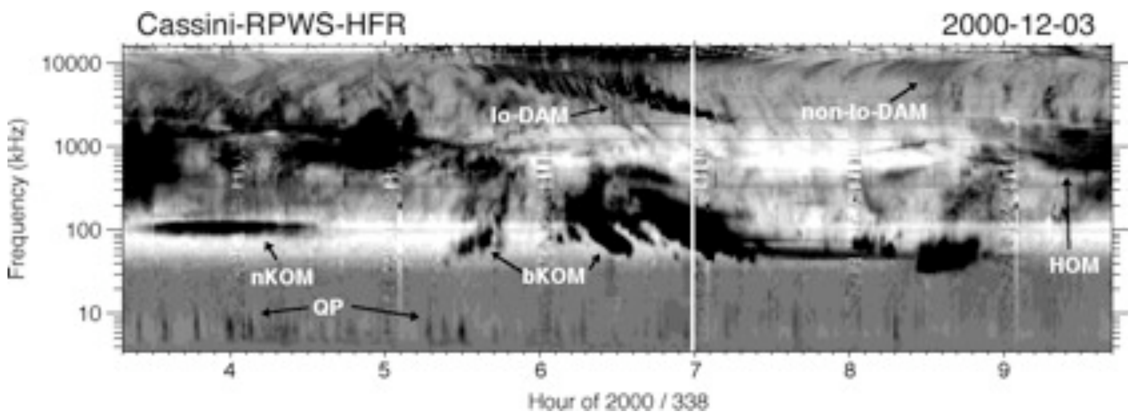
Many radiosources in the magnetospheres, depend on structure (B, $f_{pe} \ll f_{ce}$ regions)
& dynamics (regions of keV e- precipitations)

Radio component	**Planet**	**λ (m)**	**f (kHz)**	**Radiation process**
Auroral	E J S U N	10^1 - 10^3	10's kHz - 10's MHz	Cyclotron Maser (coherent)
Satellite induced	J (I,G,C?), S?	10^1 - 10^2	≥ MHz	Cyclotron Maser (")
LF e.m. (NTC…)	E J S U N	$\sim 10^4$	≤10's kHz	Mode conversion e.s.→ e.m.
Lightning	E (J) S U (N)	10^1 - 10^4	kHz - MHz	Antenna radiation (current discharge)
Radiation belts	J (E)	$\sim 10^{-1}$	GHz	Synchrotron (incoherent)
nKOM	J	$\sim 10^3$	~100 kHz	Instabilities $\sim f_{pe}$, f_{UH} ?

Jupiter

- Auroral-DAM
- HOM
- bKOM
- QP-bursts
- Io-DAM (+G,C?)
- NTC
- nKOM
- No radio lightning
- Synchrotron (DIM)





- Comparative overview (observations + theories)
    - Auroral Radio Emissions
    - LF electromagnetic emissions
    - Lightning
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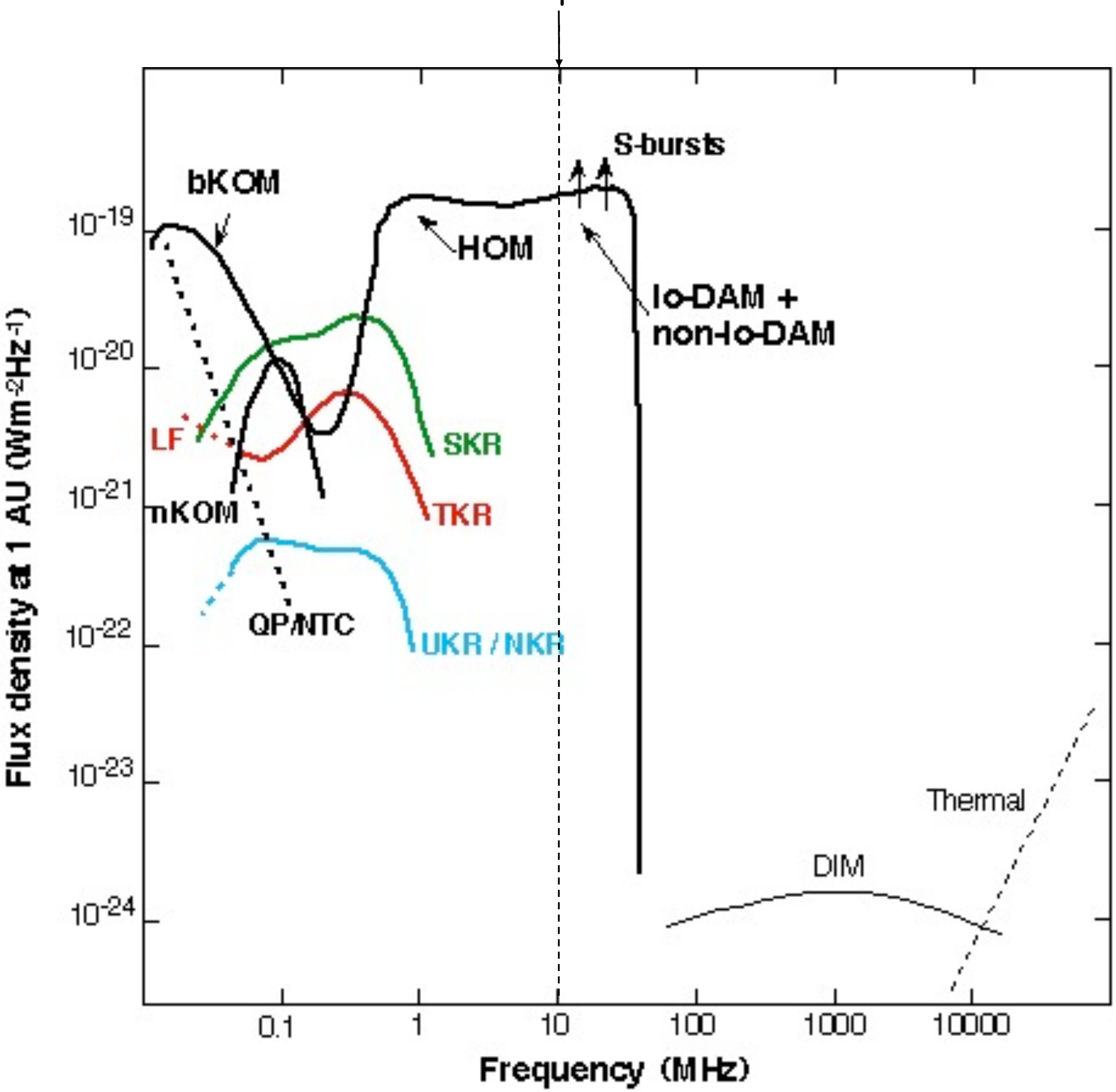
General properties of Auroral Radio Emissions :

- very intense

Earth's ionospheric cutoff



[Zarka, 2000]

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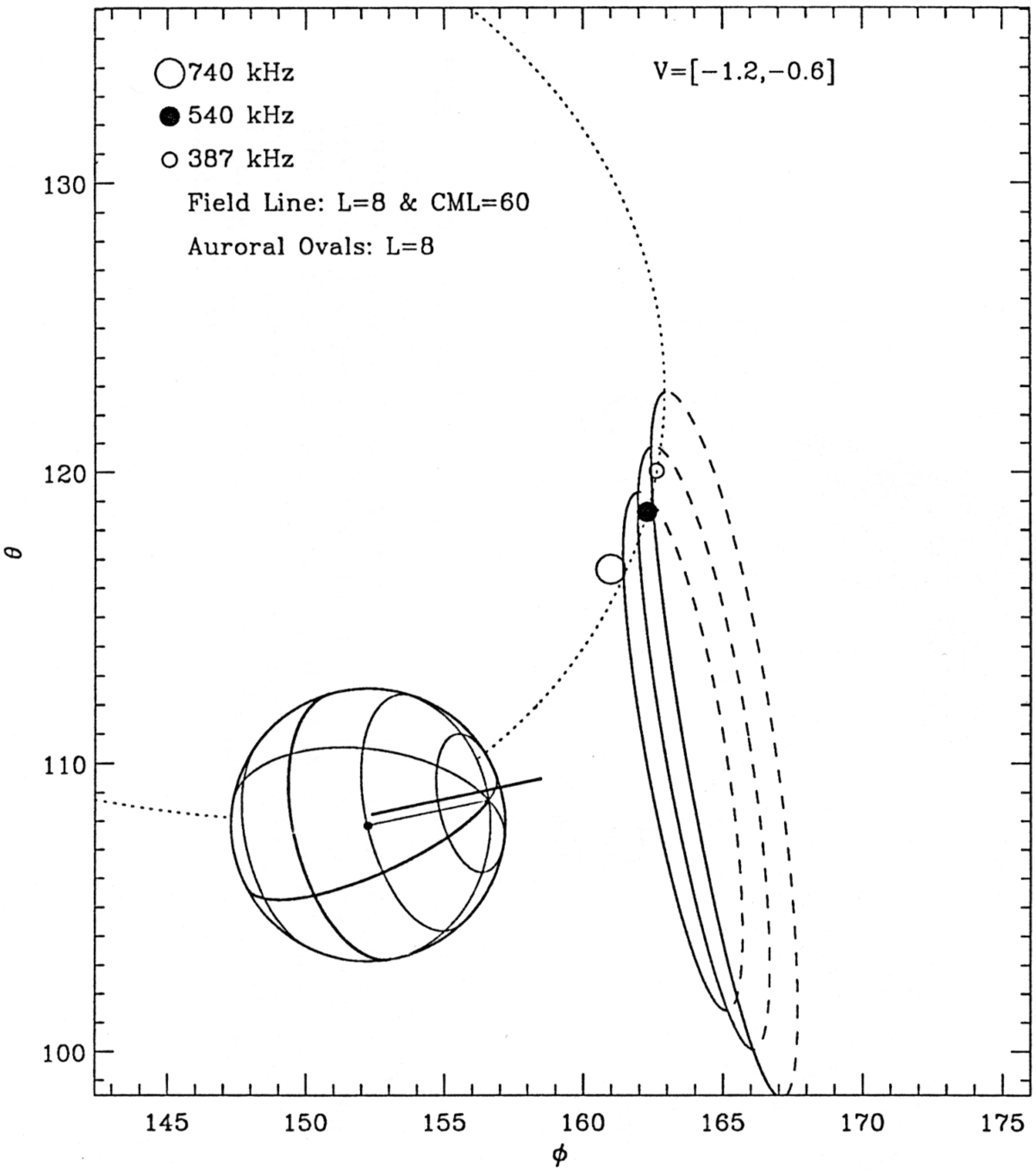

[Ladreiter et al., 1994]

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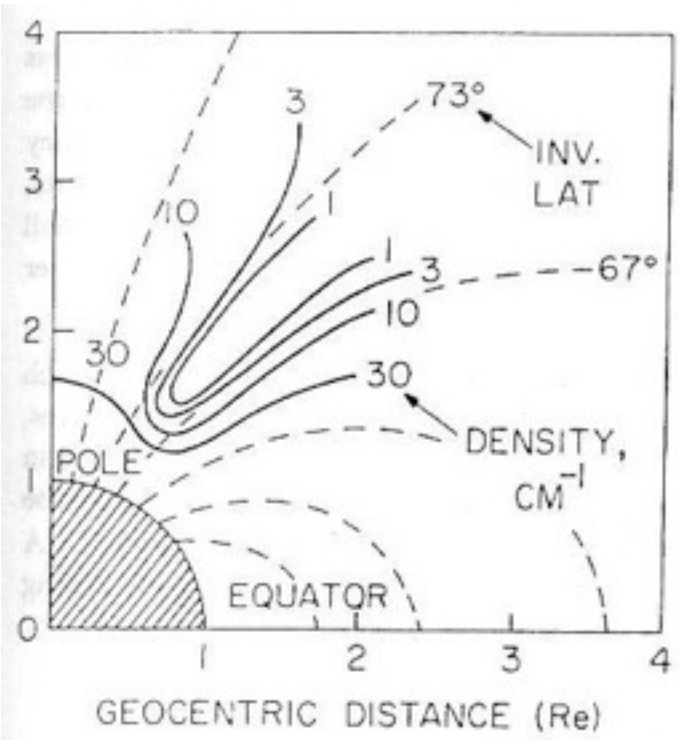
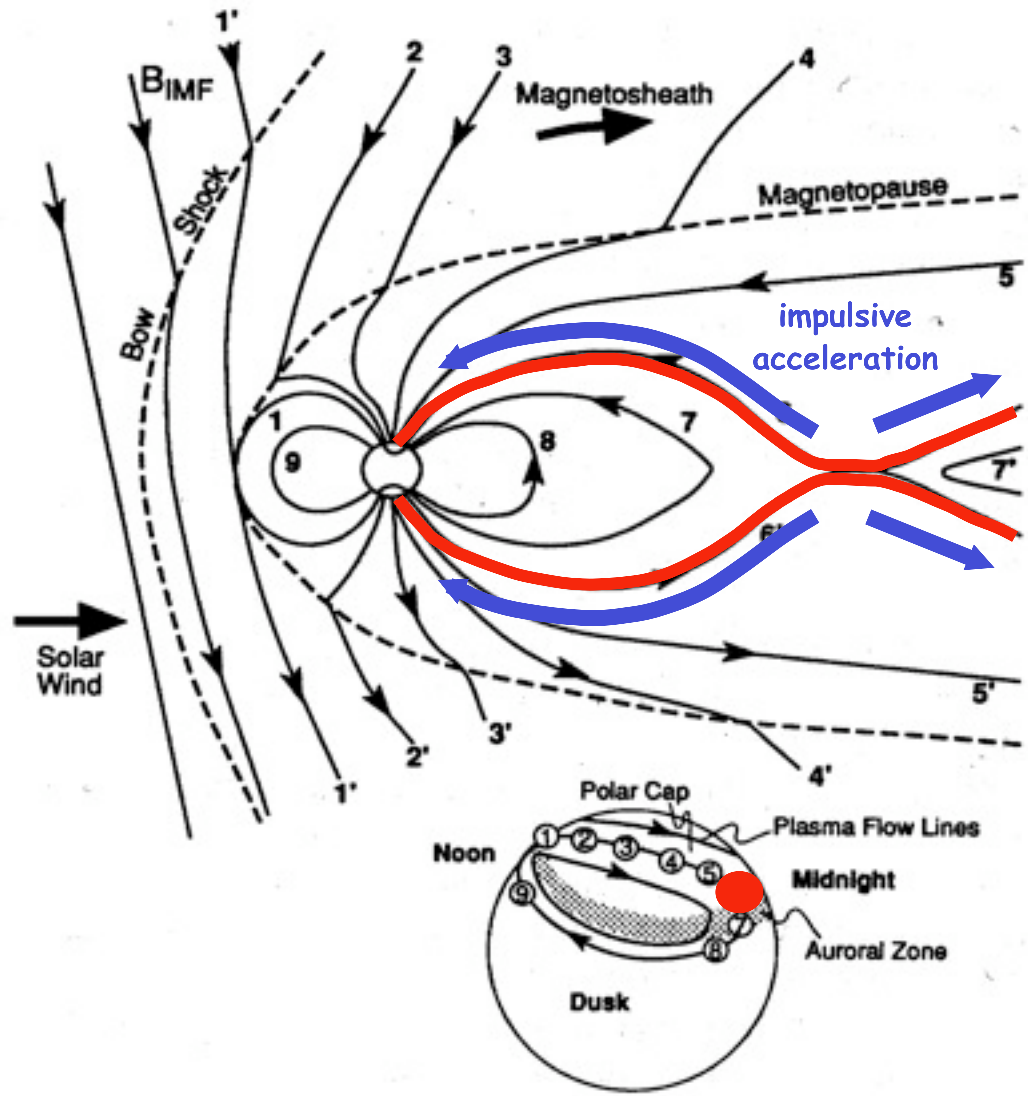
- sources where B, $f_{pe} \ll f_{ce}$, keV e- → auroral N&S

Earth : auroral plasma cavity + e- acceleration via reconnection (tail)

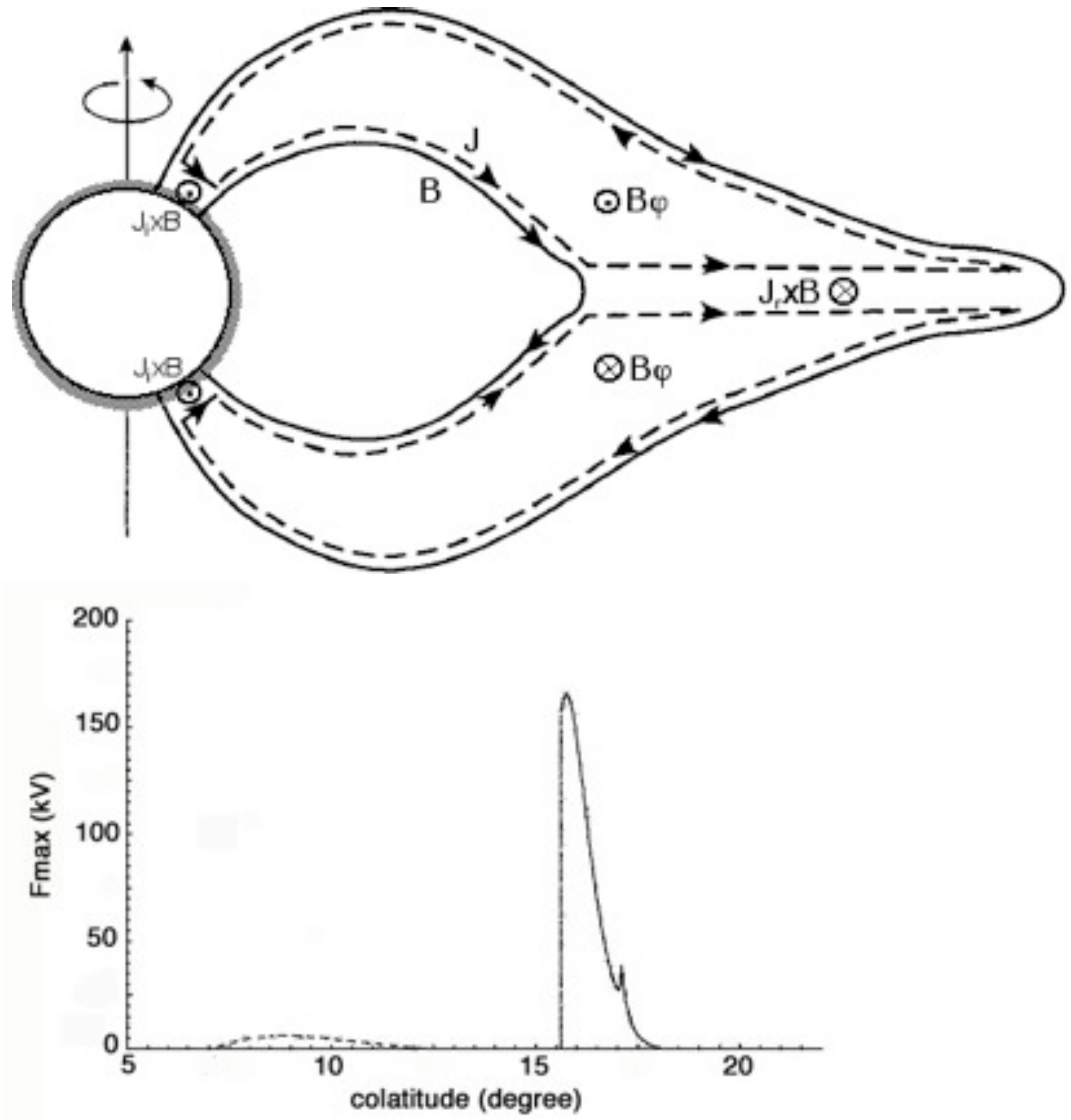


[Calvert, 1981]



[Hughes, 1995]

Jupiter : FAC due to non-rigid corotation ≥30-50 Rj → ~ all LT



Potential drop / Precipitating e- flux along B lines [Cowley & Bunce, 2001]

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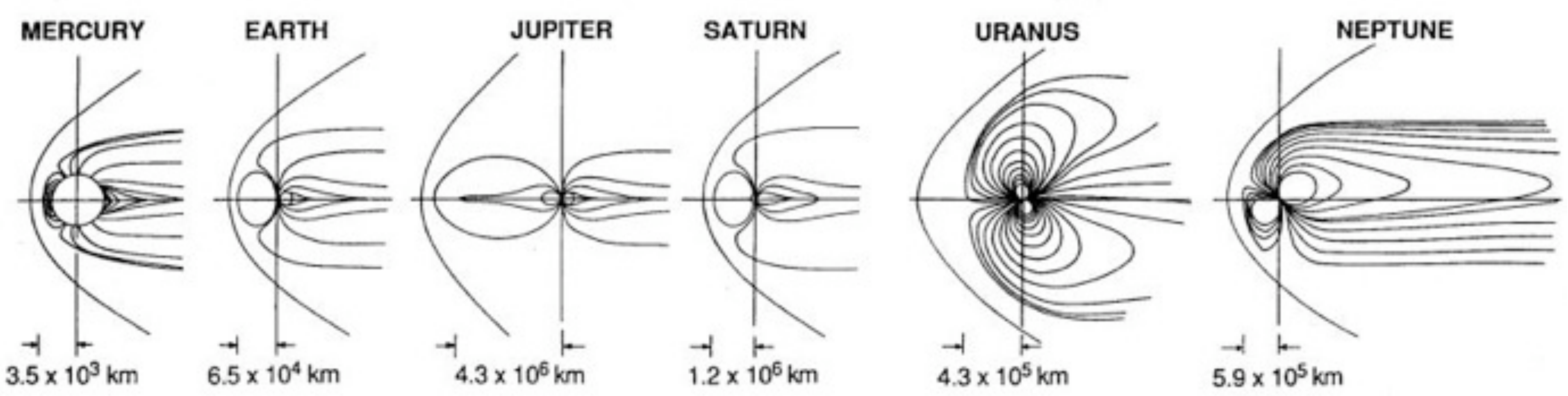

