

Radio Emissions in the Solar system and from Extrasolar Planets

Philippe Zarka

LESIA, Observatoire de Paris, Meudon

- Introduction
- Auroral Radio Emissions observations
- Theory of Auroral Radio Emissions
- New results on Jupiter
- New results on Saturn
- Radio emission from exoplanets ?

All started in 1955 ... → decameter emission → cyclotron emission
 → ∃ B Jupiter, |B| ~10 G

OBSERVATIONS OF A VARIABLE RADIO SOURCE ASSOCIATED WITH THE PLANET JUPITER

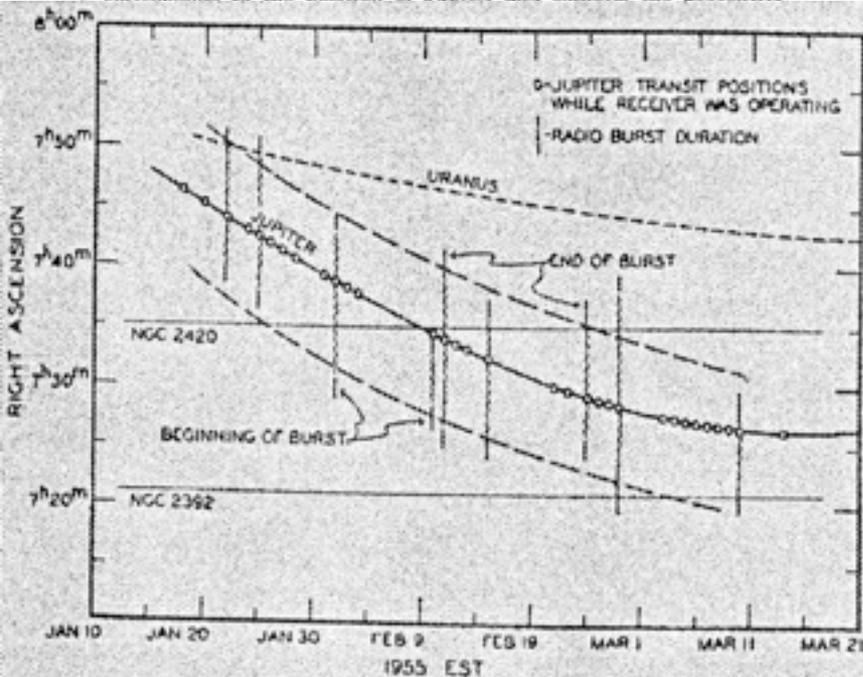
By B. F. BURKE AND K. L. FRANKLIN

Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.

(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



[Burke and Franklin, 1955]

VARIABLE RADIO SOURCE ASSOCIATED WITH JUPITER

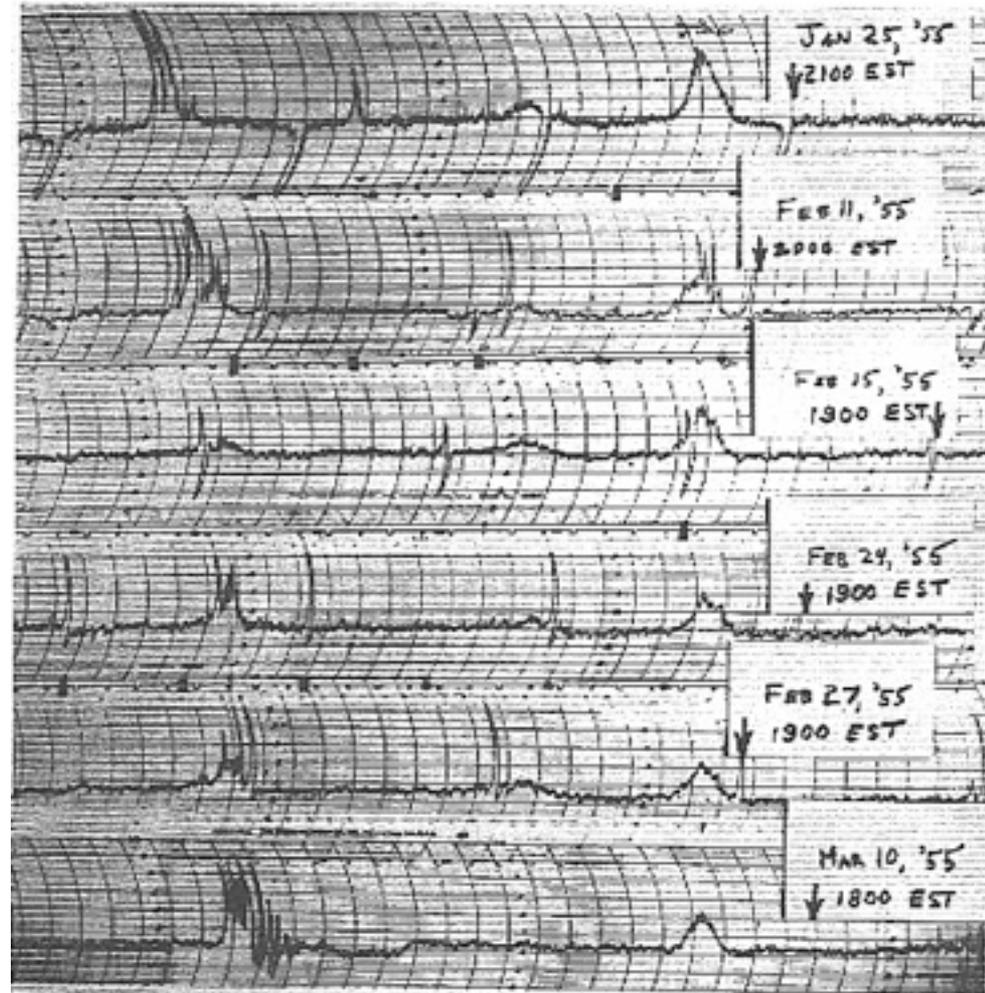
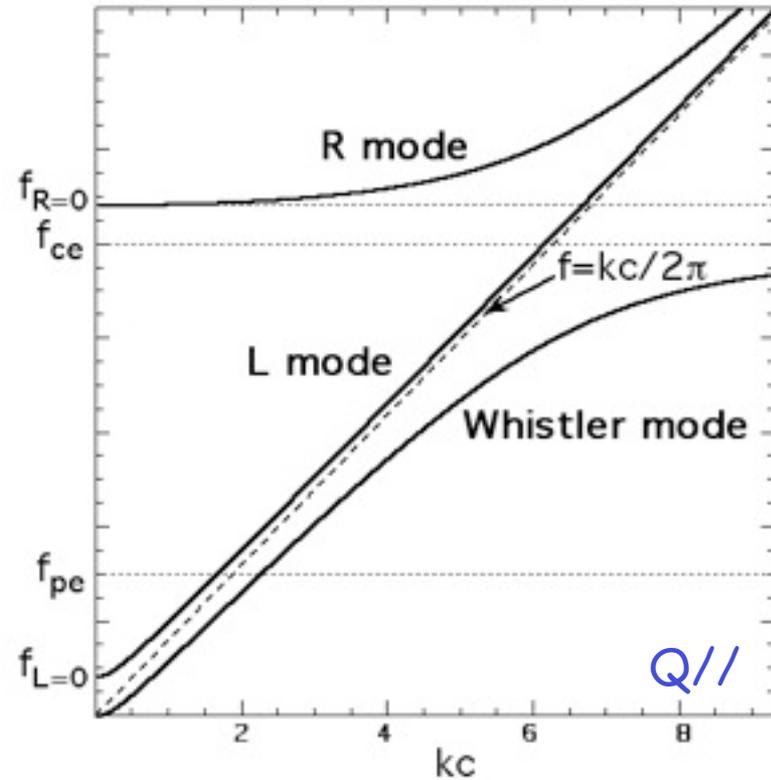
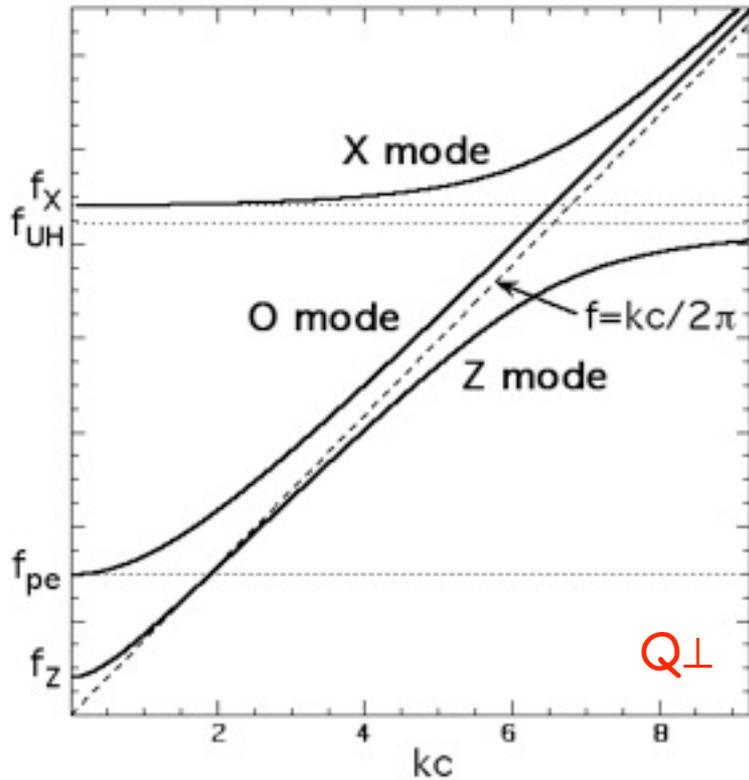


FIG. 2—Phase-switching records showing the appearance of the variable source

"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 $f_{pe}/f_{ce}=0.3$

Characteristic frequencies :

$$f_{pe} \propto N_e^{1/2}$$

$$f_{ce} \propto B$$

$$f_{UH} = (f_{pe}^2 + f_{ce}^2)^{1/2}$$

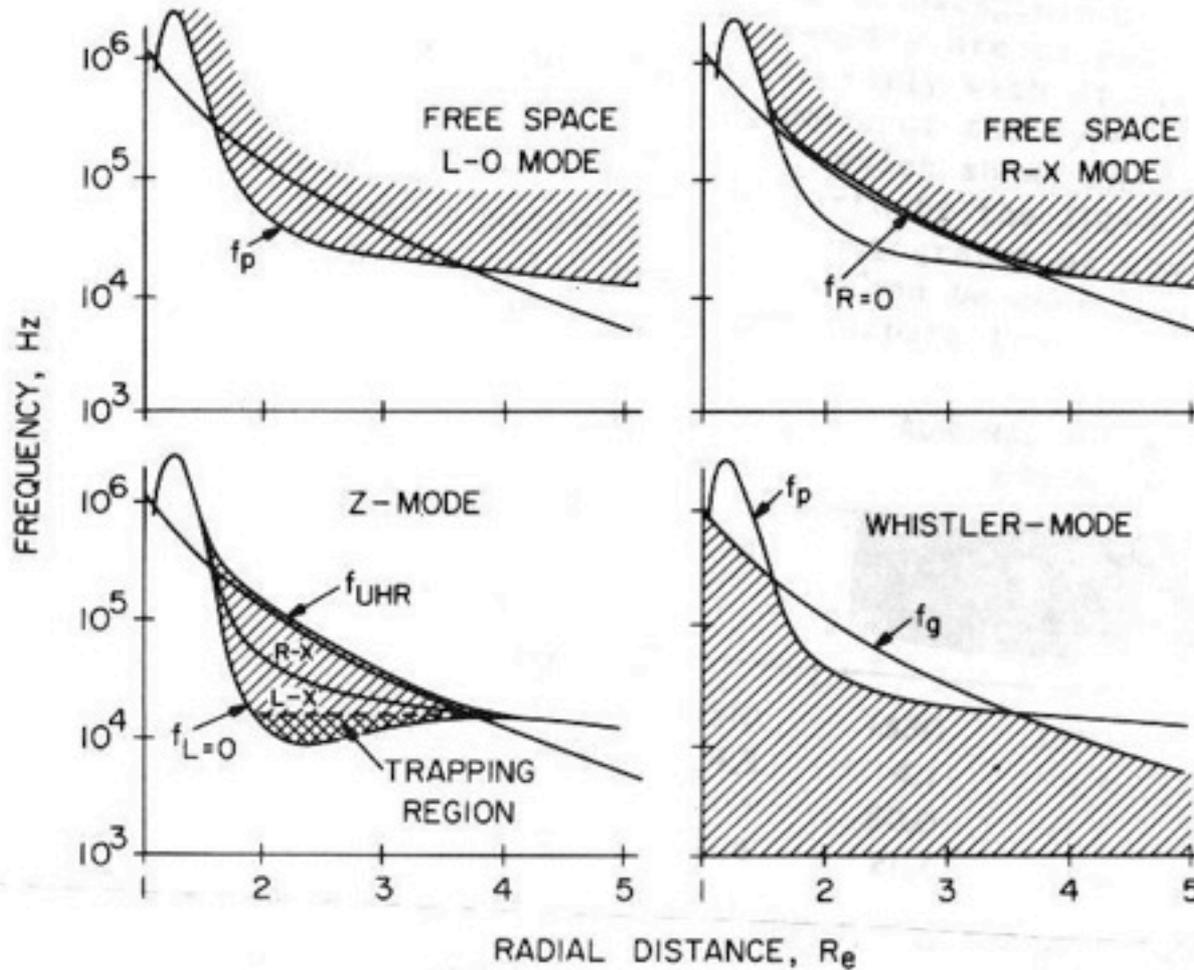
$$f_{LH} = (f_{ce} f_{ci})^{1/2}$$

$$f_{R=0} = f_X = (f_{pe}^2 + (f_{ce}/2)^2)^{1/2} + f_{ce}/2$$

$$f_{L=0} = f_Z = (f_{pe}^2 + (f_{ce}/2)^2)^{1/2} - f_{ce}/2$$

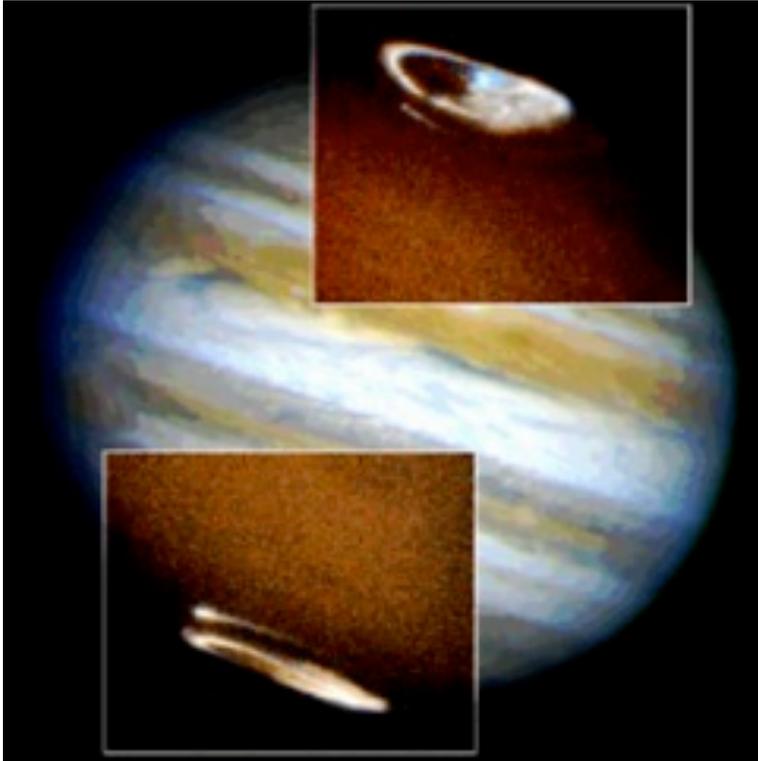
+ equivalent ion frequencies

O & X modes can propagate to 'infinity'

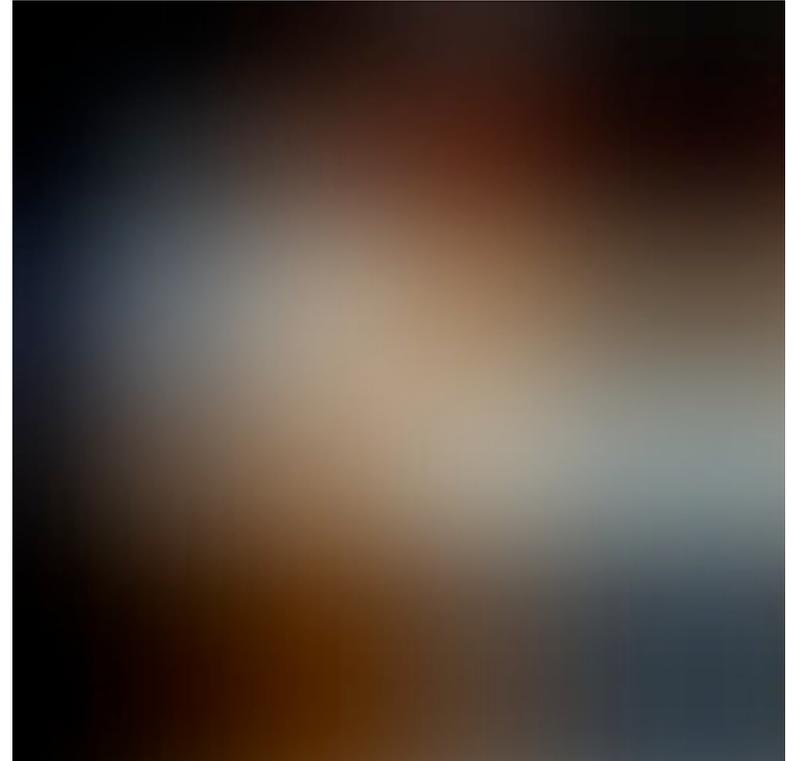


Frequency range of the four cold plasma modes for a representative electron density profile over the polar region.

λ/D generally ~ 1 or $> 1 \rightarrow$ no angular resolution



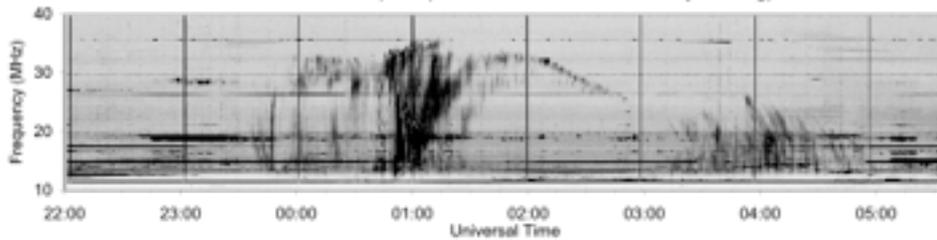
UV eyes



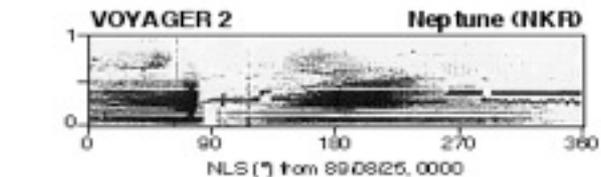
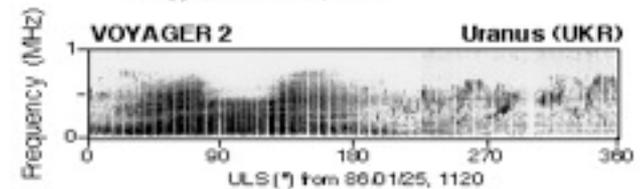
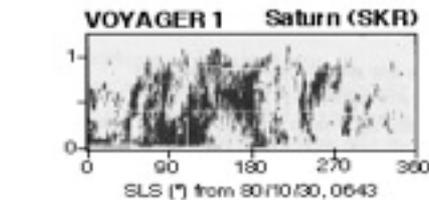
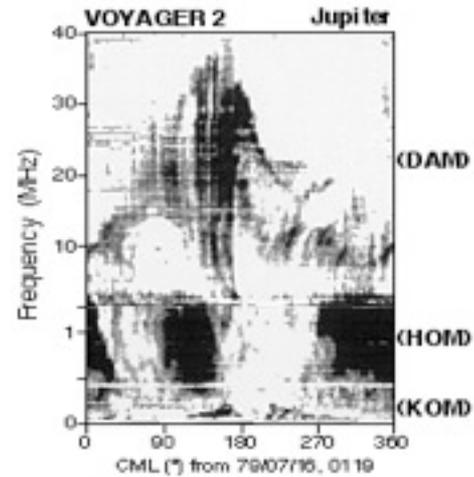
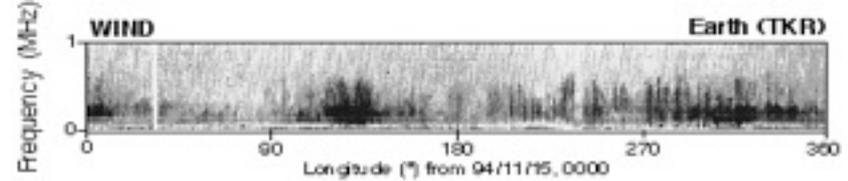
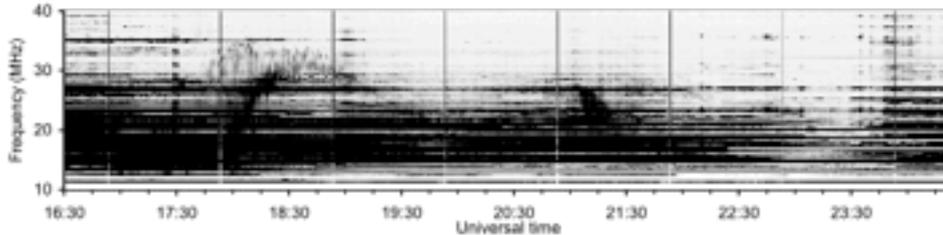
Radio eyes (optimistic)

Importance of
dynamic spectra
(t,f) distributions
of intensity or polarization

JUPITER 1991 Jan1 (Ionospheric conditions : winter - early morning)

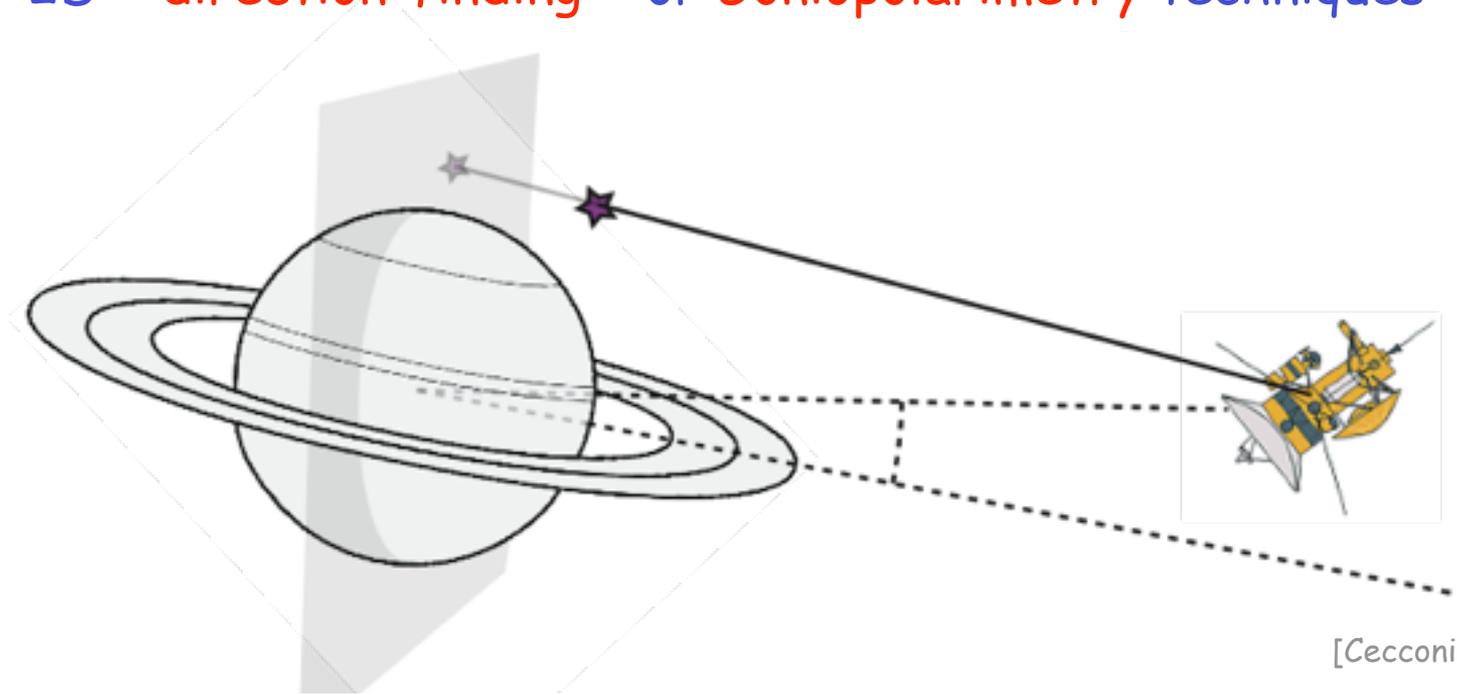


JUPITER 1991 Mar17 (Ionospheric conditions : summer - late evening)

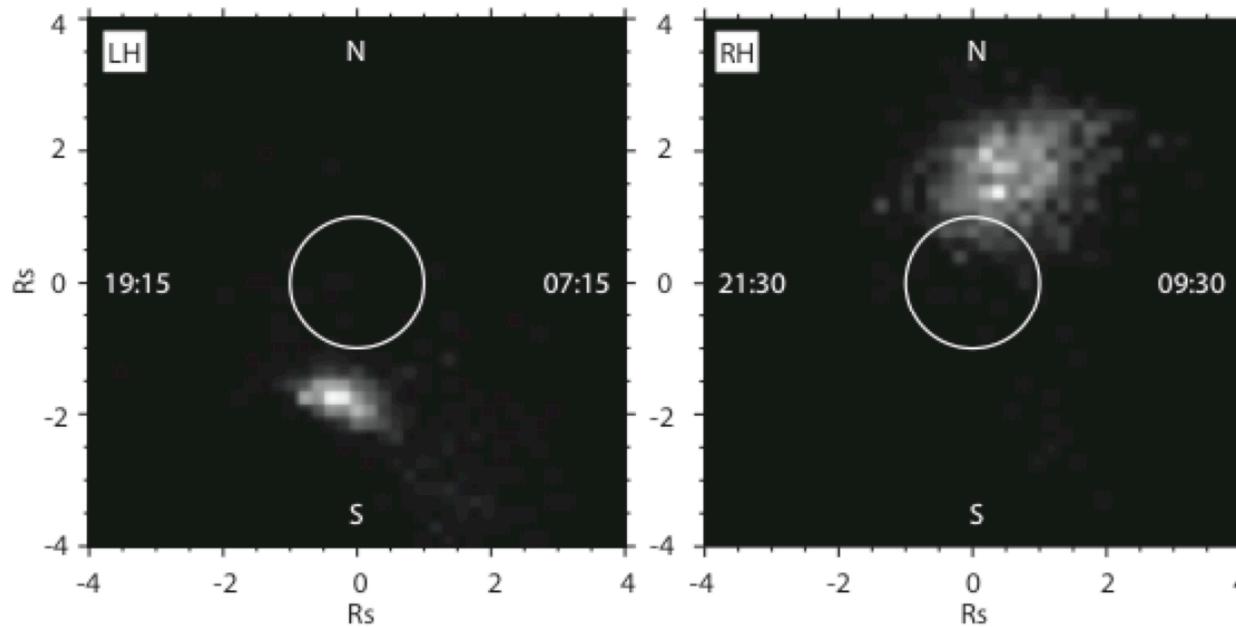


All magnetized planets produce radio emissions

2D « direction-finding » or Goniopolarimetry techniques



[Cecconi et al., 2008]



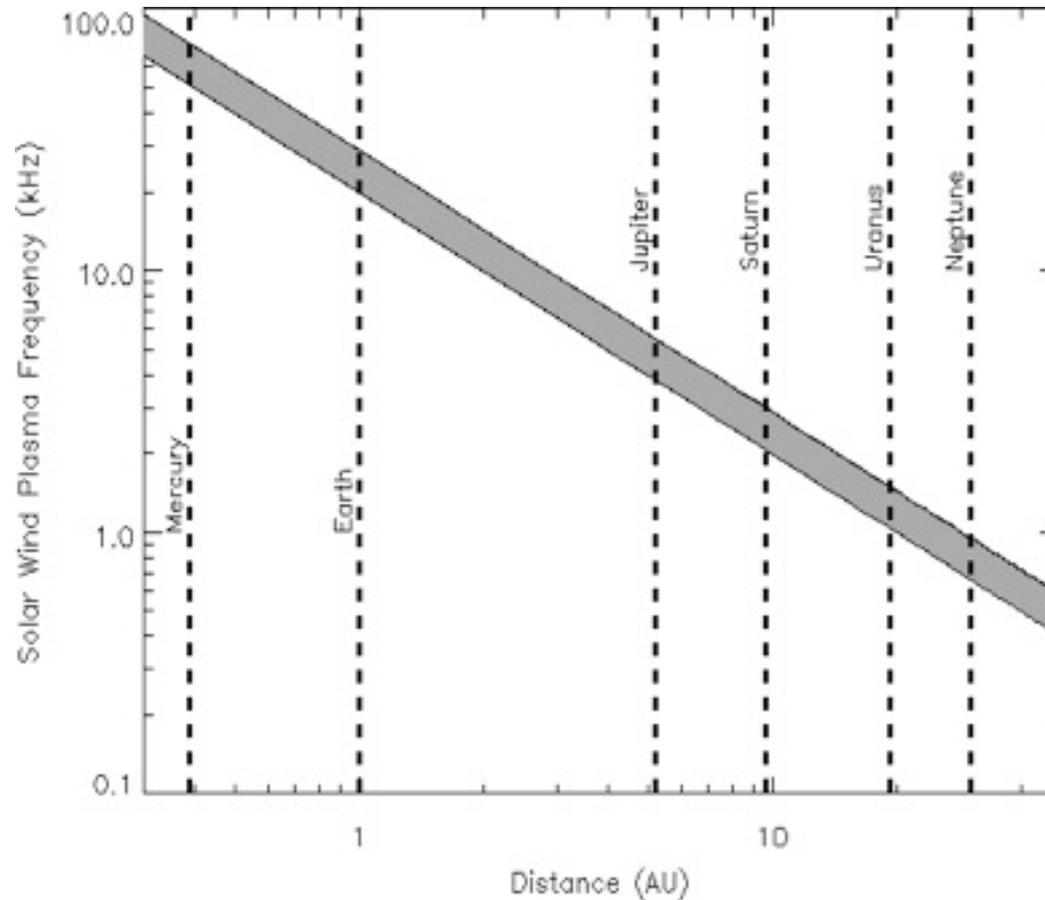
Observations of planetary radio emissions

Radiotelescope or Spacecraft	Planet	Measurement Capabilities
Ground-based radiotelescopes (≥ 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
Cassini	(E J) S	I, Q, U, V, 2D-DF

Limits on propagation

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

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



[Zarka, 2000]

NB: in a metal, $1e^{-(2\text{\AA})^3} \rightarrow N_e \sim 10^{29} \text{ m}^{-3} \rightarrow f_{pe} \sim 3 \times 10^{15} \text{ Hz}$, $\lambda \approx 100 \text{ nm}$ (UV)

Planetary radio components

Radiosources in the magnetospheres, depend on :

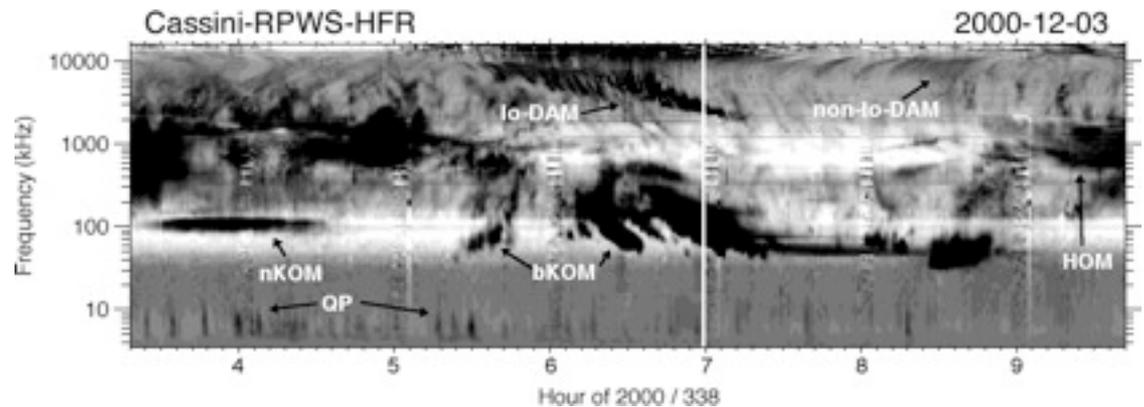
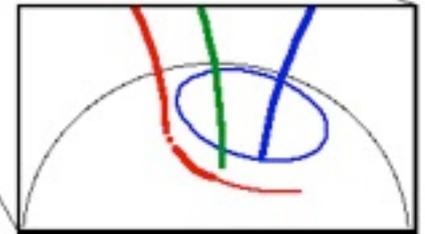
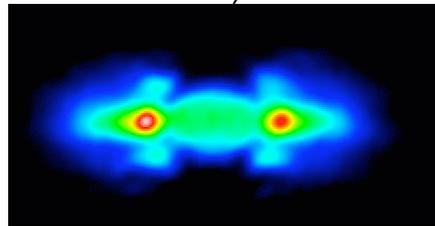
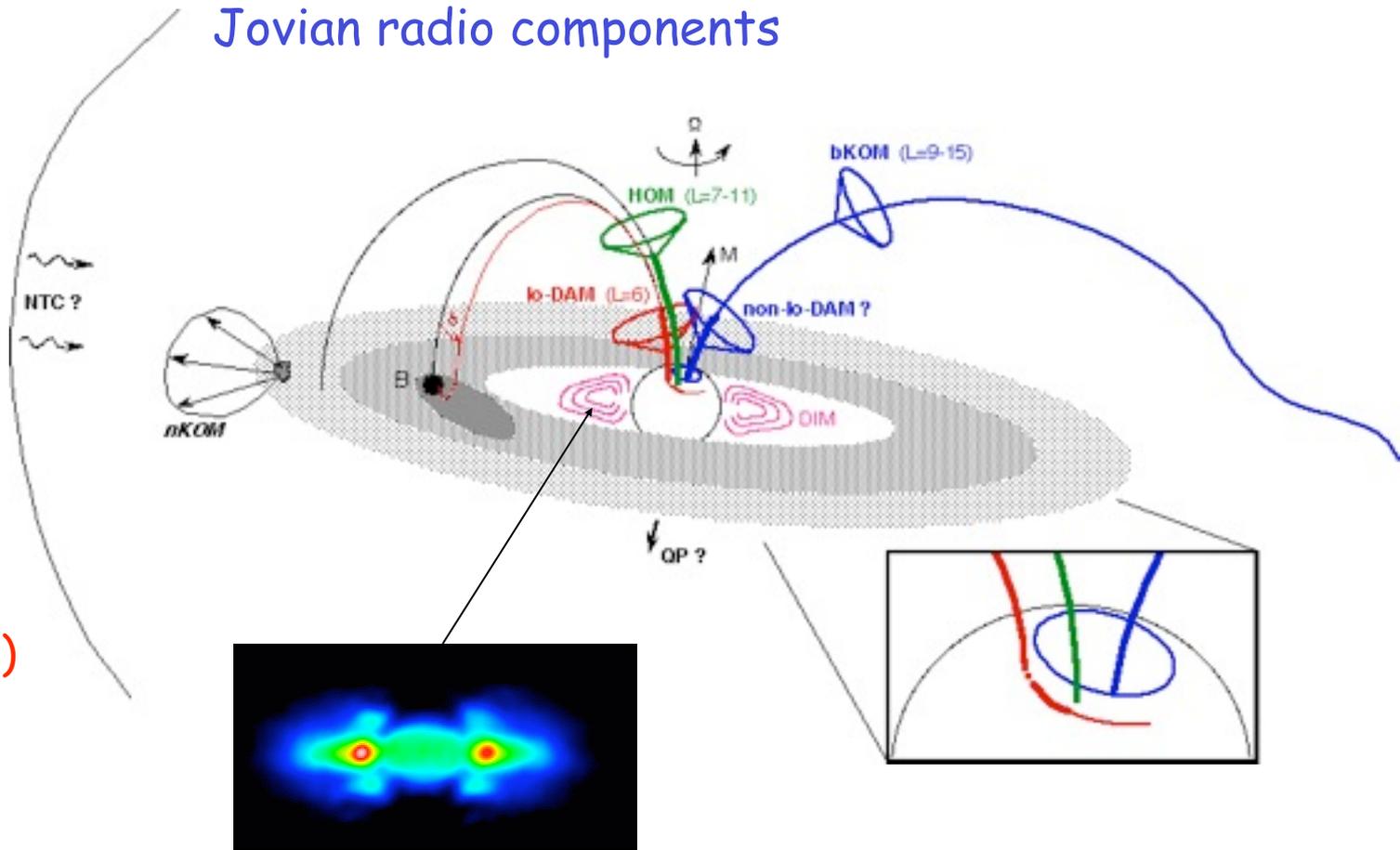
- B topology
- Plasma (N_e) distribution
- Electrons energy (MS dynamics)

Radio component	Planet	λ (m)	f (kHz)	Radiation process
Radiation belts	J (E)	$\sim 10^{-1}$	GHz	Synchrotron (incoherent)
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?	$10^1 - 10^2$	\geq MHz	Cyclotron Maser (")
LF e.m. (NTC...)	E J S U N	$\sim 10^4$	≤ 10 's kHz	Mode conversion e.s. \rightarrow e.m.
nKOM (Io torus)	J	$\sim 10^3$	~ 100 kHz	Instabilities $\sim f_{pe}, f_{UH}$?
Lightning (atmosphere)	E (J) S U (N)	$10^1 - 10^4$	kHz - MHz	Antenna radiation (current discharge)

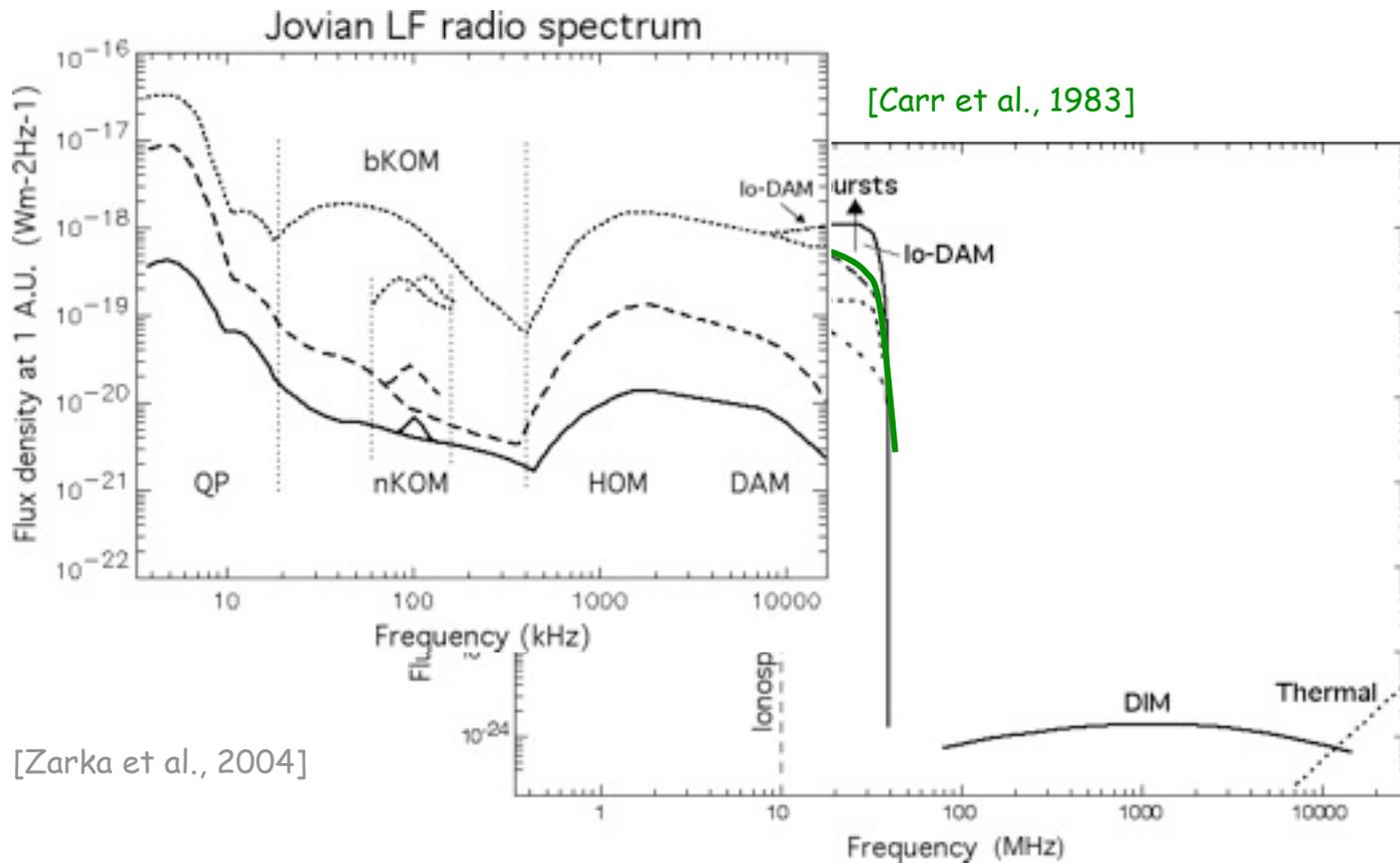
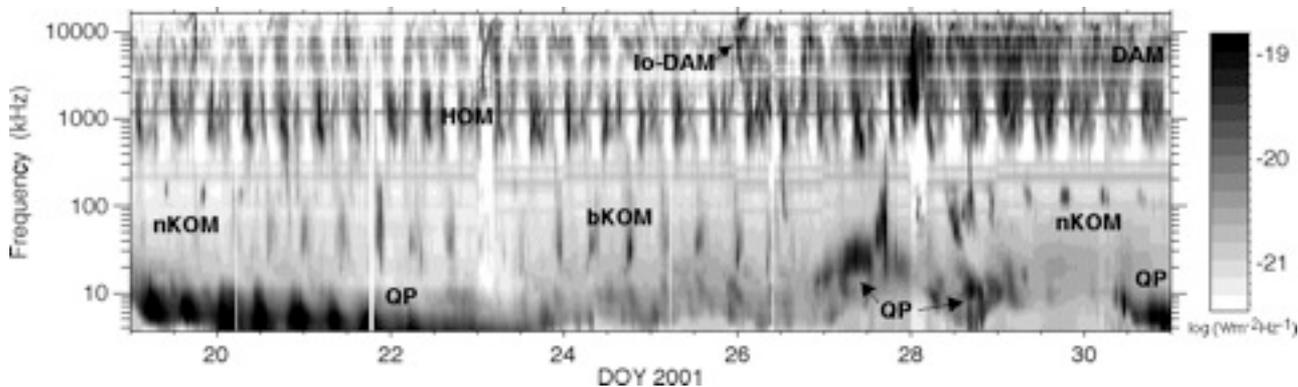
Jovian radio components

