Radio search for exoplanets

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- Low-frequency radio observations of exoplanets

- Theoretical predictions
  - planetary radio emissions
  - energy sources
  - scaling laws
  - extrapolation to exoplanets

- Ongoing observations

- Future observations

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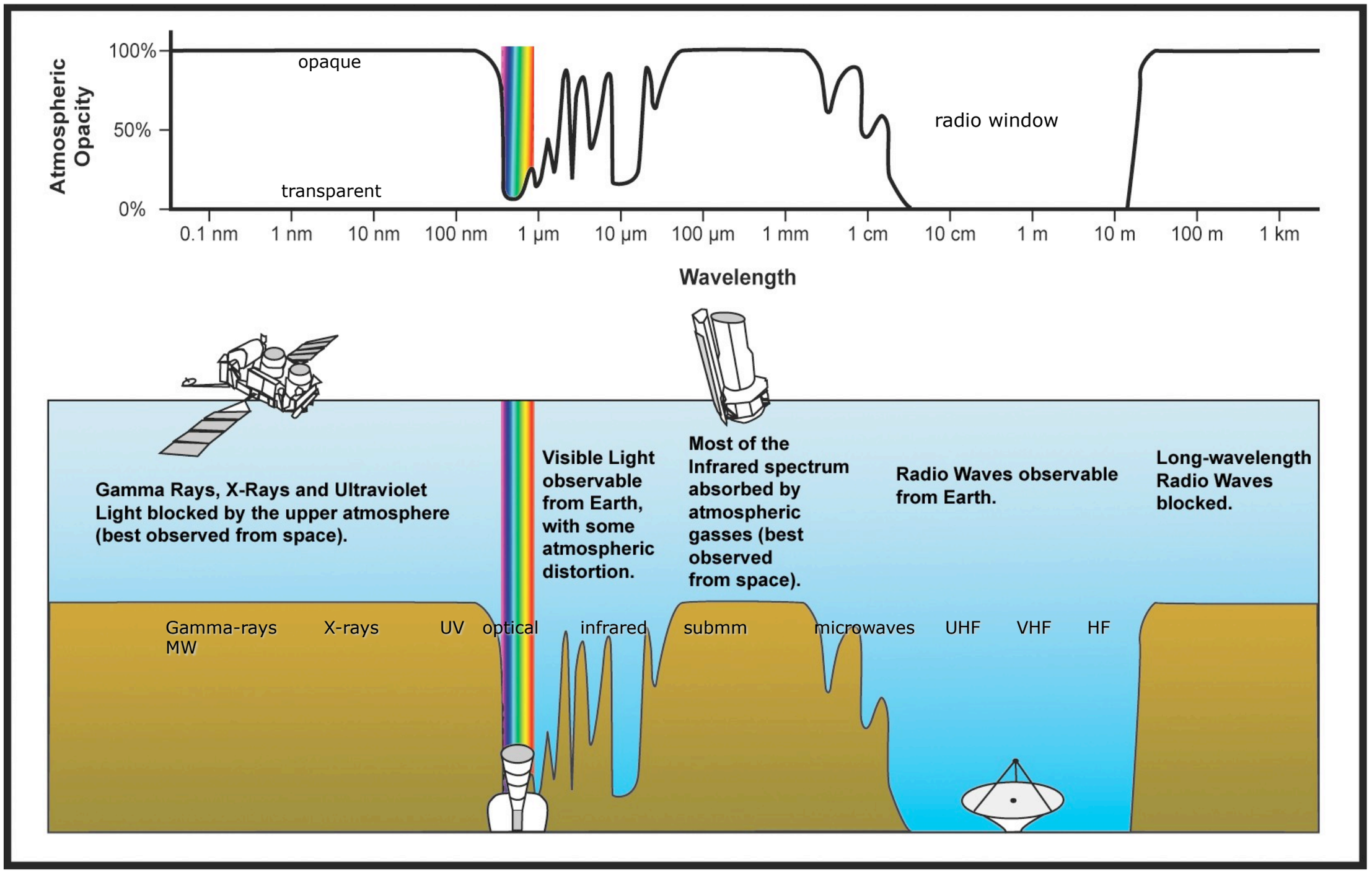
The radio window



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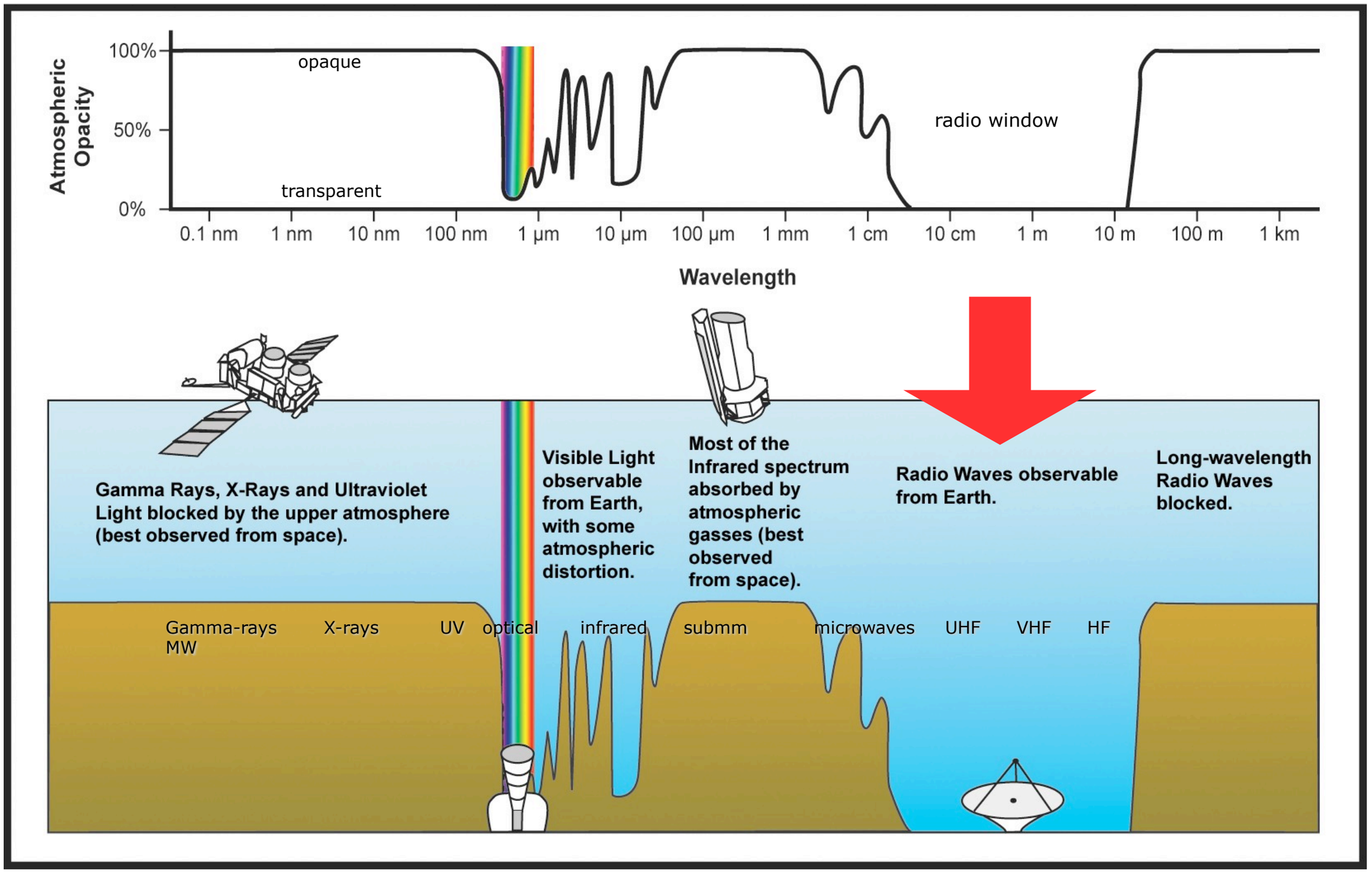
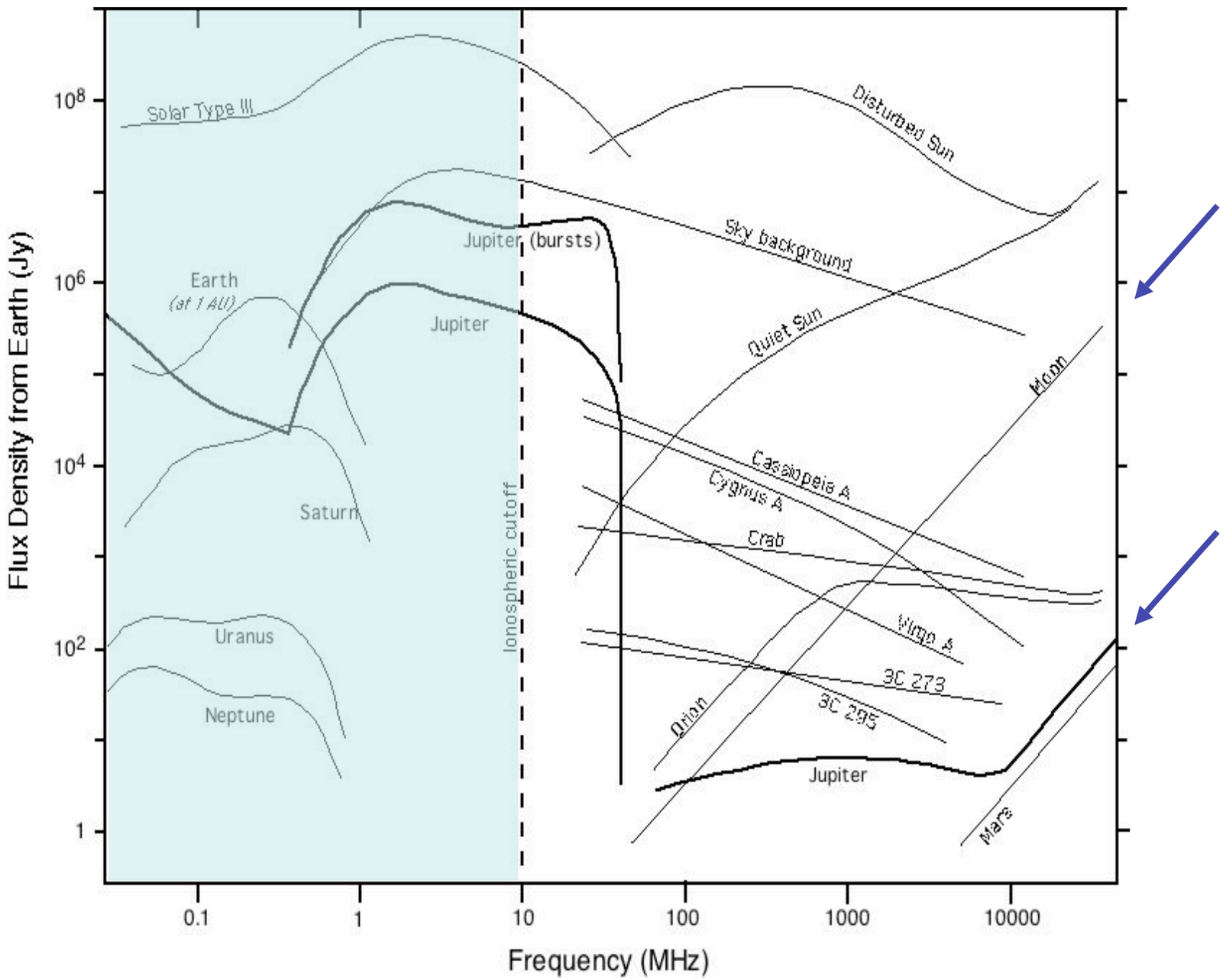


Interest of Radio observations

- A low frequencies, thermal spectrum in λ^{-2} (Rayleigh-Jeans)



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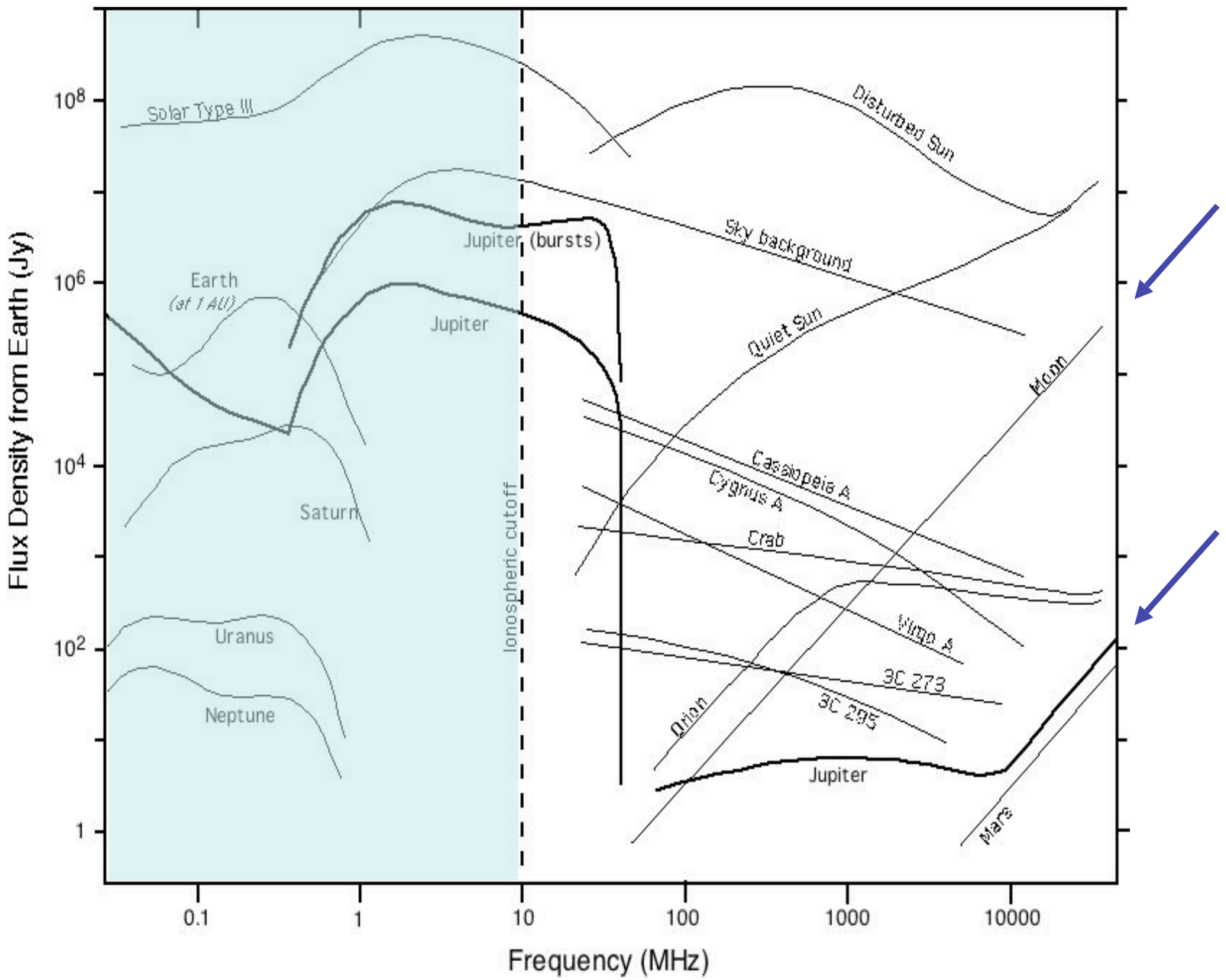

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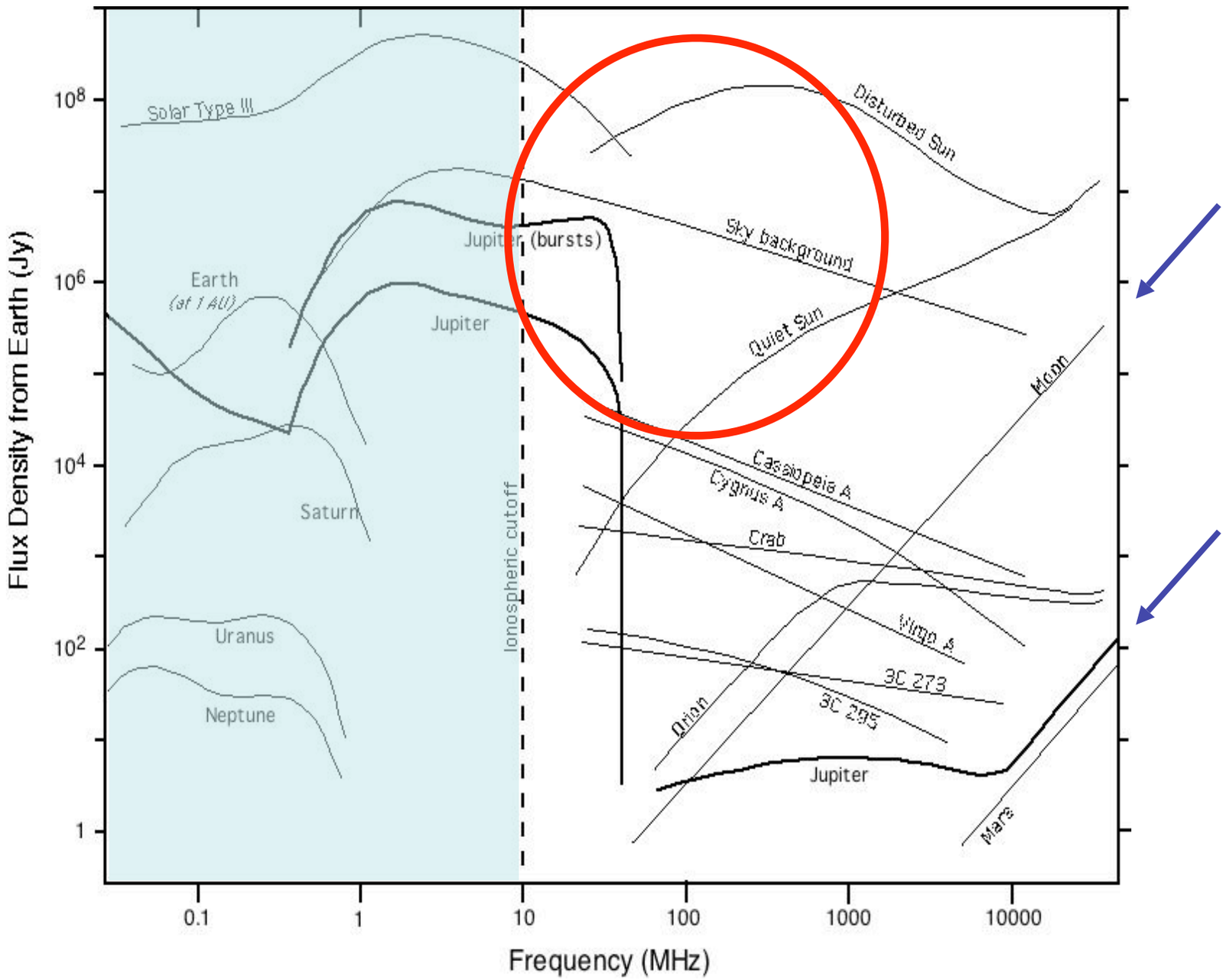

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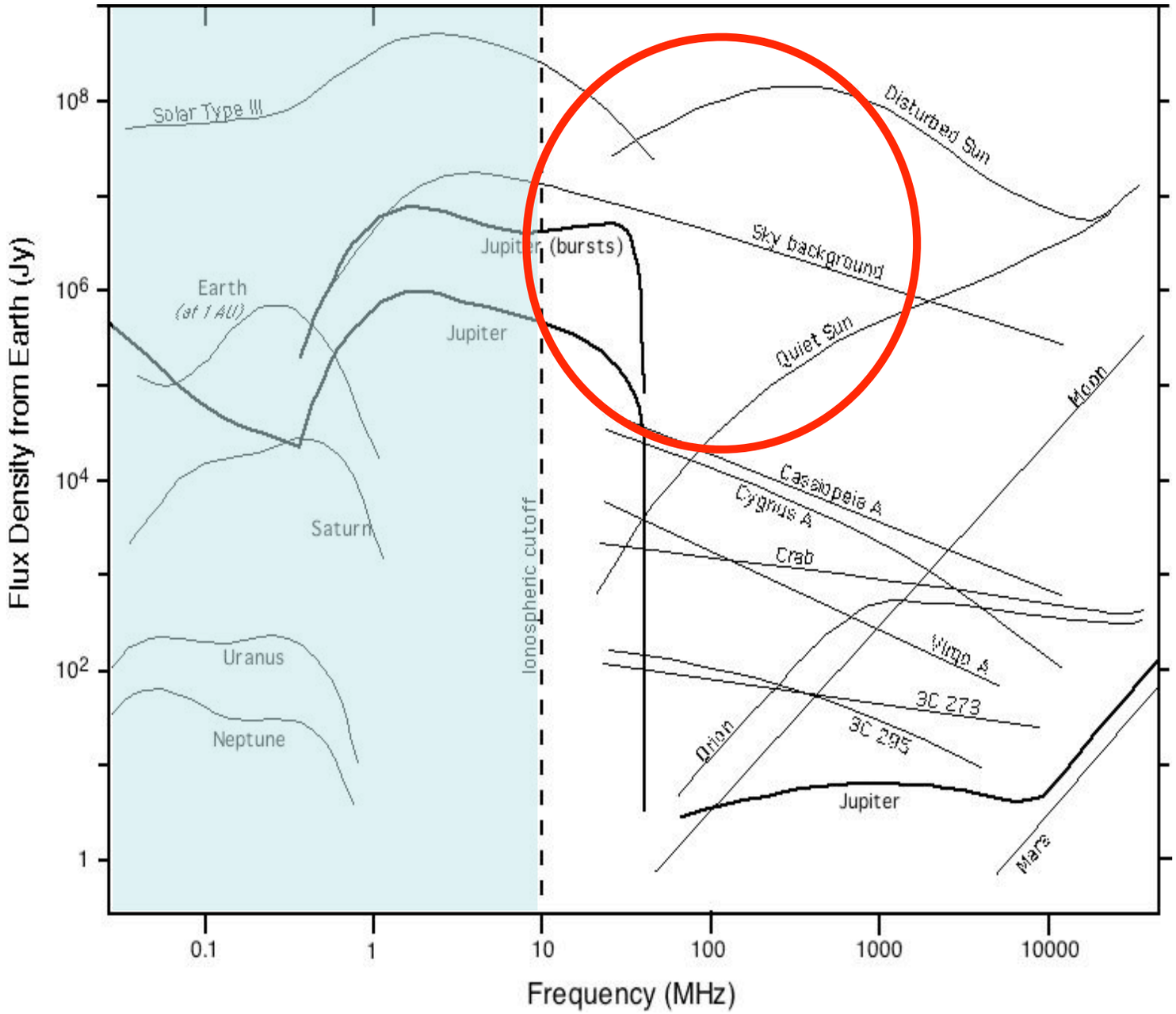
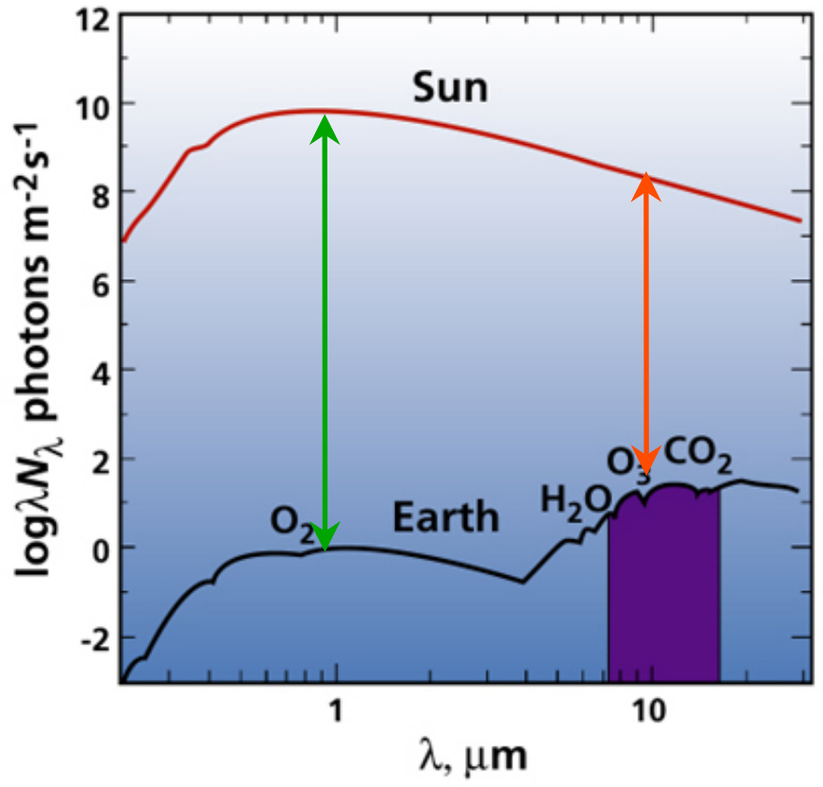


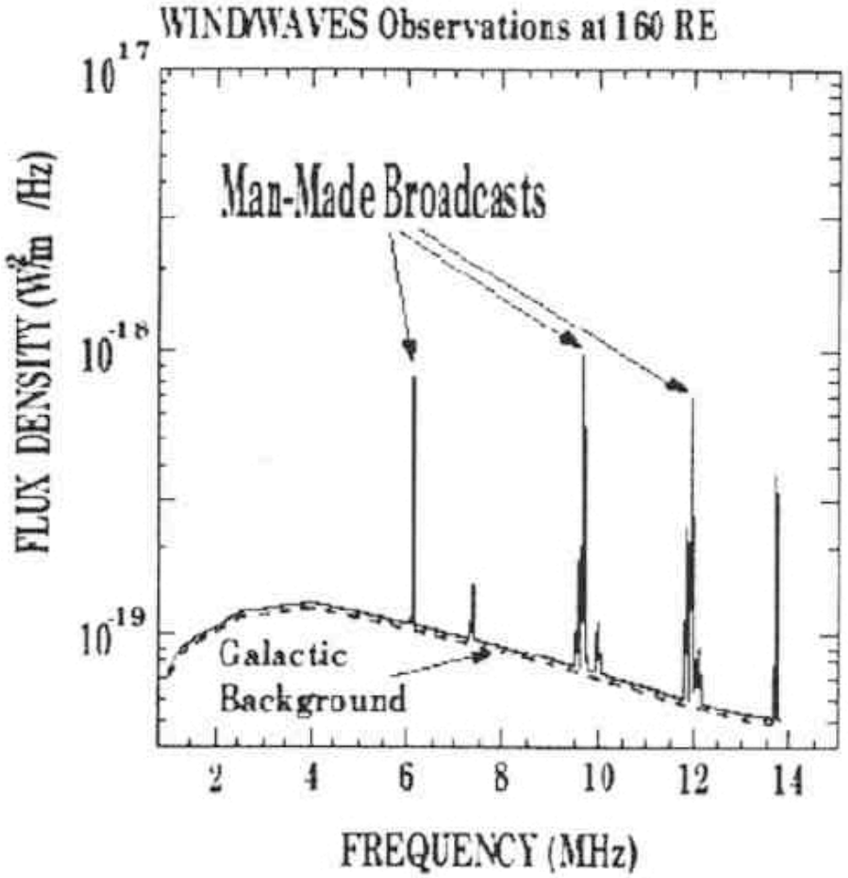


Limitations of Radio observations

- Limited angular resolution (λ/D)
- Very bright galactic background (T_b ~$10^{3\text{-}5}$ K)
- RFI (natural & anthropic origin)
- Ionospheric cutoff ~ 10 MHz,

perturbations ≤30-50 MHz,

scintillations IP/IS



Sensitivity of Radio observations

- <u>Galactic radio background</u>: $T \sim 1.15 \times 10^8 / \nu^{2.5} \sim 10^{1\text{-}5}$ K (10-1000 MHz)

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

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

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- <u>Maximum distance for Nσ detection of a source ζ x Jupiter</u> :

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

$$\Rightarrow d_{max}\,(pc) = 5\times10^{-8}\,(A_e\,\zeta)^{1/2}\,f^{5/4}\,(b\tau)^{1/4}$$

$\Rightarrow \zeta = 1$

	$b\tau = 10^6$ *(1 MHz, 1 sec)*		$b\tau = 2\times10^8$ *(3 MHz, 1 min)*		$b\tau = 4\times10^{10}$ *(10 MHz, 1 hour)*	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4$ m^2 *(~NDA)*	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5$ m^2 *(~UTR-2)*	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6$ m^2 *(~LOFAR77)*	0.03	0.5	0.1	2.	0.4	7.

(distances in parsecs)

[Zarka et al., 1997; Zarka, , 2004, 2007]

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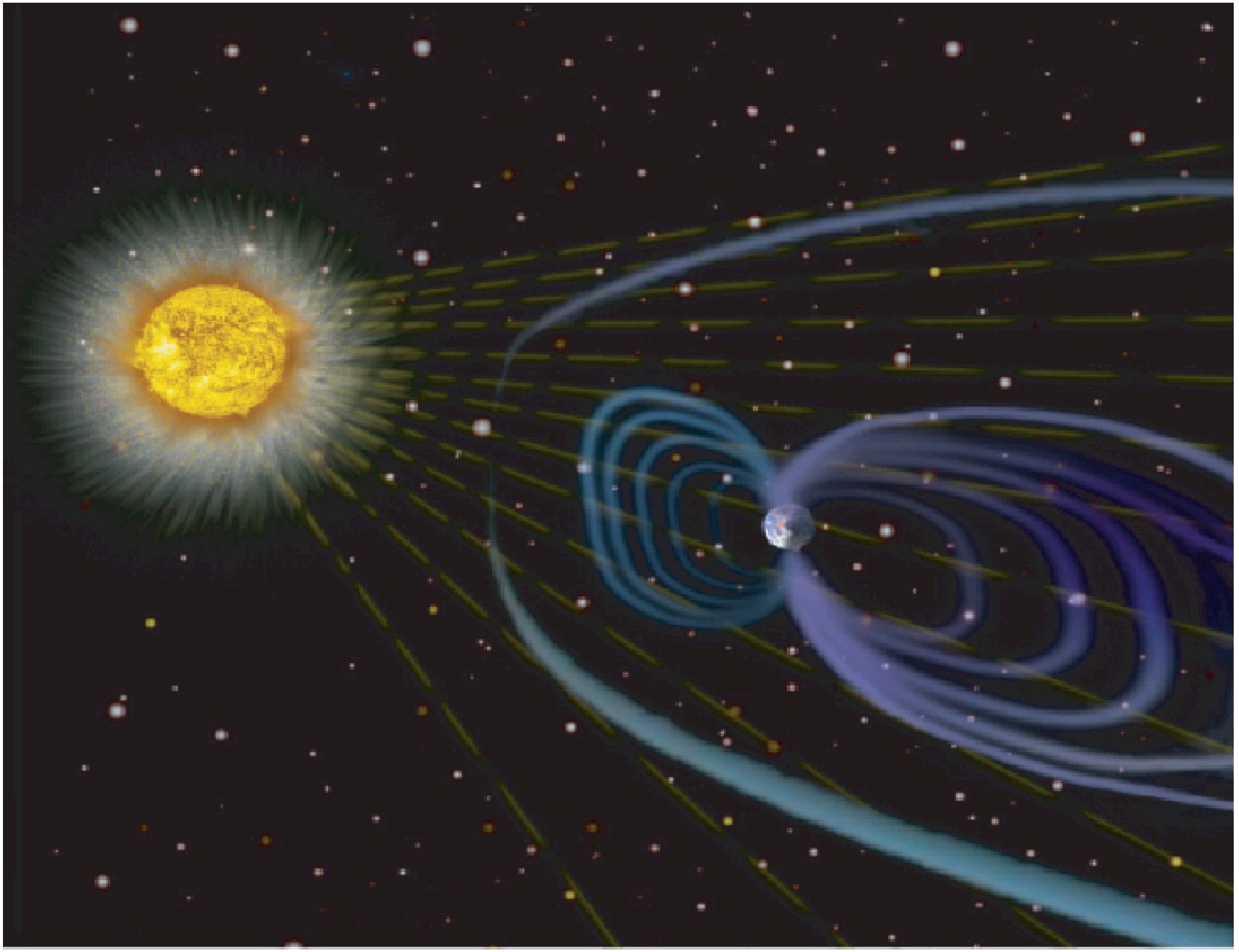
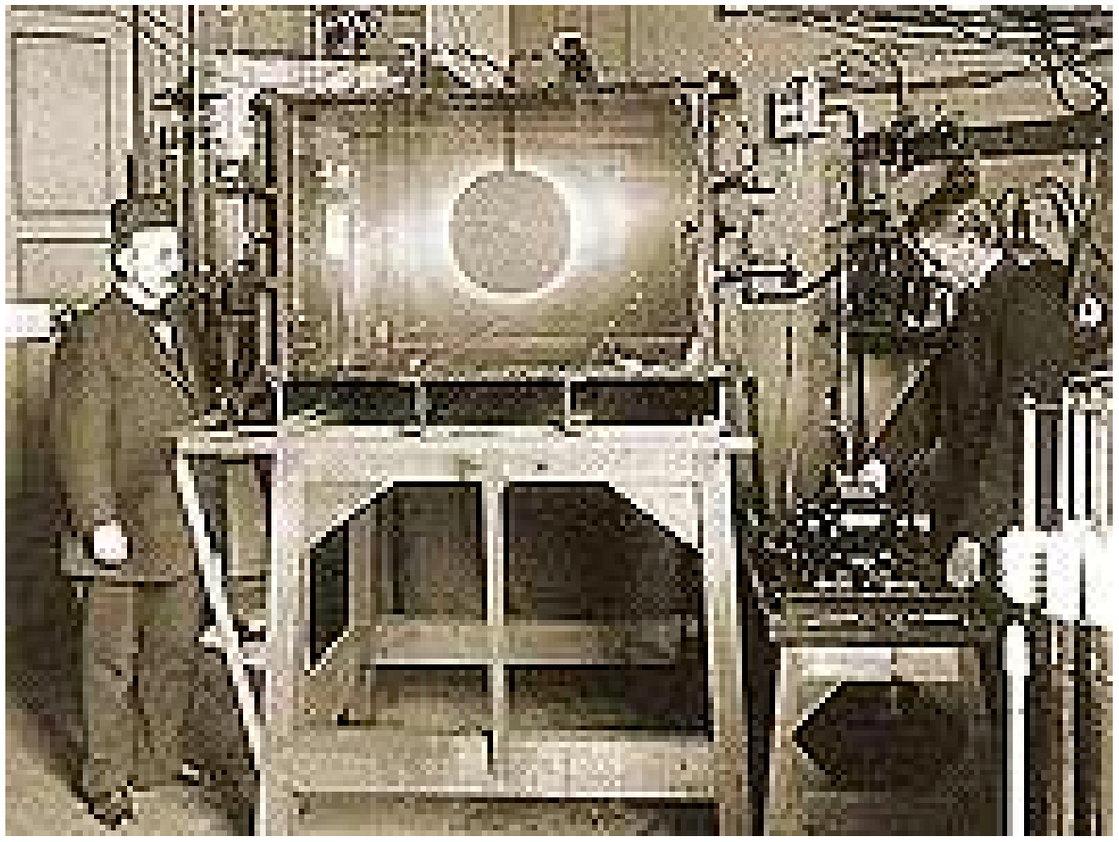
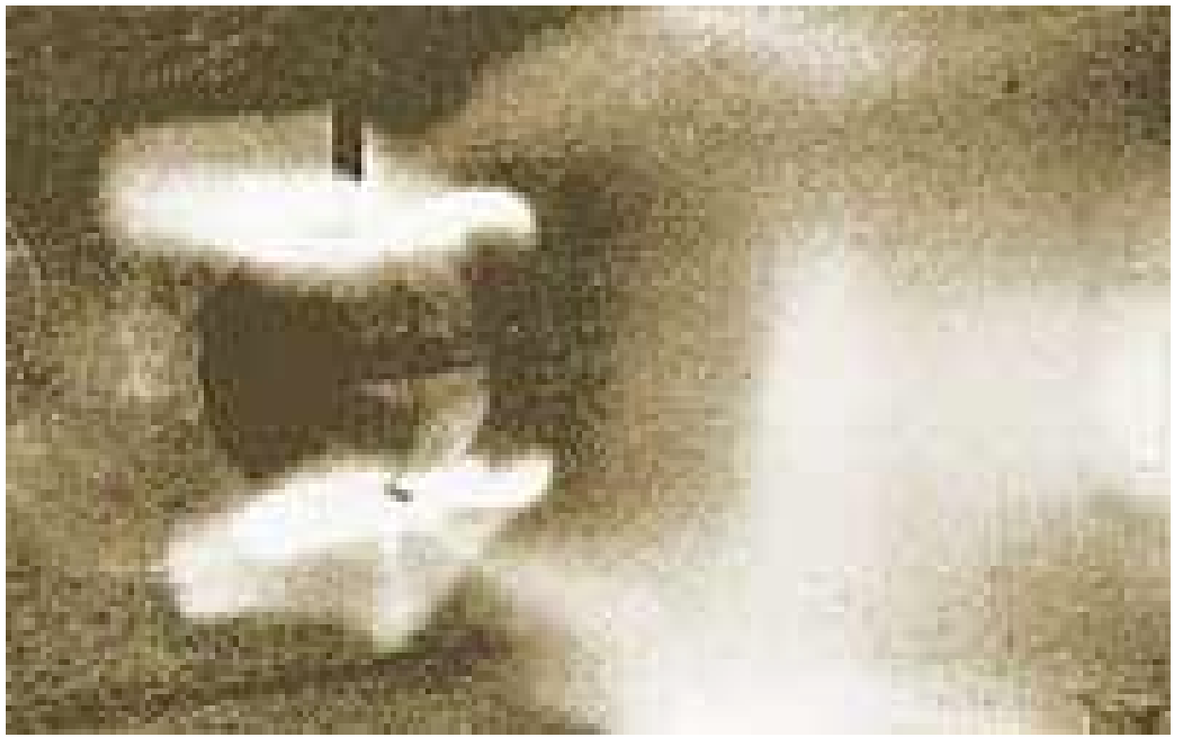
Solar Wind - Magnetosphere Interaction …



Aurorae





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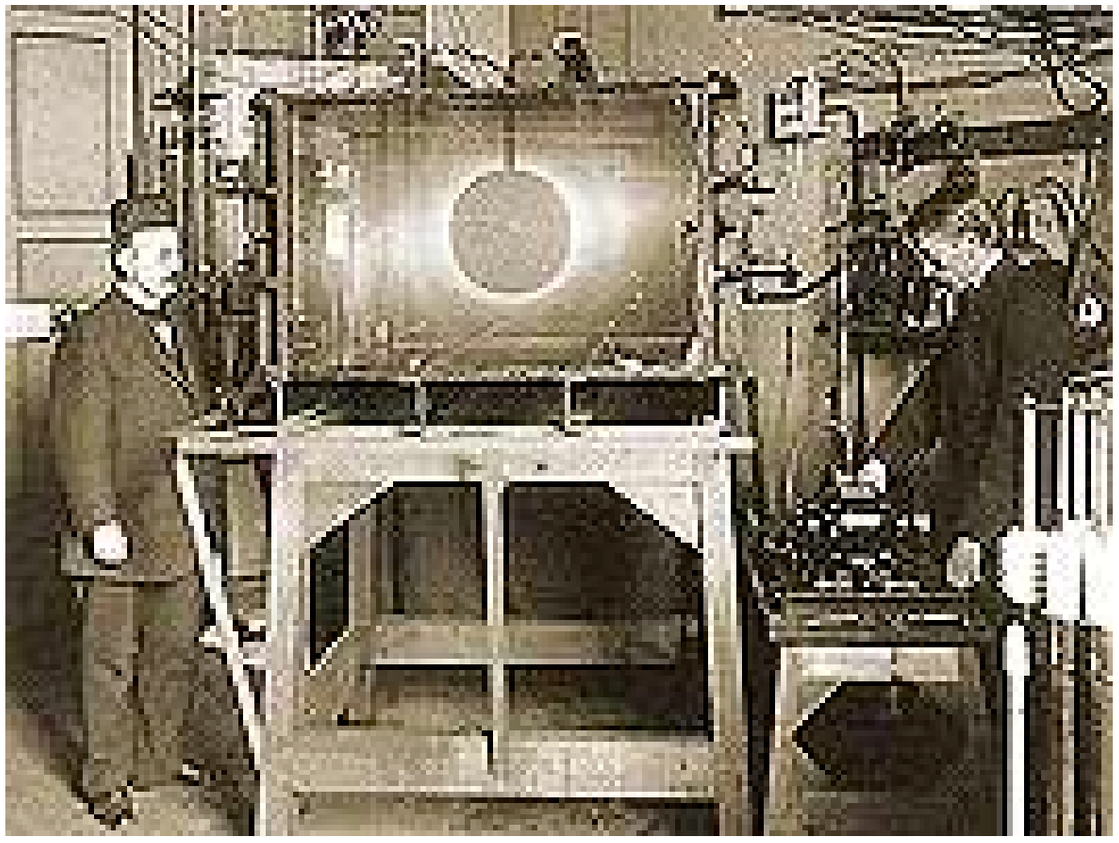
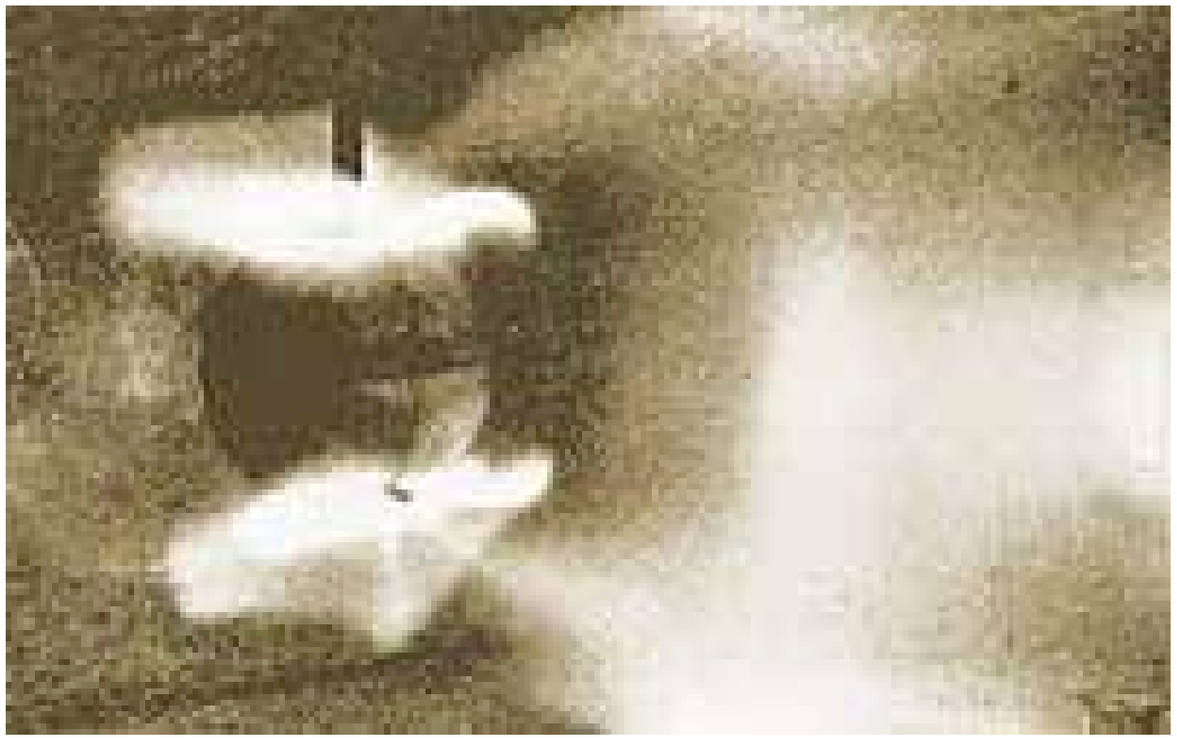
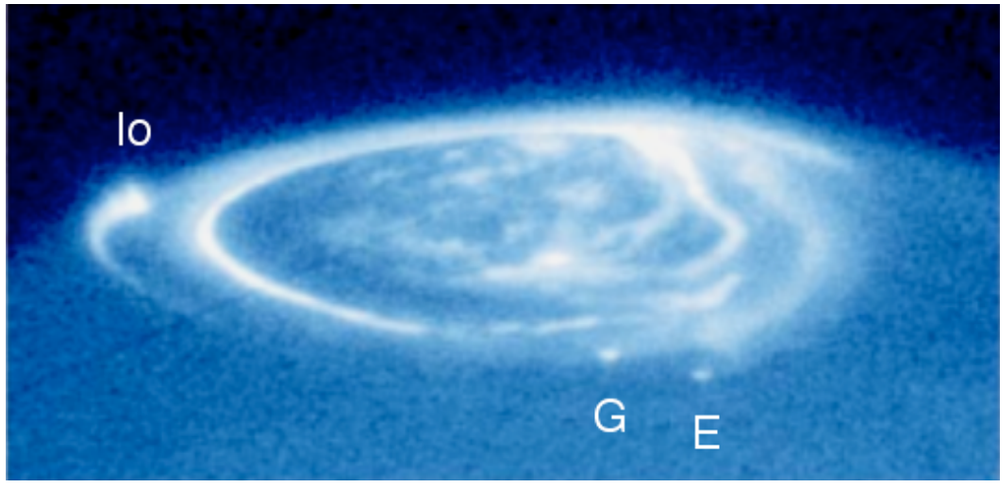
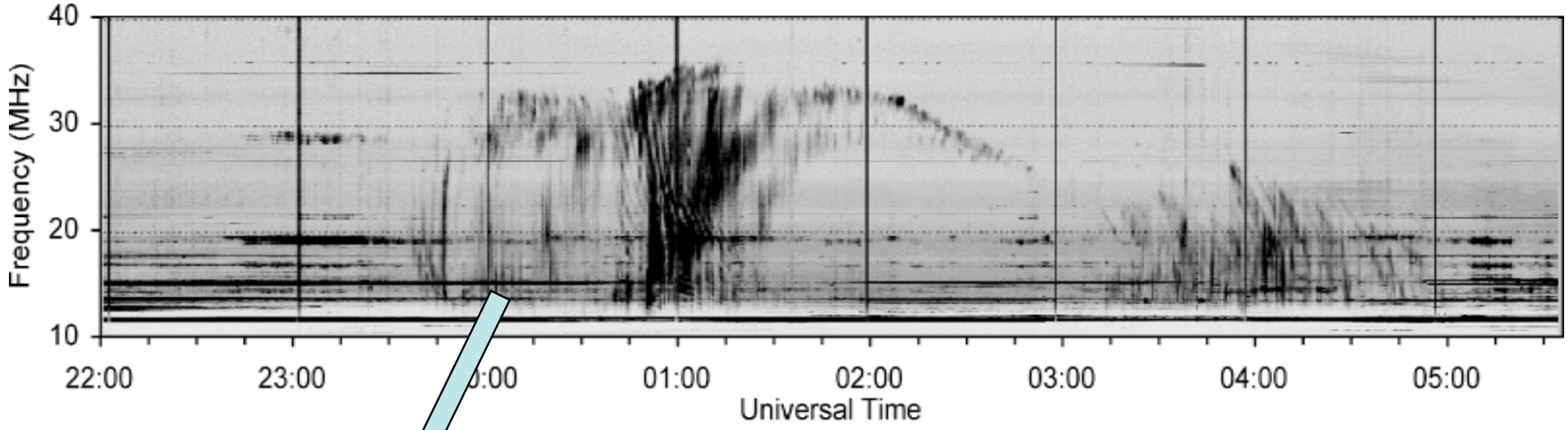
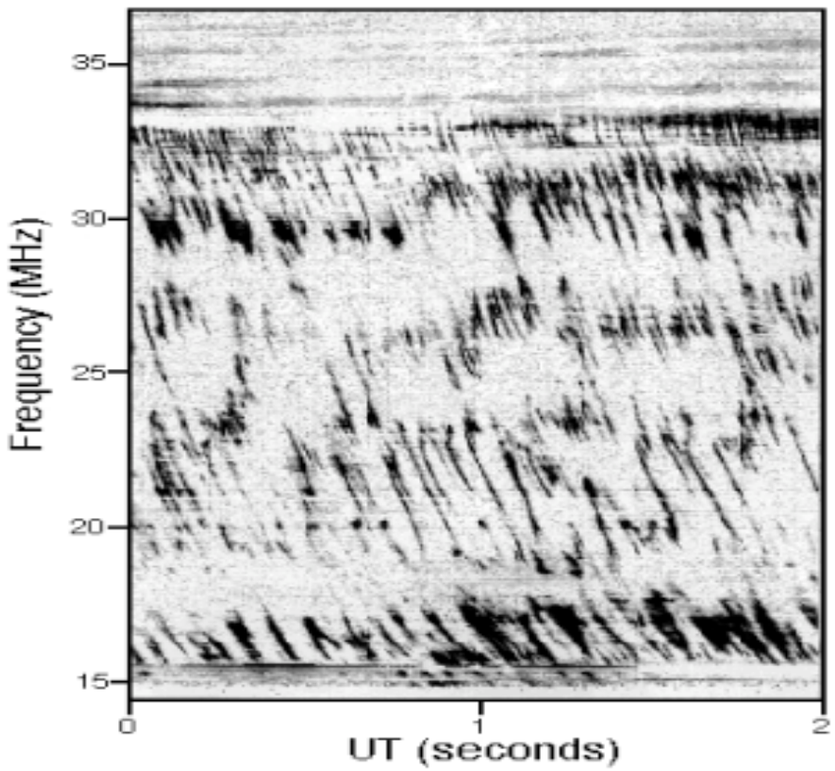