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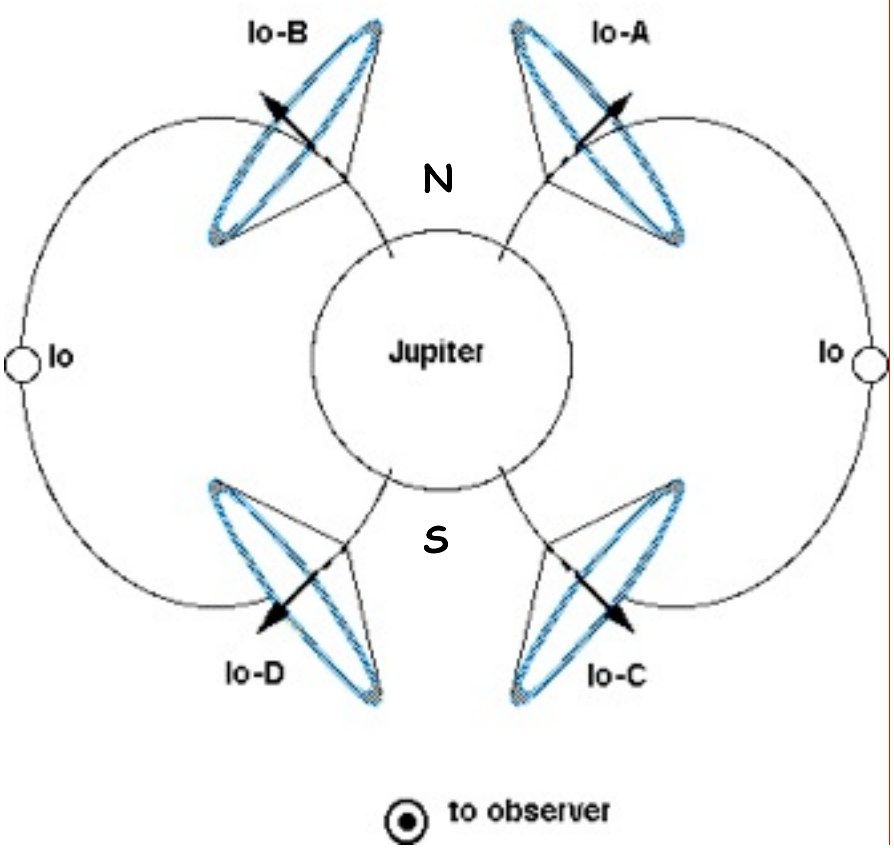
Io-controlled radio "sources



[Bigg, 1964]

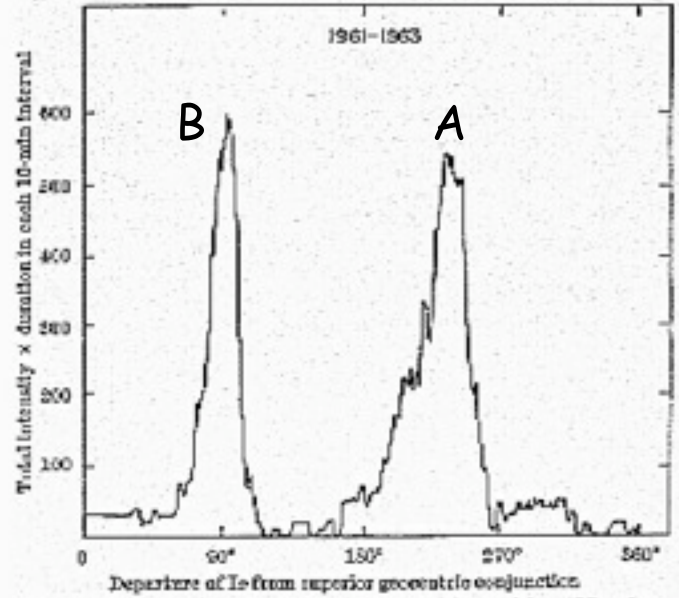


Fig. 4. Dependence of Jupiter's emission on the position of Io when only cases having top frequencies ≥30 Mc/s are considered

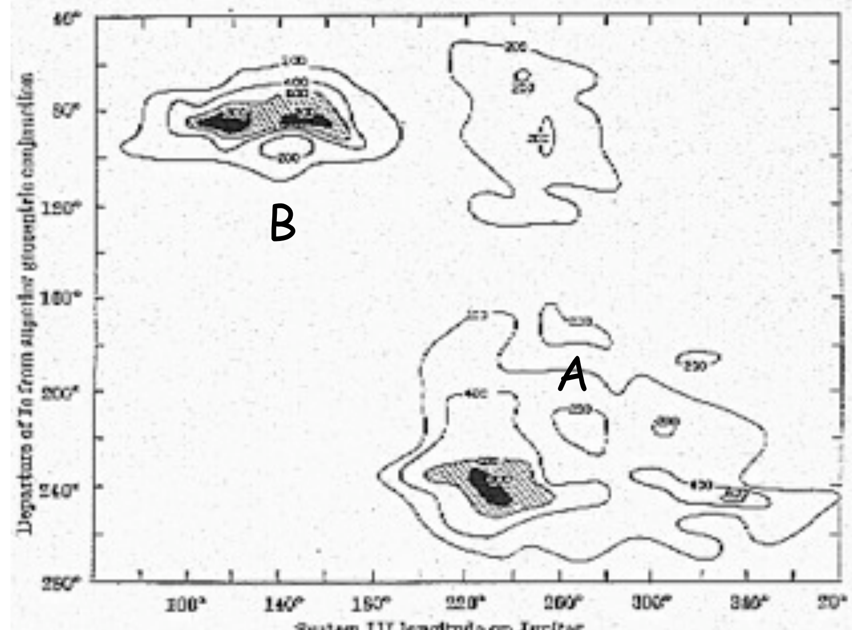


Fig. 5. The relationship between the position of Io and the orientation of Jupiter for the reception of decametric emission at the Earth

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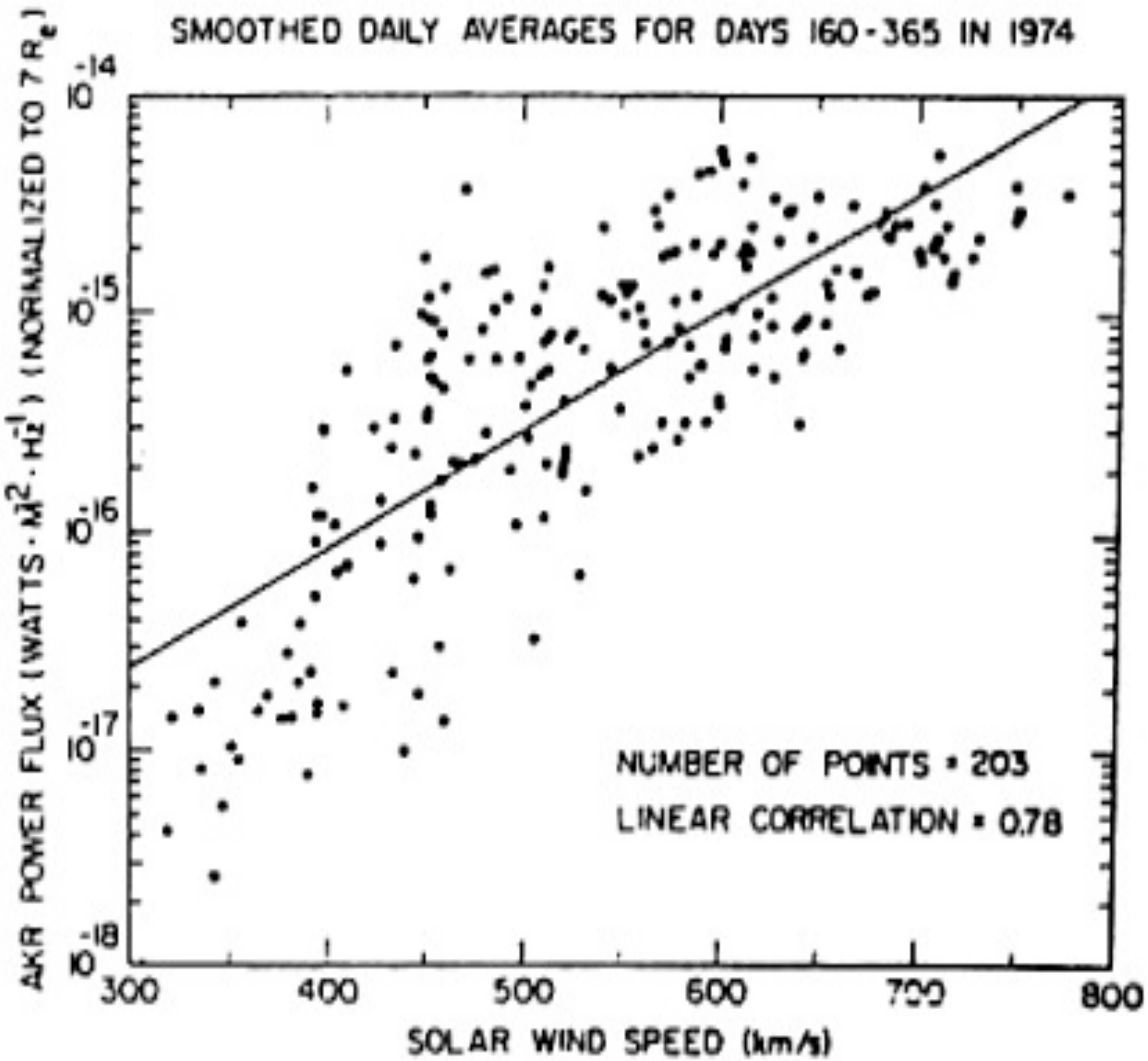

[Gallagher and d'Angelo, 1979]

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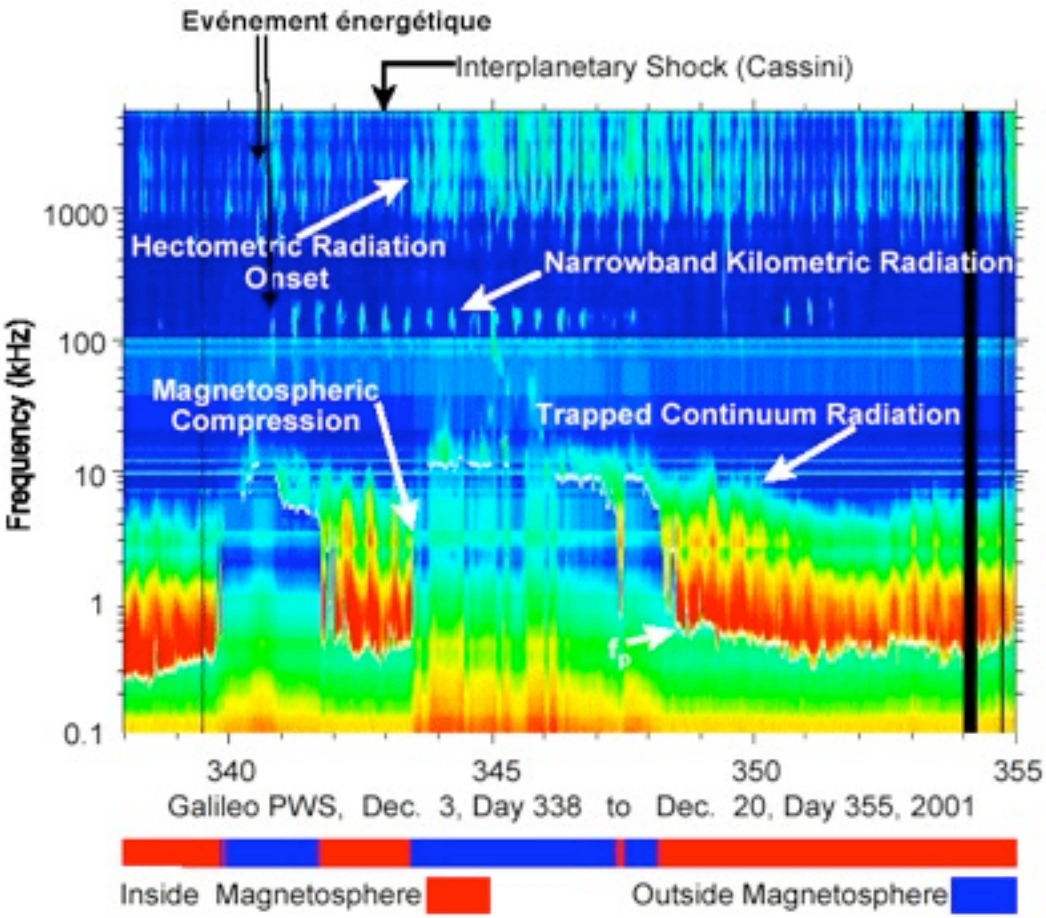

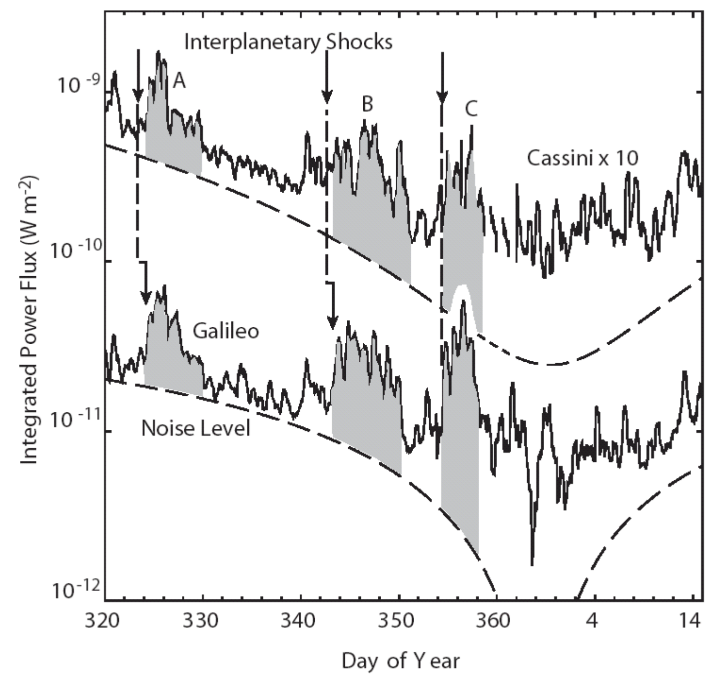

[Gurnett et al., 2002]

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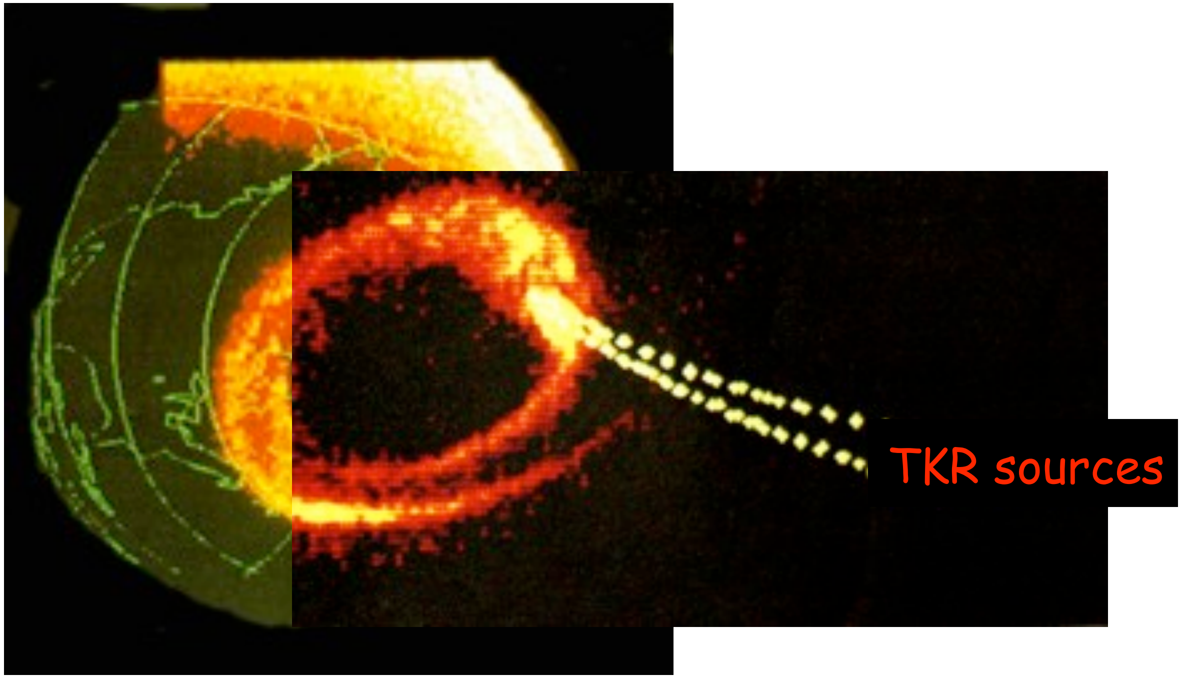
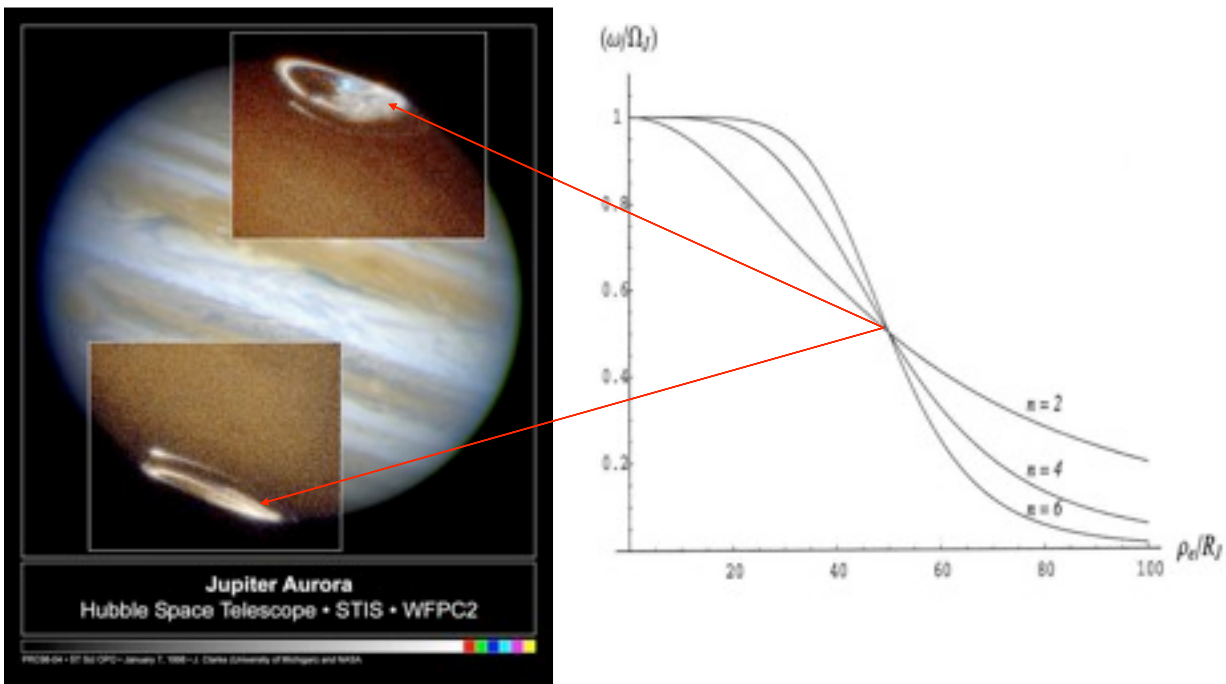
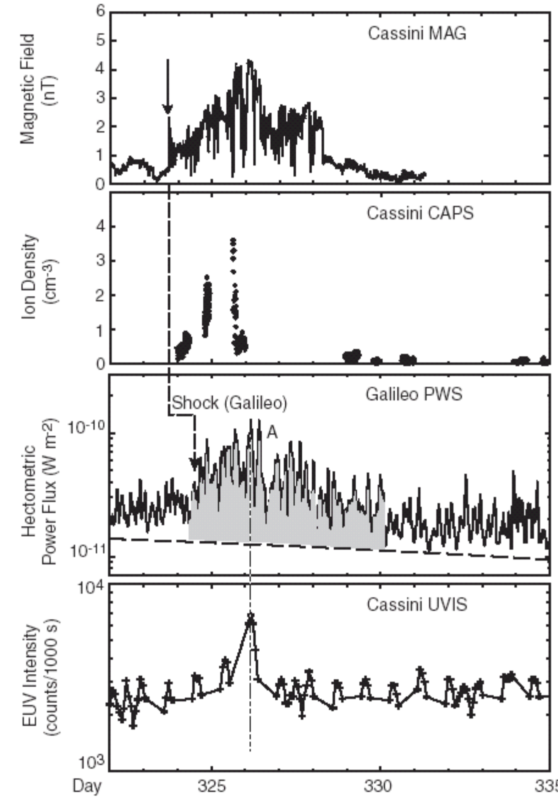
Earth
(DE-1, 130 nm)
[Huff et al., 1988]



Jupiter
(HST, 117-170 nm)
[Clarke, Prangé, Cowley, Gurnett]





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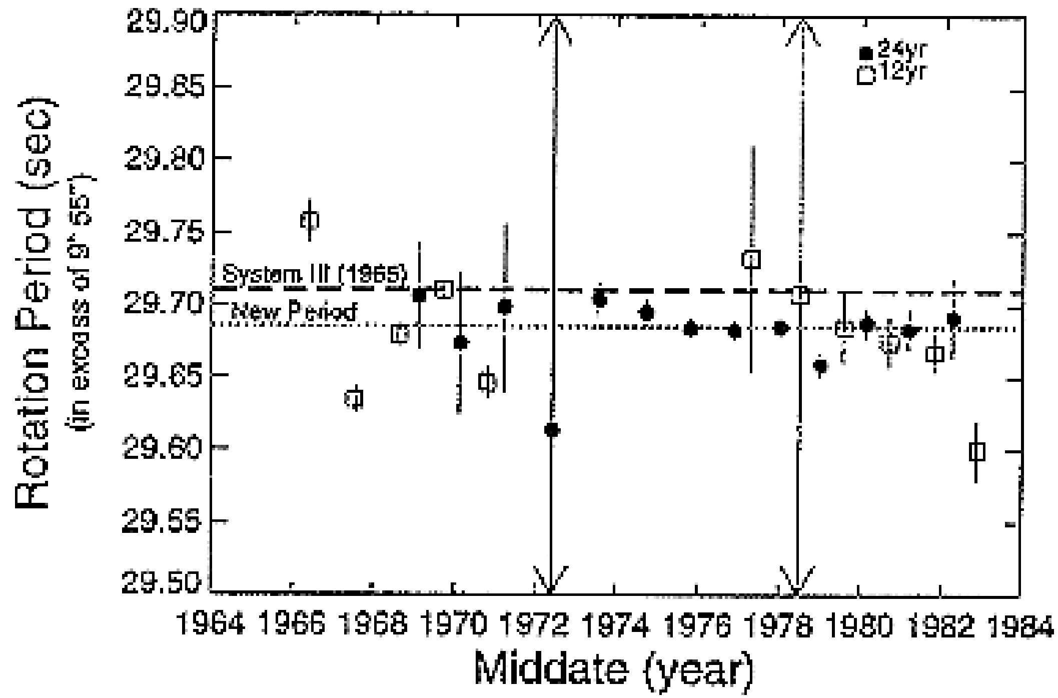
- strong correlation with UV aurora
- → planetary rotation period