Jupiter

- Auroral-DAM
- HOM
- bKOM
- Io-DAM (+G,C?)
- QP-bursts
- NTC
- nKOM
- Synchrotron (DIM)

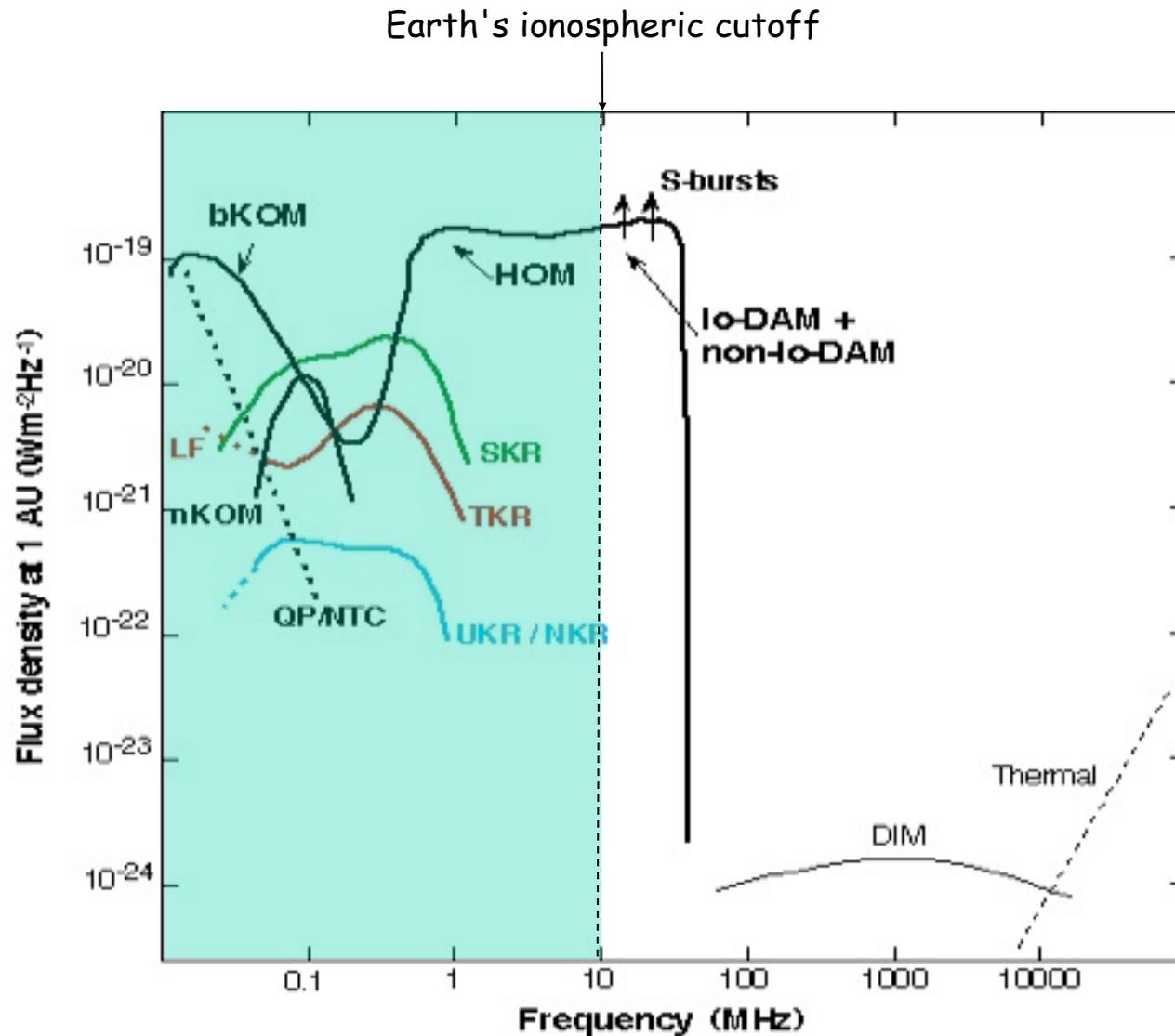


Jovian radio components



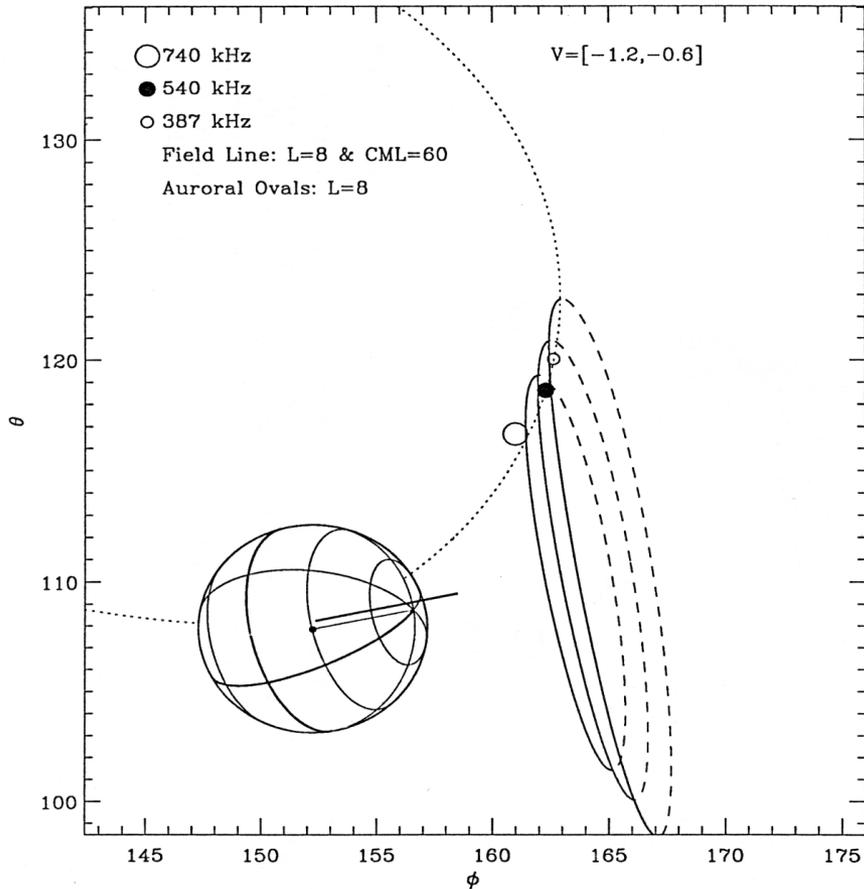
- Introduction
- Auroral Radio Emissions observations
- Theory of Auroral Radio Emissions
- New results on Jupiter
- New results on Saturn
- Radio emission from exoplanets ?

Emissions are intense : $T_B \geq 10^{15-20}$ K



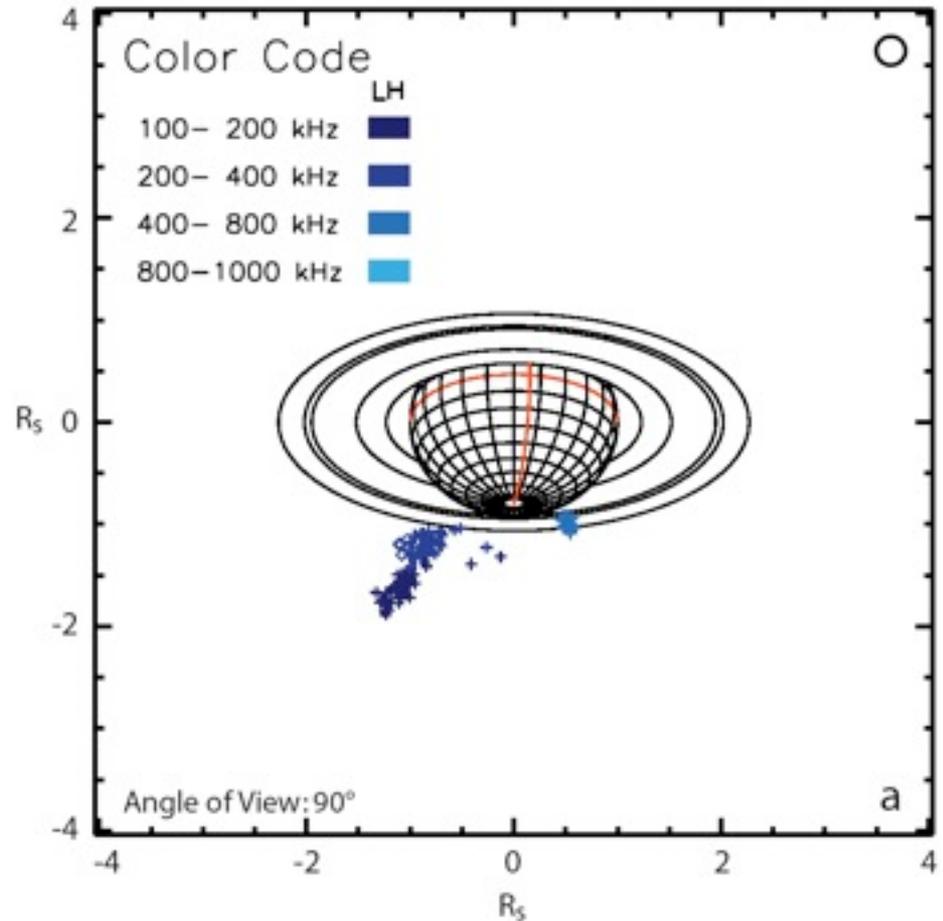
Broadband cyclotron emission : $f \sim f_{ce}$, $\Delta f \sim f$

Ulysses @ Jupiter : HOM



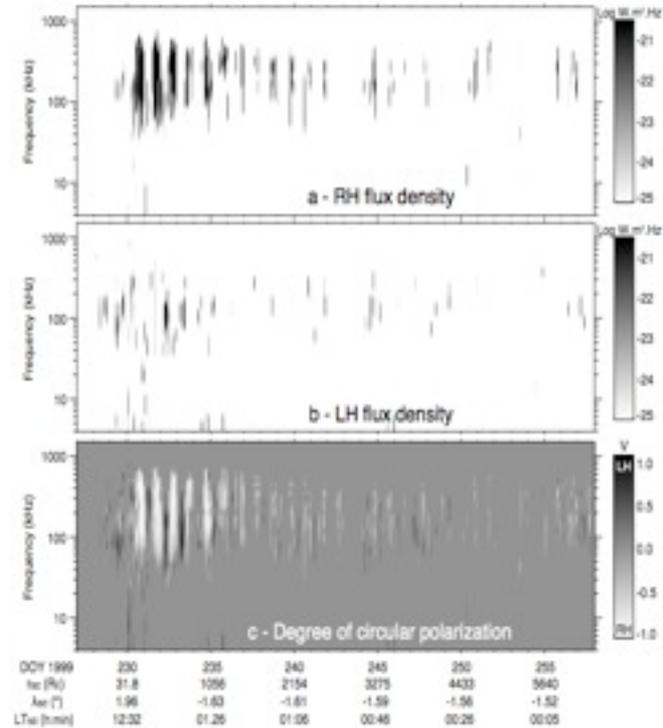
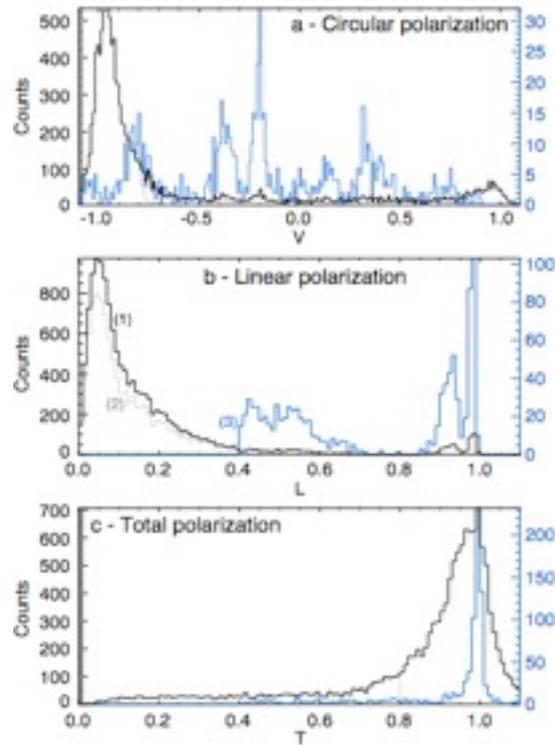
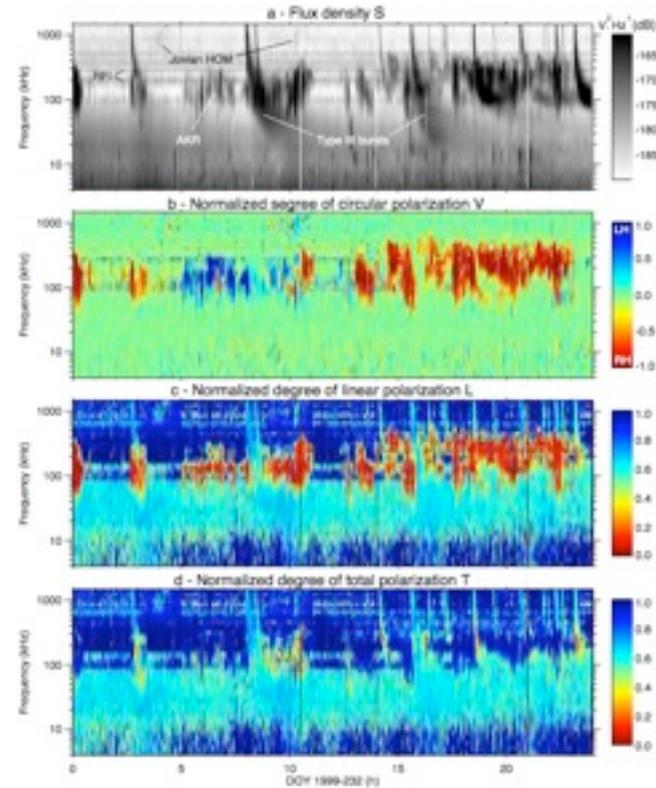
[Ladreitner et al., 1994]

Cassini @ Saturn : SKR



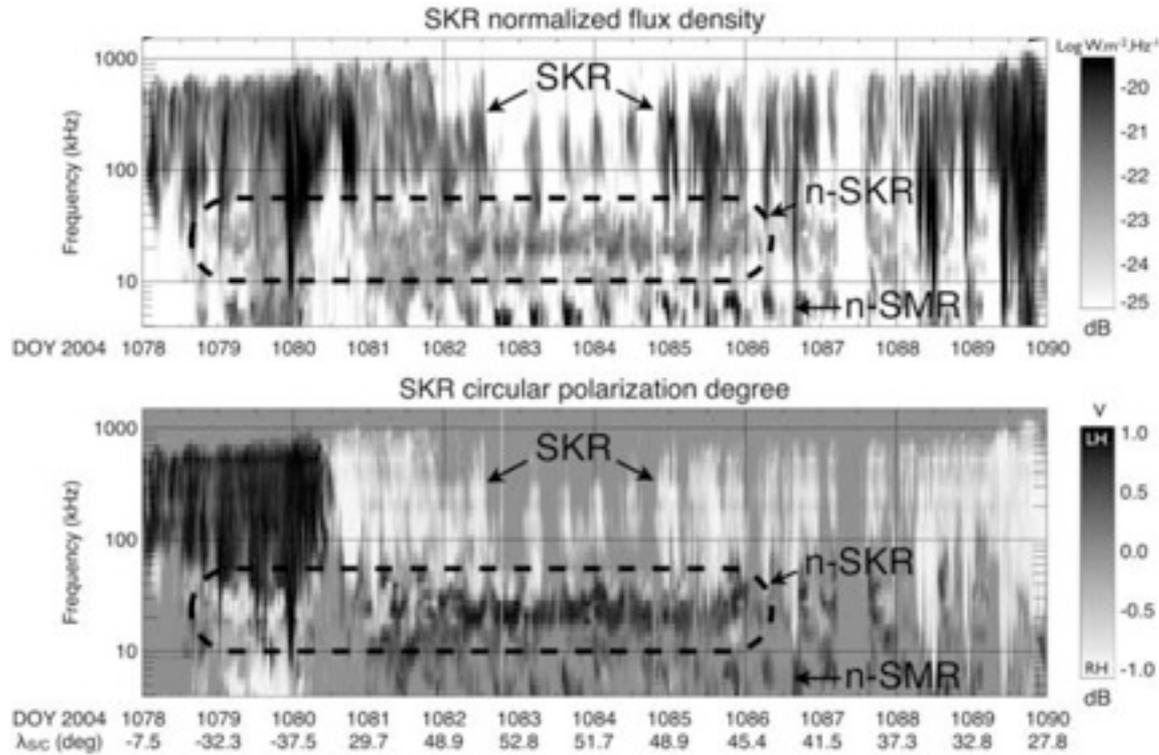
[Cecconi et al., 2008]

Polarization : 100% circular/elliptical ...

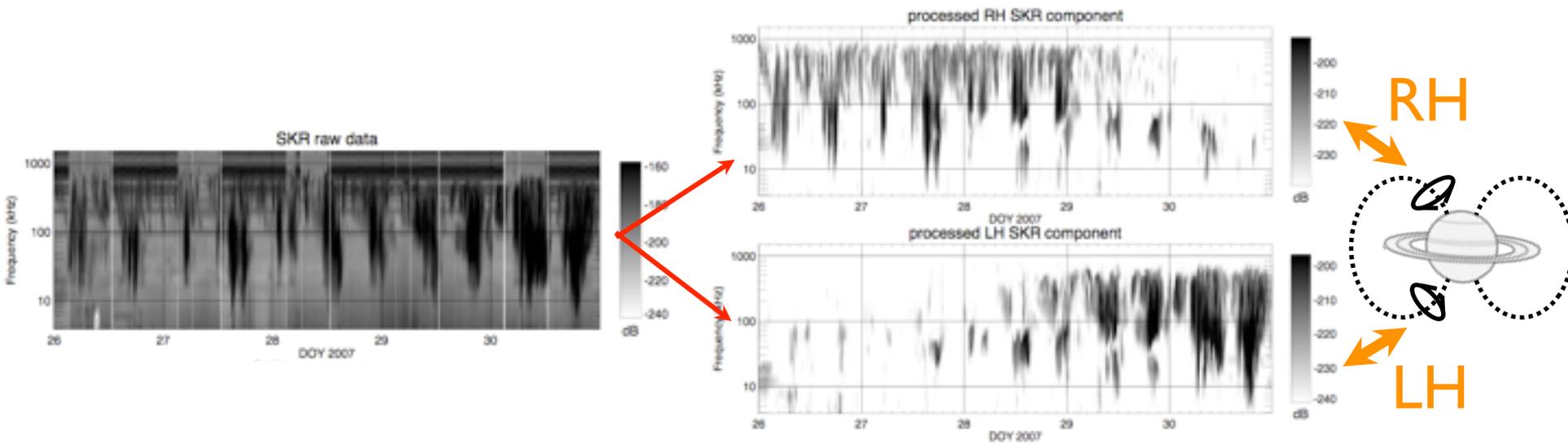


[Lamy et al., submitted, 2009]

Polarization : ... consistent with X mode



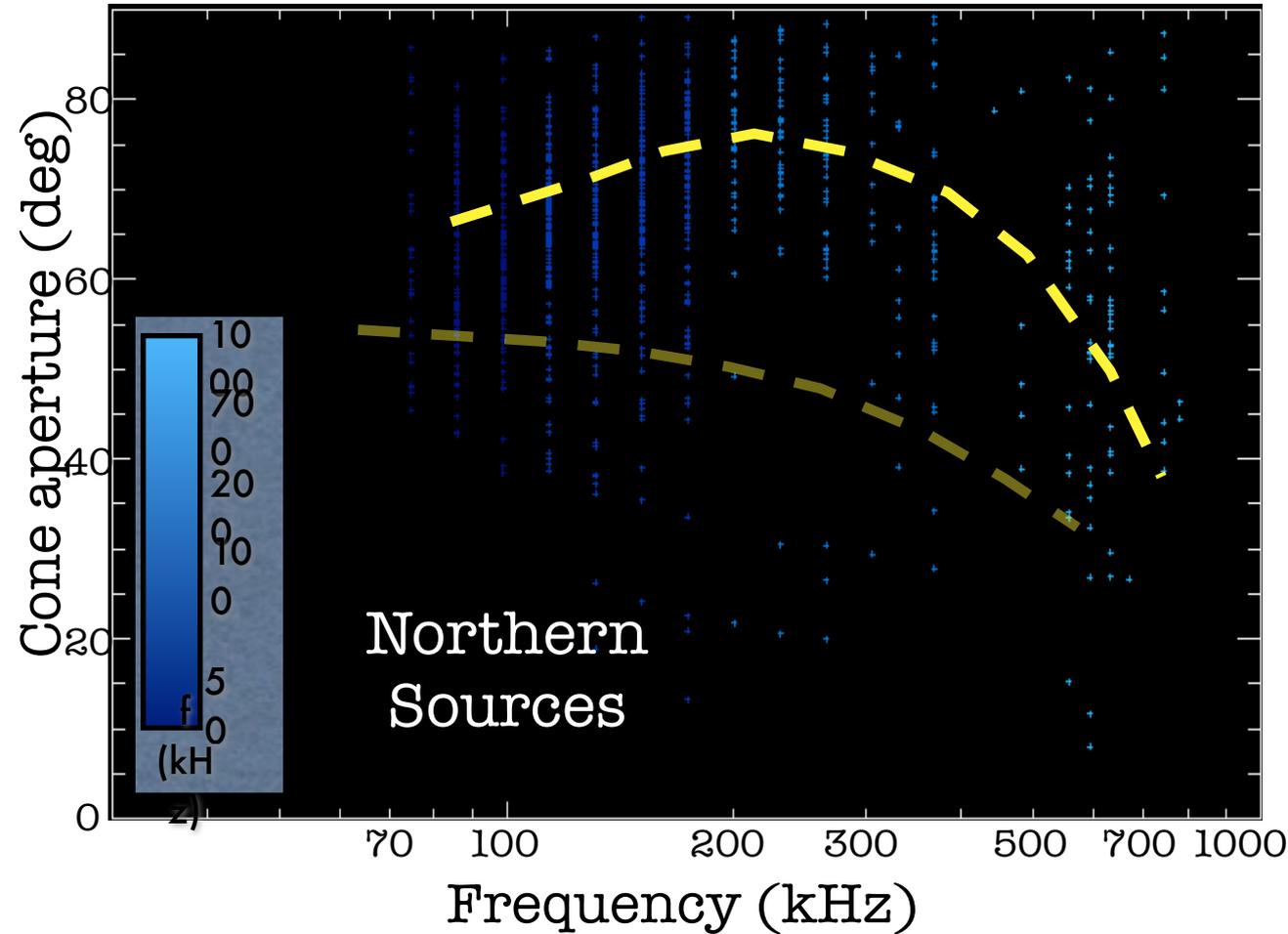
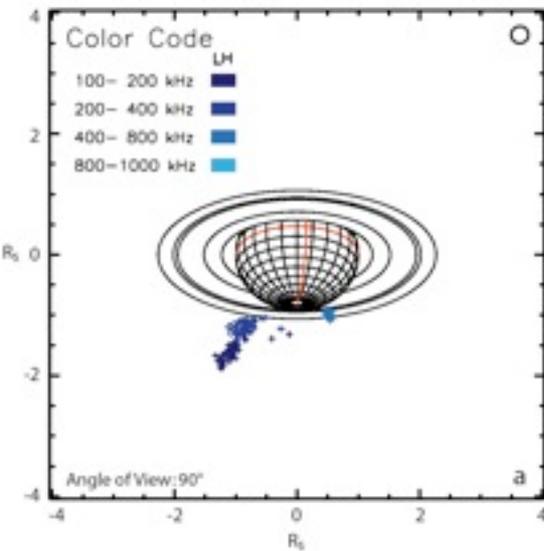
[Lamy et al., 2008]



Beaming : very anisotropic

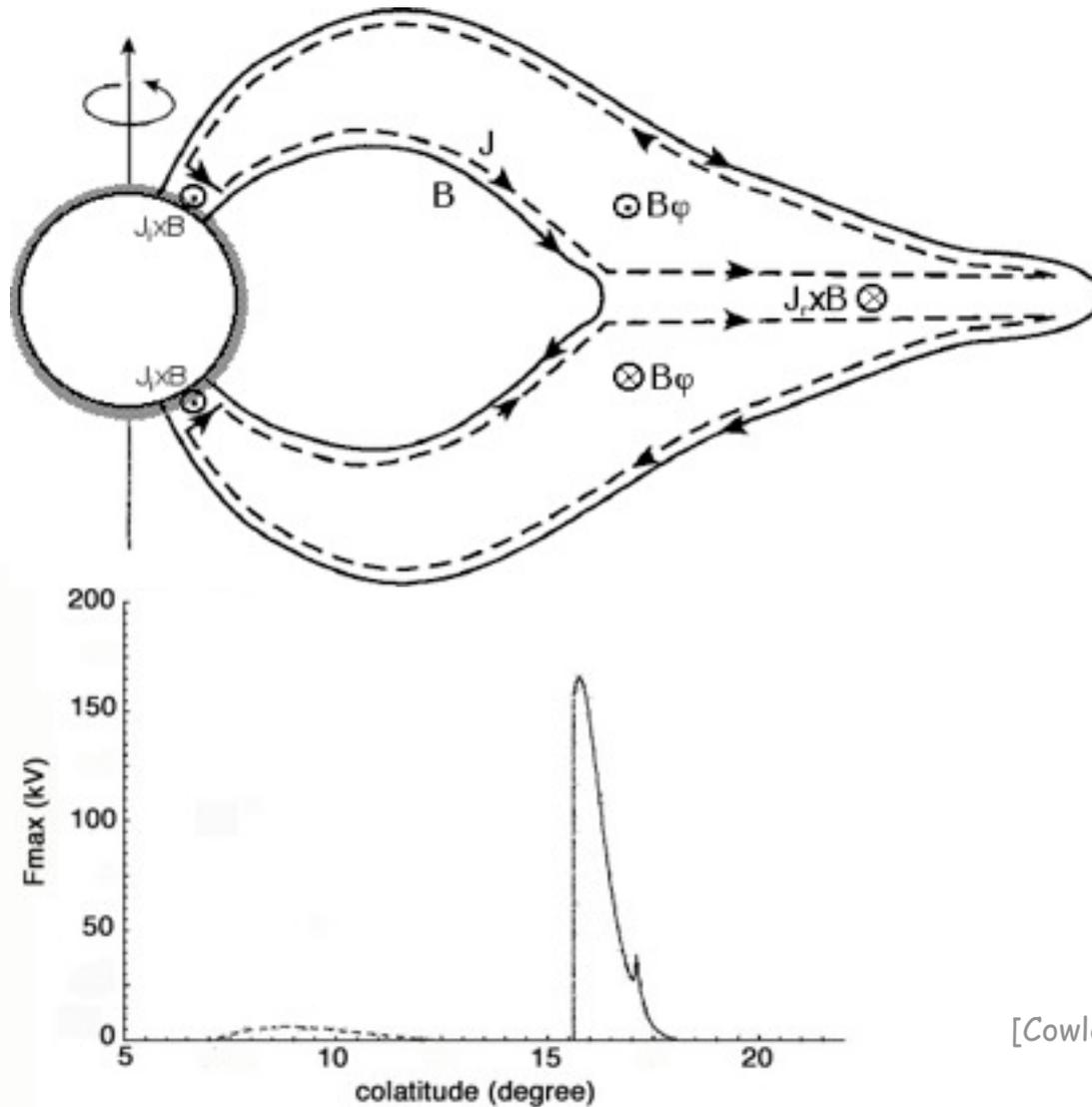
= hollow conical sheet of 30°-90° 1/2 aperture

$$\Omega \ll 4\pi \text{ sr}$$



Sources where $B, f_{pe} \ll f_{ce}$, keV e^- : generally high latitude

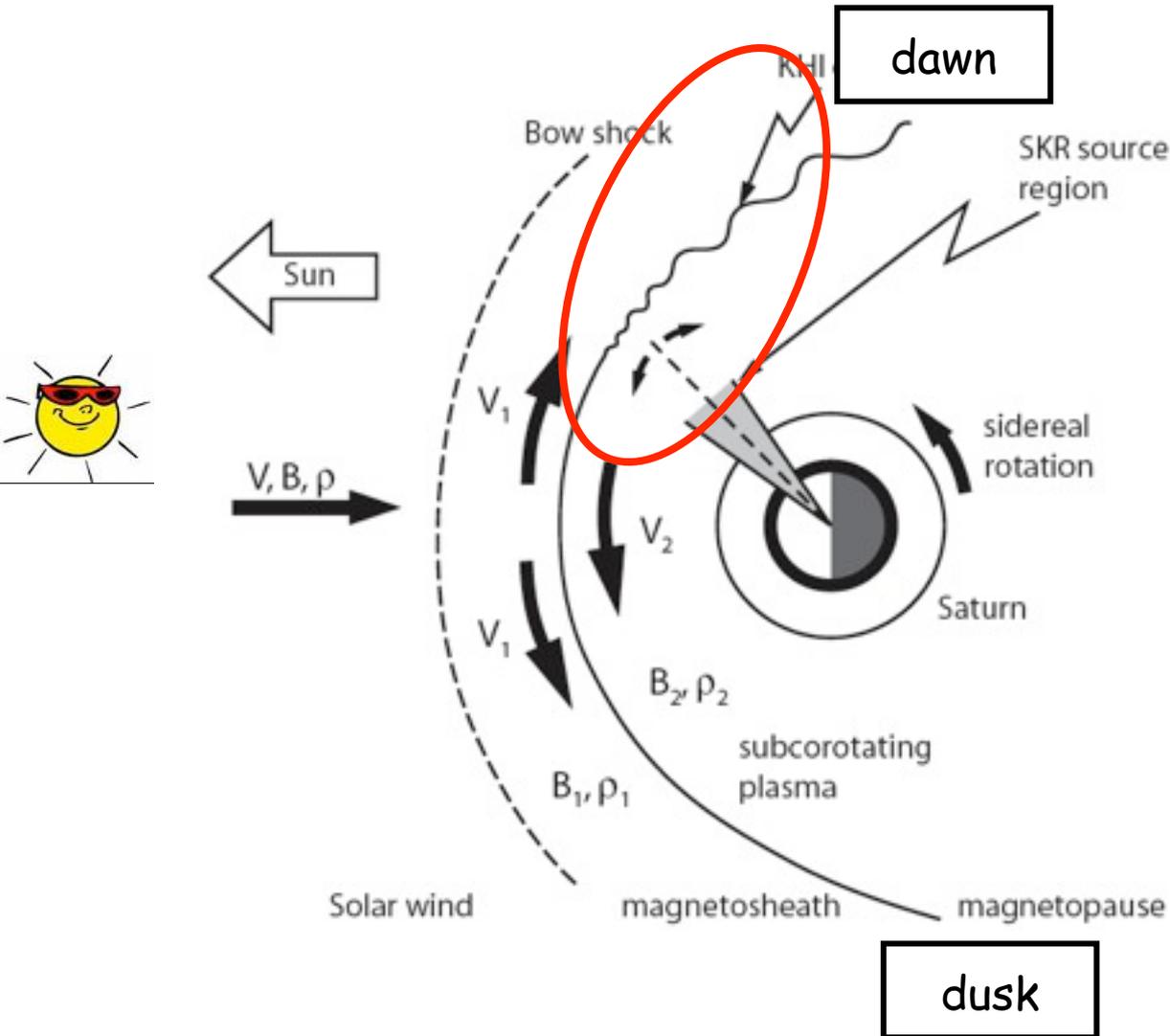
Jupiter : corotation breakdown



[Cowley & Bunce, 2001]

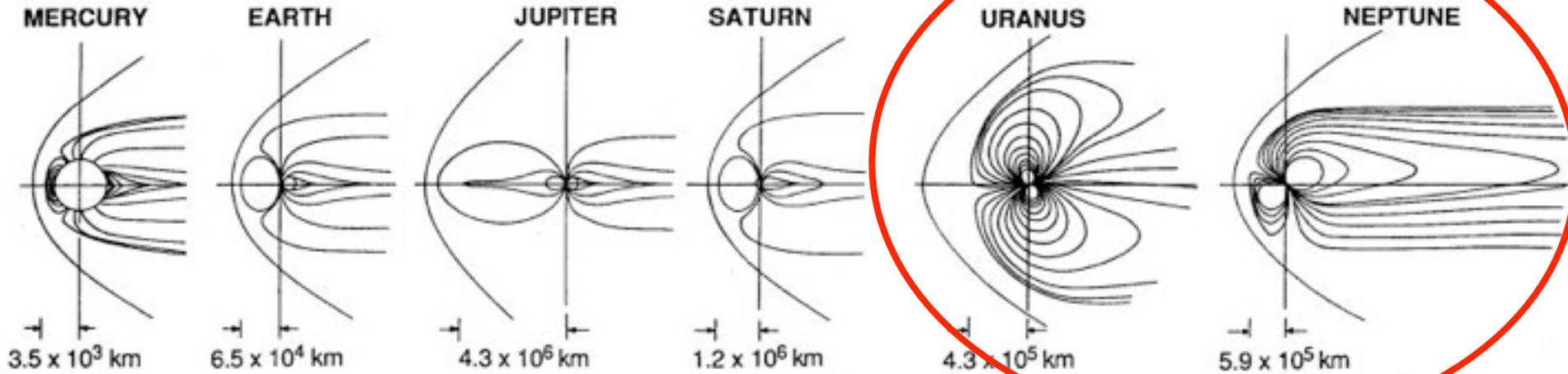
Sources where $B, f_{pe} \ll f_{ce}$, keV e^- : generally high latitude

Saturn : Kelvin-Helmholtz waves / FAC
at morningside magnetopause ?

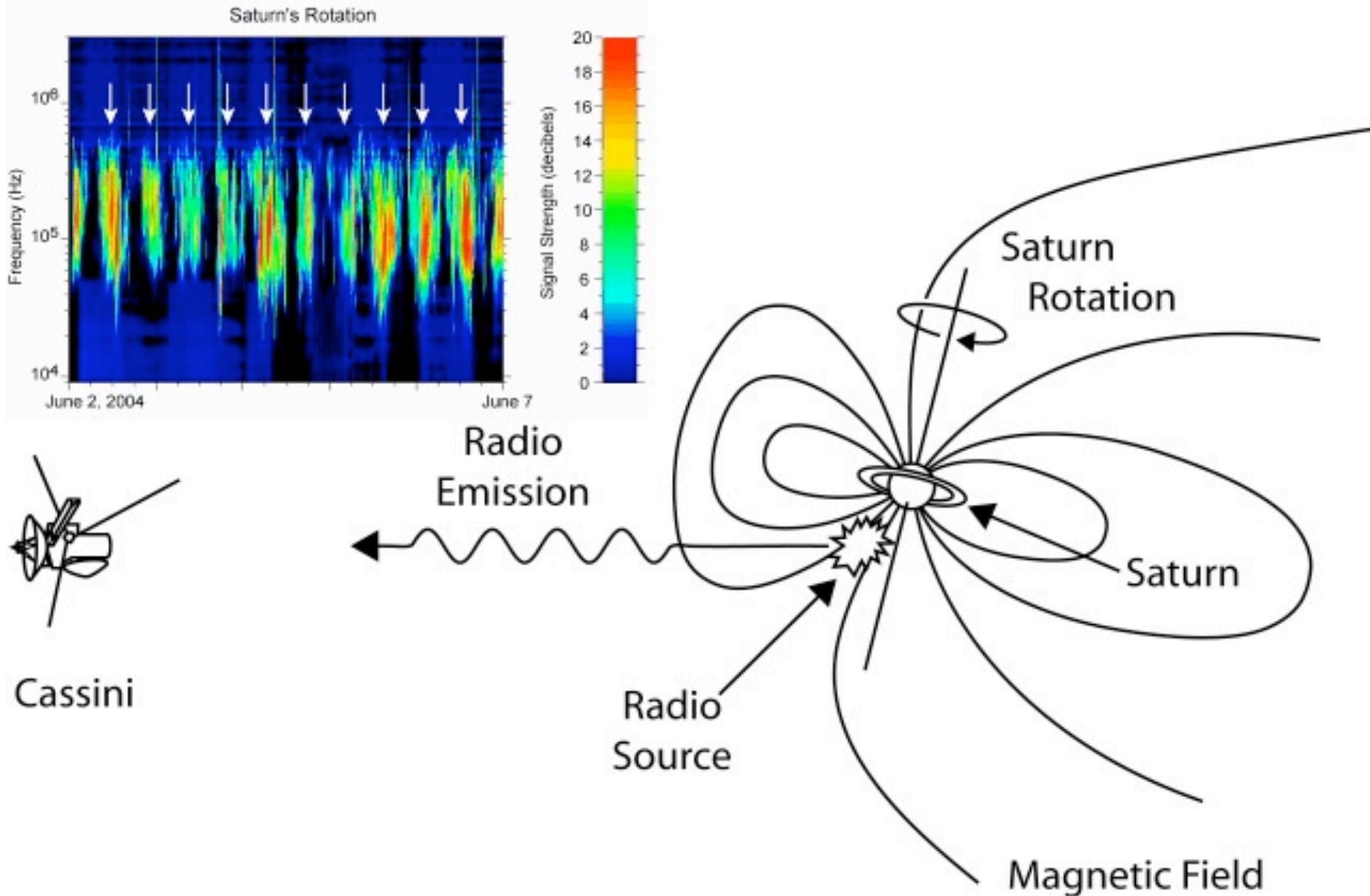


Sources where $B, f_{pe} \ll f_{ce}, \text{keV } e^-$: equatorial sources at

Uranus and Neptune

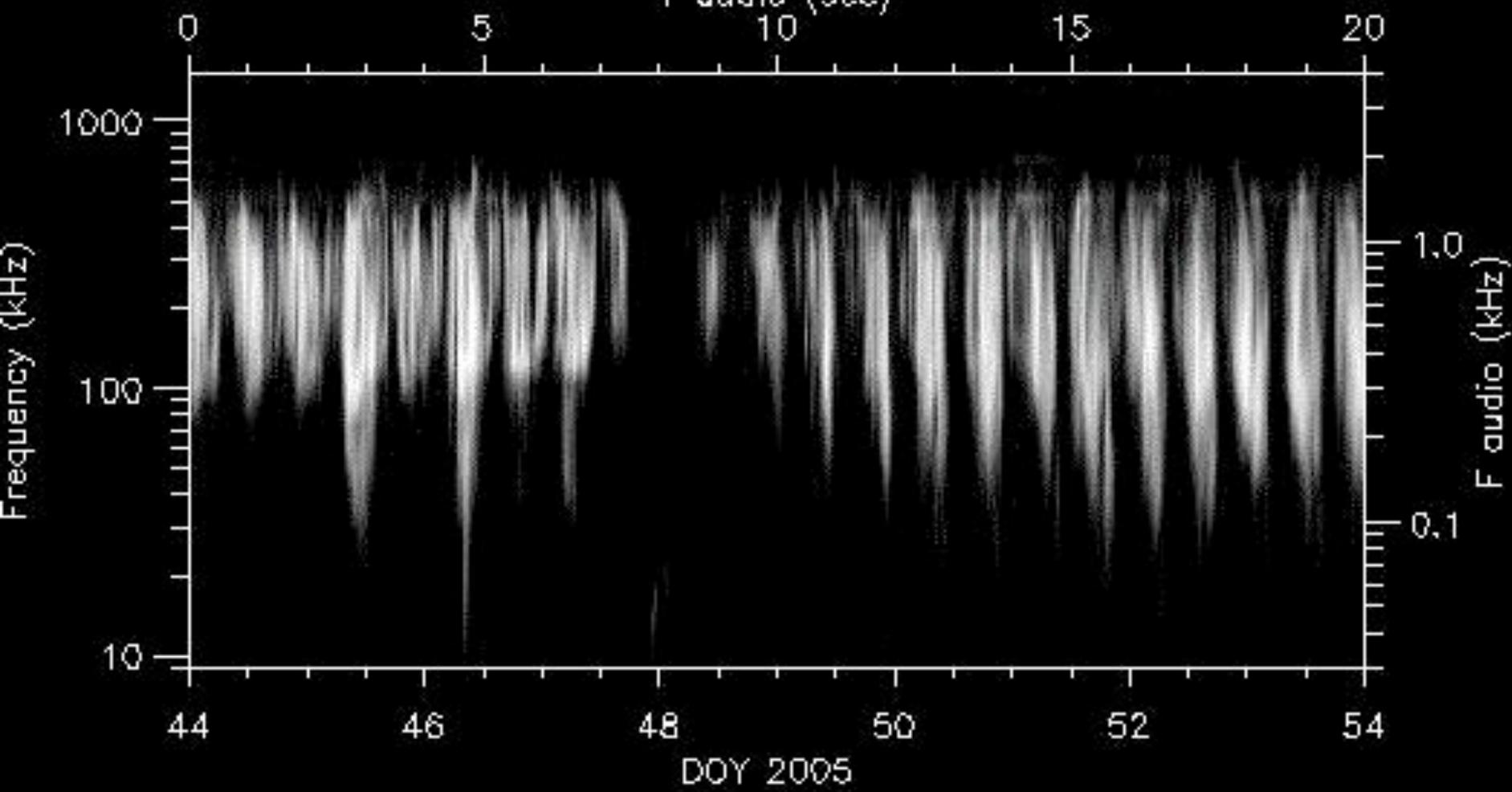


Modulations by : planetary rotation

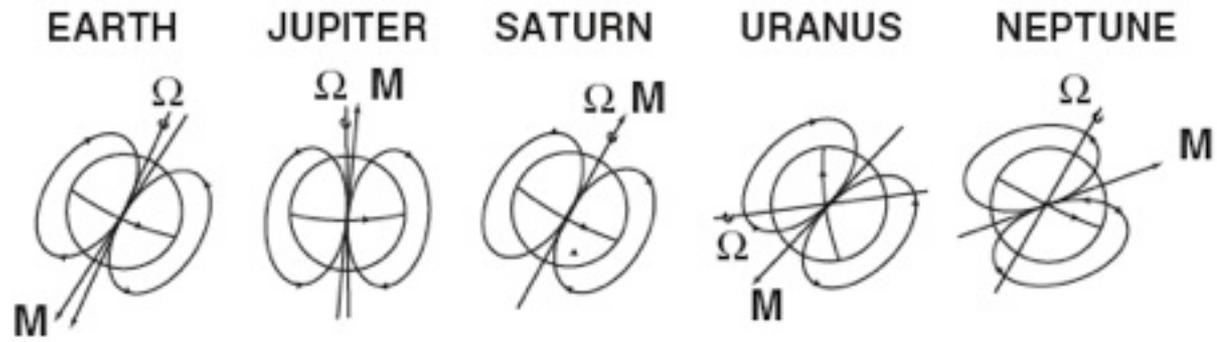
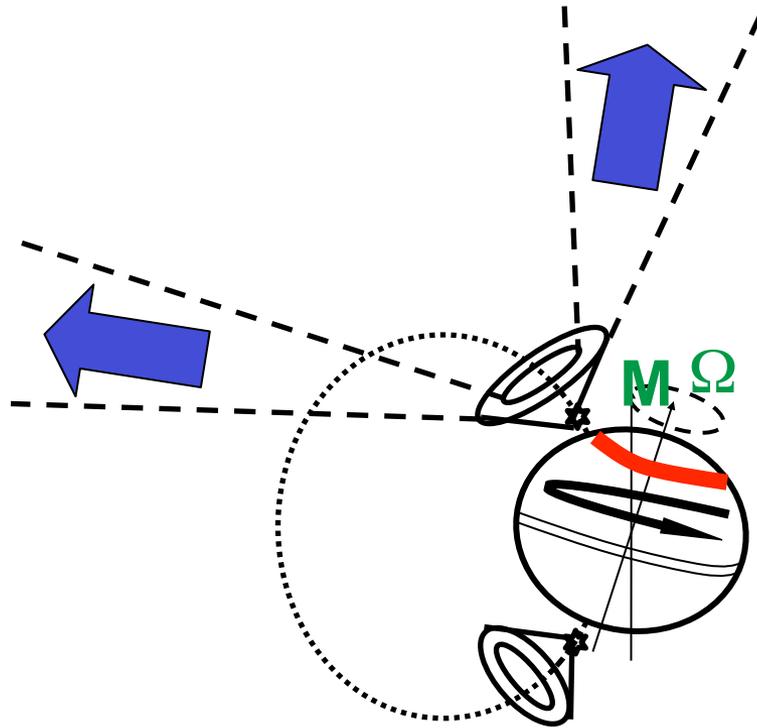