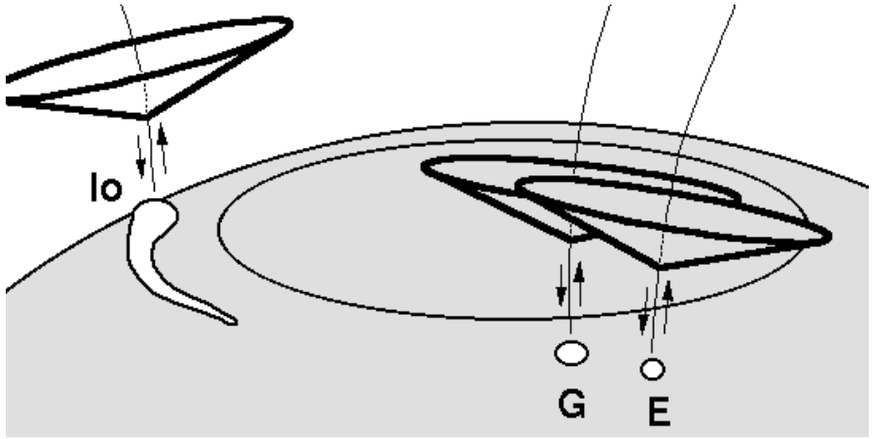


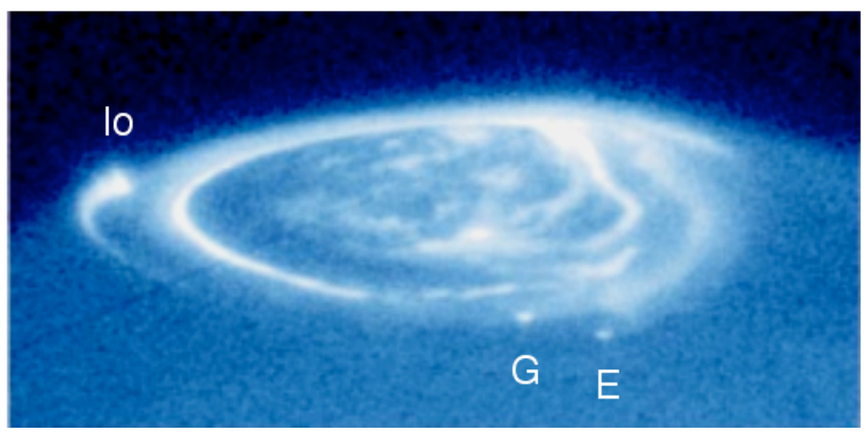


Magnetospheric (auroral) radio emissions





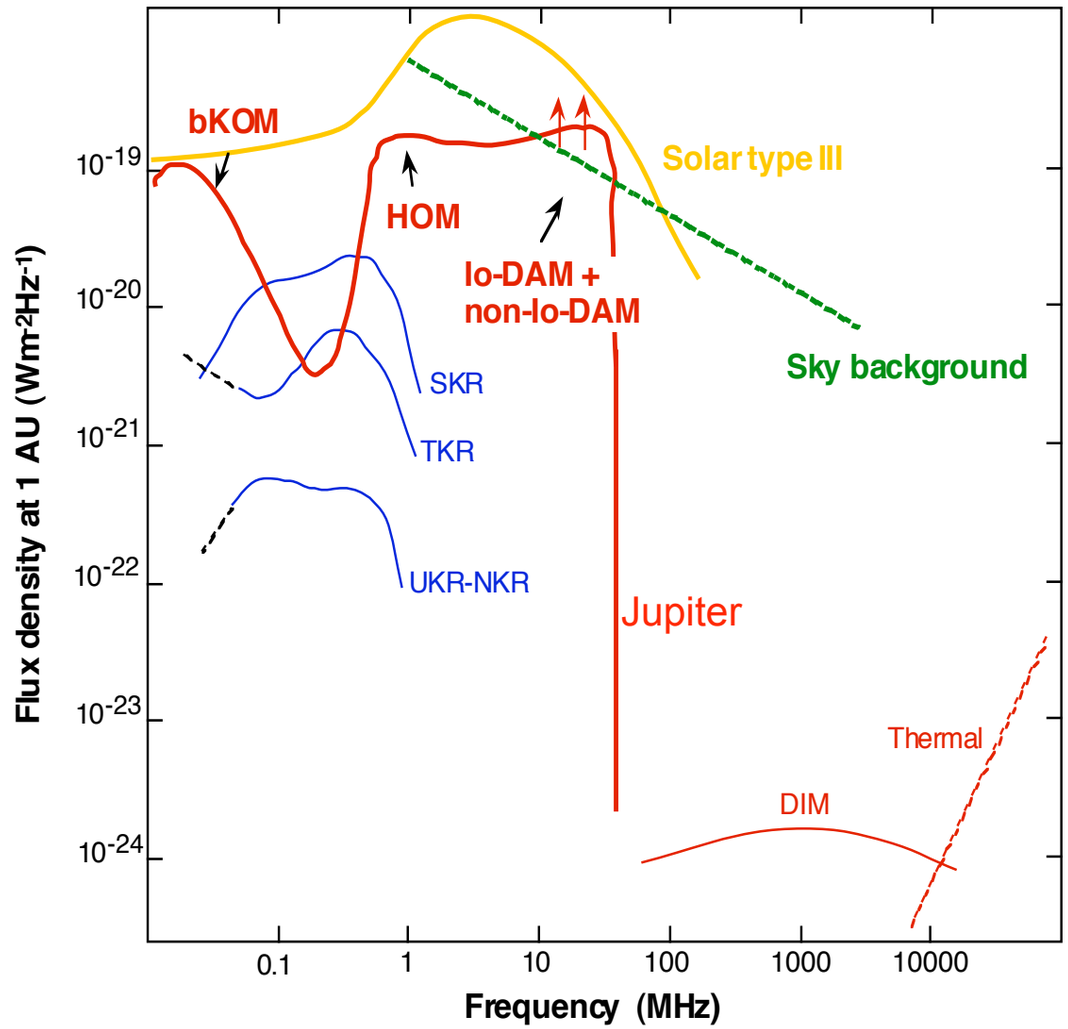




[Zarka, 1998]

Properties of auroral radio emissions

- $f \sim f_{ce}$, $\Delta f \sim f$
- $T_B > 10^{15}$ K
- circular/elliptical polarization (X mode)
- very anisotropic beaming (conical, $\Omega << 4\pi$ sr)
- variability /t (bursts, rotation, solar wind…)
- correlation radio / UV
- radiated power : $10^{6\text{-}11}$ W



[Louarn, 1992; Zarka, 1998]

Generation of auroral radio emissions

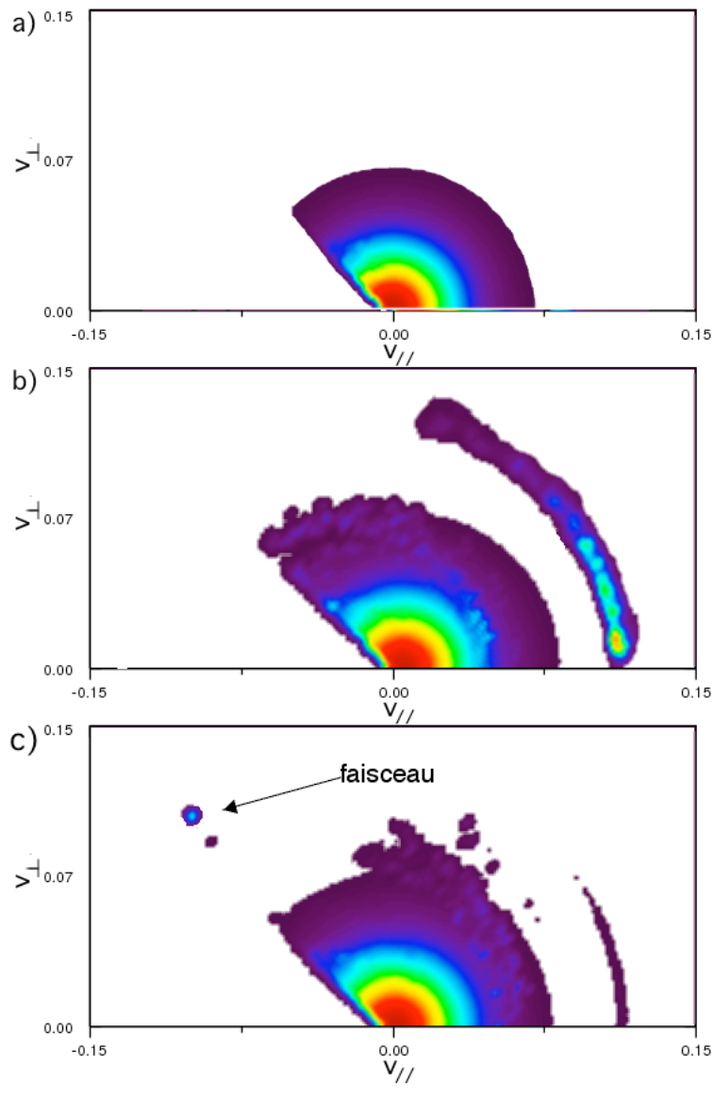
- Cyclotron-Maser (coherent) emission : 2 conditions within sources :

  - low β magnetized plasma ($f_{pe} << f_{ce}$)

  - energetic electrons (keV) with non-Maxwellian distribution

  → high magnetic latitudes

  → direct emission at $f \sim f_x \approx f_{ce}$



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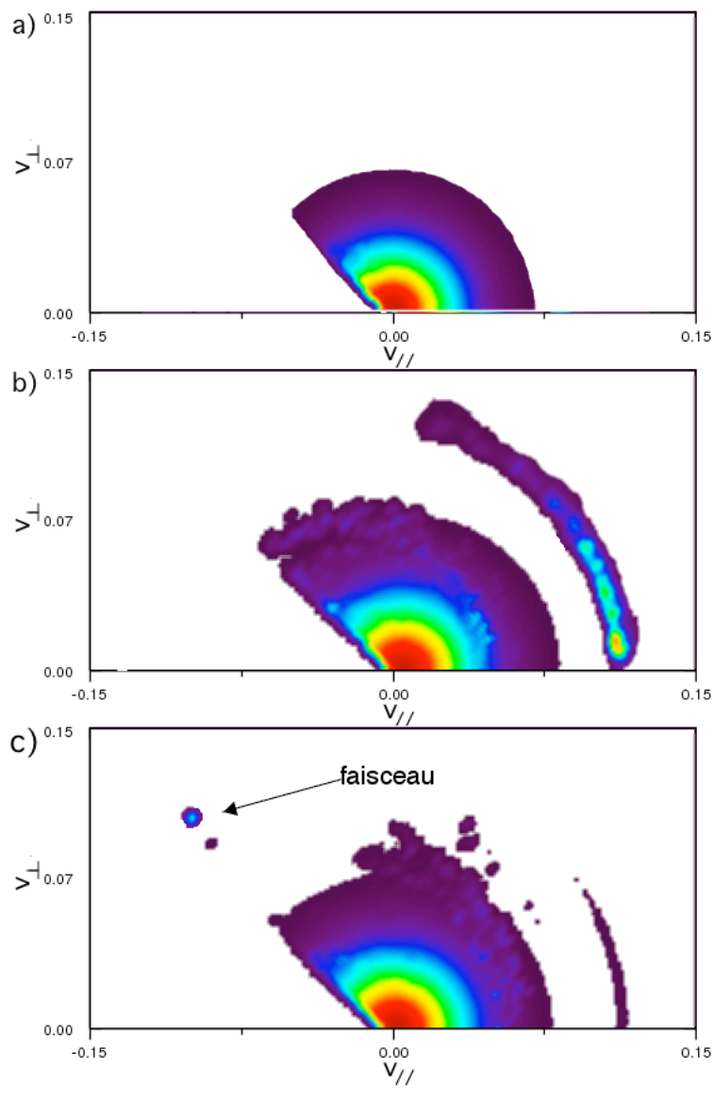
- Acceleration of electrons :

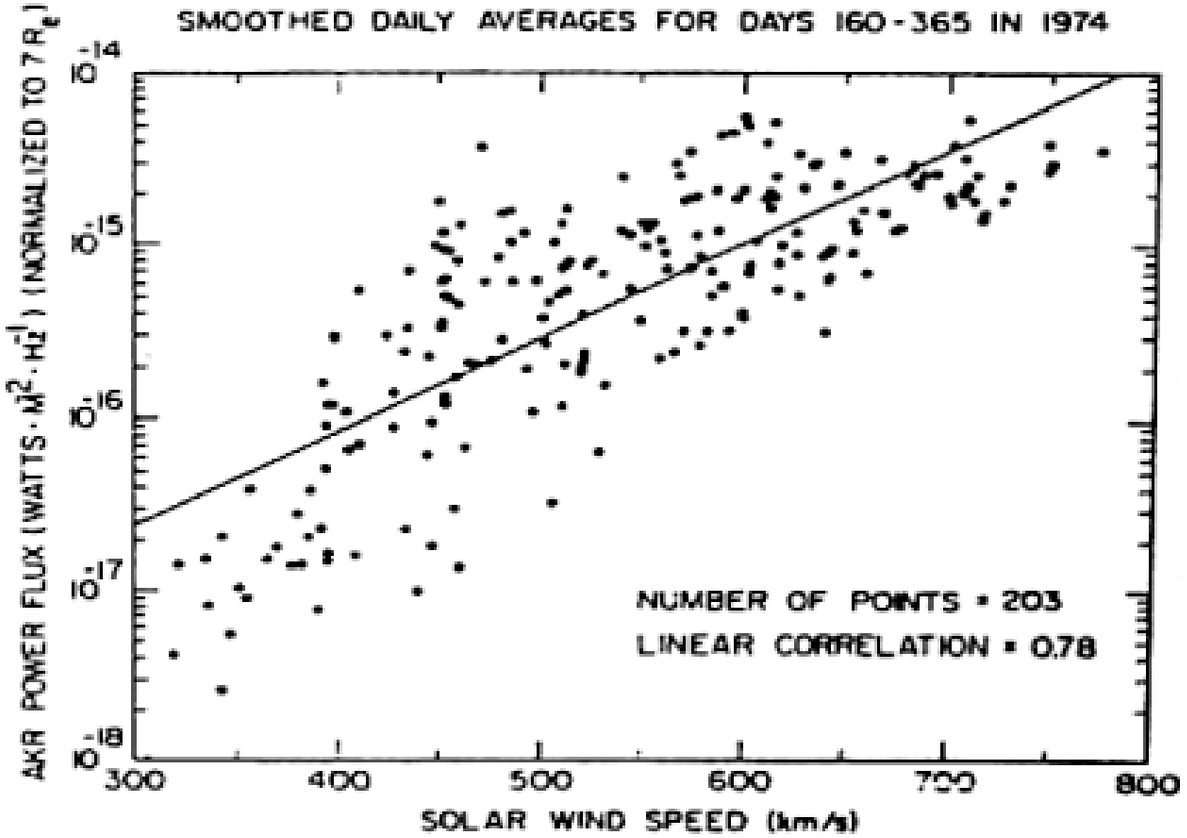
  - interactions B/satellites → $E_{//}$, heating

  - magnetic reconnection

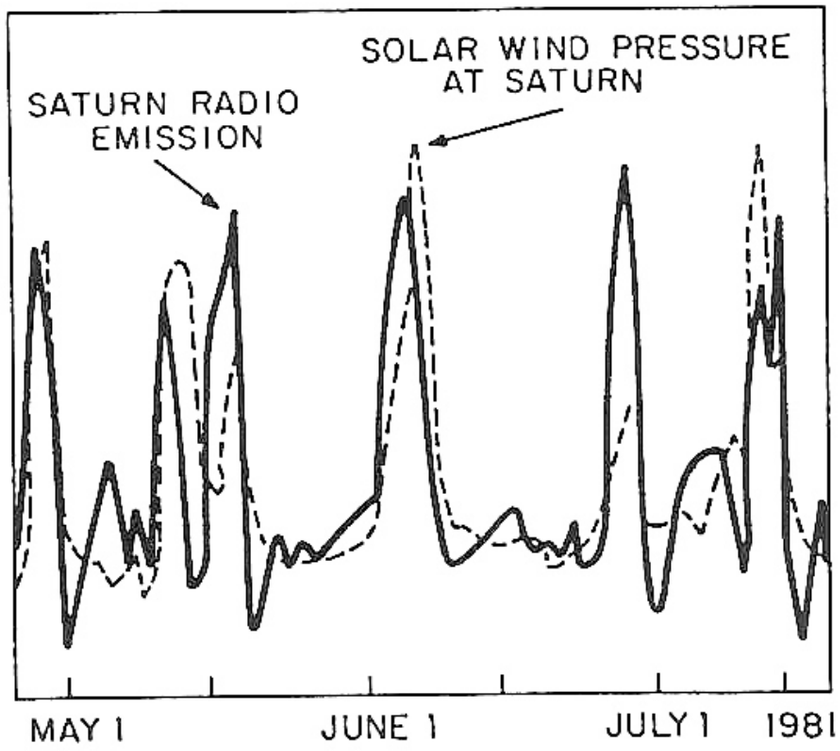
  - MS compressions

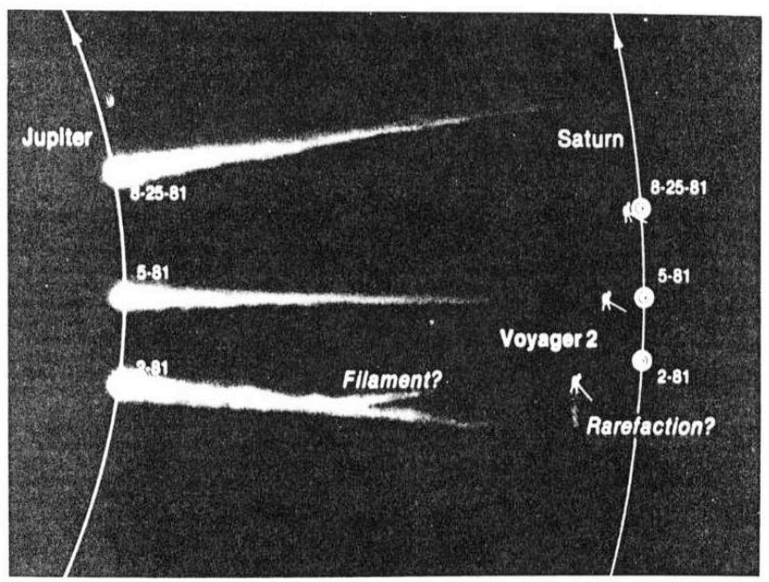


NB : Strong correlation between Solar Wind (P, V…) and auroral radio emissions



[Gallagher et d'Angelo, 1981]





[Desch, 1981,]

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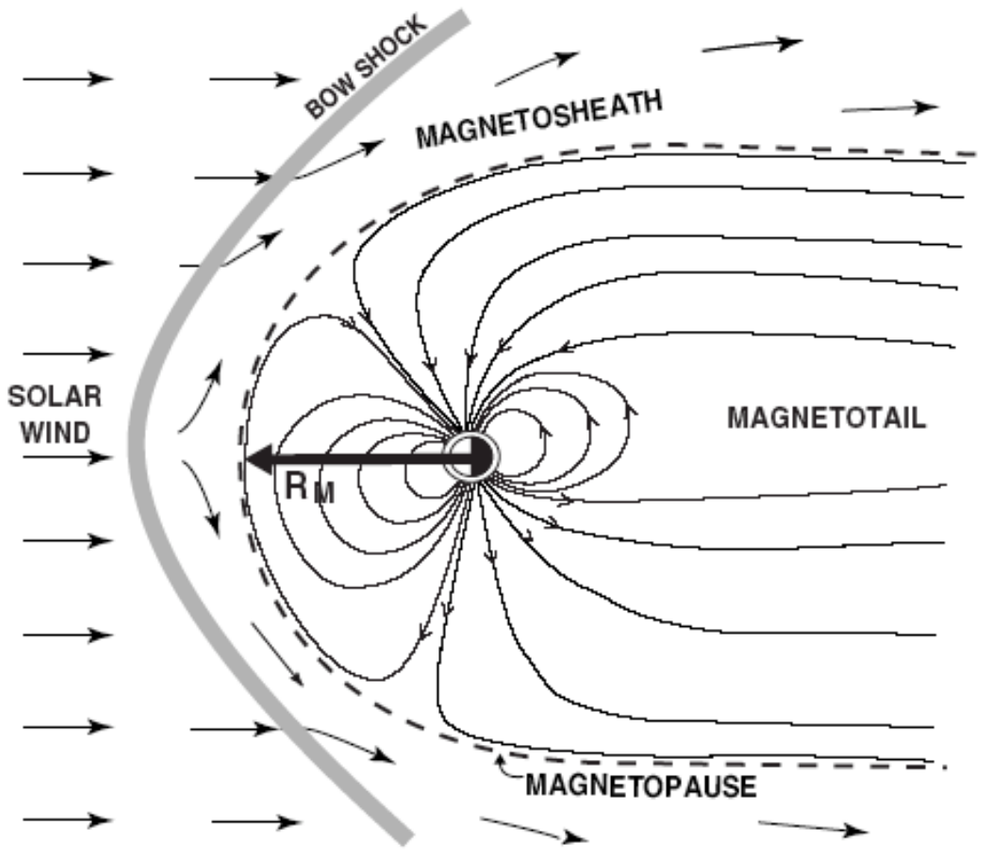
Solar Wind - Magnetosphere Interaction



[Akasofu, 1981, 1982]

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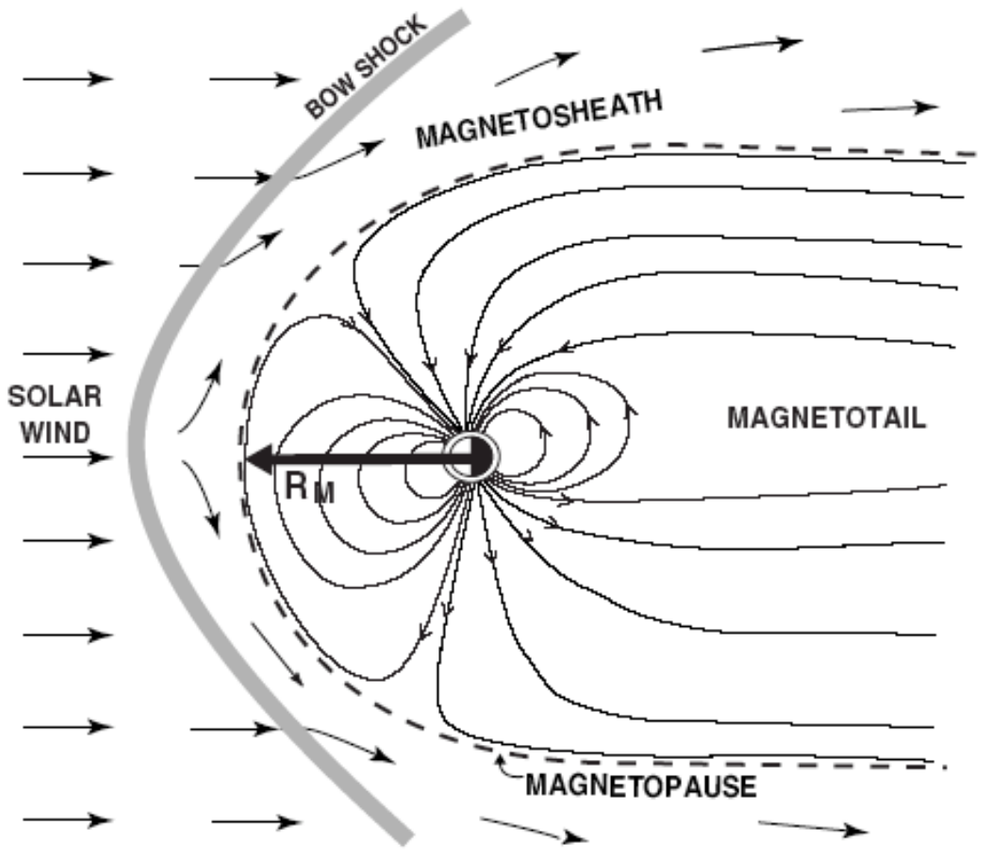

Magnetopause radius R_{MP} from pressure equilibrium :

[Akasofu, 1981, 1982]

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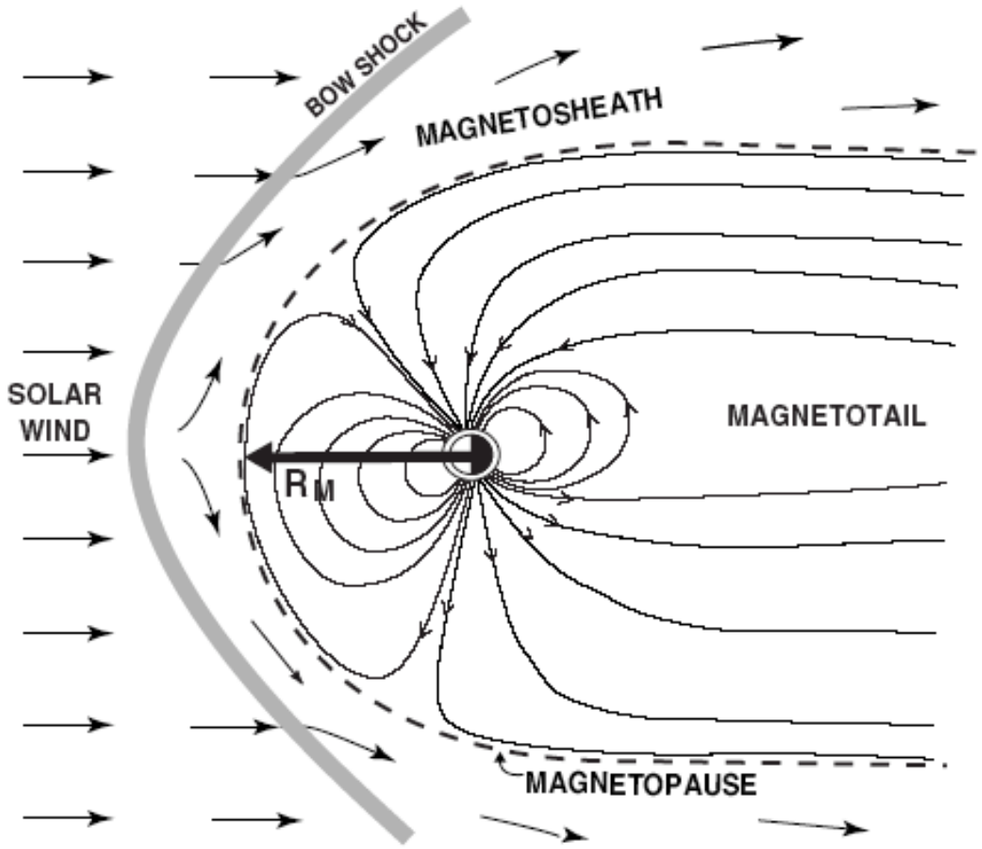

Magnetopause radius R_{MP} from pressure equilibrium :

- Kinetic energy flux on MS cross-section : $P_C \sim NmV^2 \; V \; \pi R_{MP}^2$

$N=N_o/d^2$ $N_o=5\ cm^{-3}$ $m\sim1.1\times m_p$

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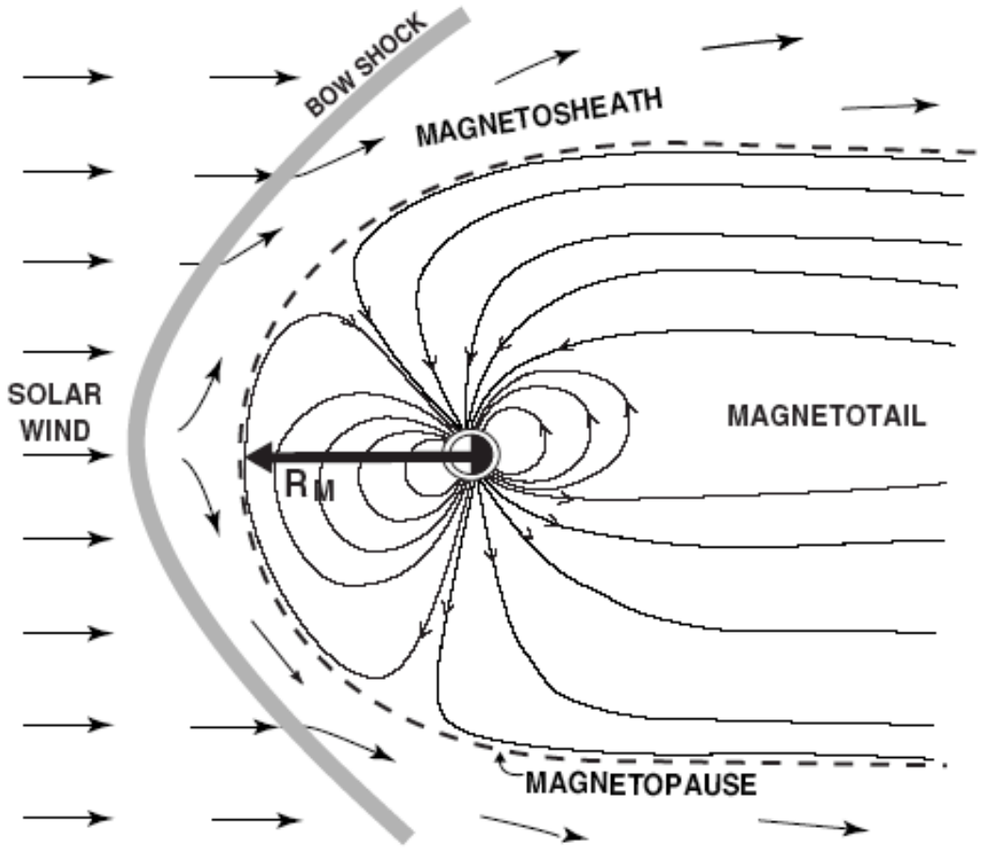

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- Poynting flux of B_{IMF} on MS cross-section : $P_B = \int_{MP}(\mathbf{E}\times\mathbf{B}/\mu_o).\mathbf{dS}$

  $\mathbf{E}=-\mathbf{V}\times\mathbf{B} \rightarrow \mathbf{E}\times\mathbf{B} = VB_\perp^2 \rightarrow$ $P_B = B_\perp^2/\mu_o\ V\ \pi R_{MP}^2$

[Akasofu, 1981, 1982]

Solar Wind expansion

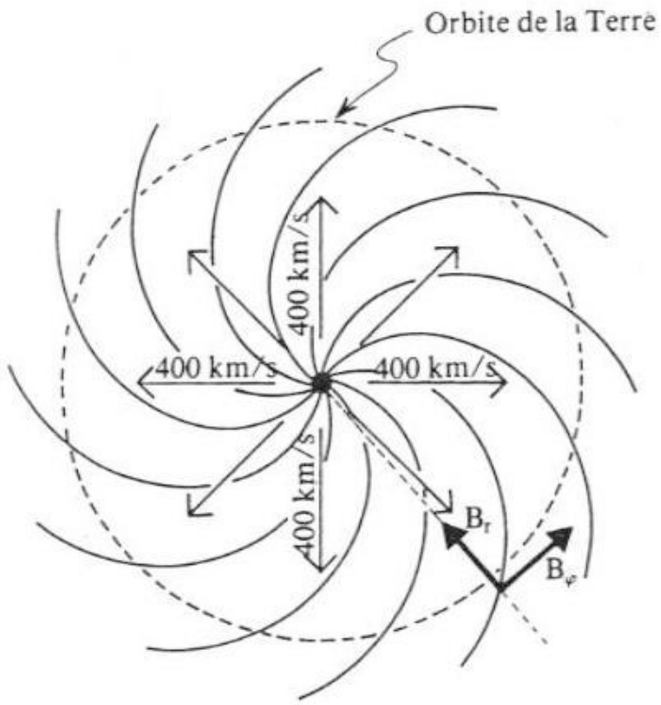
$V \sim c^{te}$

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

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

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

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



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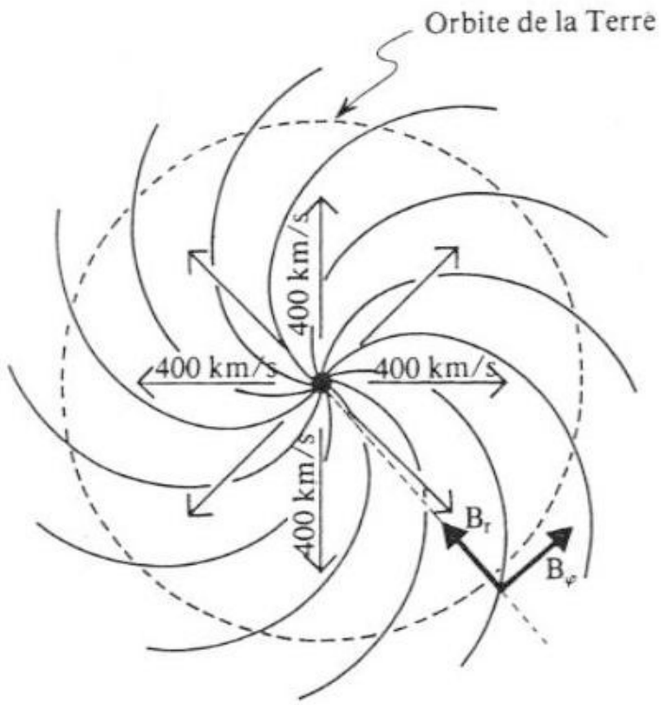

→ B^2 varies as NV^2 thus P_C varies as P_B

→ $P_C / P_B \sim 170$ beyond 1 UA

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

[Zarka, 2007]

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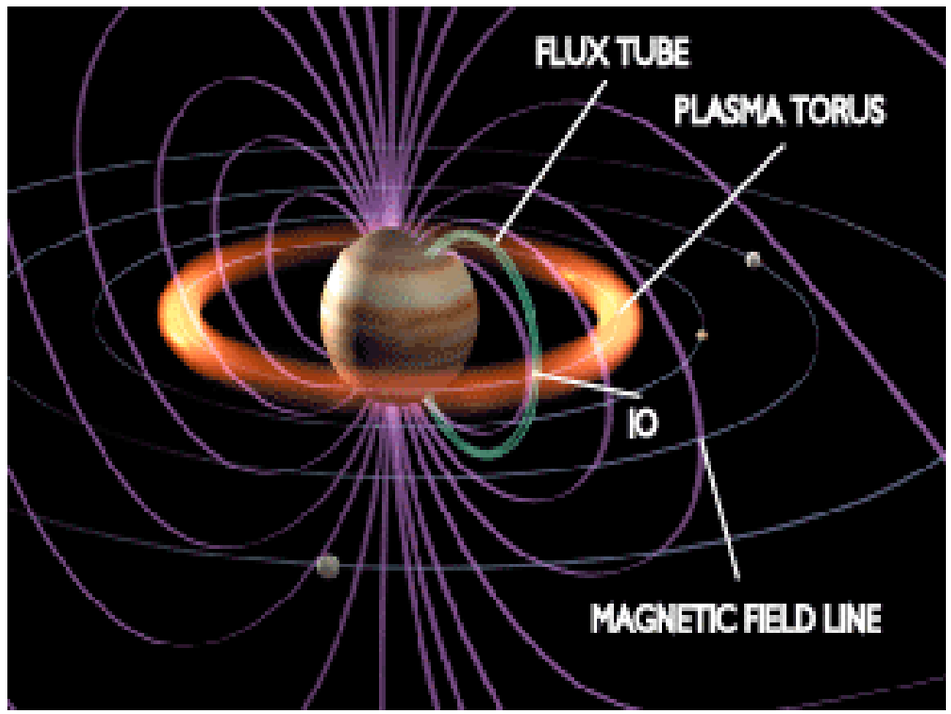
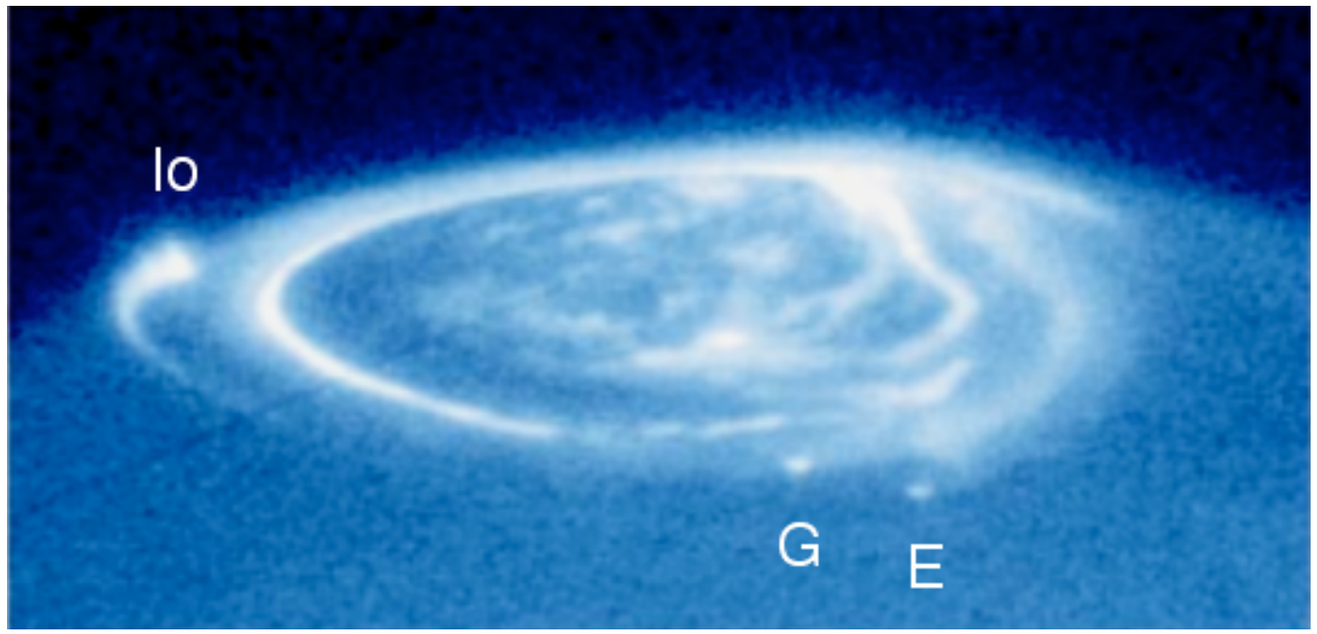
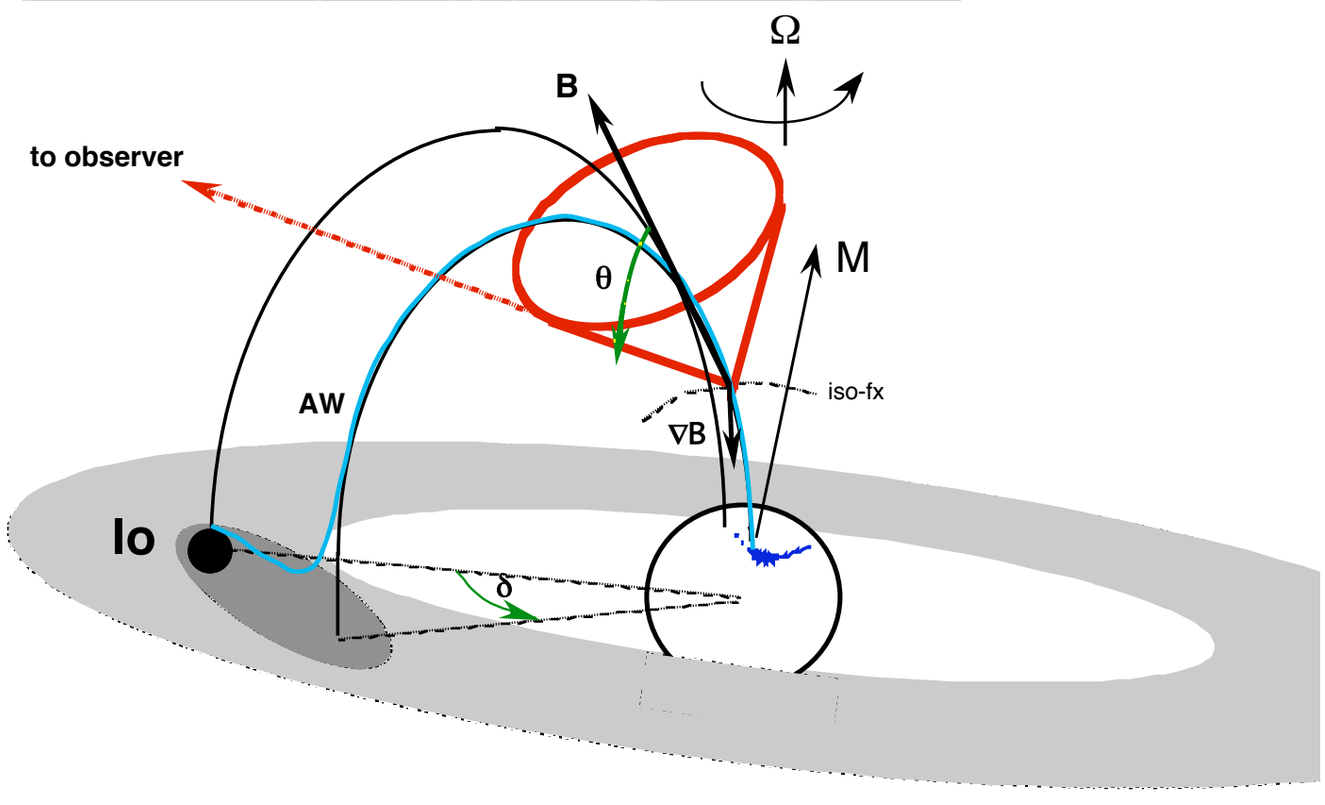
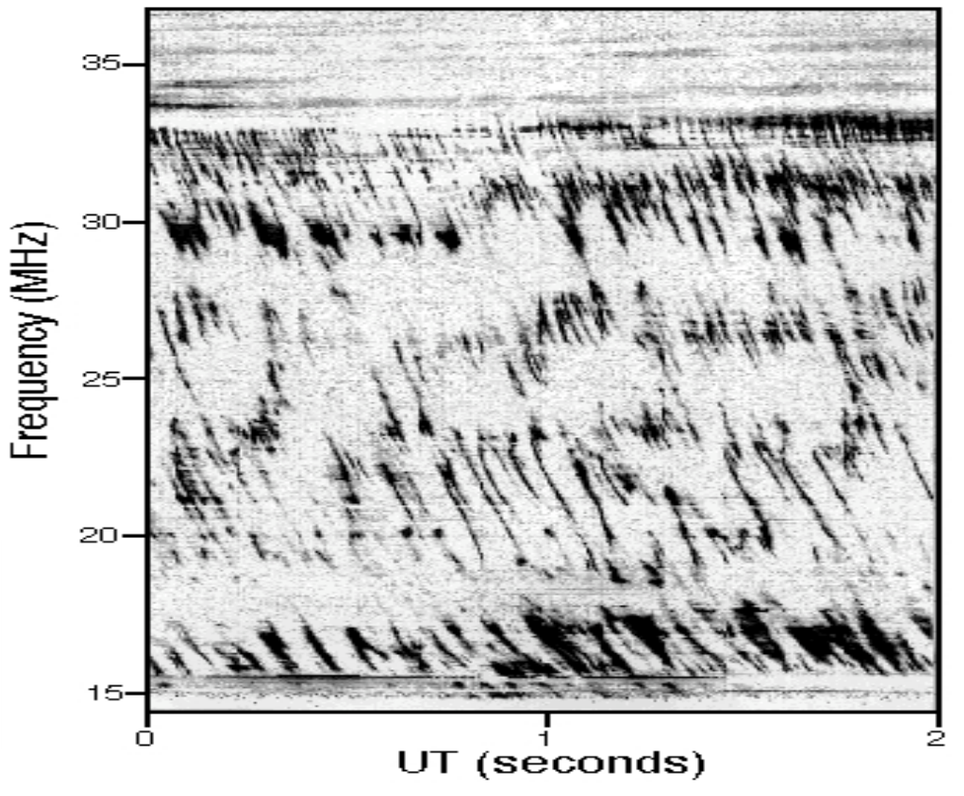
[Zarka, 2007]