[Jupiter](#) : 9h 55m 29.7s ± 0.1s

→ 24 years of Io-DAM ground-based observations

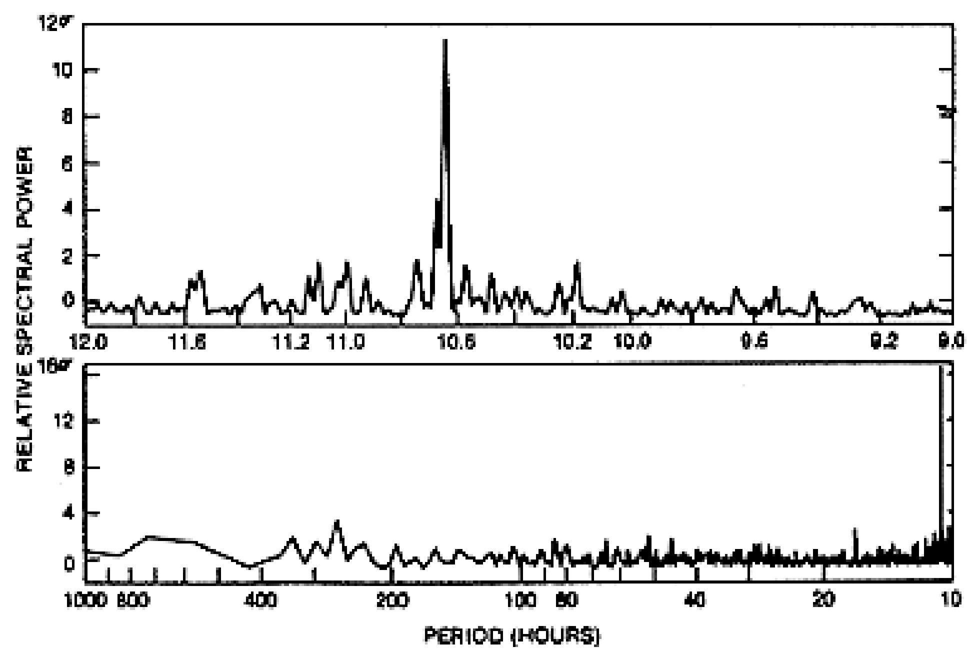
[Higgins et al., 1997]



[Saturn](#) : 10h 39m 22.4s ± 7s

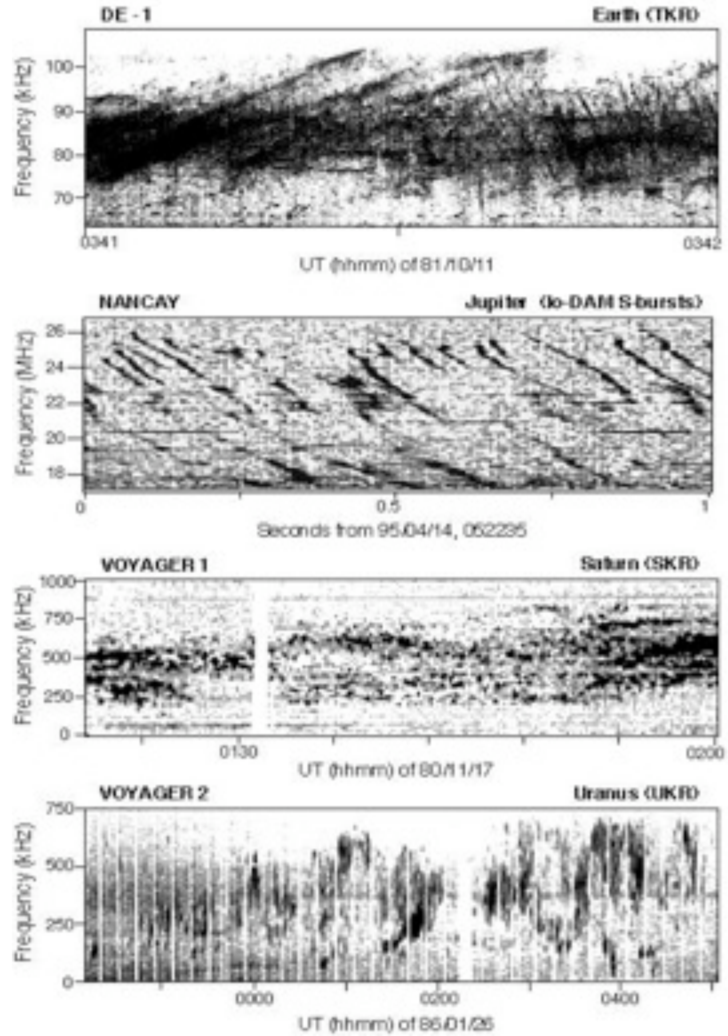
→ 267 days of SKR Voyager-PRA observations

[Desch and Kaiser, 1981]



• various sources, smooth and bursty components co-exist

→ ≠ sources or
≠ mechanisms ?



Earth	Jupiter	Saturn	Uranus	Neptune
TKR (AKR) :	bKOM	SKR	UKR : B-smooth	NKR : Smooth
mostly bursts ?	HOM		Dayside-smooth	Main-bursts
LF-bursts (ITKR)	auroral-DAM		B-bursts	Anomalous-bursts
HOM, auroral-	QP-bursts ? (JtIII)		N-bursts	HF-smooth (low-lat?)
roar	Io-DAM, S-bursts		N-smooth (low-lat)	

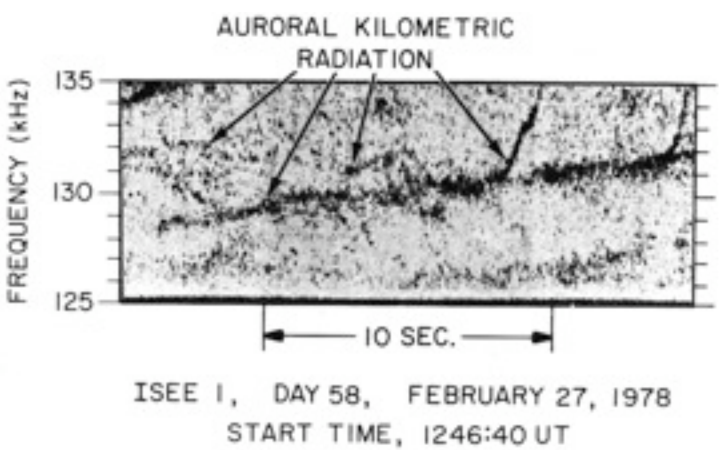
Theory of Auroral Radio Emissions :

- Need for highly efficient, coherent generation mechanism, for direct generation of free-space X-mode (no conversion)

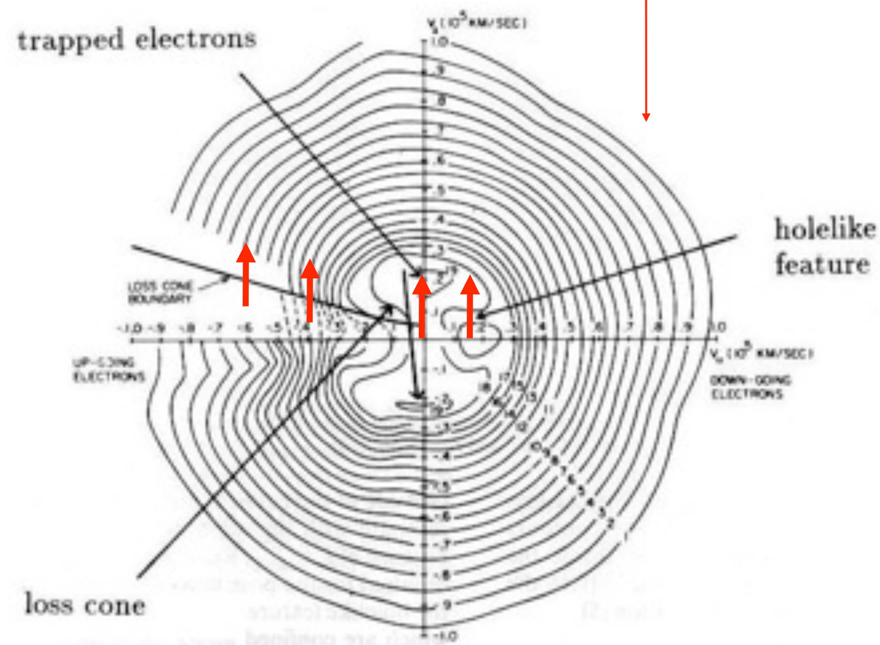
→ Cyclotron Maser Instability   [Wu & Lee, 1979]

Theory of Auroral Radio Emissions :

- requires $f_{pe} \ll f_{ce}$, produces $f \sim f_X \approx f_{ce}(1+(f_{pe}/f_{ce})^2) \approx f_{ce}$ (at expense of $m_e v_\perp^2/2$)
- amplification requires $\partial f/\partial v_\perp > 0$ at keV energies (loss-cone, hollow beam)
- intense emission, beamed at large angle / B
- CMI overall efficiency up to 1% at saturation
- may produce fine structures (resonance, saturation by trapping)



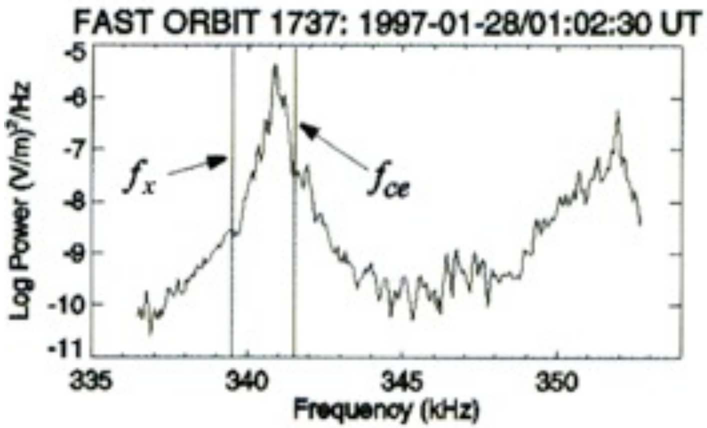
[Baumback and Calvert, 1981]



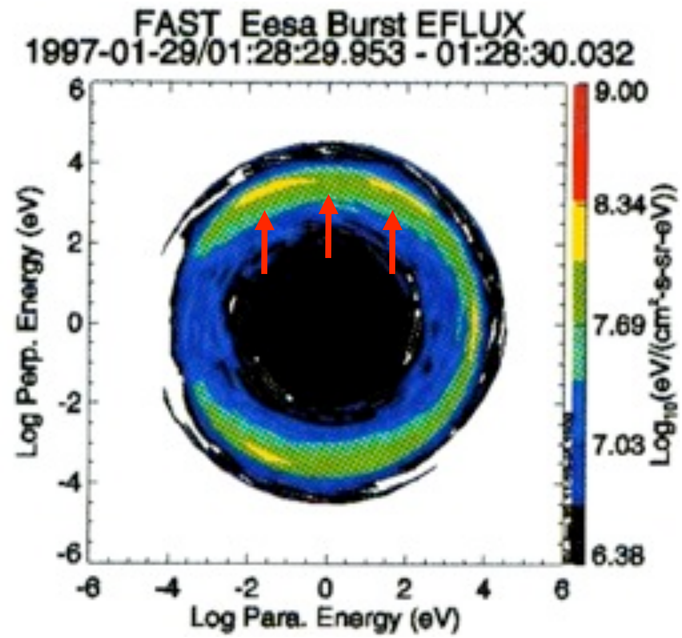
[Mizera and Fennel, 1977]

Theory of Auroral Radio Emissions :

- Viking in AKR sources : laminar cavities (km), dominated by tenuous hot plasma (1-5 keV) with quasi-trapped population
- hot plasma dispersion → $f \leq f_{ce}$ at $k_{//}=0$ (beaming at ~90°)
- FAST : direct confirmation + shell e- distribution (beam + adiabatic evolution)
- laser cavity ?



[Ergun et al., 1998]



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- 2^{nd} to Jupiter in intensity
- Δf from ≤20 kHz to 1.3 MHz, peak 100-400 kHz (B_{sat})

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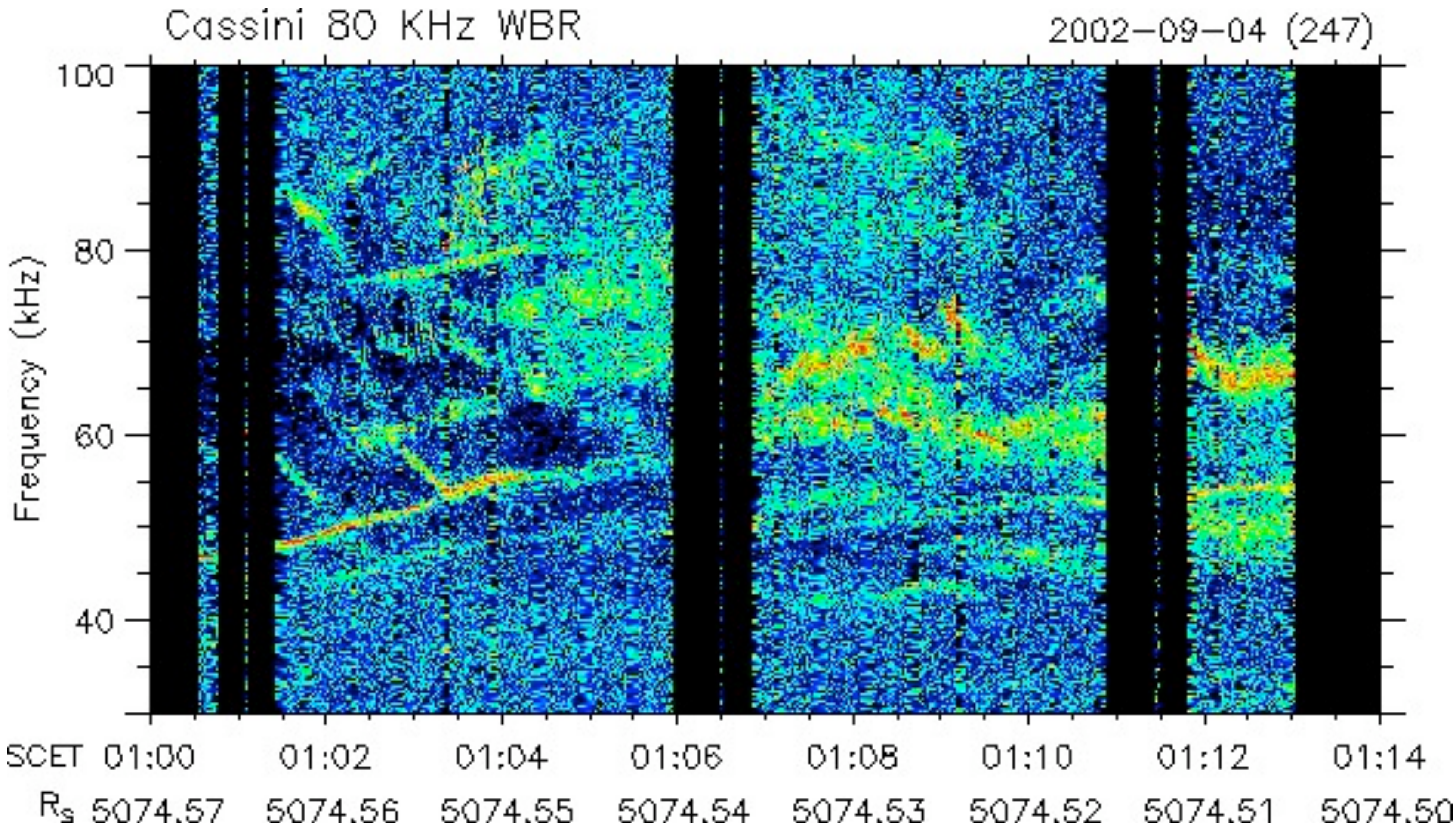

Cassini 80 KHz WBR
2002-09-04 (247)
100
80
60
40
Frequency (kHz)
SCET 01:00 01:02 01:04 01:06 01:08 01:10 01:12 01:14
Rs 5074.57 5074.56 5074.55 5074.54 5074.53 5074.52 5074.51 5074.50

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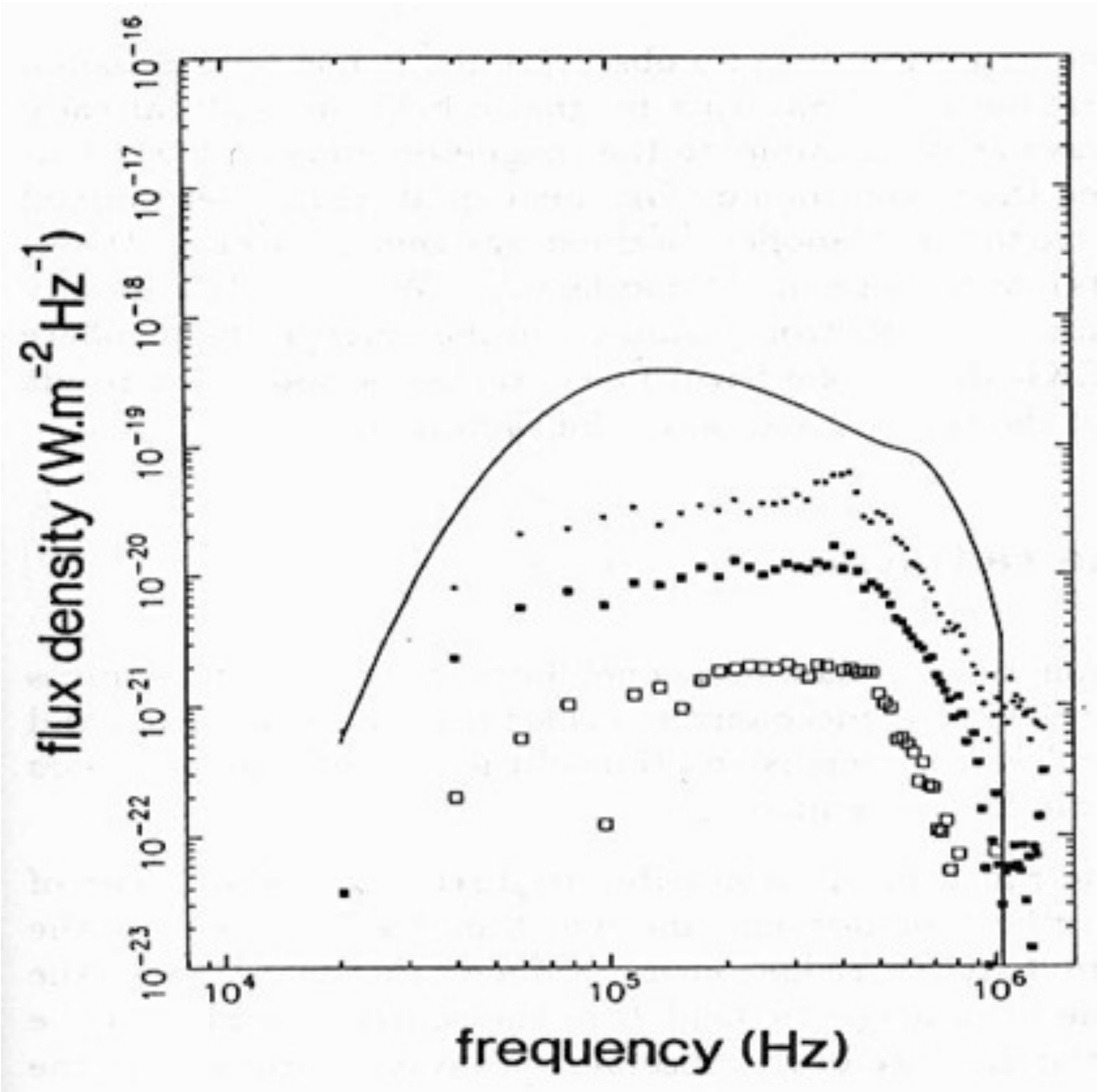

[Galopeau et al., 1989]

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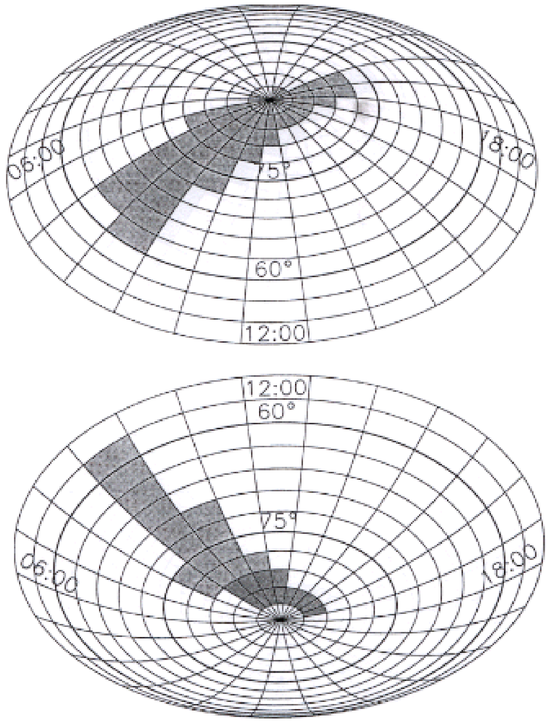
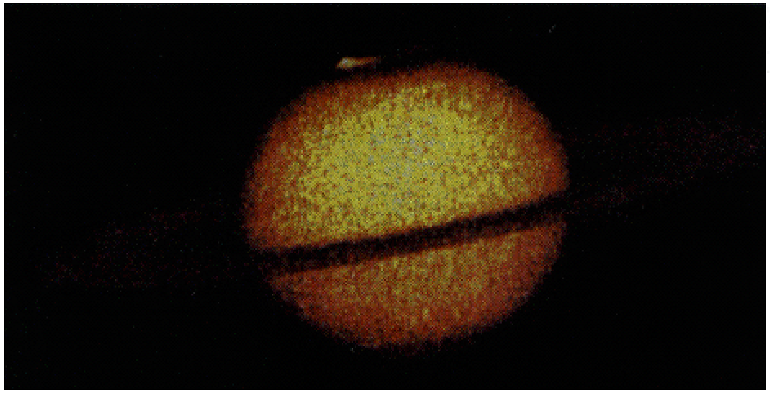
- rotation modulation but source fixed in LT, correlated with UV aurorae

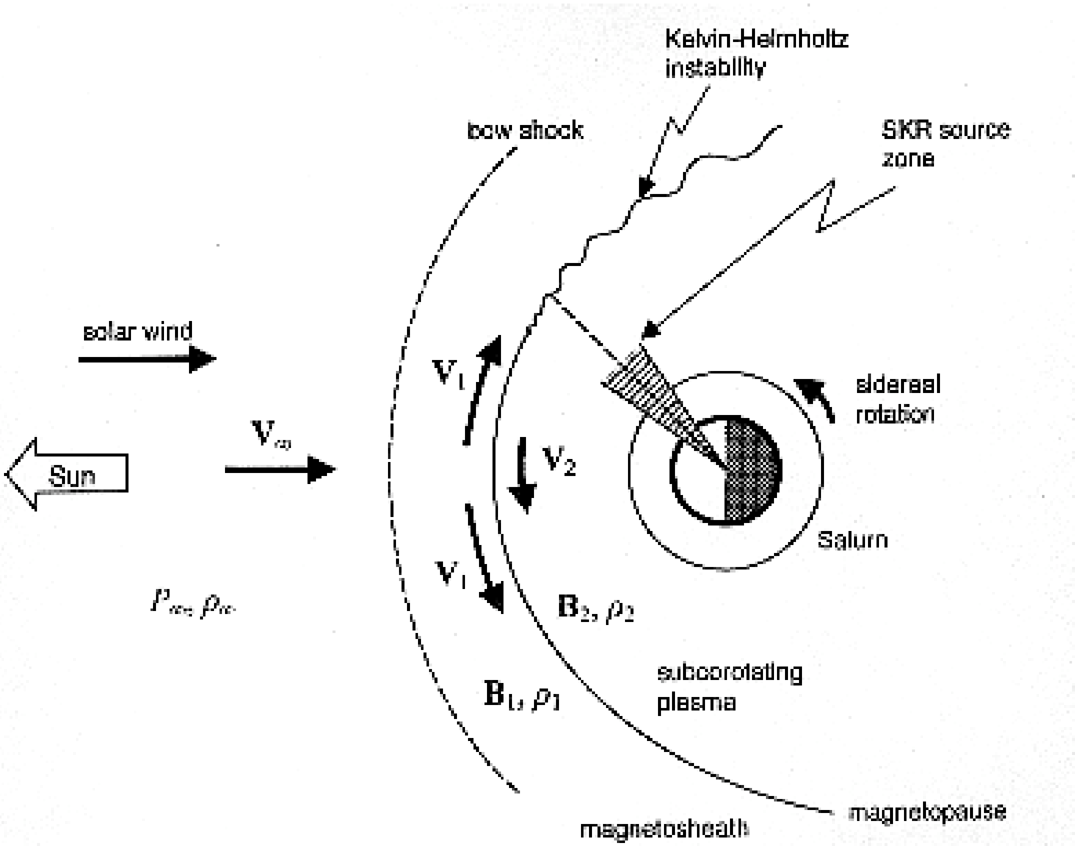
[Galopeau et al., 1995]





[Trauger et al., 1998]

→ Kelvin-Helmholtz instability at Magnetopause ?