Saturn Clock

T audio (sec)



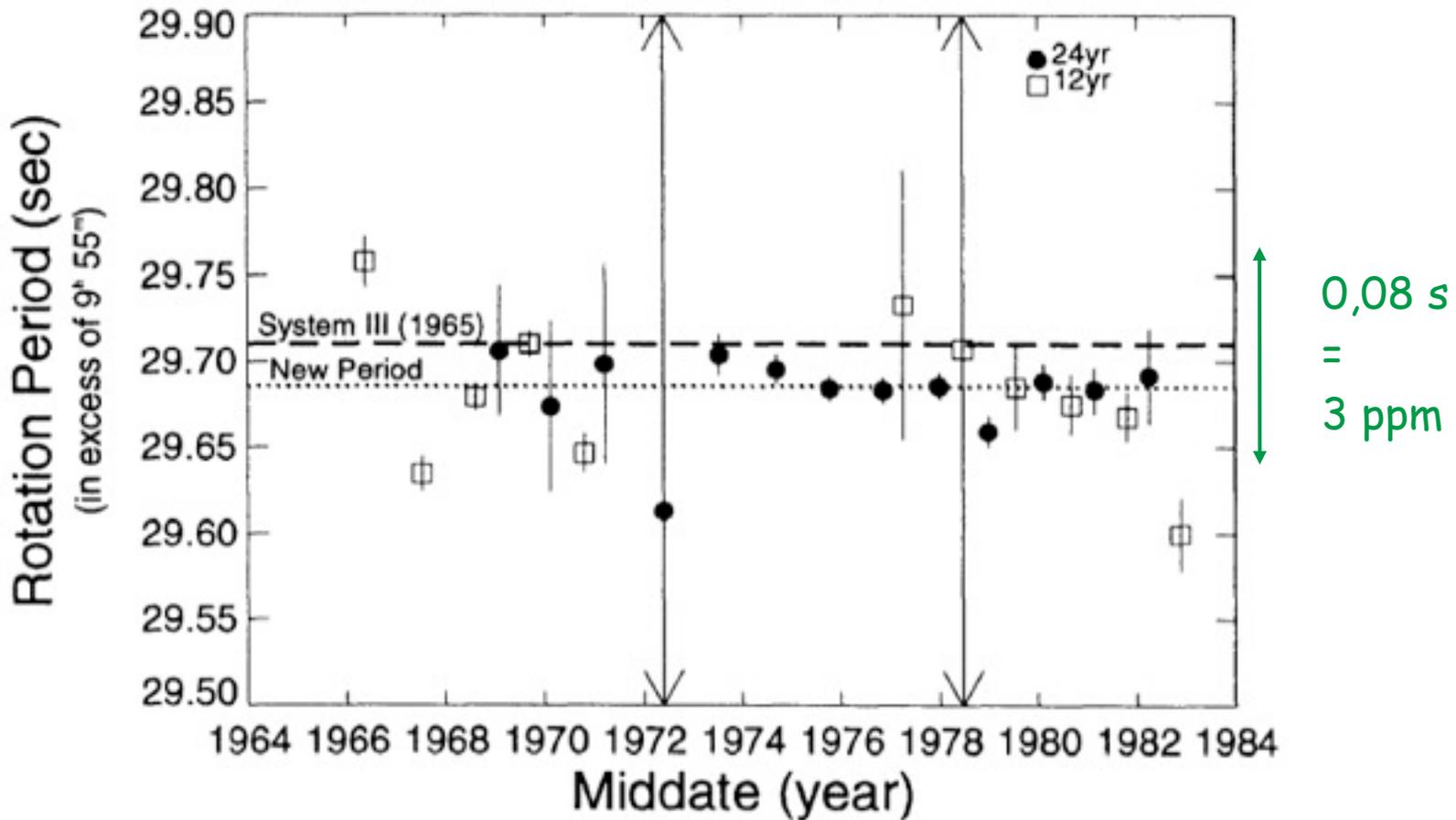
Modulations by : partly due to tilt M / Ω



Dipole Tilt	+10.8°	-9.6°	-0.0°	-59°	-47°
-------------	--------	-------	-------	------	------

Modulations : rotation of Jupiter

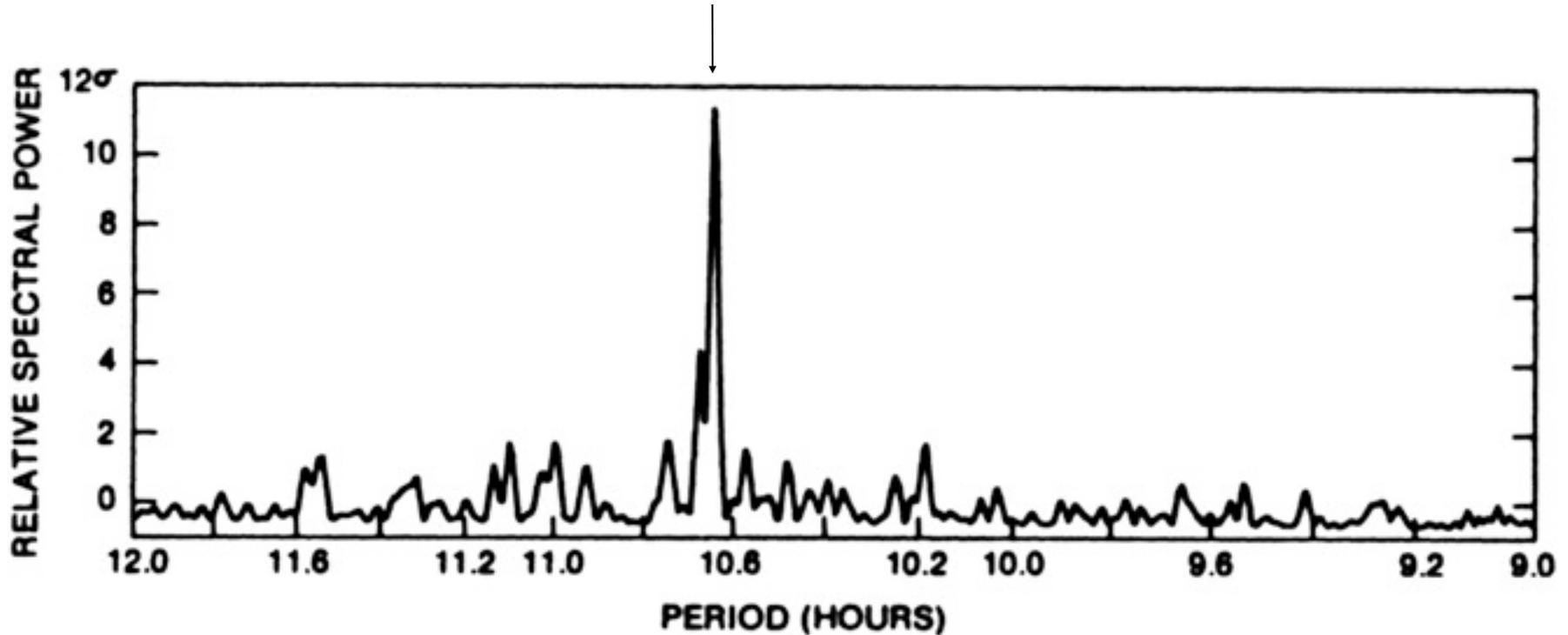
- Analysis of 24 years of ground-based radio observations
⇒ $P = 9\text{h } 55\text{m } 29,685\text{s} \pm 0,04\text{s}$



Modulations : rotation of Saturn

- Analysis of 267 days of Voyager 1 observations

$$\Rightarrow P = 10\text{h } 39\text{m } 24\text{s} \pm 7\text{s} \quad (\sim 2 \times 10^{-4})$$



[Desch & Kaiser, 1981]

In spite of non-tilted B field !

Modulations by : **satellites**

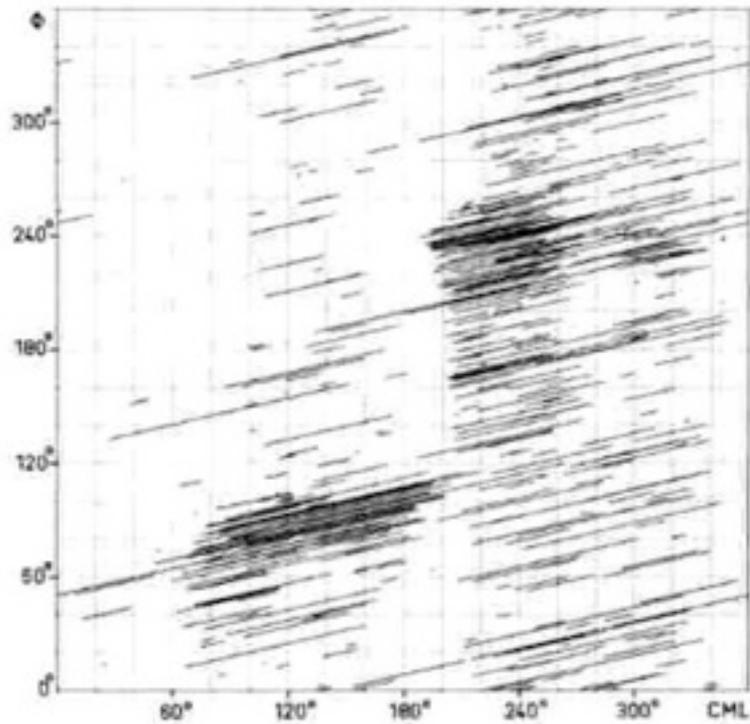
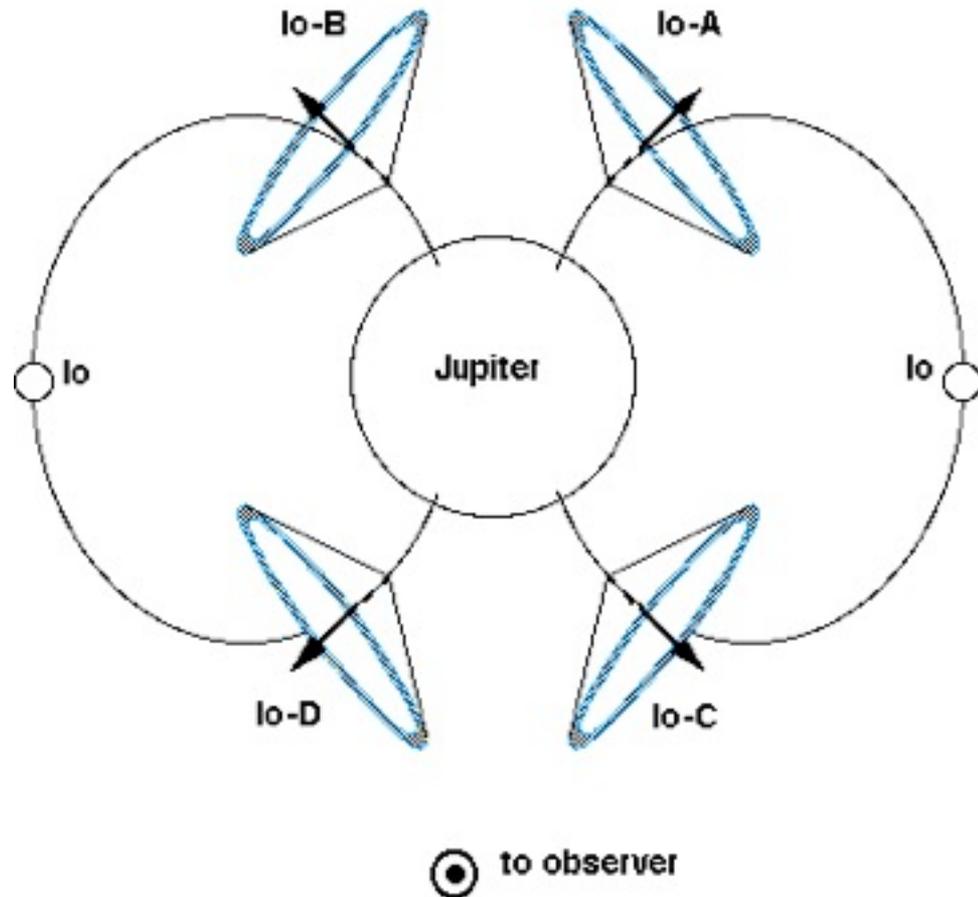
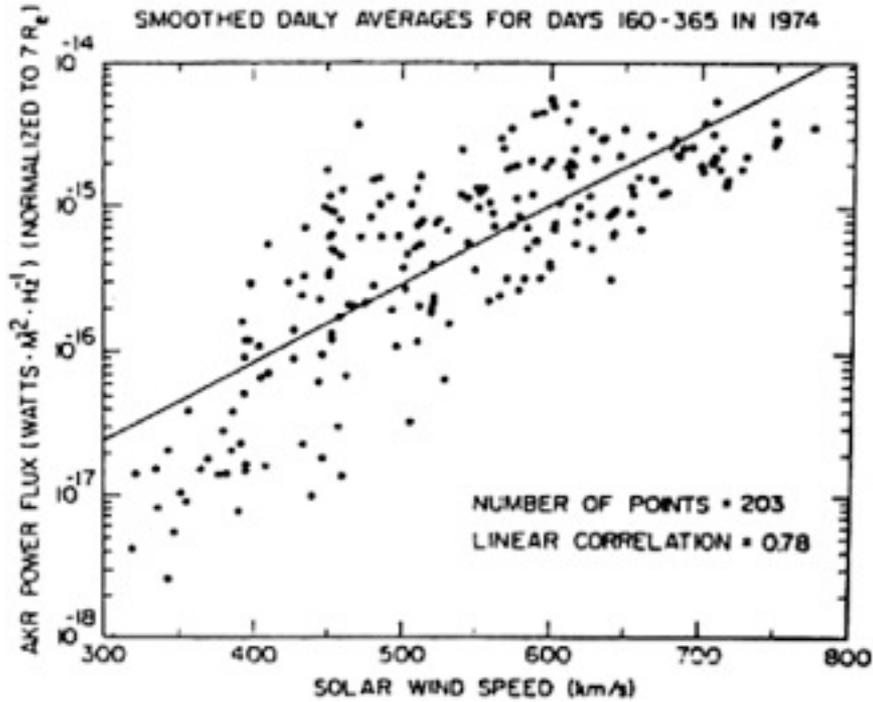


FIGURE 6. — The CML and Io-phase diagram for the period of January 1978 to December 1979. a) the observation tracks ; b) the emission tracks.

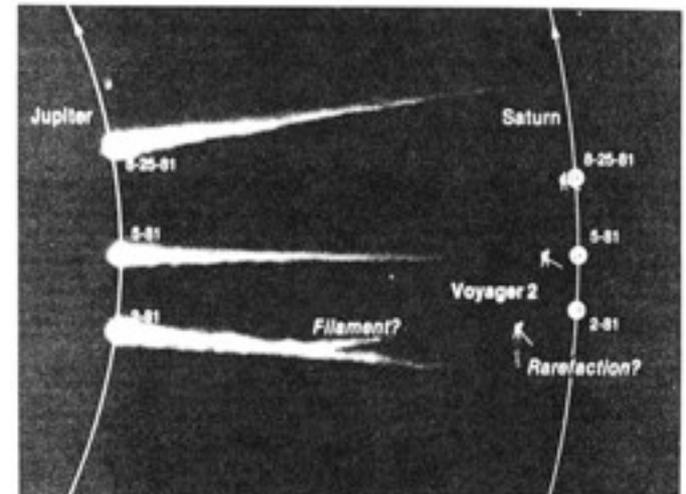
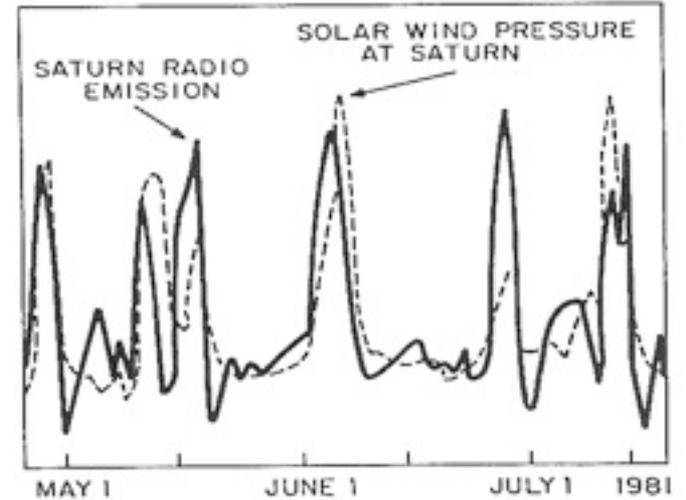
Io-controlled radio "sources"



Modulations by : Solar Wind

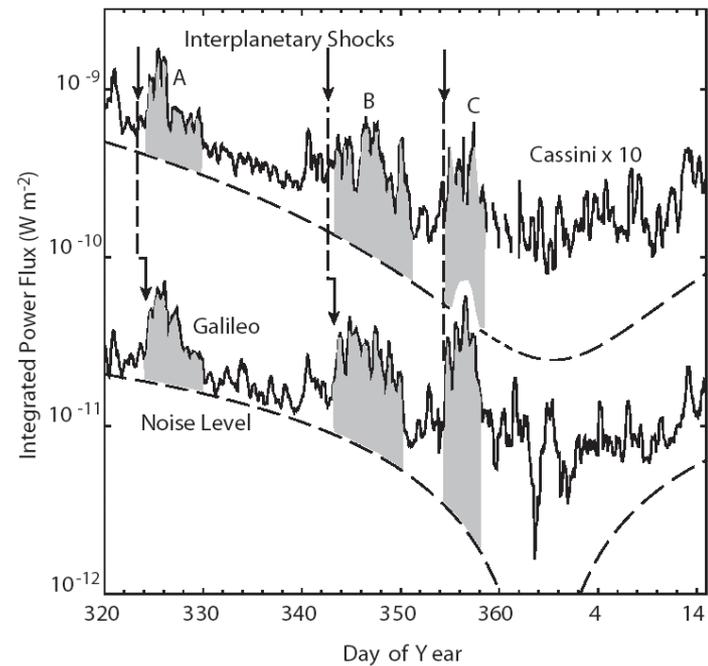
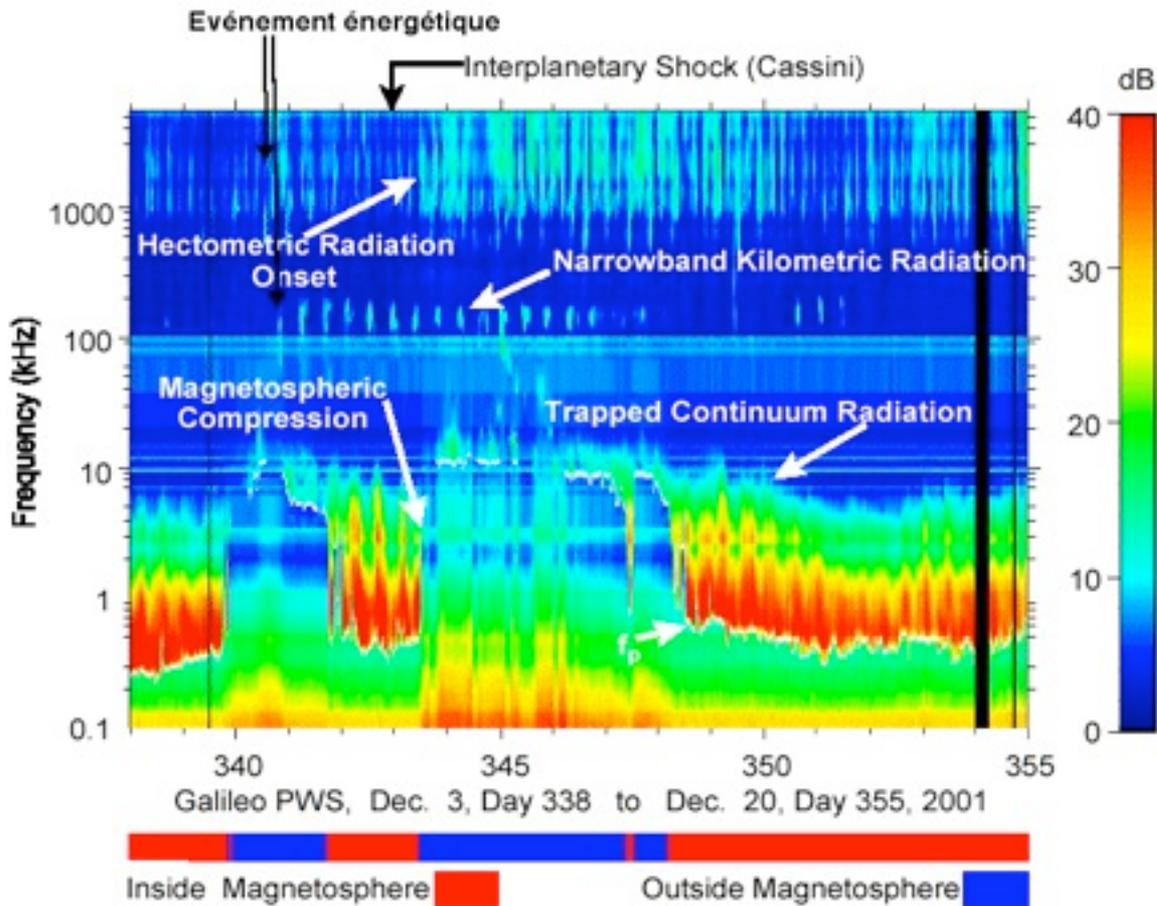


[Gallagher and d'Angelo, 1981]



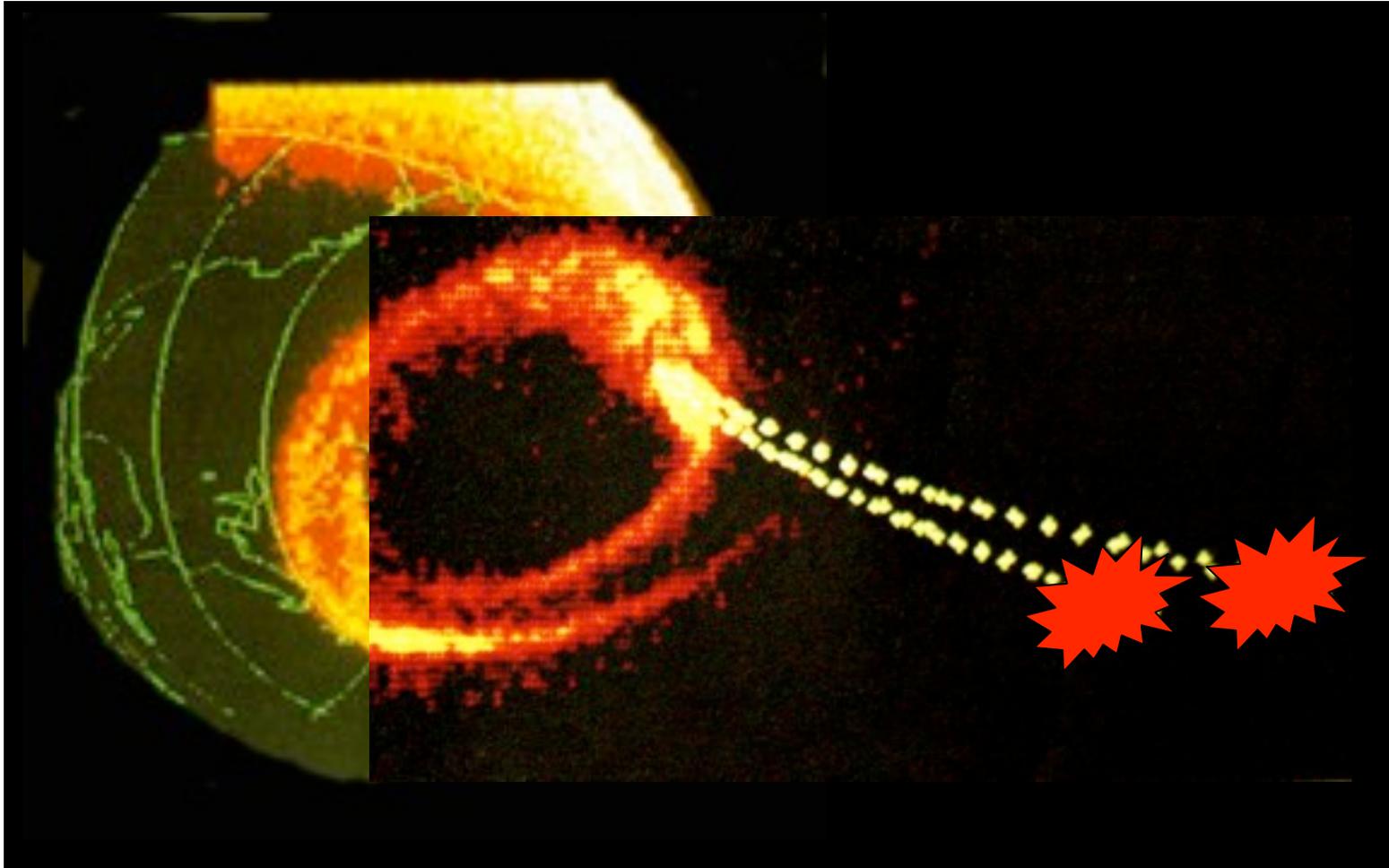
[Desch, 1981, 1982]

Modulations by : Interplanetary Shocks, CMEs



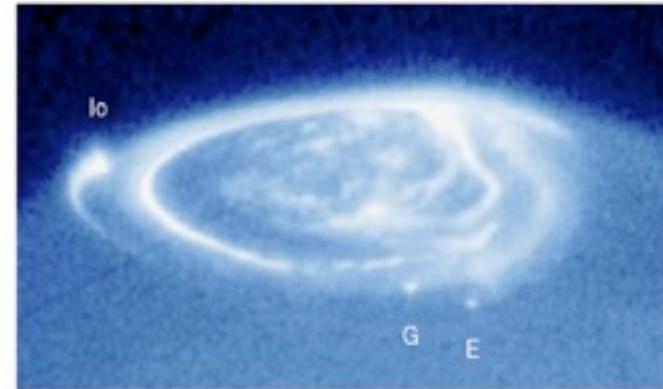
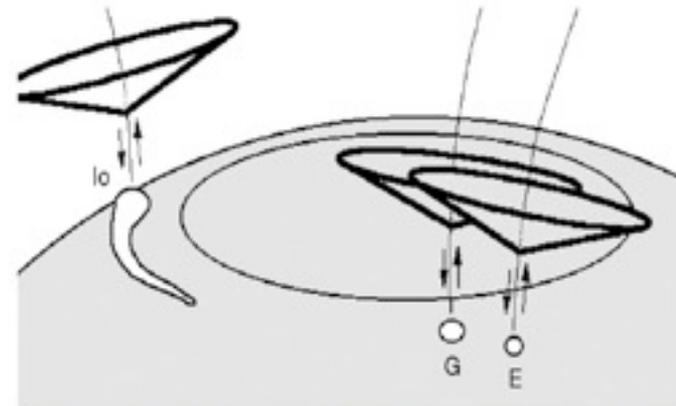
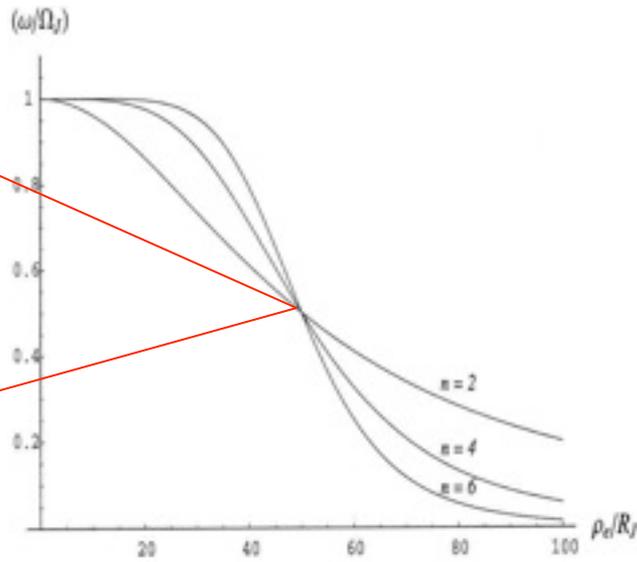
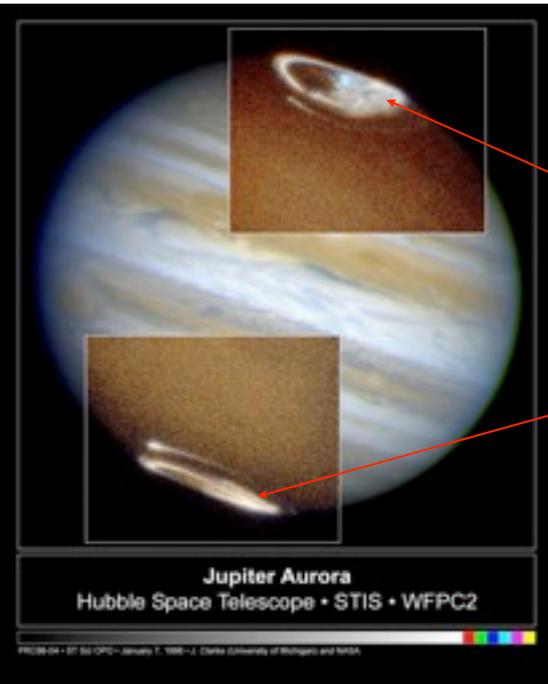
[Gurnett et al., 2002]

Correlation with UV aurorae



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

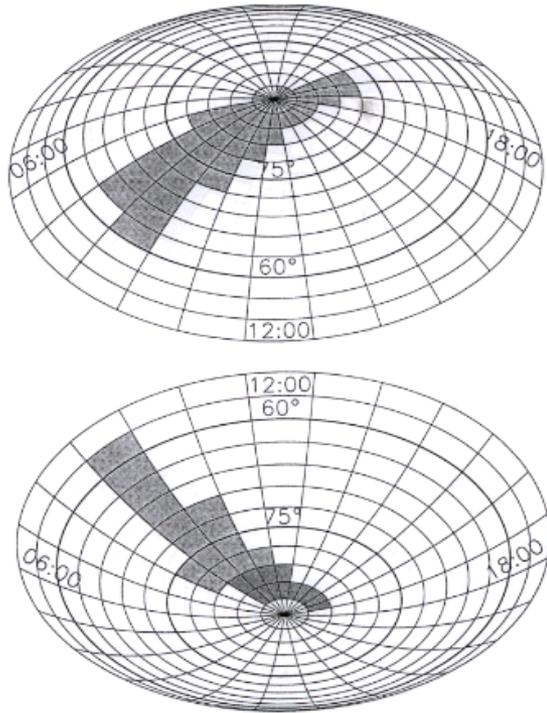
Correlation with UV aurorae



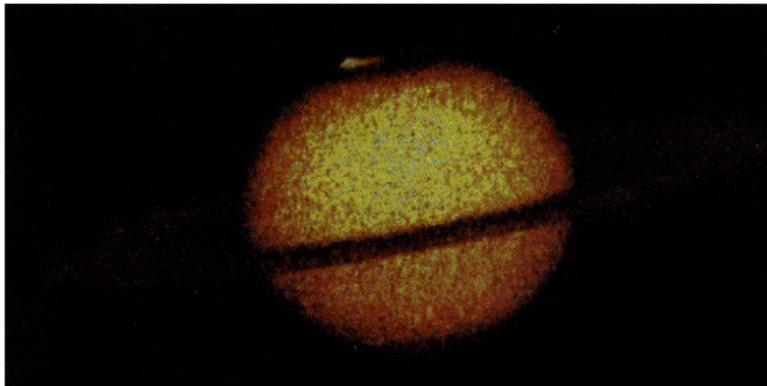
Jupiter (HST, Nançay...)

[Prangé et al., 1993; Cowley and Bunce, 2001]

Correlation with UV aurorae



[Galopeau et al., 1995]



[Trauger et al., 1998]



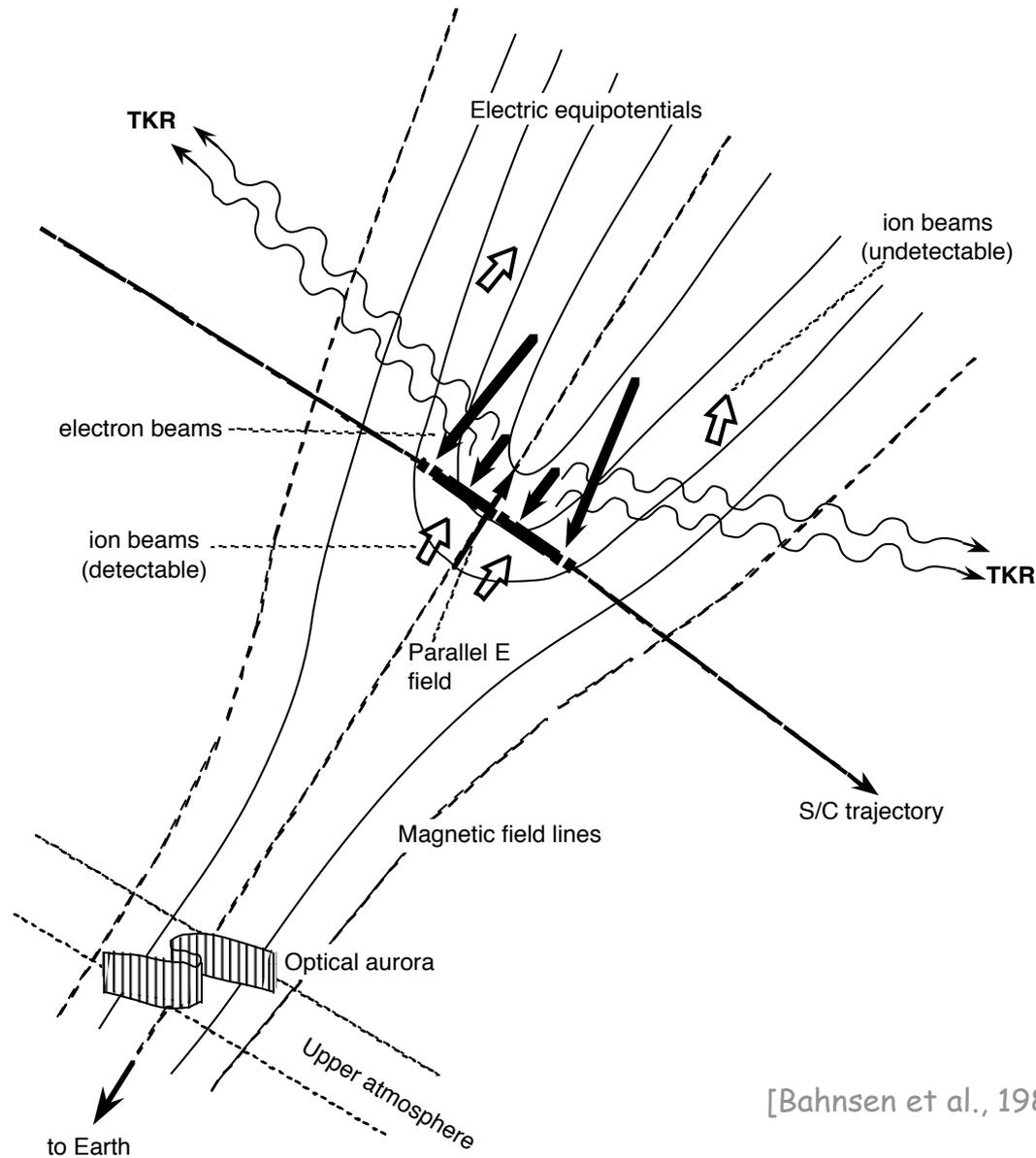
Saturn Aurora

HST • STIS

PRC98-05 • ST Sci OPO • January 7, 1998 • J. Trauger (JPL) and NASA

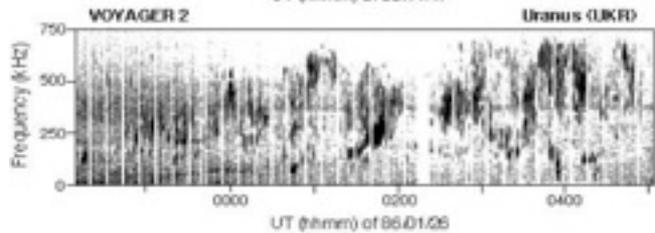
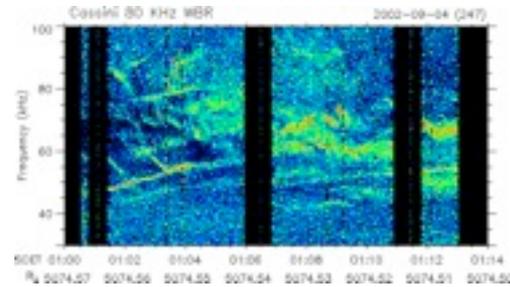
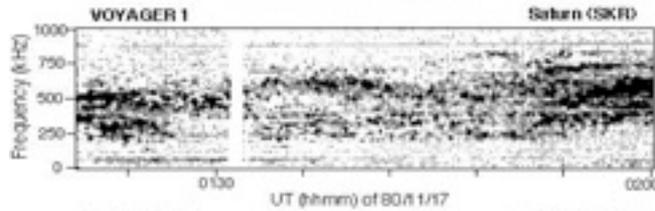
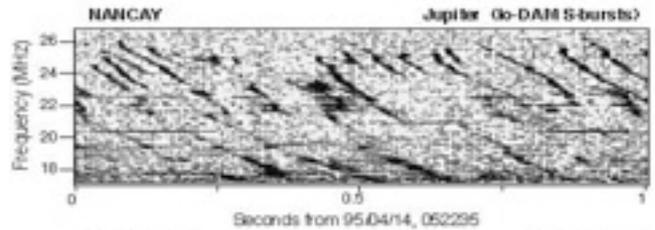
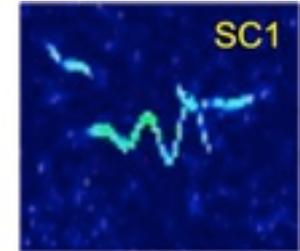
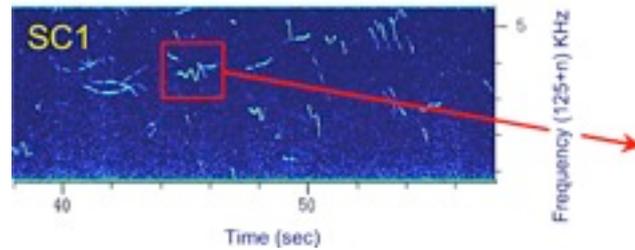
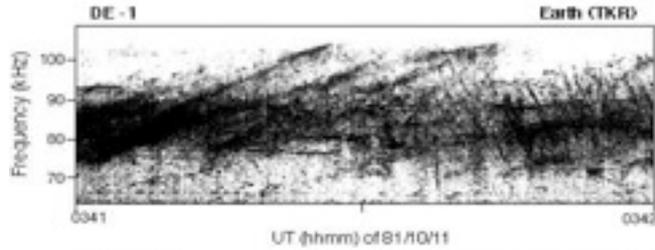
Saturn
(HST, Voyager)

Radiosource understood as an acceleration region



[Bahnsen et al., 1989; Louarn et al., 1990]