Satellite - $B_{Jupiter}$ interaction









[Zarka, 2004]

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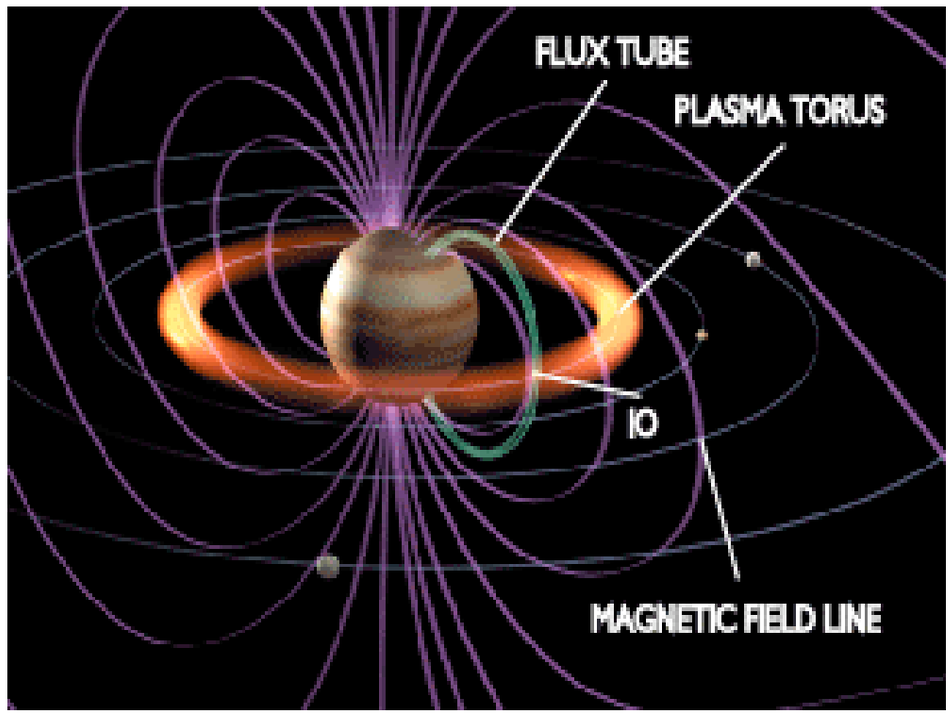

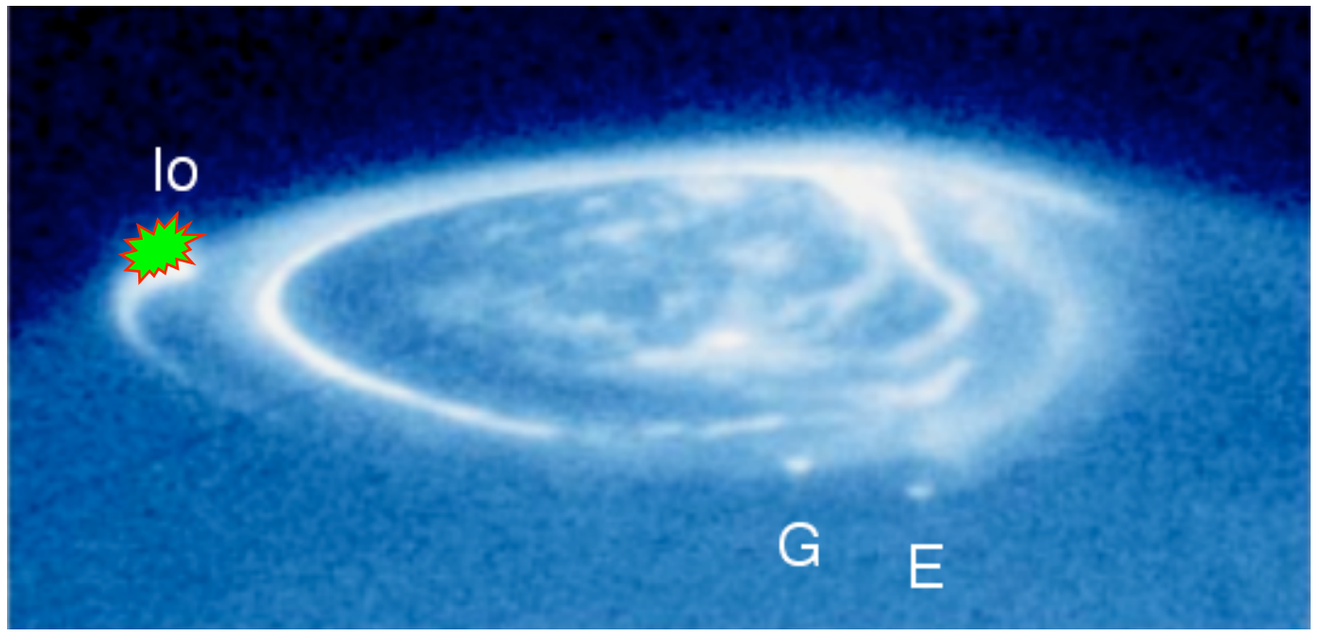

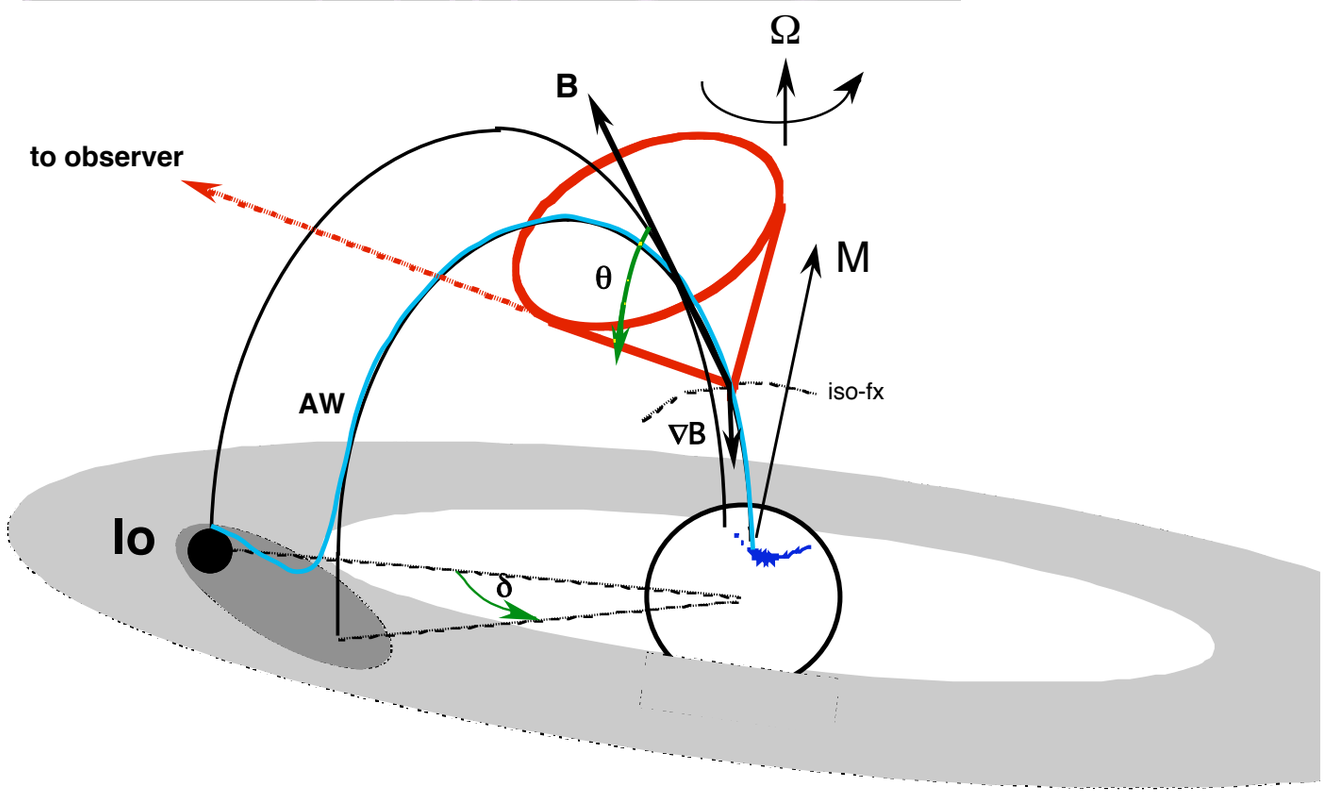

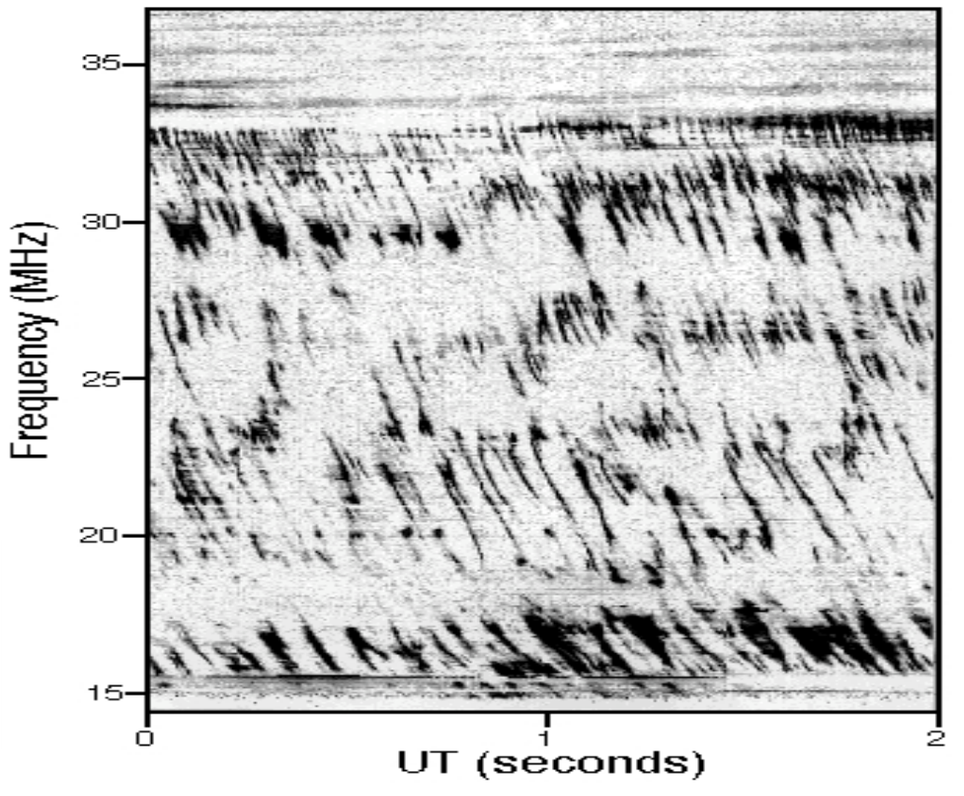

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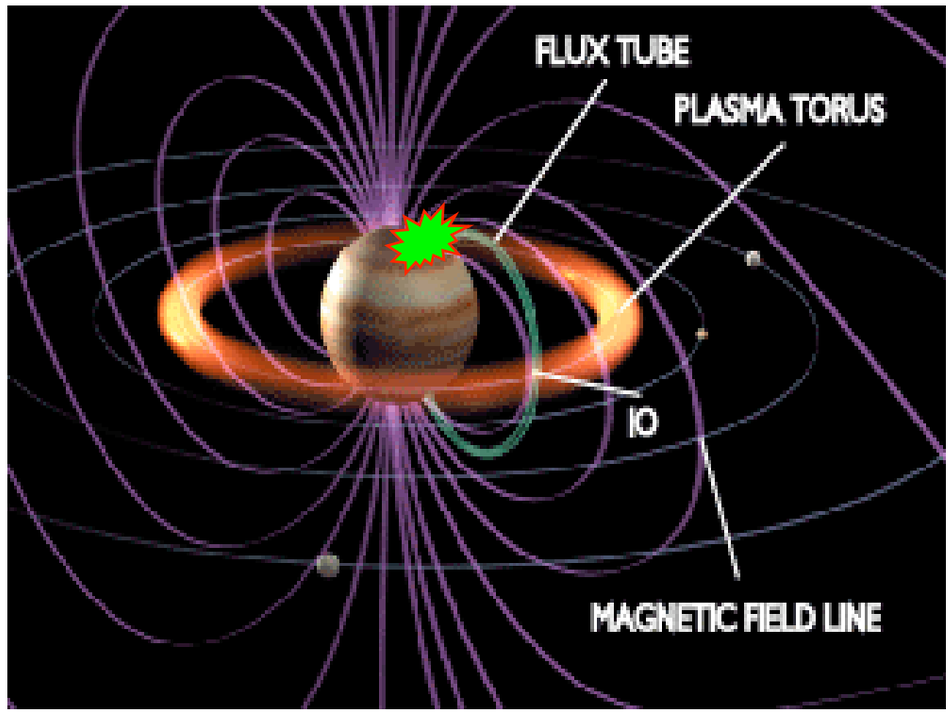

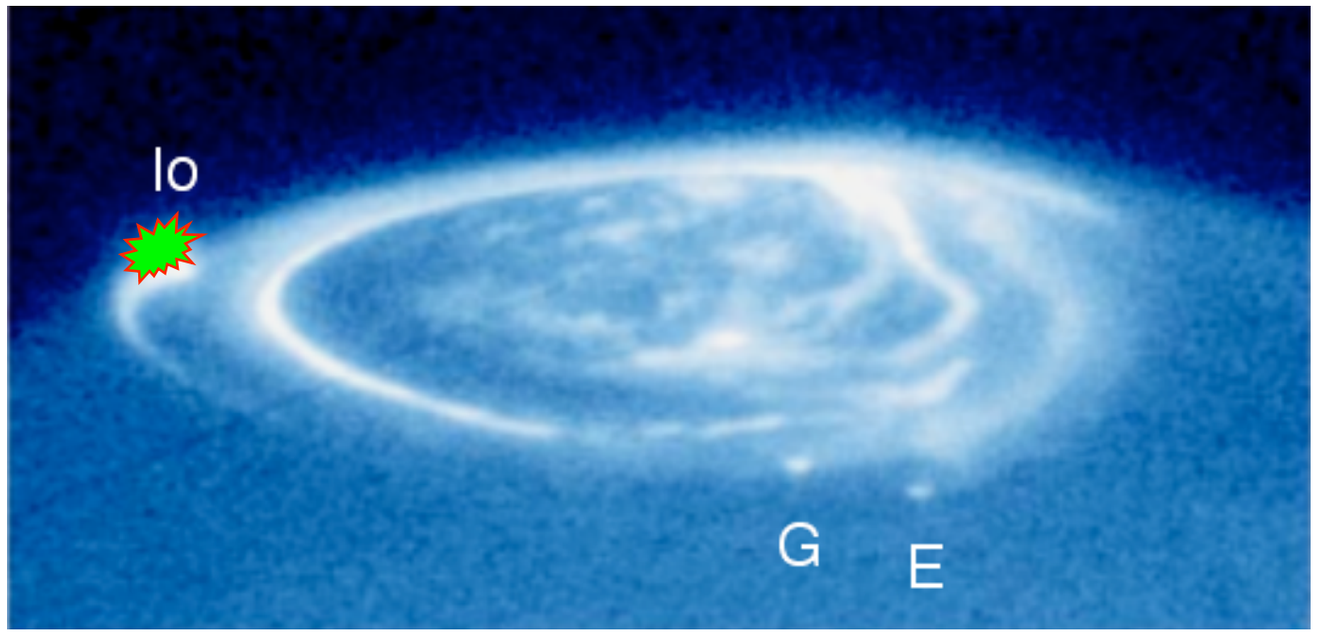

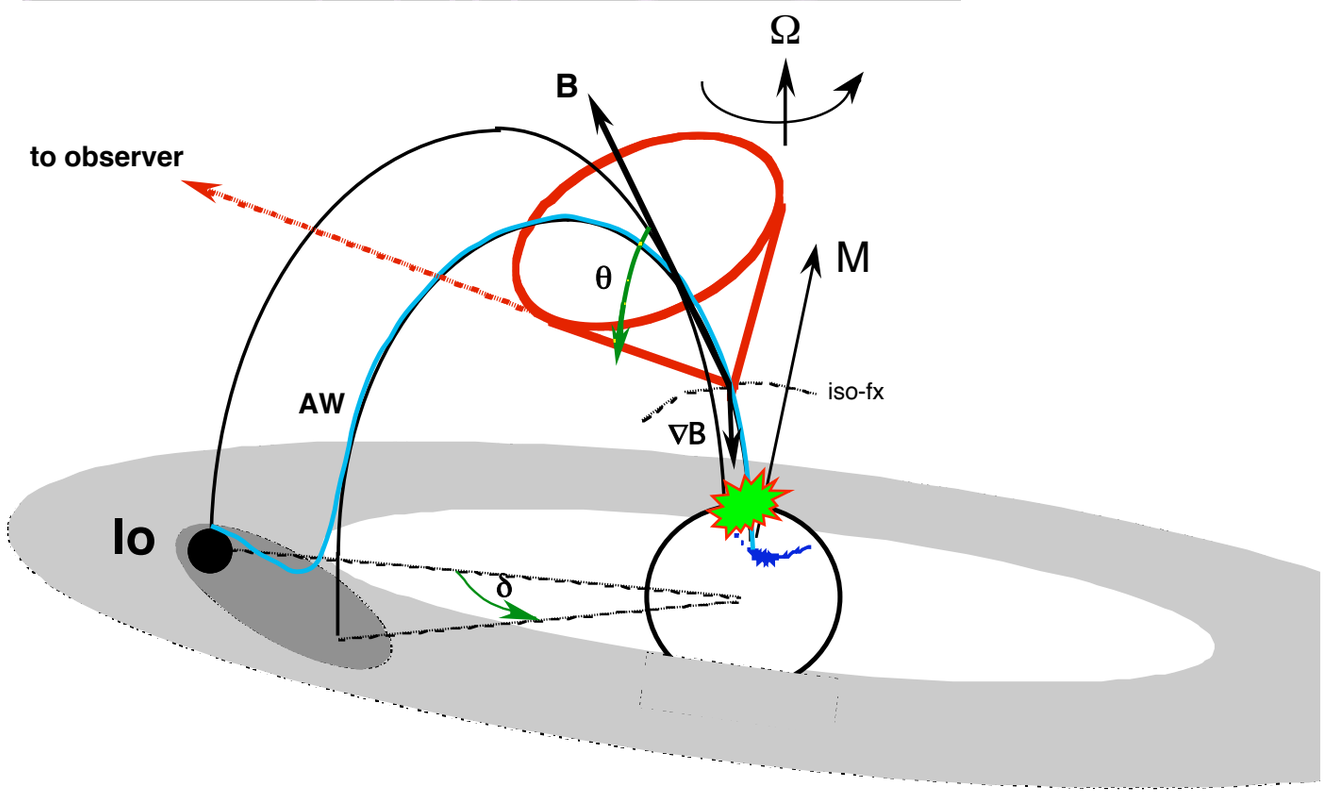

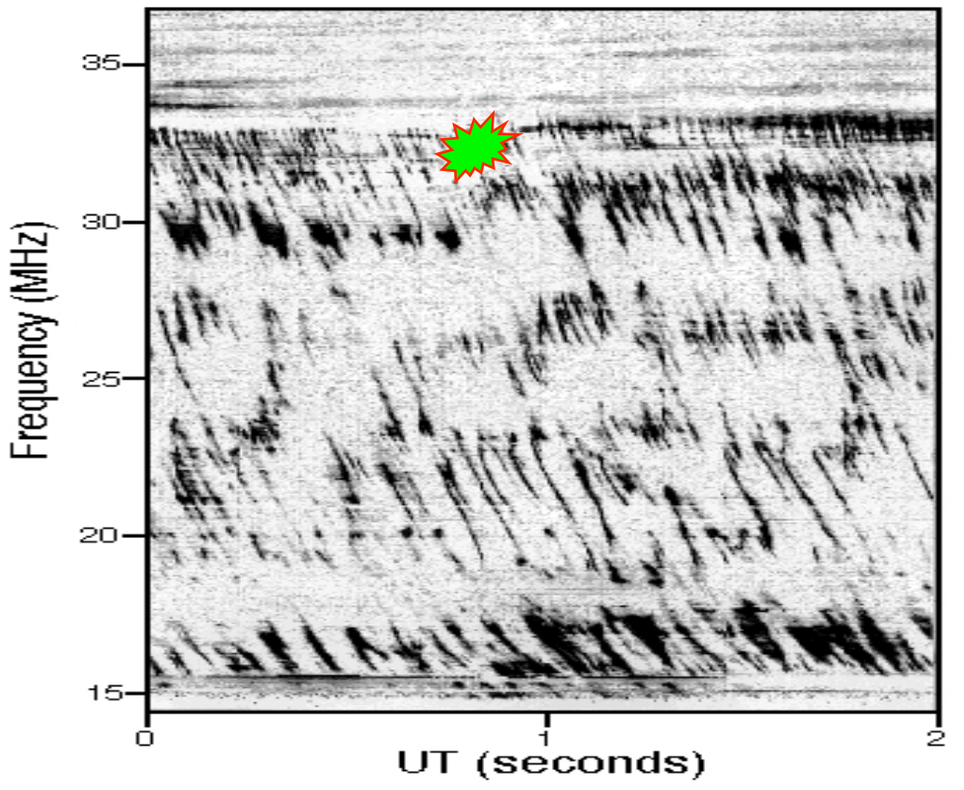

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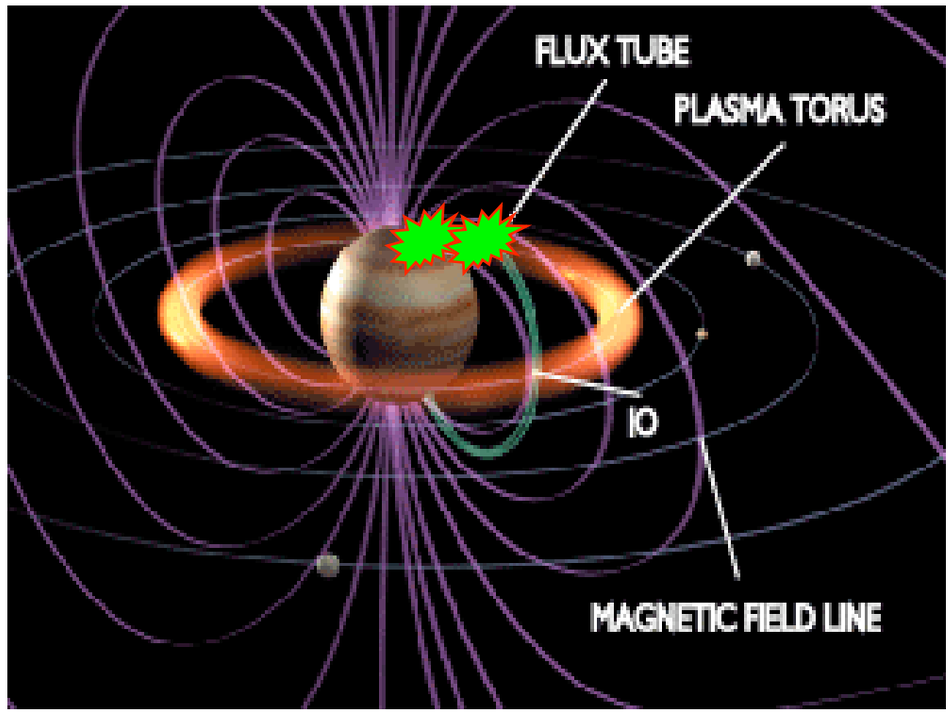

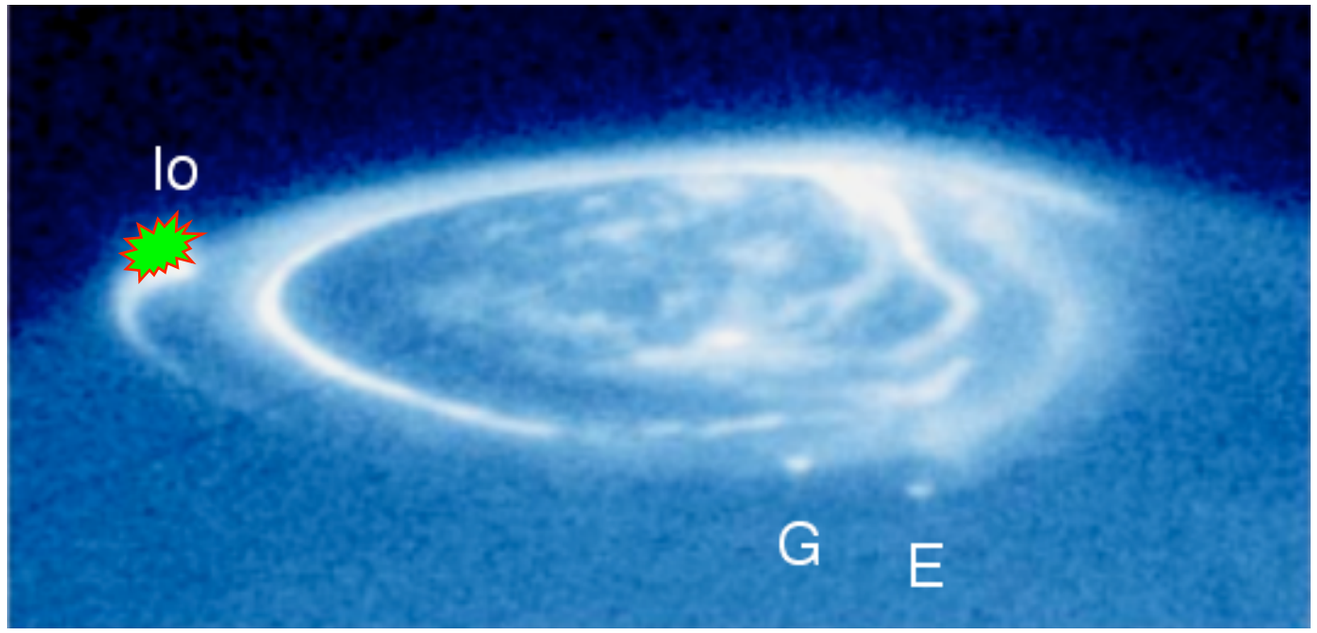

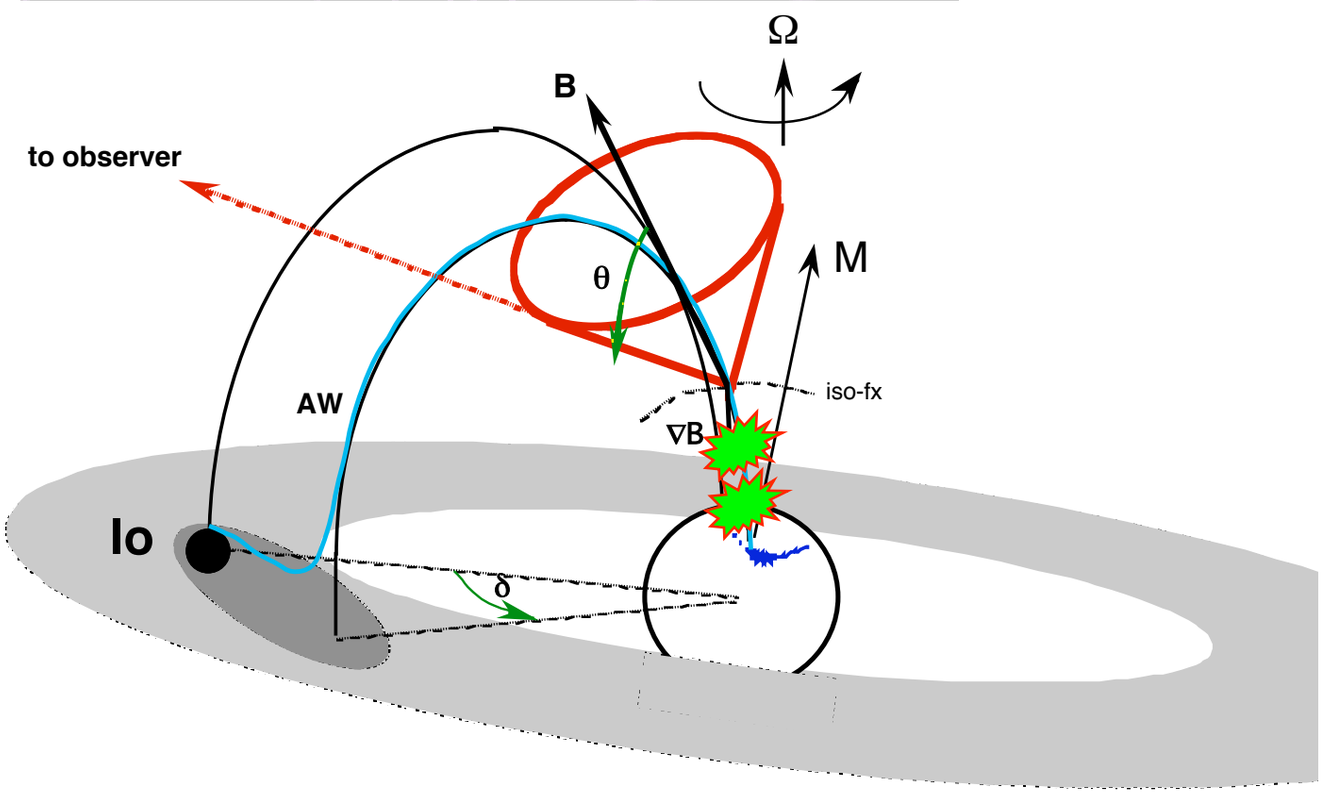

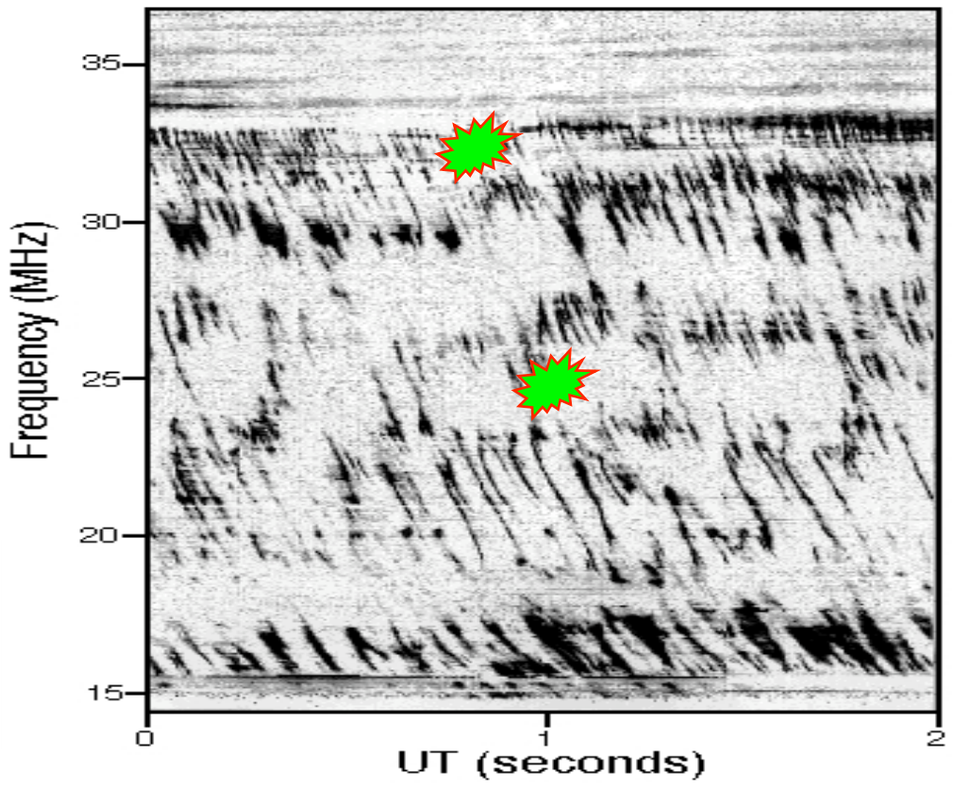

[Zarka, 2004]

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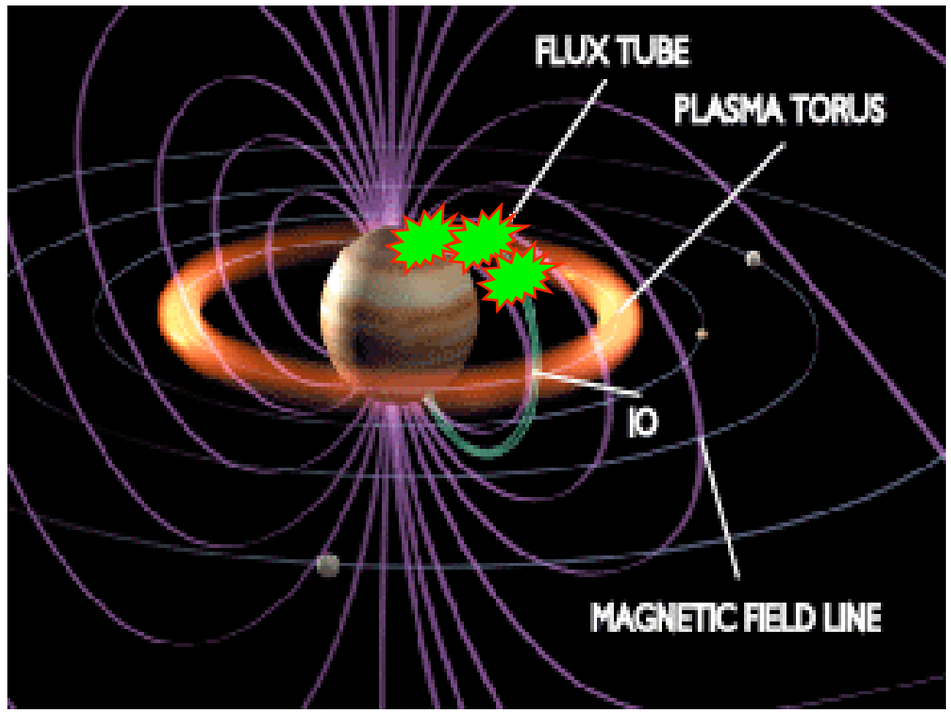

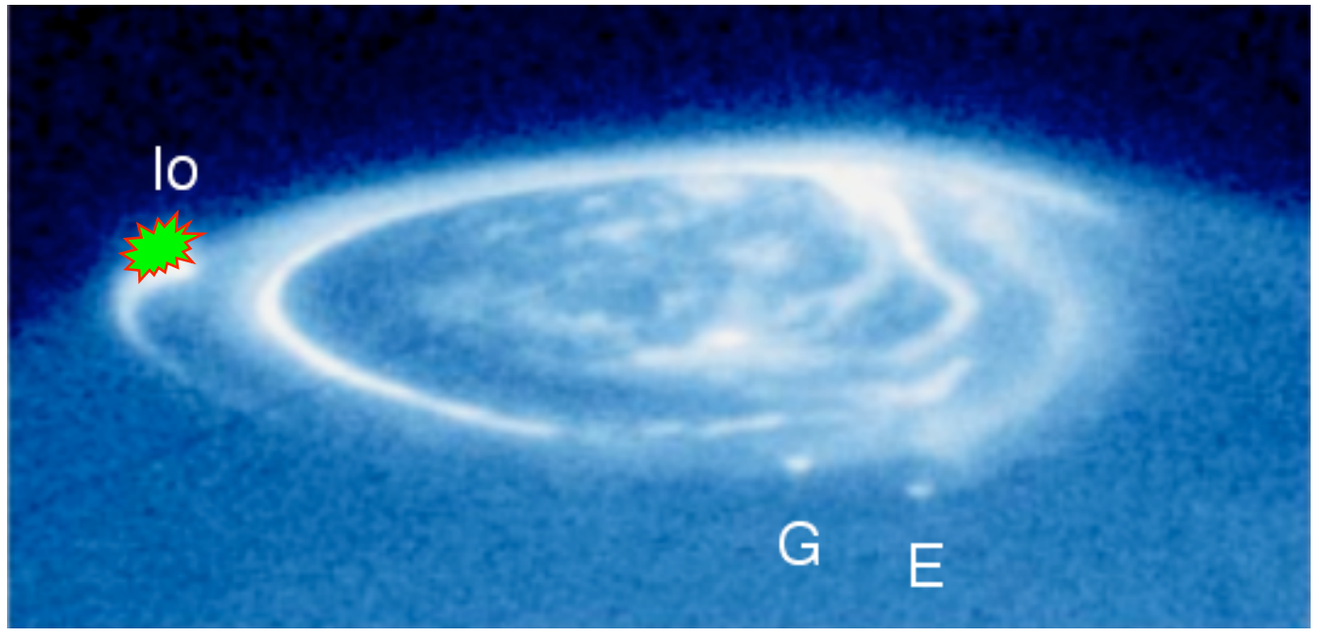

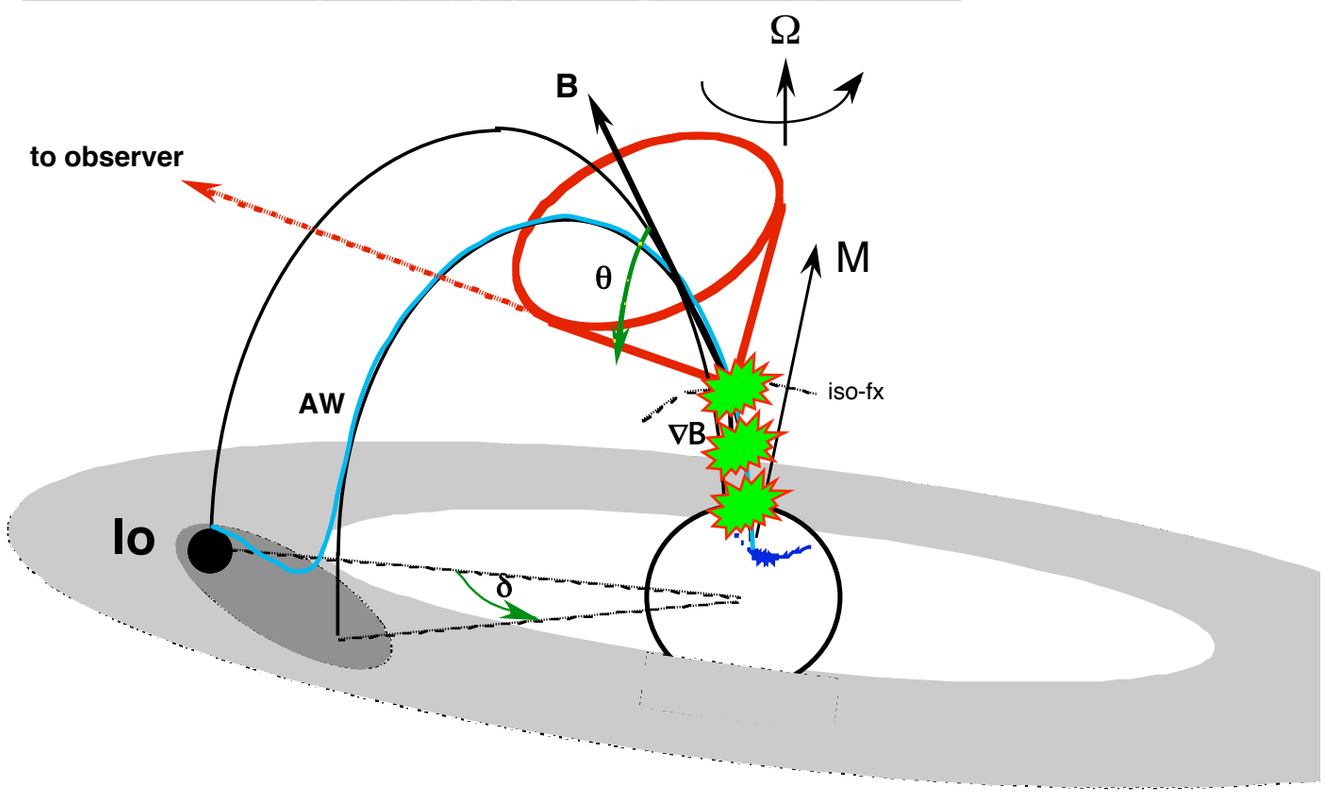

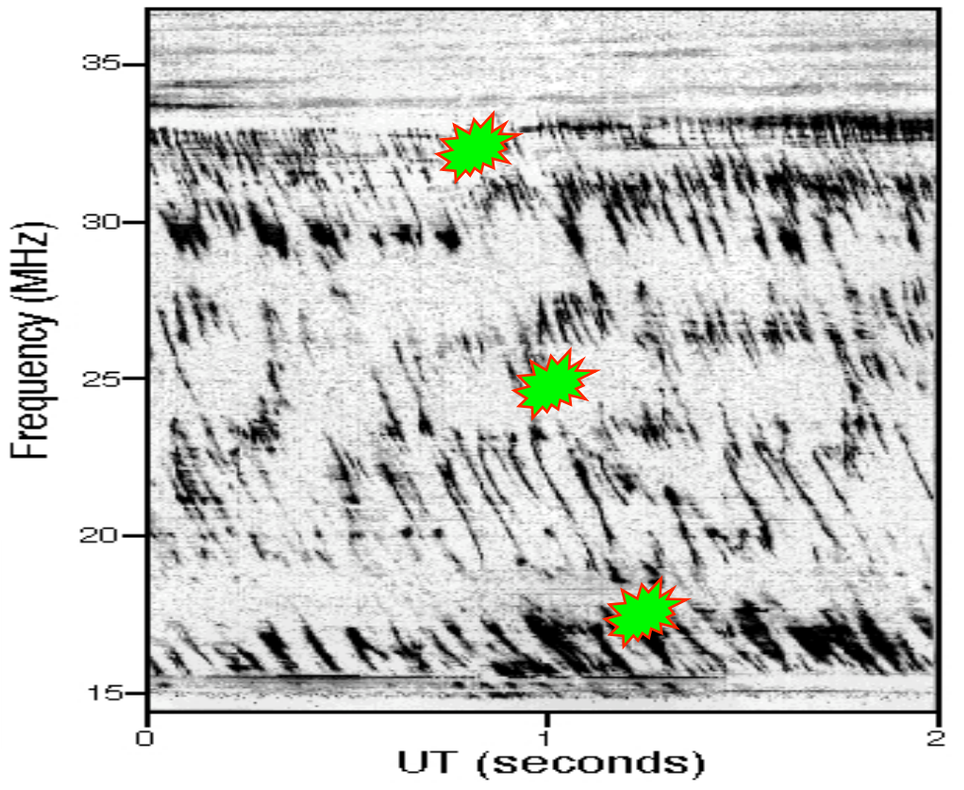

[Zarka, 2004]