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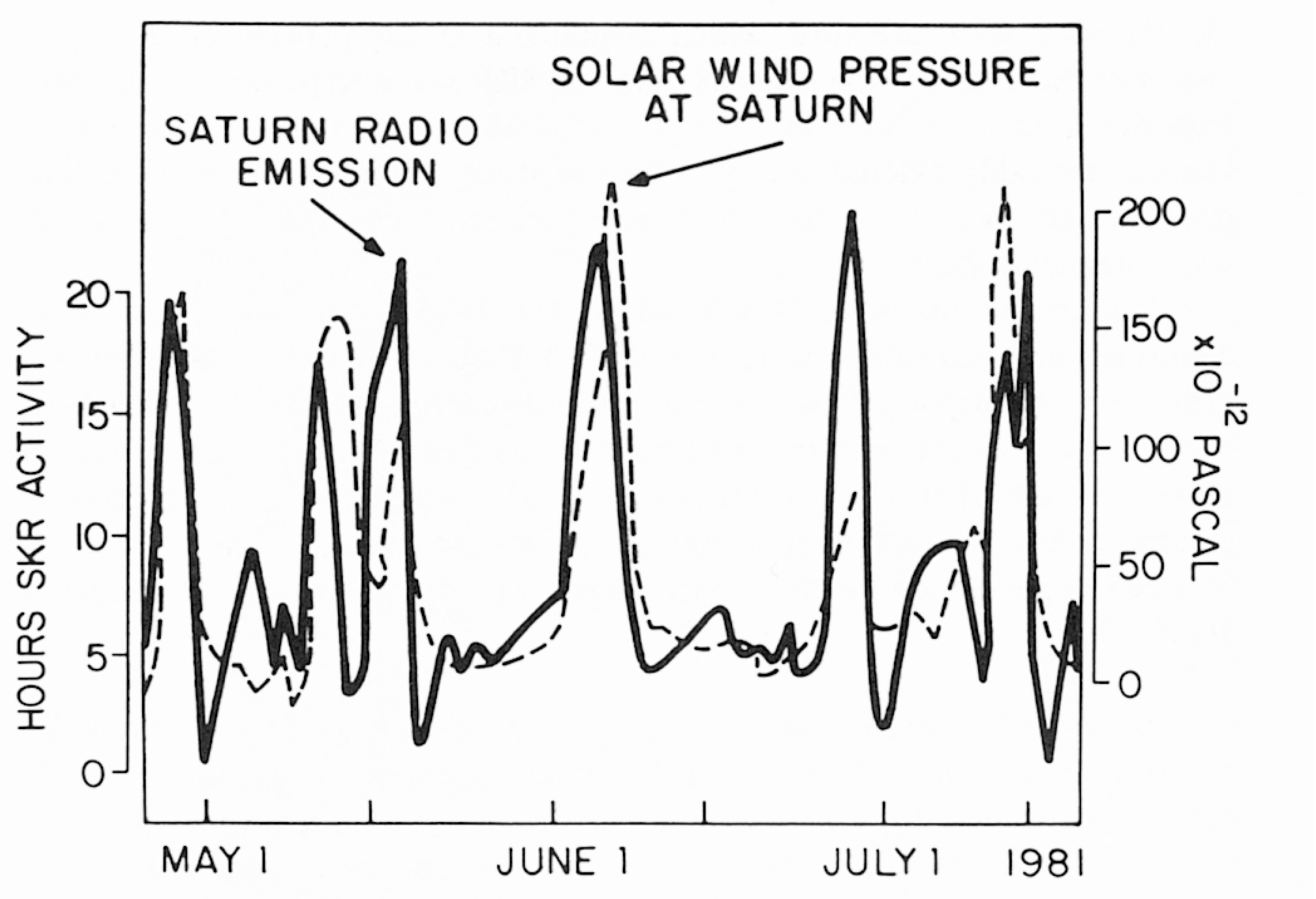
- strong SW control



[Desch, 1982]

- SKR extinctions in Jupiter's magnetospheric tail

→ SKR as a Solar Wind monitor ?

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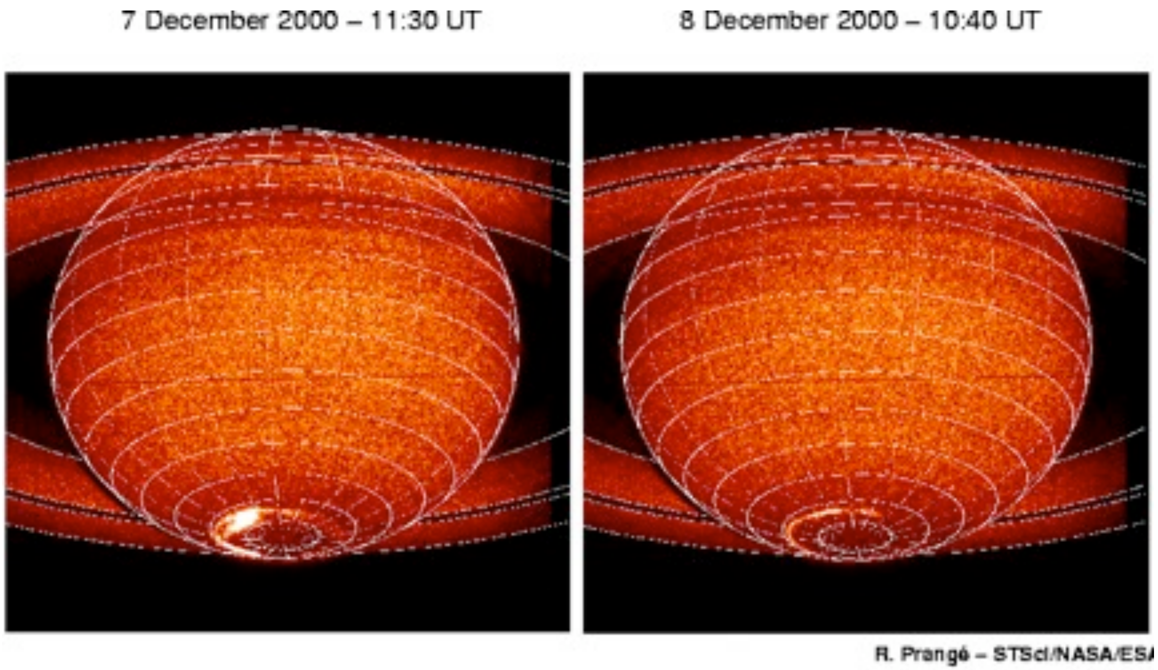
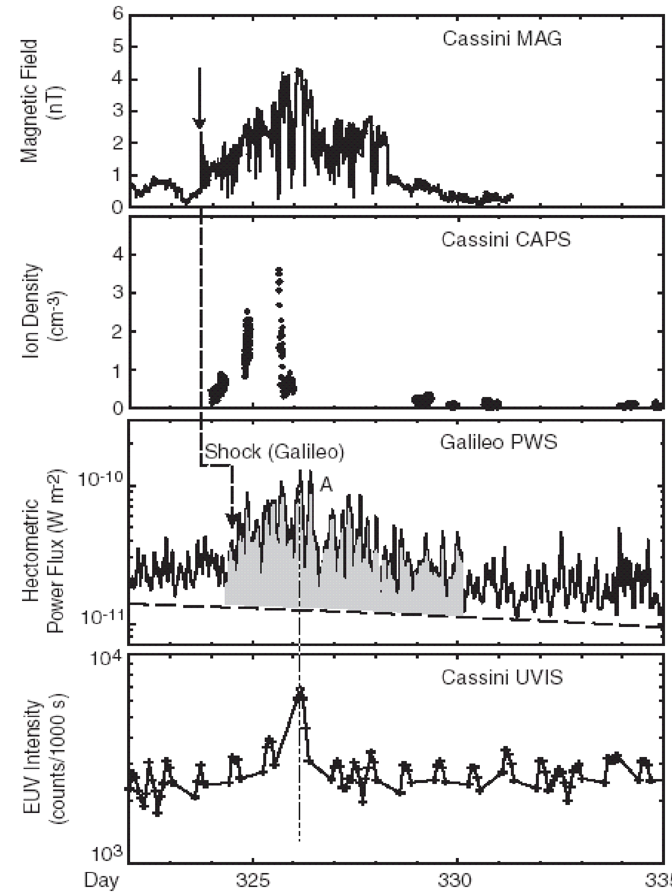


SATURN – FUV south aurora

HST – STIS/F25SFR2 (H2 Ly–We bands > 1300 A)

[Prangé et al., 2003]



19-25 Nov. at Jupiter projects ballistically as 1-7 Dec. at Saturn

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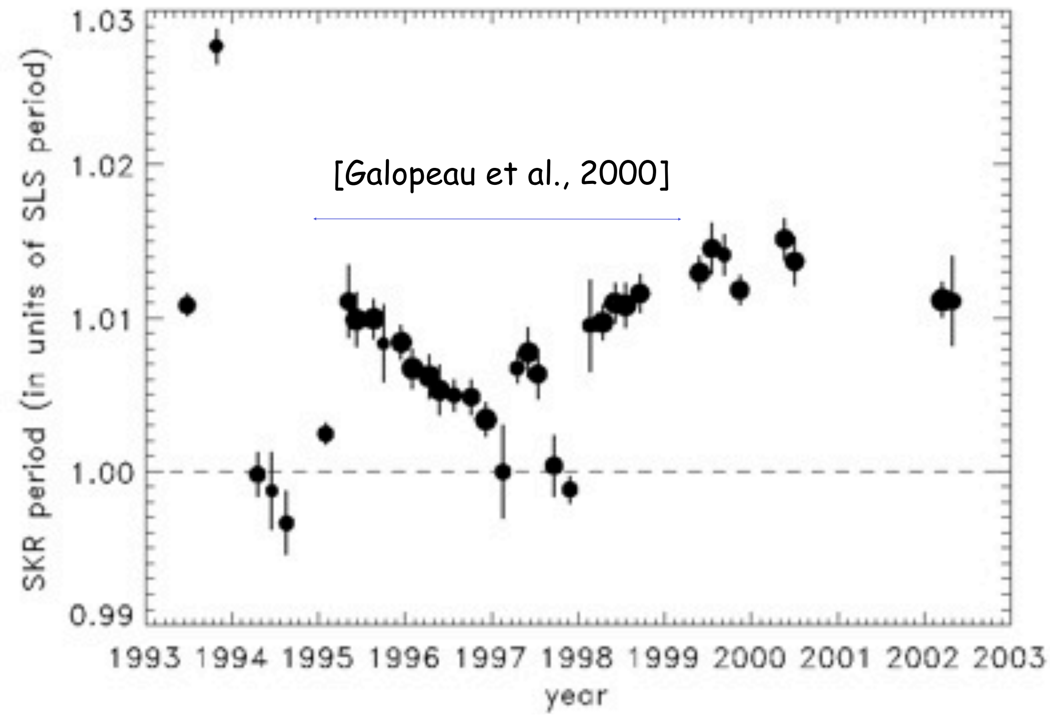
- strong SW control, correlation with IP shocks ?
- P_{sat} = 10h39.4 m ±7s, in spite of B axisymmetrical [Connerney et al., 1982]
- magnetic anomaly ? [Galopeau etal., 1991, 1992; Ladreiter et al., 1994]

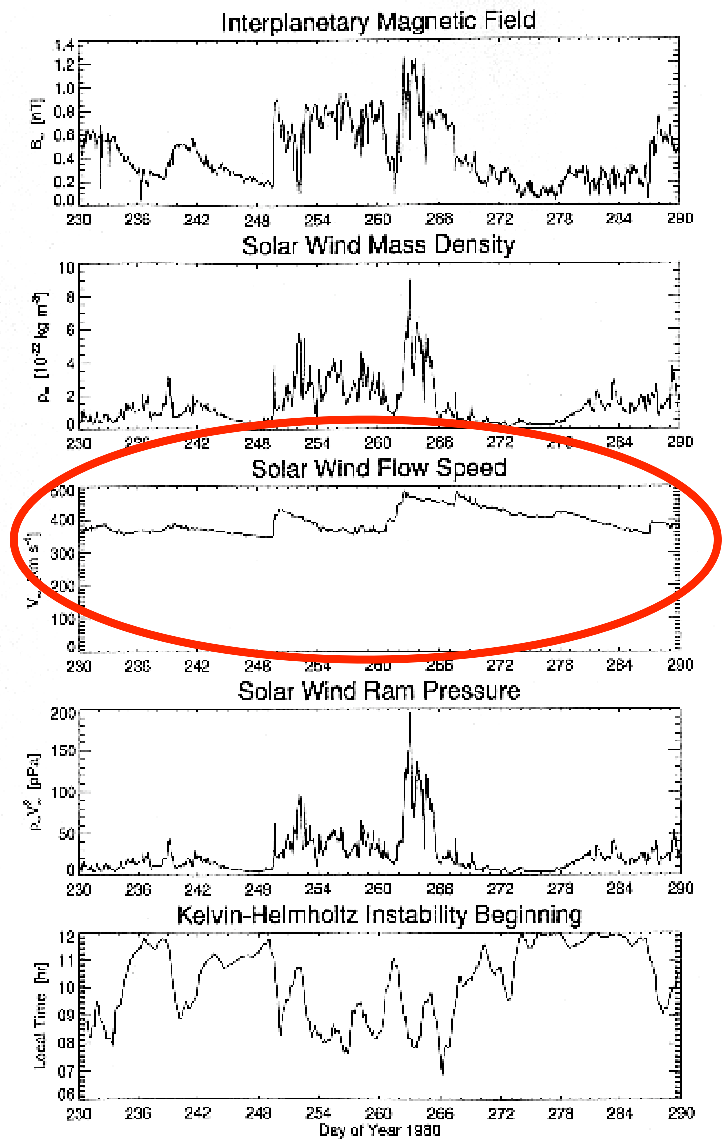
Saturn Kilometric Radiation :

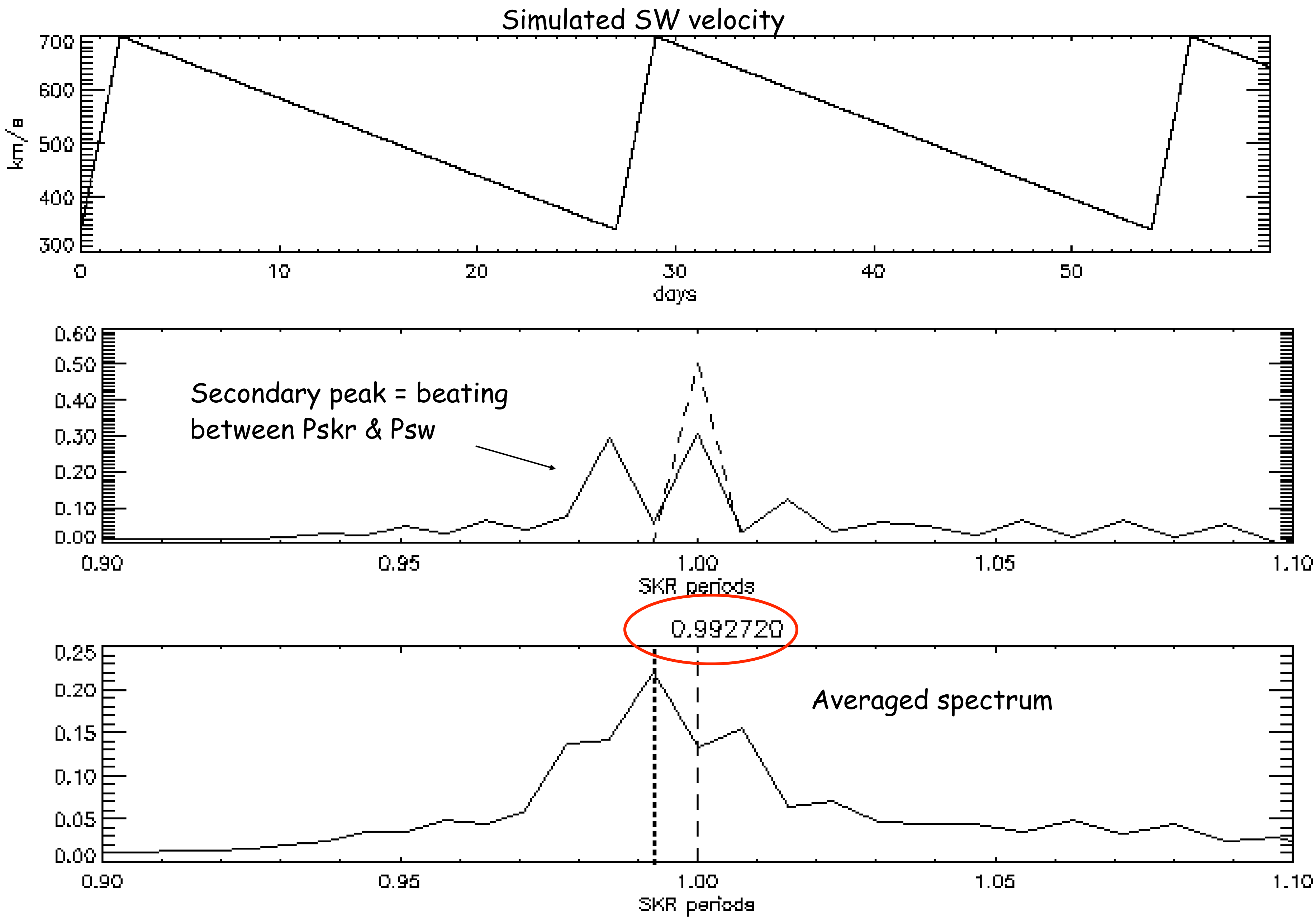
- 2^{nd} to Jupiter in intensity
- Δf from ≤20 kHz to 1.3 MHz, peak 100-400 kHz (B_{sat})
- arcs, bursts
- spectrum successfully modelled, marginally saturated
- polarization → source location → KHI at magnetopause ?
- rotation modulation but source fixed in LT, correlated with UV aurorae
- strong SW control, correlation with IP shocks ?
- P_{sat} = 10h39.4 m ±7s, in spite of B axisymmetrical
- magnetic anomaly ?
- P_{sat} variable by ~1%

1% variation of radio period … due to non-random SW variations ?



[Galopeau et al., 2000] + Ulysses update





[Cecconi and Zarka, 2001]

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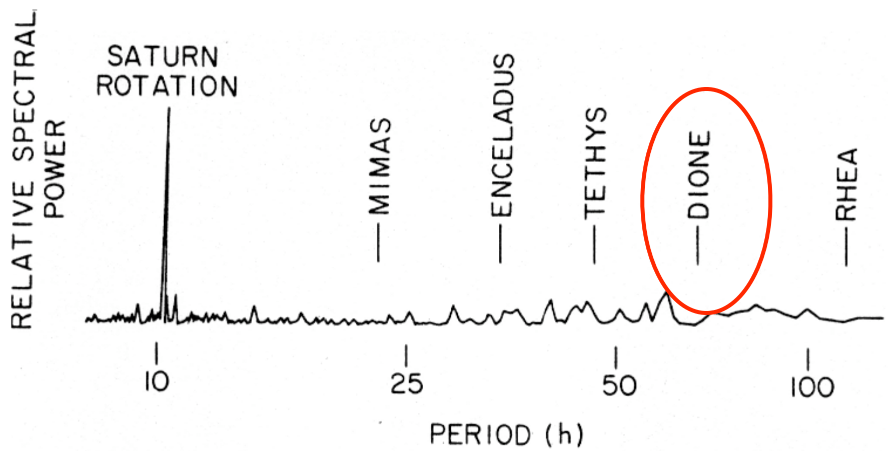
- control by Dione ?