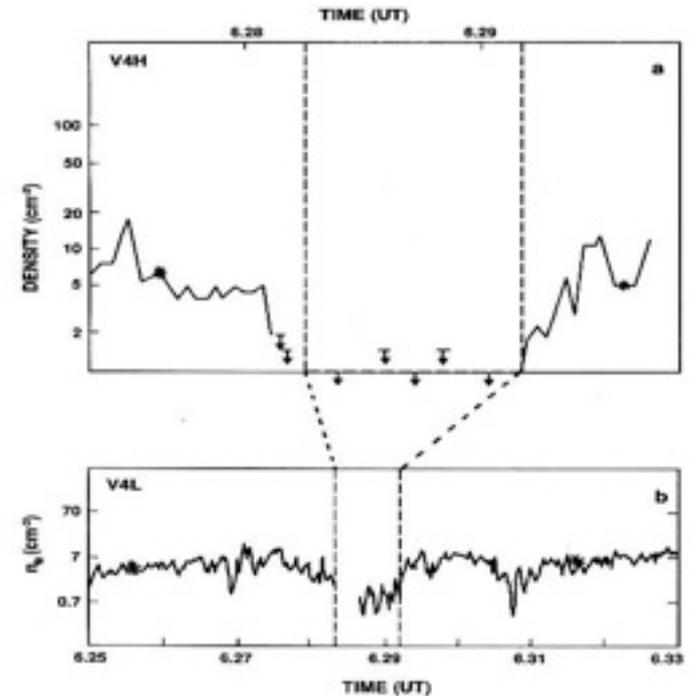
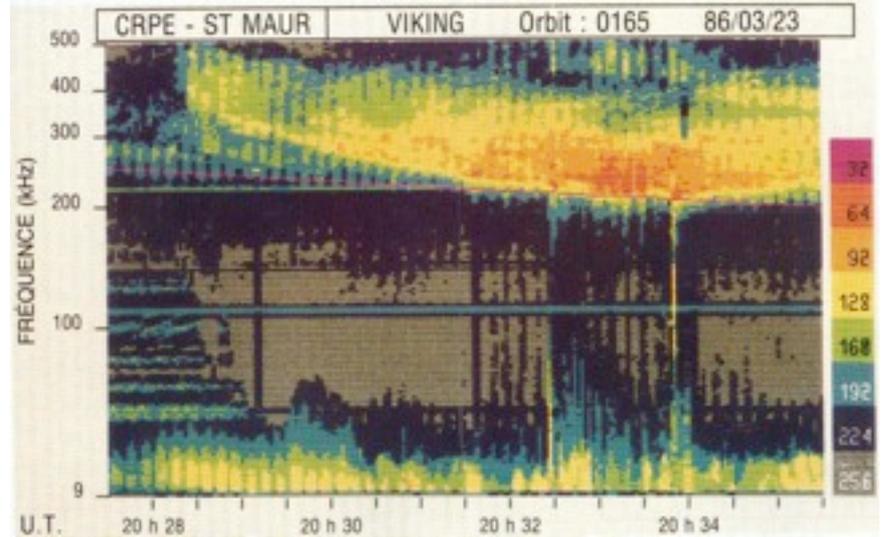
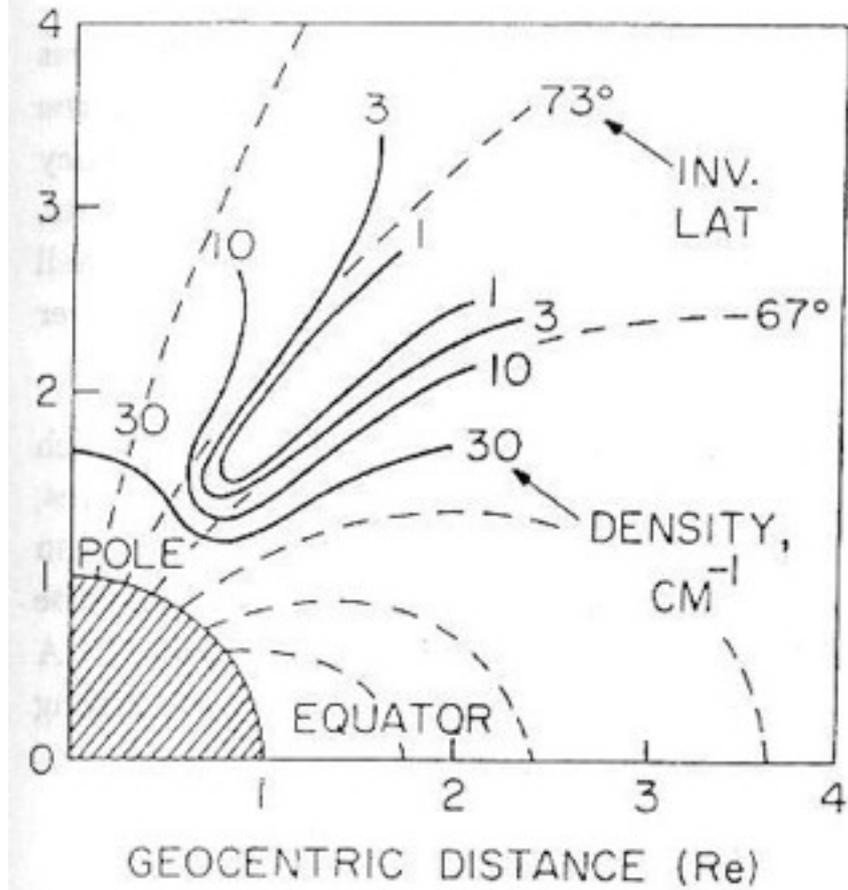
Fine (t,f) structures



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

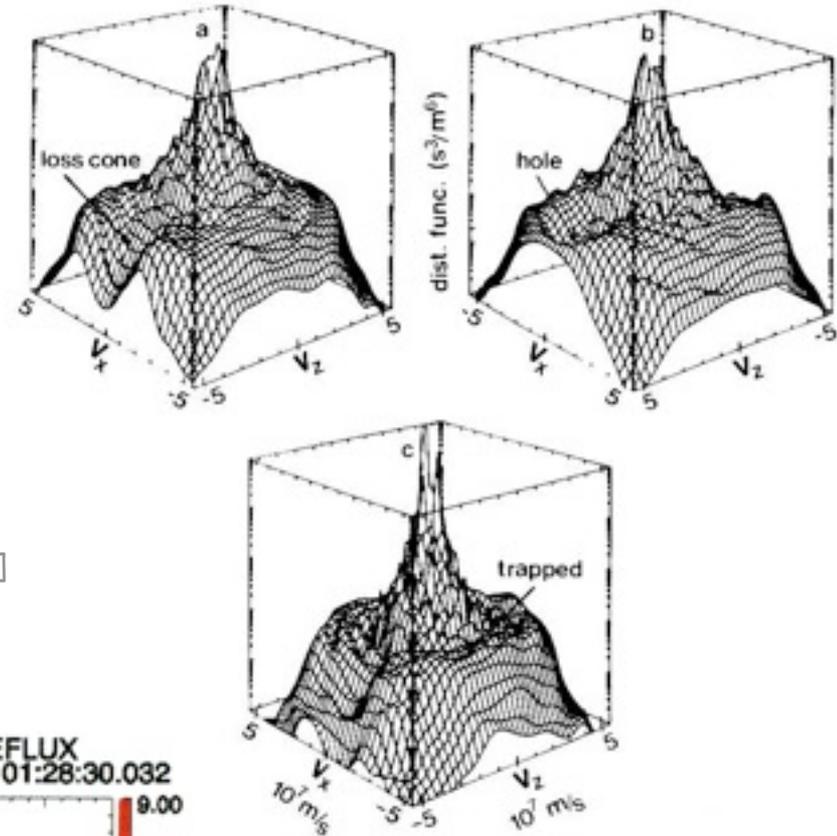
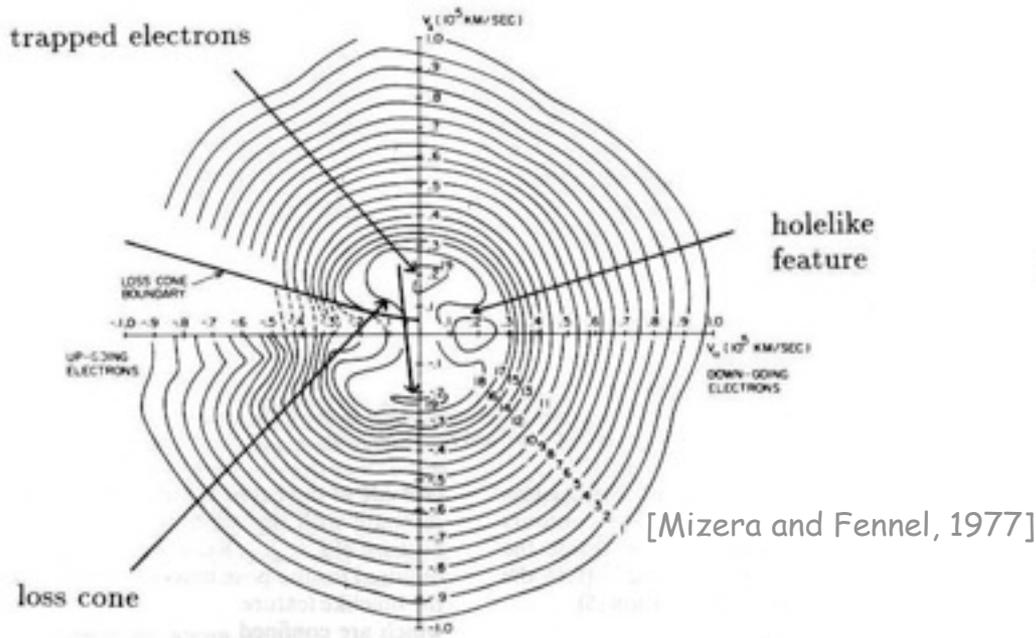
- Introduction
- Auroral Radio Emissions observations
- Theory of Auroral Radio Emissions
- New results on Jupiter
- New results on Saturn
- Radio emission from exoplanets ?

Radiosources = plasma cavities (small-scale)

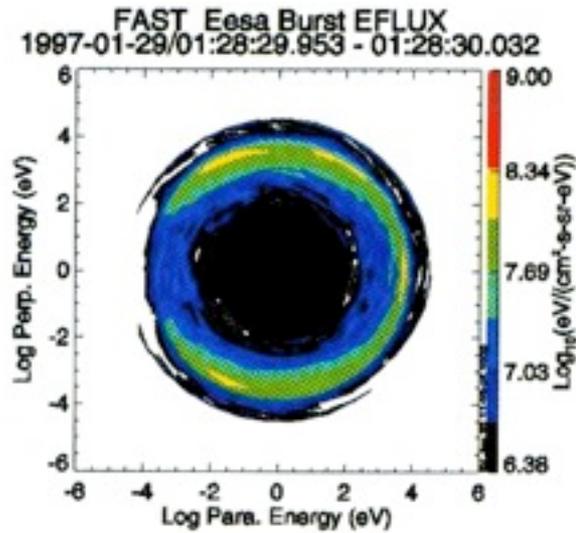


[Calvert, 1981; de Féraudy et al., 1988;
Bahnsen et al., 1989; Hilgers, 1992]

Non-Maxwellian electron distributions : loss-cone, hole/shell

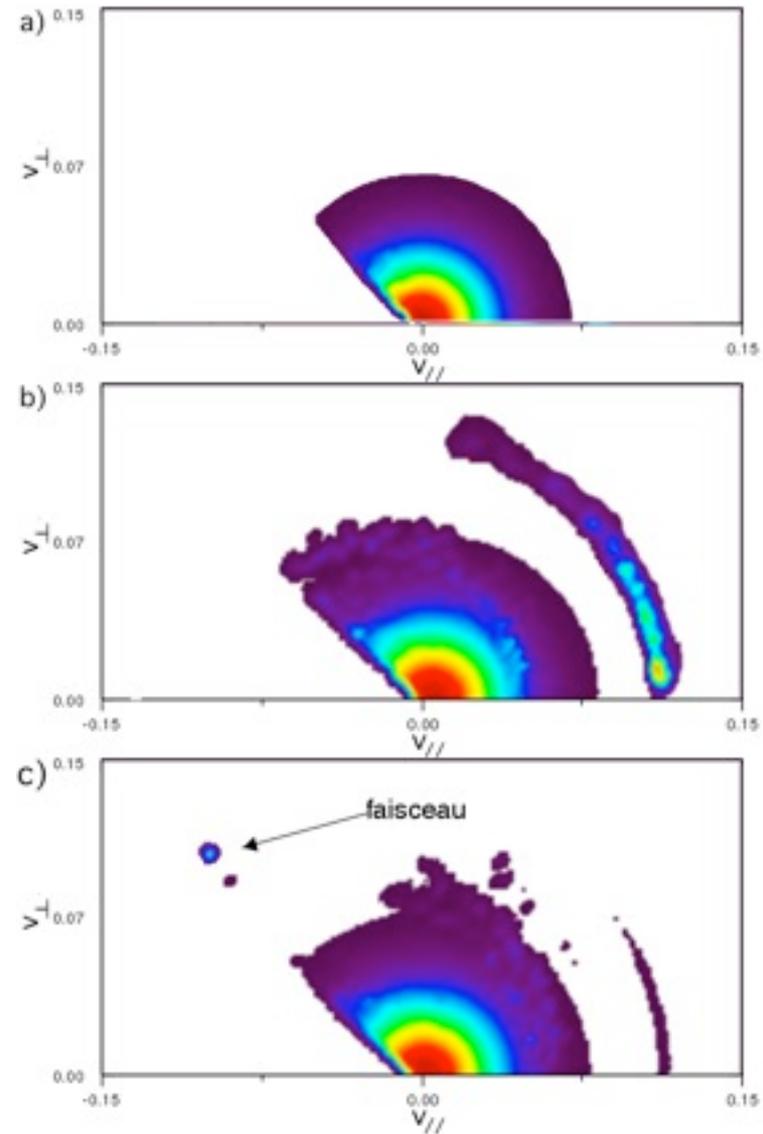
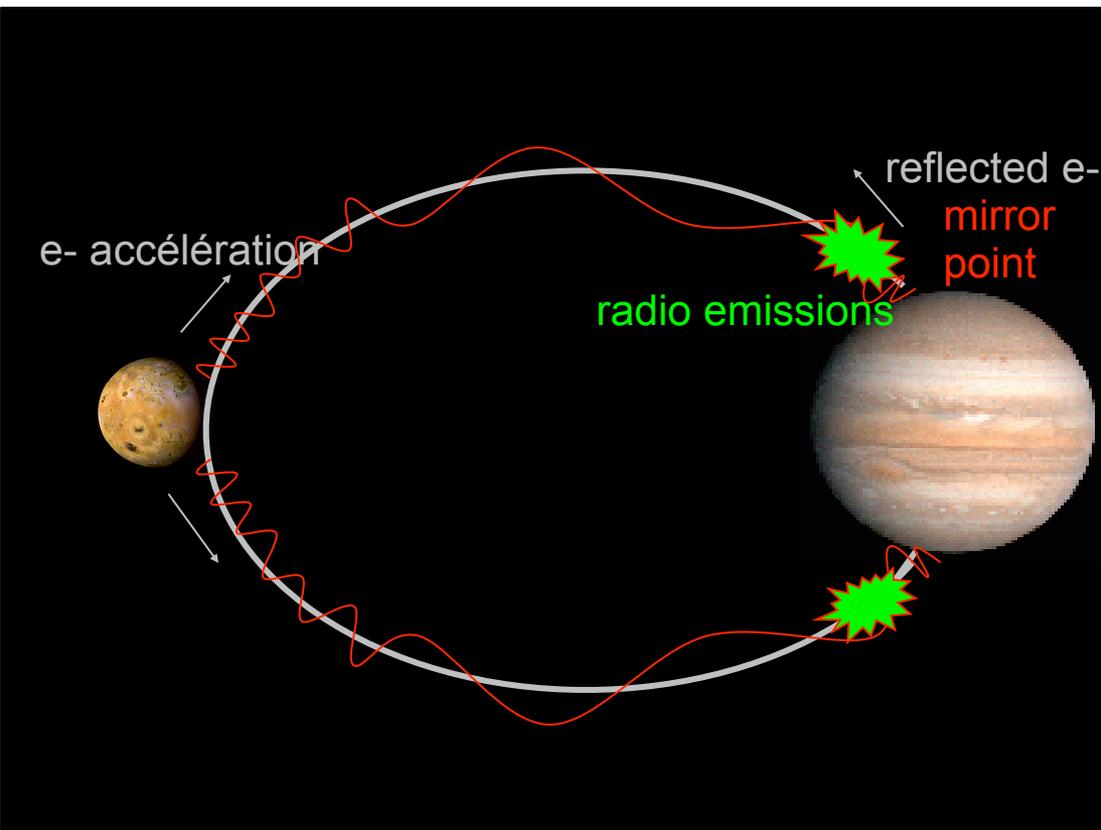


[Ergun et al., 1998]



[Louarn et al., 1990]

Non-Maxwellian electron distributions : loss-cone, hole/shell



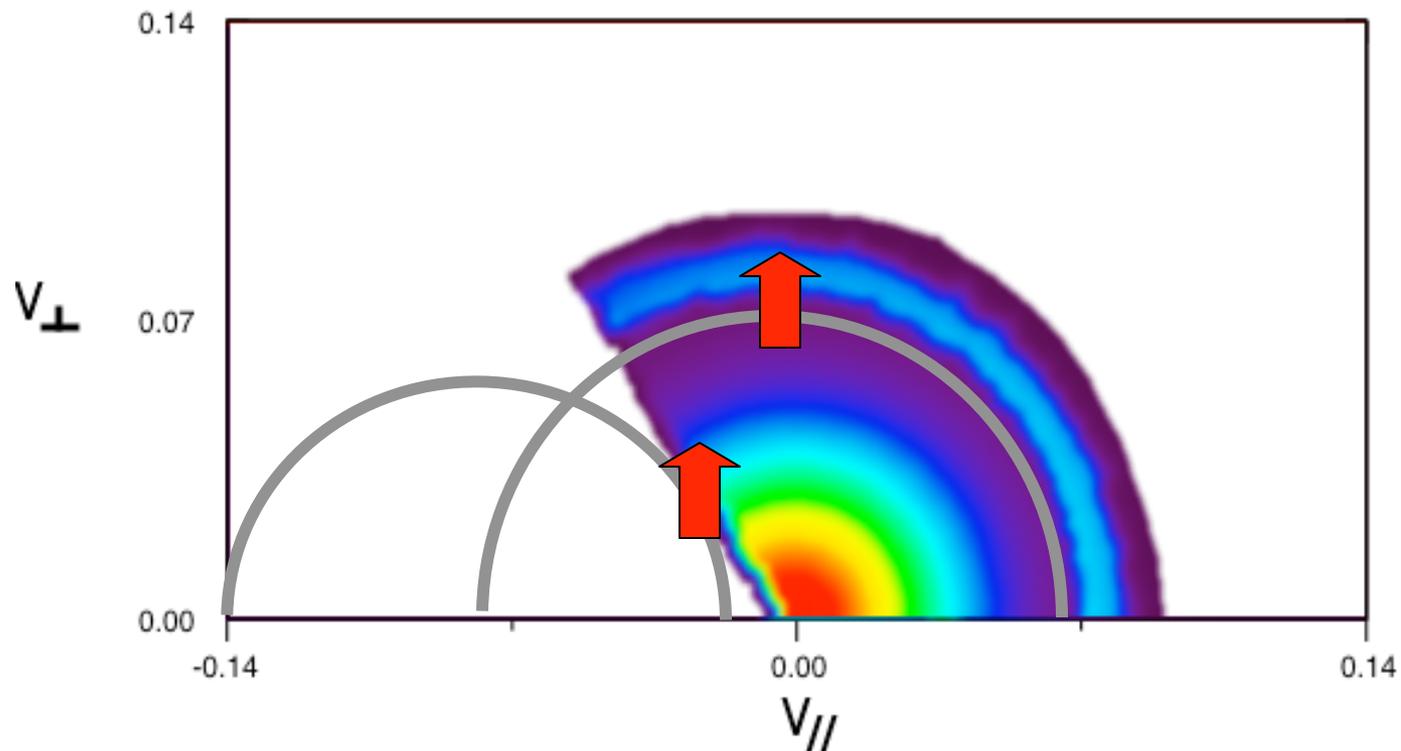
Cyclotron-Maser Instability

- emission intensity \Rightarrow **direct, coherent** radiation
- in low β magnetized plasma ($f_{pe} \ll f_{ce}$), **X mode emission** (+ weak O) produced at $f \sim f_x \approx f_{ce} (1 + \varepsilon) \approx f_{ce}$ $\varepsilon = (f_{pe}/f_{ce})^2$
- gyrating electrons excite f_{ce} at the **expense of $m_e v_{\perp}^2/2$**
- relativistic resonance condition : $\omega - k_{//} v_{//} - n \omega_{ce} / \Gamma = 0$
- growth rate : $\text{Im}(\omega) = \gamma \propto \iint v_{\perp}^2 \partial f / \partial v_{\perp} \delta(\text{R.C.}) dv_{//} dv_{\perp}$
- $\partial f / \partial v_{\perp} > 0$ from keV electron distributions

Cyclotron-Maser Instability : Resonance & Gradients

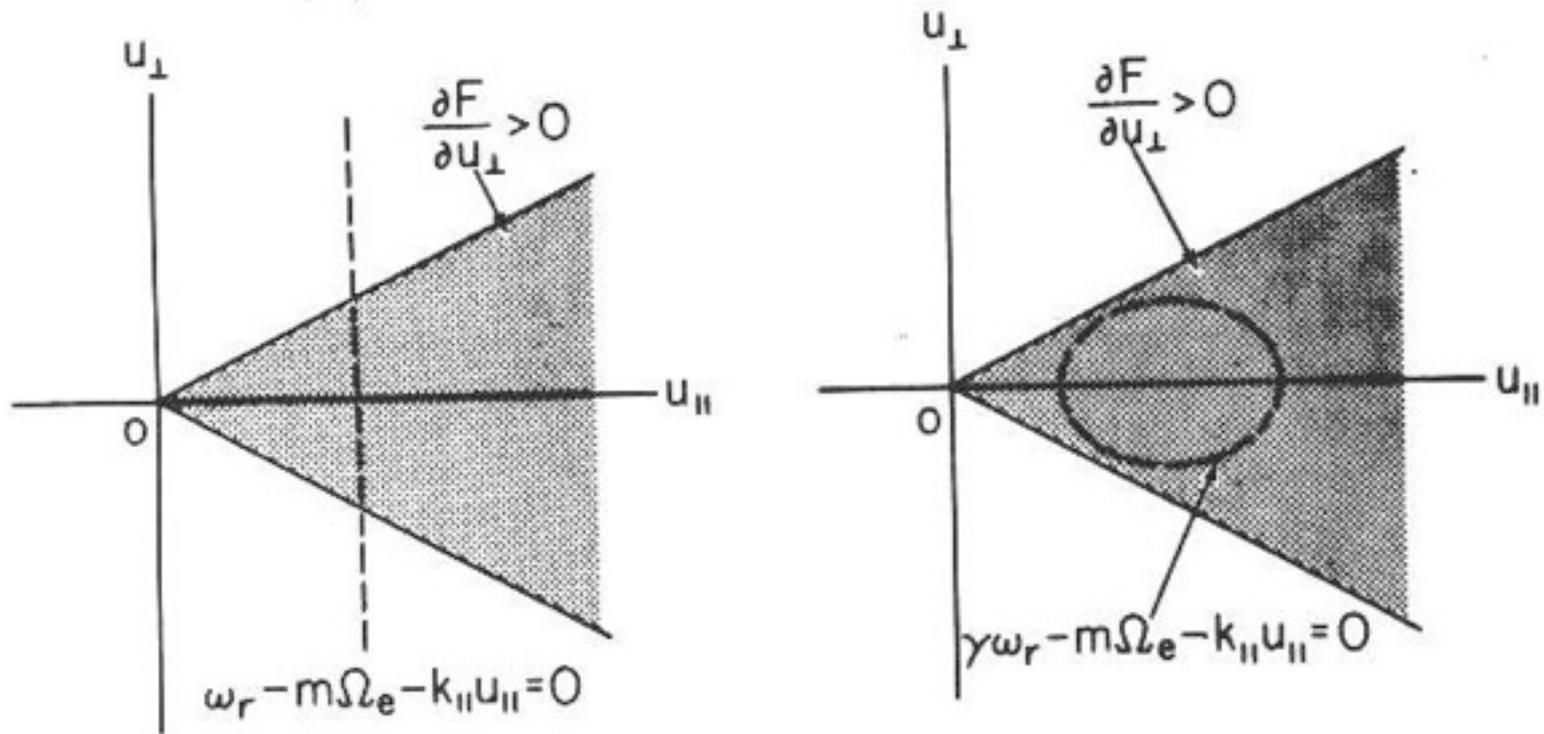
Resonance : $\omega = \omega_c / \Gamma + k_{\parallel} v_{\parallel}$

Growth rate : $\gamma = \frac{\omega_p^2 c^2}{8\omega_c} \int_0^{2\pi} v_{\perp}^2(\theta) \nabla_{v_{\perp}} f(\mathbf{v}_0, \mathbf{R}(\theta)) d\theta$ with $\omega > \omega_c$

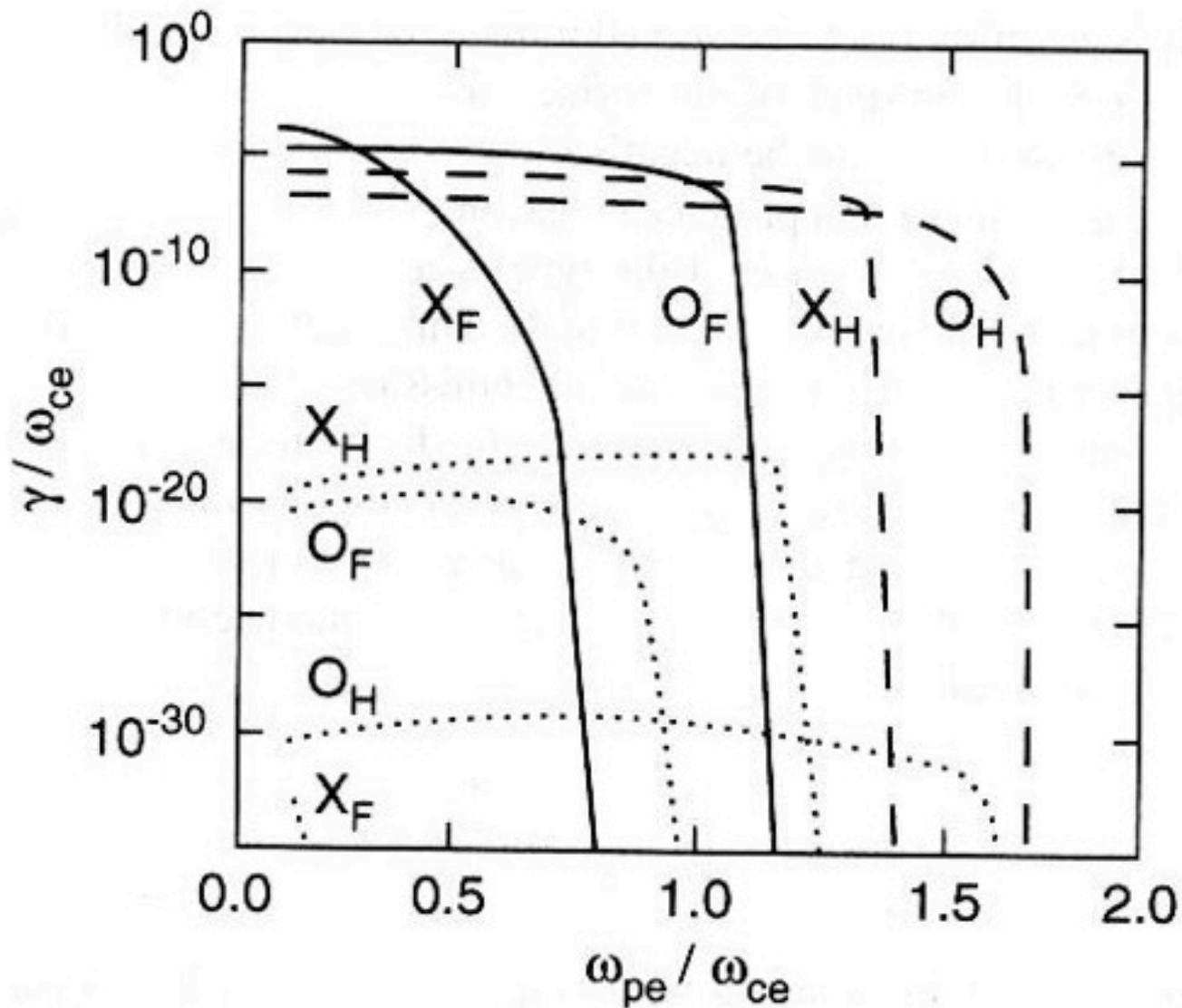


Cyclotron-Maser Instability : a weakly relativistic theory

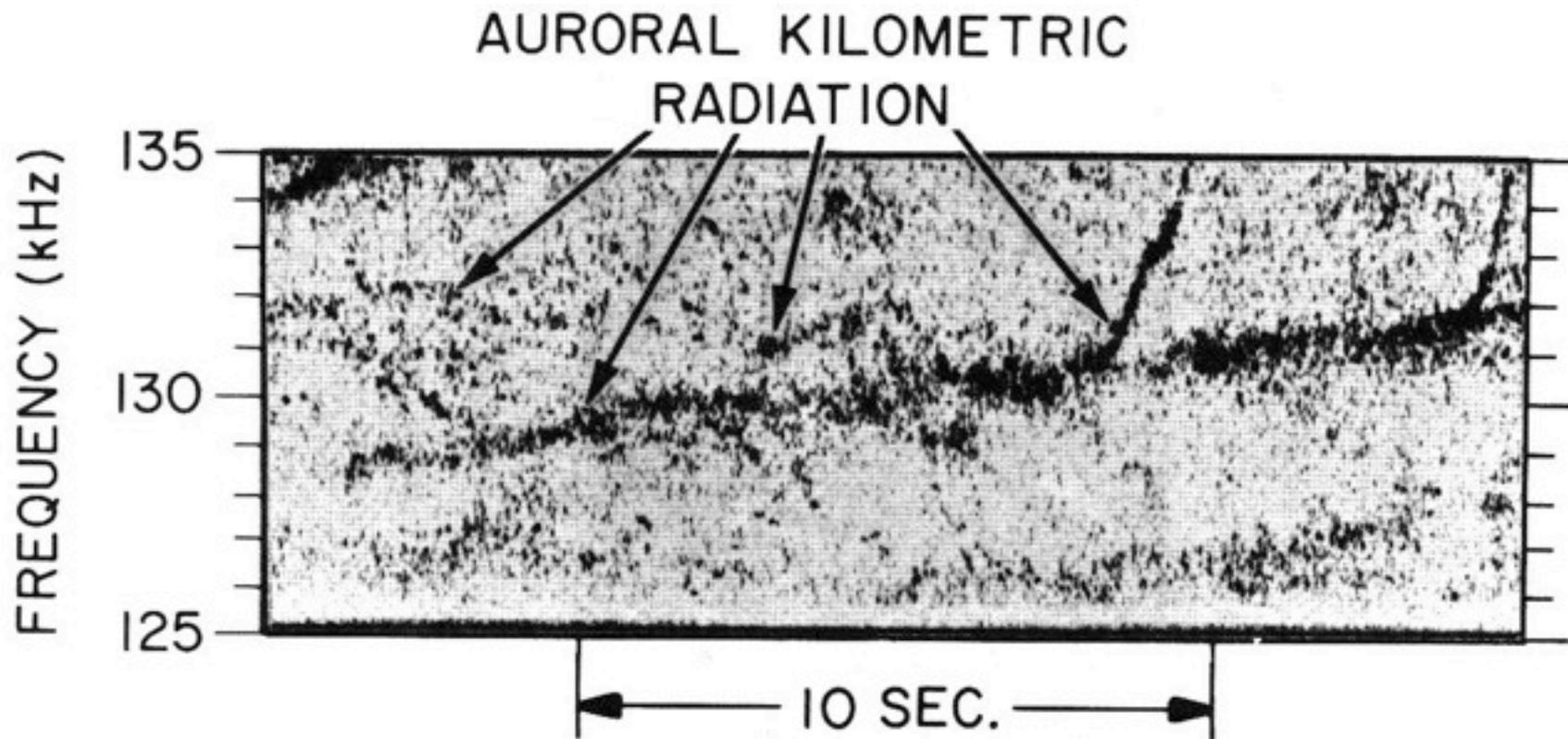
$$\omega - k_{\parallel} v_{\parallel} - n \omega_{ce} / \Gamma = 0$$



Cyclotron-Maser Instability : X & O modes growth rates
fundamental & harmonic

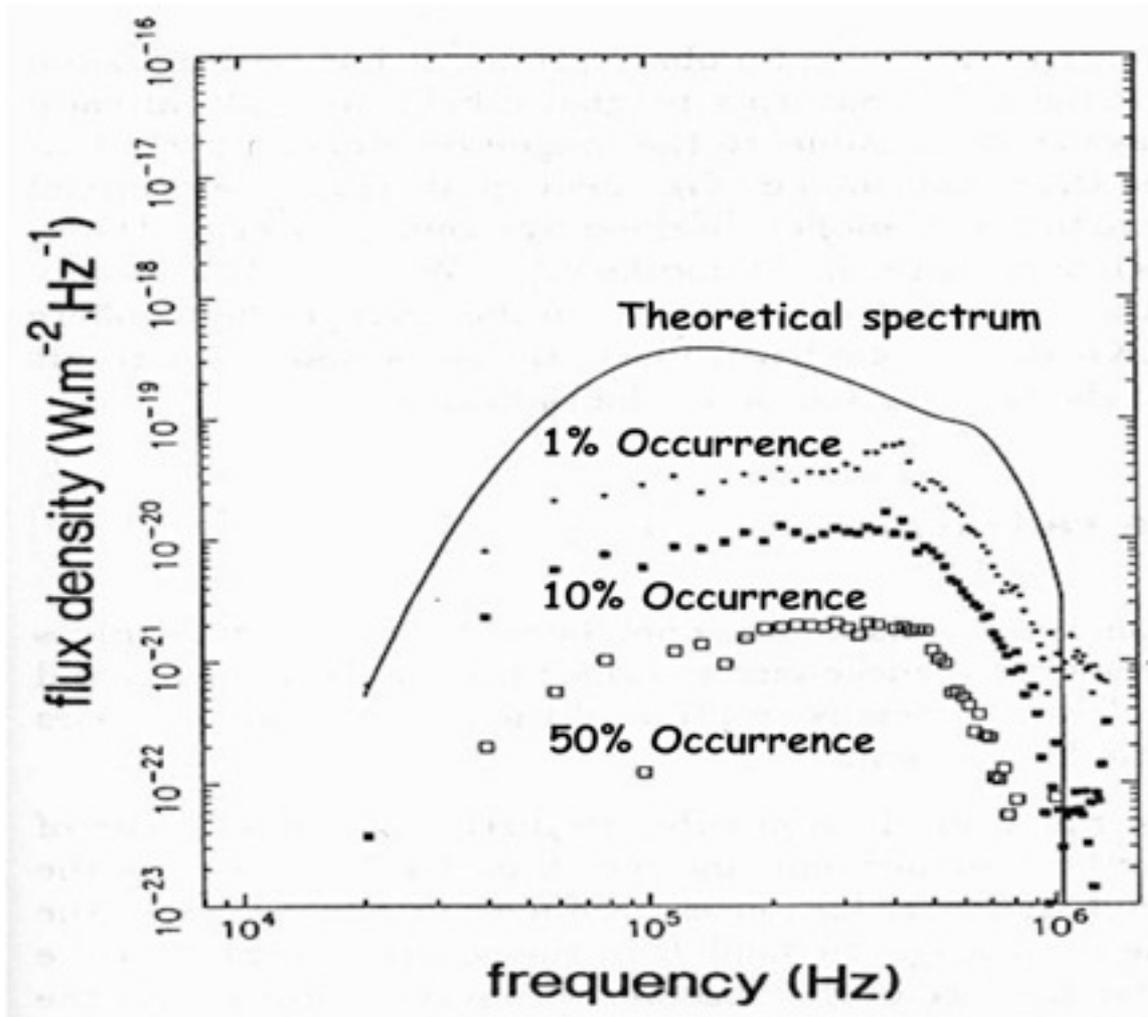


Narrow spectral structures : saturation by trapping ?



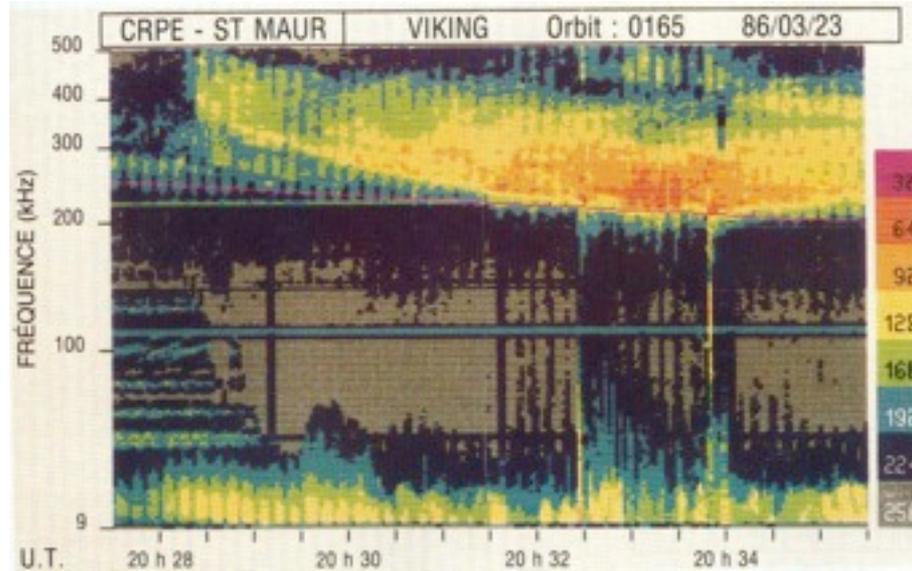
ISEE 1, DAY 58, FEBRUARY 27, 1978
START TIME, 1246:40 UT

Modelled trapping-saturated SKR spectrum



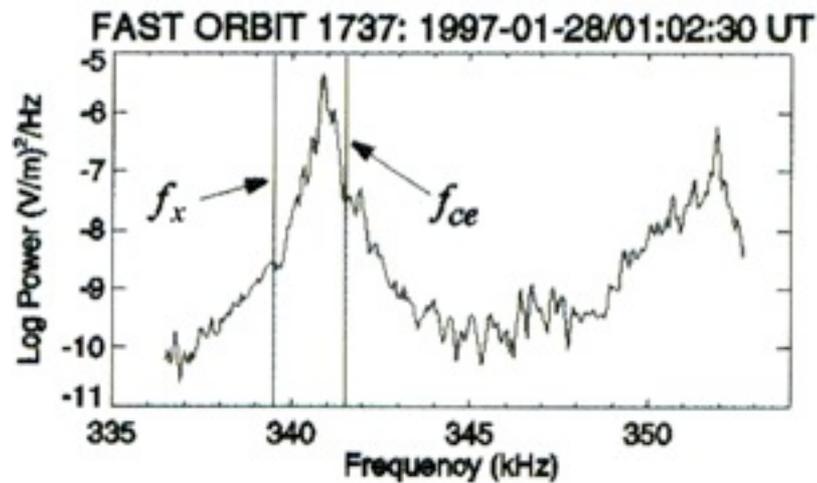
[Galopeau et al., 1989]

$f \sim f_x < f_{ce}$ in sources : deep cavities & hot plasma dispersion



Viking

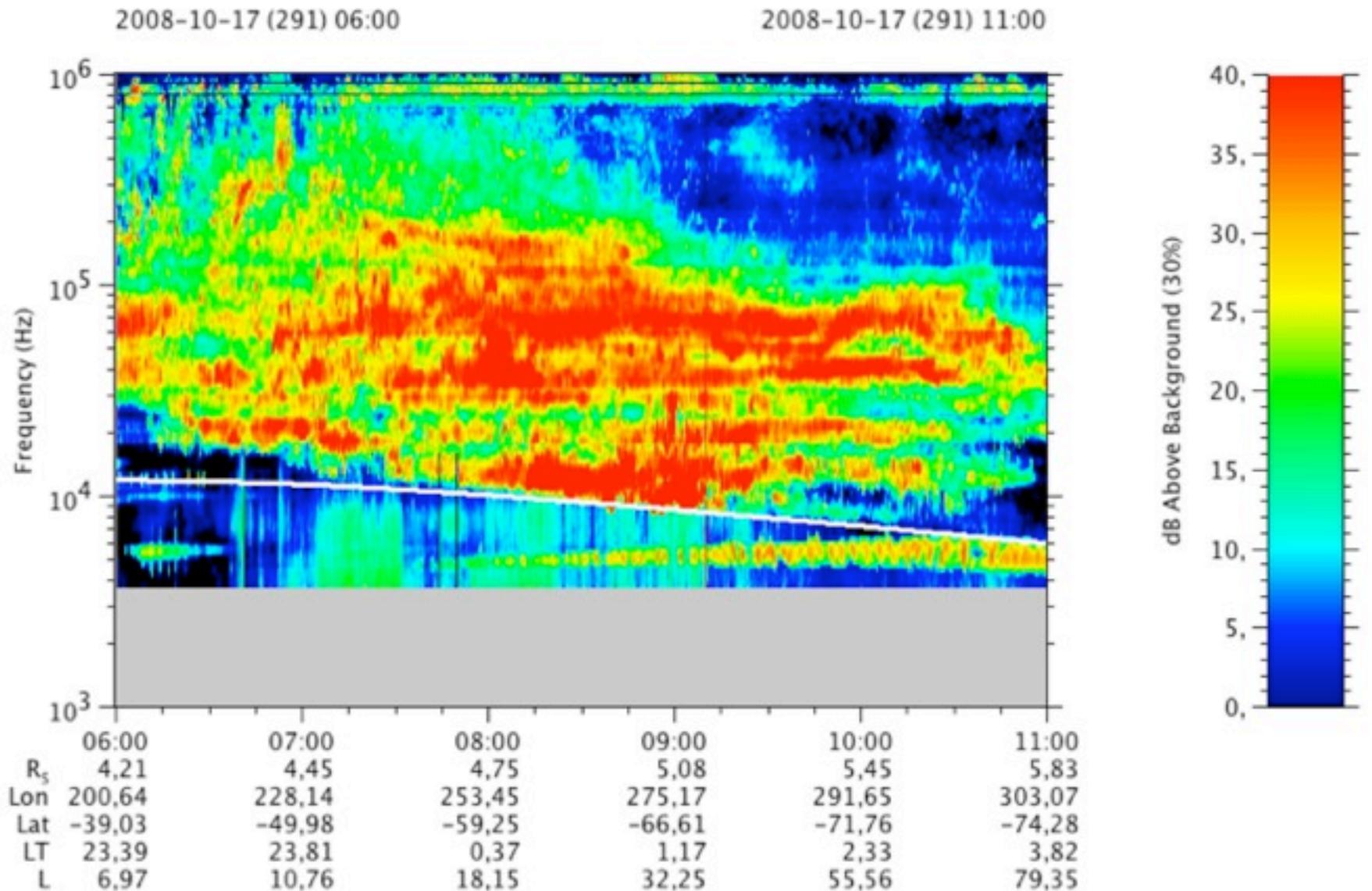
[Bahnsen et al., 1989]



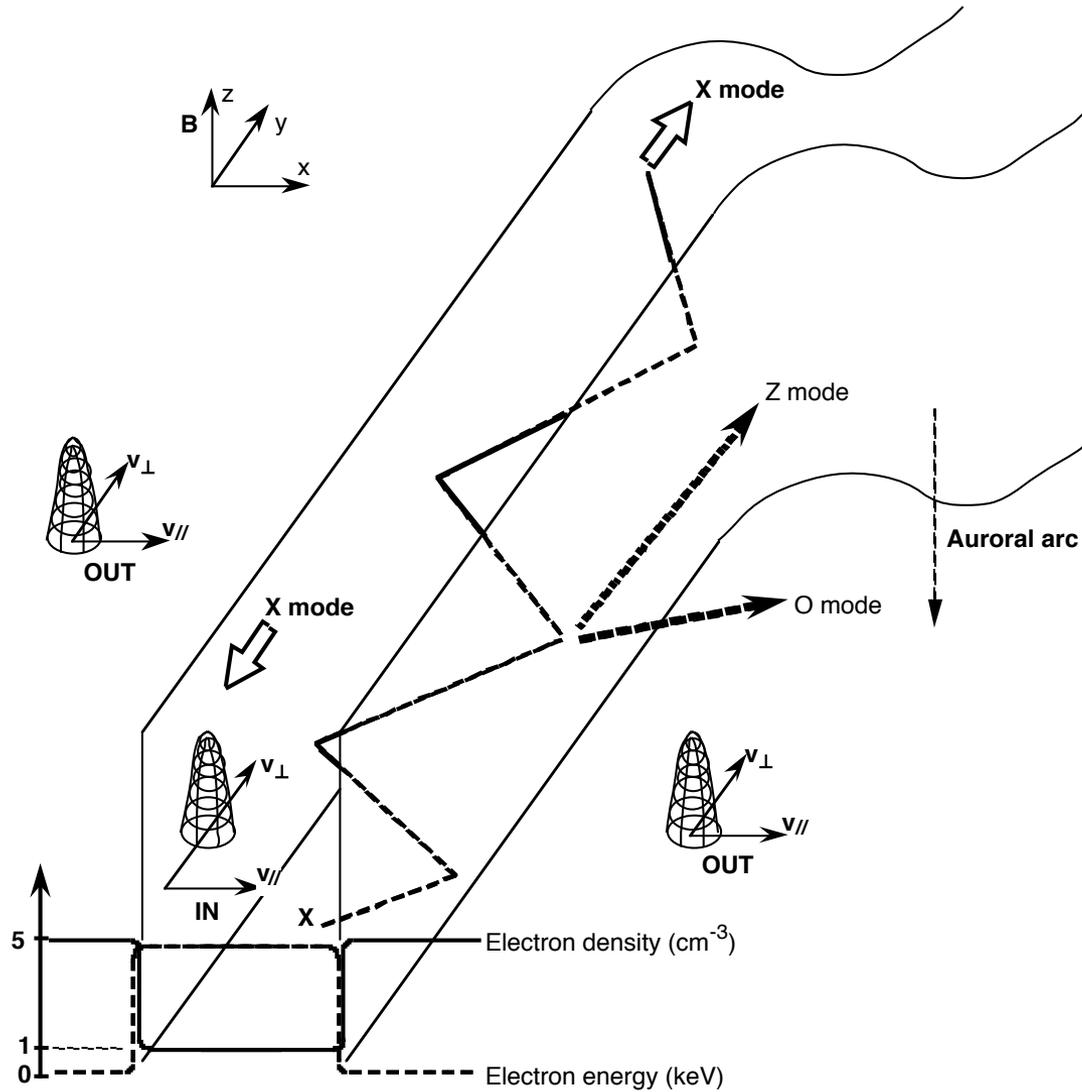
FAST

[Ergun et al., 1998]

SKR source crossings by Cassini

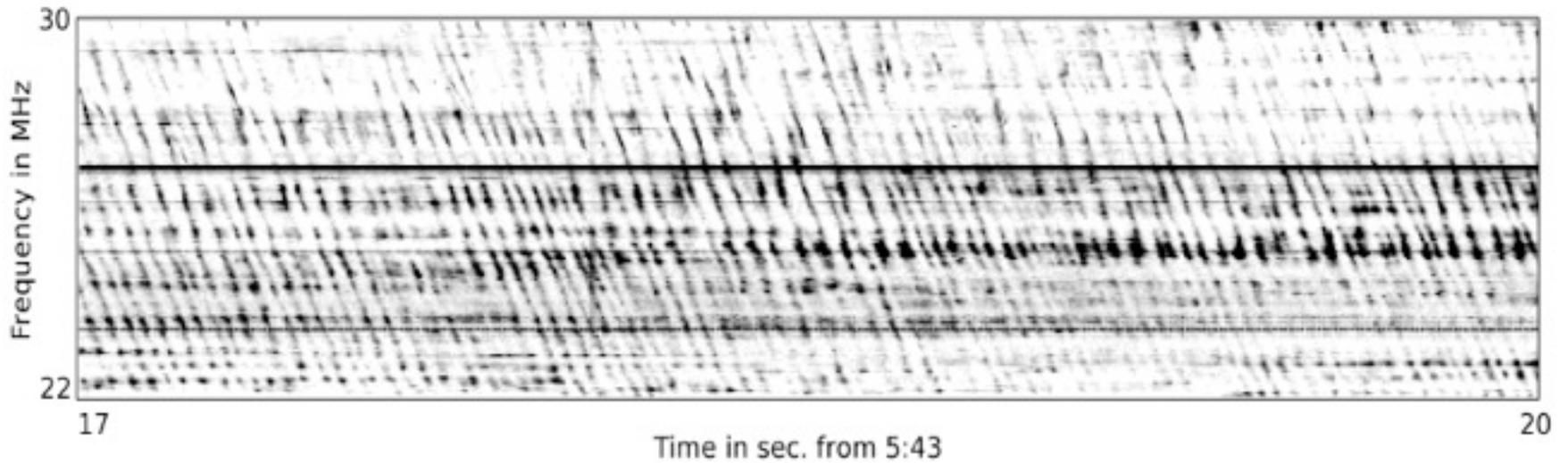
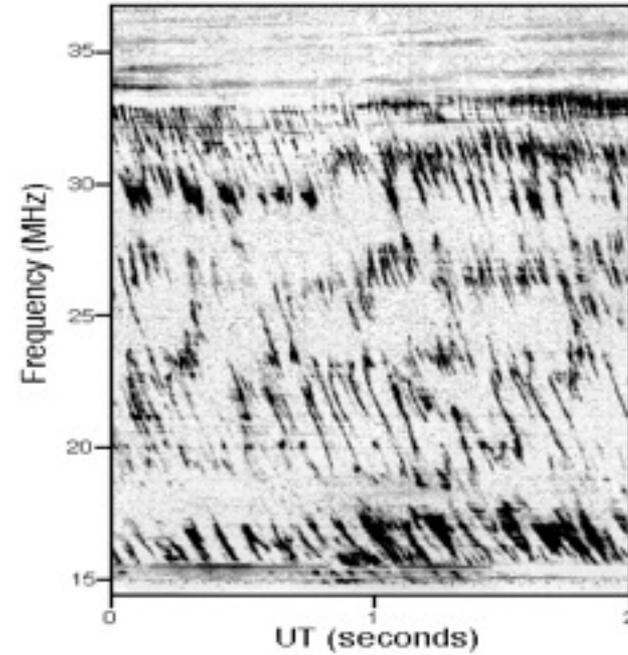


The AKR laminar source model



- Introduction
- Auroral Radio Emissions observations
- Theory of Auroral Radio Emissions
- New results on Jupiter
- New results on Saturn
- Radio emission from exoplanets ?