Unipolar interaction

- Interaction via Alfvén waves & currents

(e.g. Io-Jupiter) $\phi = E \times 2R_{obs} = V \times B_{\perp} \times 2R_{obs}$

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

$\varepsilon' = (1+M_A^{-2})^{-1/2}$ $\qquad M_A \leq \varepsilon' \leq 1$

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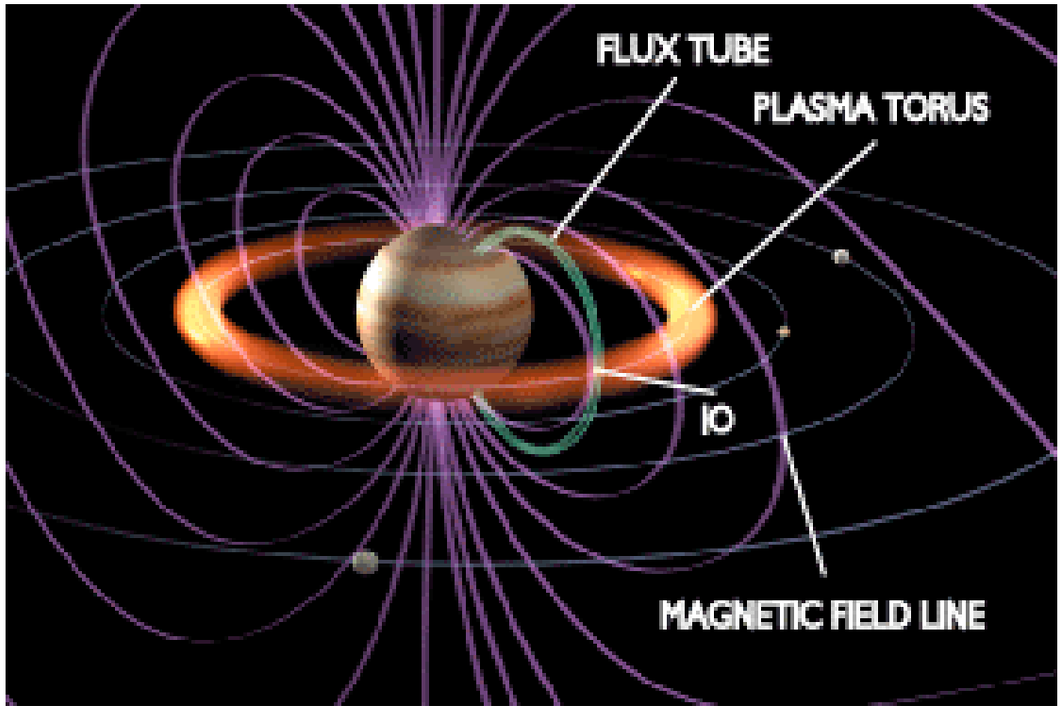

[Neubauer, 1980; Zarka et al., 2001]

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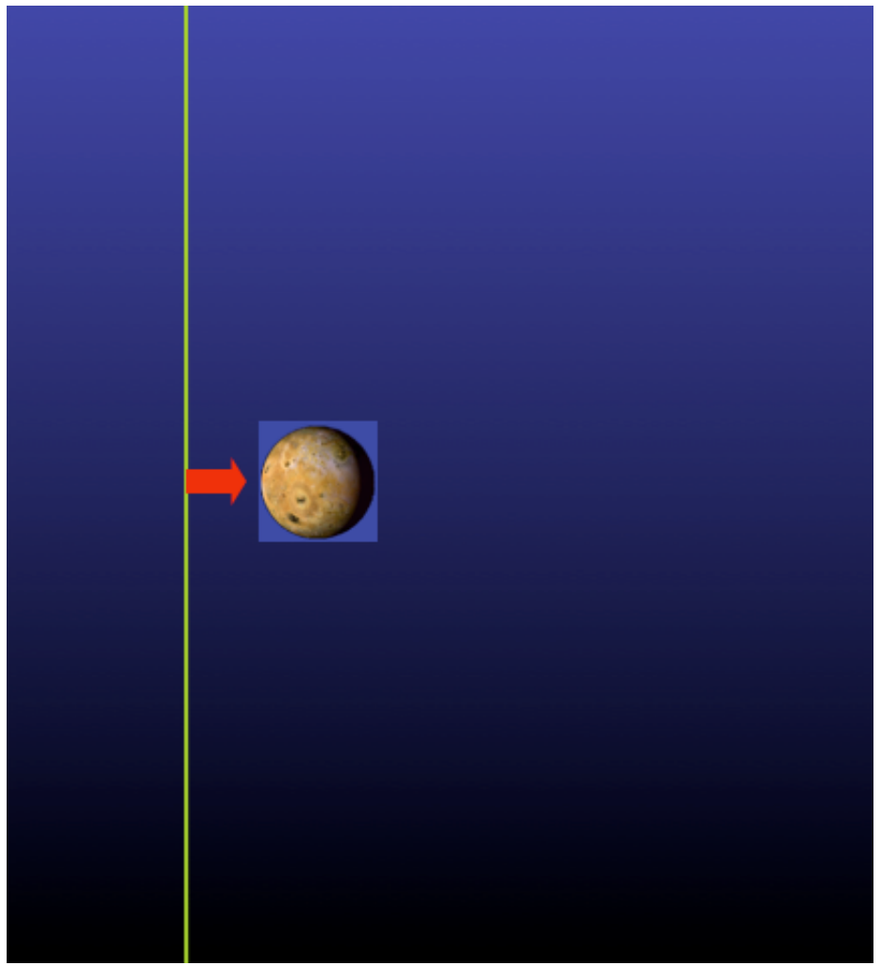

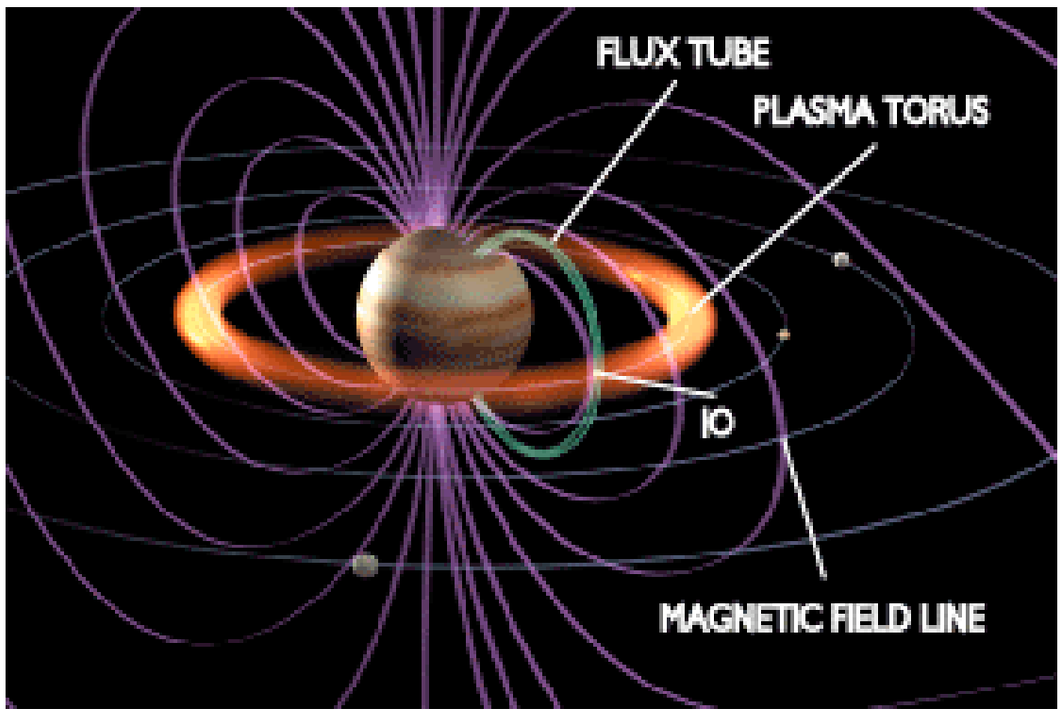

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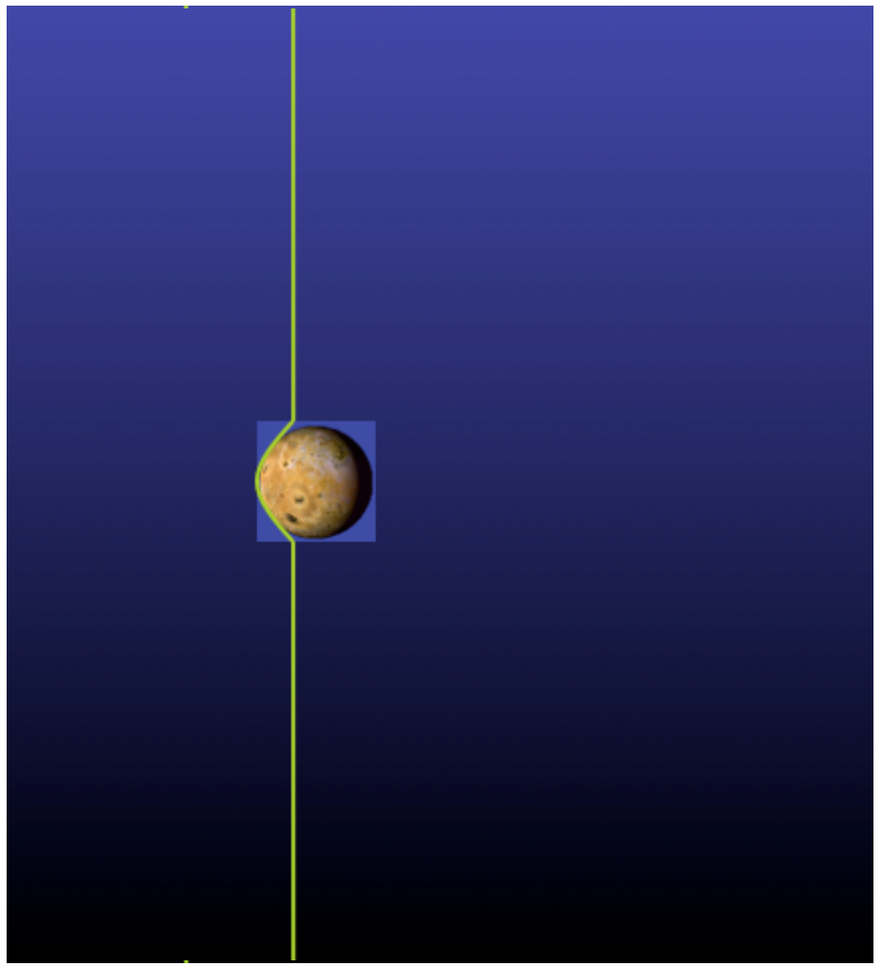

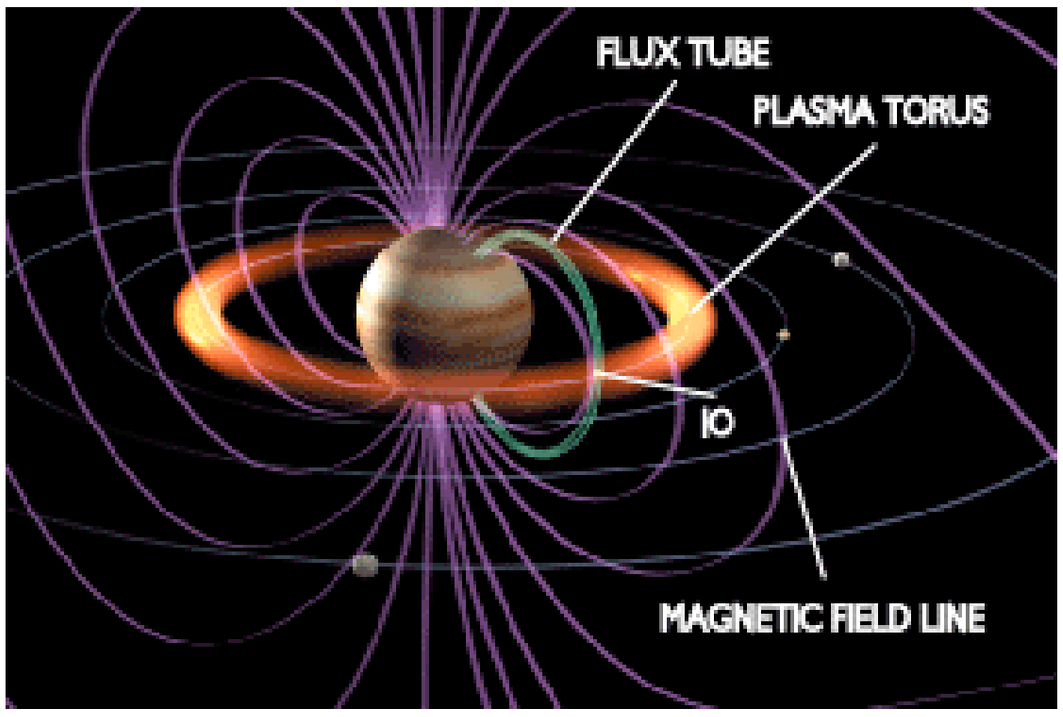

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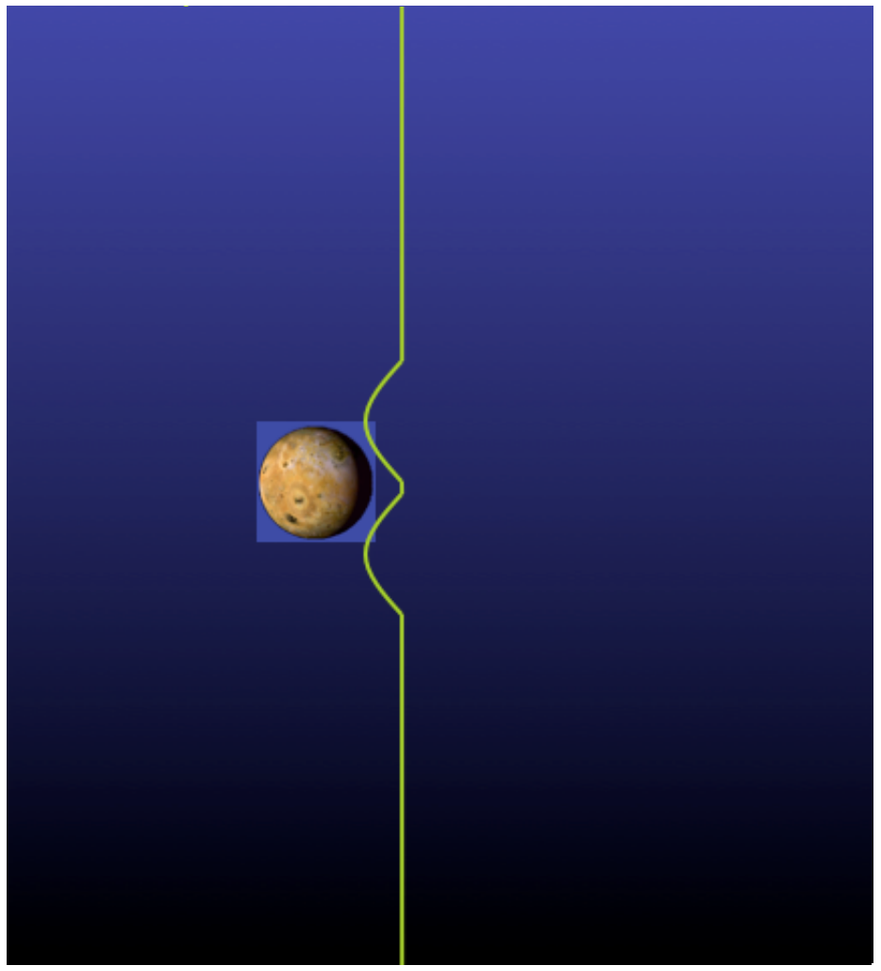

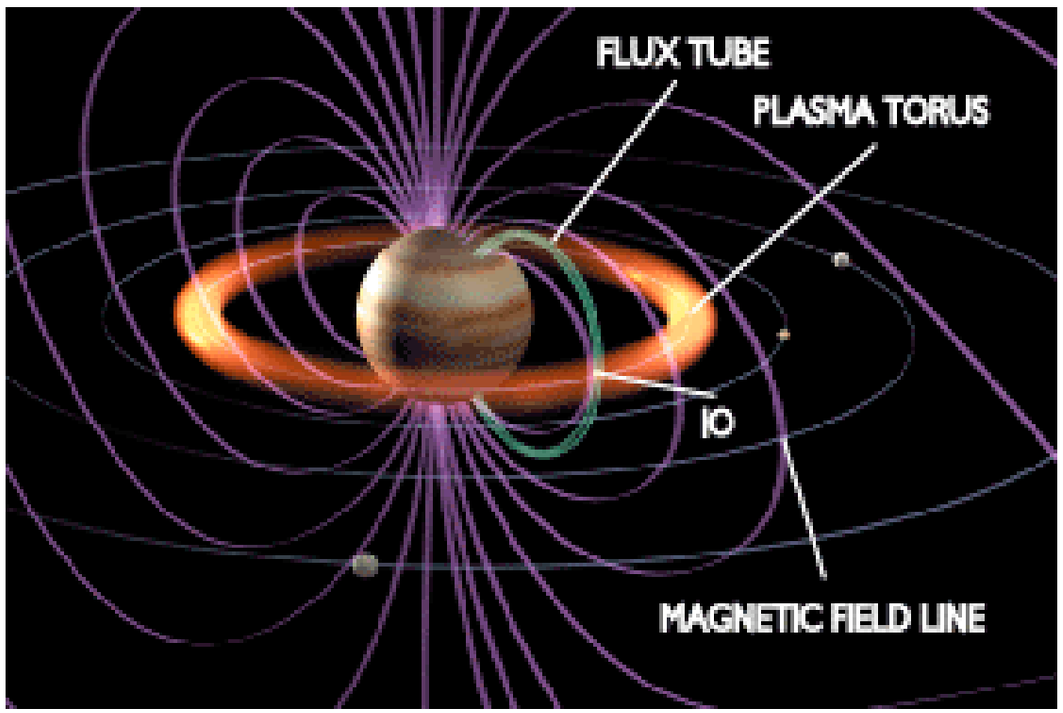

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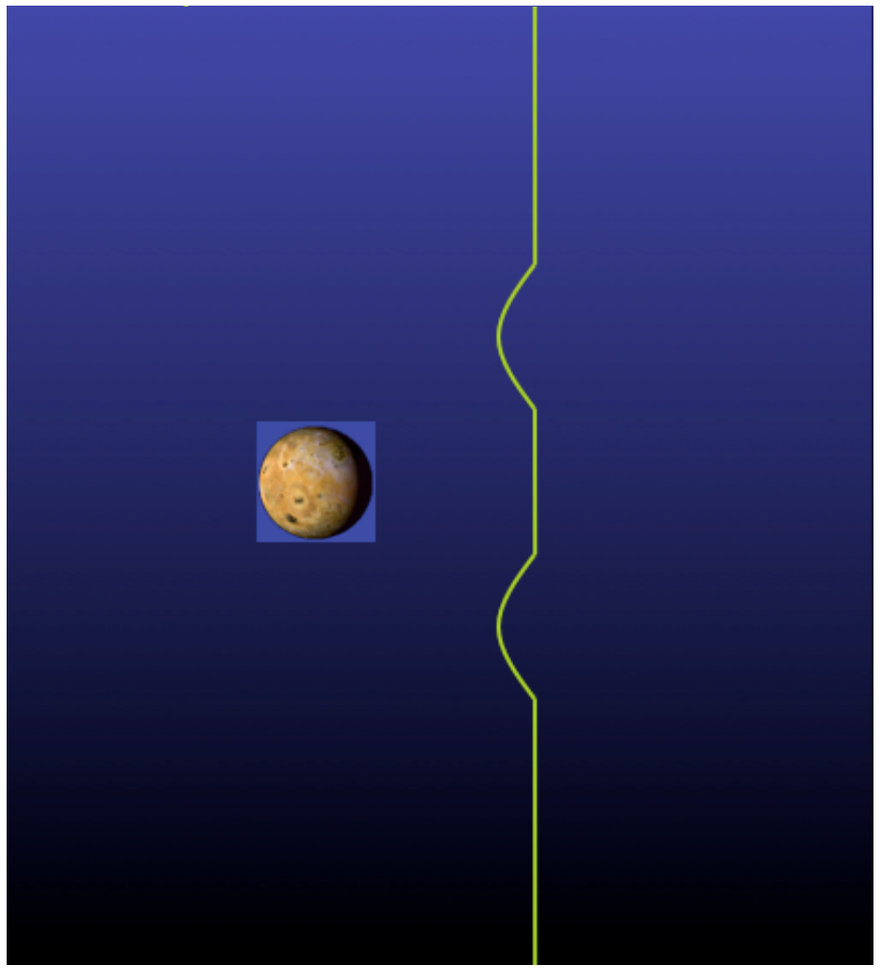

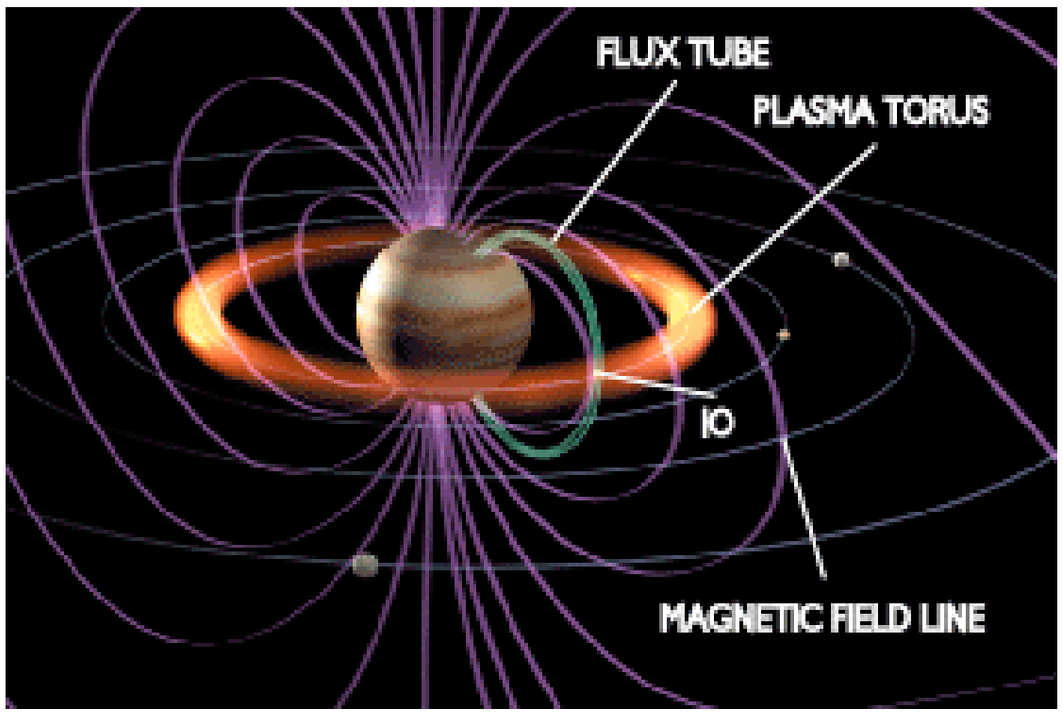

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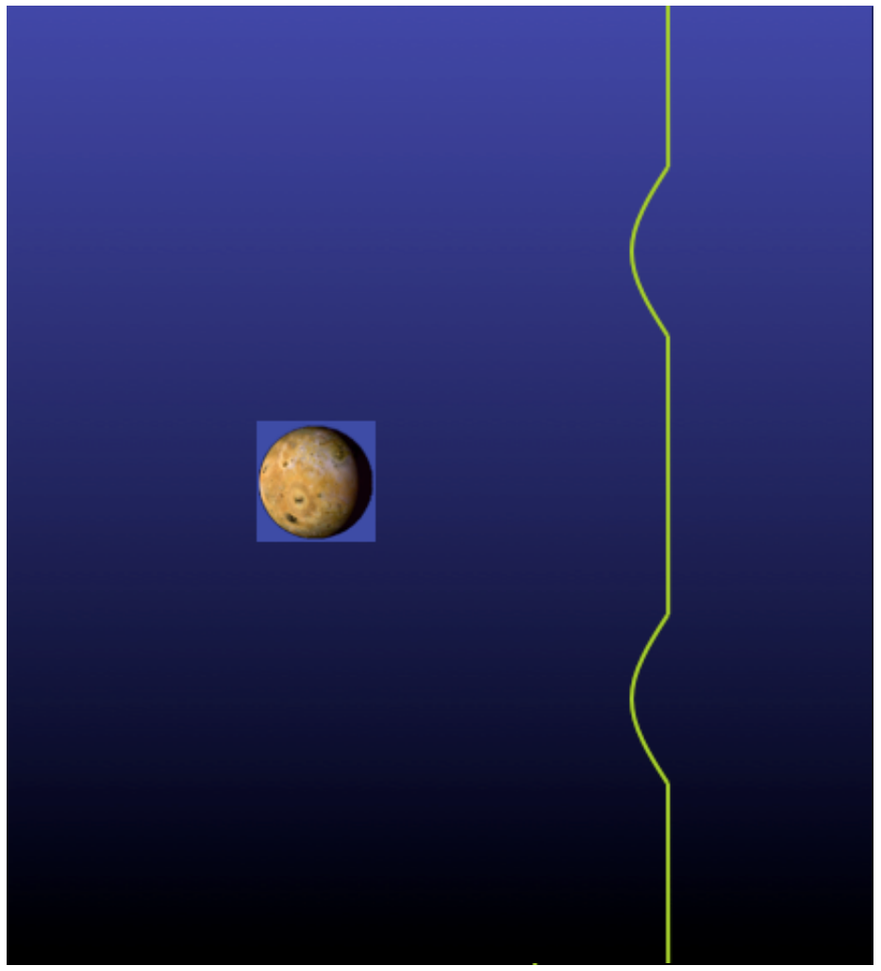

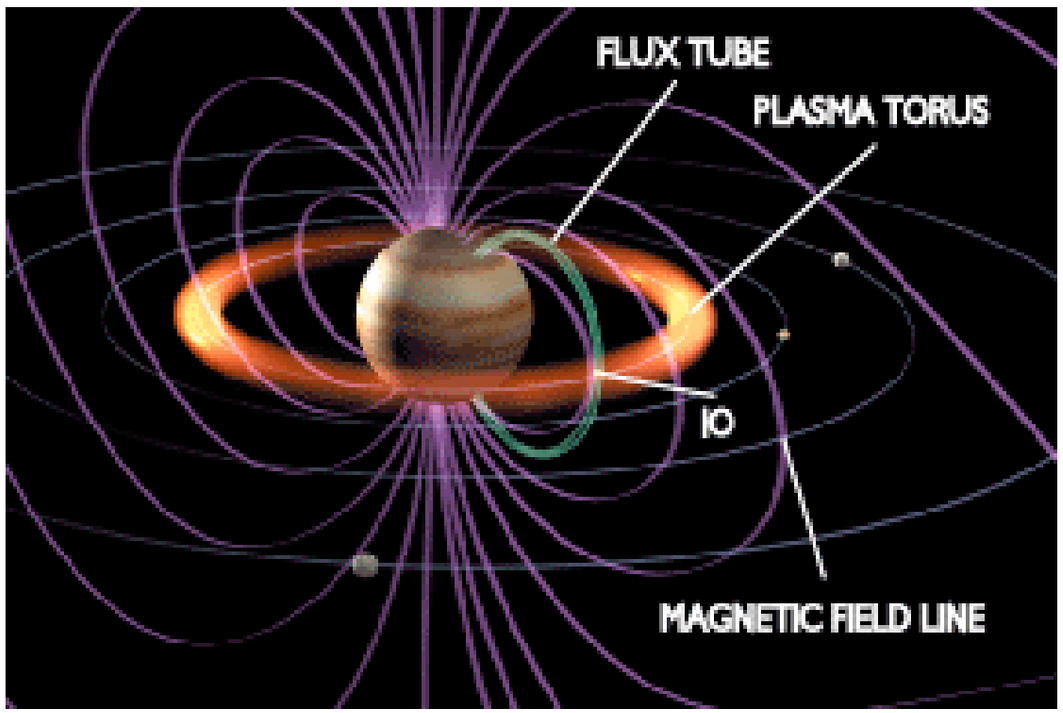

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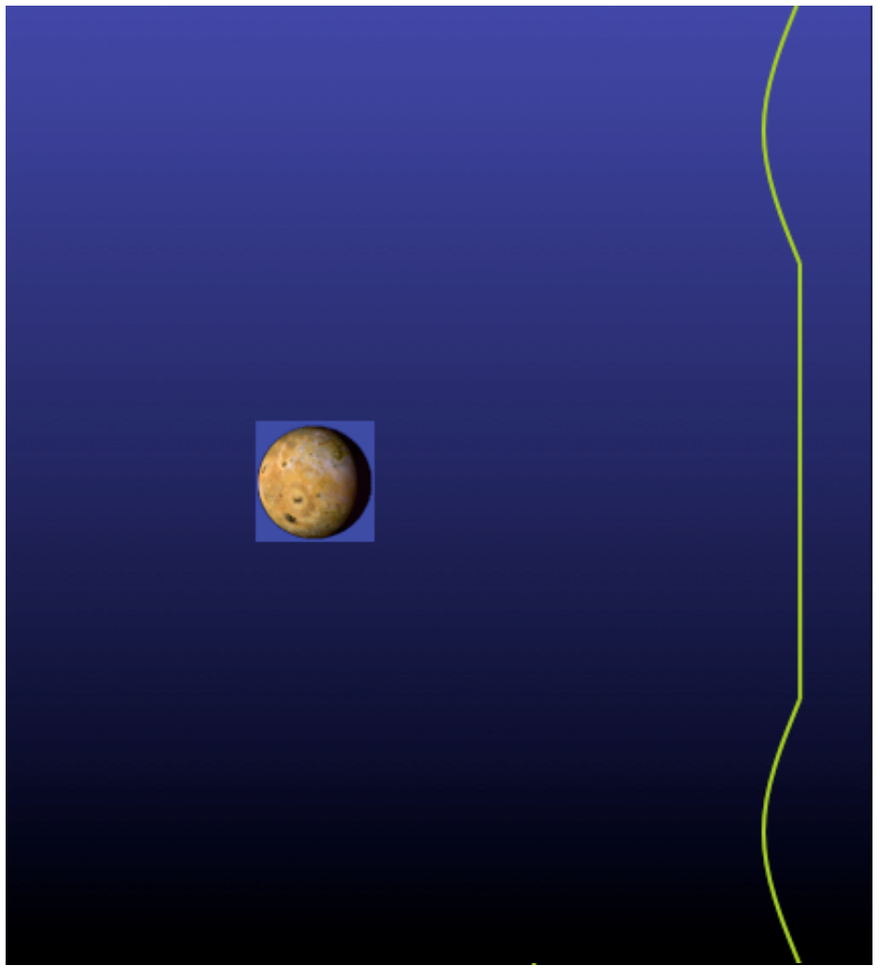

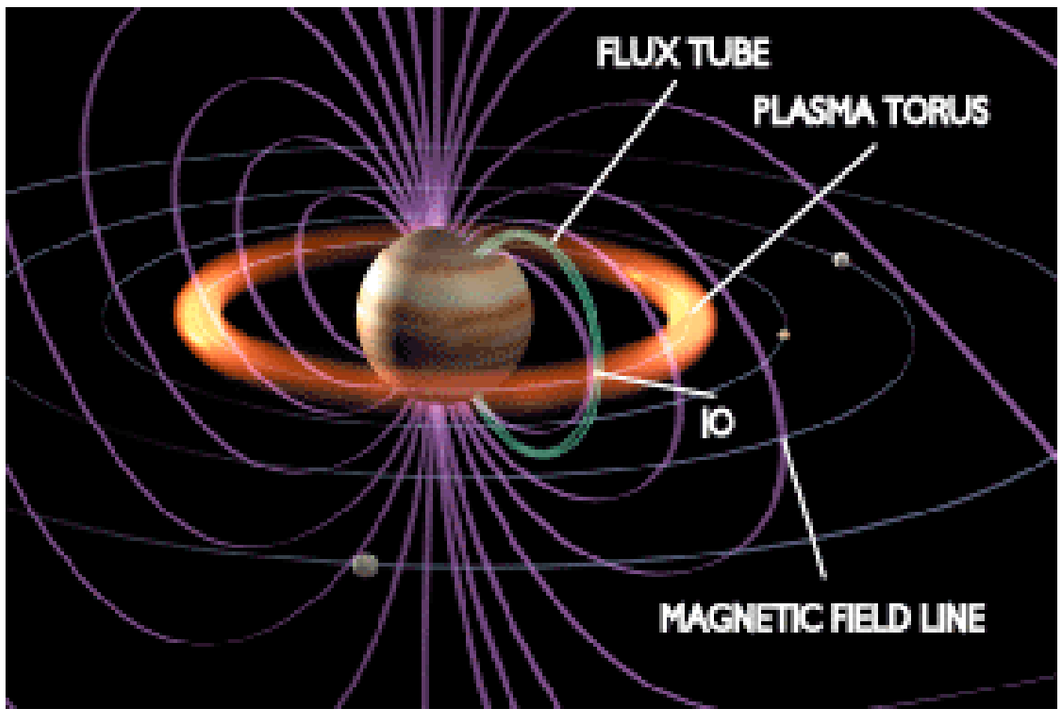

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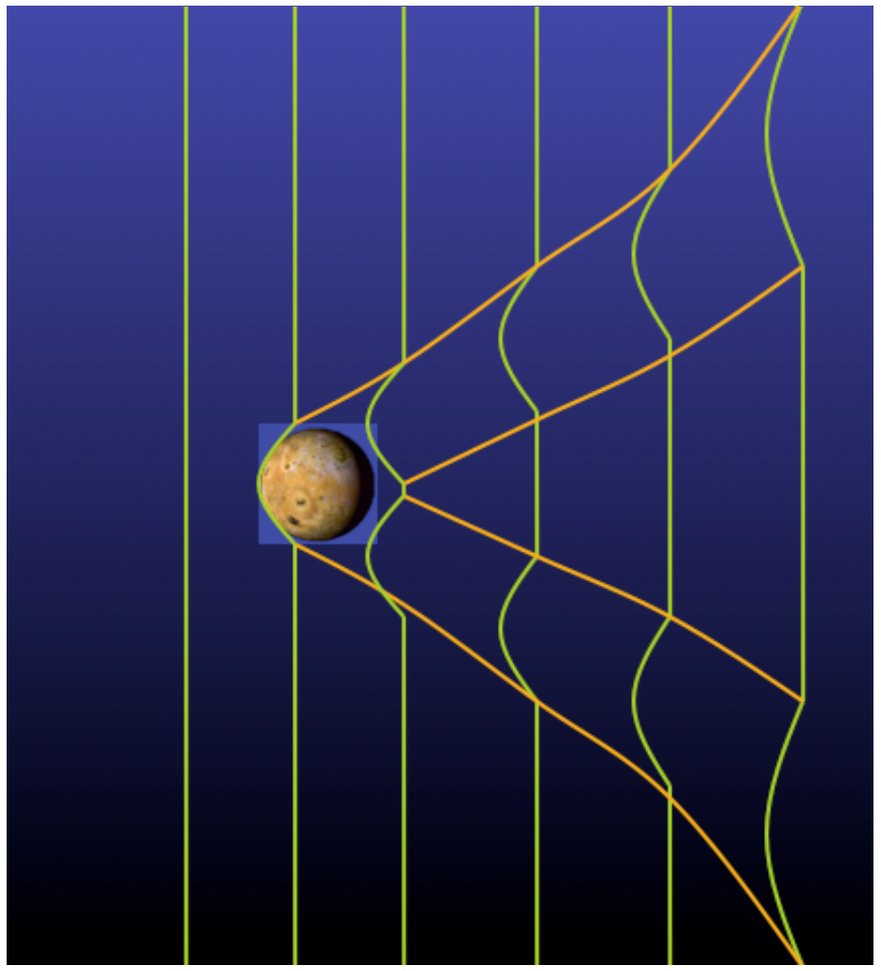

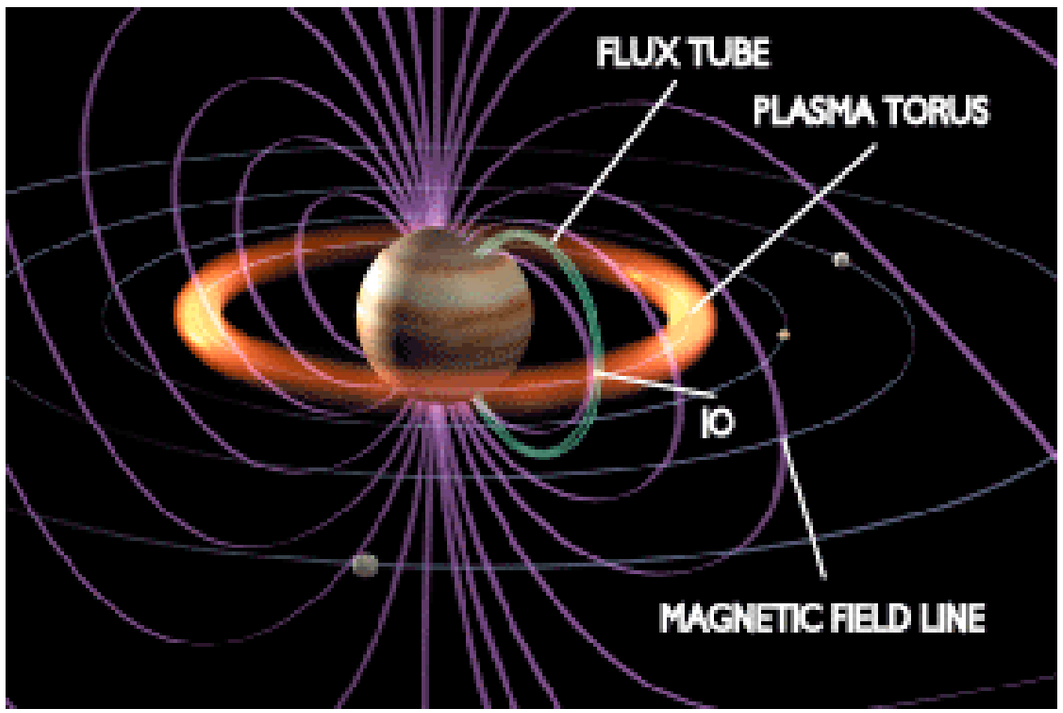

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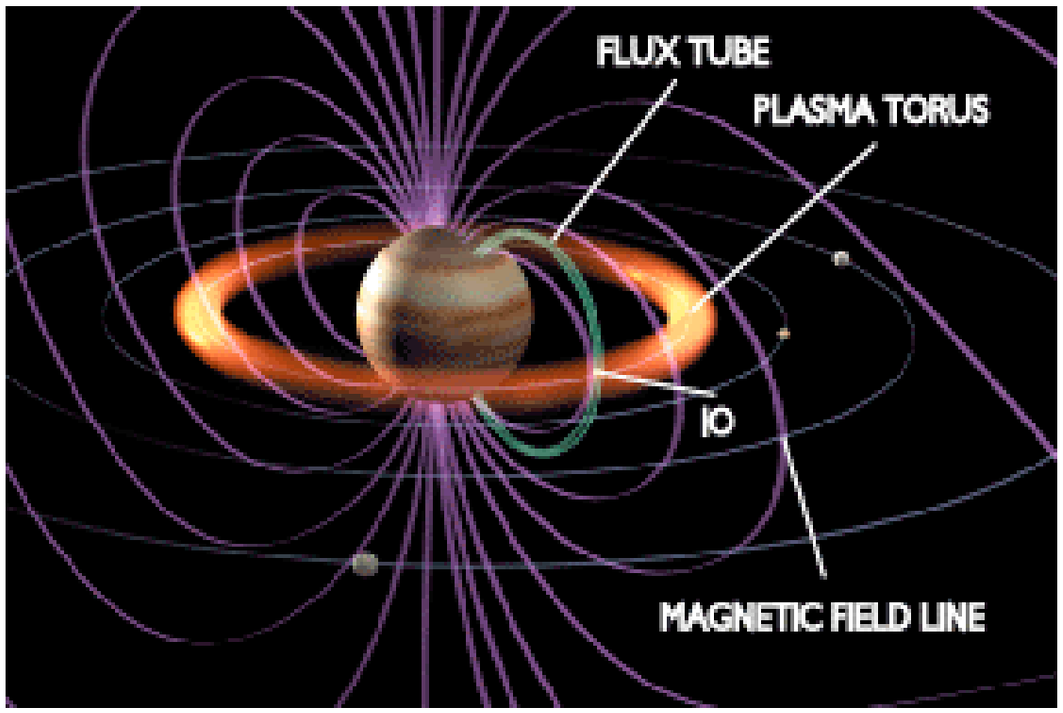

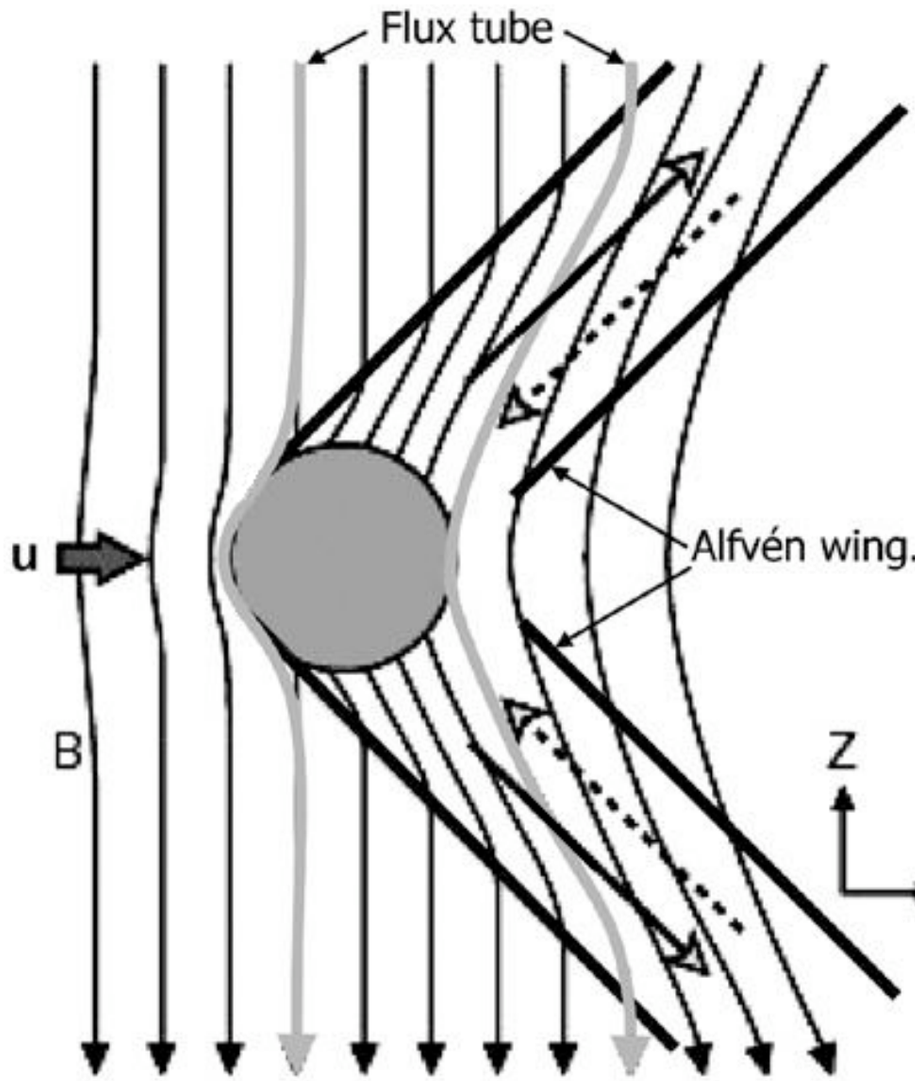

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Obstacle \ Flow	Weakly/Not magnetized *(Solar wind)*	Strongly magnetized *(Jovian magnetosphere)*
Weakly/Not magnetized *(Venus, Mars, Io)*	No Intense Cyclotron Radio Emission	<u>Unipolar interaction</u> → Io-induced Radio Emission,
Strongly magnetized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

[Zarka, 2007]