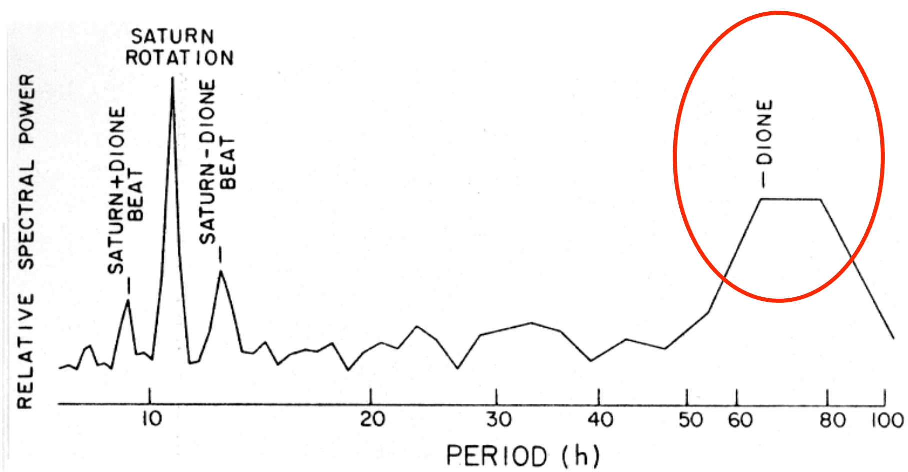
Dione effect :

→ SKR occultation by plasma released at certain orbital phase ?

→ induced radio emission (~Io-DAM) ?



SKR @ 174 kHz, 28 Oct. - 18 Dec. 1980



SKR @ 59 kHz, 10-18 Nov. 1980

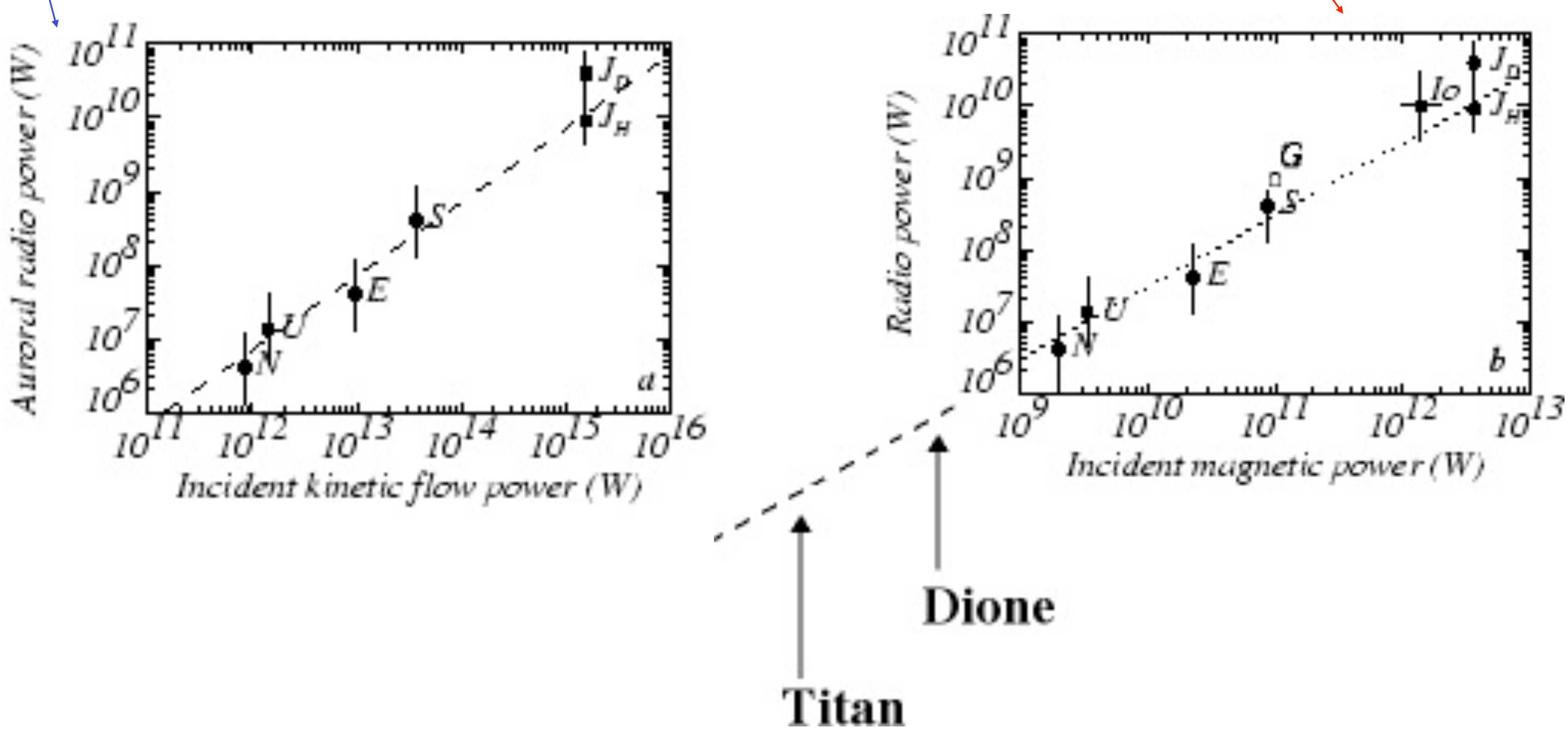
[Desch & Kaiser, 1981; Kurth et al., 1981]

- Radio Bode's law(s) :

$P_{auroral} = \alpha\, \varepsilon_{ram}\, V\, \pi R_{mp}^2 = \alpha\, (N_o/d^2)\, m_p V^3\, \pi R_{mp}^2$ [Desch and Kaiser,1984; Zarka, 1992]

$P_{radio} \approx \beta\, P_d = \beta\, (B_\perp^2/2\mu_o)\, V\, \pi R_{obstacle}^2$ [Zarka et al., 2001]

→ induced radio emission (if real) requires intrinsic B or extended exosphere



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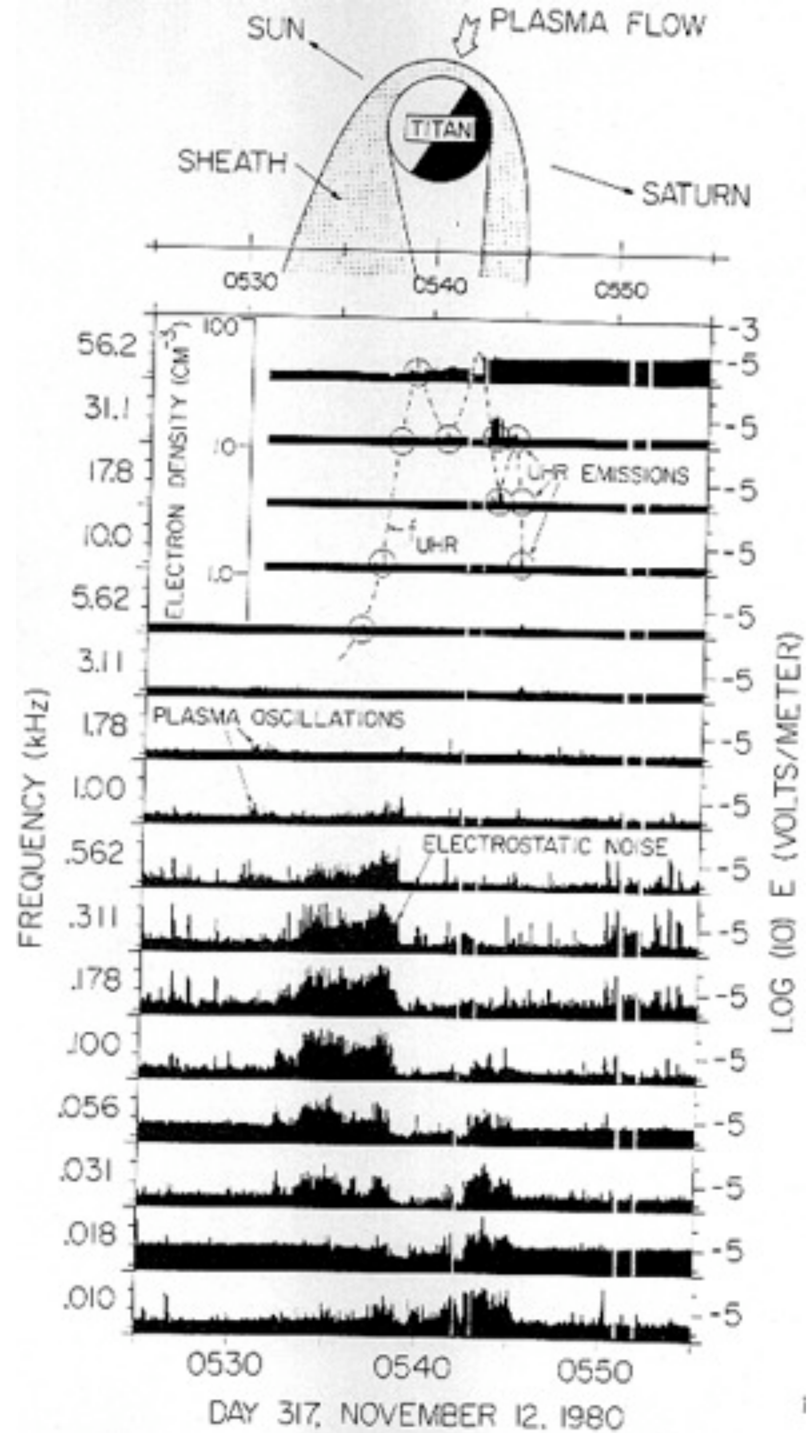
- control by Dione ? Titan ?

Titan :

- no induced radio emission expected
- local plasma waves (wake)
- SKR occultations by Titan's ionosphere



[Gurnett et al.]

- Comparative overview (observations + theories)
    - Auroral Radio Emissions
    - LF electromagnetic emissions
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    - Radiation belts
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LF electromagnetic emissions :

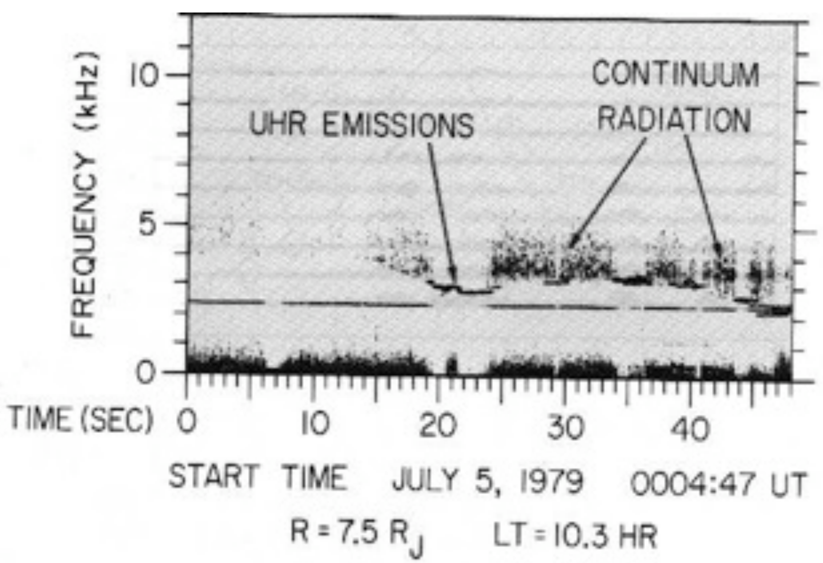
- NTC escaping / trapped

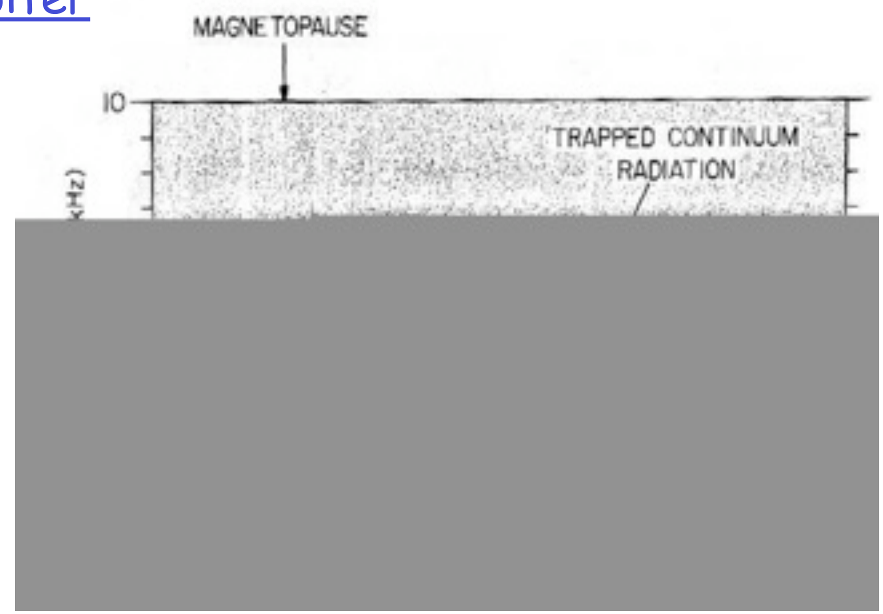
  from narrow lines a few/a few tens kHz, ≥ local f_{pe}

→conversion process of electrostatic UH waves on N_e gradients ?

(+ Doppler smoothing)

Jupiter





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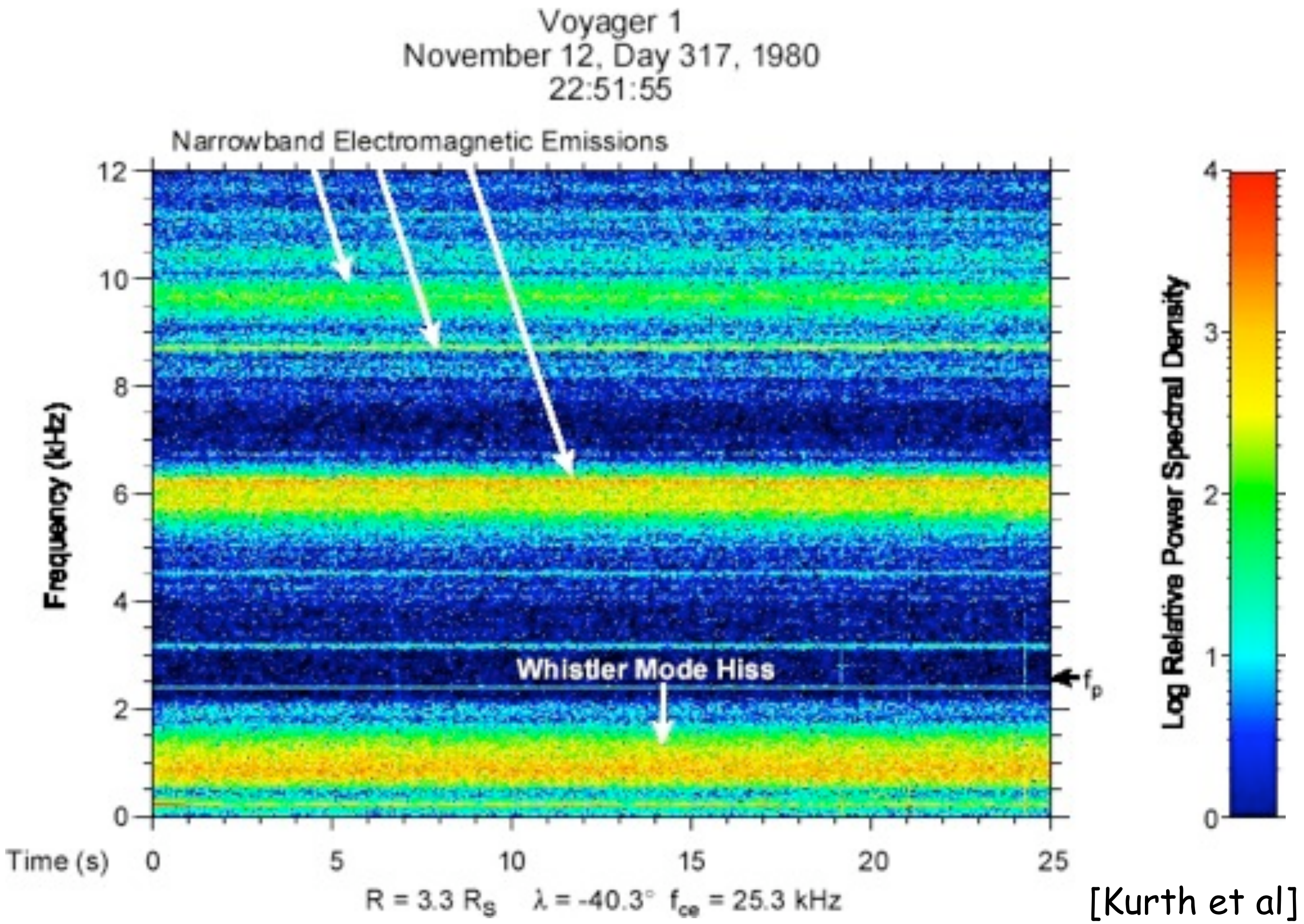
Saturn's LF e.m. emissions :

• narrow bands with spacing ~f_{ce} at Tethys, Dione, Rhea

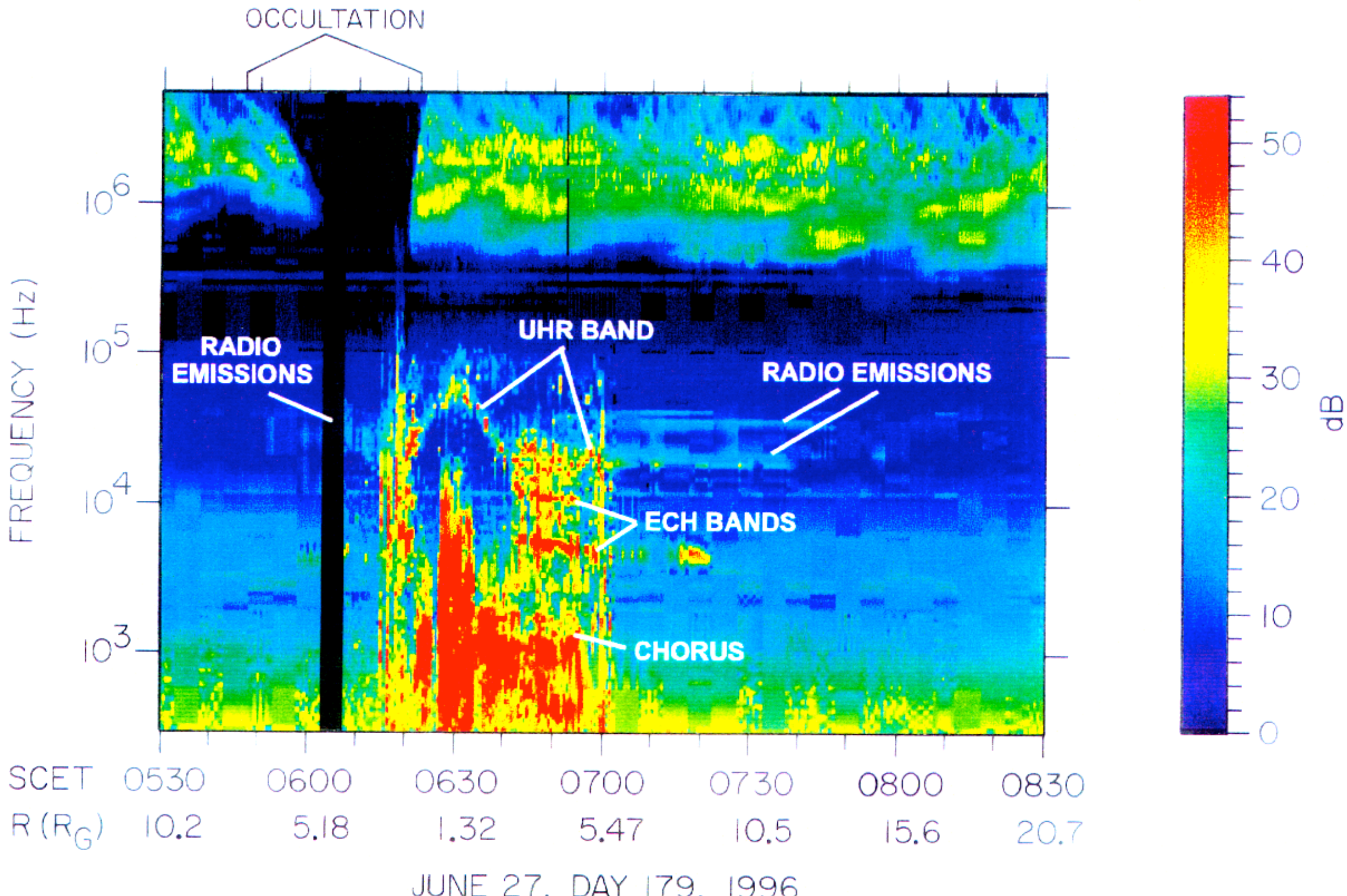
→ origin = satellites/B interaction ?



[Kurth et al]

Saturn's LF e.m. emissions :

- similarities with Ganymede ?