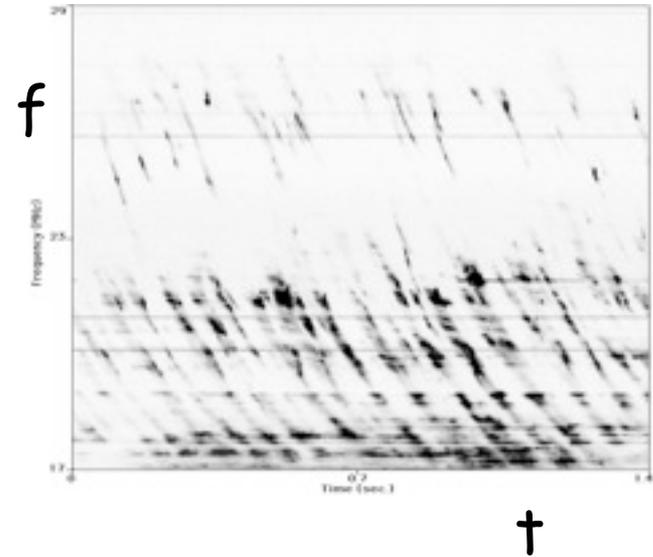
Ground-based observations of S-bursts



S-bursts drift-rates

$$df/dt = df_{ce}/ds \times ds/dt$$

↓ ↘
∇B parallel
(B model) velocity



Electrons adiabatic motion in the absence of // E-field :

$$\mu = v_{\perp}^2 / f_{ce} = v^2 / f_{\text{mirror}} = C^{\text{te}}$$

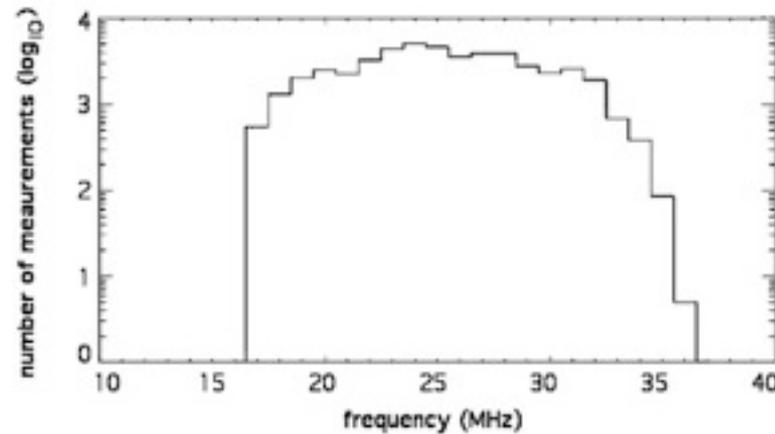
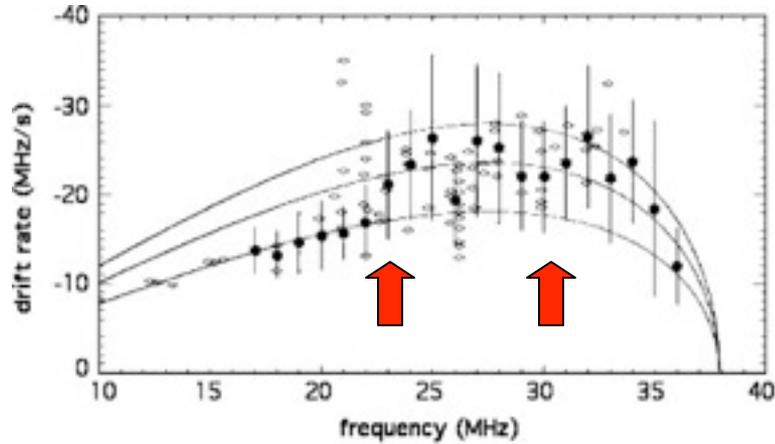
$$v^2 = v_{//}^2 + v_{\perp}^2 = C^{\text{te}}$$

$$v_{//} = v (1 - f_{ce} / f_{\text{mirror}})^{1/2}$$

pitch angle $\Phi = (\mathbf{v}, \mathbf{B})$: $\sin^2 \Phi = v_{\perp}^2 / v^2 = f_{ce} / f_{\text{mirror}}$

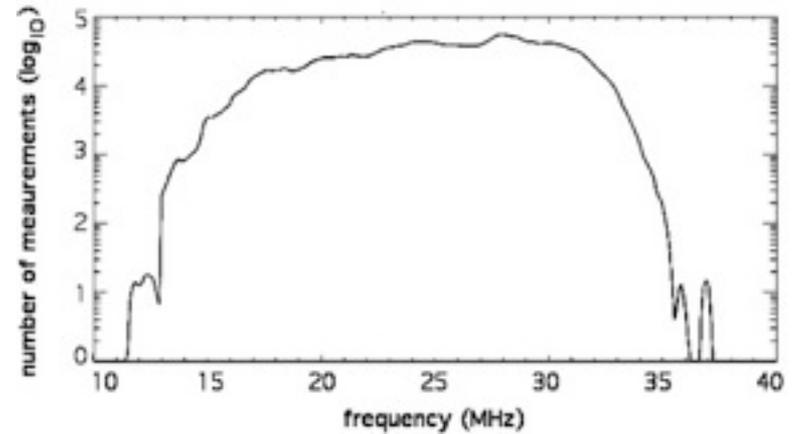
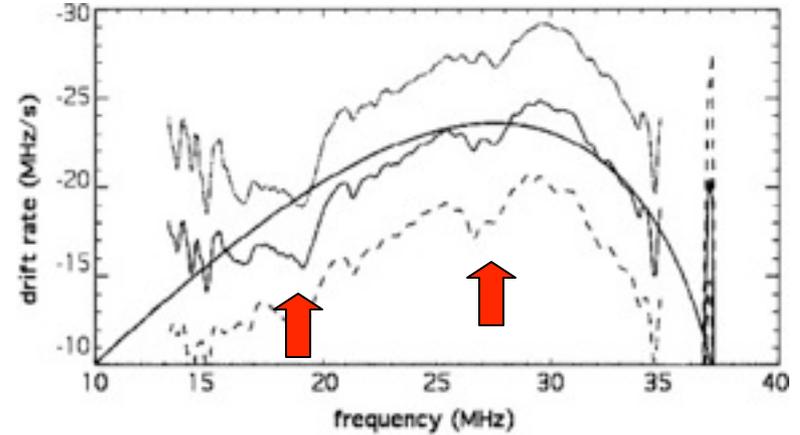
S-bursts drift-rates : comparison with observations

$$E = 5.3 \pm 2.2 \text{ keV}, \phi_{eq} \sim 2.8^\circ$$



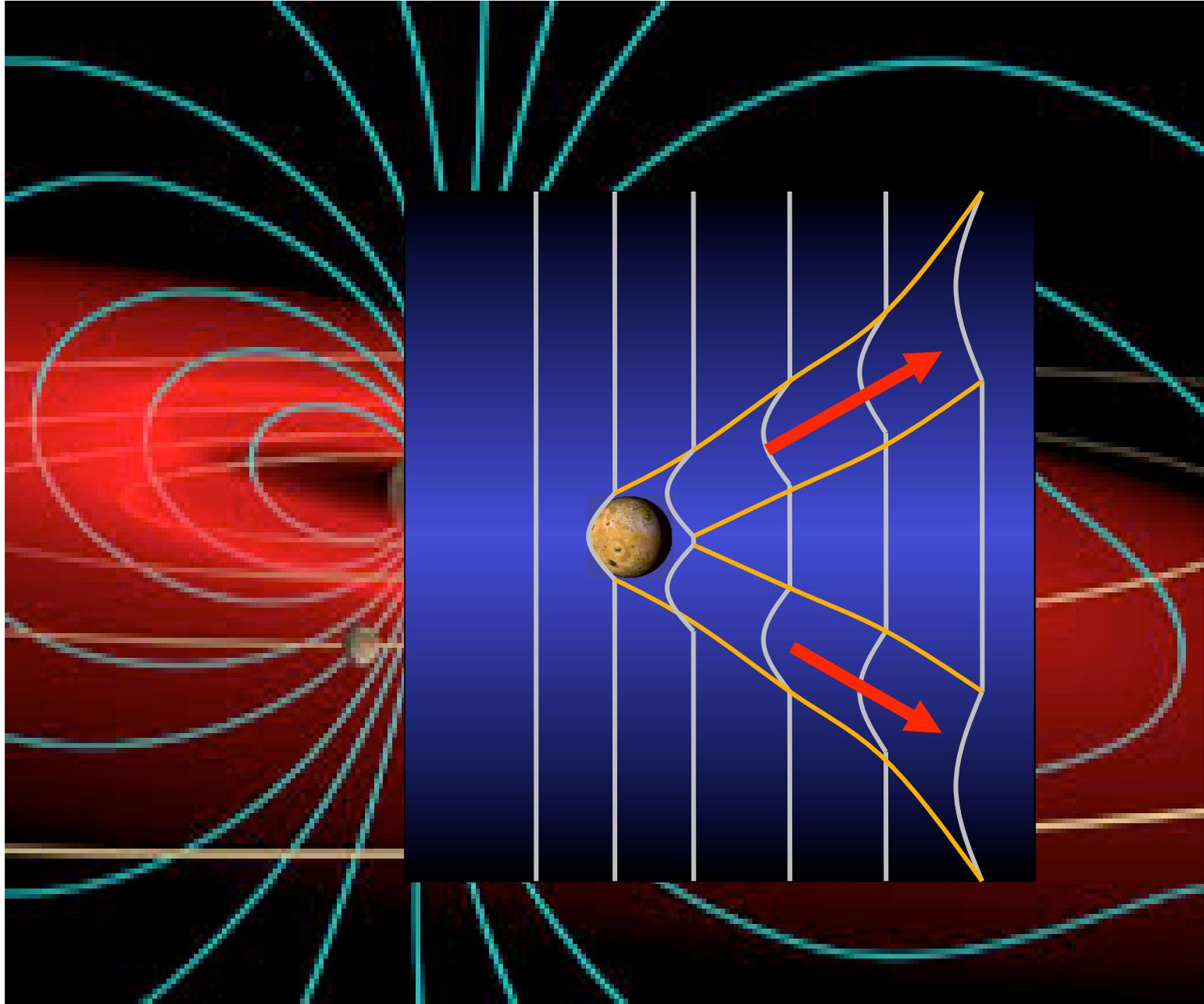
[Zarka et al., 1996]

$$E = 4.5 \pm 1.1 \text{ keV}, \phi_{eq} \sim 2.7^\circ$$

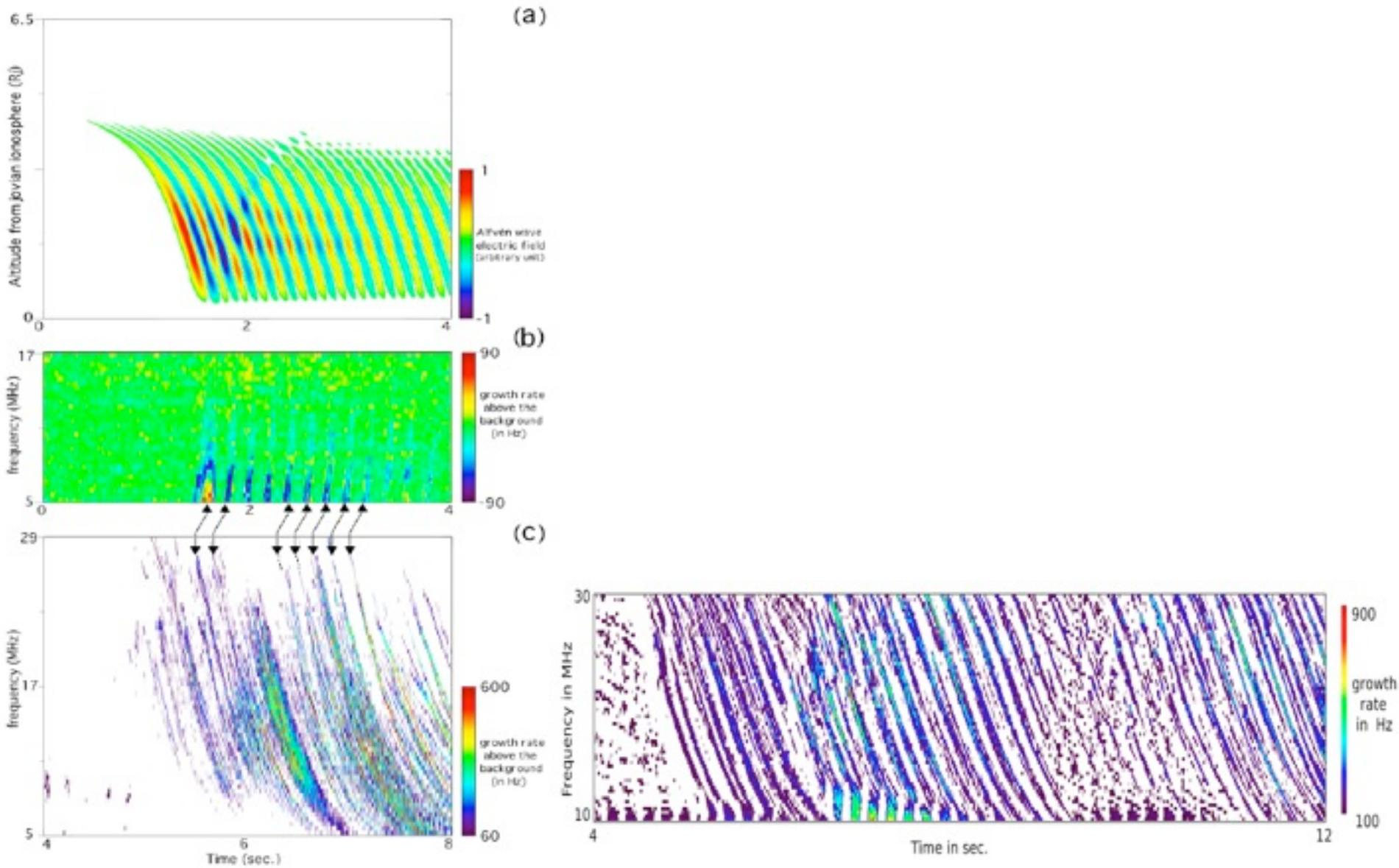


[Hess et al., 2007a]

Electron acceleration by Alfvén waves



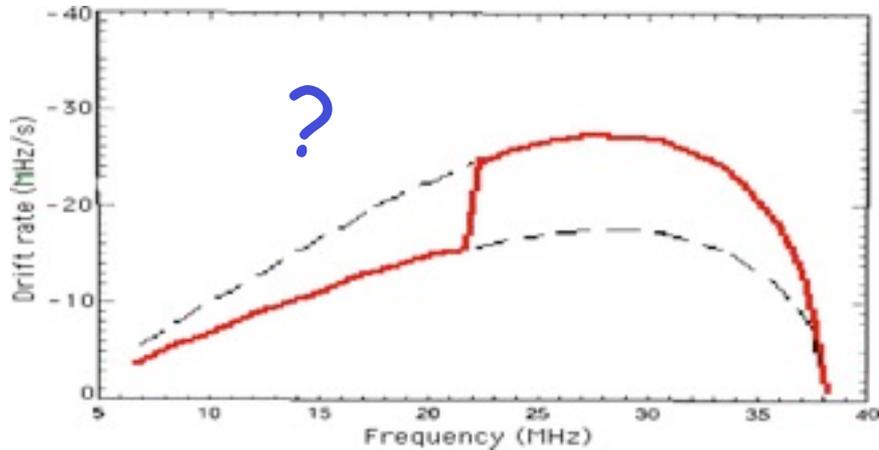
Electron acceleration by *Alfvén waves*



[Hess et al., 2007b]

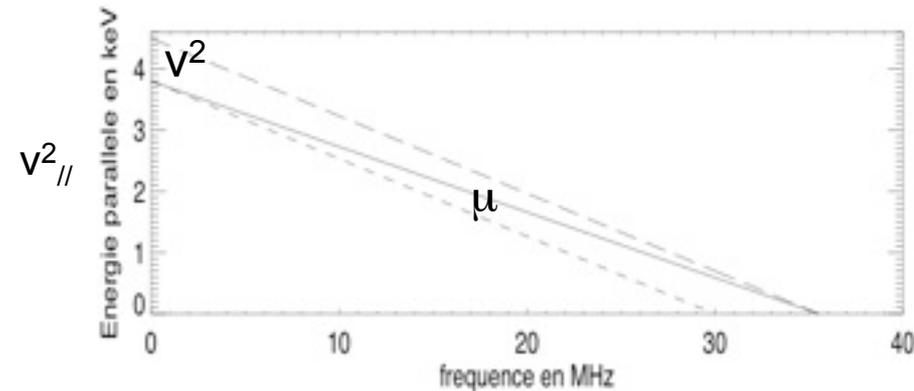
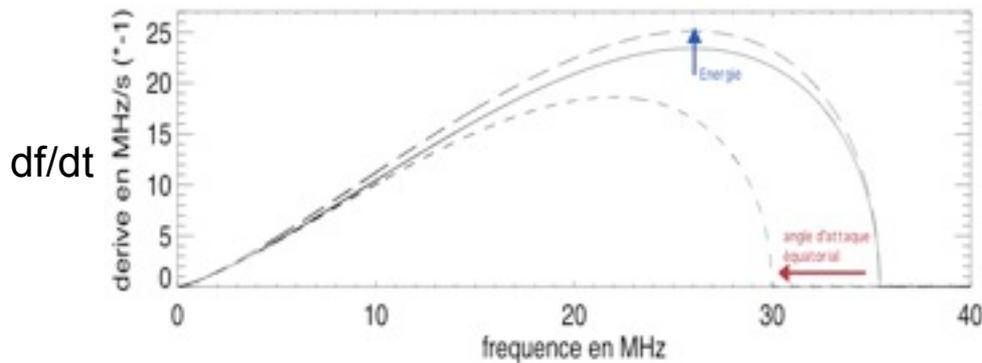
Search for non-adiabatic discontinuities in df/dt :

→ Study of 2 years of high resolution dynamic spectra (total ~1h30)

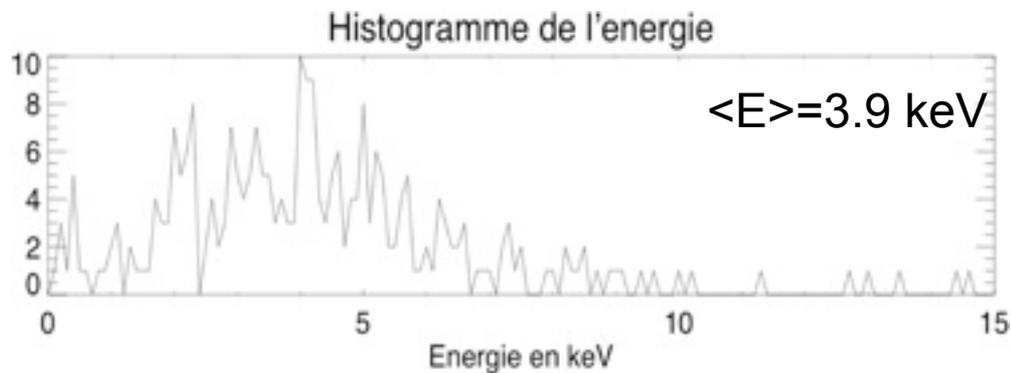
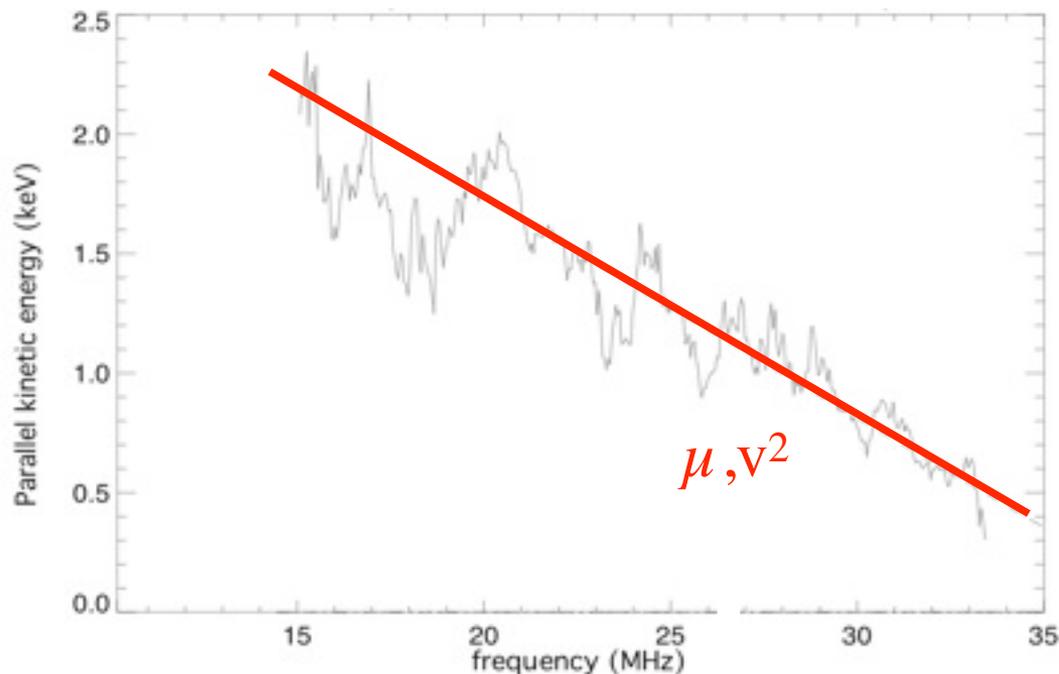
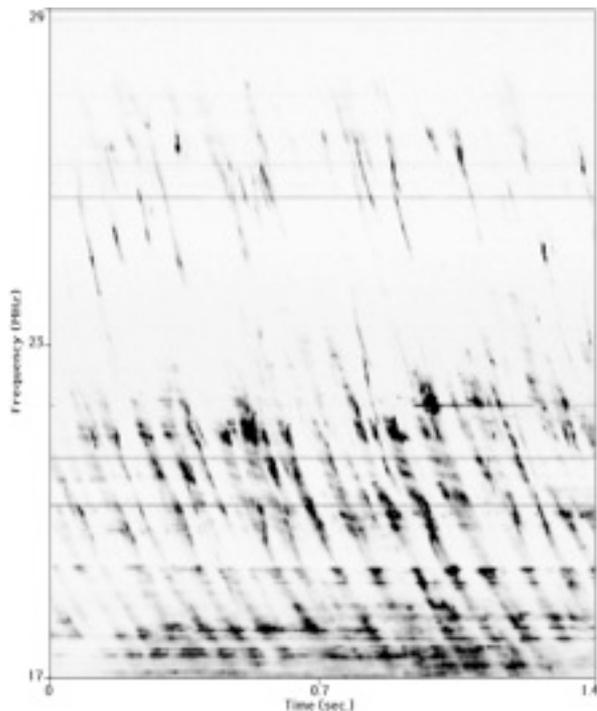


Parallel energy:

$$v_{//}^2 = v^2 - v_{\perp}^2 = v^2 - \mu \cdot f_{ce}$$

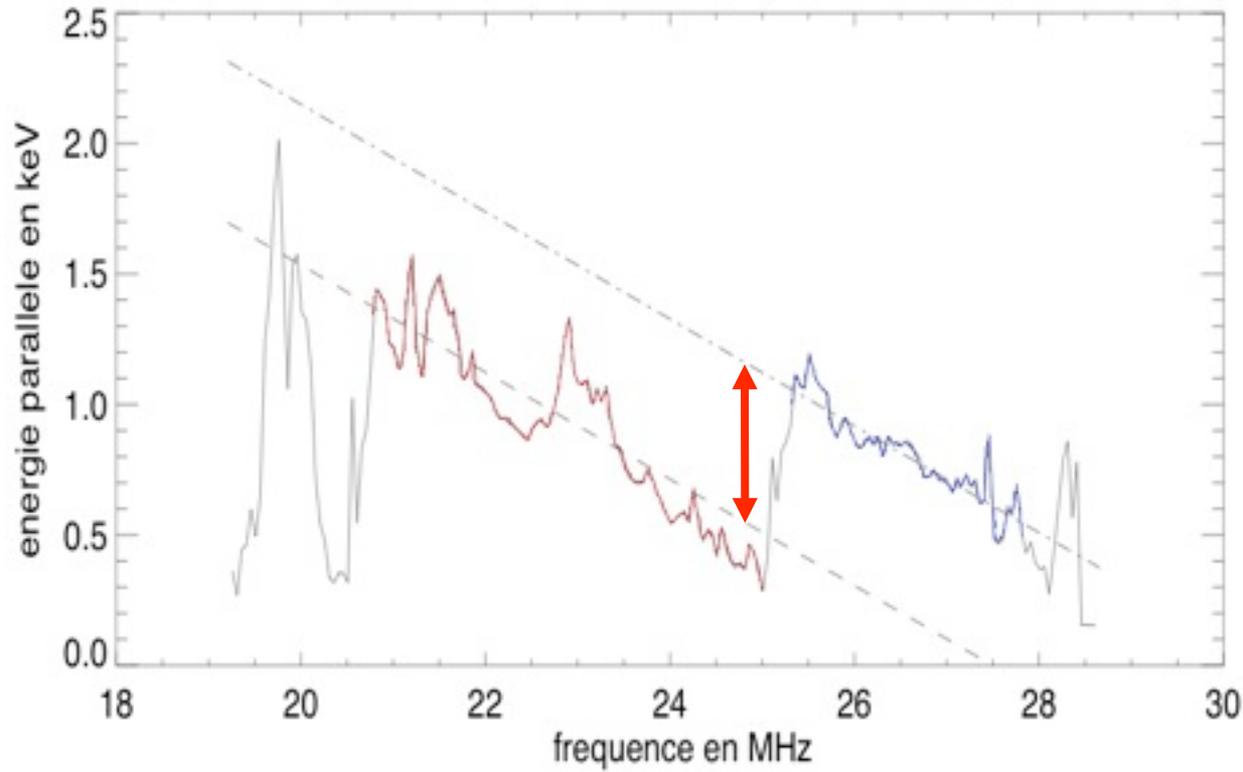


Confirmation of electrons adiabatic motion for most (>80%) observed dynamic spectra

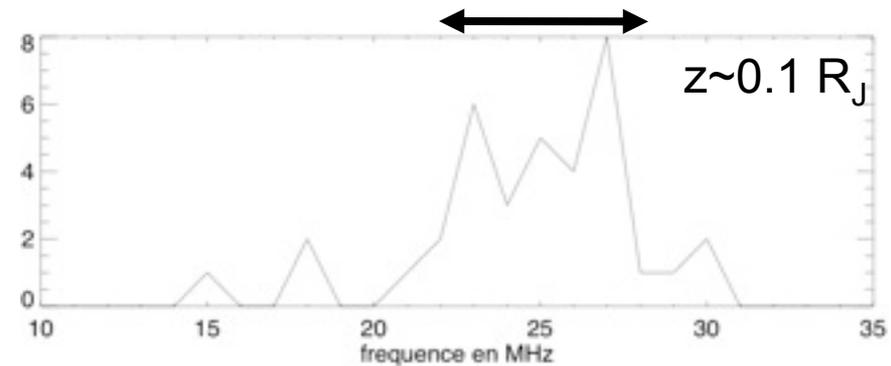
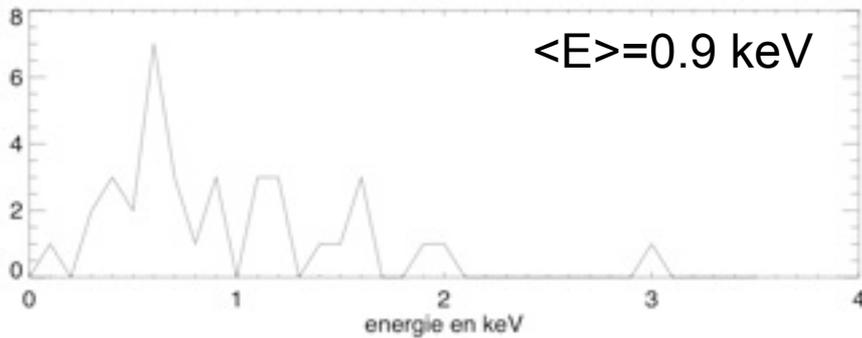
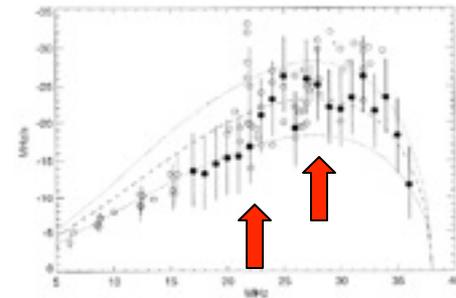


[Hess et al., 2007a]

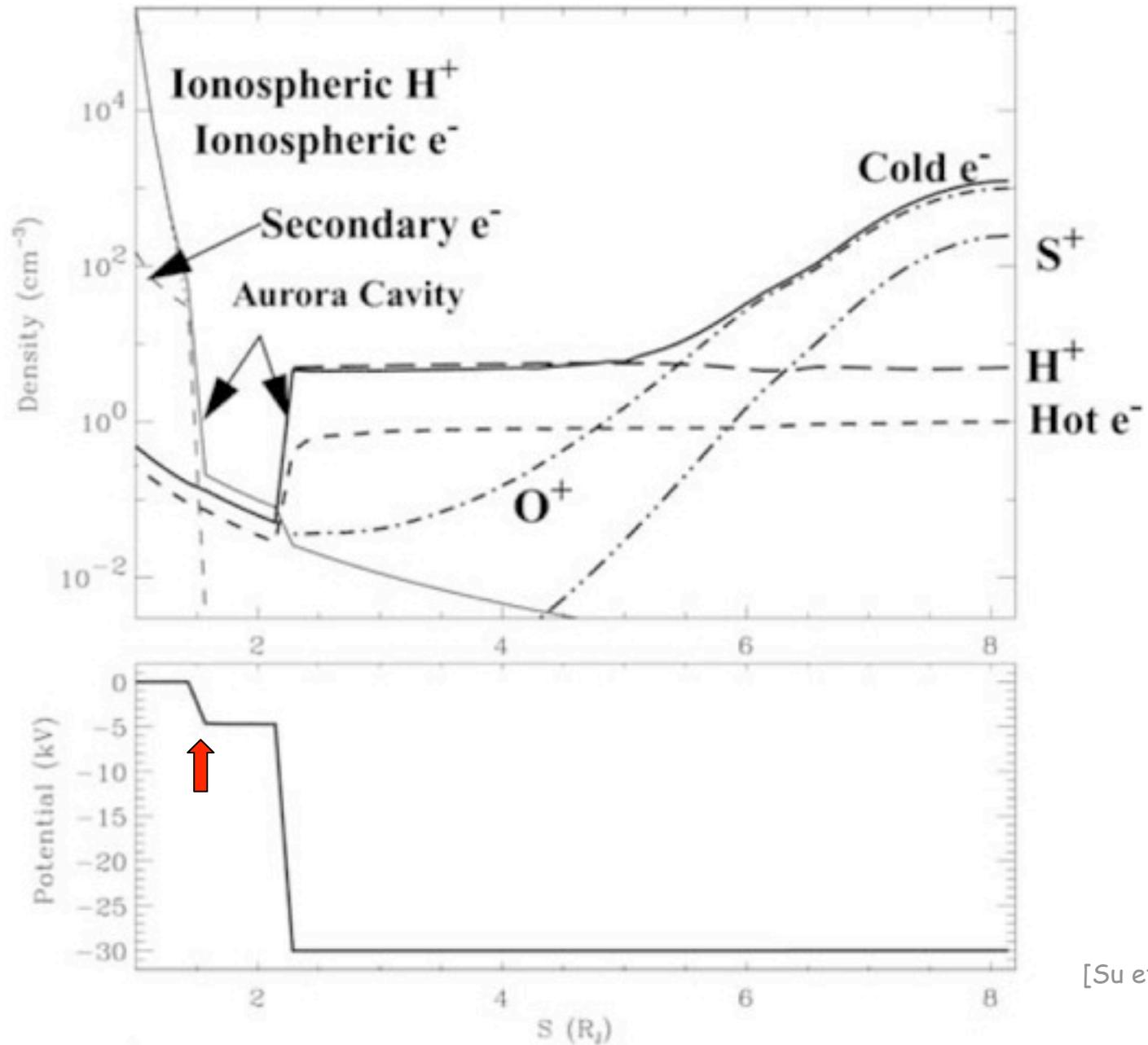
Strong doubles-layers detected in 15% of the cases



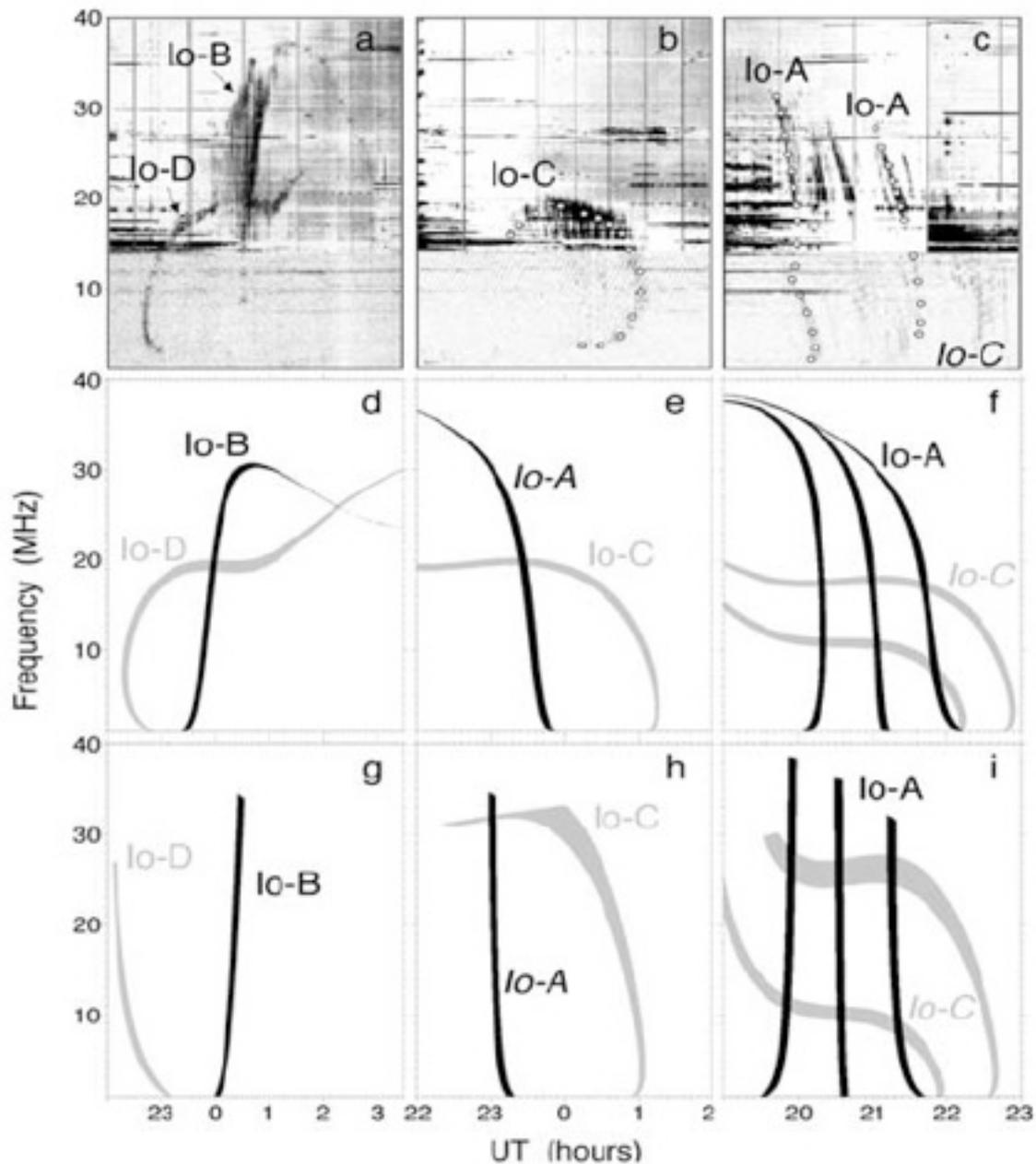
[Hess et al., 2007a]