Dipolar interaction

- Magnetic reconnection

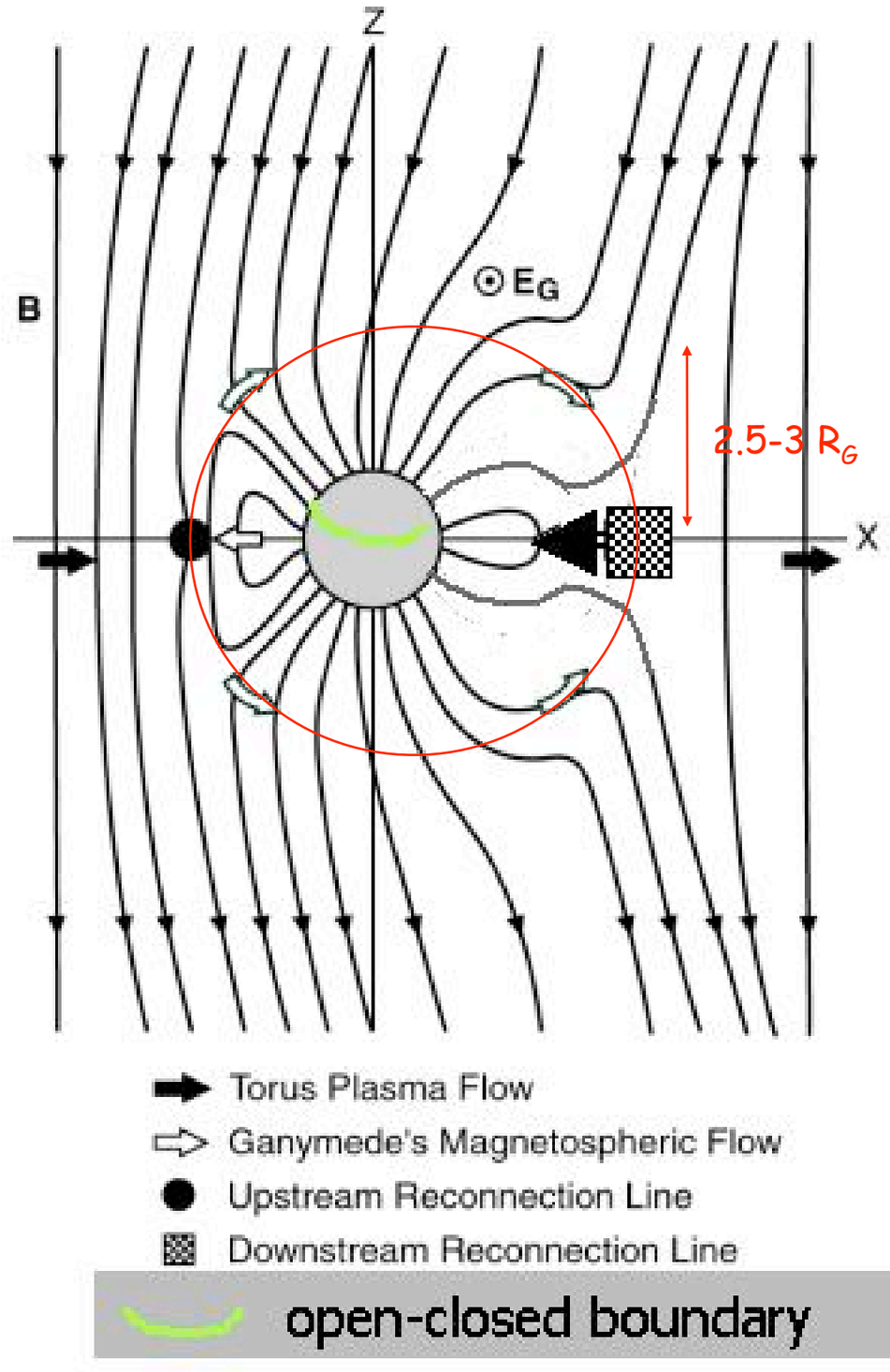
  (e.g. Ganymede-Jupiter)

$P_d = \varepsilon\ K\ VB_\perp^2/\mu_o\ \pi R_{MP}^2$

Efficiency $\varepsilon \sim 0.1\text{–}0.2$

$K = \sin^4(\theta/2)$ ou $\cos^4(\theta/2)$

→ $P_d = \varepsilon\ P_B$



[Ip et al., 2004]

[Kivelson et al., 1997]

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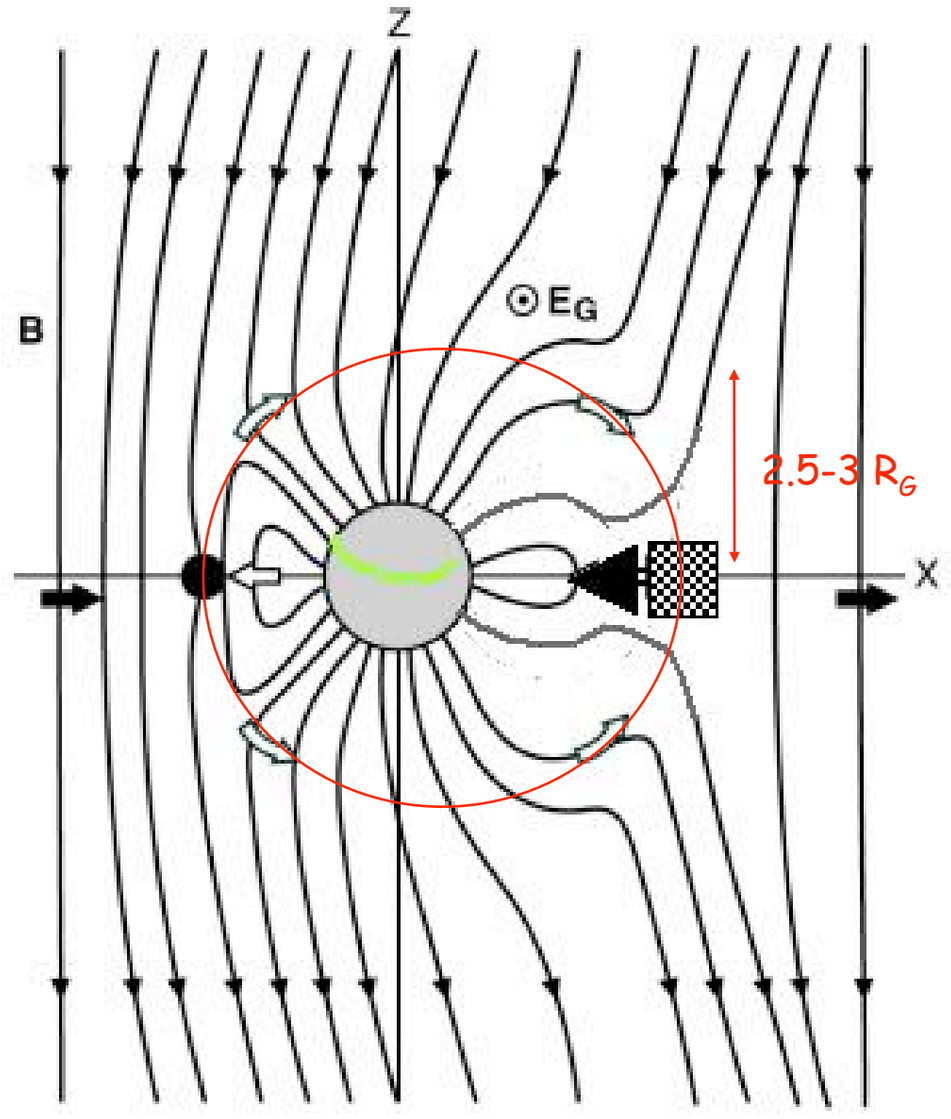
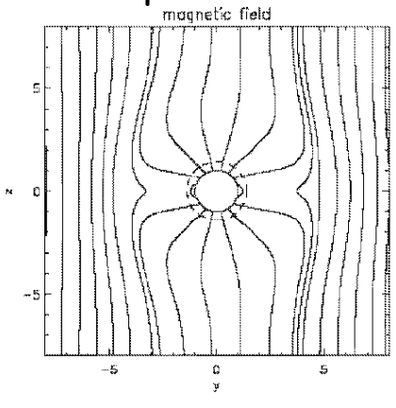
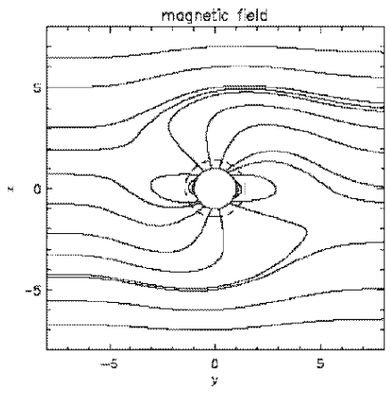


[Kivelson et al., 1997]

Open



Radial B



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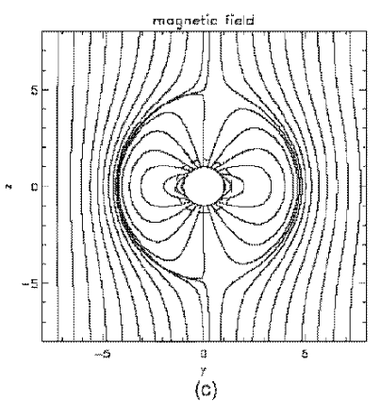

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[Zarka, 2007]

- Low-frequency radio observations of exoplanets

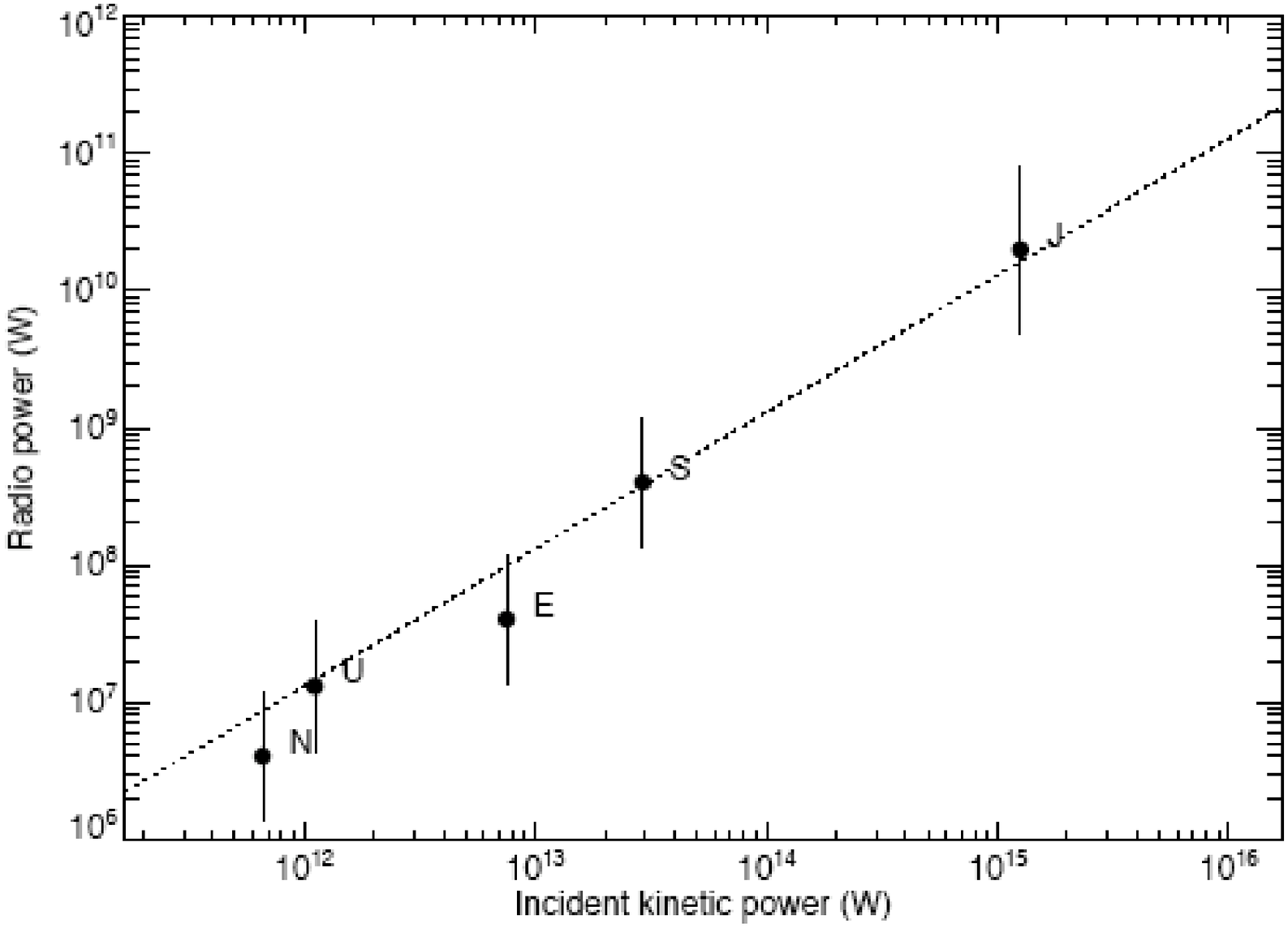
- Theoretical predictions
  - planetary radio emissions
  - energy sources
  - scaling laws
  - extrapolation to exoplanets

- Ongoing observations

- Future observations

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

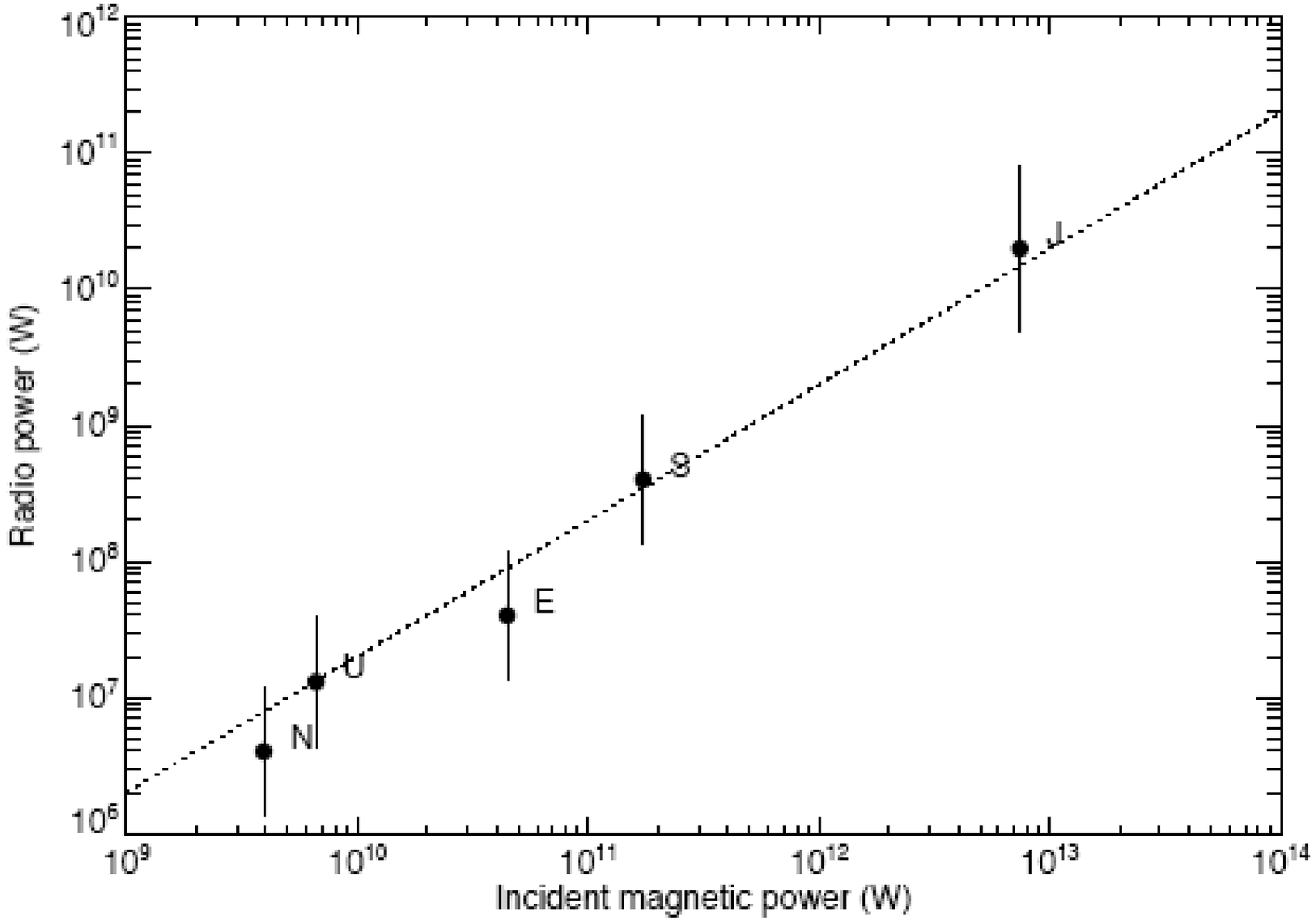
$P_{Radio} \sim \eta_1 \times P_C$ with $\eta_1 \sim 10^{-5}$



[Desch and Kaiser, 1984 ; Zarka, 1992]

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

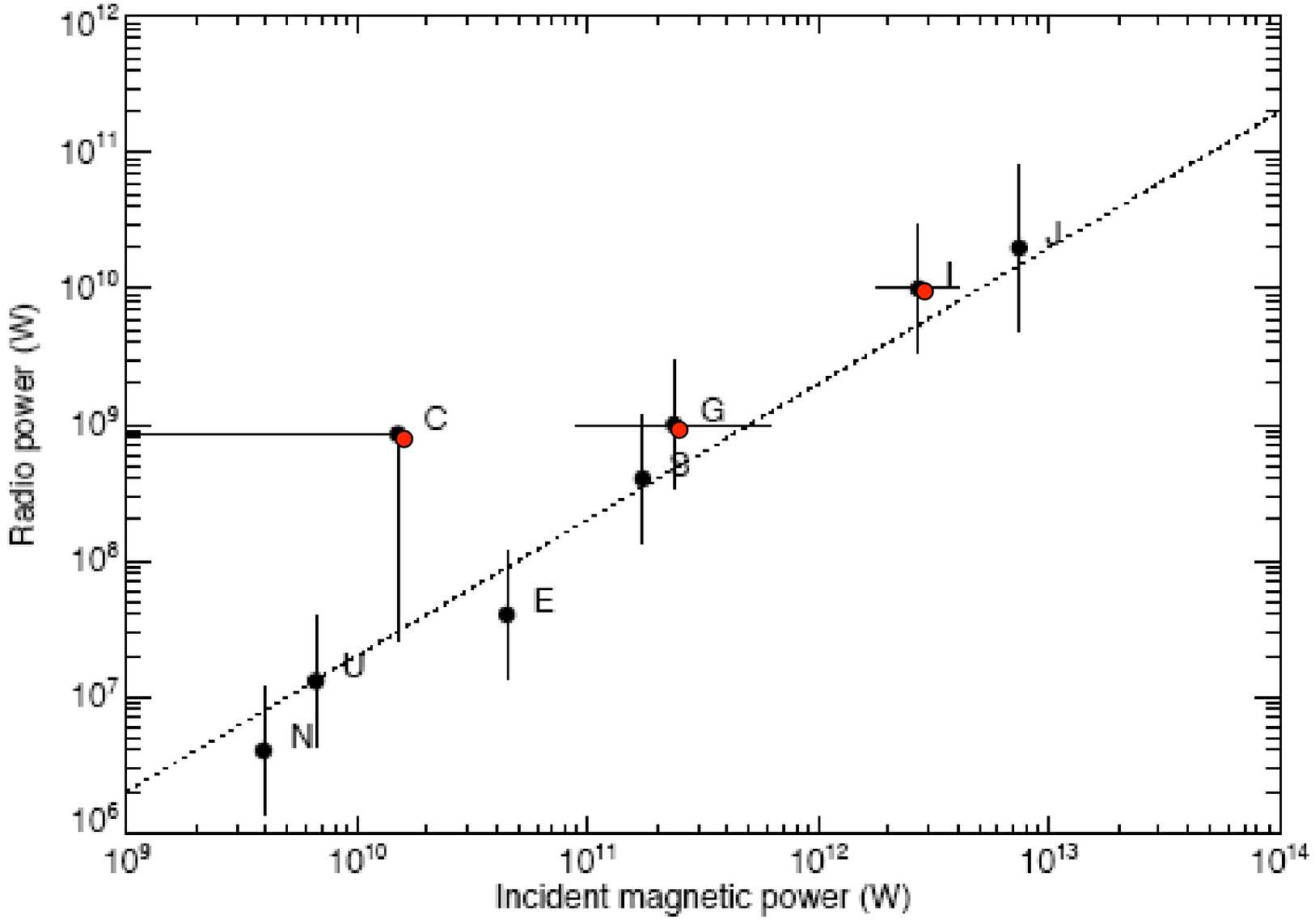
$P_{Radio} \sim \eta_2 \times P_B$ with $\eta_2 \sim 2\times10^{-3}$



[Zarka et al., 2001]

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

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



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Planet & Star data

~330 exoplanets (in ~260 systems)

exoplanet.eu

60 with $a \leq 0.05$ AU = 10 Rs (18%)

93 with $a \leq 0.1$ AU (28%)

→ >50 « hot Jupiters » with periastron @ ~5-10 R_S

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Magnetic field at Solar surface :

→ large-scale ~1 G (10^{-4} T)

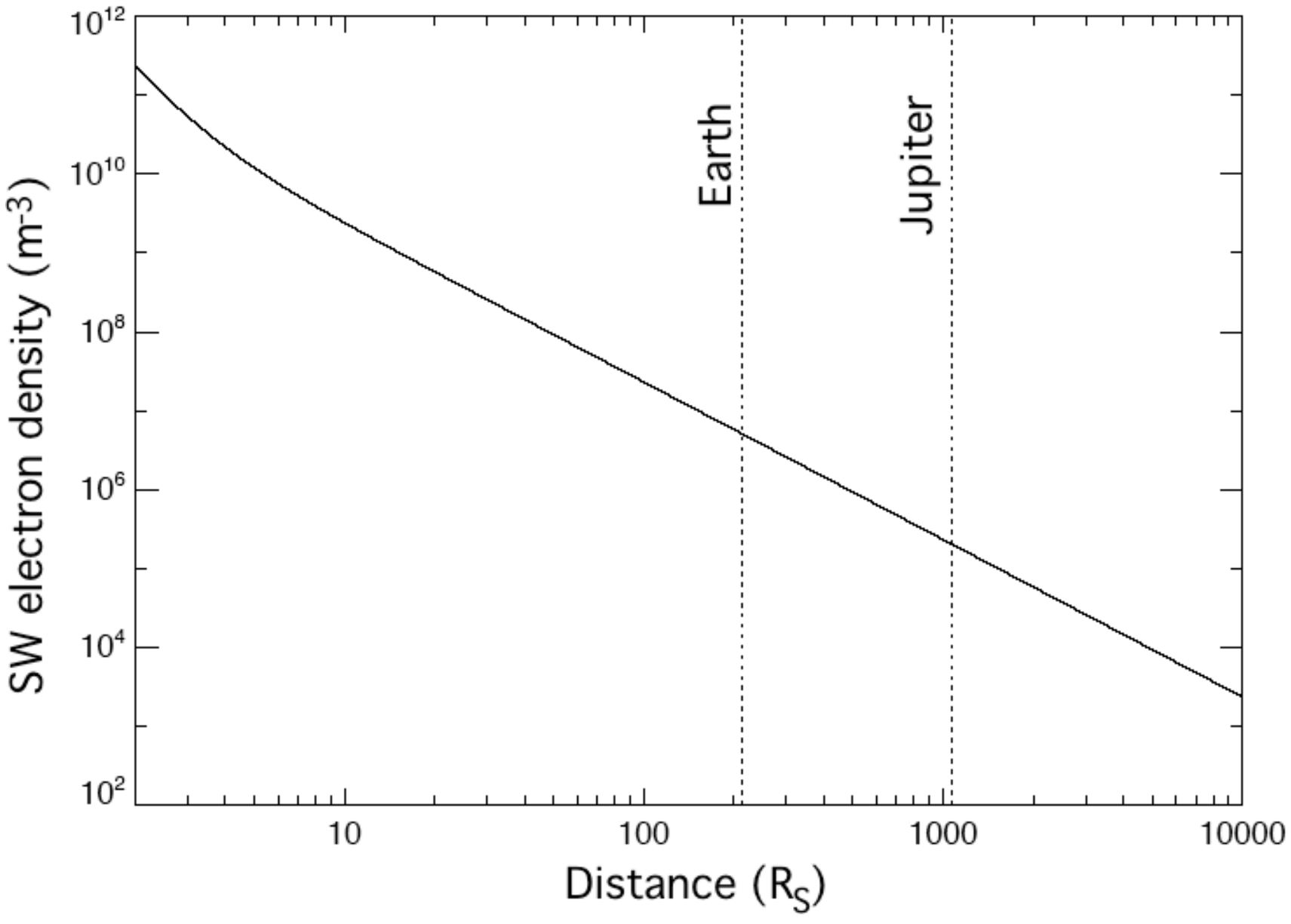
→ magnetic loops ~10^3 G,

over a few % of the surface

Magnetic stars : > 10^3 G

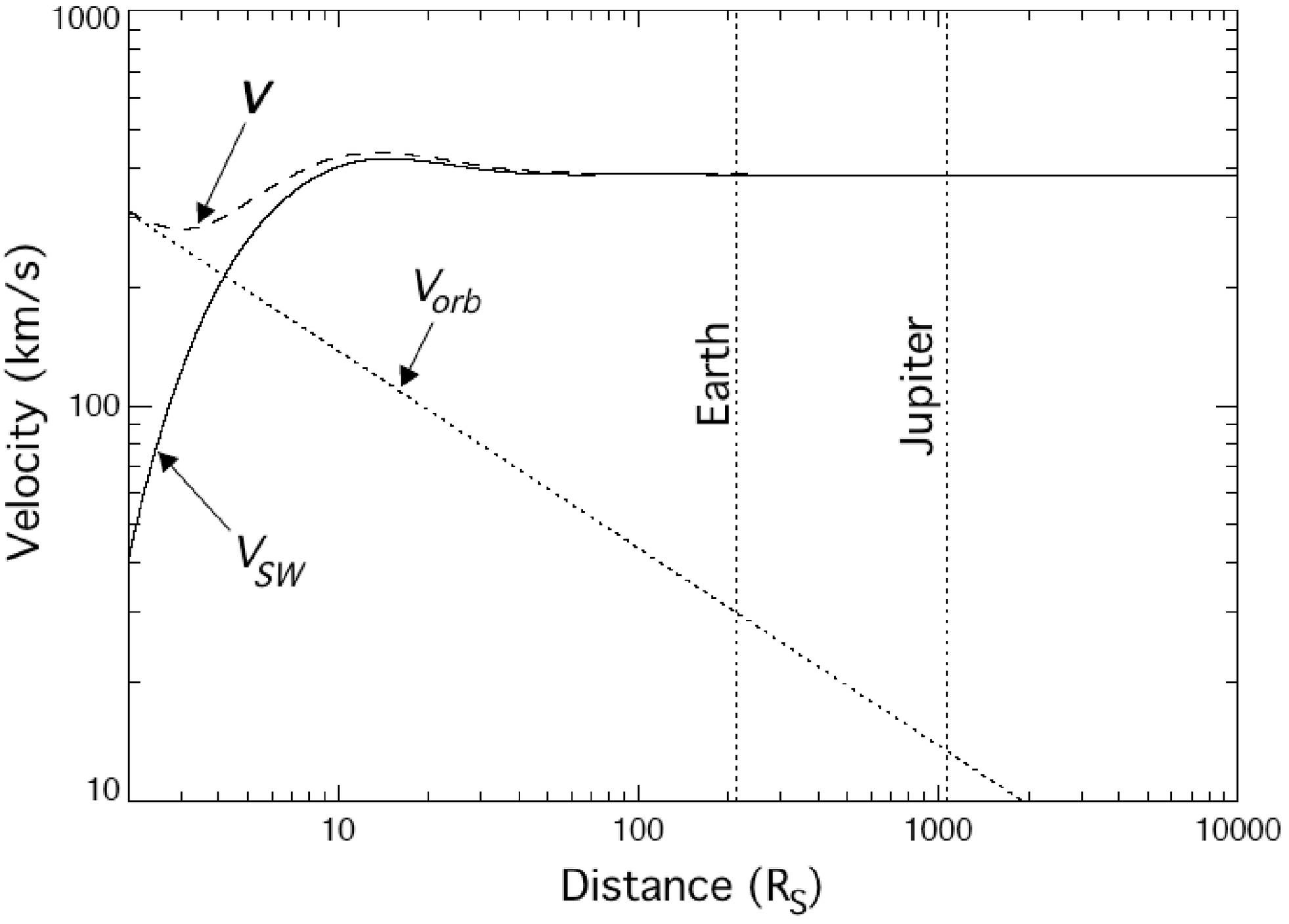
Modelling of a hot Jupiter (magnetized) orbiting a Solar type star

- Electron density in Solar corona

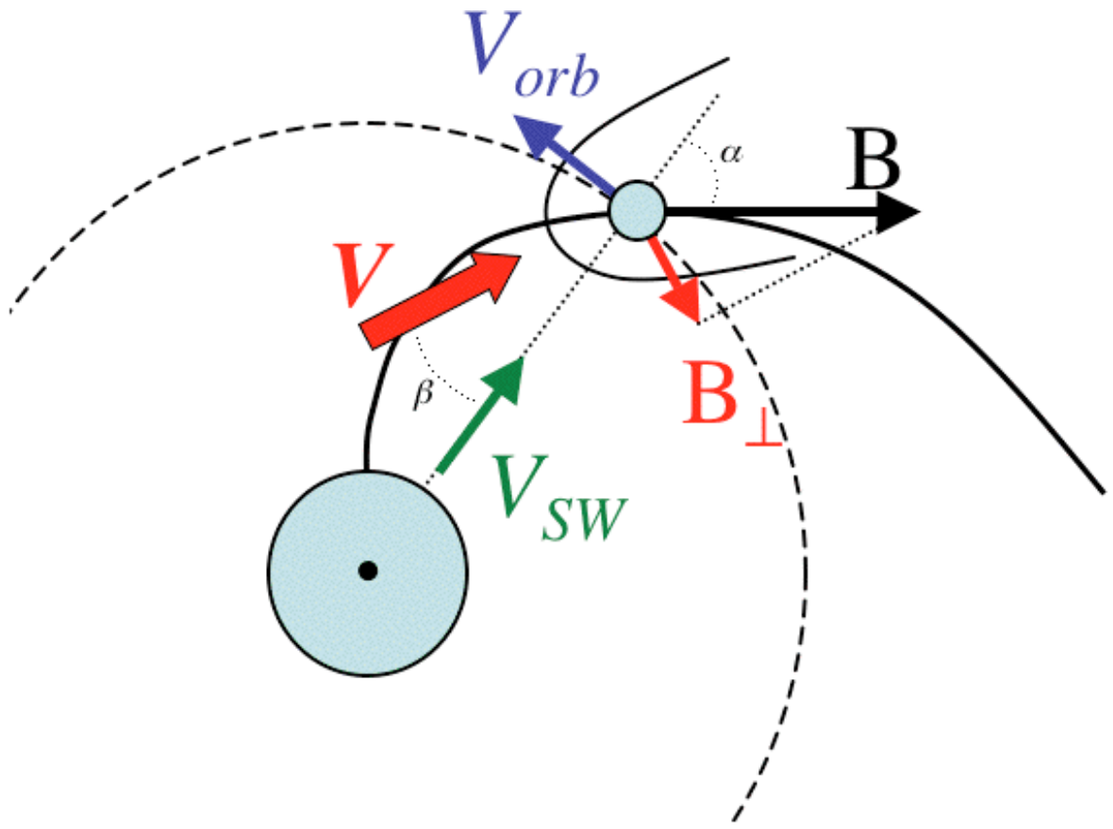


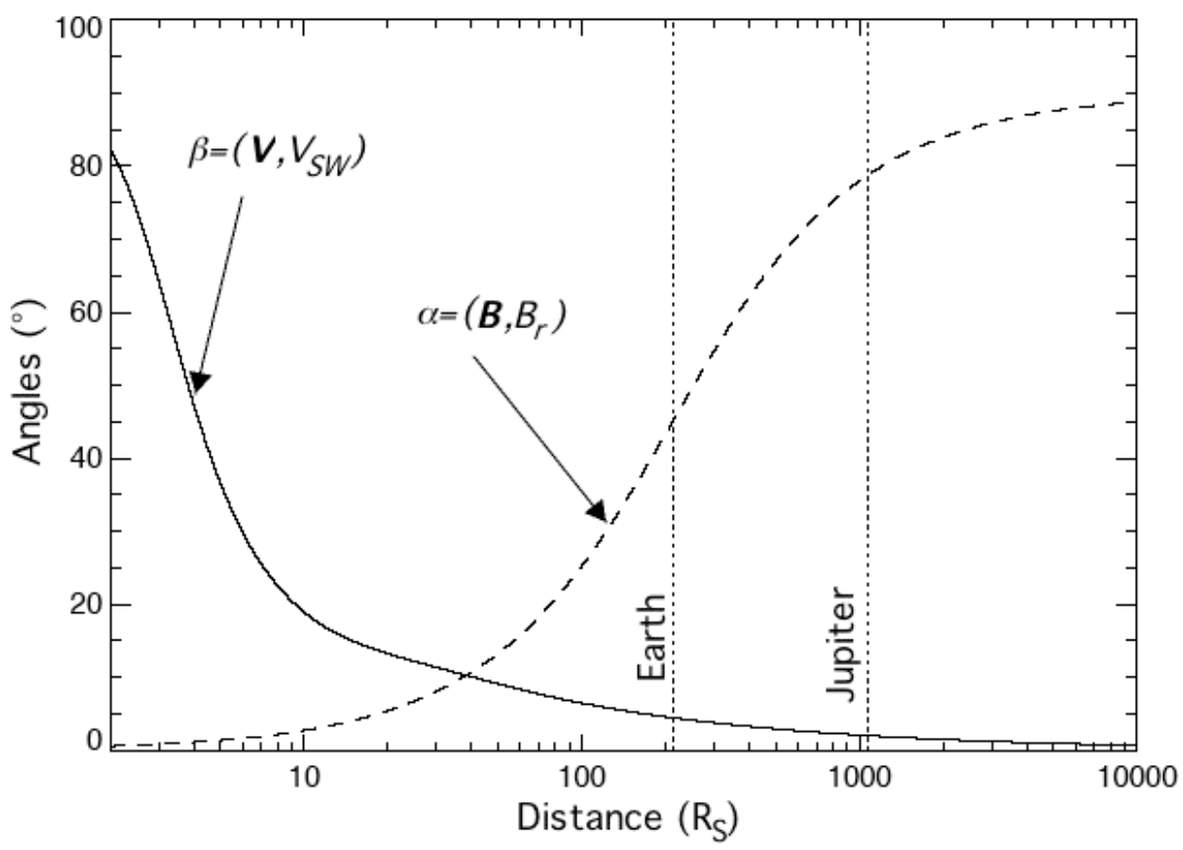
[Zarka, 2007]

- Solar wind speed in the planet's frame



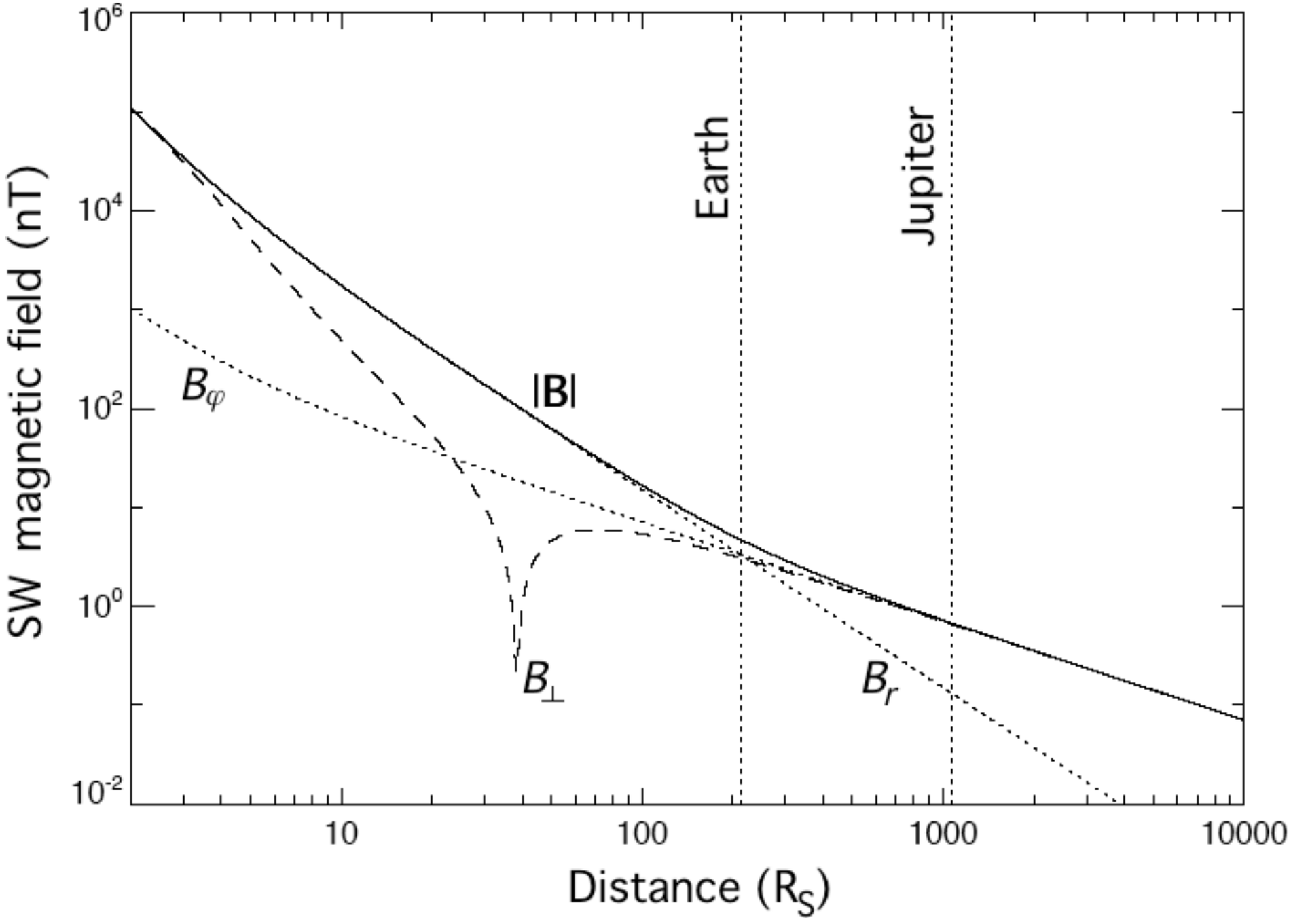
[Zarka, 2007]


V_{orb}
B
α
V
β
$B_\perp$
V_{SW}


100
80
60
40
20
0
Angles (°)
$\beta=(\boldsymbol{V},V_{SW})$
$\alpha=(\boldsymbol{B},B_r)$
Earth
Jupiter
10
100
1000
10000
Distance (R_S)

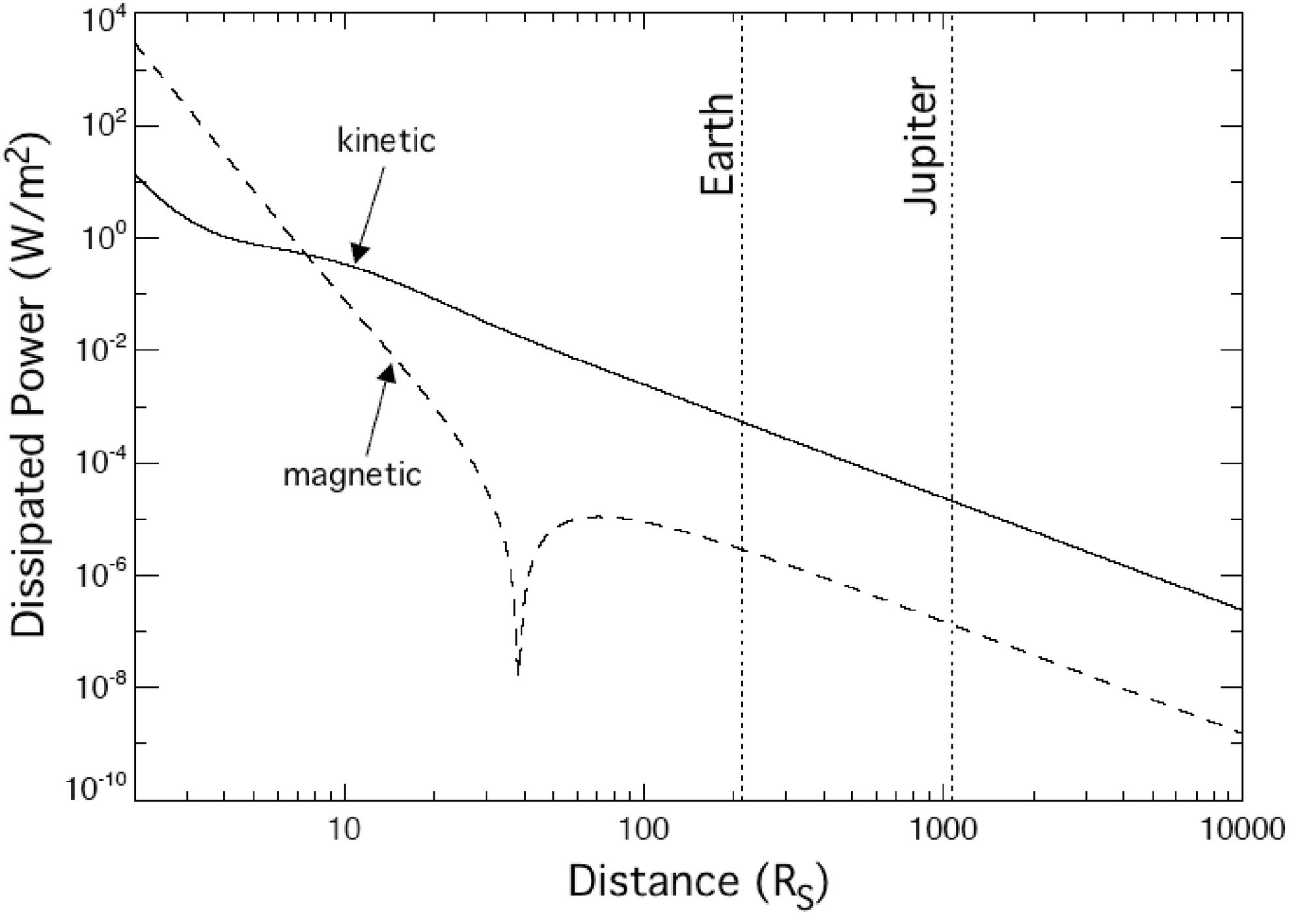
[Zarka, 2007]

- Interplanetary magnetic field



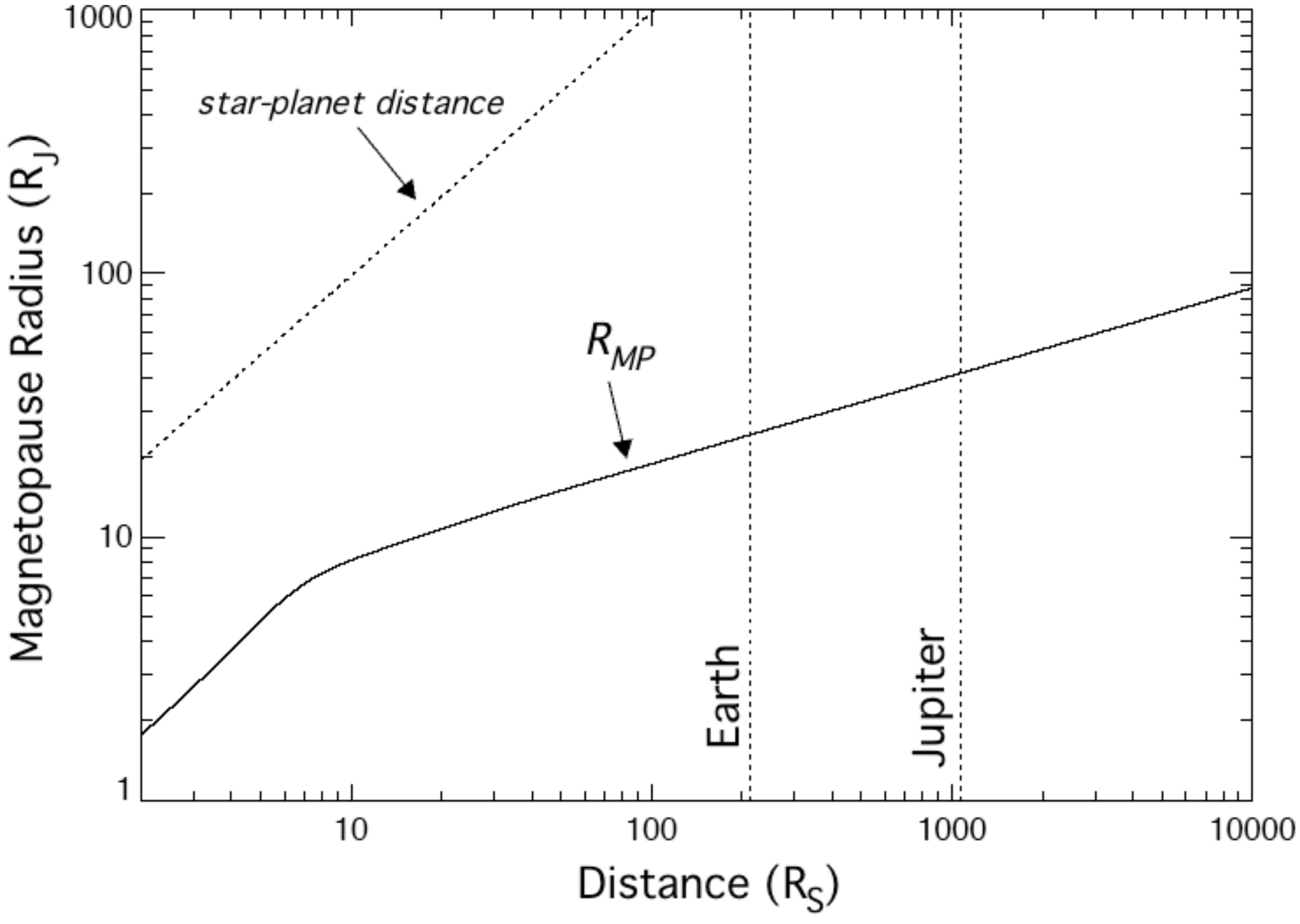
[Zarka, 2007]