[Gurnett et al., 1996]

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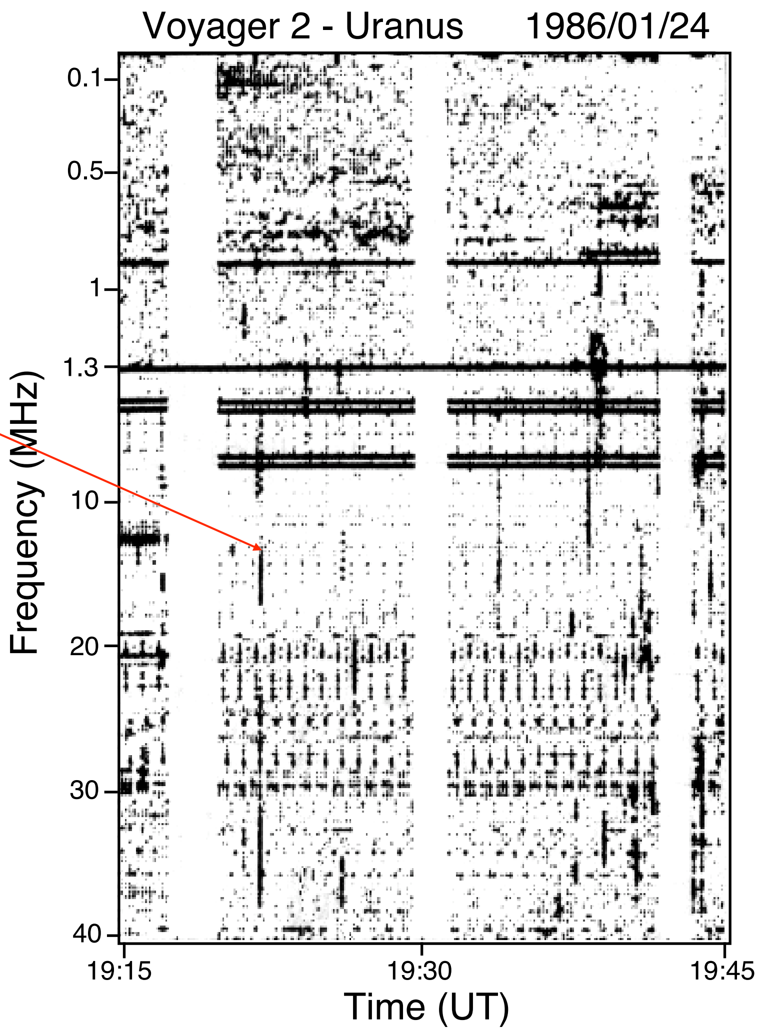
Planetary Lightning :

- SED, UED, (NED)



[Zarka and Pedersen, 1986]

Planetary Lightning :

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- No Jovian radio lightning

  (ionospheric absorption [Zarka, 1985]

  / slow discharges [Farrell et al., 2000])

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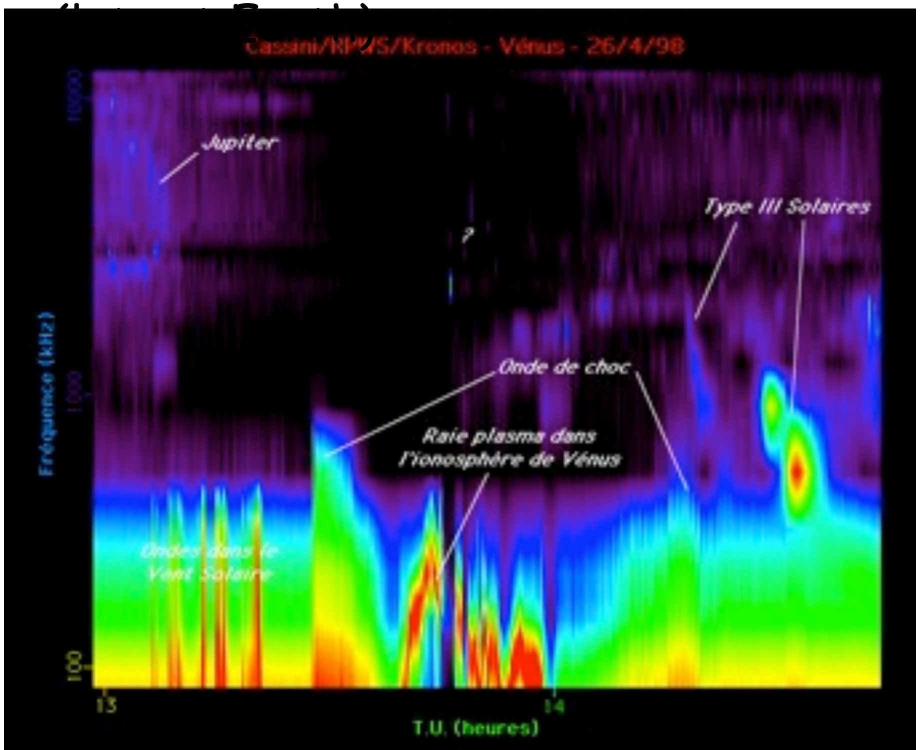
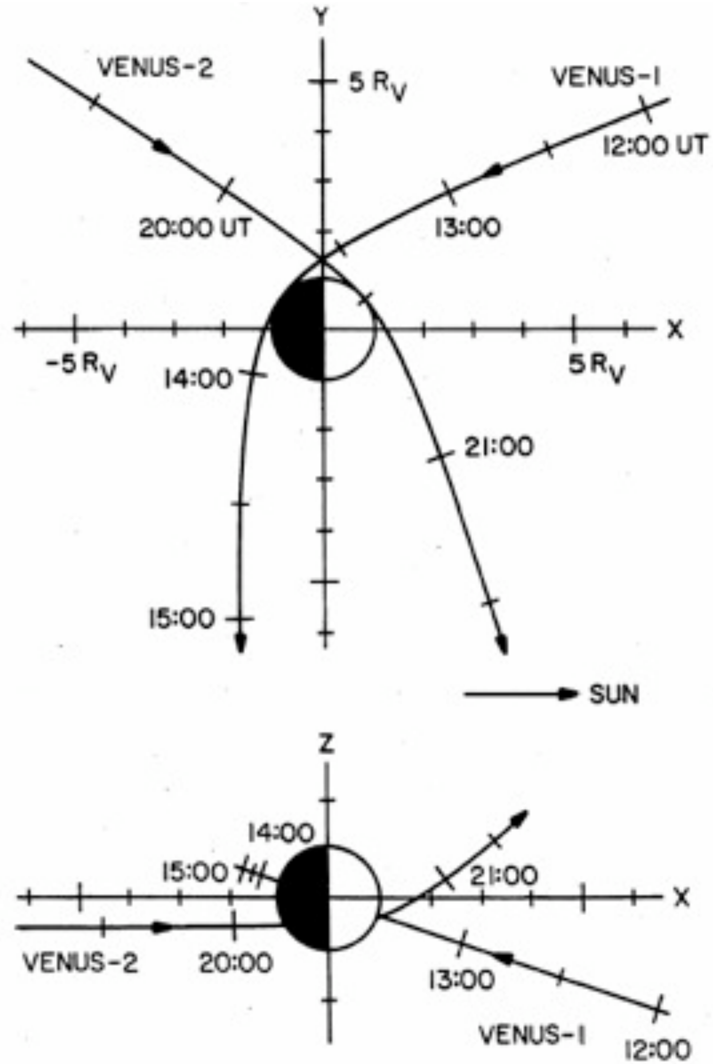
- No lightning at Venus with RPWS !





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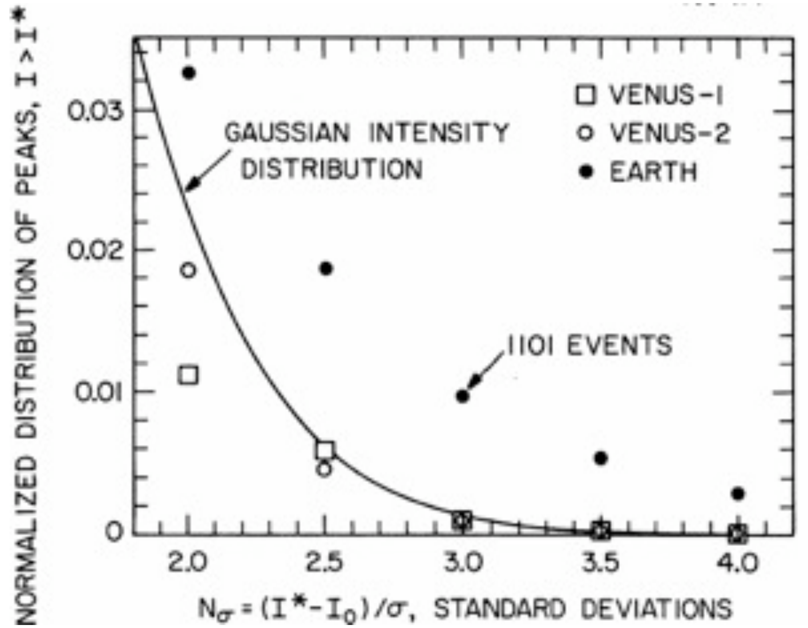
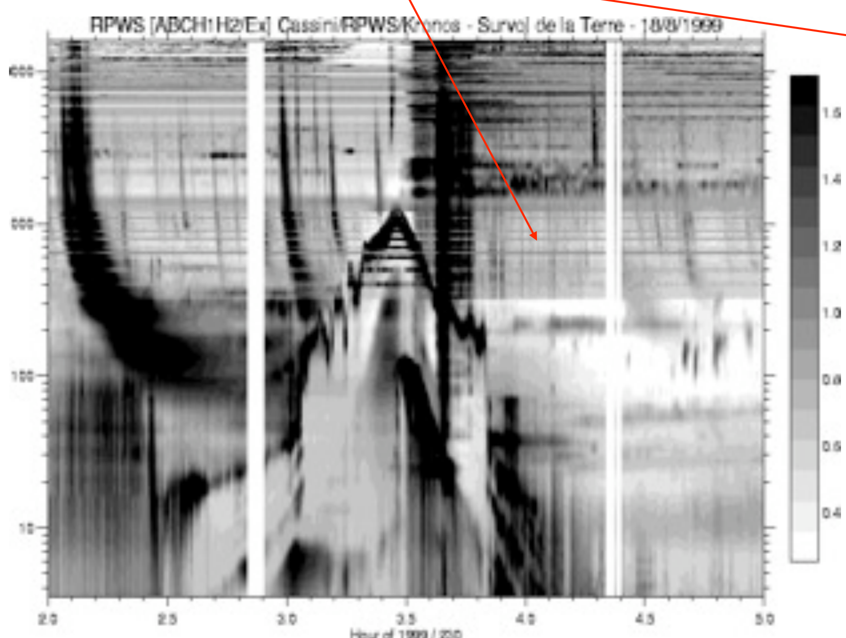
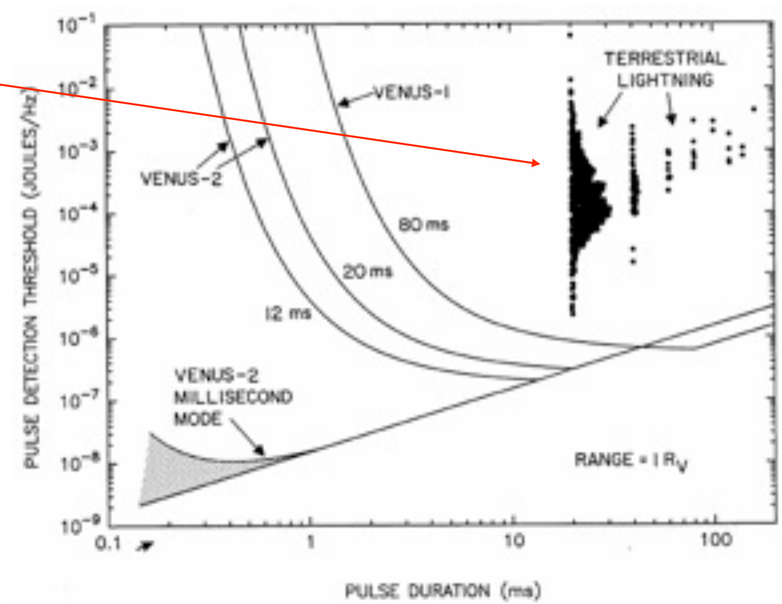
- No Jovian radio lightning
  (ionospheric absorption [Zarka, 1985]
  / slow discharges [Farrell et al., 2000])
- No lightning at Venus with RPWS !
  (>1000 at Earth fly-by)







[Gurnett et al., 2001]

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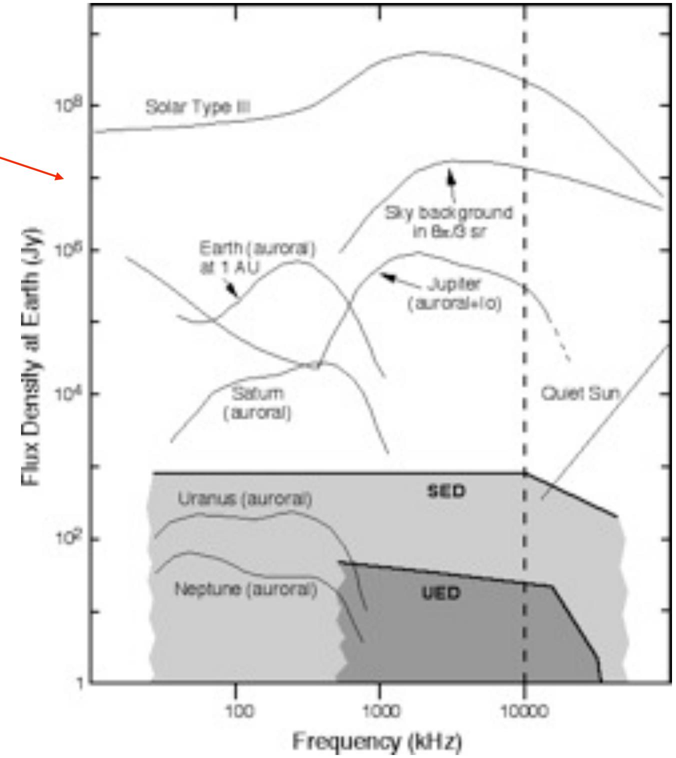
Saturn's Electrostatic Discharges :

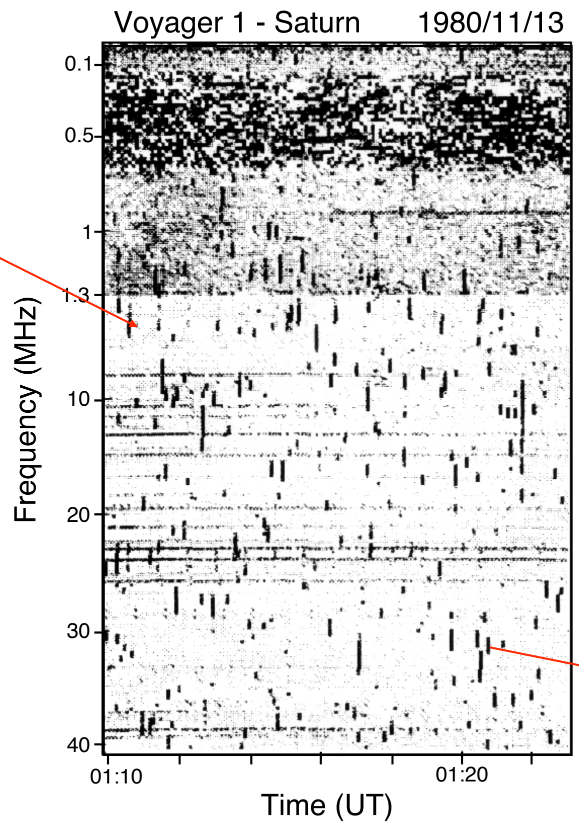
- 30-450 msec, intense (60-100 W/Hz, 10^{8-10} W)
- spectrum from ≲20 kHz to ≳40 MHz (↓ in f^{0}-f^{-1})
- equatorial storm at V1 flyby, spread at V2-flyby
- controversial ? (no whistlers = B lines not sampled,

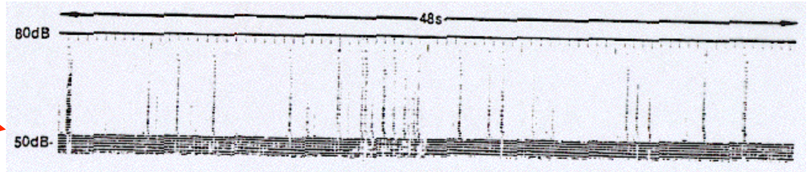
  no optical = scattered ring light)

→ ionospheric probing



[Zarka et al., 2003]





[Warwick et al., 1981]

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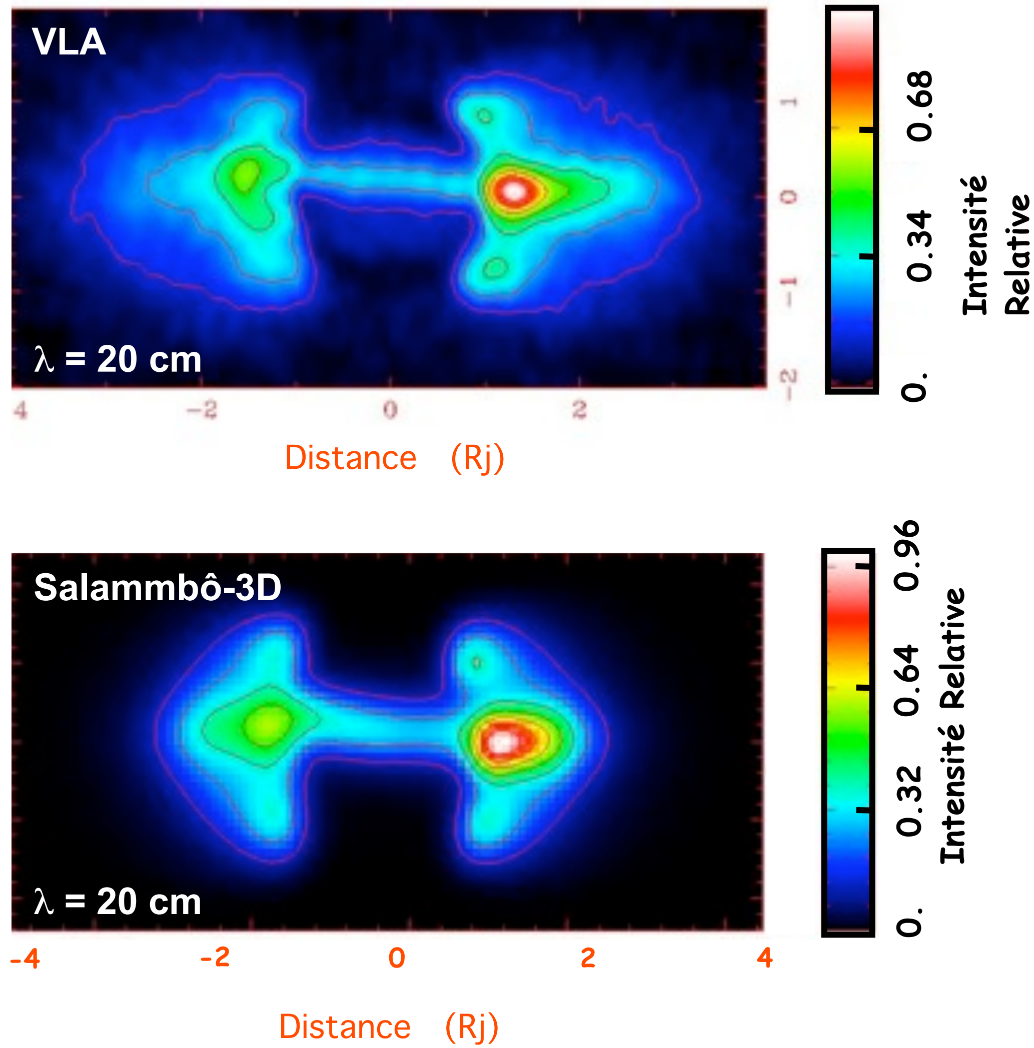
Jupiter



[Santos-Costa, 2001]

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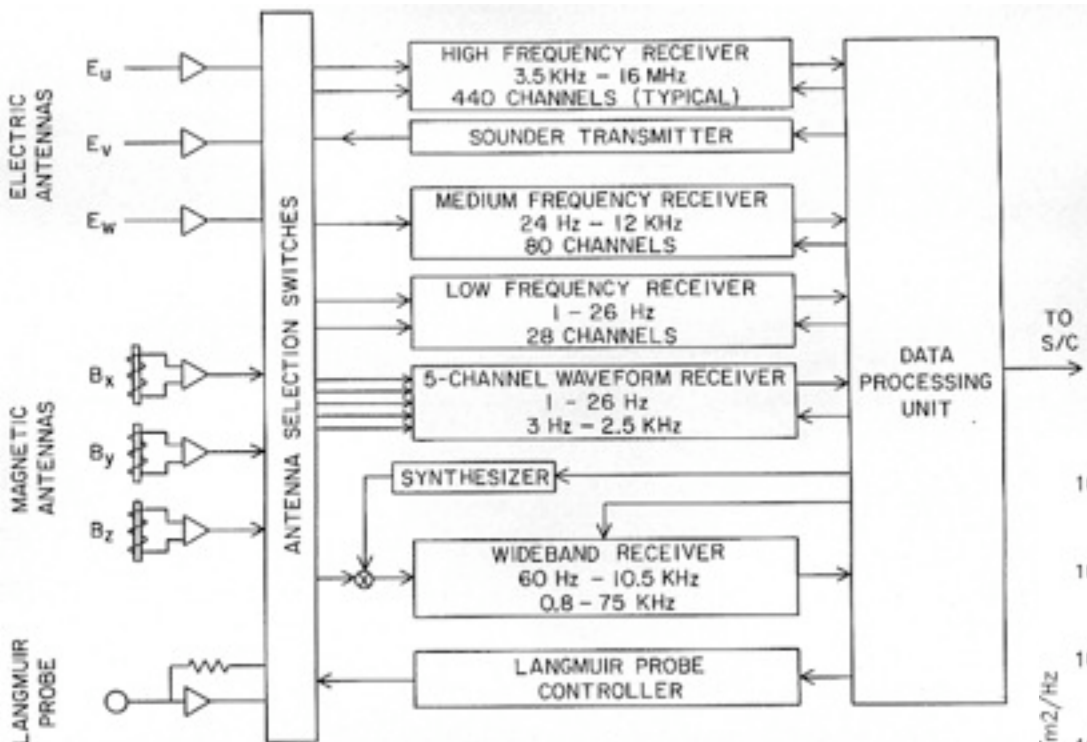
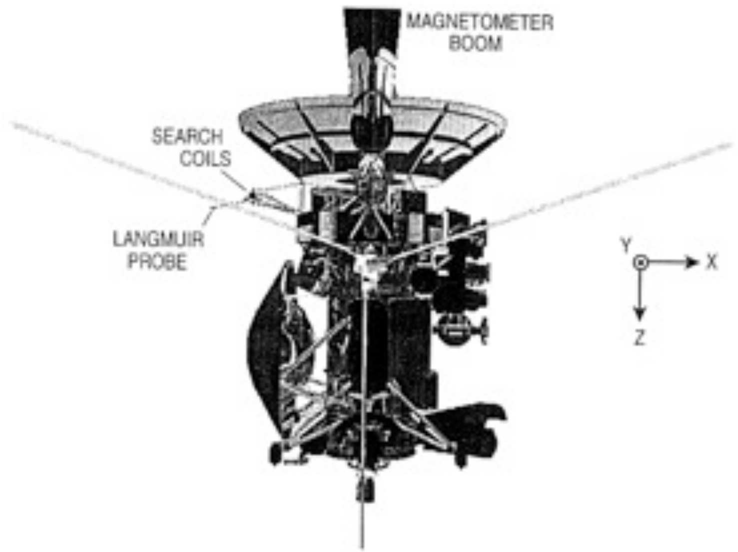
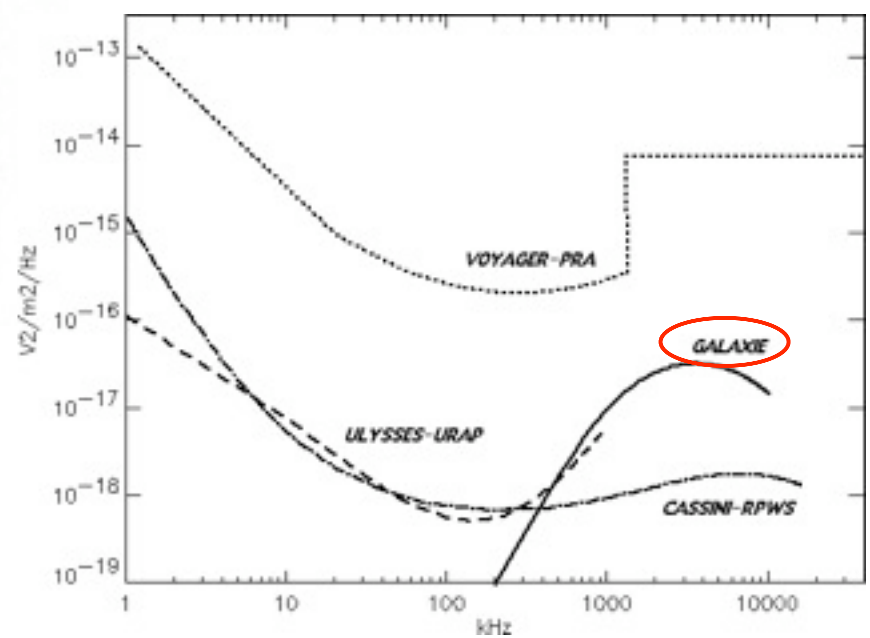
Cassini-RPWS : HFR + WBr