Strong double-layers theoretically predicted



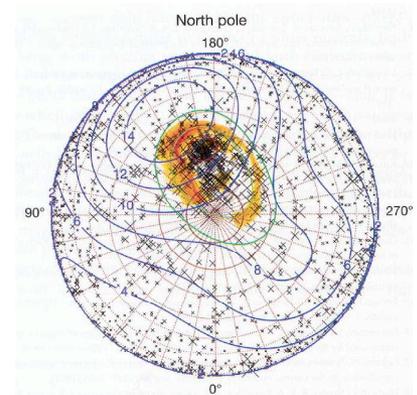
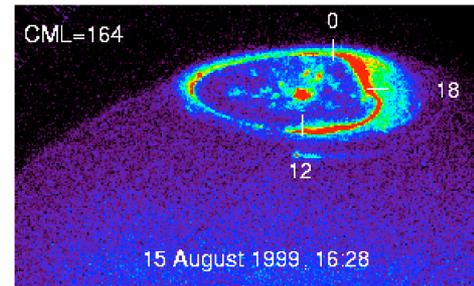
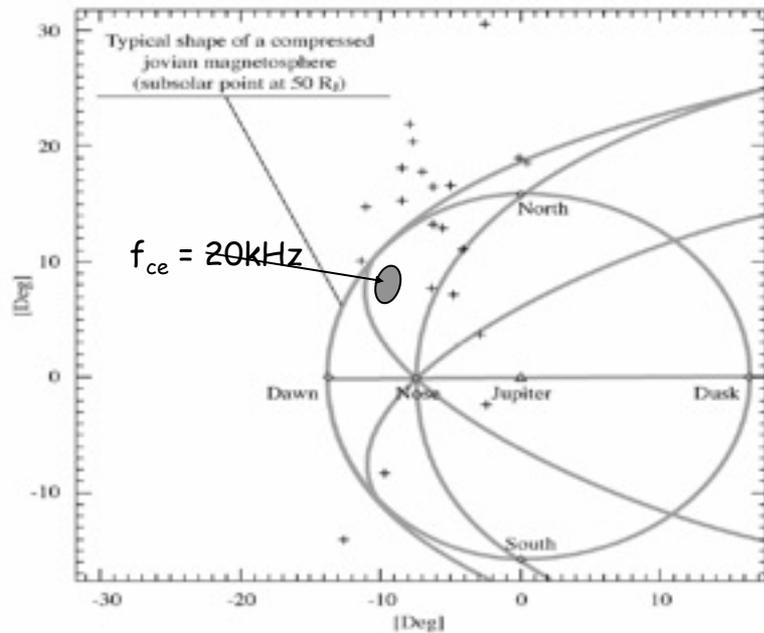
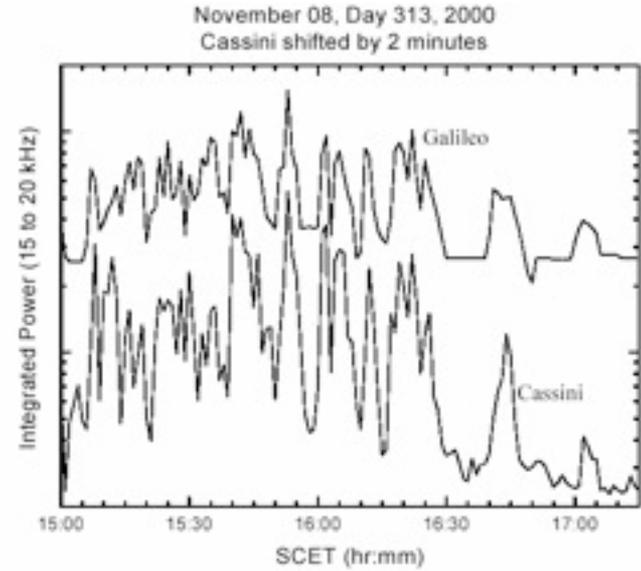
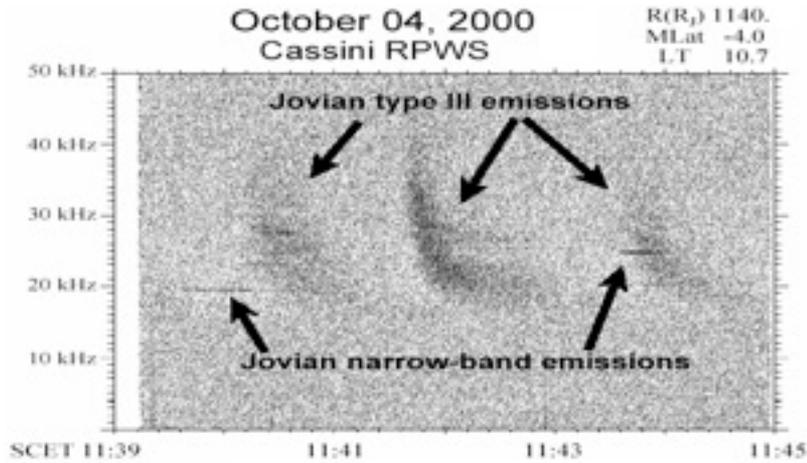
Dynamic spectrum (CMI) modeling



Loss-cone CMI

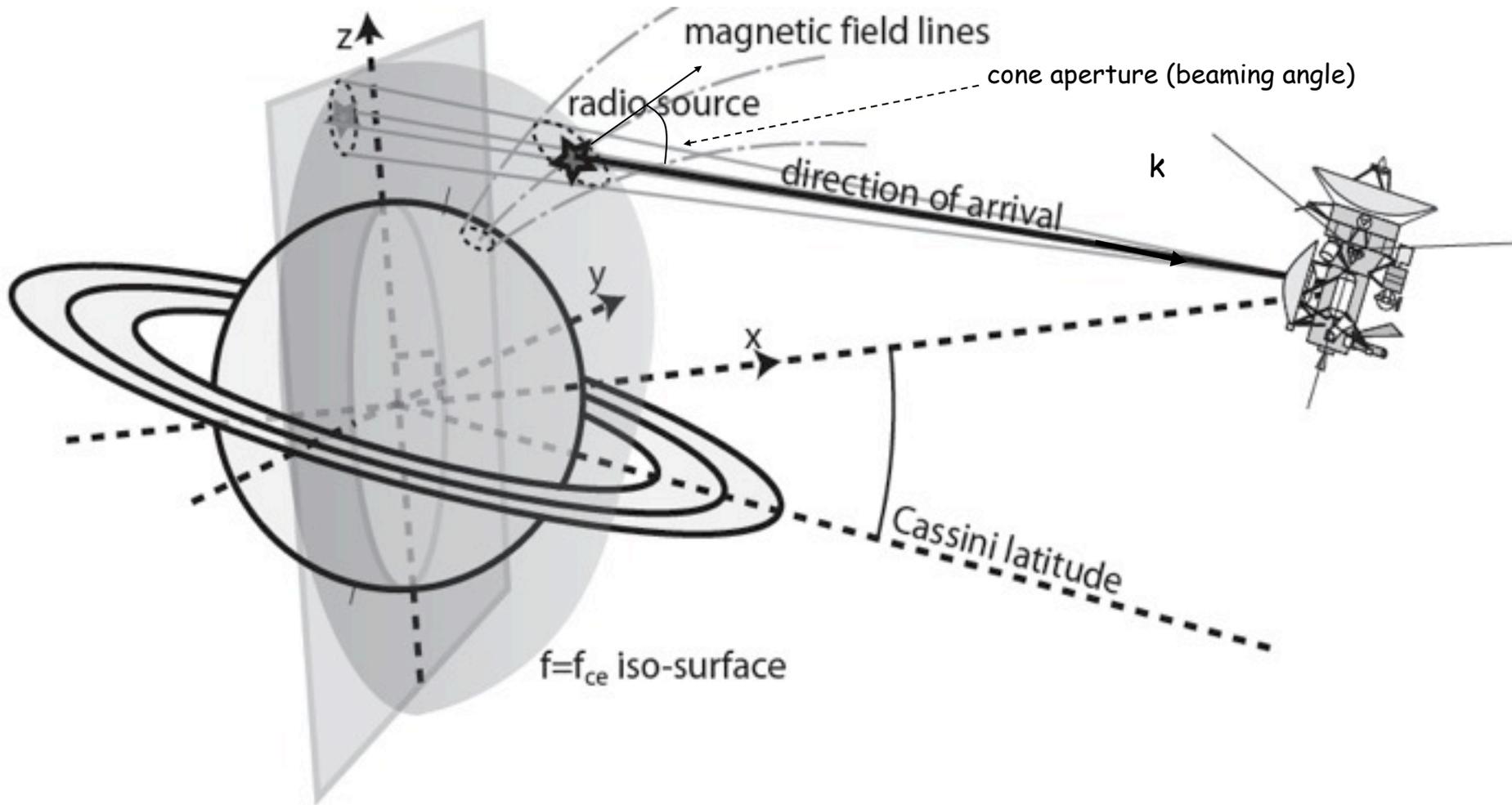
Shell CMI

Jovian LF « quasi-periodic » QP bursts

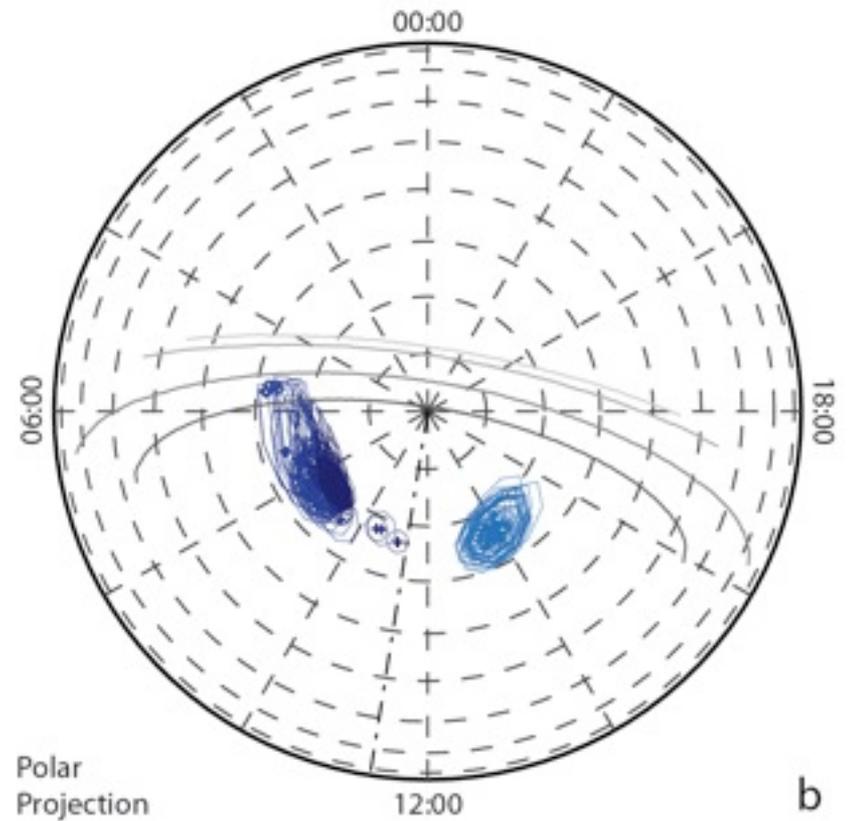
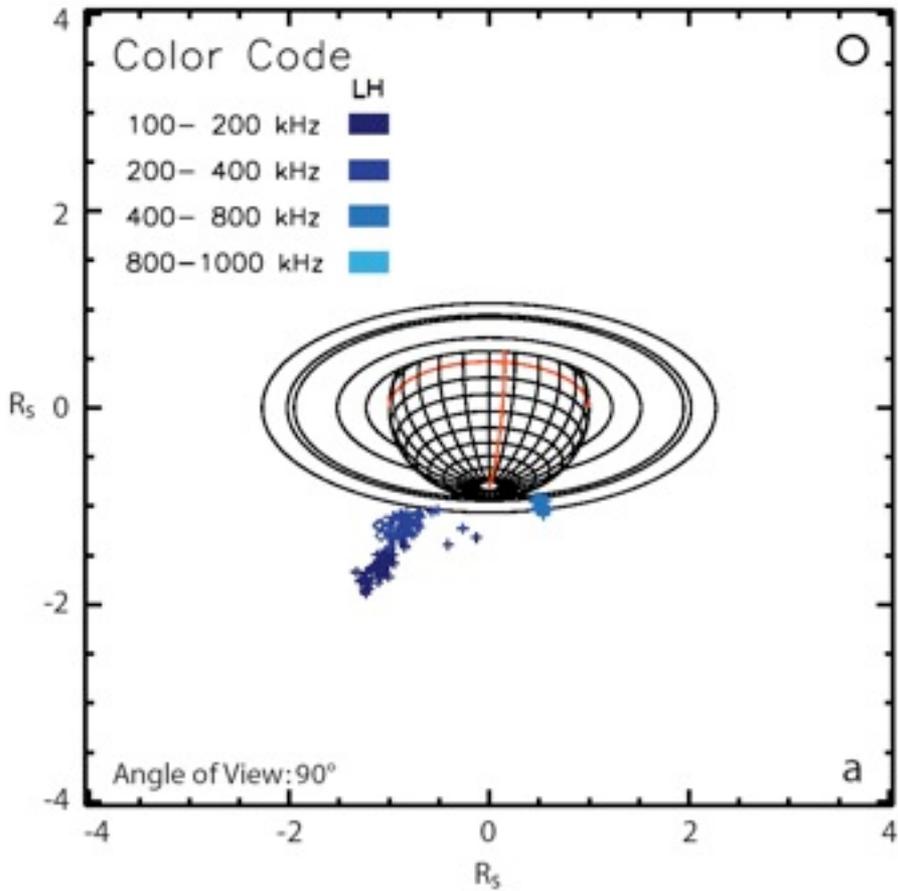


- Introduction
- Auroral Radio Emissions observations
- Theory of Auroral Radio Emissions
- New results on Jupiter
- New results on Saturn
- Radio emission from exoplanets ?

3D - goniopolarimetry (direction-finding)

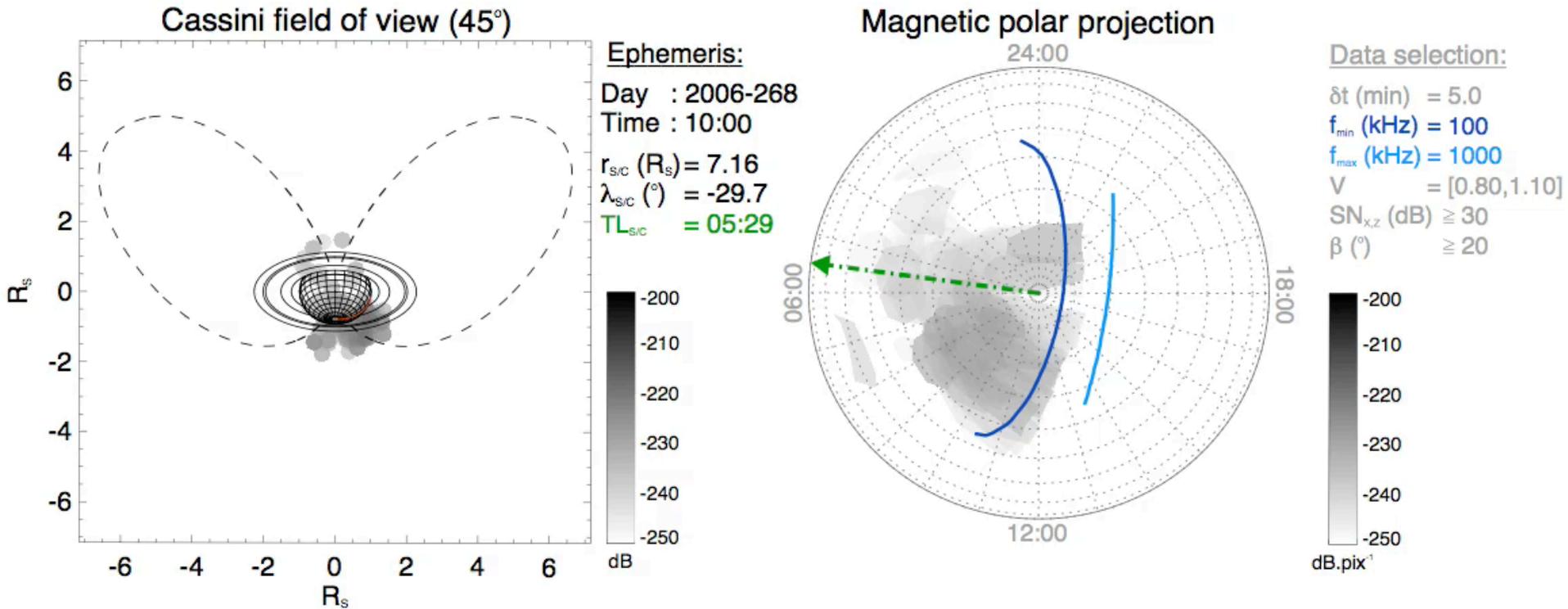


3D - goniopolarimetry (direction-finding)



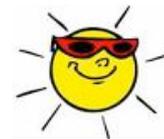
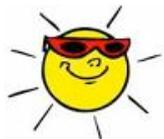
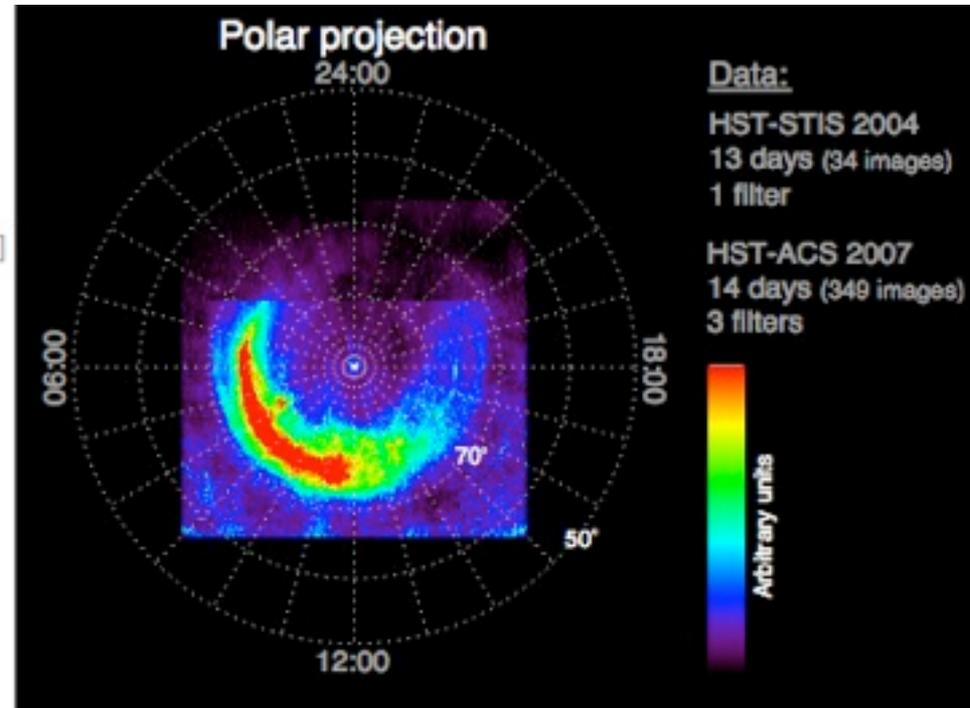
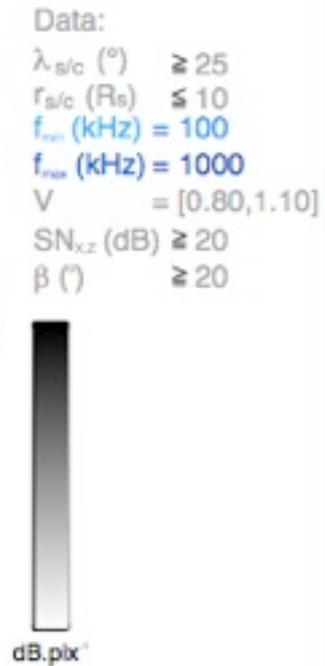
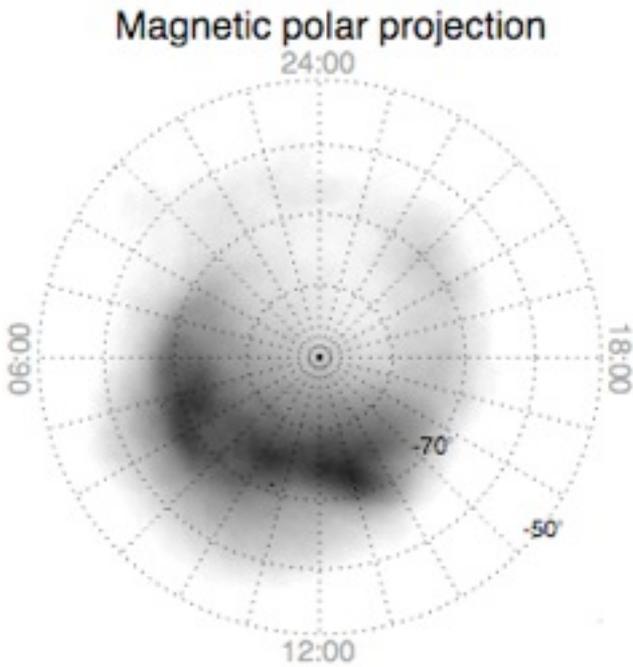
[Cecconi et al., 2008]

2D & 3D radiosources imaging with Cassini



[Lamy et al., 2009a]

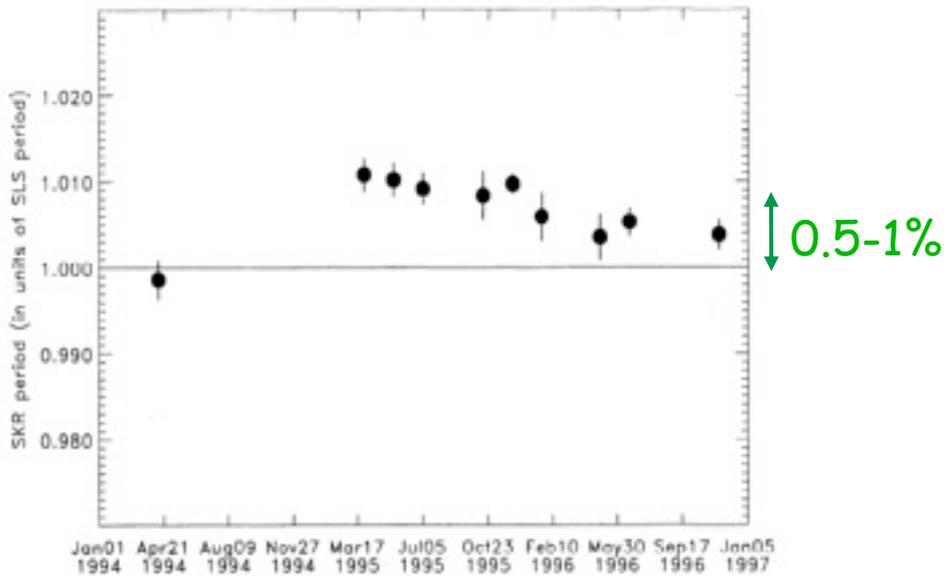
Auroral radio oval (statistical) similar to UV one



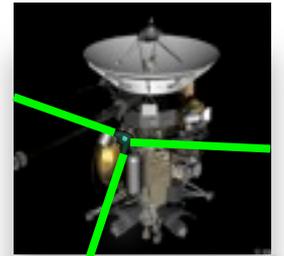
Saturn's variable radio period



Ulysses

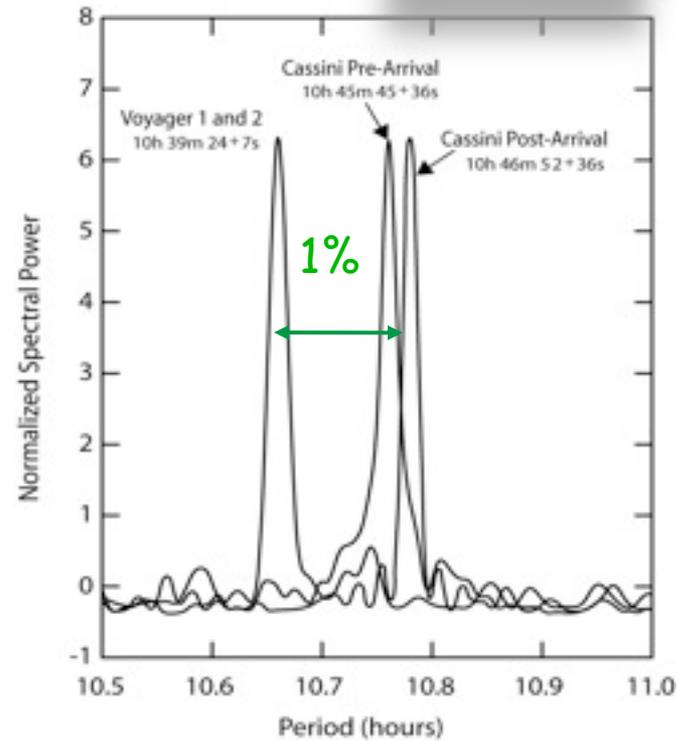


[Galopeau & Lecacheux, 2000]



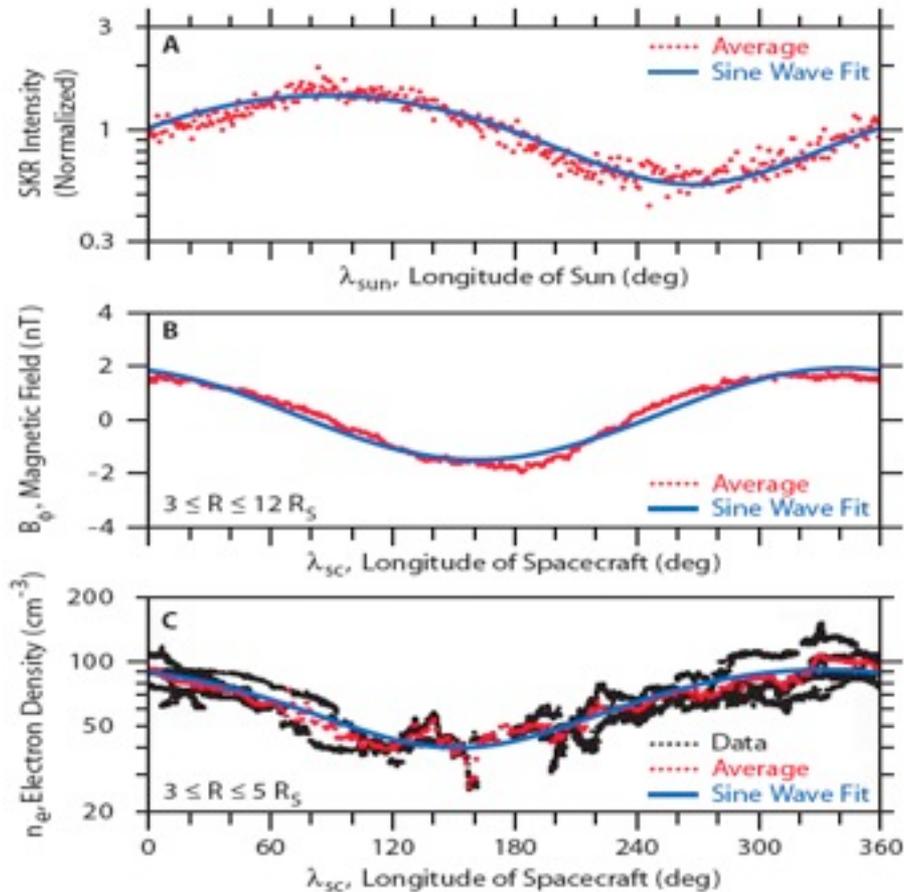
A-D04-222-8

Cassini



[Gurnett et al., 2005]

Similar variations for ...



radio emissions

magnetic field

plasma density ?

+ UV aurora ?

+ magnetopause location ?

+ currents ?

+ energetic particles ?

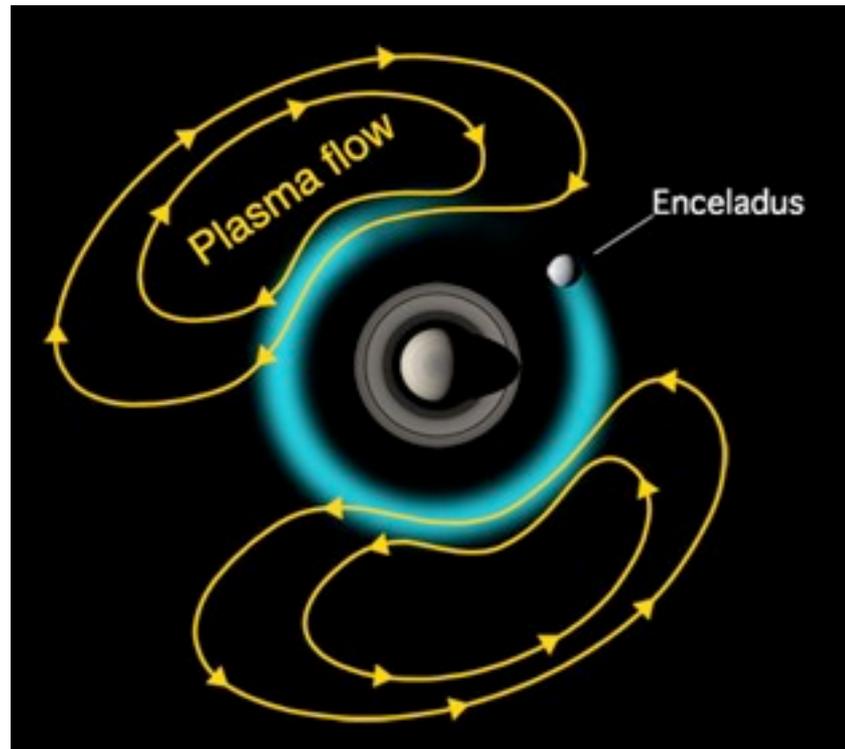
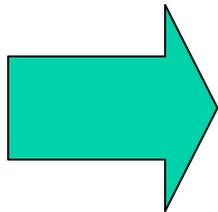
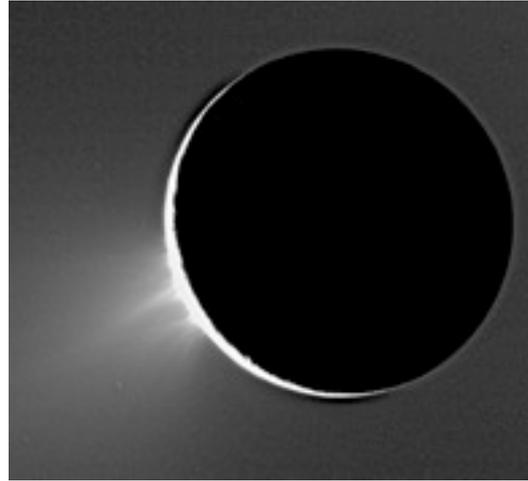
[Gurnett et al., 2007]

Origin ?

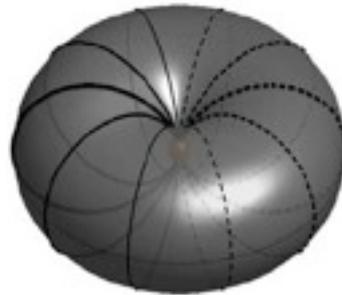
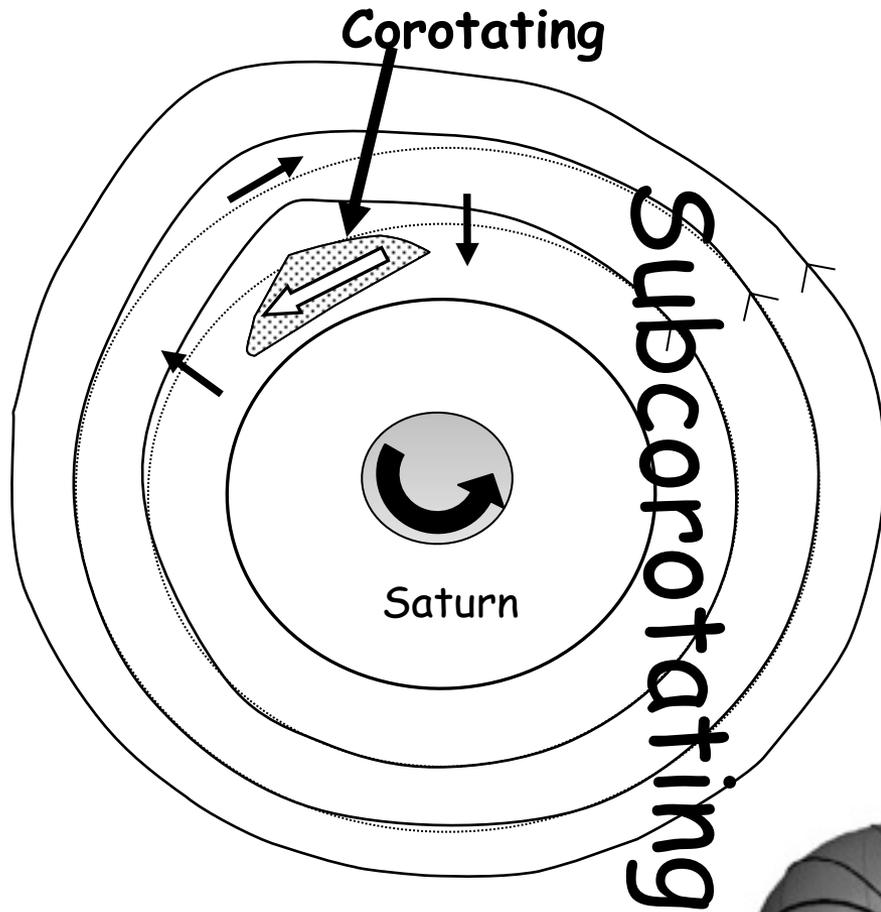
→ not a real change of Saturn's rotation rate !



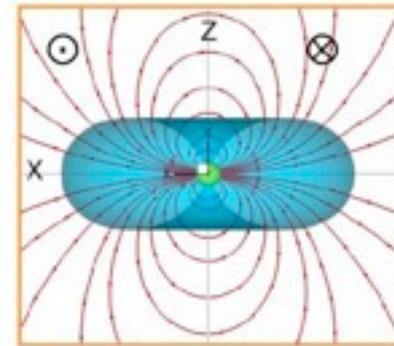
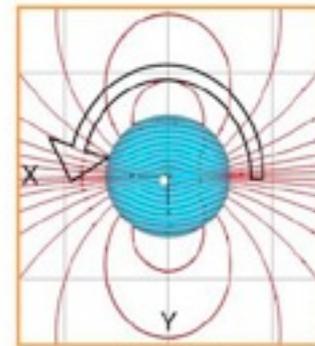
Variable plasma flow from Enceladus ?



Magnetic « cam » due to rotating currents system ?

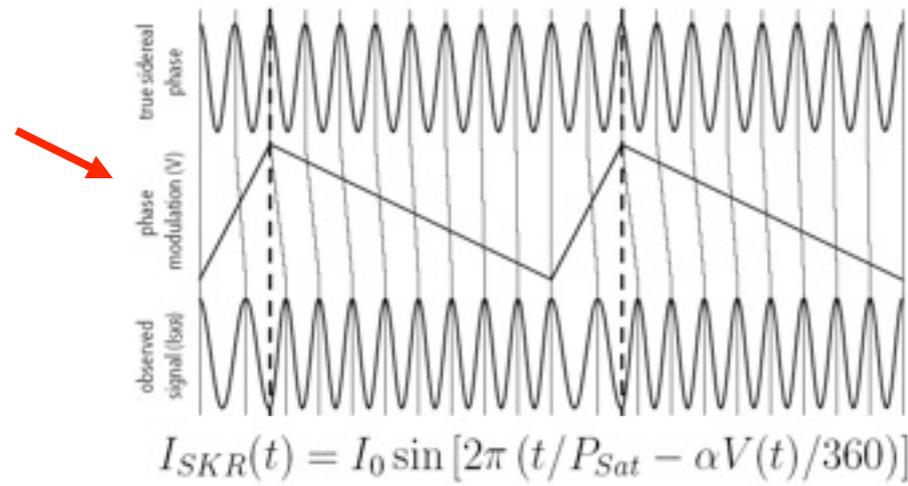
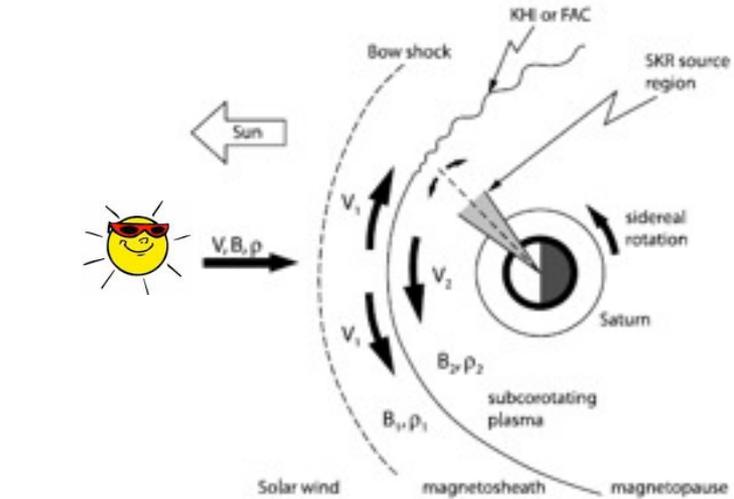
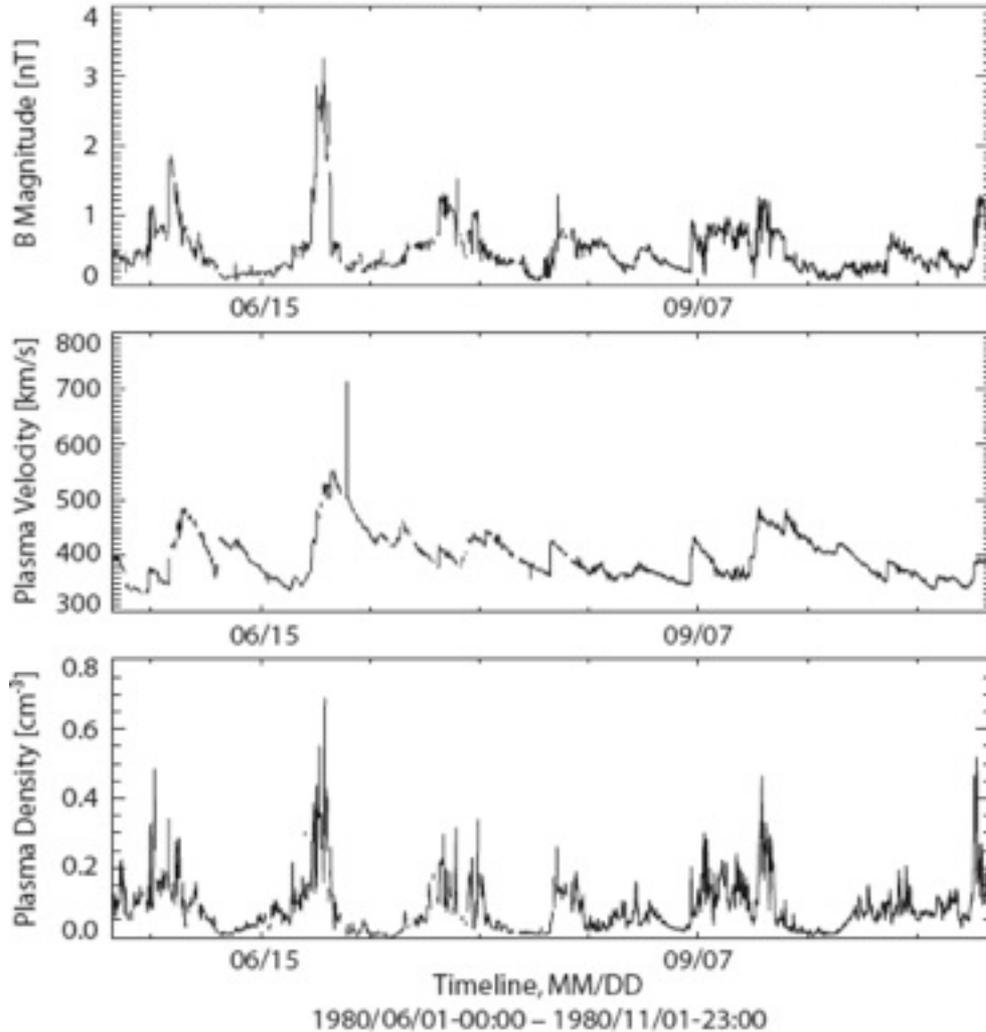


[Southwood & Kivelson, 2007]



Source location jitter due to Solar Wind speed fluctuations ?