- Dissipated power per unit area of the obstacle



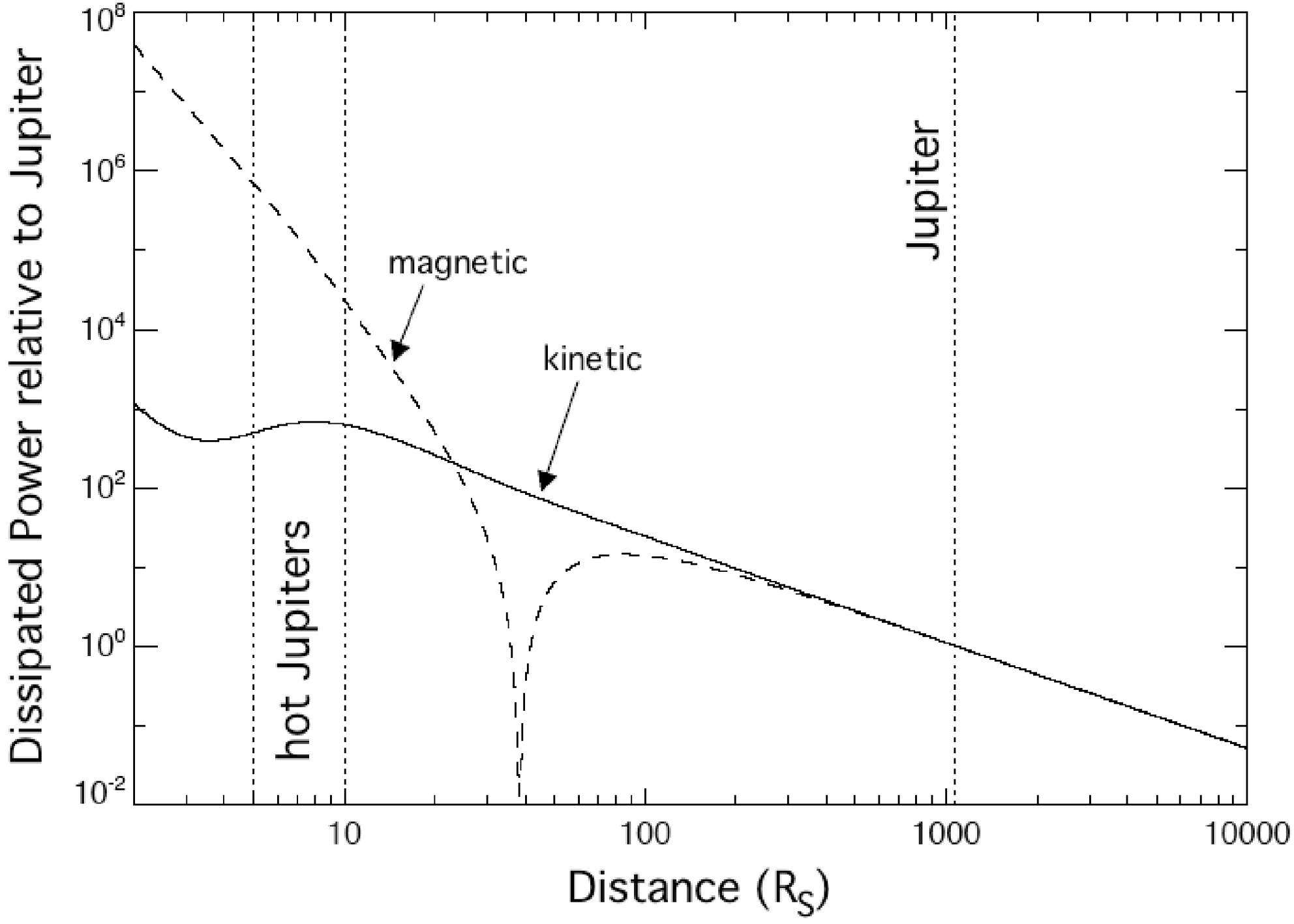
[Zarka, 2007]

- Magnetospheric compression



[Zarka, 2007]

- Total dissipated power on obstacle



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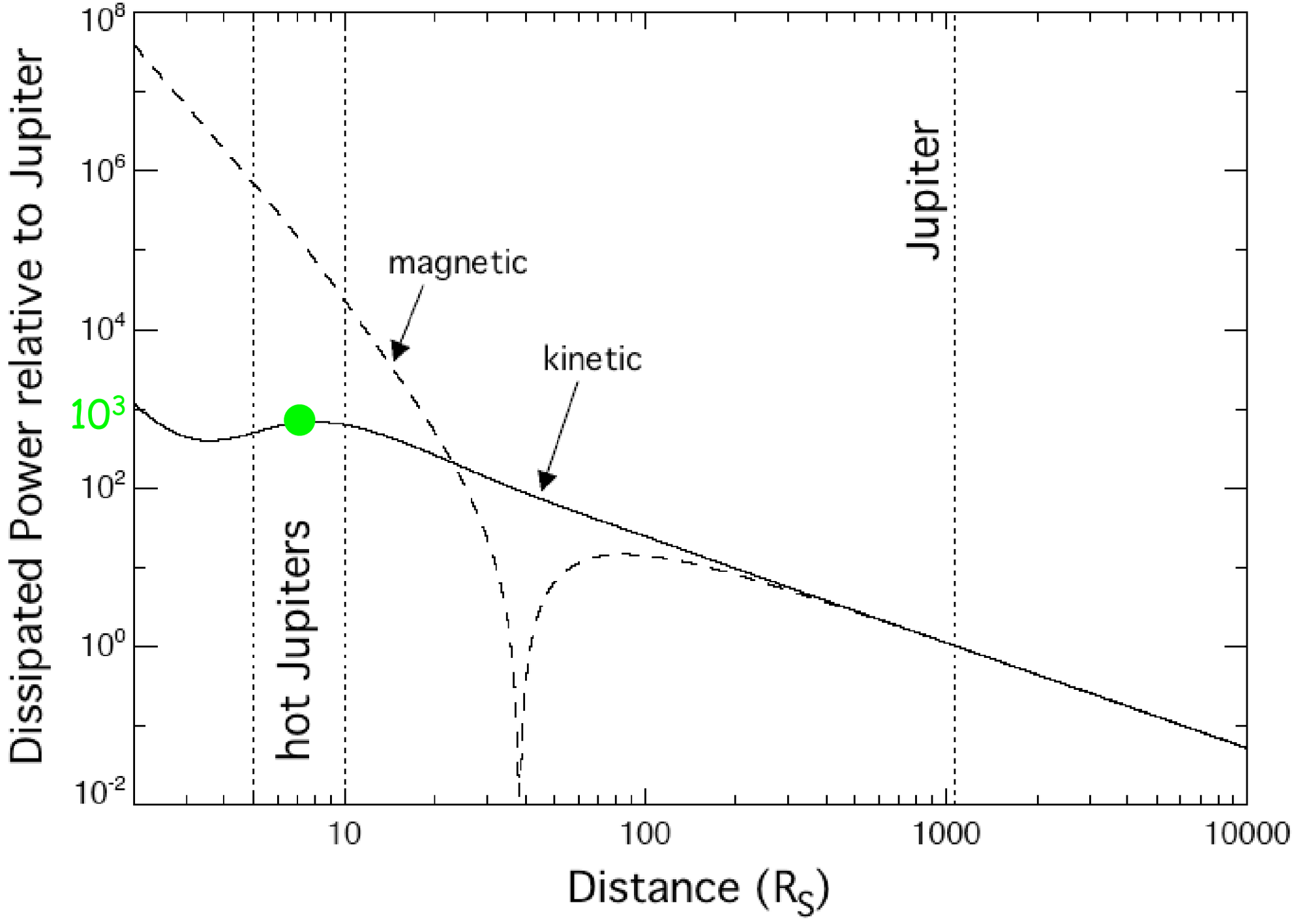

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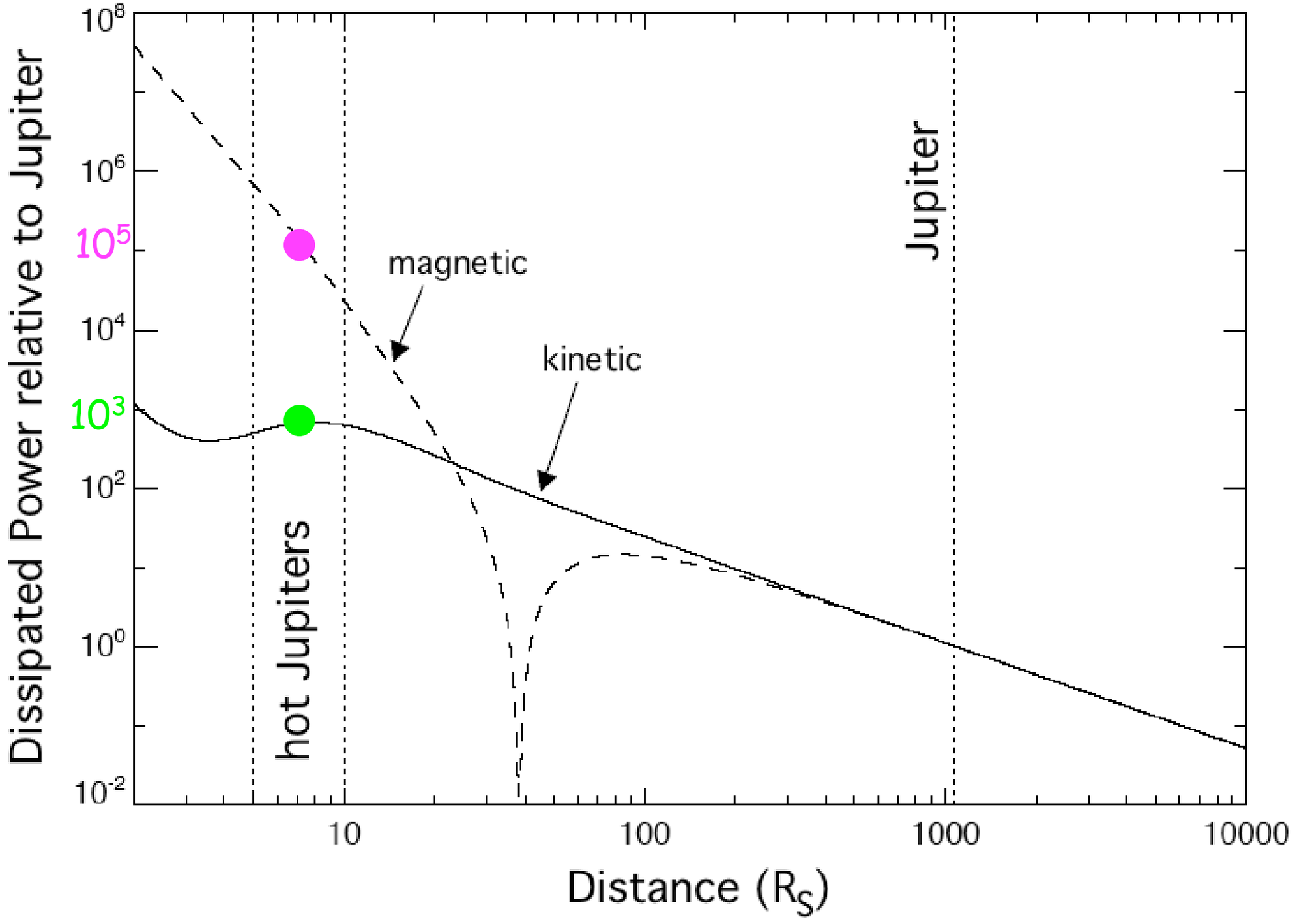

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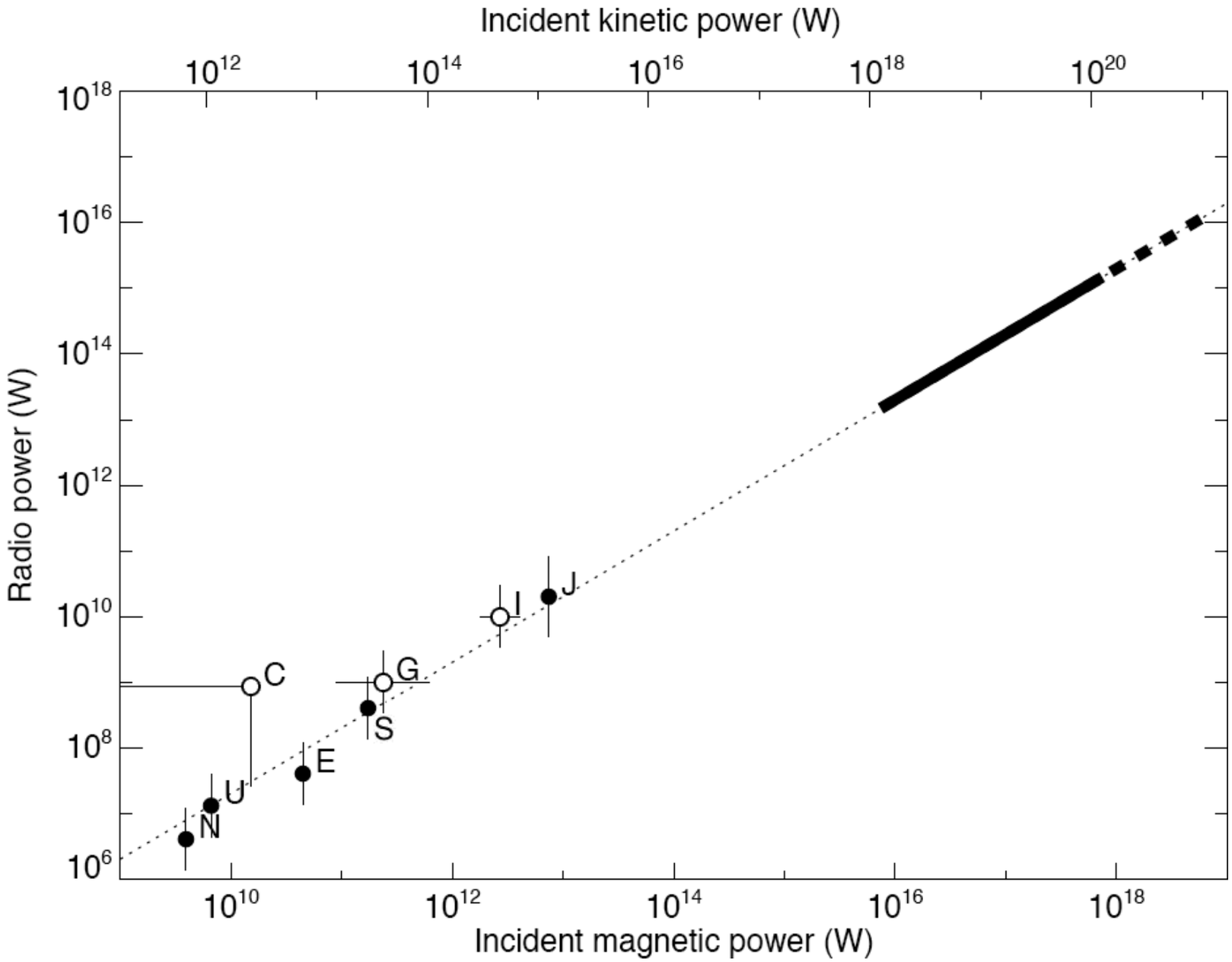
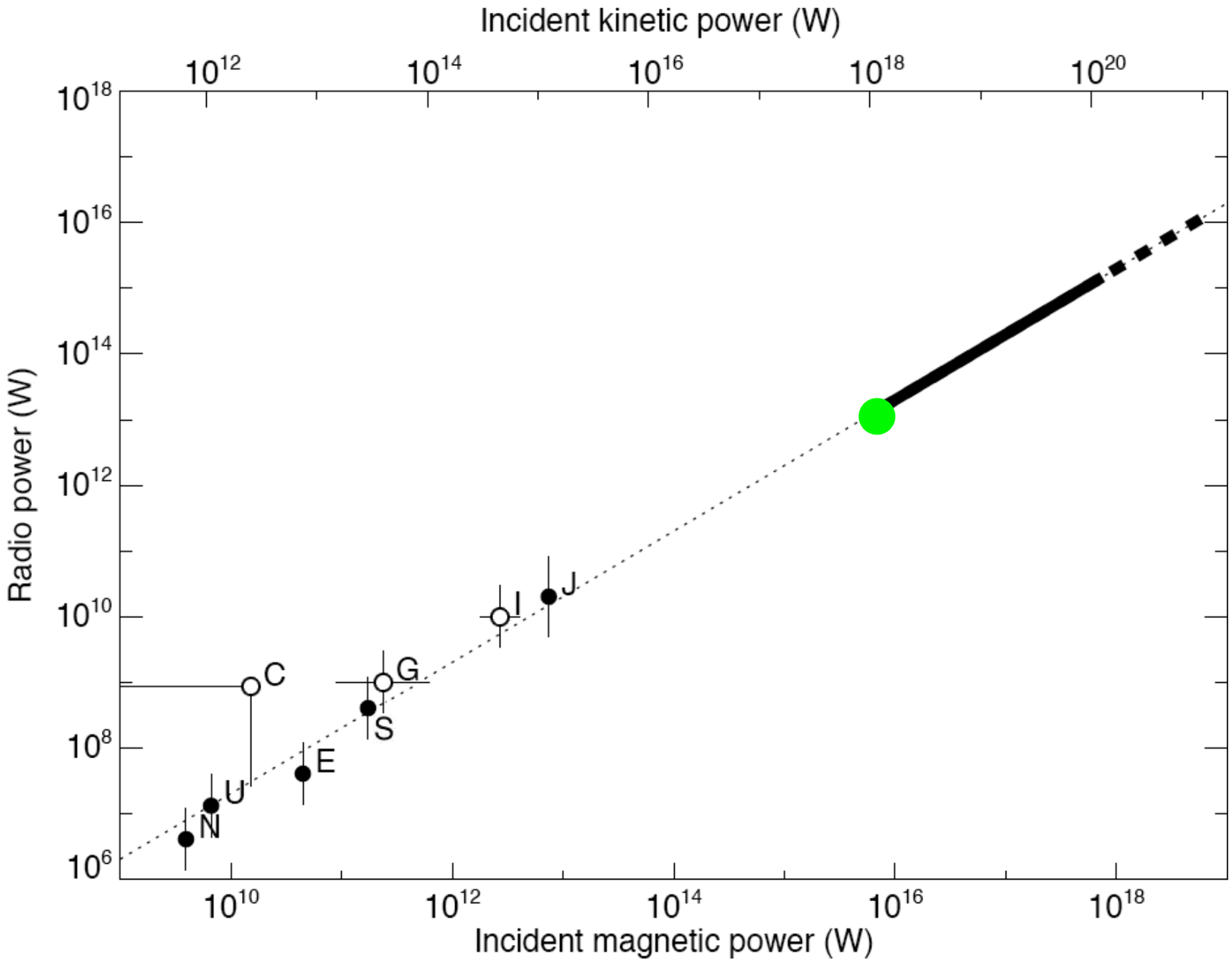


[Zarka et al., 2001; Zarka, 2007]



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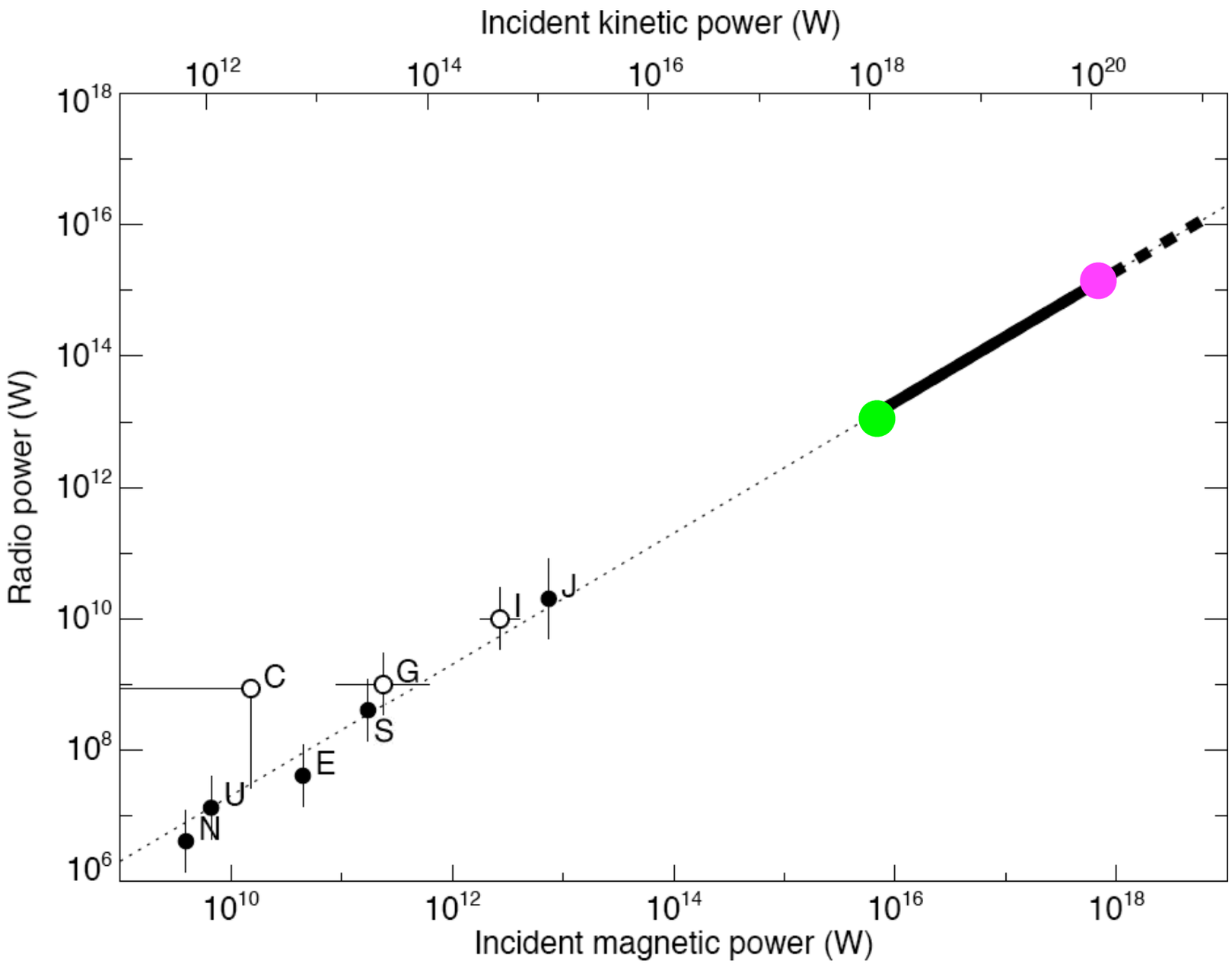

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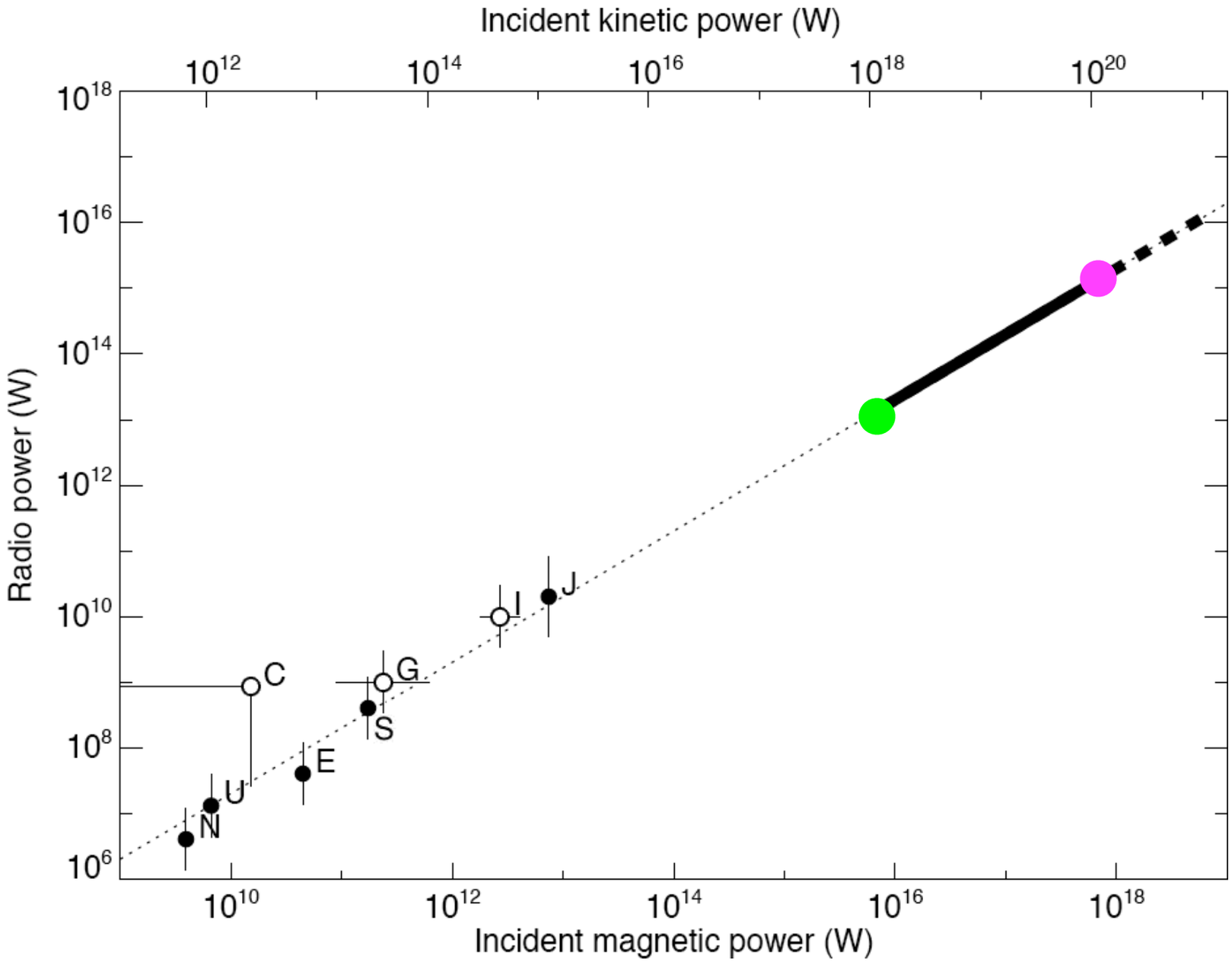

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except if there is a « saturation » mechanism

[Zarka et al., 2001; Zarka, 2007]

Planetary magnetic field decay ?

- Radio detection → f > 10 MHz → $B_{max\text{-}surface} \geq 4$ G
- Jupiter : $\mathcal{M} = 4.2\ G.R_J^3$, $B_{max\text{-}dipole} = 8.4$ G, $B_{max\text{-}surface} = 14$ G, $f_{max} = 40$ MHz
- Spin-orbit synchronisation (tidal forces) → $\omega\downarrow$
- But $\mathcal{M} \propto \omega^{\alpha}$ with $\frac{1}{2} \leq \alpha \leq 1$ → $\mathcal{M}\downarrow$ (B decay) ?

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- Internal structure + convection models

→ self-sustained dynamo → $\mathcal{M}$ could remain ≥ a few

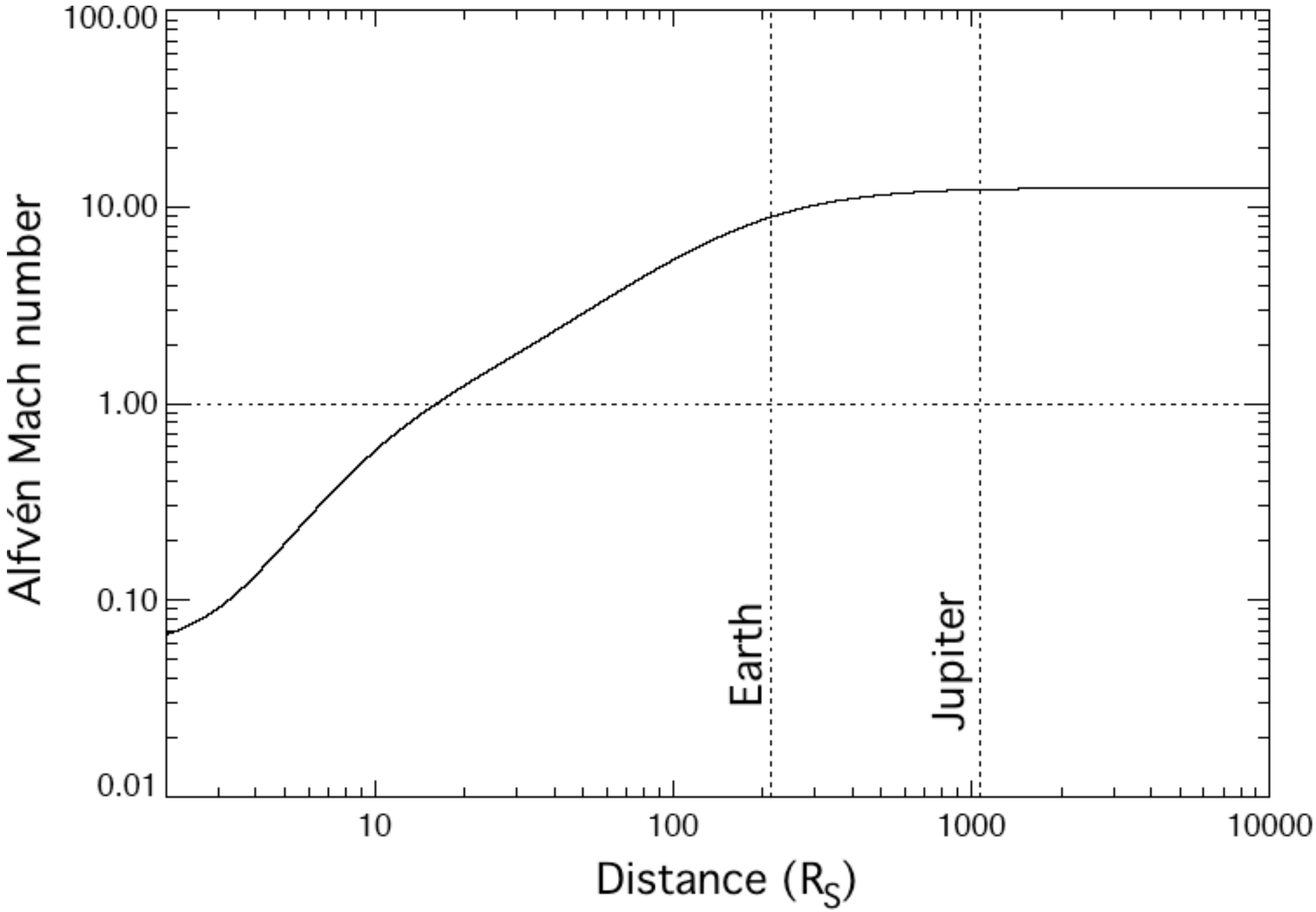
UPPER LIMIT OF MAGNETIC FIELDS IN HOT JUPITERS

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

[Sanchez-Lavega, 2004]

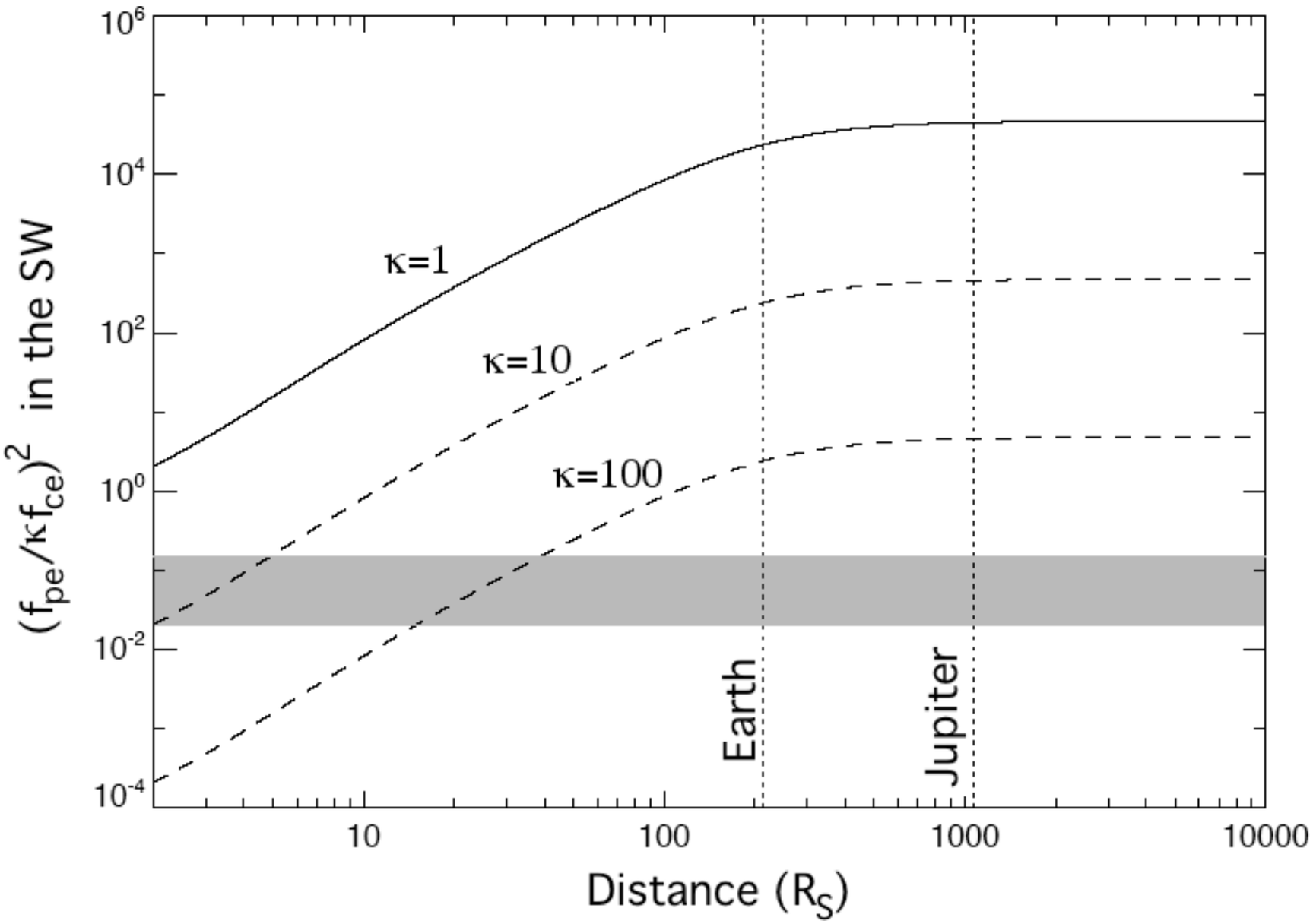
Unipolar inductor in sub-Alfvénic regime

(as for Io-Jupiter)



[Zarka, 2007]

- But radio emission possible only if $f_{pe}/f_{ce} << 1$
  → intense stellar B required (κ = 10-100 x B_{Sun})
  → emission ≥30-250 MHz from 1-2 R_S

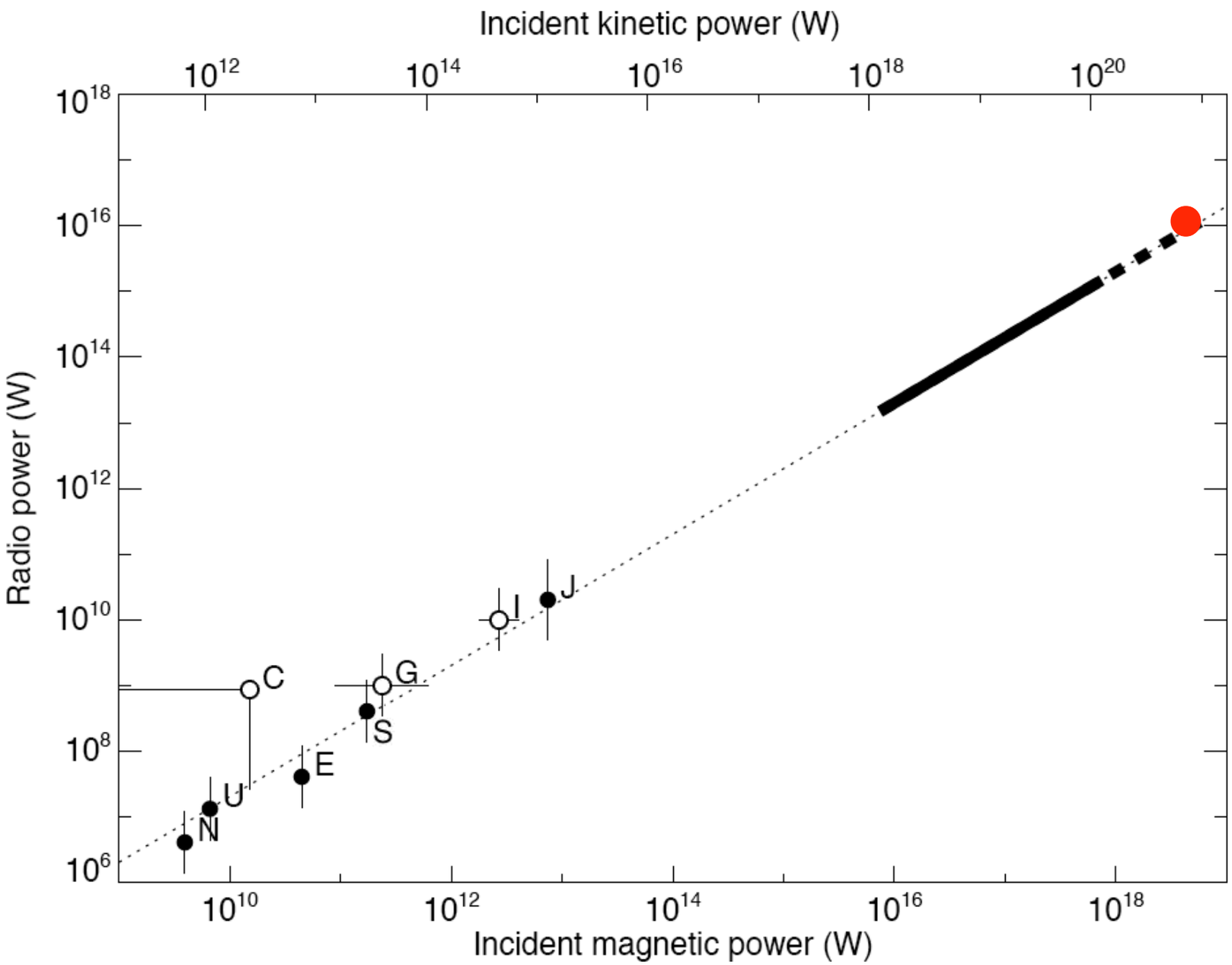


[Zarka, 2007]

- Extrapolation / Radio-magnetic Bode's law

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

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



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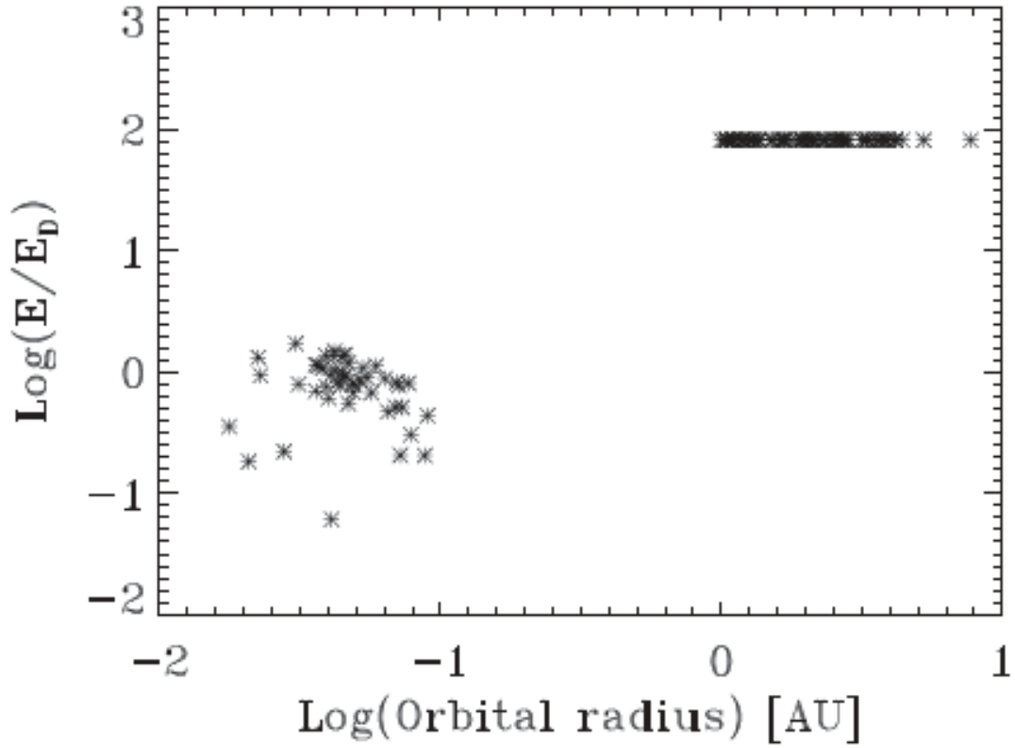
Magnetic reconnection and electron acceleration at the magnetopause

[Jardine & Collier-Cameron, 2008]

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \mathbf{j}/H$$

$$\mathbf{E}_{||} = \mathbf{E} \cdot \mathbf{B} = E_{||}(0) e^{-z^2 H}$$

$$E_{||}(0) = -\frac{2\sqrt{2\pi}}{\Gamma(1/4)} H^{-1/4} v_0 B_0$$



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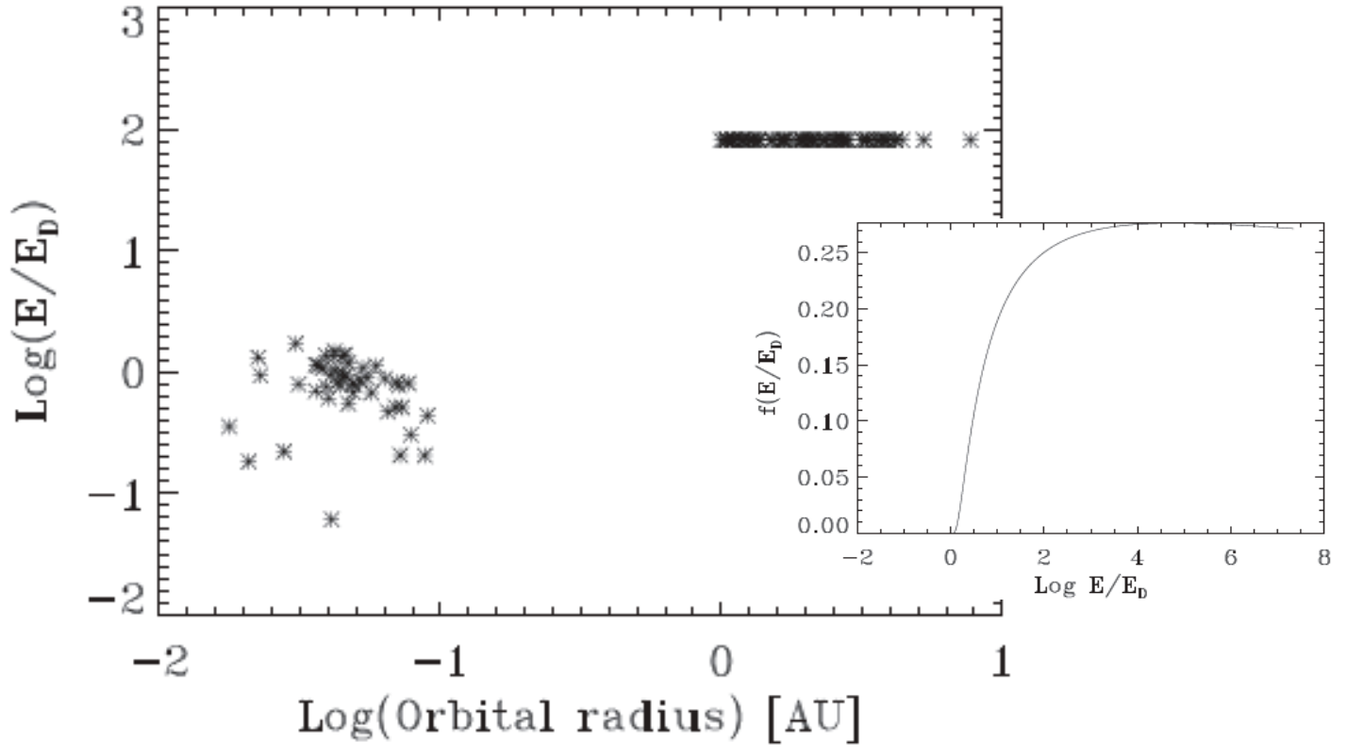