→ polar., DF, hi-res., sensitivity, flexibility



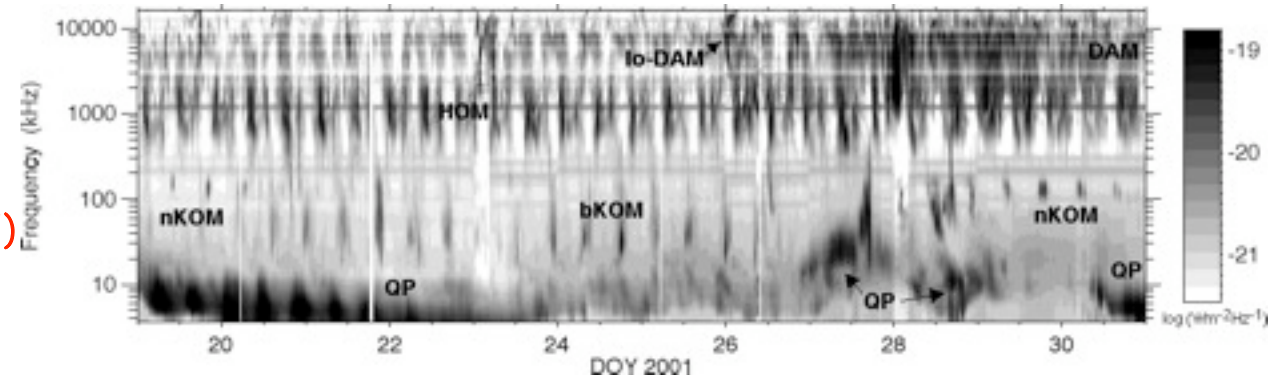


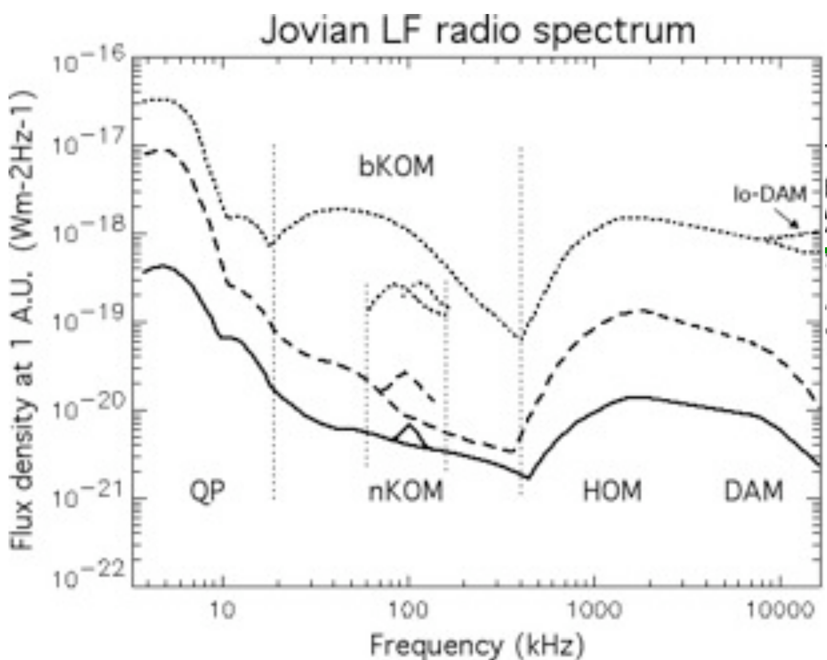


RPWS observations at Jupiter :

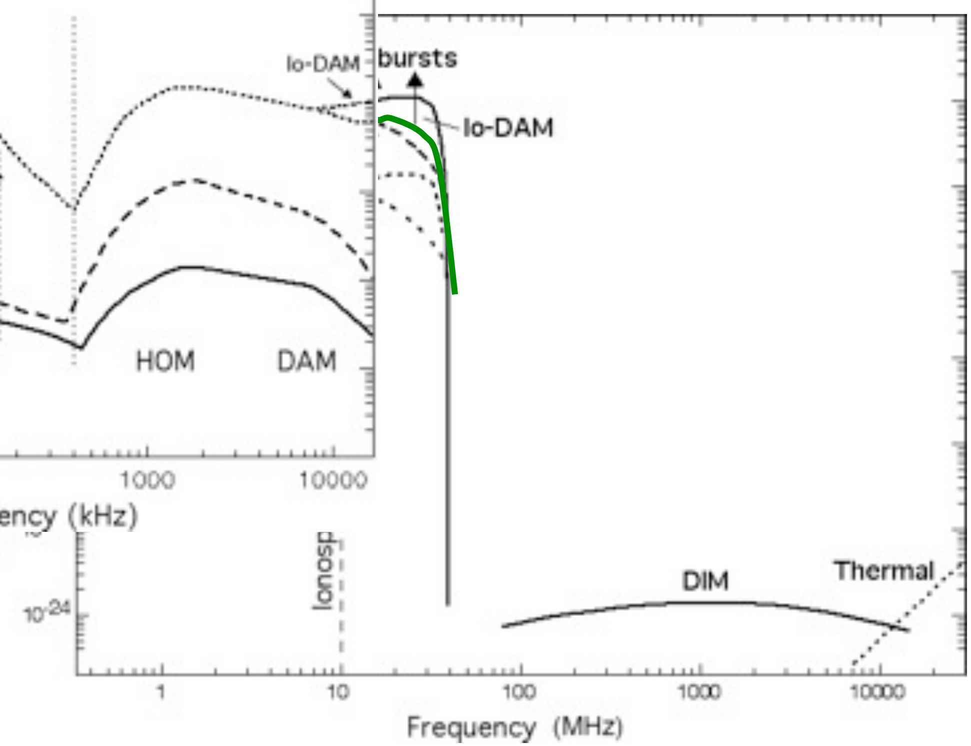
- updated radio spectrum and variability

(reference = galactic background)





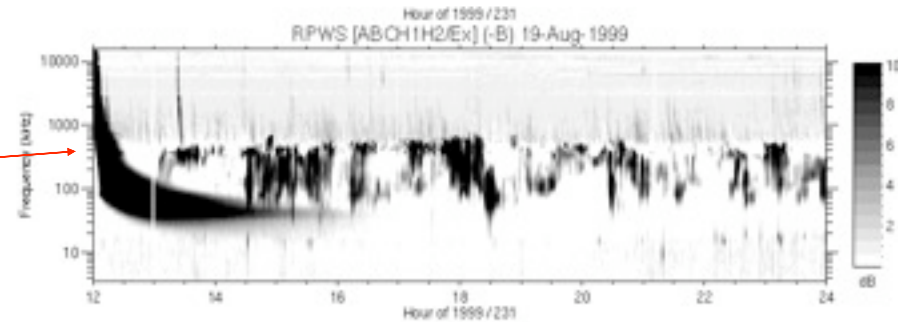
[Carr et al., 1983]



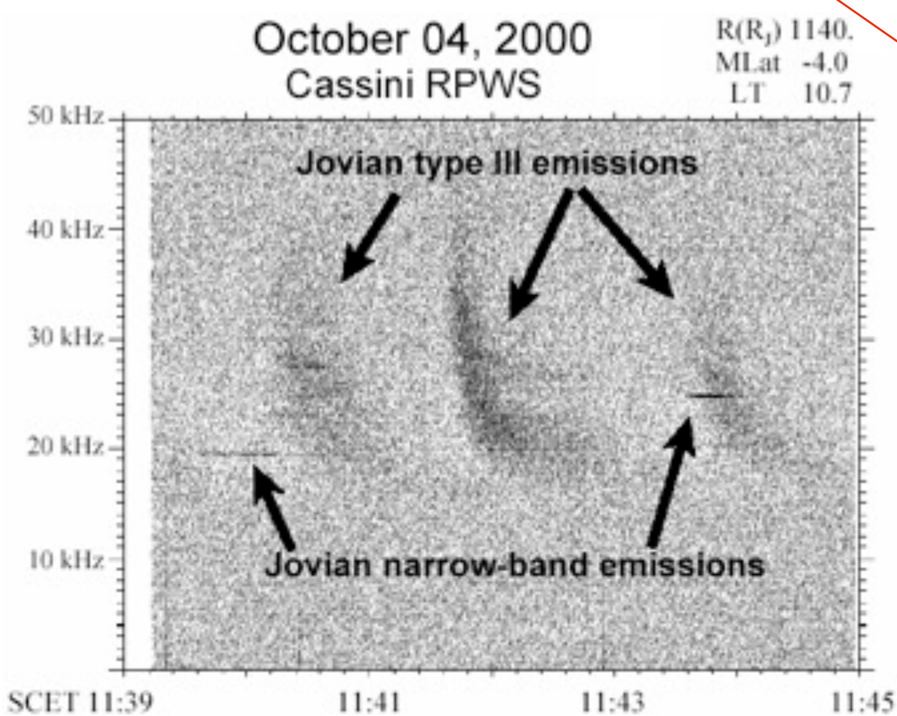
[Zarka et al., 2003]

RPWS observations at Jupiter :

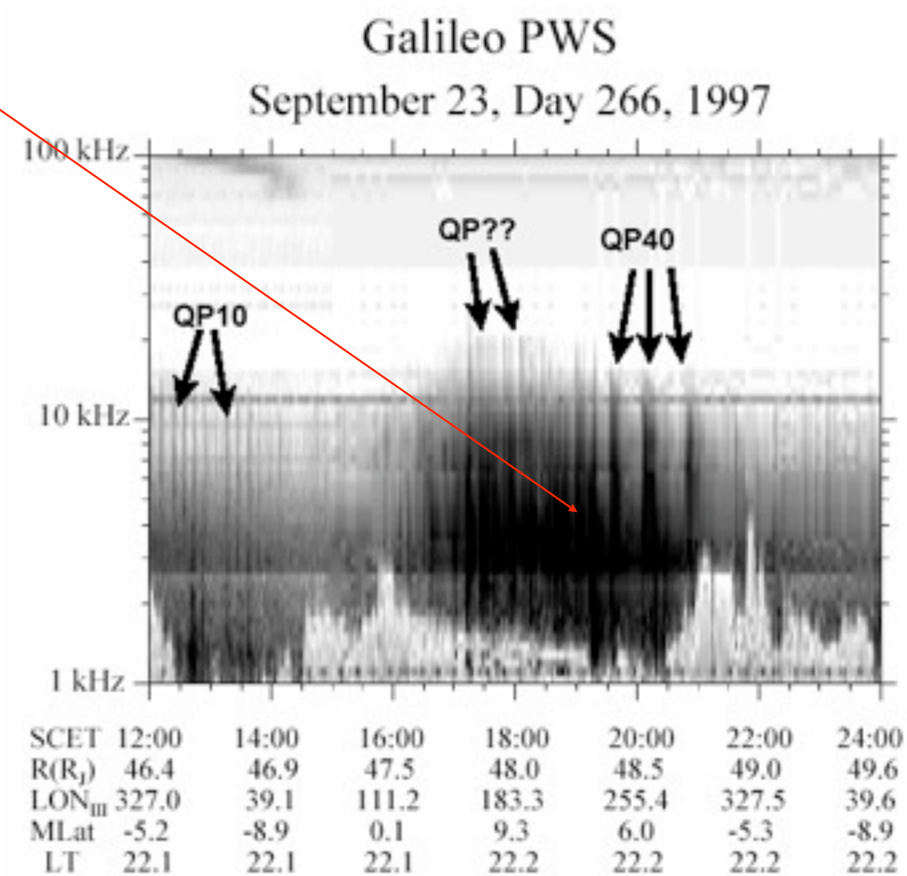
- updated radio spectrum
- QP bursts (JtIII ; LF bursts at Earth)
- link with escaping NTC ?



[Steinberg et al., 2003]

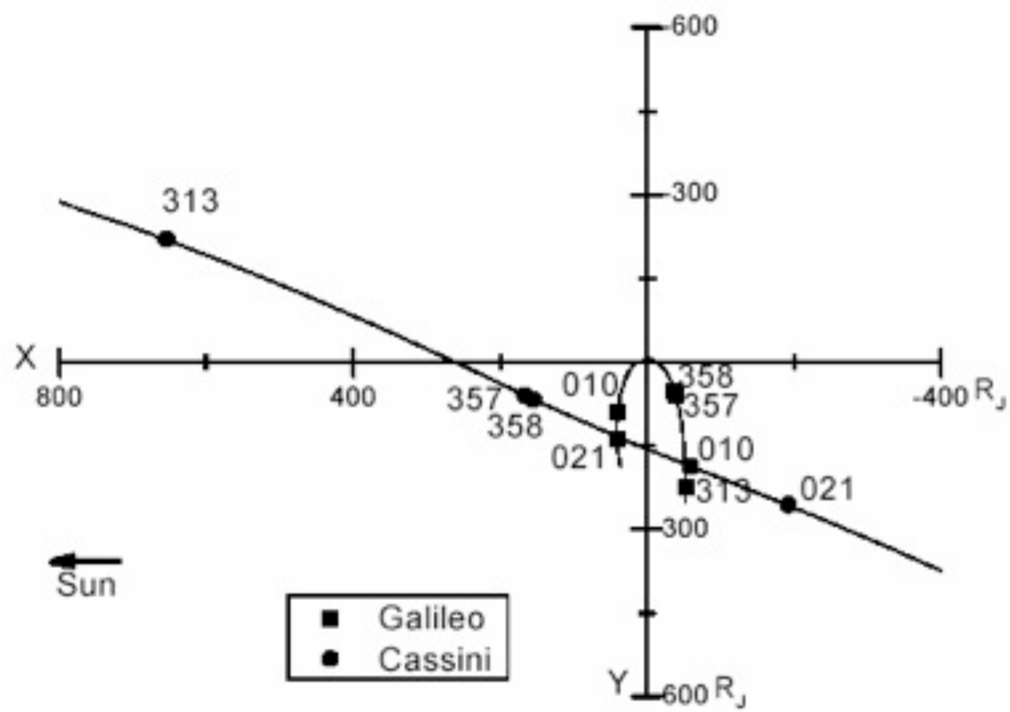


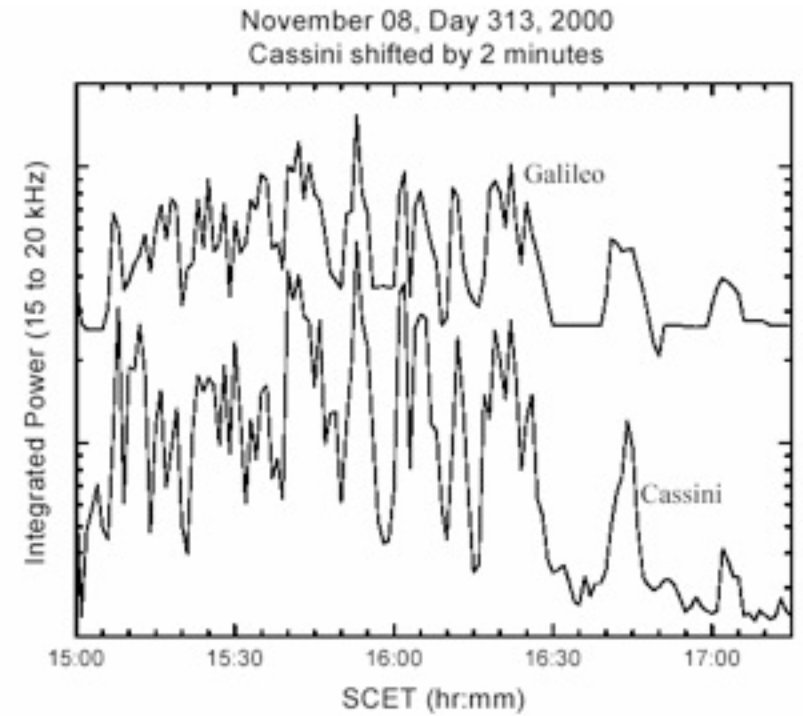
[Hospodarsky et al., 2003]



RPWS observations at Jupiter :

- updated radio spectrum
- QP bursts : ≥2π sr beam





[Hospodarsky et al., 2003]

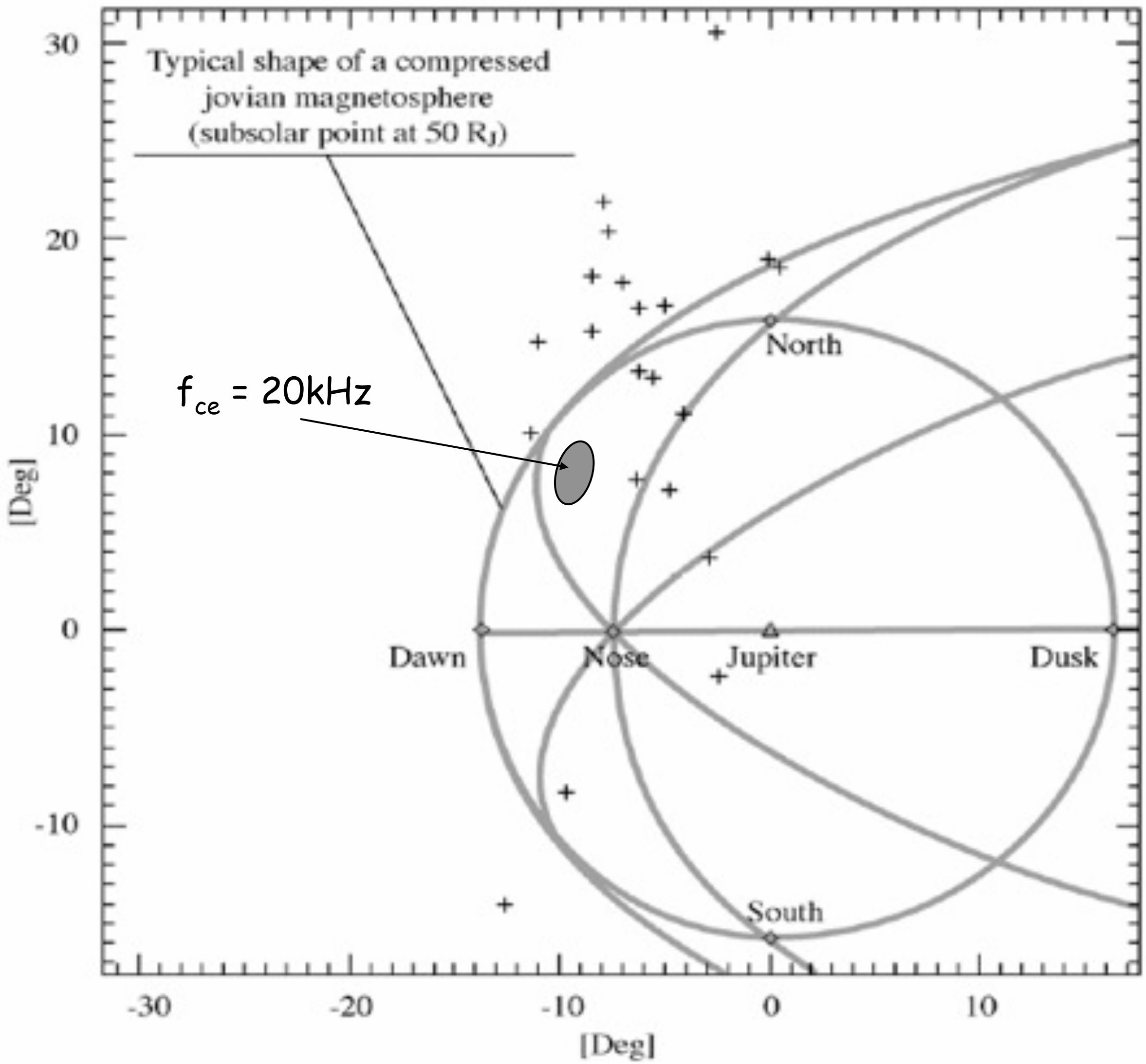
RPWS observations at Jupiter :

- updated radio spectrum
- QP bursts : ≥2π sr beam
- Direction-Finding :

  very high-lat. source (propagation?)