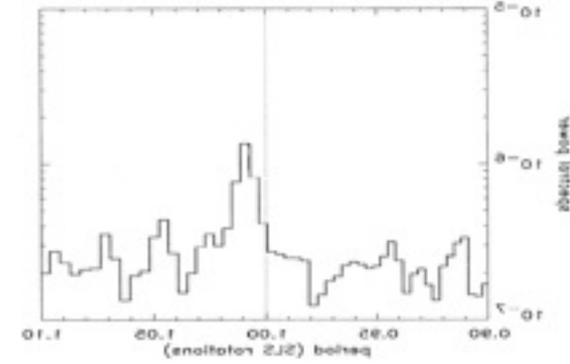
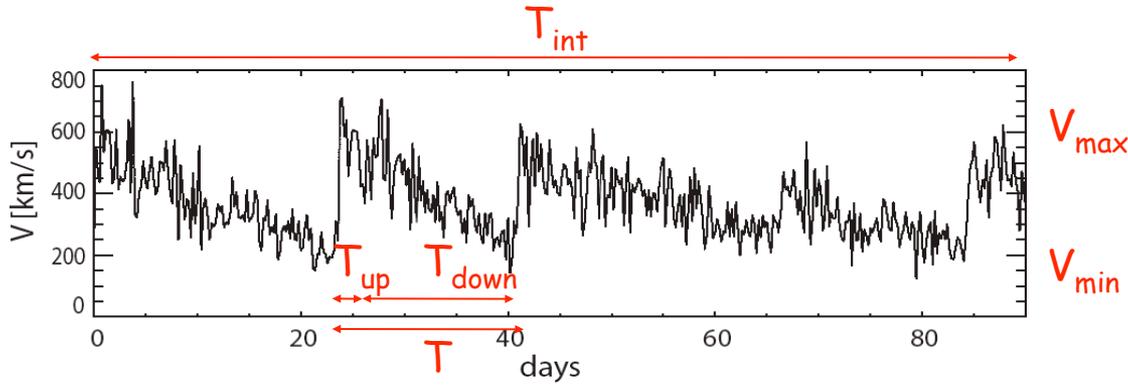
VOYAGER-1 Hourly Interplanetary Parameters by COHOWeb



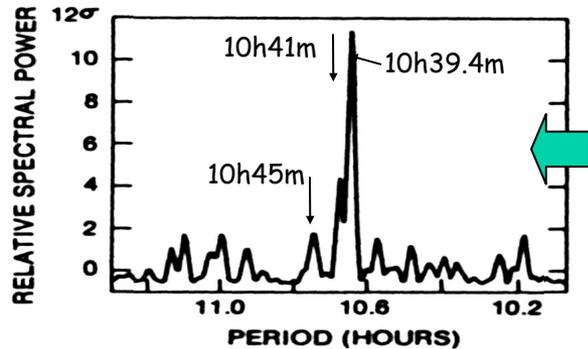
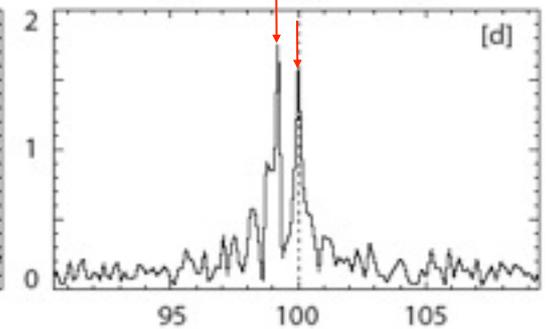
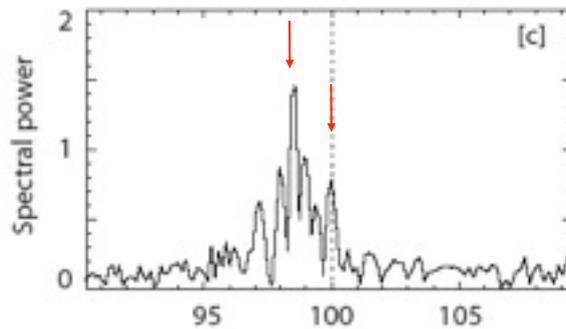
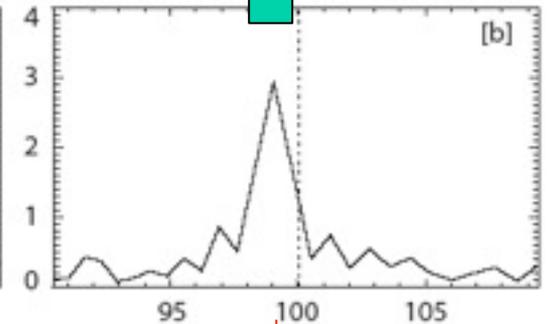
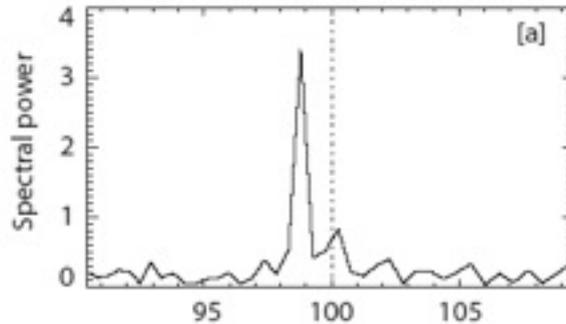
$$I_{SKR}(t) = I_0 \sin [2\pi (t/P_{Sat} - \alpha V(t)/360)]$$

[Cecconi & Zarka, 2005]

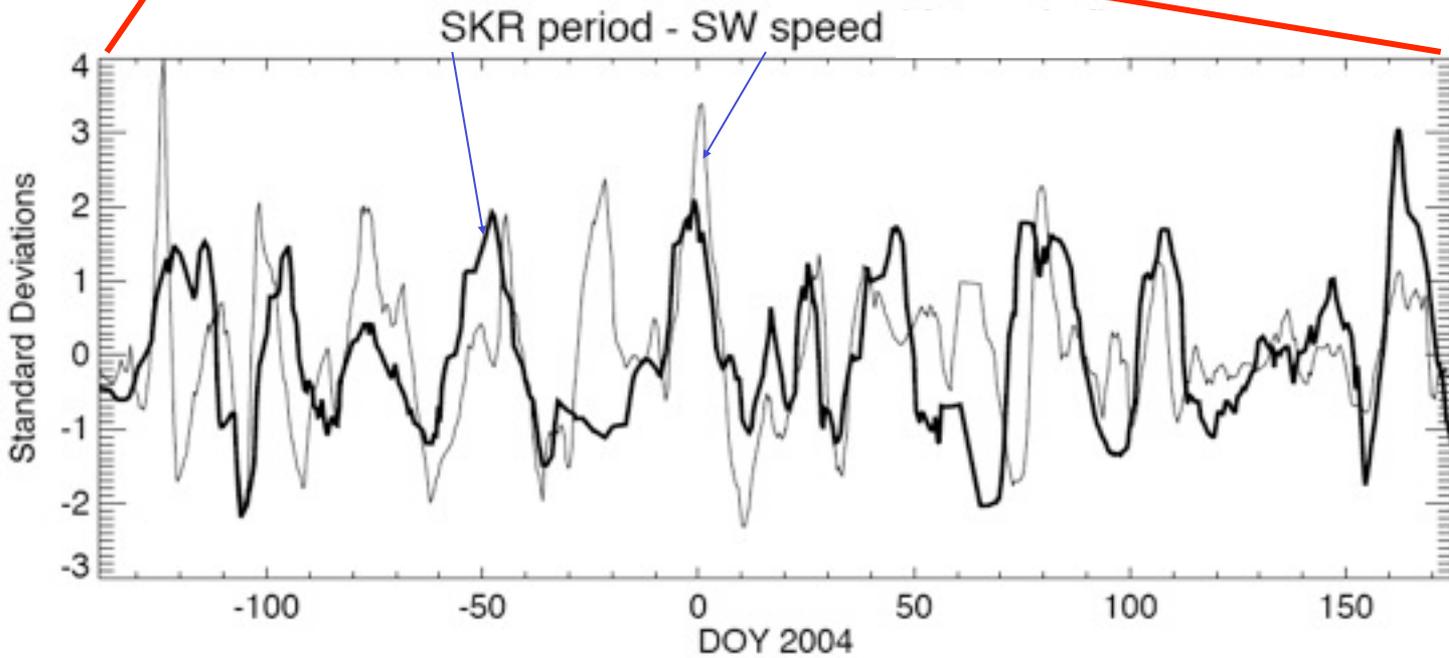
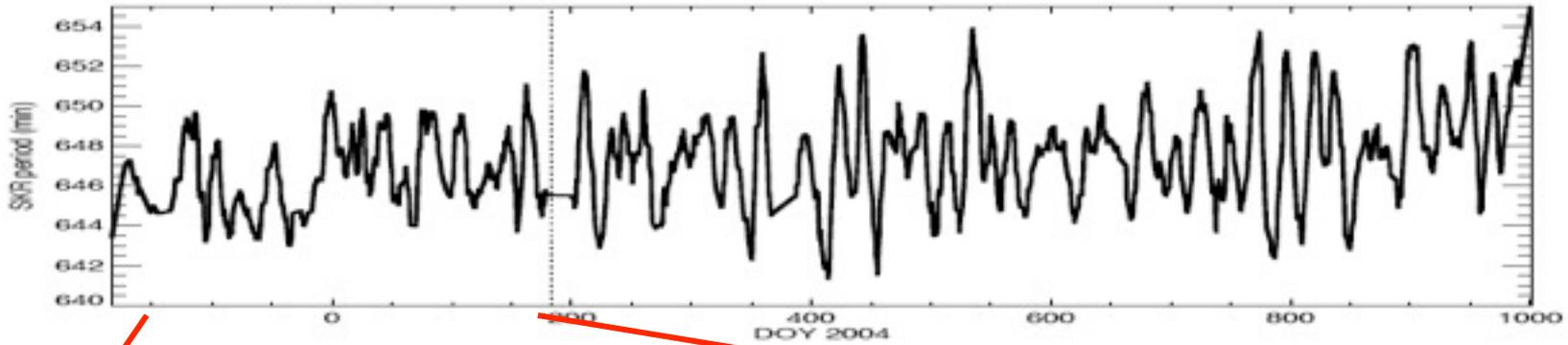
Source location jitter due to Solar Wind speed fluctuations ?



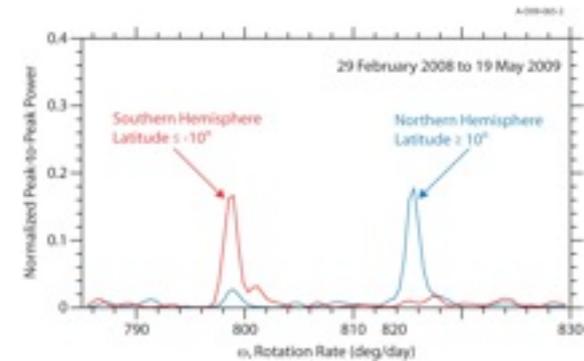
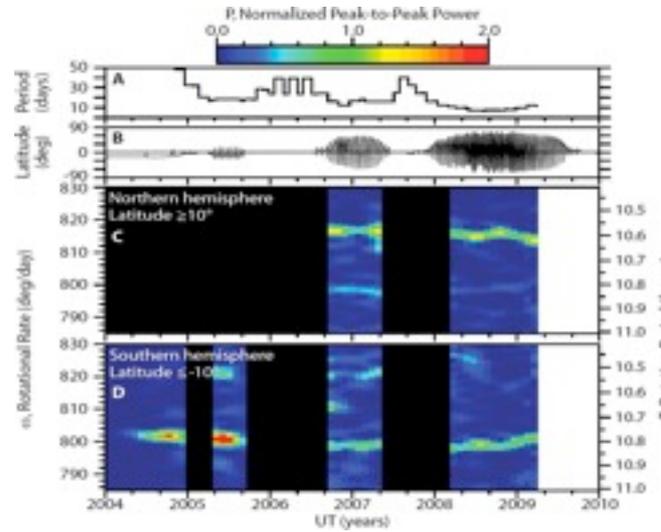
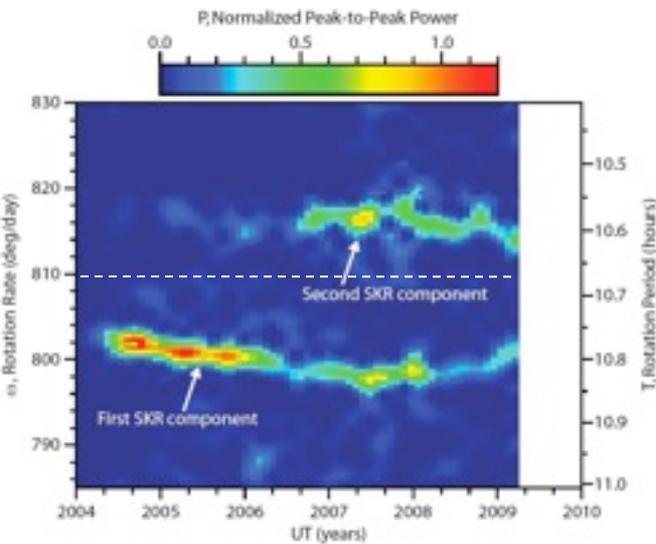
	T_{int}	T	α	R	P_{SKR}/P_{Sat}
[a]	90	26	0.5	0.2	0.987
[b]	60	26	0.4	0.2	0.993
[c]	270	26	0.6	0.2	0.985
[d]	270	26	0.6	0.2	0.991



Source location jitter due to Solar Wind speed fluctuations ?

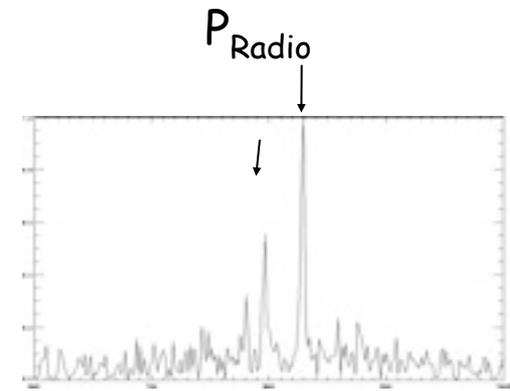
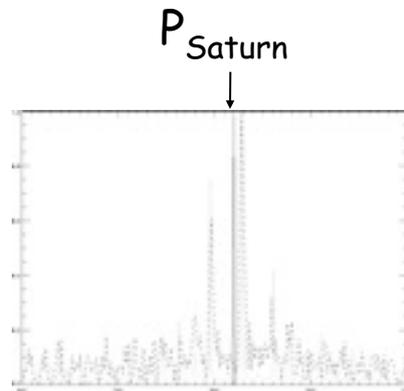
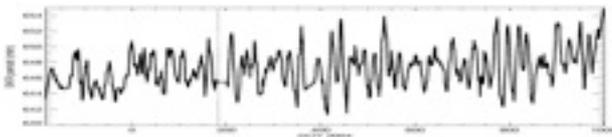


Different rotational modulation in N & S hemispheres



[Gurnett et al., 2009]

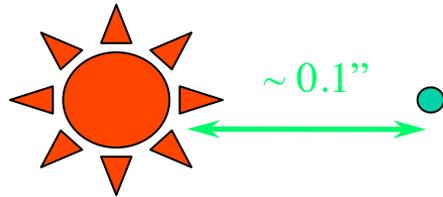
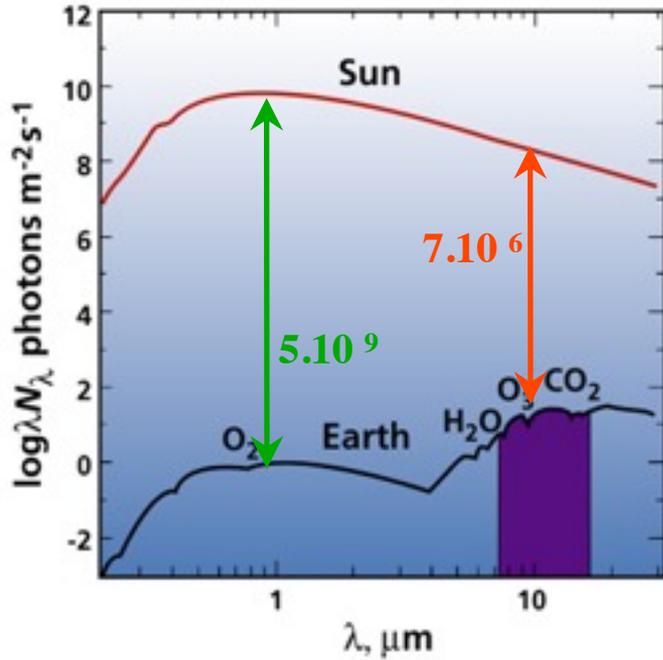
- Asymmetric currents / conductivities ?
- Oscillating period due to SW jitter ?



- Introduction
- Auroral Radio Emissions observations
- Theory of Auroral Radio Emissions
- New results on Jupiter
- New results on Saturn
- Radio emission from exoplanets ?

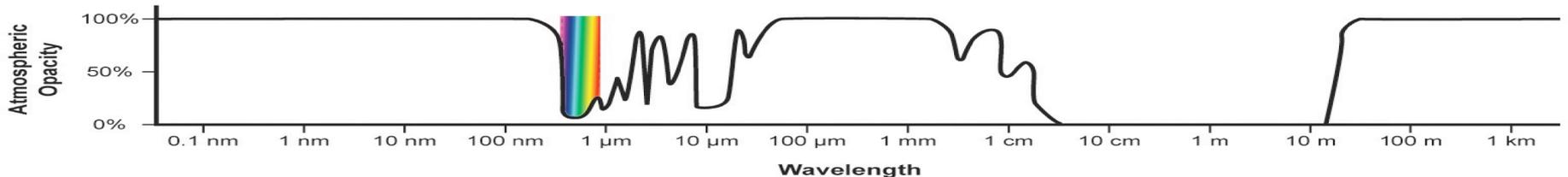
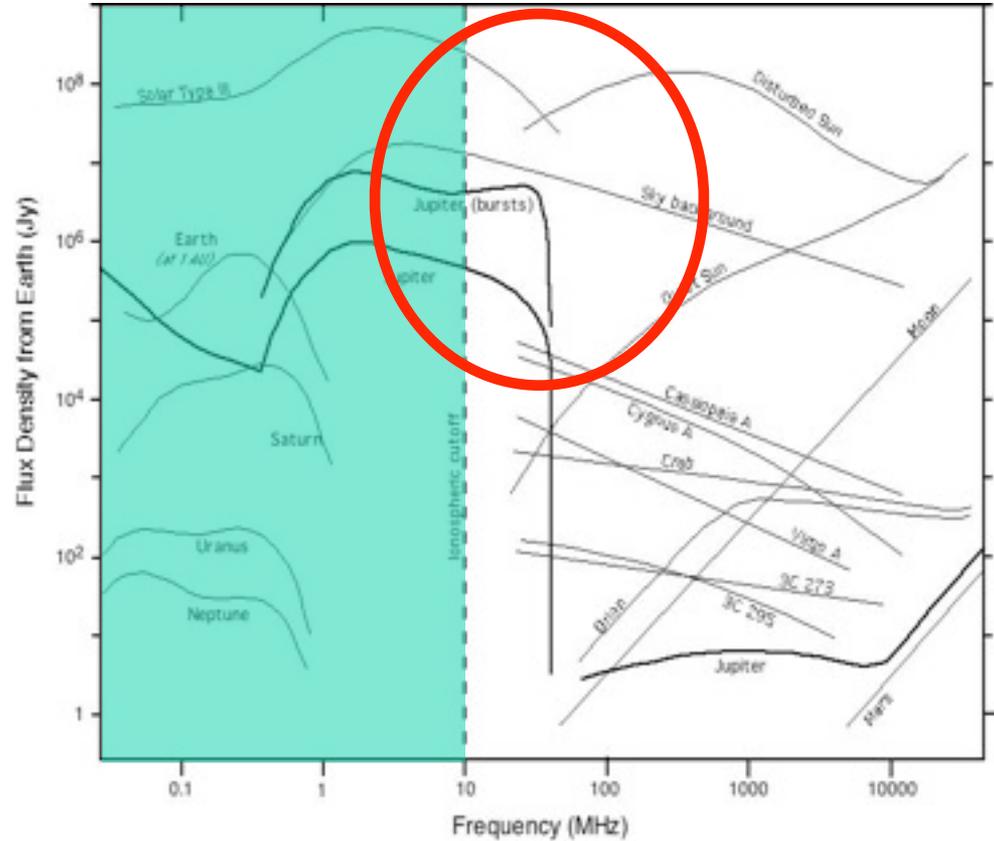
Detectability at stellar distances ?

Star/planet proximity
→ contrast



Intense non-thermal radio emissions :
« Plasma » processes

→ Contrast Sun/Jupiter ~1 !



Radio detectability

- Galactic radio background: $T \sim 1.15 \times 10^8 / \nu^{2.5} \sim 10^{3-5} \text{ K}$ (10-100 MHz)

→ statistical fluctuations $\sigma = 2kT/A_e(b\tau)^{1/2}$

→ $N = s / \sigma$ with $s = \xi S_J / d^2$

$$S_J \sim 10^{-18} \text{ Wm}^{-2}\text{Hz}^{-1} \quad (10^8 \text{ Jy}) \quad \text{à 1 UA}$$

- Maximum distance for $N\sigma$ detection of a source $\xi \times$ Jupiter :

$$d_{\max} = (\xi S_J A / 2NkT)^{1/2} (b\tau)^{1/4}$$

$$\Rightarrow d_{\max} (\text{pc}) = 5 \times 10^{-8} (A_e \xi)^{1/2} f^{5/4} (b\tau)^{1/4}$$

Maximum distance of detectability

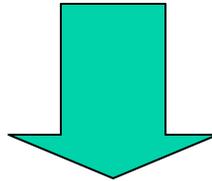
of Jupiter's radio emissions

	$b \tau = 10^6$ (1 MHz, 1 sec)		$b \tau = 2 \times 10^8$ (3 MHz, 1 min)		$b \tau = 4 \times 10^{10}$ (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4 \text{ m}^2$ (~NDA)	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5 \text{ m}^2$ (~UTR-2)	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6 \text{ m}^2$ (~LOFAR77)	0.03	0.5	0.1	2.	0.4	7.

(distances in parsecs)

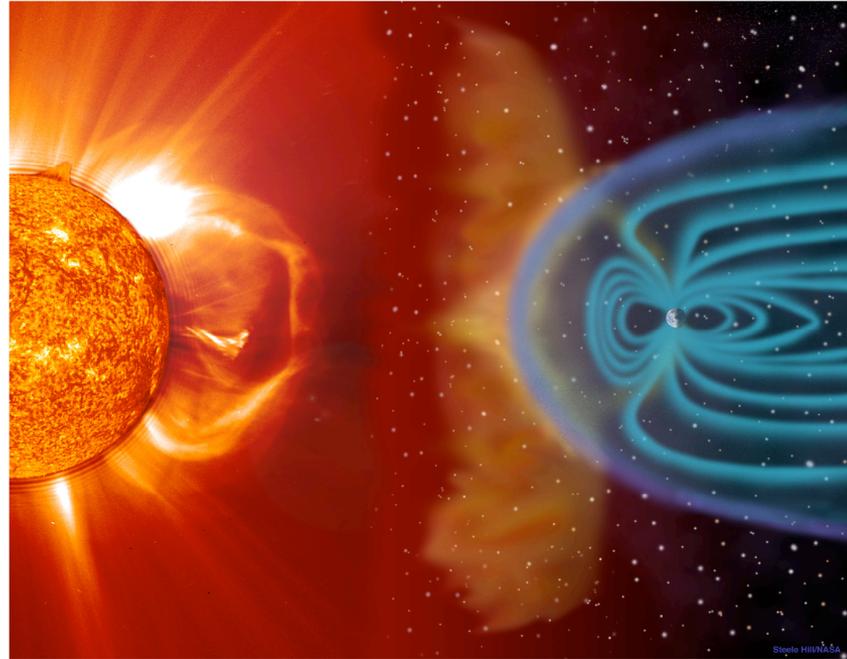
Auroral radio emissions generation

- Electron acceleration
- Coherent cyclotron emission



Emission intensity not
predictable from first
principles

Energy sources : solar wind - magnetosphere interaction



- Kinetic energy flux on obstacle cross-section : $P_k \sim NmV^2 V \pi R_{obs}^2$

$$N = N_0 / d^2$$

$$N_0 = 5 \text{ cm}^{-3} \quad m \sim 1.1 \times m_p$$

- Poynting flux of B_{IMF} on obstacle cross-section : $P = \int_{obs} (\mathbf{E} \times \mathbf{B} / \mu_0) \cdot d\mathbf{S}$

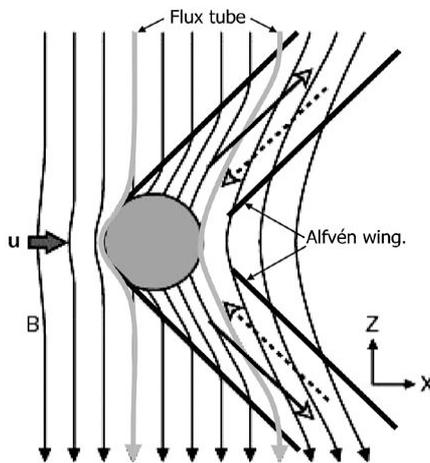
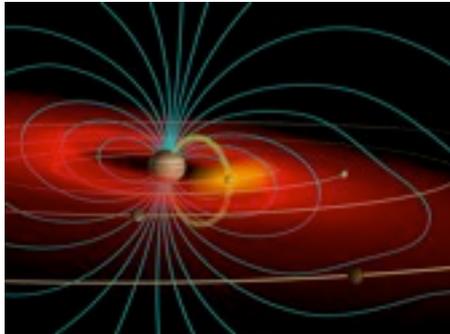
$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} \rightarrow \mathbf{E} \times \mathbf{B} = V B_{\perp}^2$$

$$\rightarrow P_m = B_{\perp}^2 / \mu_0 V$$

$$\pi R_{obs}^2$$

Energy sources : unipolar interaction

- Io-Jupiter : Alfvén waves & currents



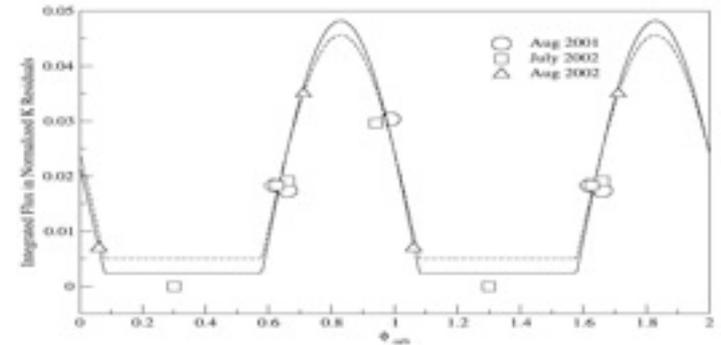
$$\phi = E \times 2R_{\text{obs}} = V \times B_{\perp} \times 2R_{\text{obs}}$$

$$P_d = \varepsilon V B_{\perp}^2 / \mu_0 \pi R_{\text{obs}}^2 = \varepsilon P_m$$

$$M_A \leq \varepsilon \leq 1$$

[Neubauer, 1980 ; Saur et al., 2004]

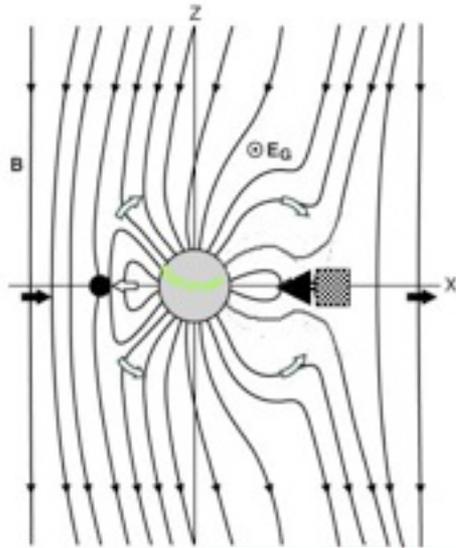
- Chromospheric hot spot on HD179949 & ν And ?



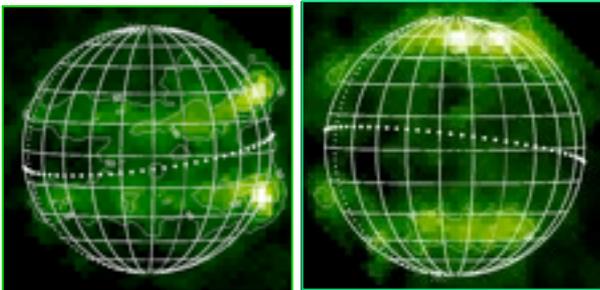
[Shkolnik et al. 2003, 2004, 2005]

Energy sources : dipolar interaction

- Ganymede-Jupiter : reconnection



- Interacting magnetized binaries or star-planet systems ?



Downstream

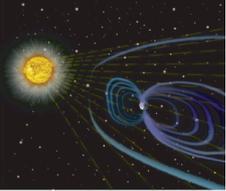
Upstream



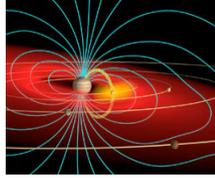
$$P_d = \epsilon K V B_{\perp}^2 / \mu_0 \pi R_{MP}^2 = \epsilon K P_m$$

$$K = \sin^4(\theta/2) \text{ or } \cos^4(\theta/2) = 0/1$$

$$\epsilon \sim 0.1 - 0.2$$



Radio emissions from flow-obstacle interactions



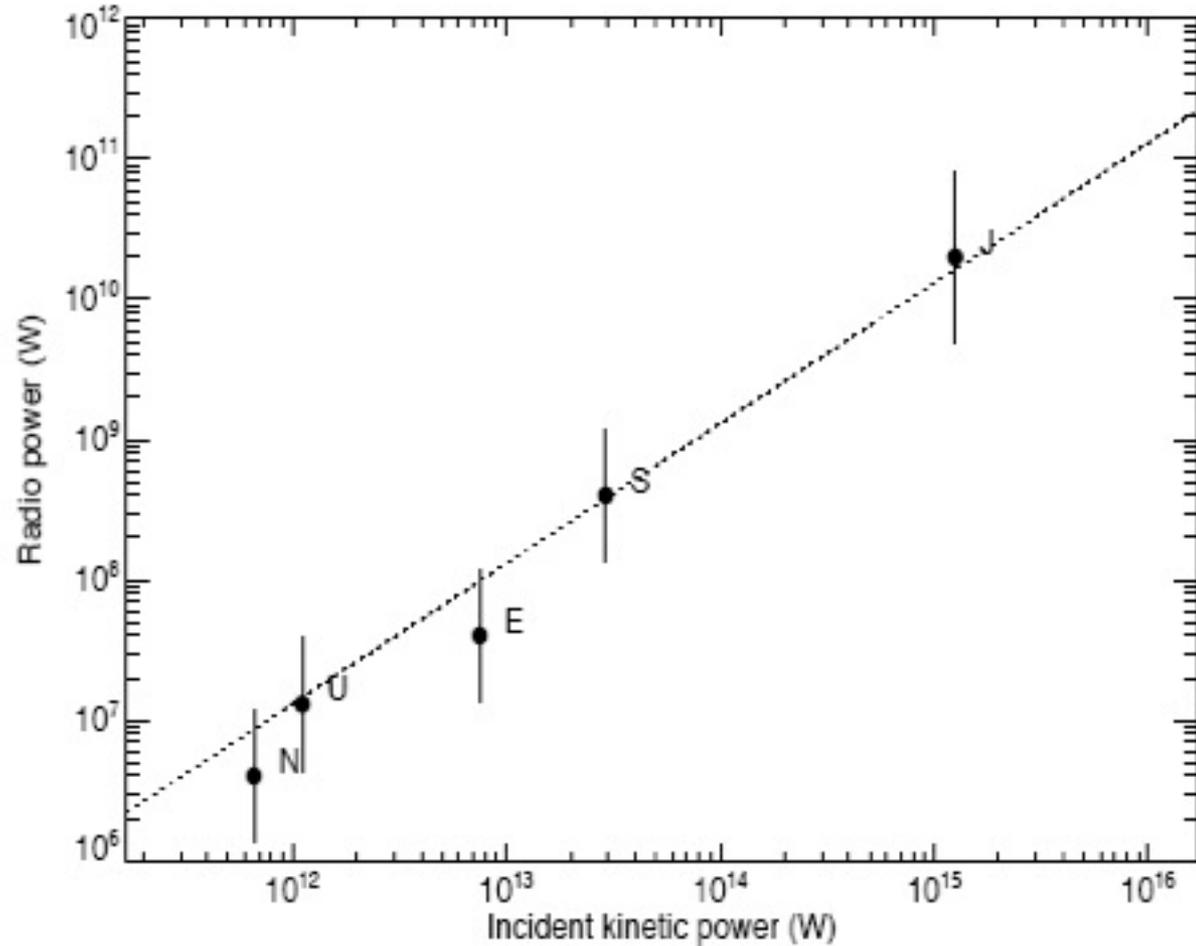
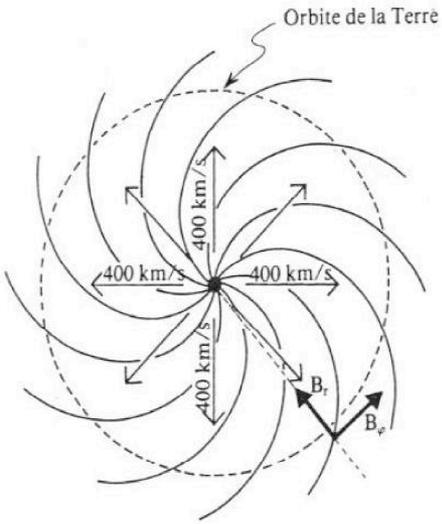
Obstacle \ Flow	Weakly/Not magnetized <i>(Solar wind)</i>	Strongly magnetized <i>(Jovian magnetosphere)</i>
	Weakly/Not magnetized <i>(Venus, Mars, Io)</i>	No Intense Cyclotron Radio Emission
Strongly magnetized <i>(Earth, Jupiter, Saturn, Uranus, Neptune, Ganymede)</i>	<u>Magnetospheric Interaction</u> → Auroral Radio Emissions : E, J, S, U, N,	<u>Dipolar interaction</u> → Ganymede-induced Radio Emission

$$P_d = \varepsilon V B_{\perp}^2 / \mu_0 \pi R_{obs}^2$$

$$\varepsilon \sim 0.2 \pm 0.1$$

« Radio-kinetic Bode's law » (auroral emissions)

$$P_{\text{Radio}} \sim \eta_1 \times P_C \text{ with } \eta_1 \sim 10^{-5}$$



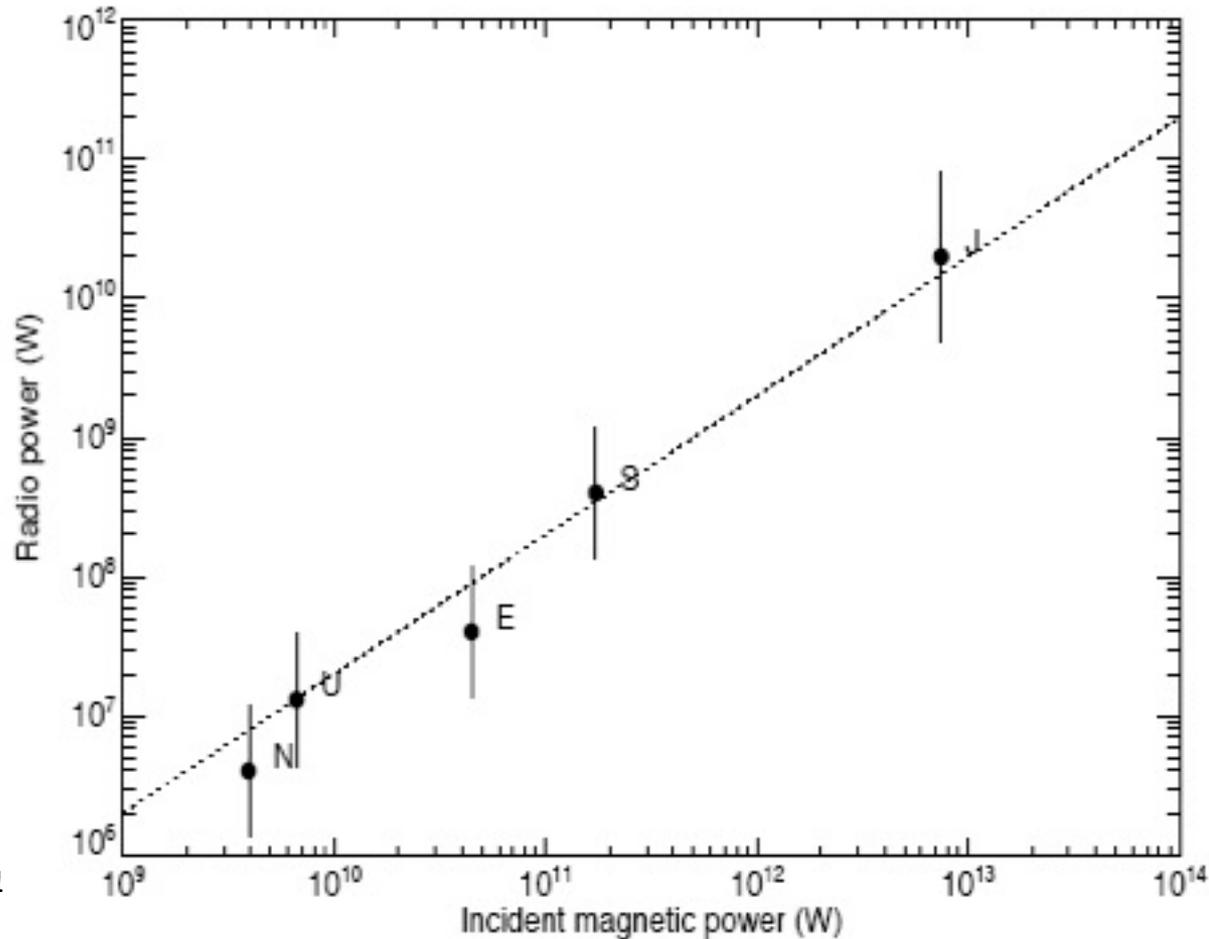
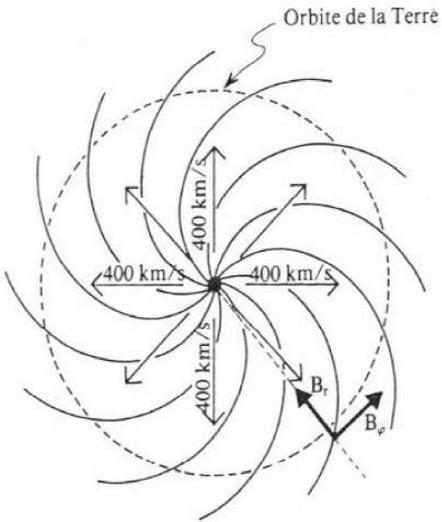
Solar Wind expansion

$$V \sim c^{te}$$

$$N \sim d^{-2} \text{ (mass conservation)}$$

« Radio-magnetic Bode's law » (auroral emissions)

$$P_{\text{Radio}} \sim \eta_2 \times P_B \text{ with } \eta_2 \sim 2 \times 10^{-3}$$



Solar Wind expansion

$$V \sim c^{te}$$

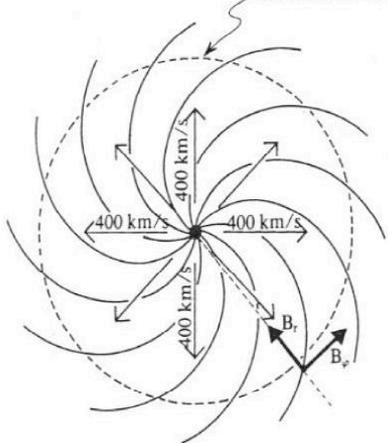
$$N \sim d^{-2} \text{ (mass conservation)}$$

$$B_R \sim d^{-2} \text{ (mag flux conservation)}$$

$$B_\varphi \sim d^{-1} \text{ (} B_R/B_\varphi = V/\Omega d \text{)} \rightarrow B \sim d^{-1}$$

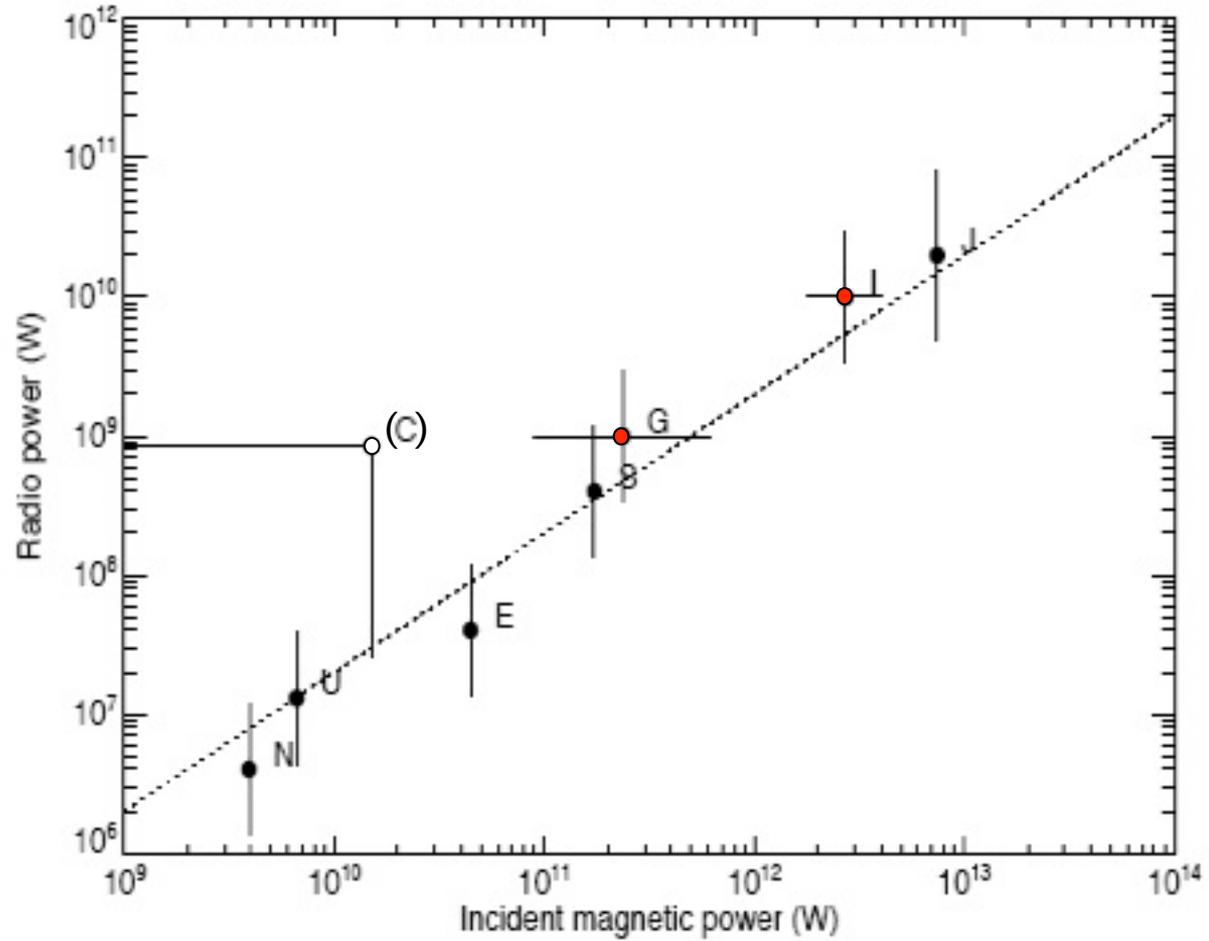
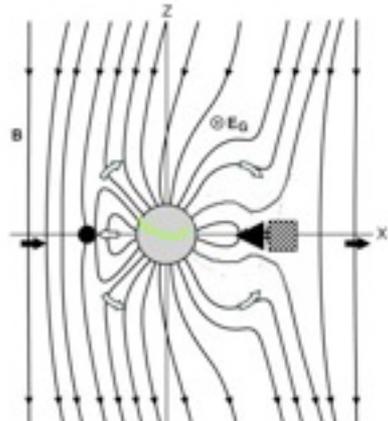
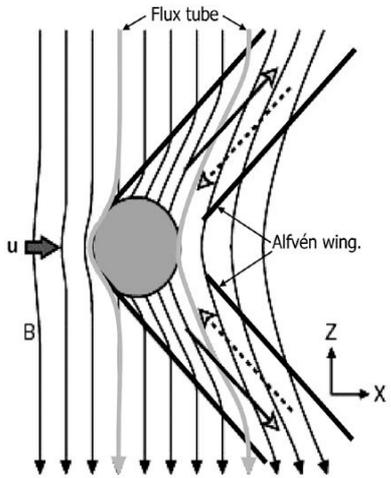
(beyond Jupiter orbit, $B \sim B_\varphi$)

Orbite de la Terre



« Generalized radio-magnetic Bode's law » (all emissions)

$$P_{\text{Radio}} \sim \eta \times P_B \text{ with } \eta \sim 2-10 \times 10^{-3}$$



Large-scale stellar magnetic fields

Magnetic field at Solar surface :

→ large-scale $\sim 1 \text{ G}$ (10^{-4} T)

→ magnetic loops $\sim 10^3 \text{ G}$,
over a few % of the surface

Magnetic stars : $> 10^3 \text{ G}$

Spectropolarimeters : ESPaDOnS@CFHT & NARVAL@TBL

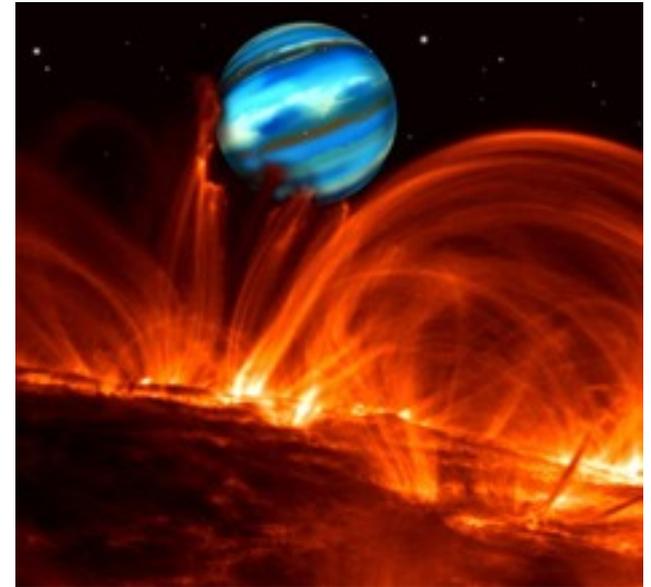
Tau Boo : 5-10 G

HD 76151 : $\sim 10 \text{ G}$

HD 189733 : $> 50 \text{ G}$

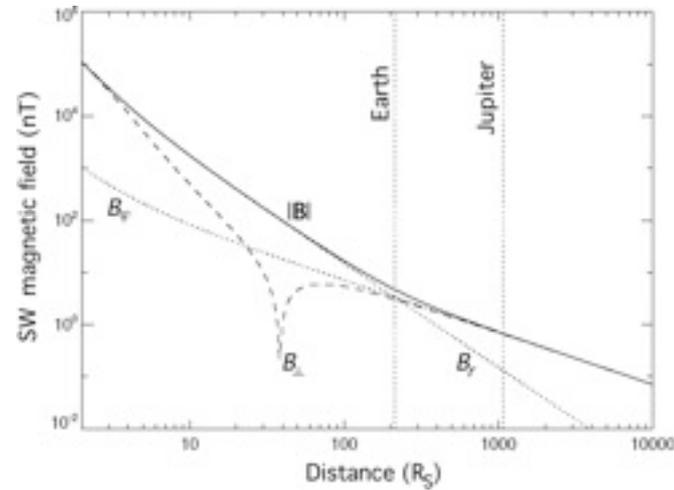
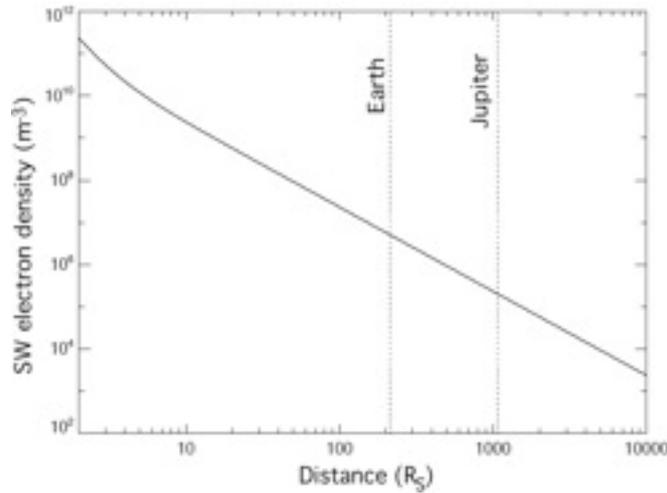
HD 171488 : 500G

...