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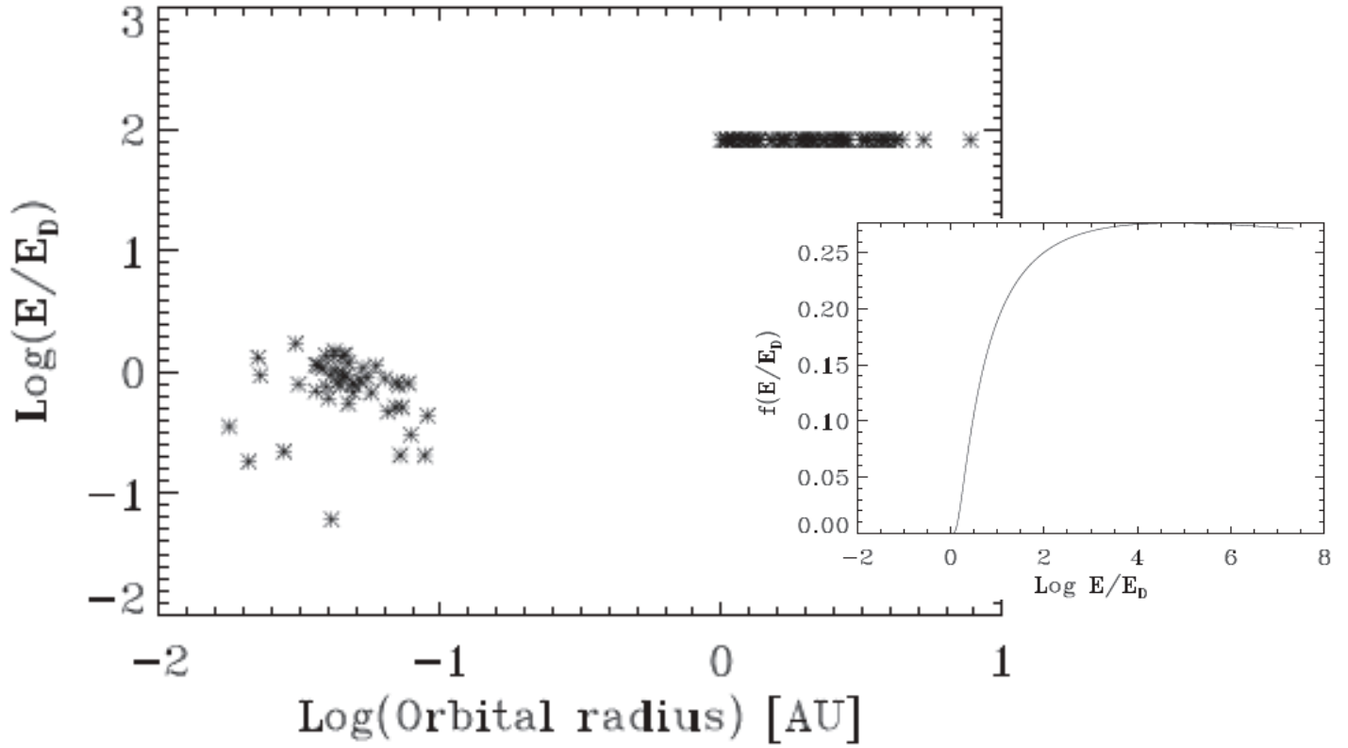

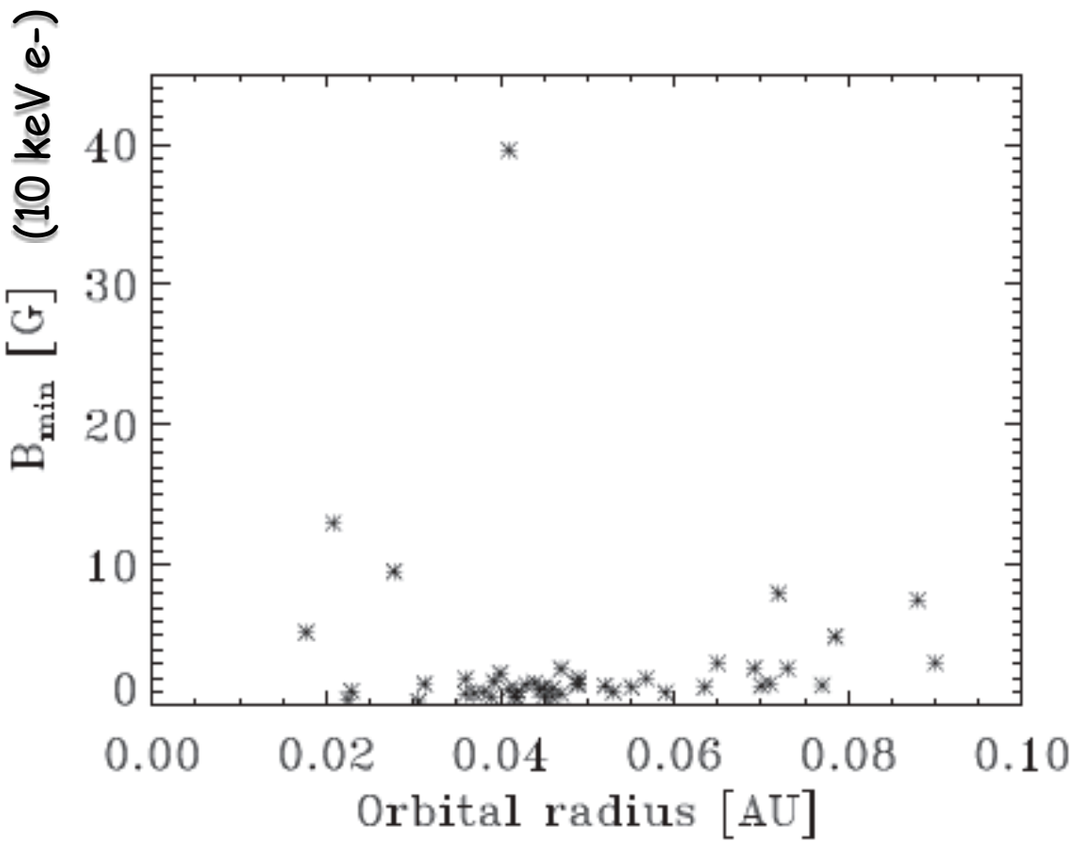

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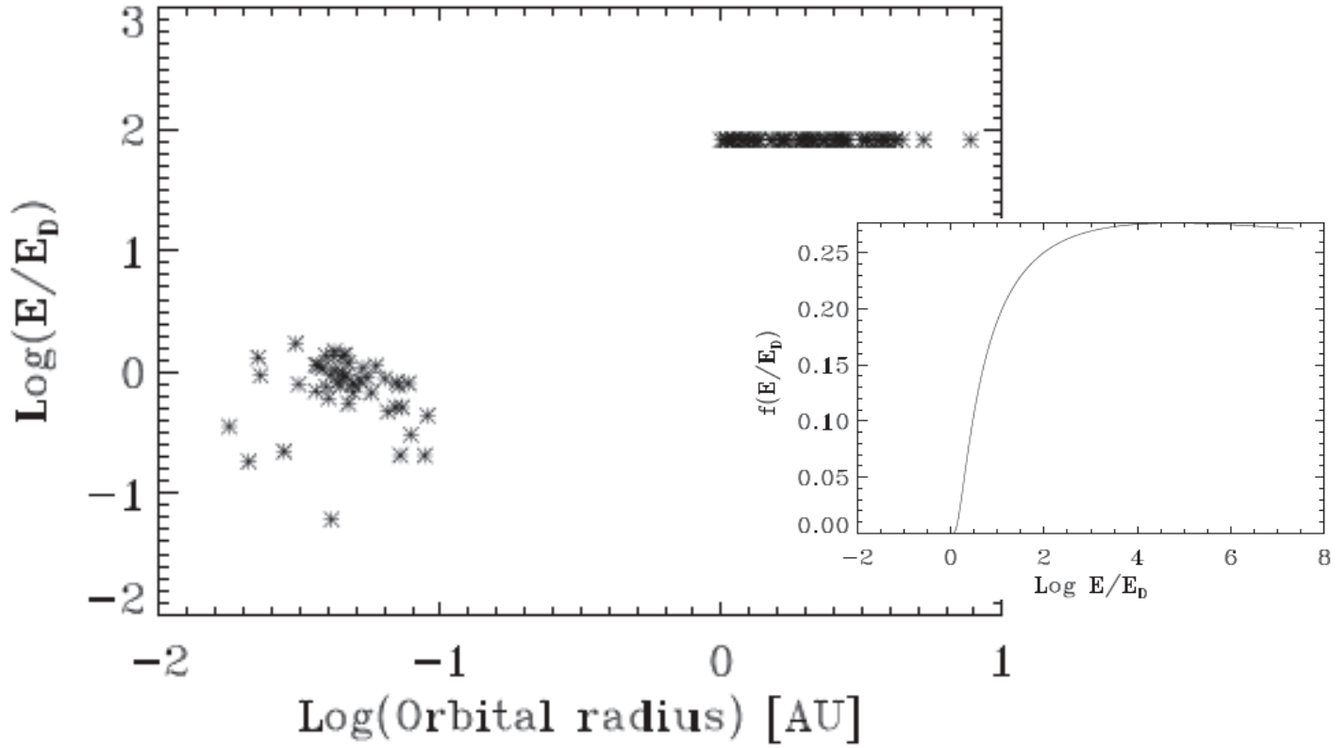

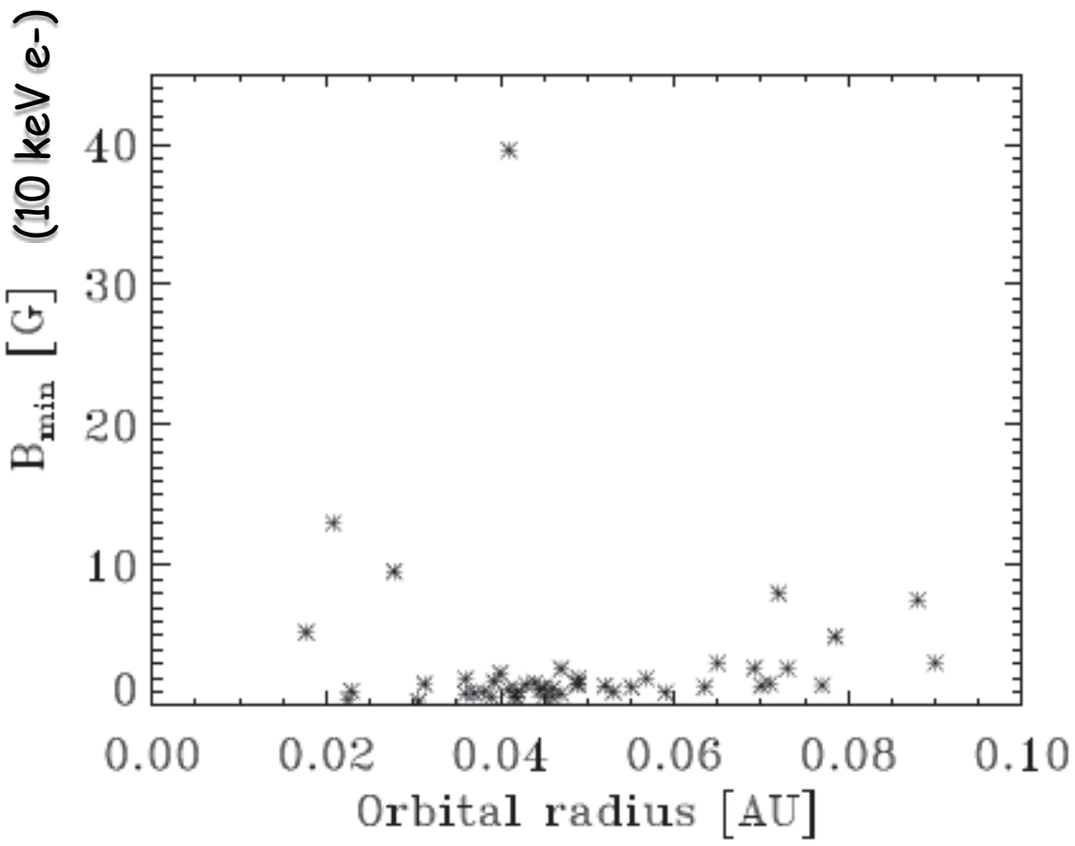

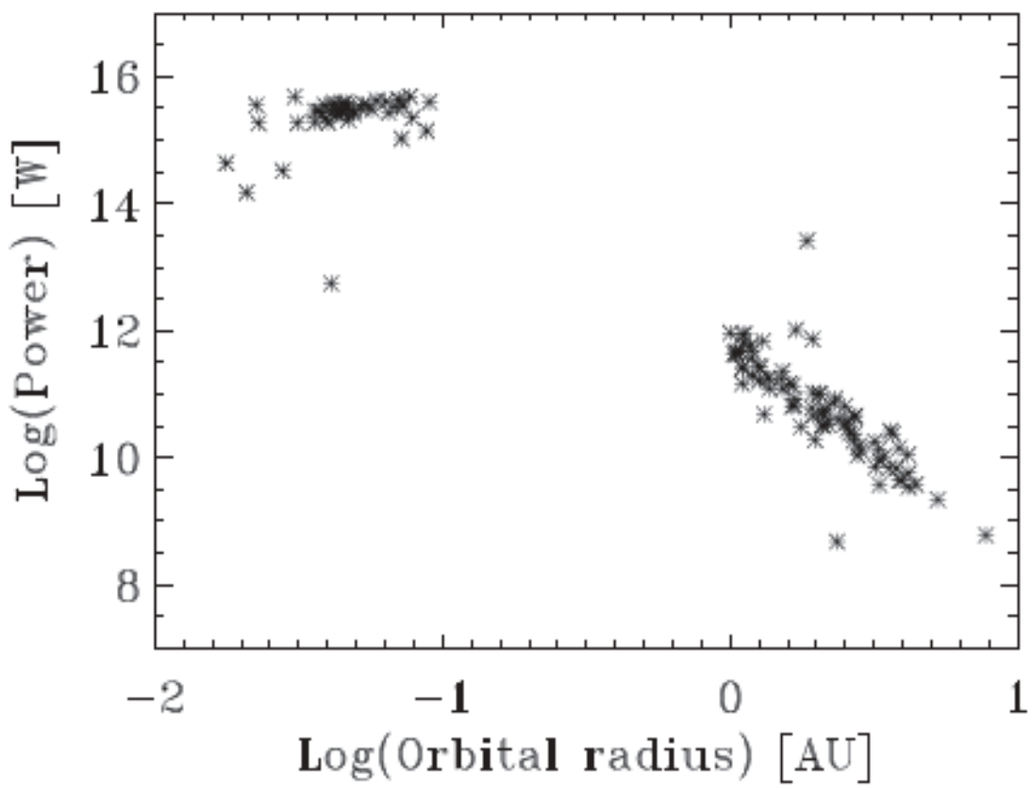

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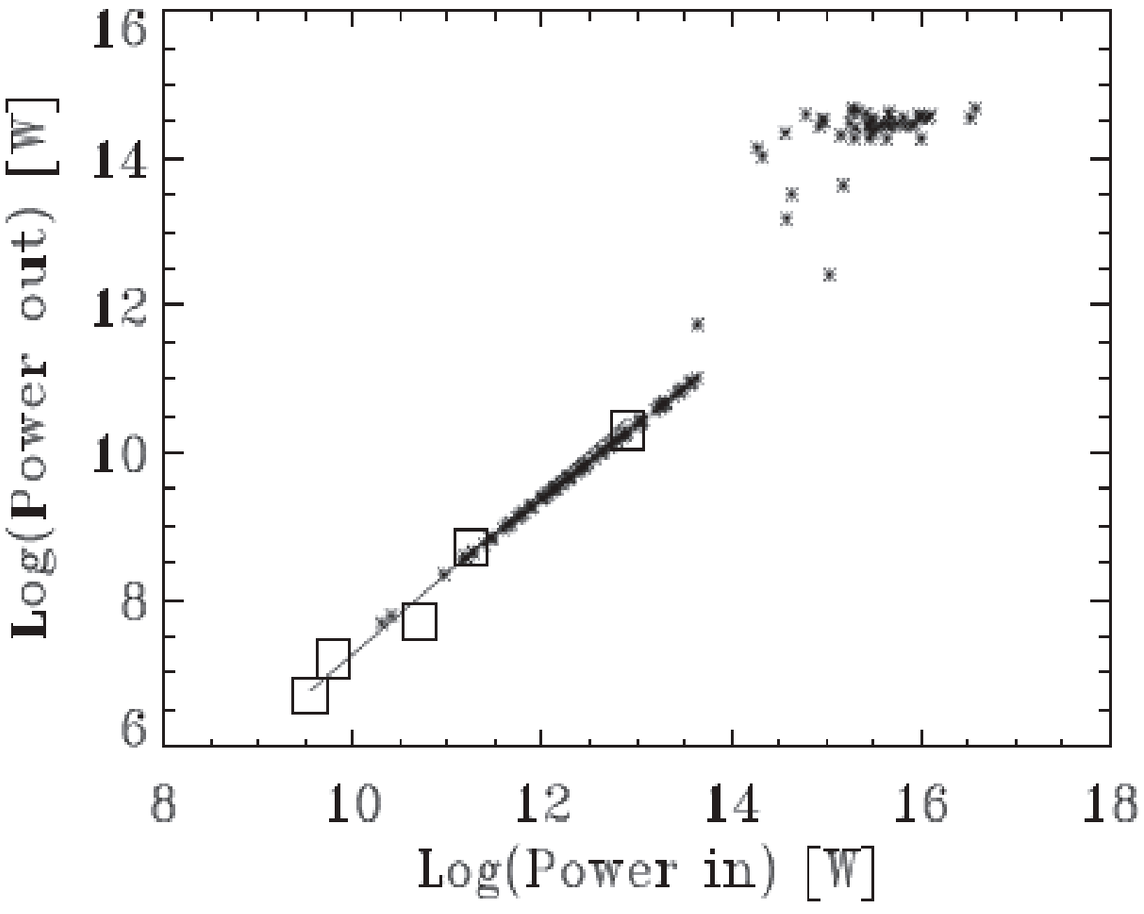
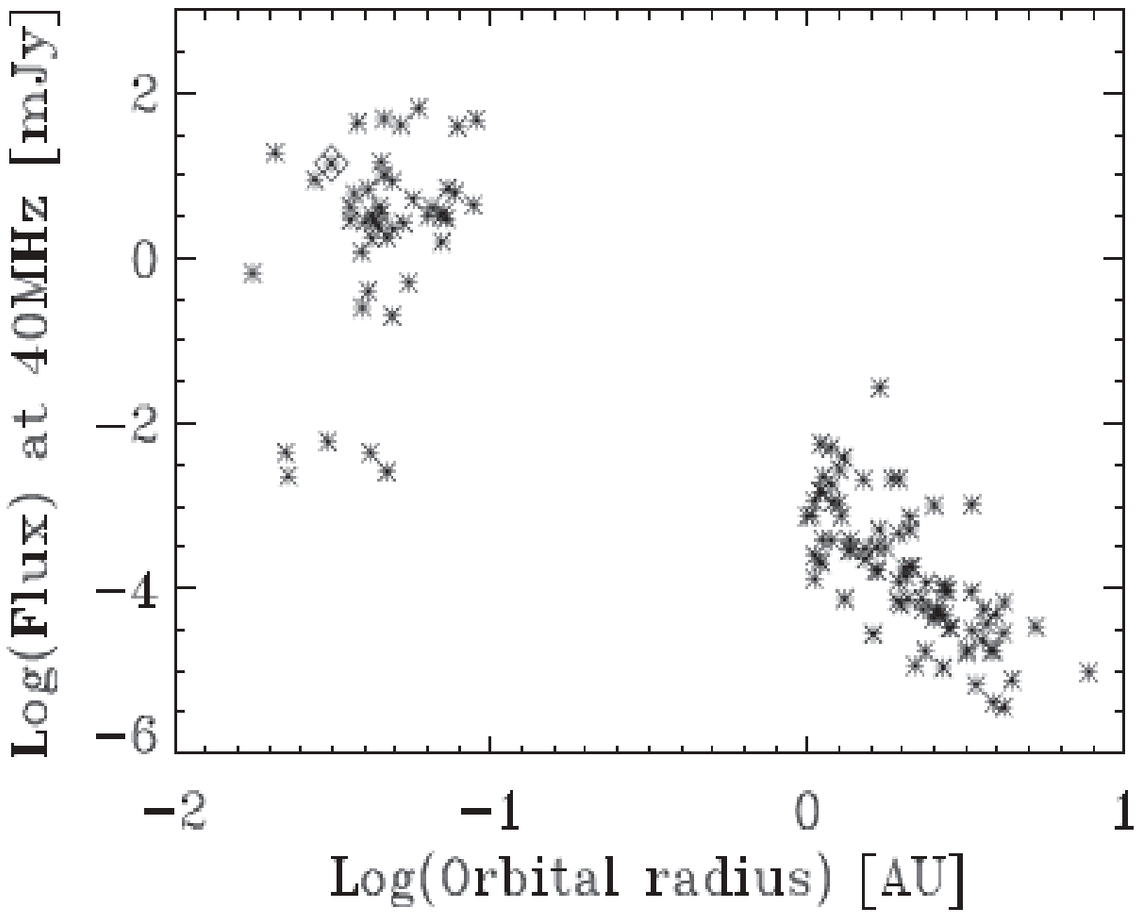
[Jardine & Collier-Cameron, 2008]

B*=1G, η=10%





$\Rightarrow \zeta = 10^5$

	$b\tau = 10^6$ *(1 MHz, 1 sec)*		$b\tau = 2\times10^8$ *(3 MHz, 1 min)*		$b\tau = 4\times10^{10}$ *(10 MHz, 1 hour)*	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4$ m^2 *(~NDA)*	1	16	3	59	13	220
$A_e = 10^5$ m^2 *(~UTR-2)*	3	50	11	190	40	710
$A_e = 10^6$ m^2 *(~LOFAR77)*	9	160	33	600	130	2200

(distances in parsecs)

[Zarka, 2007]

Other studies …

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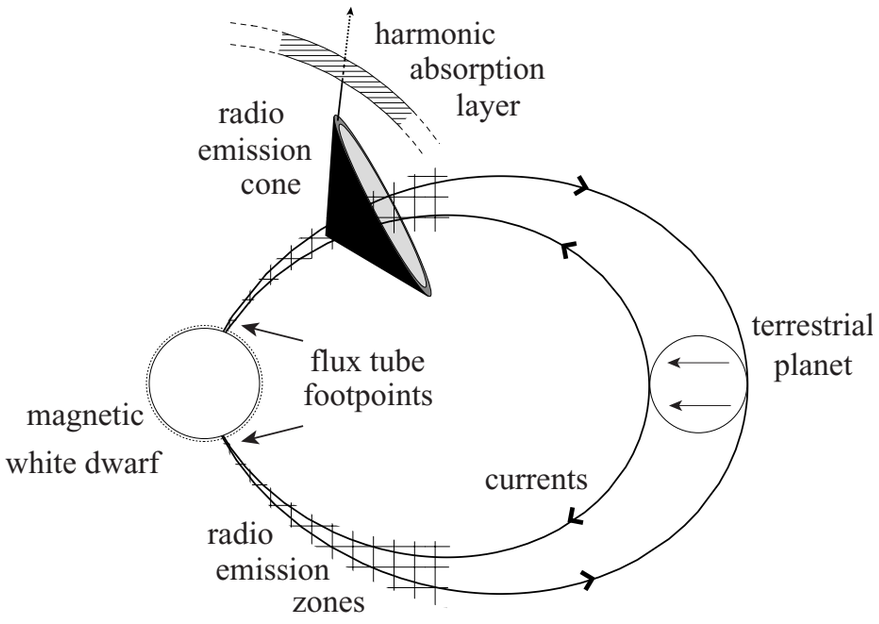
[Willes and Wu, 2004, 2005]



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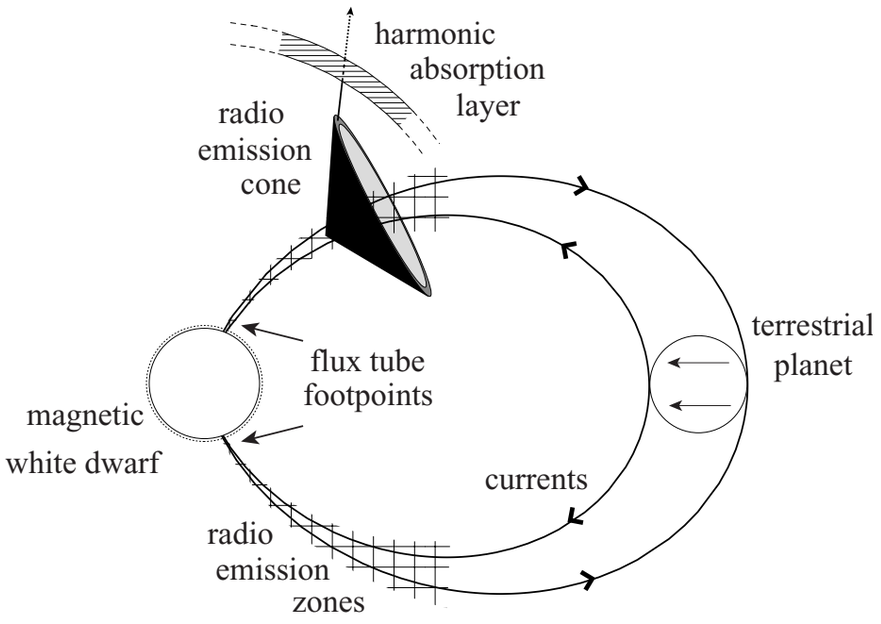

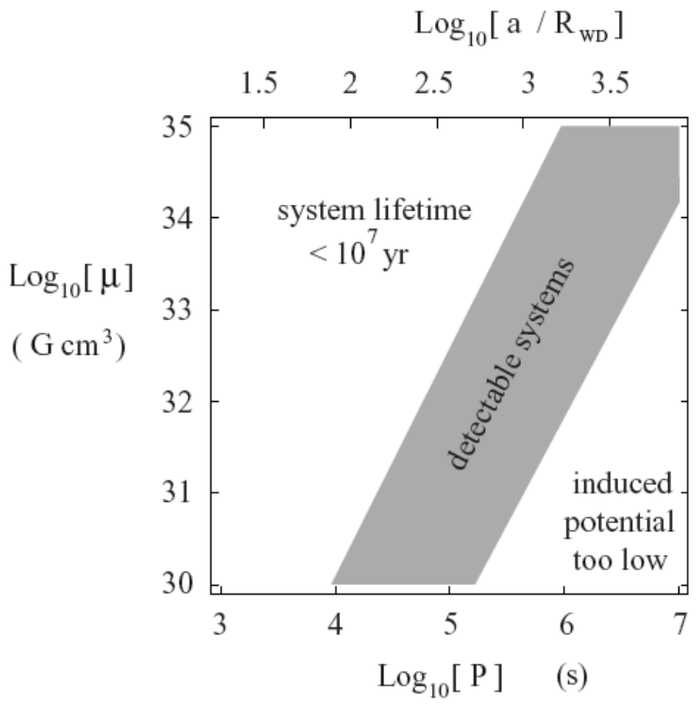

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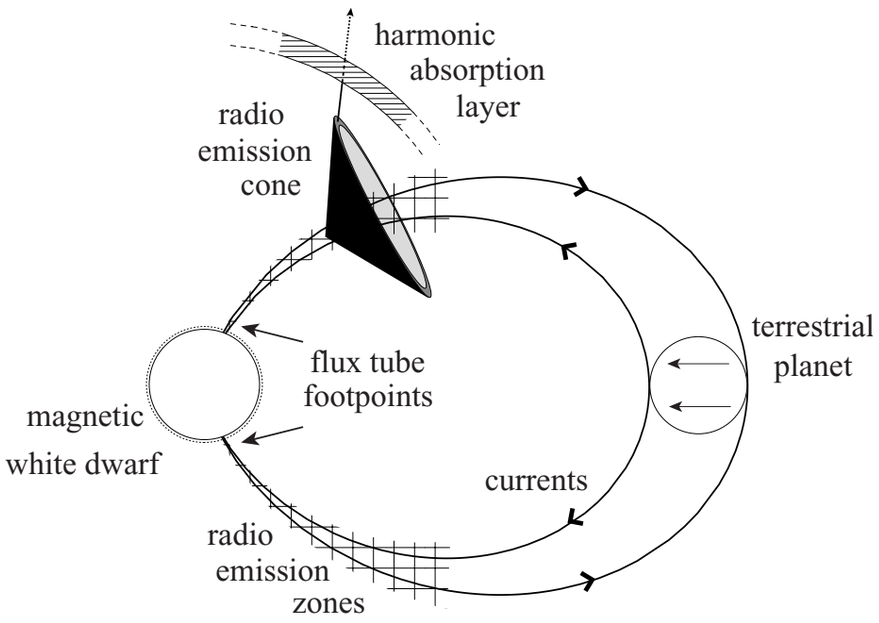

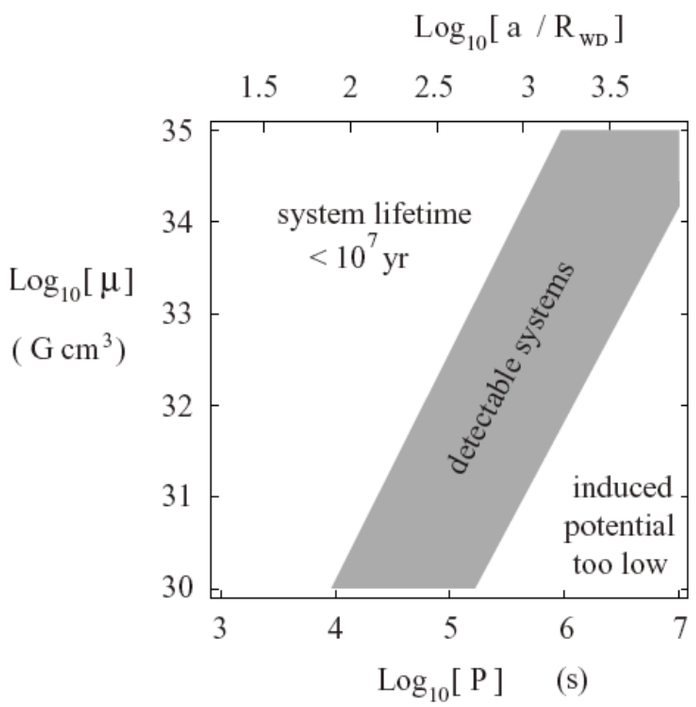

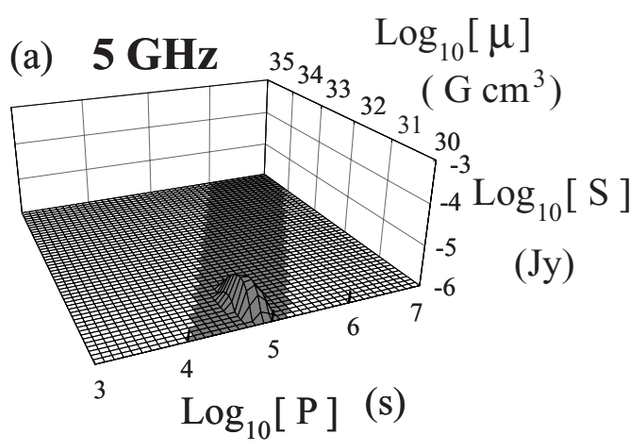

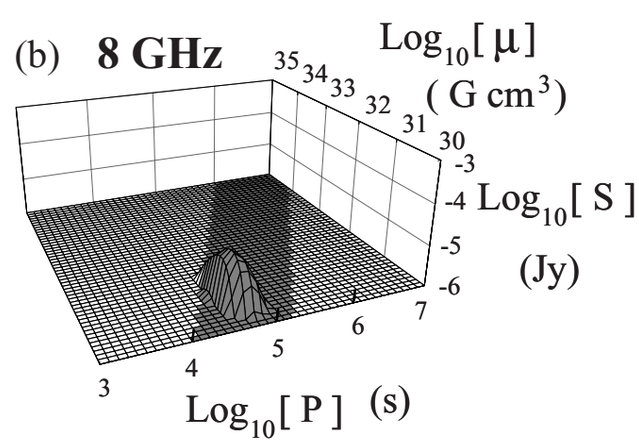

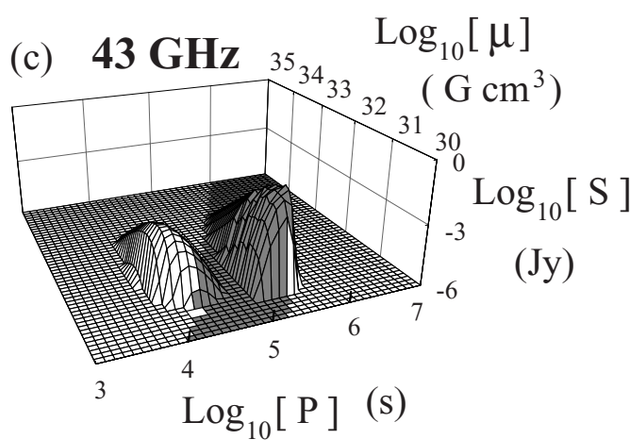

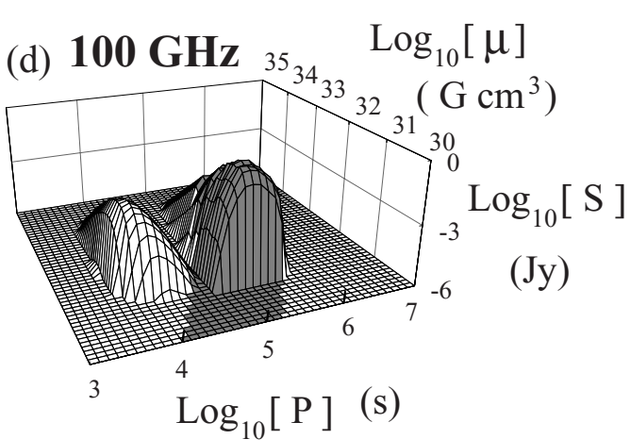

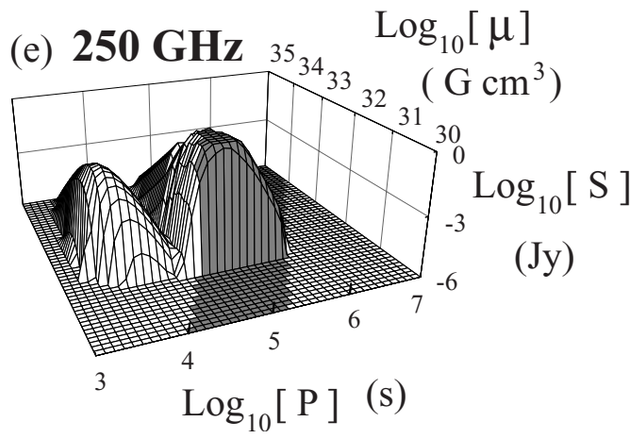

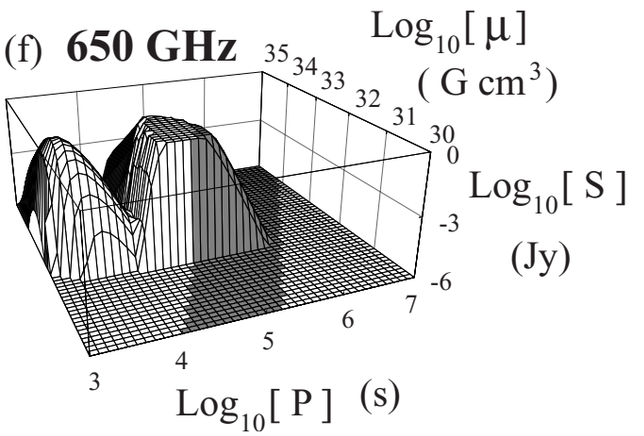

saturated loss-cone driven cyclotron-maser emission

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- Predictions for the whole exoplanet census

  ➡ radio-kinetic extrapolation

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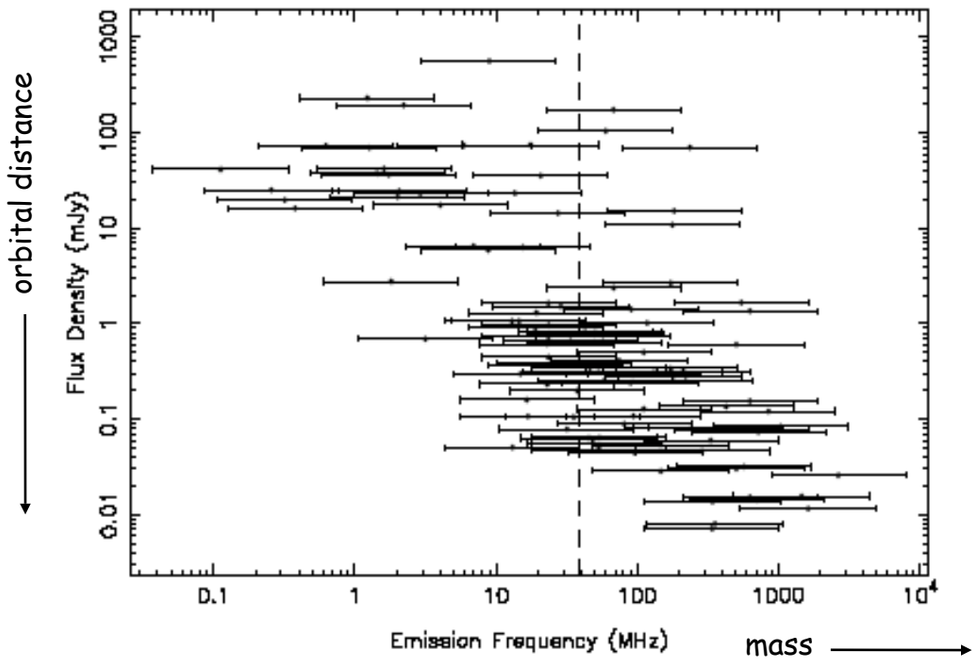

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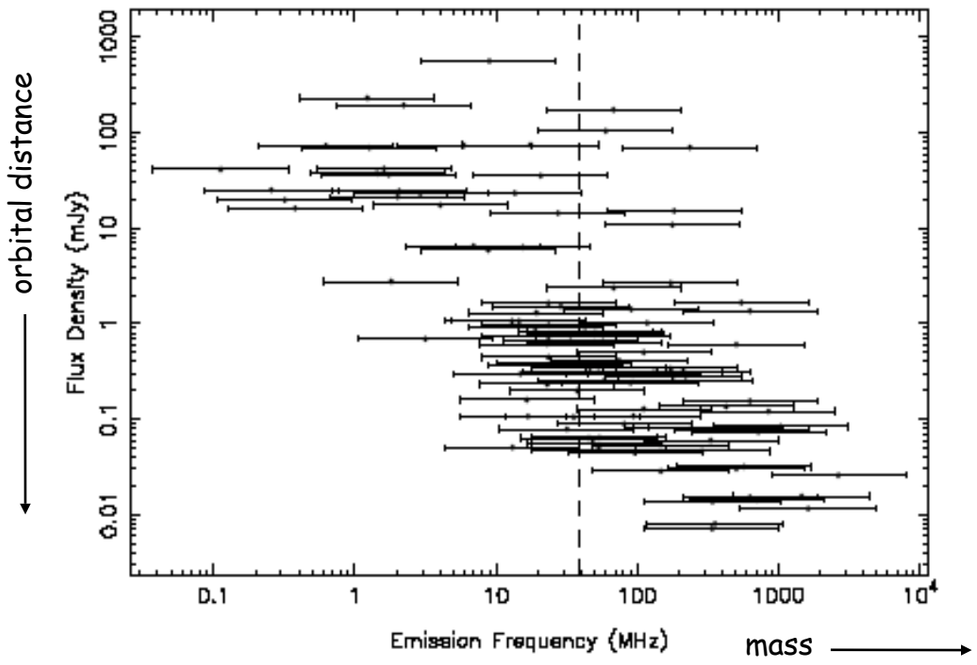

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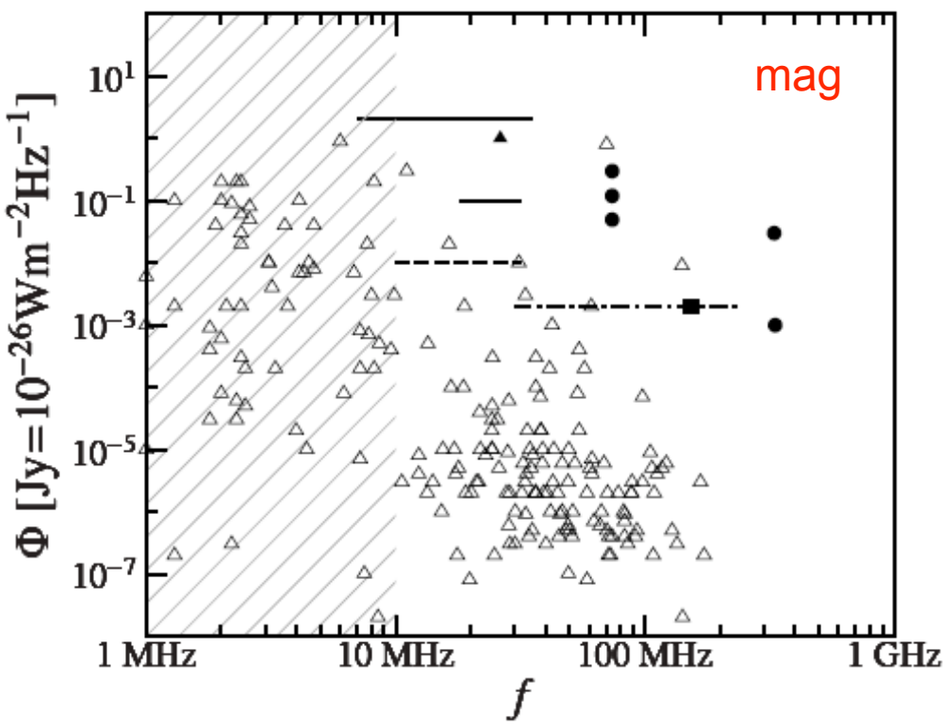

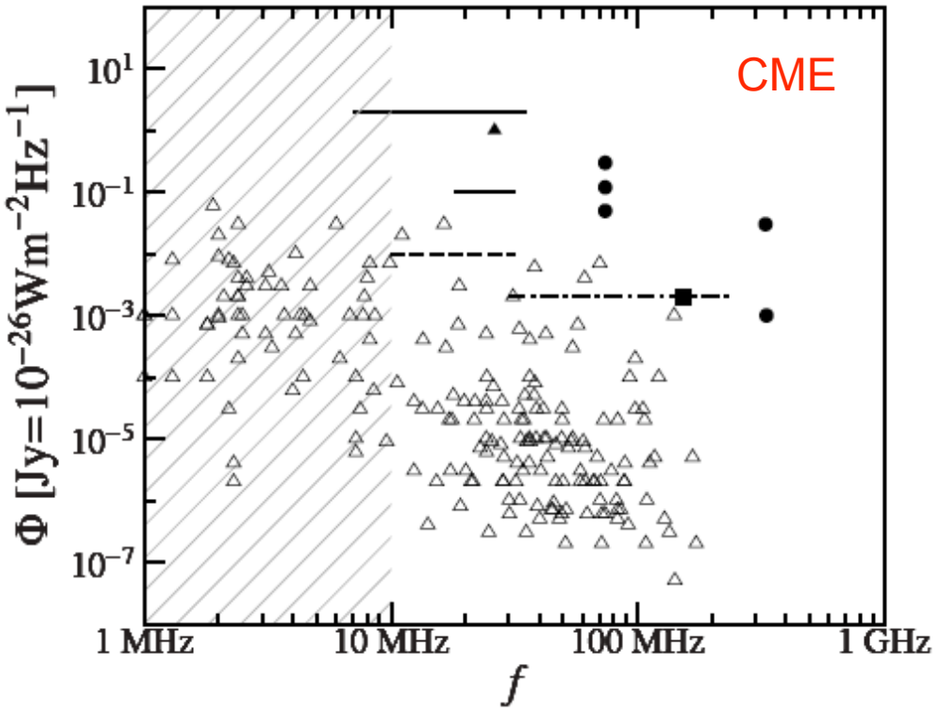

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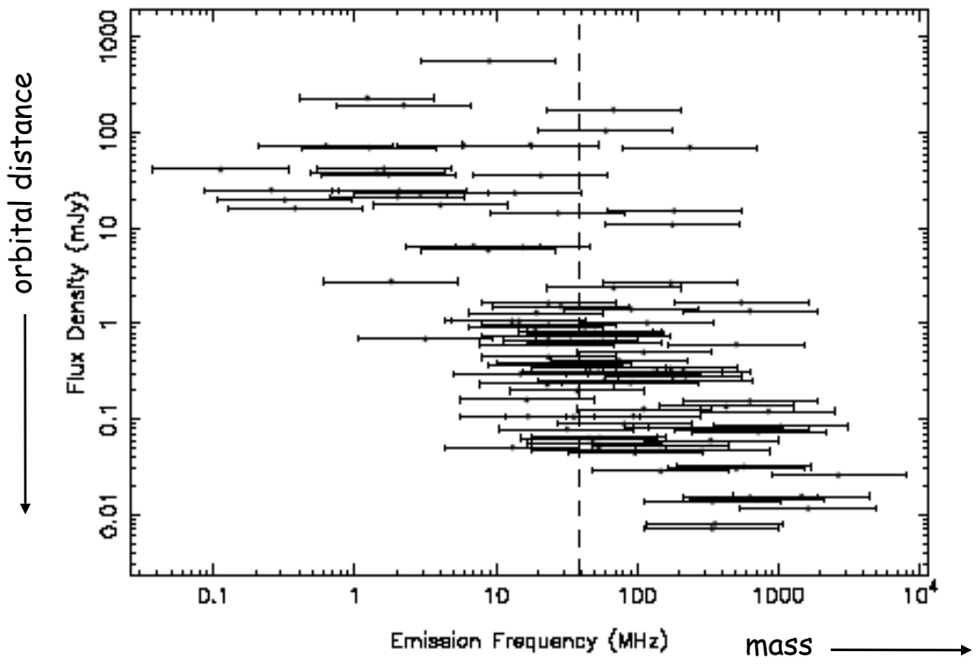

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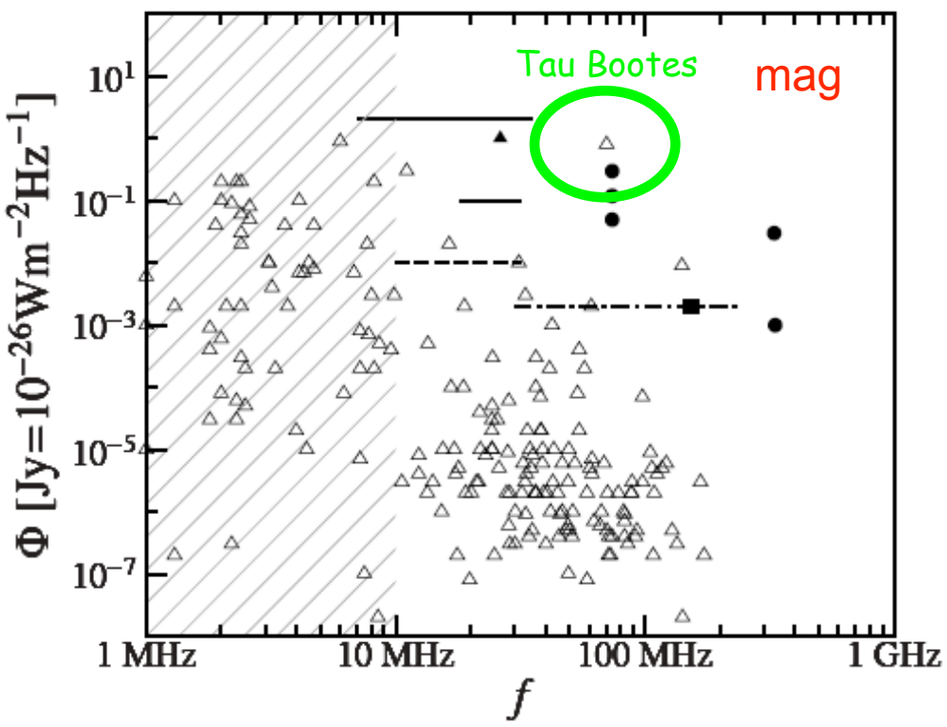

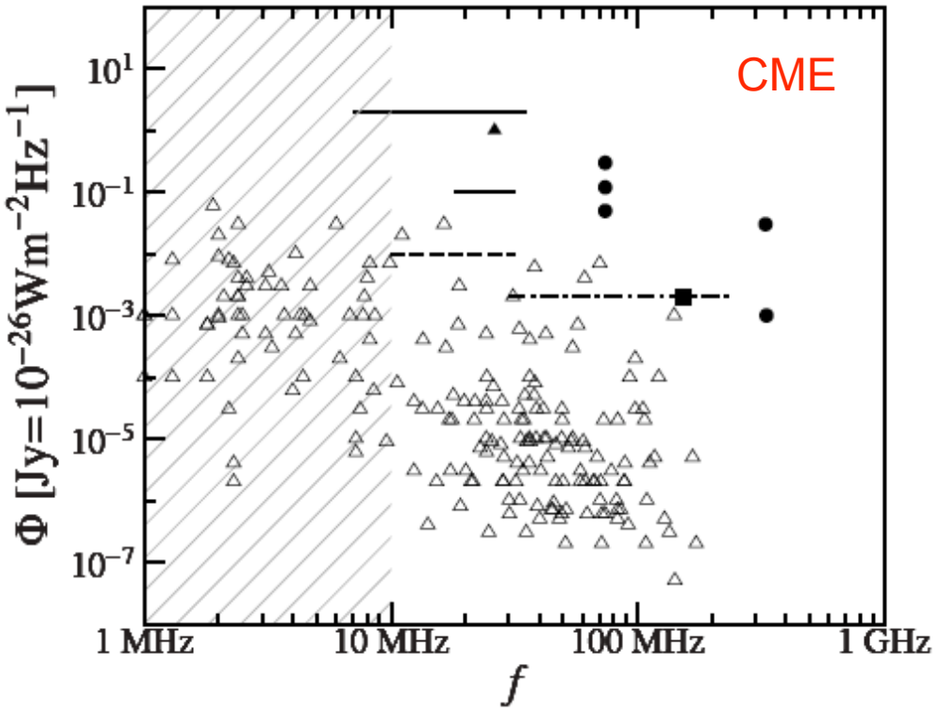

- Low-frequency radio observations of exoplanets

- Theoretical predictions
  - planetary radio emissions
  - energy sources
  - scaling laws
  - extrapolation to exoplanets

- Ongoing observations

- Future observations

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→ Comparative magnetospheric physics (star-planet interactions)

Low-frequency radio observations

1 UA à 1 pc = 1 " ⇒ No imagery

→ Direct detection of a Jovian like emission / burst

→ Planet-Star distinction via polarization (circular/elliptical) & periodicity (orbital ?)