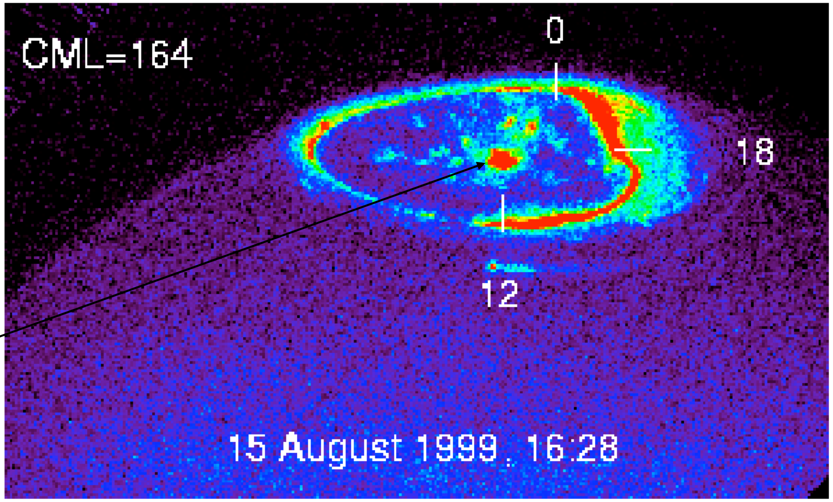
  [Hospodarsky, Cecconi]

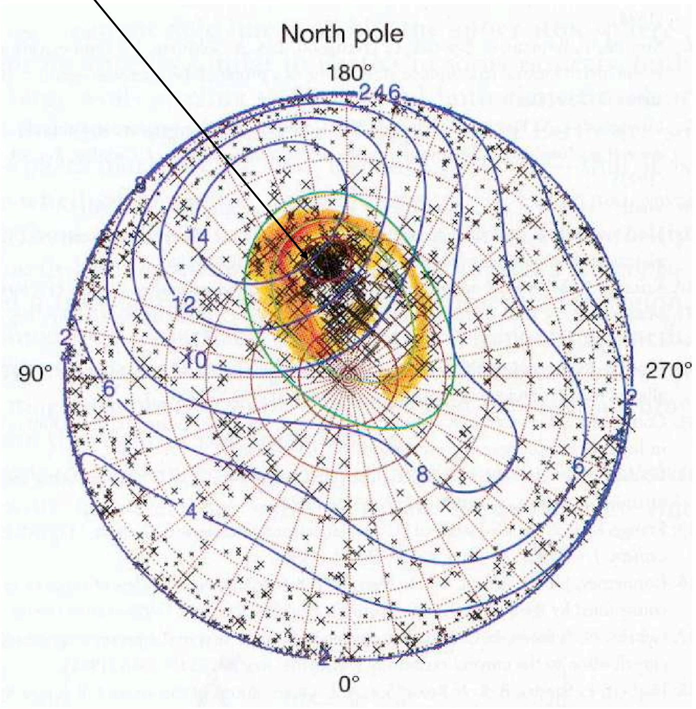
Cassini-RPWS 2000/357, 01:35, f=20 kHz



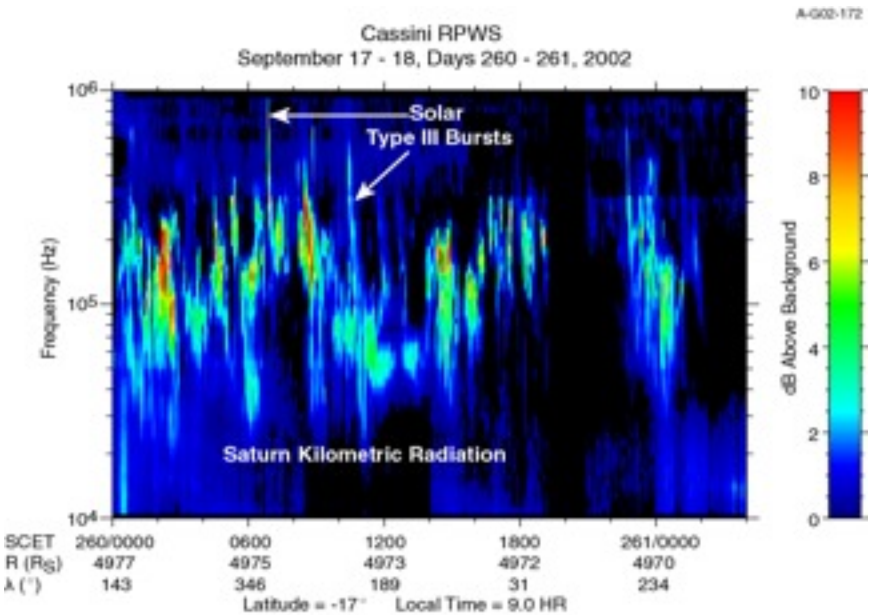
RPWS observations at Jupiter :

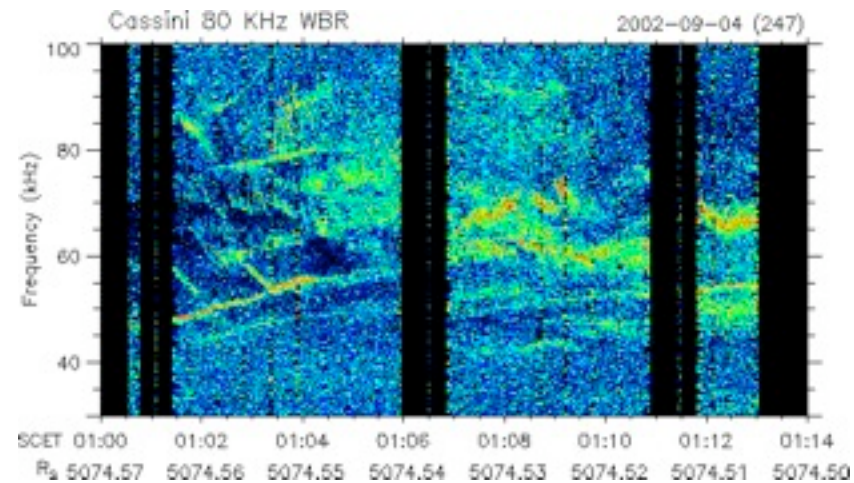
- updated radio spectrum
- QP bursts : ≥2π sr beam
- Direction-Finding
- comparisons with UV, X
  - → UV cusp ? [Pallier and Prangé, 2001]
  - → X spot : P~45 min. [Gladstone et al., 2001]

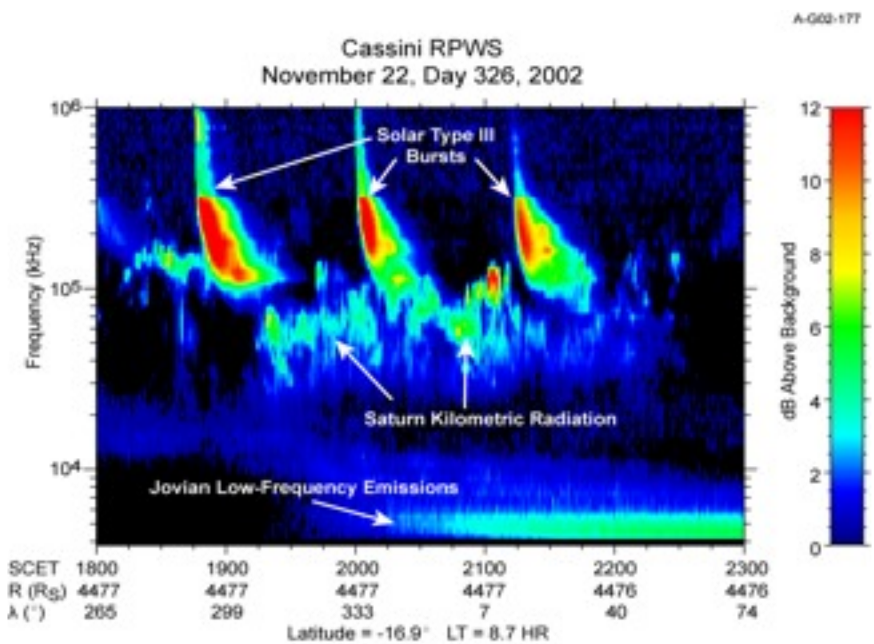


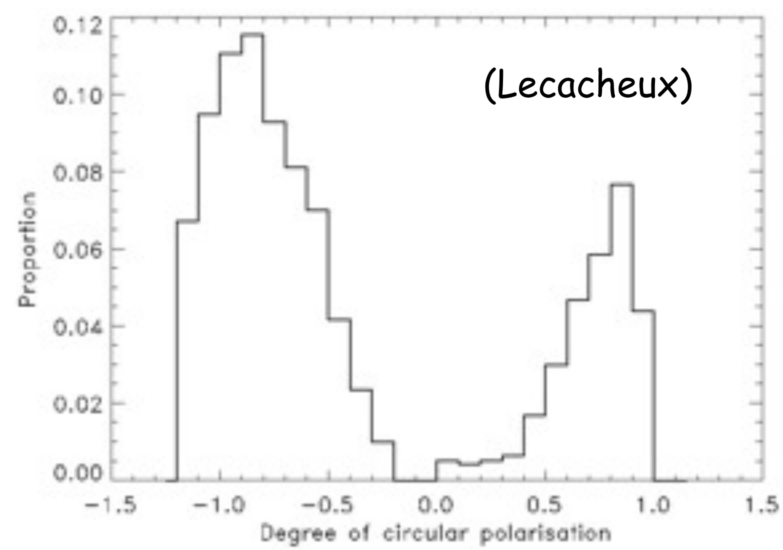


First RPWS observations of SKR :









Open questions about Saturn's radio emissions :

[Kurth & Zarka, 2001]

- SKR source : KHI at magnetopause ?
- e- populations in SKR sources (end of mission, + particle measurements)
- fine structures (arcs, bursts) ? mechanism ? saturation ?
- origin of rotational modulation ?
- B anomaly (+ MAG measurements at SOI)
- 1% variations of P_{sat} → source shift ?
- quality of SKR as SW proxy
- correlate SKR modulation with IP shocks, energetic events ? (J)
- correlation with UV auroras

Open questions about Saturn's radio emissions (ctd) :

[Kurth & Zarka, 2001]

- SKR control by Dione ? confirm / explain

  by other satellites (Titan, icy) ?

- Saturn's analog of QP / LF bursts ?

- n-bands from satellite plasma/B interaction ? link with NTC ?

- confirm SED source, locate individual bursts,

  detect whistlers, characterize lightning, meteorology

- extended ionospheric probing

- Titan lightning ? RPWS : ~ 40 close flybys

  (+ atmospheric probe measurements)

- Synchrotron radiation ?

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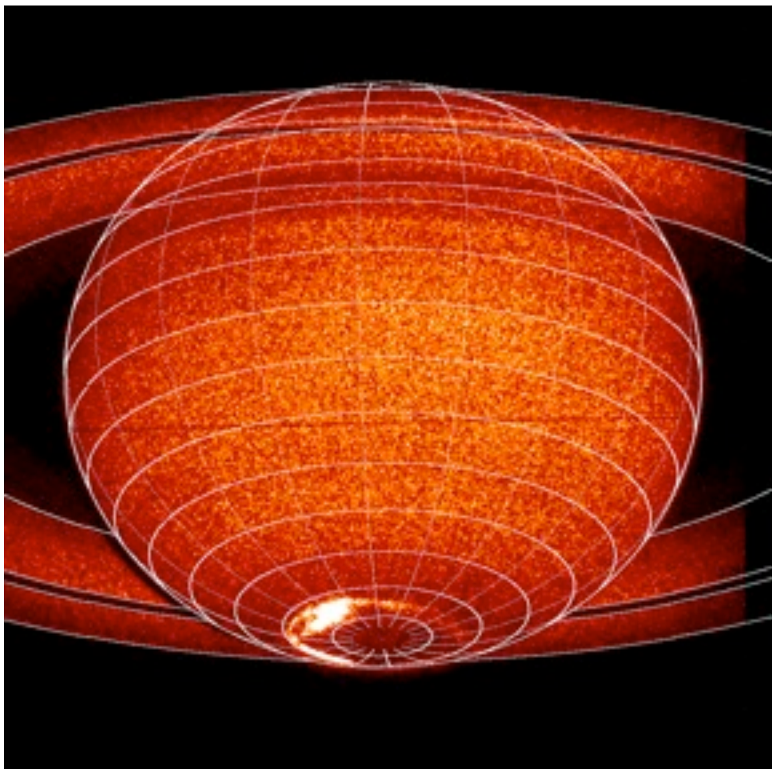
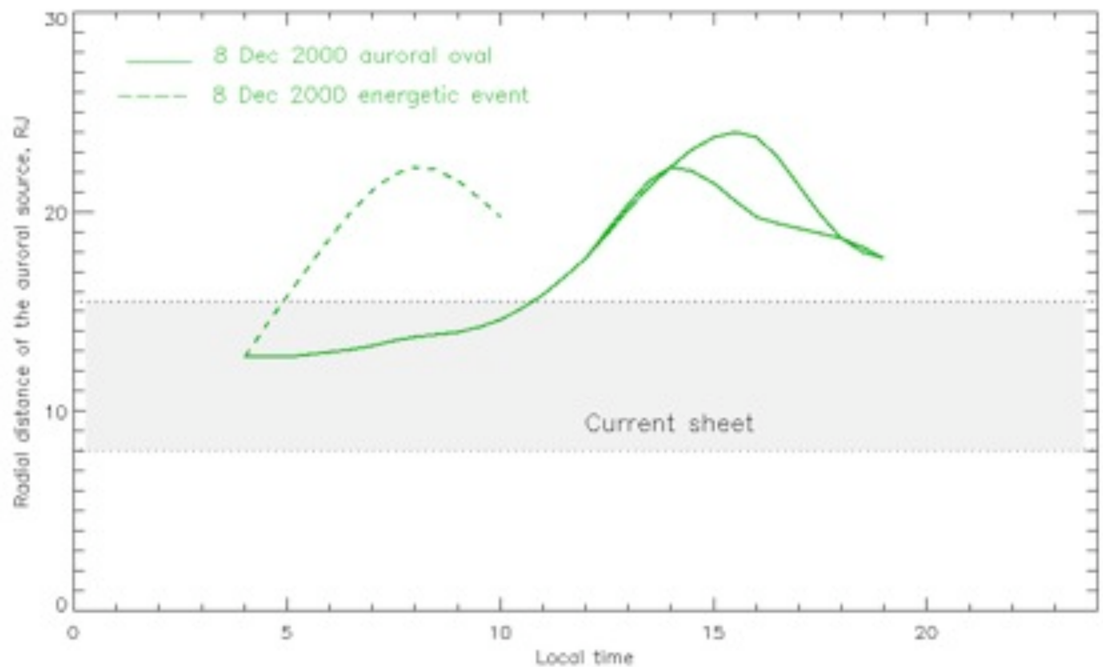
- HST, JMEX
  - → UV auroras, compared magnetospheric response at E, J, S

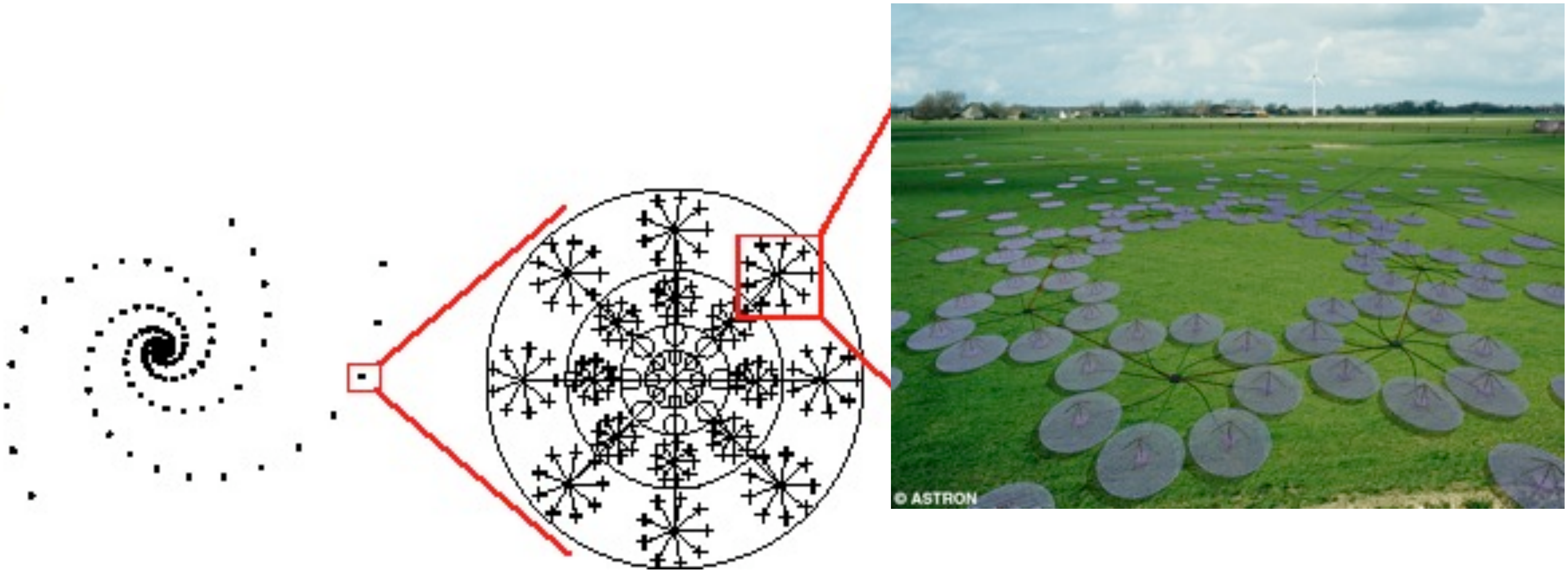


[Prangé et al., 2003]



- LOFAR (LOw Frequency ARray)

  1 km^2, 10-250 MHz → SED



www.lofar.org

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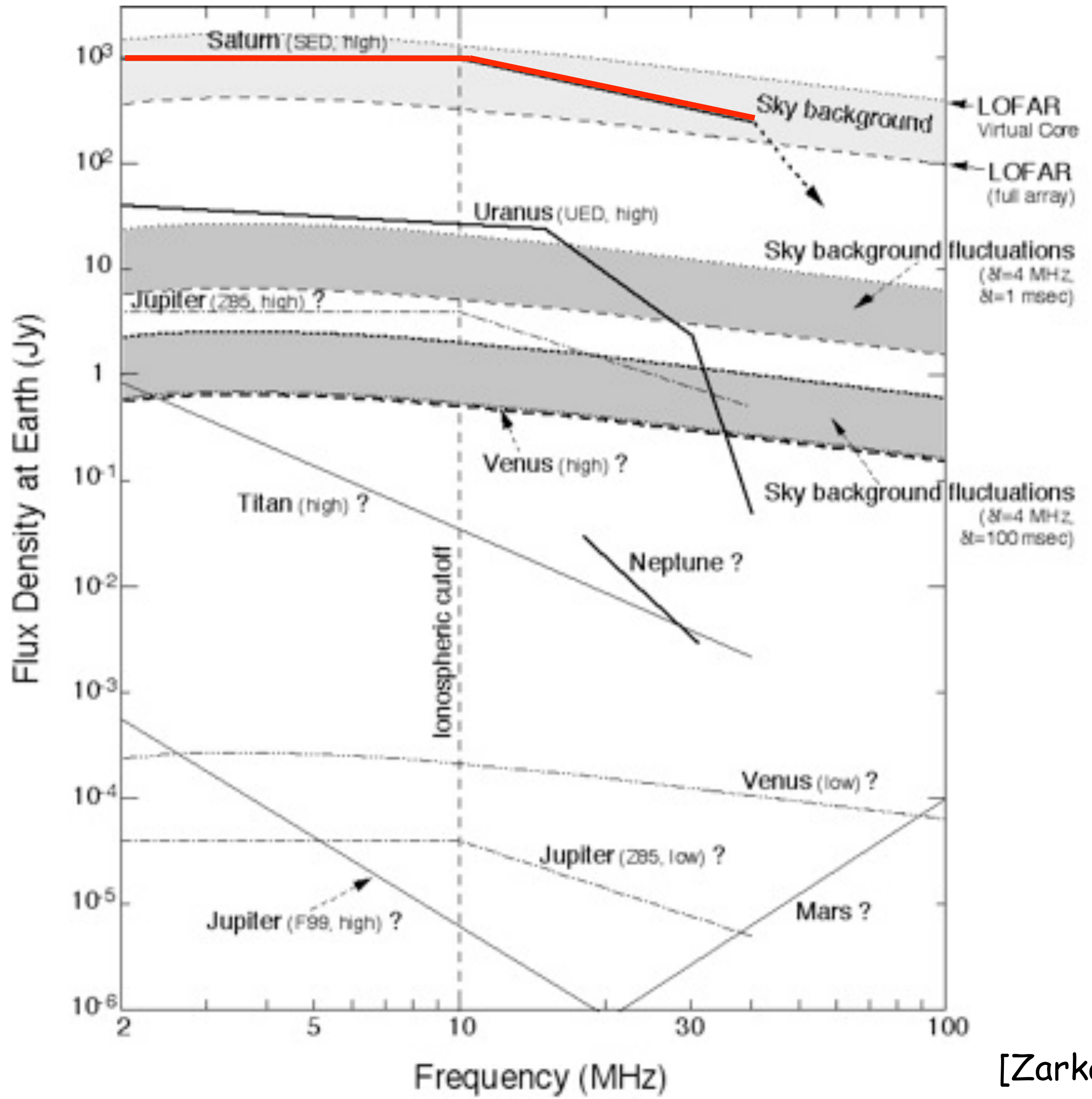

[Zarka et al., 2004]

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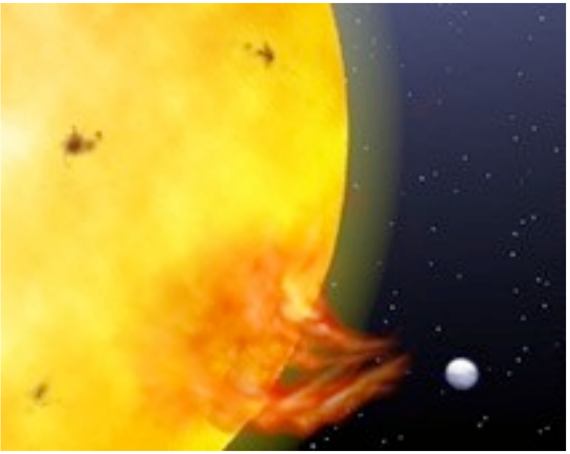
- Back to Jupiter : JPO, JIMO
- Mercury : BepiColombo/MMO
- Uranus, Neptune ?

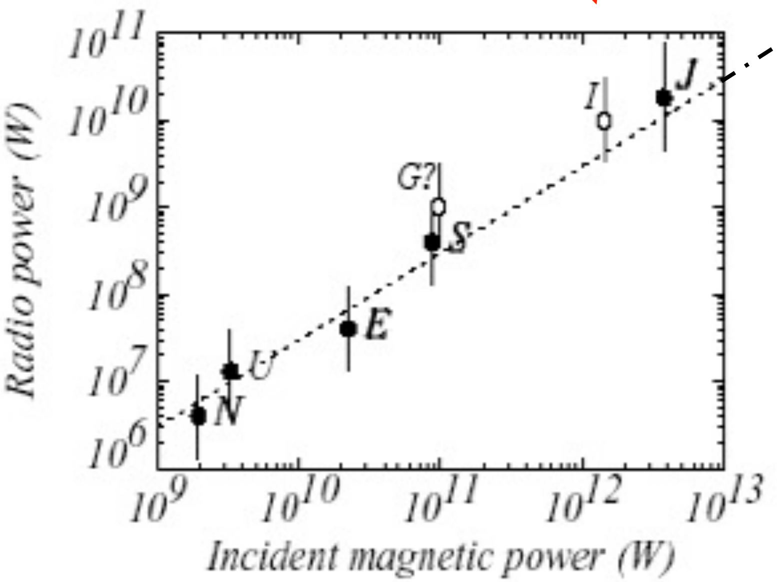
- Why bother with … that ?
  (Radio emissions energetically negligible ~10^{-6} of power input in MS)

  but

- Remote sensing of MS structure & dynamics
  ('MS machine' = plasma phys. lab.)
- e.g. insights to microphysics with hi-res. observations
- Radio and UV bring very complementary (spatial/spectral) information
- Remote sensing of atmospheric electricity (lightning)
- Application to 'plasma-interacting' bodies
  (natural/artificial satellite - planetary B, magnetized binaries, hot Jupiter - star)



[Shkolnik et al., 2003]



[Zarka et al., 2001]