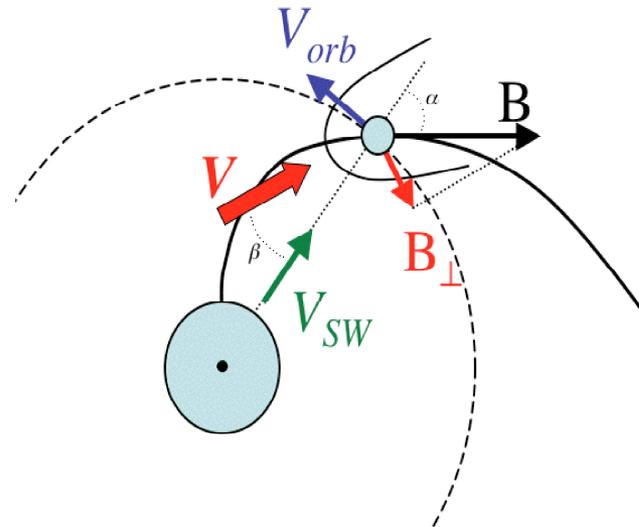
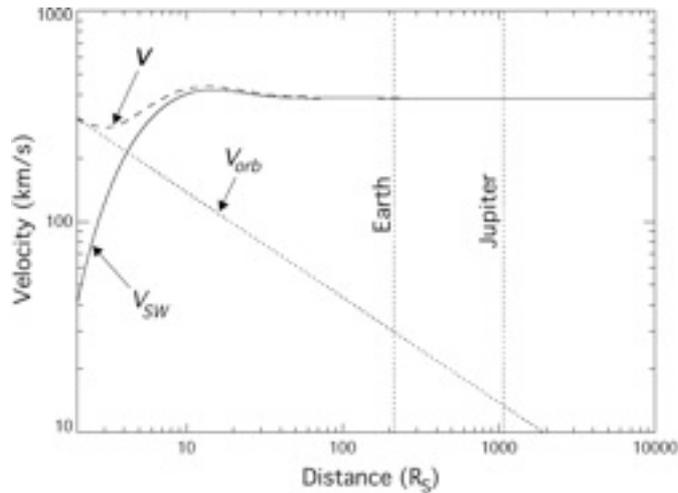


Modelling a magnetized hot Jupiter orbiting a Solar type star

- Ne & B variations in Solar corona and interplanetary medium



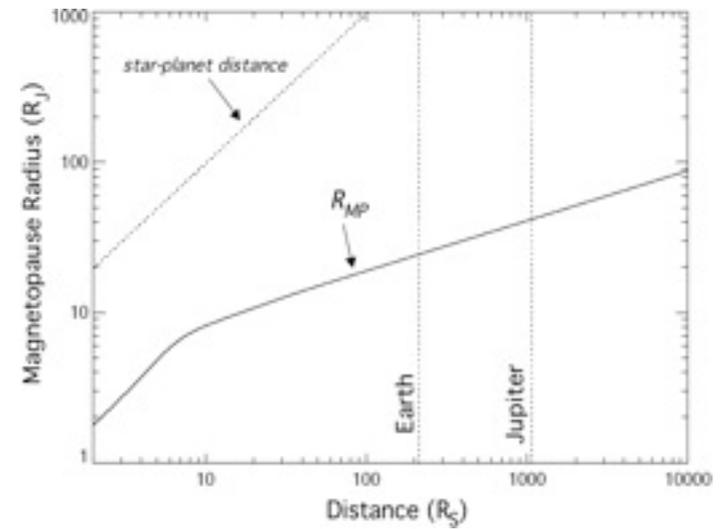
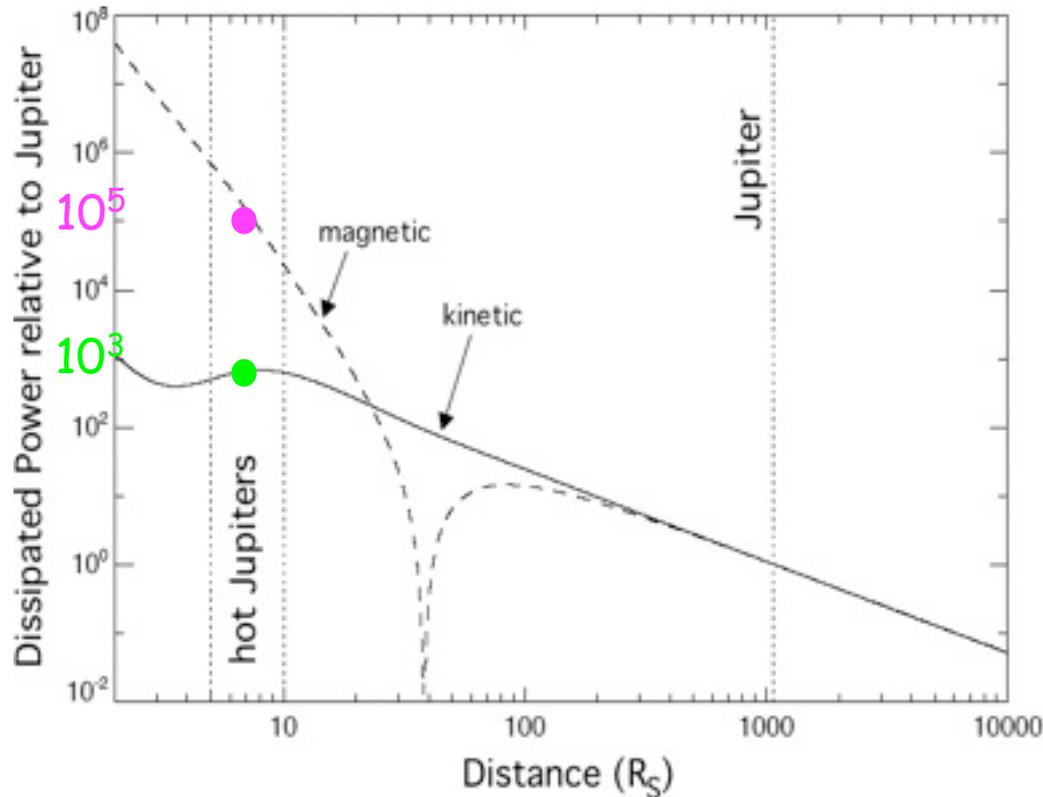
- Solar wind speed in the planet's frame



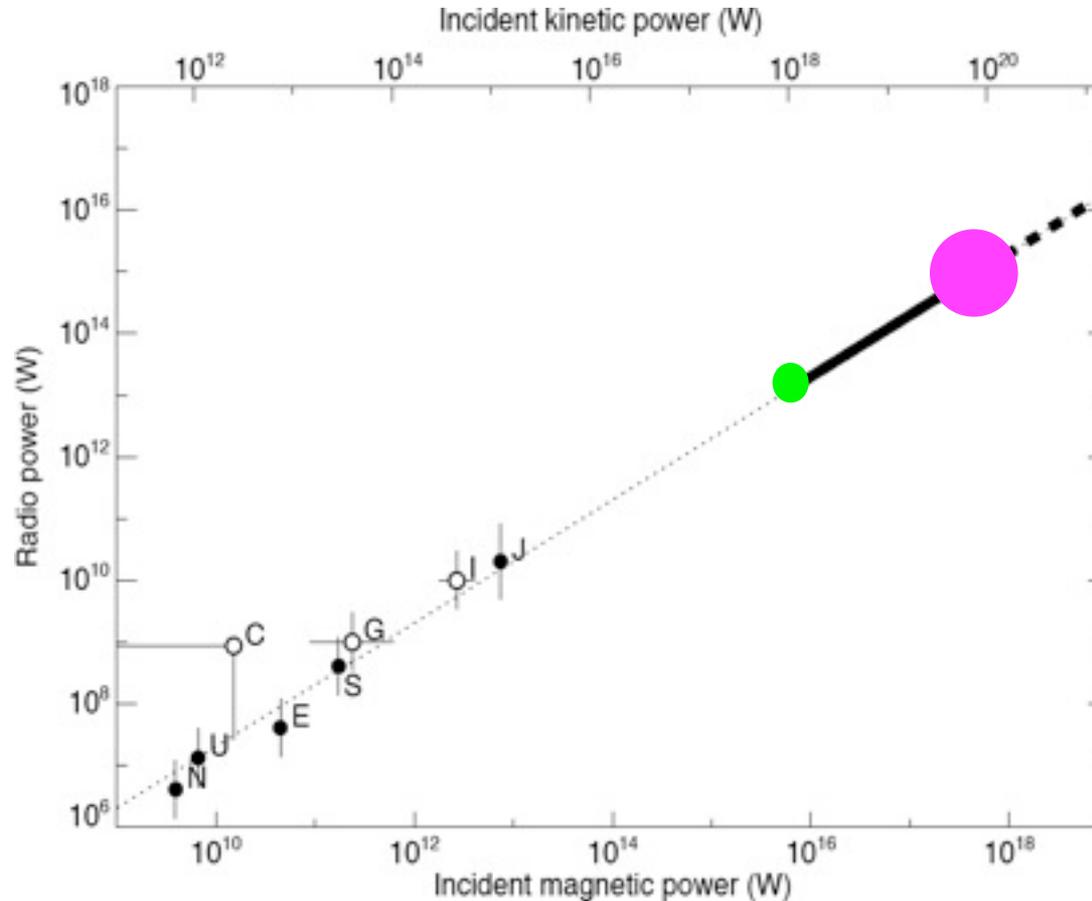
Modelling a magnetized hot Jupiter orbiting a Solar type star

- Magnetospheric compression

→ Total dissipated power on obstacle



and applying the generalized radio-magnetic Bode's law



$$\rightarrow P_{\text{radio-max}} = P_{\text{Radio-J}} \times 10^5$$

if no "saturation" nor planetary magnetic field decay

Planetary magnetic field decay ?

- Radio detection $\rightarrow f > 10 \text{ MHz} \rightarrow B_{\text{max-surface}} \geq 4 \text{ G}$
- Jupiter : $\mathcal{M} = 4.2 \text{ G} \cdot R_J^3$, $B_{\text{max-surface}} = 14 \text{ G}$, $f_{\text{max}} = 40 \text{ MHz}$
- But Spin-orbit synchronisation (tidal forces) $\rightarrow \omega \downarrow$
and $\mathcal{M} \propto P_{\text{sid}}^\alpha$ $-1 \leq \alpha \leq -\frac{1}{2}$ $\rightarrow \mathcal{M} \downarrow$ (B decay) ?

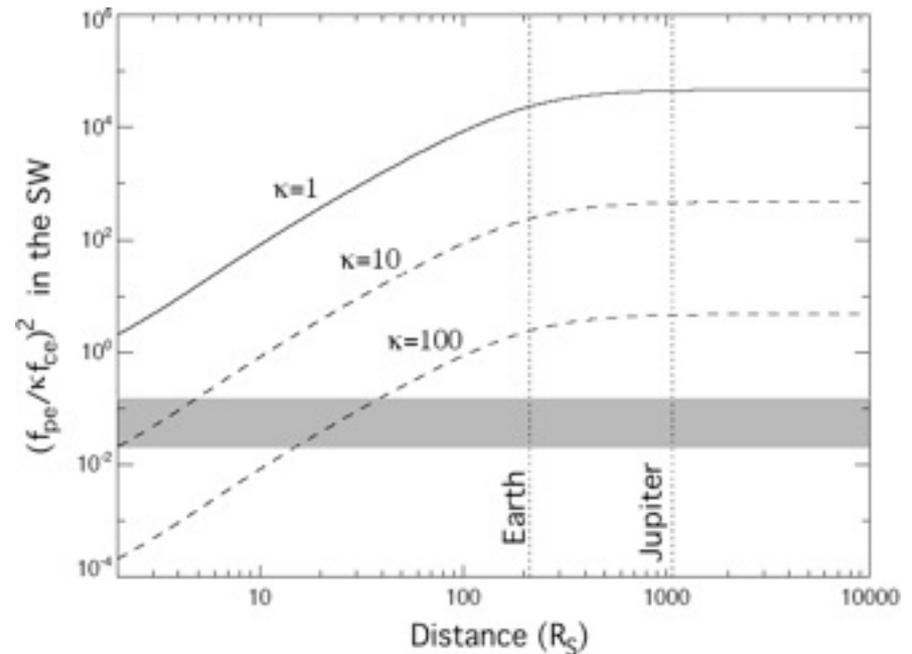
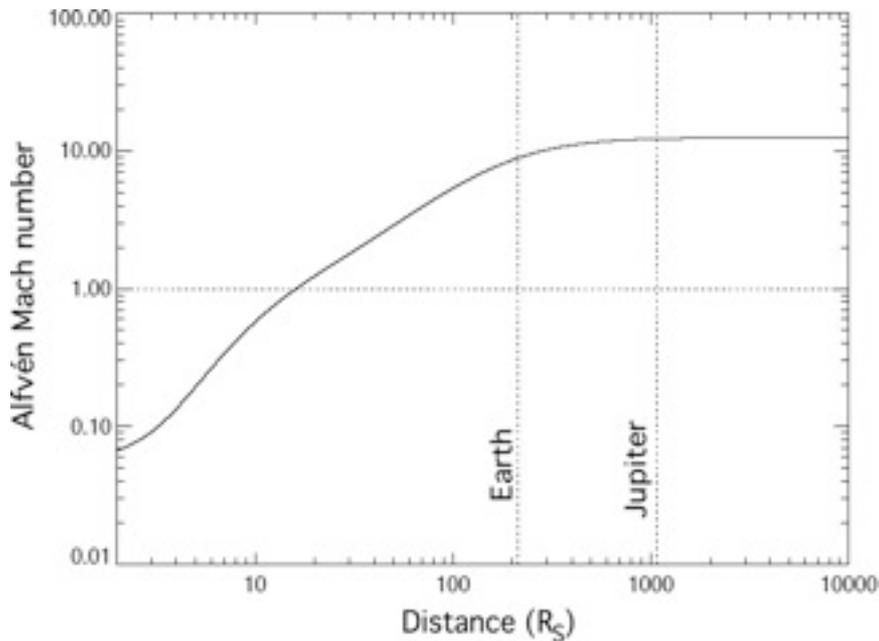
UPPER LIMIT OF MAGNETIC FIELDS IN HOT JUPITERS

Planet	M (M_J)	P_{orb} (days)	R (R_J)	M_D (G m^3)	B_s (G)
HD 179949b ^a	0.84	3.093	1.3	1.1×10^{24}	1.4
HD 209458b	0.69	3.52	1.43	0.8×10^{24}	0.8
τ Boo b ^a	3.87	3.31	1.3	1.6×10^{24}	2
OGLE-TR-56b	0.9	1.2	1.3	2.2×10^{24}	2.8

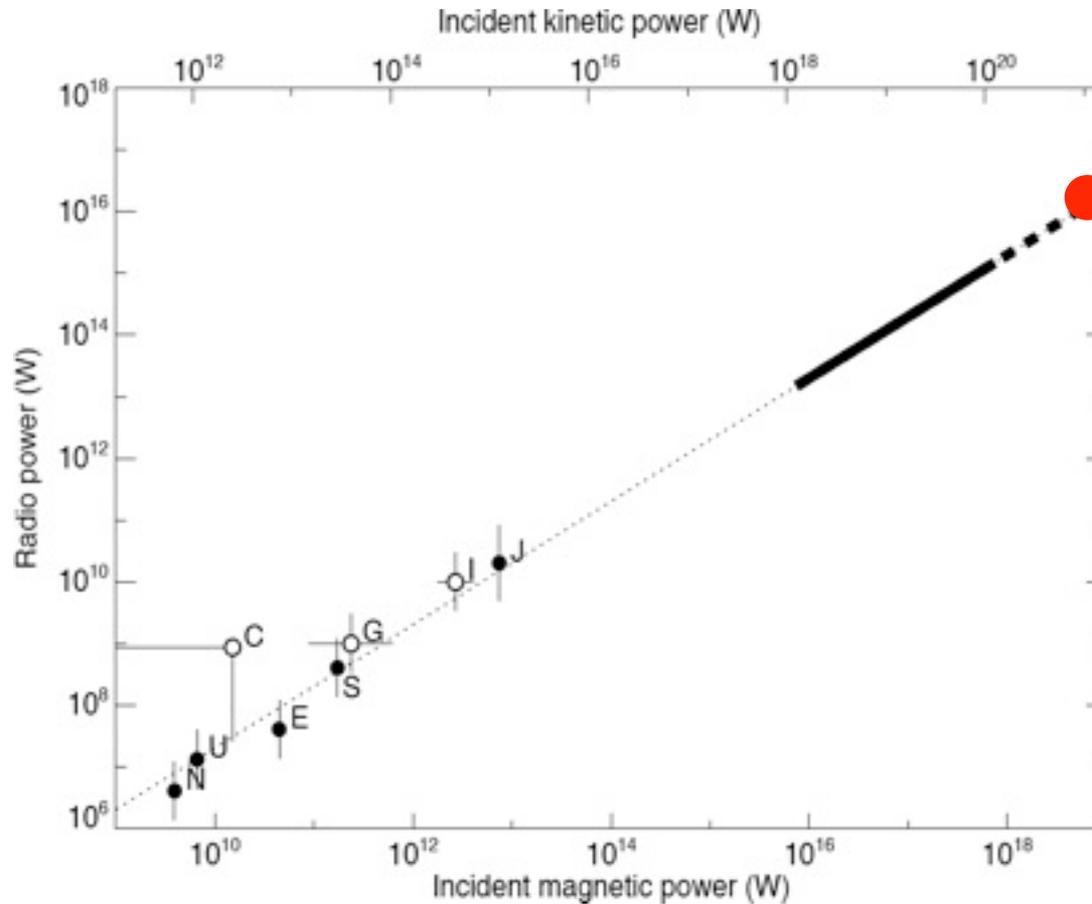
- Internal structure + convection models
 \rightarrow self-sustained dynamo $\rightarrow \mathcal{M}$ may remain \geq a few $\text{G} \cdot R_J^3$

Unipolar inductor in sub-Alfvénic regime

- Similarities with Io-Jupiter case
- But radio emission possible only if $f_{pe}/f_{ce} \ll 1$
 - intense stellar B required (κB_{sun} with $\kappa=10-100$)
 - emission $\geq 30-250$ MHz from 1-2 R_S



Unipolar inductor in sub-Alfvénic regime

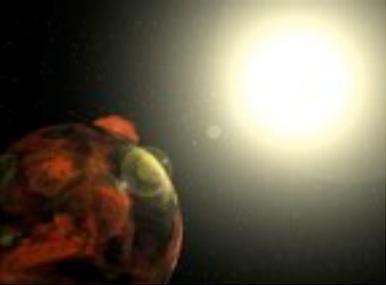


Algol magnetic binaries
[Budding et al., 1998]

- Extrapolation / Radio-magnetic Bode's law

$$\rightarrow P_{\text{radio-max}} = P_J \times 10^5 \times (R_{\text{exo-ionosphere}}/R_{\text{magnetosphere}})^2 \times (B_{\text{star}}/B_{\text{Sun}})^2$$

$$= \text{up to } P_{\text{Radio-J}} \times 10^6$$



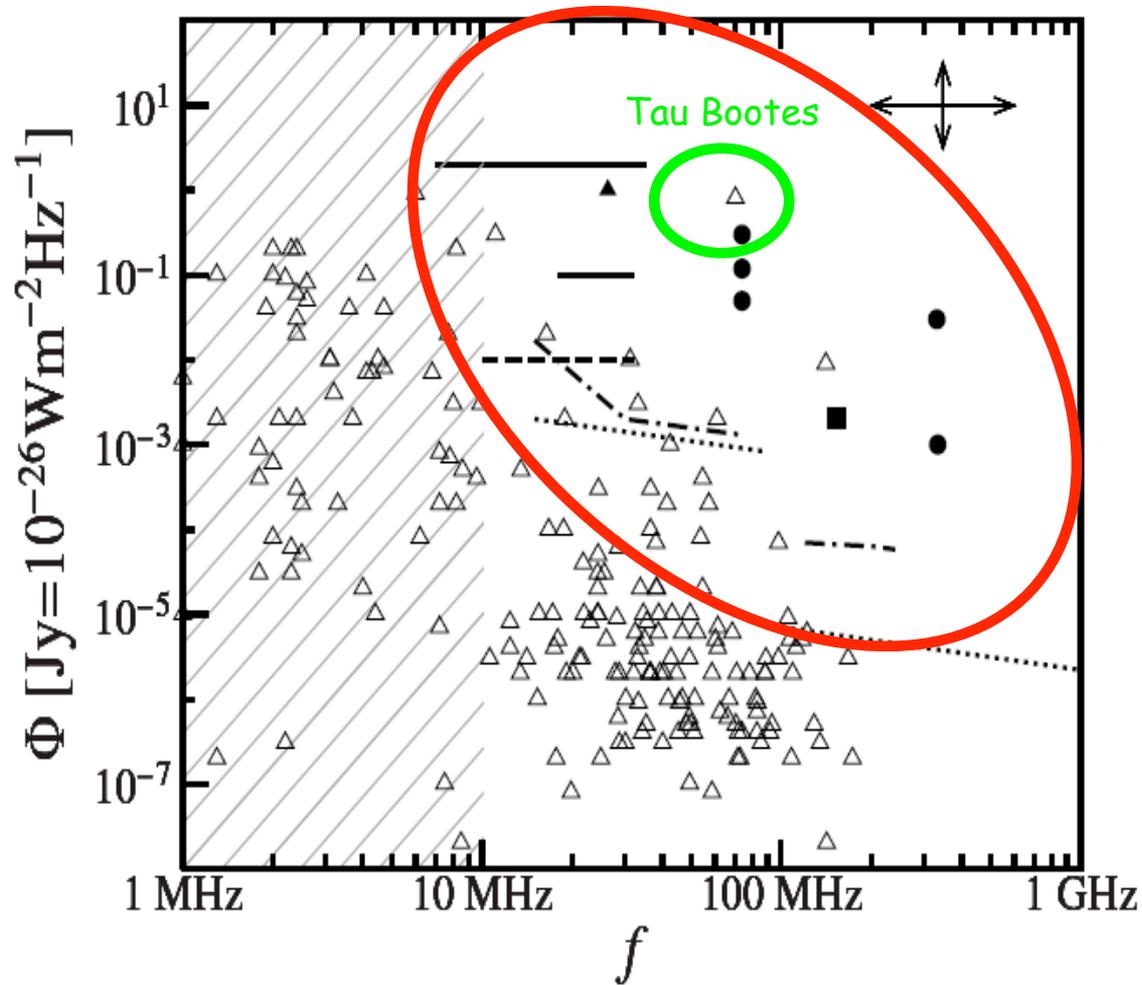
Maximum distance of detectability of $10^5 \alpha$ Jupiter's radio emissions

$\zeta = 10^5$

	$b \tau = 10^6$ (1 MHz, 1 sec)		$b \tau = 2 \times 10^8$ (3 MHz, 1 min)		$b \tau = 4 \times 10^{10}$ (10 MHz, 1 hour)	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4 \text{ m}^2$ (~NDA)	1	16	3	59	13	220
$A_e = 10^5 \text{ m}^2$ (~UTR-2)	3	50	11	190	40	710
$A_e = 10^6 \text{ m}^2$ (~LOFAR77)	9	160	33	600	130	2200

(distances in parsecs)

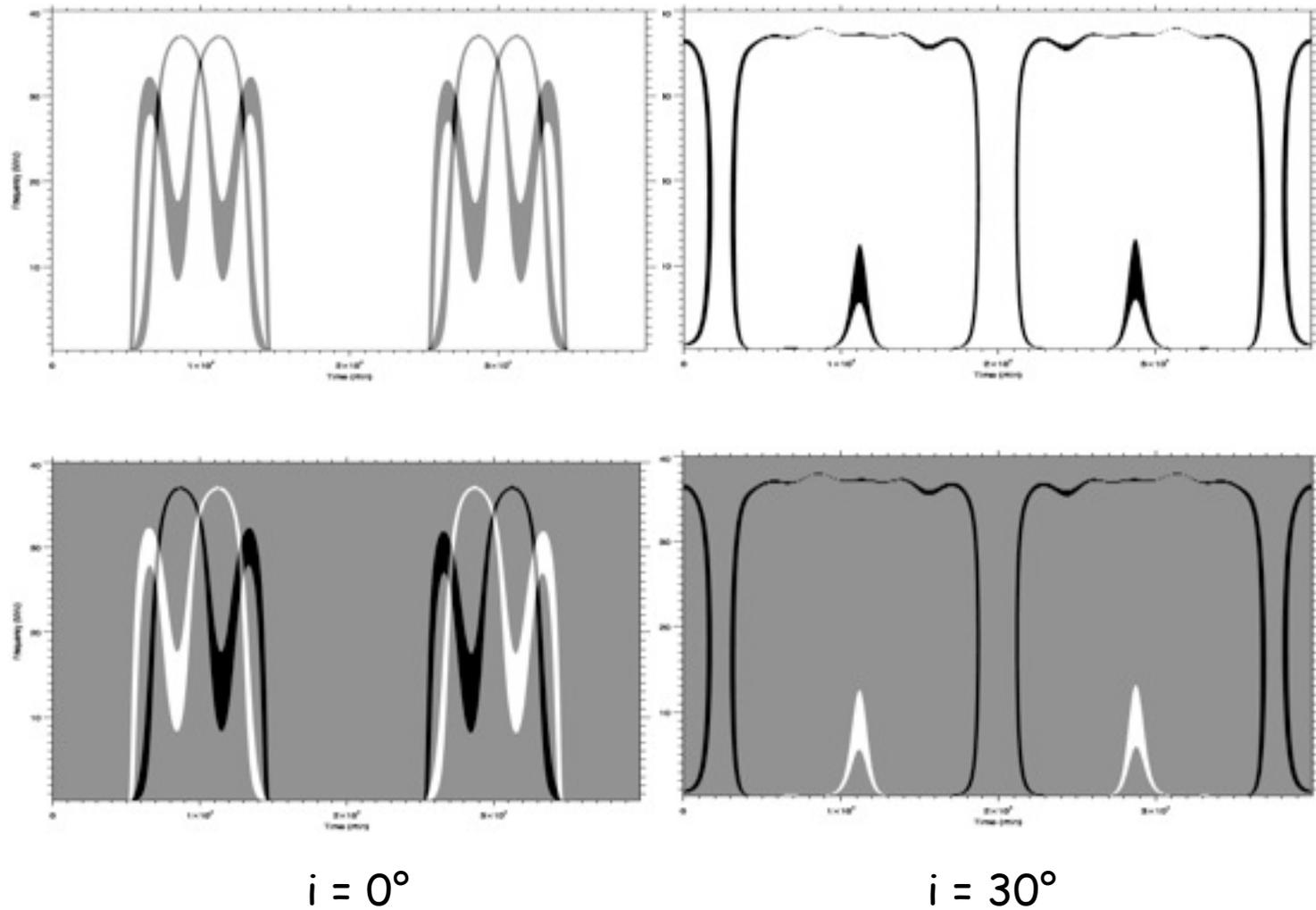
Predictions for the whole exoplanet census



Other studies ...

- Possibilities for **radio scintillations** \Rightarrow burts $P_{\text{radio}} \times 10^2$ [Farrell et al., 1999]
- Estimates of **exoplanetary \mathcal{M}** (scaling laws - **large planets better**) $\rightarrow f_{\text{ce}}$ & radio flux
[Farrell et al., 1999 ; Griessmeier et al., 2004]
- F_x as **wind strength** estimator [Cuntz et al., 2000 ; Saar et al., 2004, Stevens, 2005]
- Stellar wind modelling (**spectral type** spectral, **activity**, stellar rotation) [Preusse et al., 2005]
- **Time evolution** of stellar wind and planetary radius (**young systems better**) [Griessmeier et al., 2004 ; Stevens, 2005]
- Different solar wind conditions, Role of (frequent) **Coronal Mass Ejections** [Khodachenko et al., 2006; Griessmeier et al., 2007]
- Magnetosphere limits **Atmospheric Erosion** [Griessmeier et al., 2004]
- Application of unipolar inductor model to **white dwarfs systems** [Willes and Wu, 2004, 2005]
- Magnetic **reconnection**, E-field and **runaway electrons** at the magnetopause ?

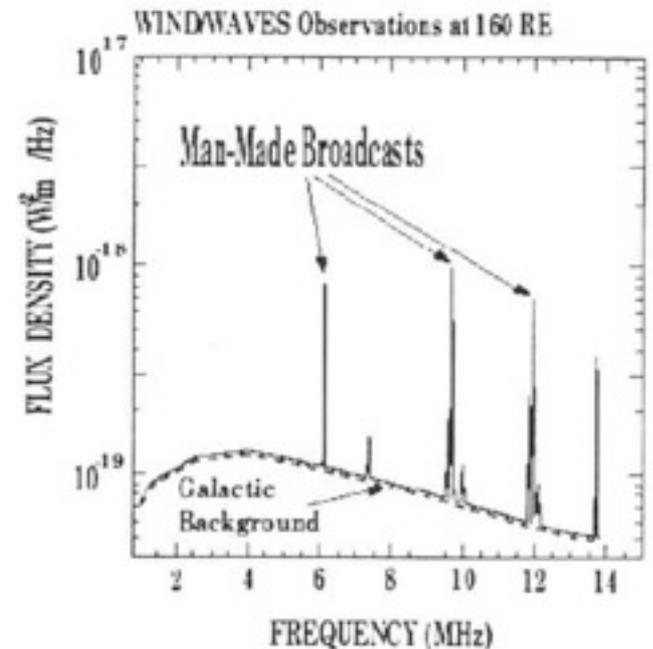
Dynamic spectrum modeling for exoplanets



Low-Frequency radio observations

- Limited angular resolution (λ/D) : 1 UA à 1 pc = 1 " \Rightarrow no imagery
 - \rightarrow (1) detect a signal, (2) star or planet ?
 - \rightarrow discriminate via emission polarization (circular/elliptical)
 - + periodicity (orbital)
 - \rightarrow search for Jovian type bursts ?

- Very bright galactic background ($T_b \sim 10^{3-5}$ K)
- RFI (natural & anthropic origin) \longrightarrow
- Ionospheric cutoff ~ 10 MHz, and perturbations $\leq 30-50$ MHz
- IP/IS scintillations

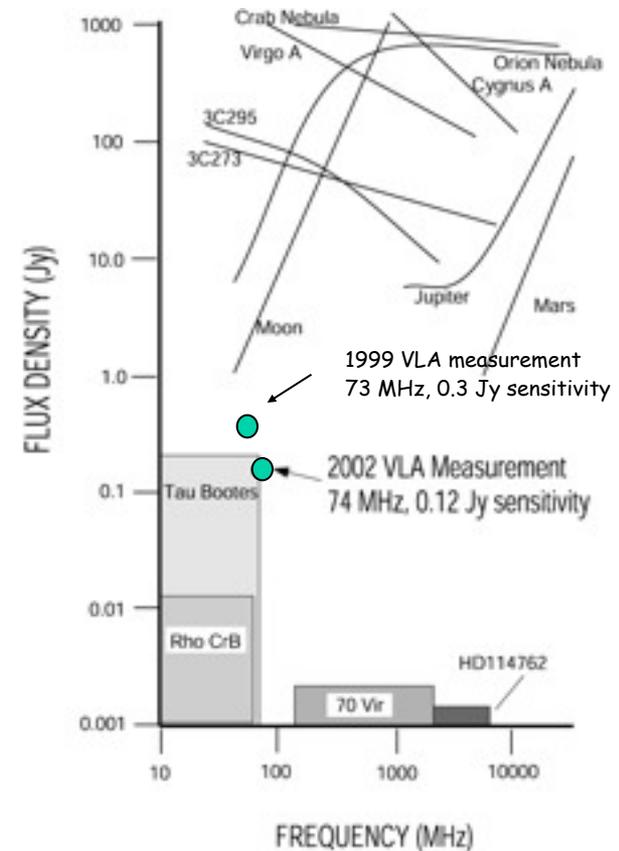
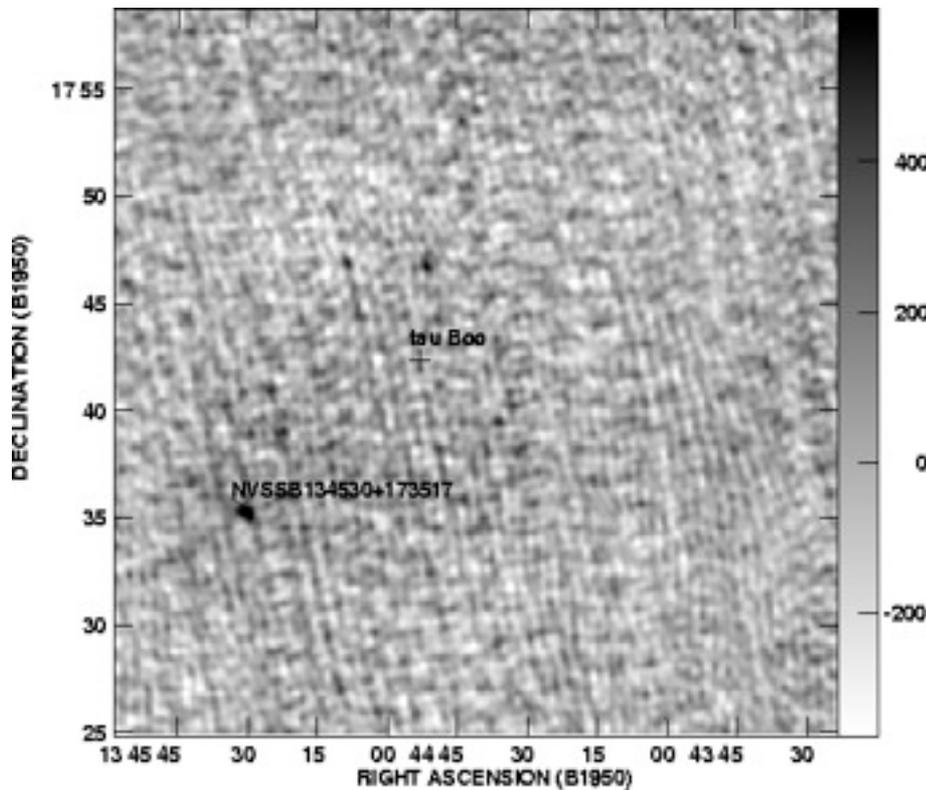


• VLA

- $f \sim 74$ MHz
- target Tau Bootes
- epochs 1999 - 2003
- imaging
- ~ 0.1 Jy sensitivity

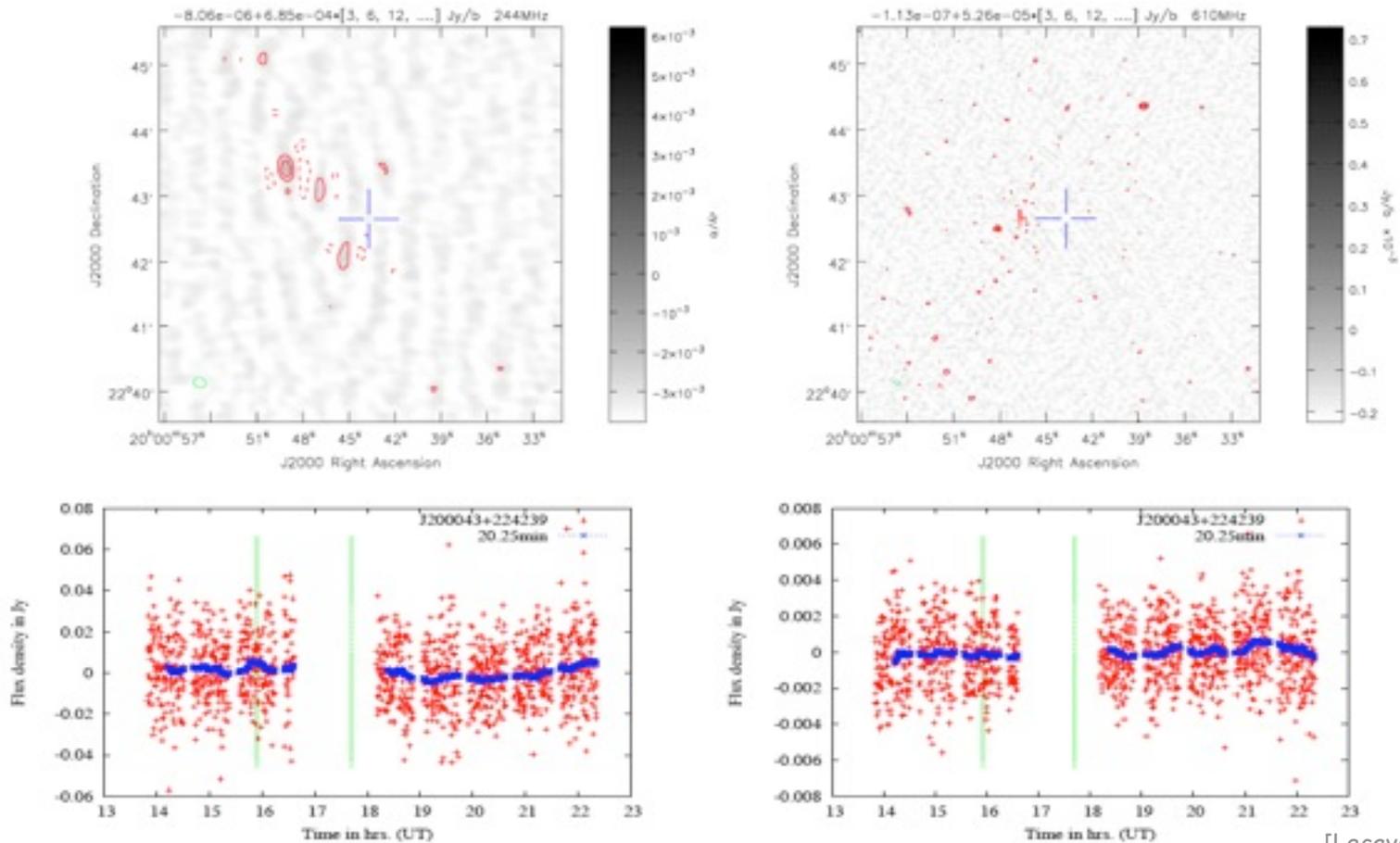


Very Large Array



• GMRT

- $f \sim 153, 244 \text{ \& } 614 \text{ MHz}$
- targets : Tauu Boo, Ups And, HD 189733
- epochs 2005-2007, 2008 (anti-transit of HD 189733)
- imaging + tied array beam
- $\ll 1 \text{ mJy}$ sensitivity



• UTR-2



- $f \sim 10\text{-}32$ MHz
- a few 10's targets (hot Jupiters)
- epochs (1997-2000) & 2006-2008+
- Simultaneous ON/OFF (2 tied array beams)
- sensitivity ~ 1 Jy within (1 s x 5 MHz)
- t,f resolution (~ 10 msec x 5 kHz)
- RFI mitigation



Fig. 3. A diagram of the east-west array section.

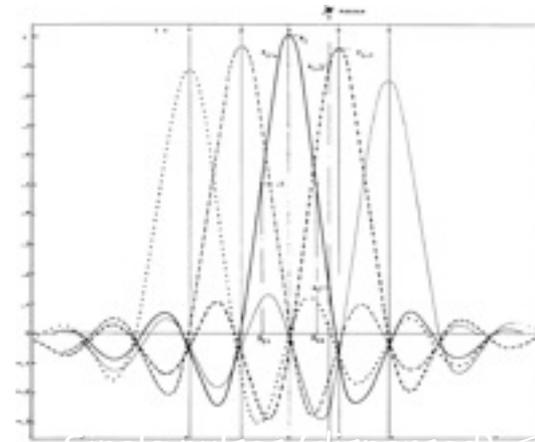


Fig. 5. Five-beam pattern of the north-south array.

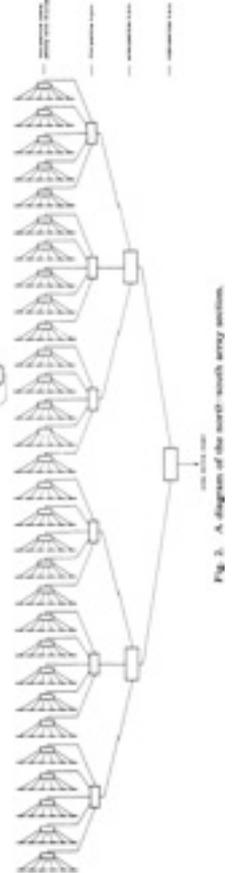
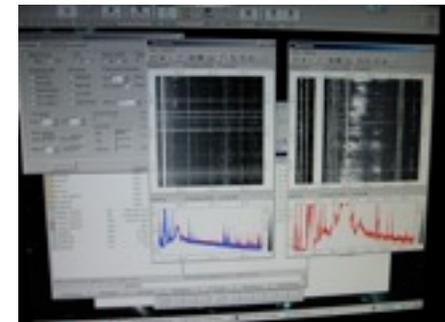


Fig. 2. A diagram of the north-south array section.



• LOFAR

- 30-250 MHz
- Epoch 2009+
- Sensitivity \leq mJy
- Imaging + Tied array beams (≥ 8)
- Built-in RFI mitigation & ionospheric calibration



➔ Exoplanet search part of “Transients” Key Project



- Systematic search
+
- Targeted observations

Interest of low-frequency radio observations of exoplanets

- Direct detection
- Planetary rotation period \Rightarrow tidal locking ?
- Possible access to orbit inclination
- Measurement of $B \Rightarrow$ constraints on scaling laws & internal structure models
- Comparative magnetospheric physics (star-planet interactions)
- Discovery tool (search for more planets) ?