→ Planetary rotation period ⇒ tidal locking ?

→ Measurement of B ⇒ contraints on scaling laws & internal structure models

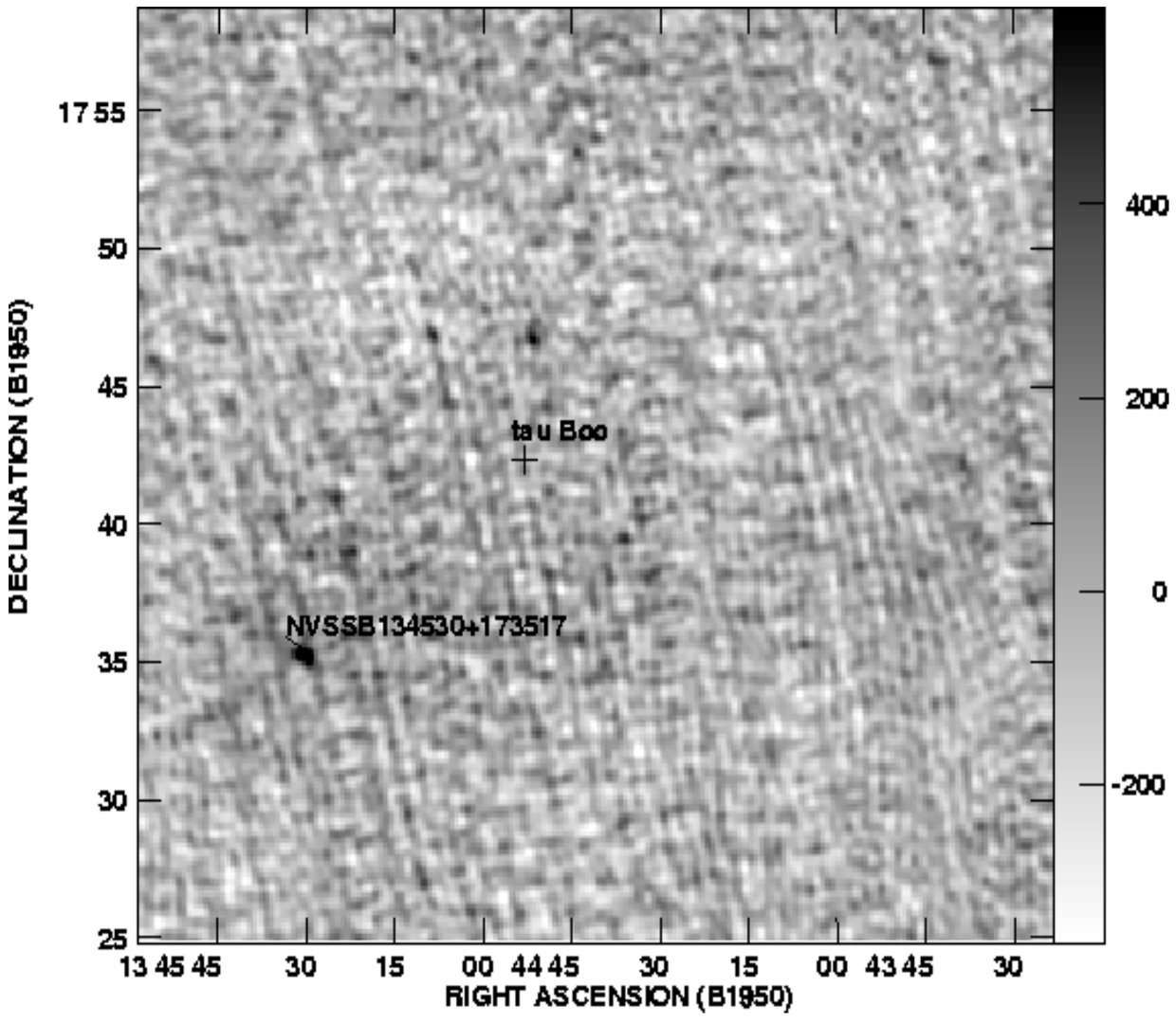
→ Comparative magnetospheric physics (star-planet interactions)

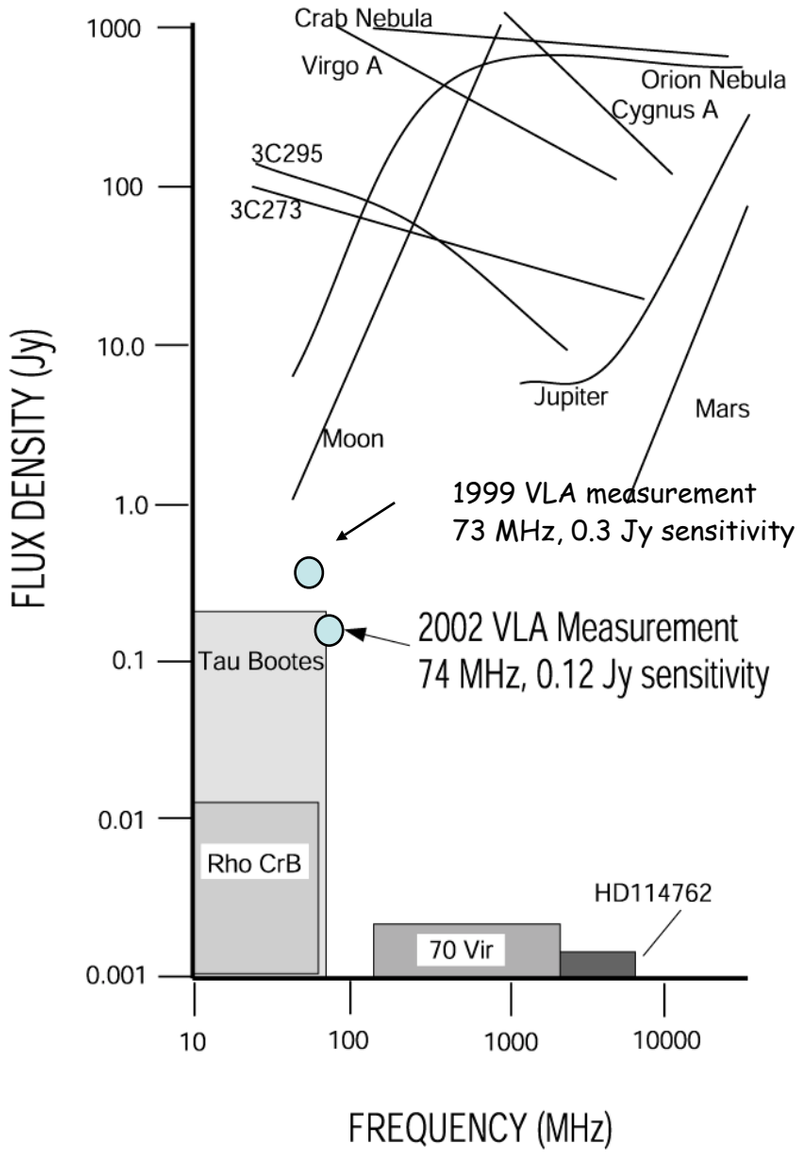
→ Discovery tool (search for more planets) ?

- VLA

  - f ~ 74 MHz
  - target Tau Bootes
  - epochs 1999 - 2003
  - imaging

Very Large Array

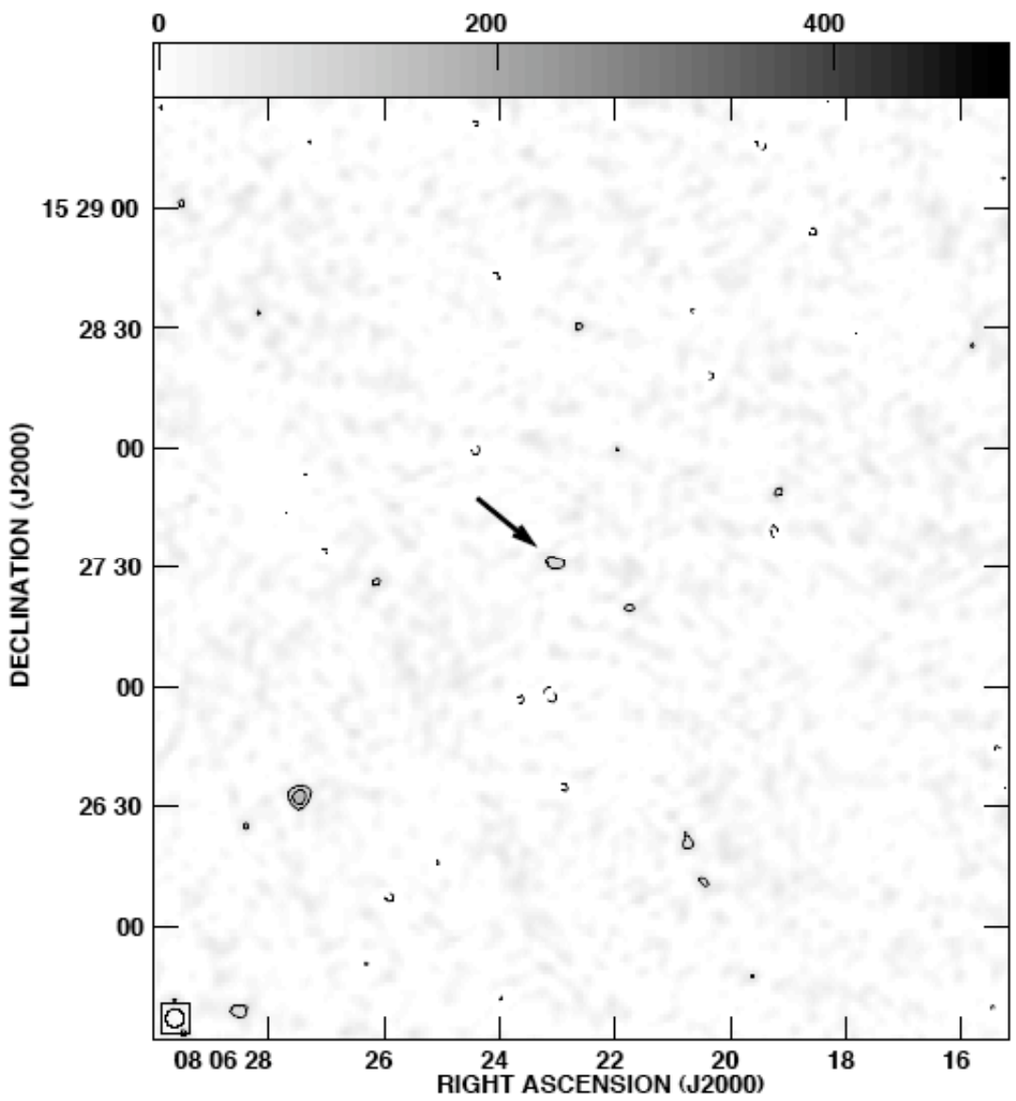


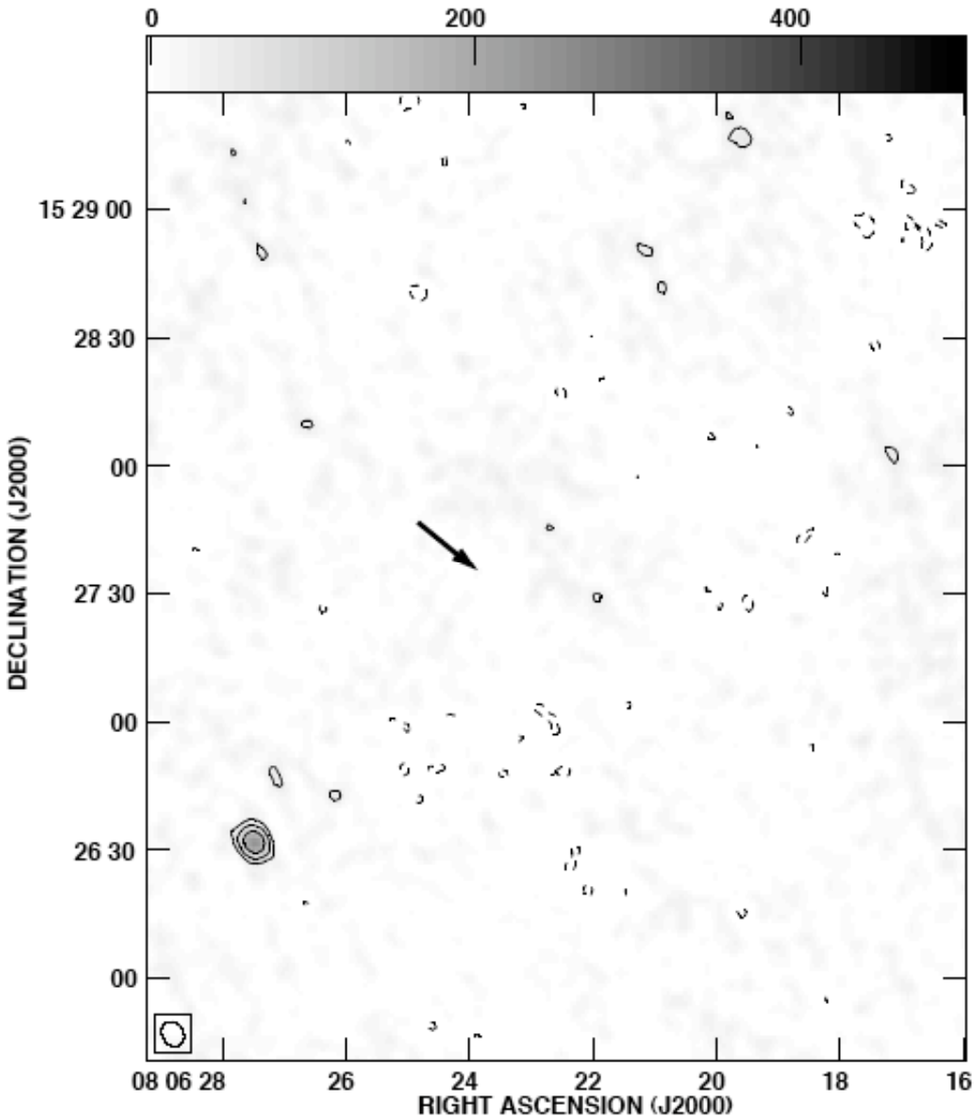


[Bastian et al., 2000 ; Farrell et al., 2003, 2004; Lazio & Farrell, 2007]

- *VLA*
  - f ~ 300 MHz
  - target RX J0806+15 = binary white dwarf
    (+ unipolar induction ?)
  - epochs 2005 & 2006
  - transient ~0.1 mJy

Very Large Array

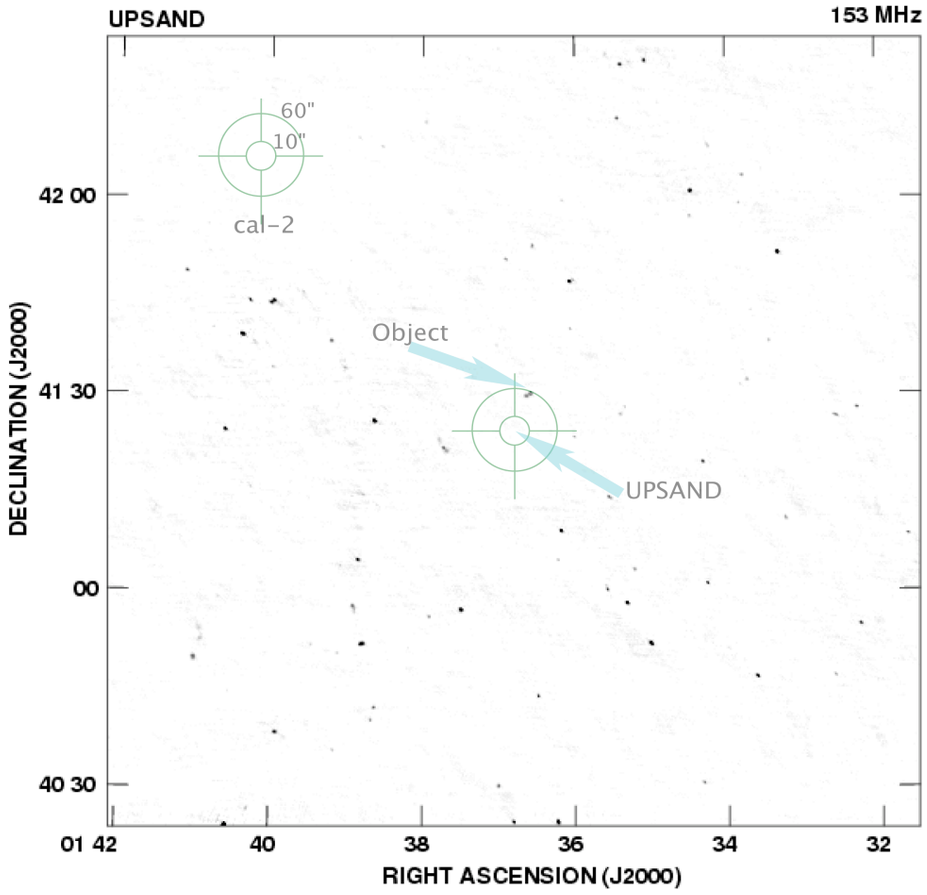


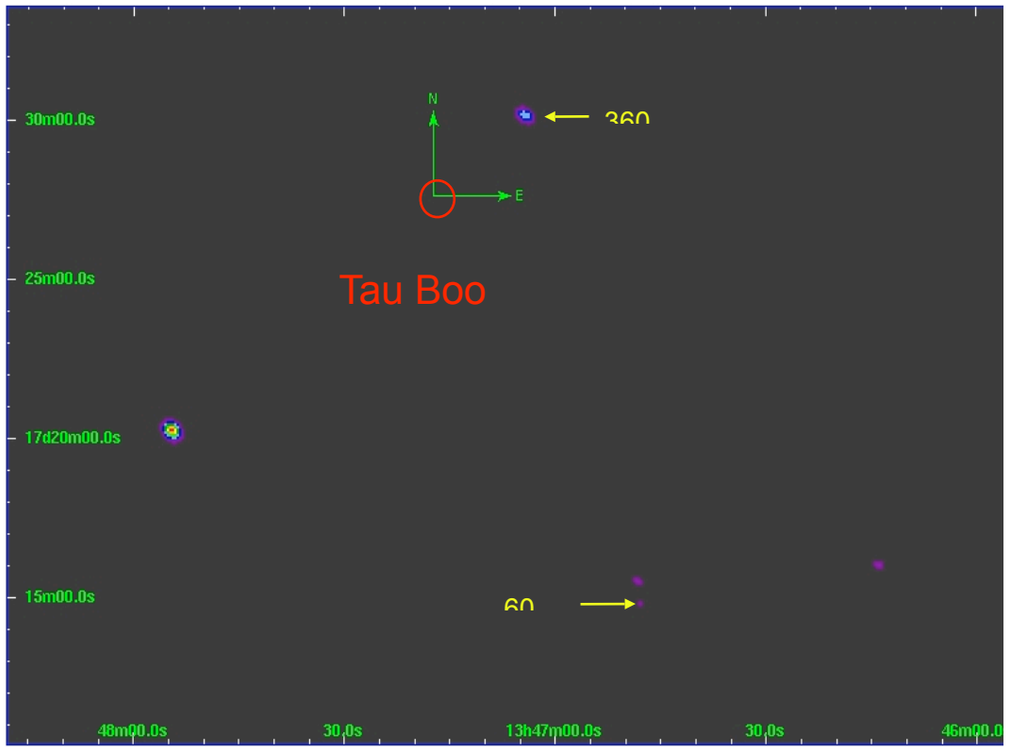


[Ramsay et al., 2007]

- GMRT

- f ~ 153 MHz
- several targets (Tau Boo, Ups And...)
- epochs 2005 - 2007
- imaging + tied array mode
- sensitivity ~ a few mJy





[Winterhalter et al., 2005 ; George and Stevens, 2007 ; ...]

• UTR-2

N

W X E

S

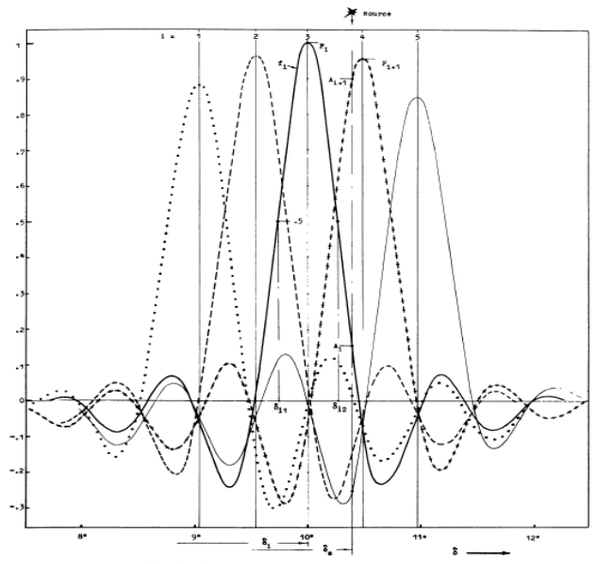


Fig. 5. Five-beam pattern of the north–south array.

- f ~ 10-32 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)

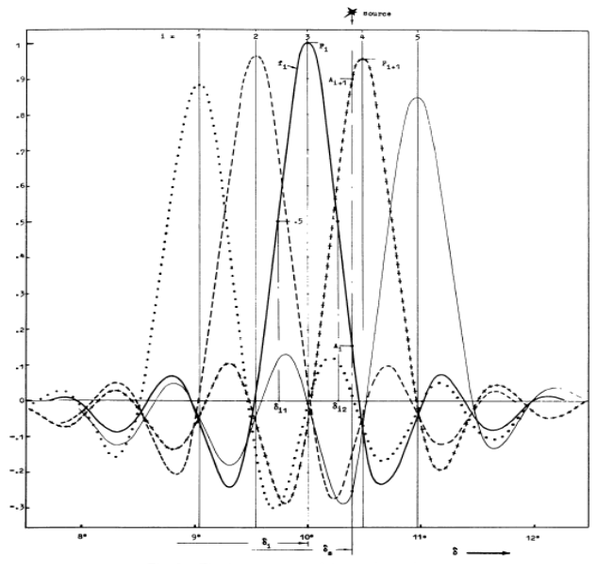
[Zarka et al., 1997 ; Ryabov et al., 2004]

• UTR-2

N

W X E

S



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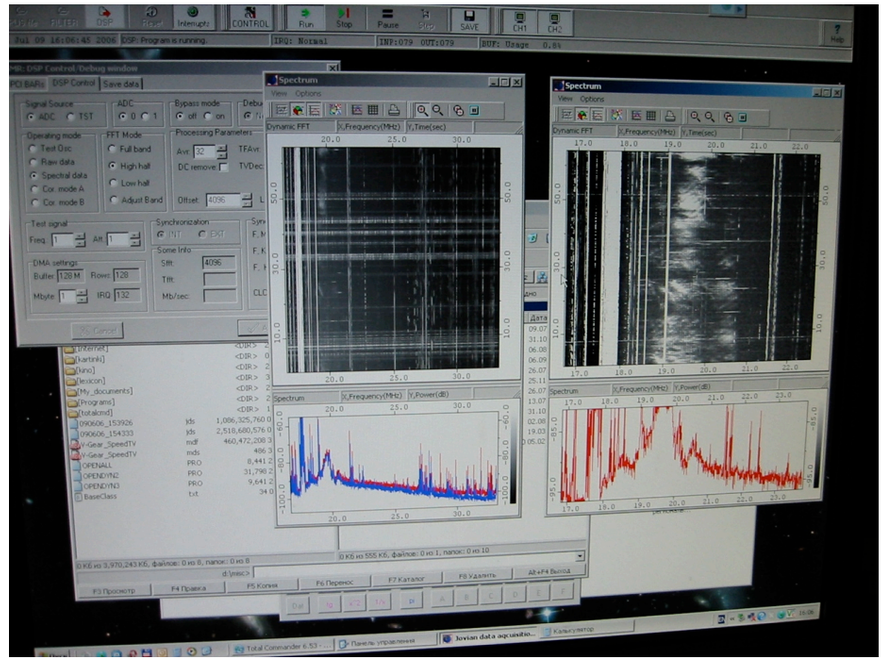

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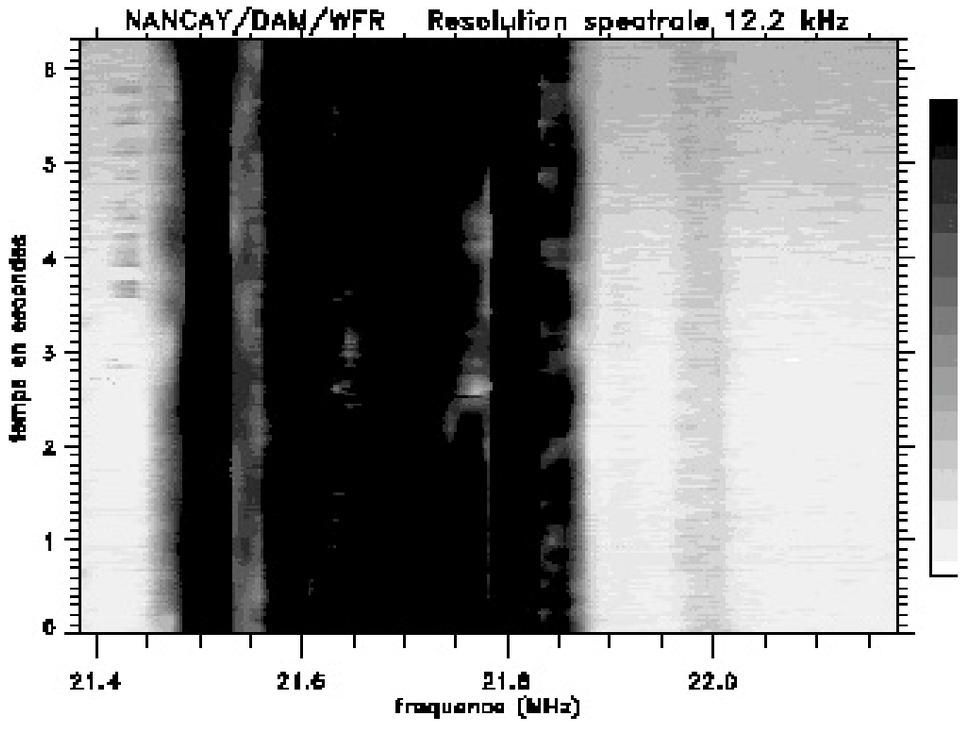
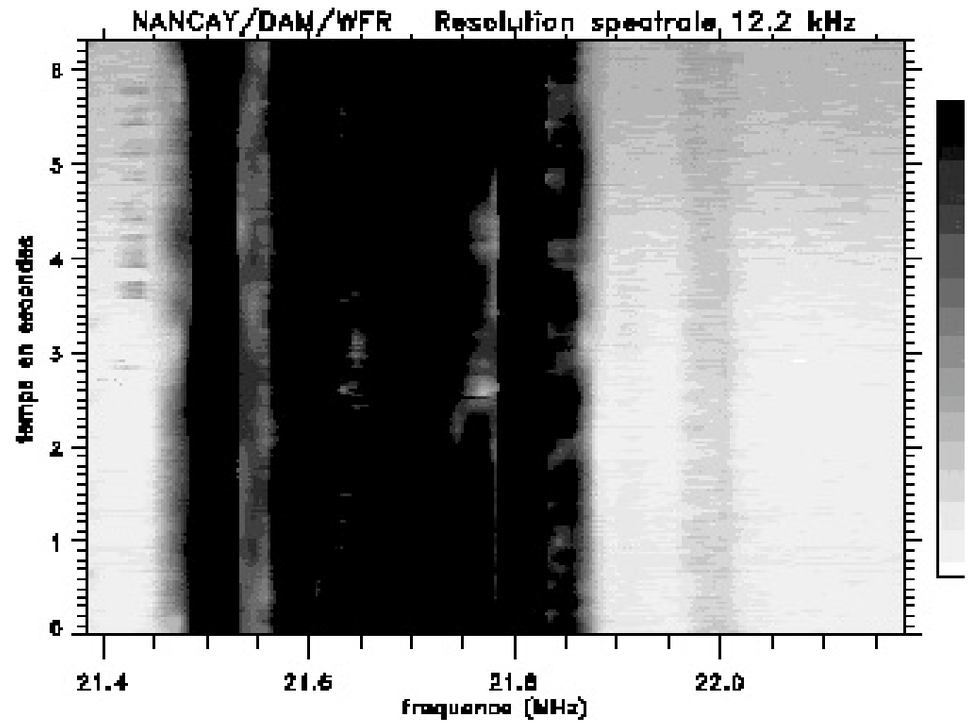
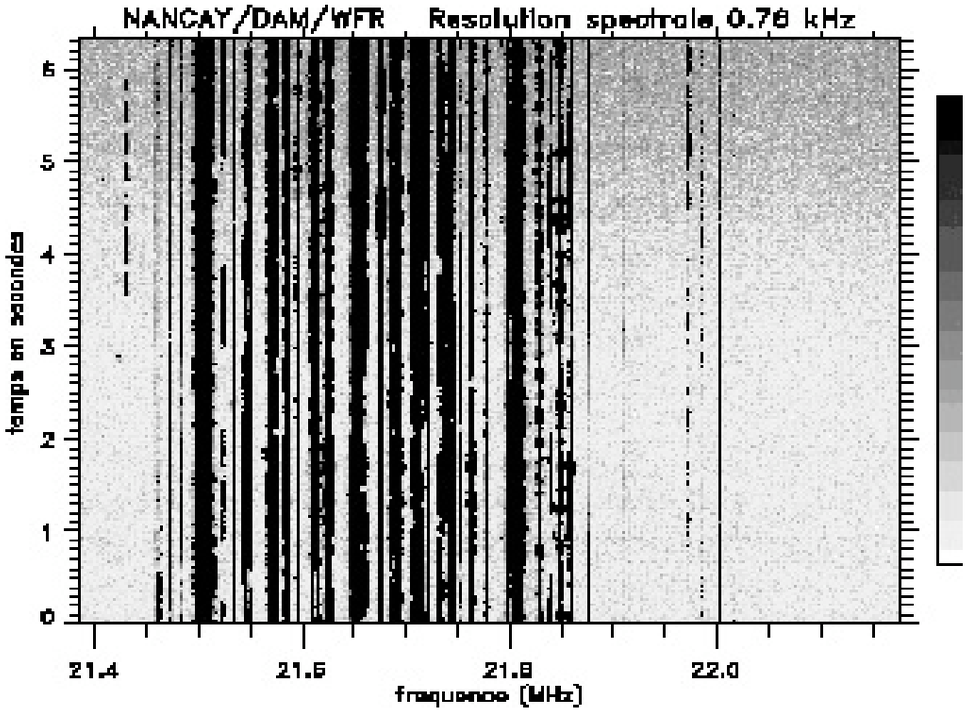
- RFI mitigation



[Zarka et al., 2004]

- RFI mitigation





[Zarka et al., 2004]

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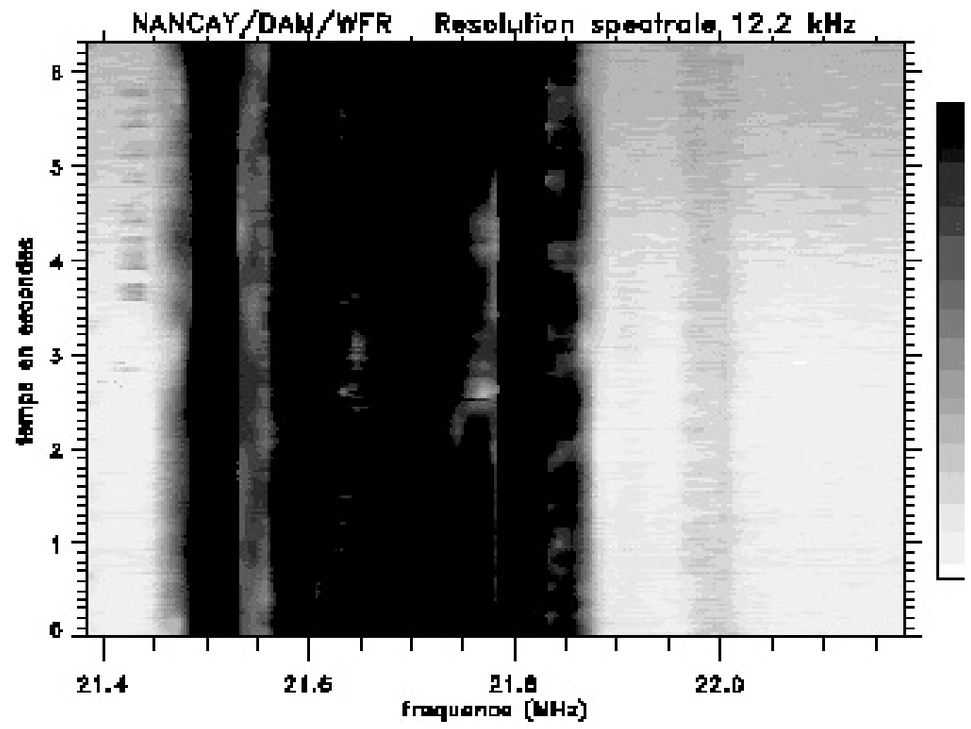
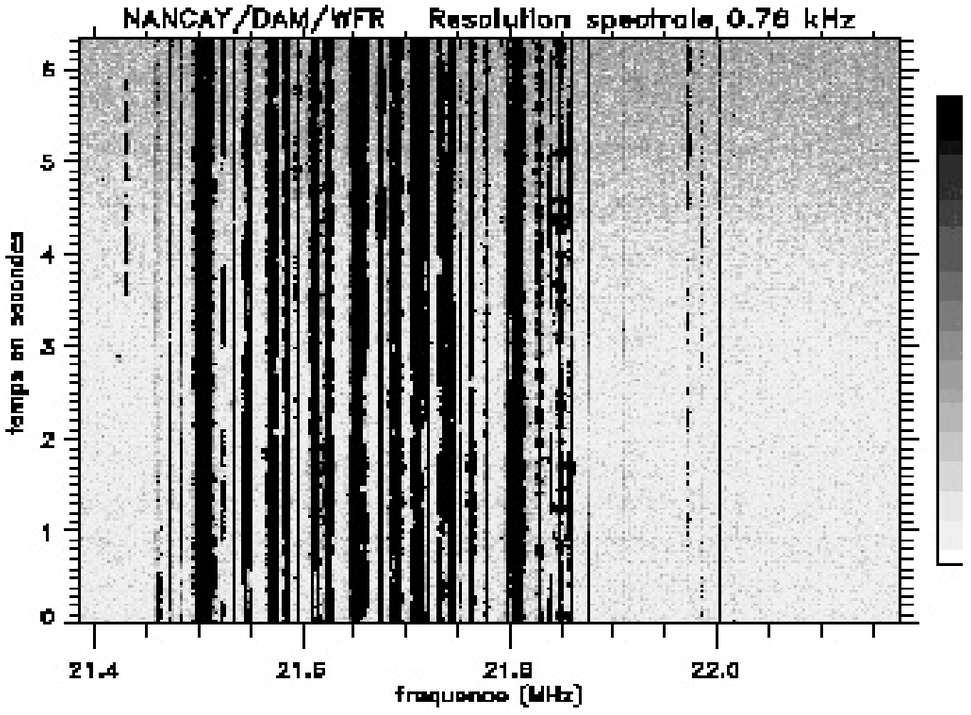
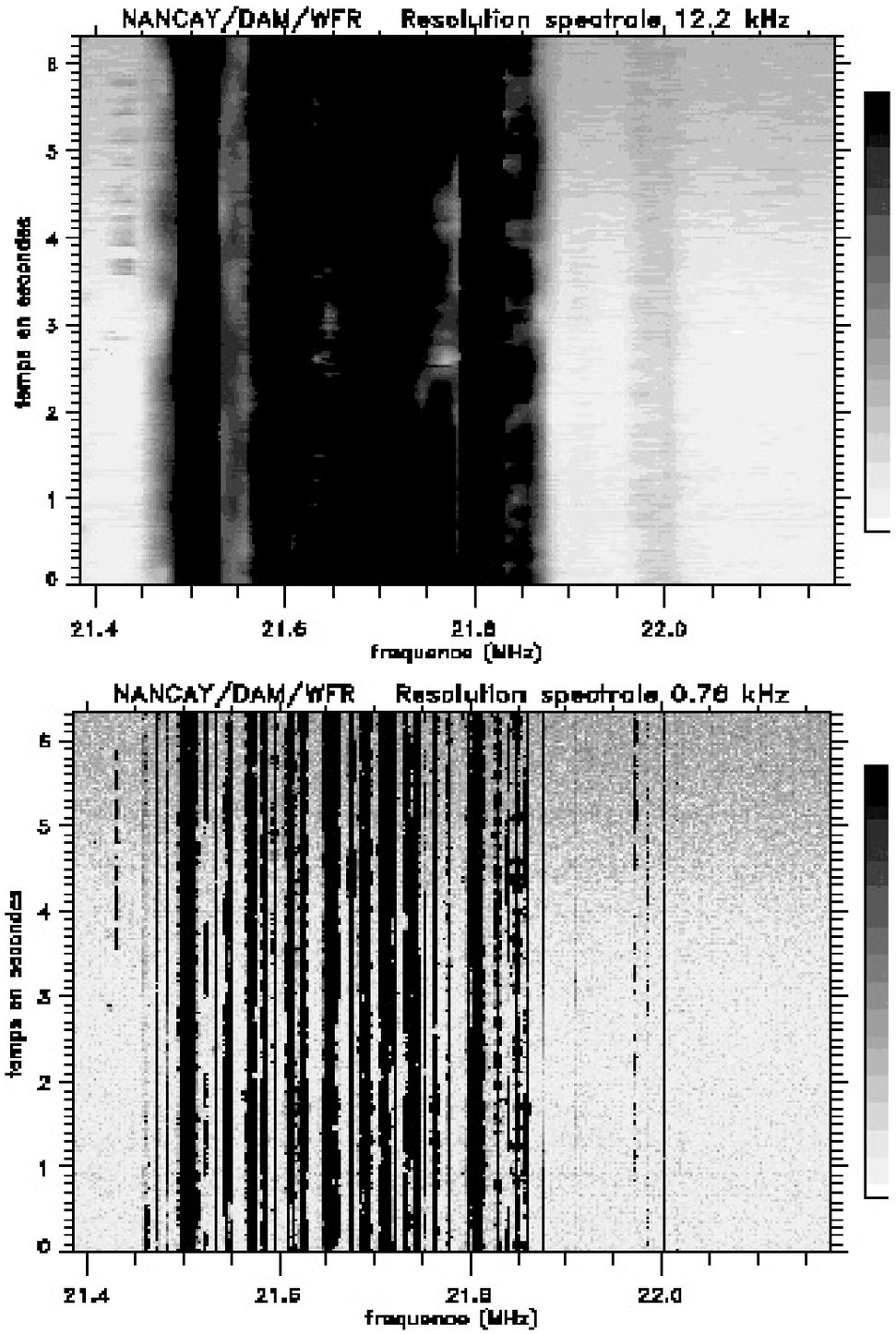


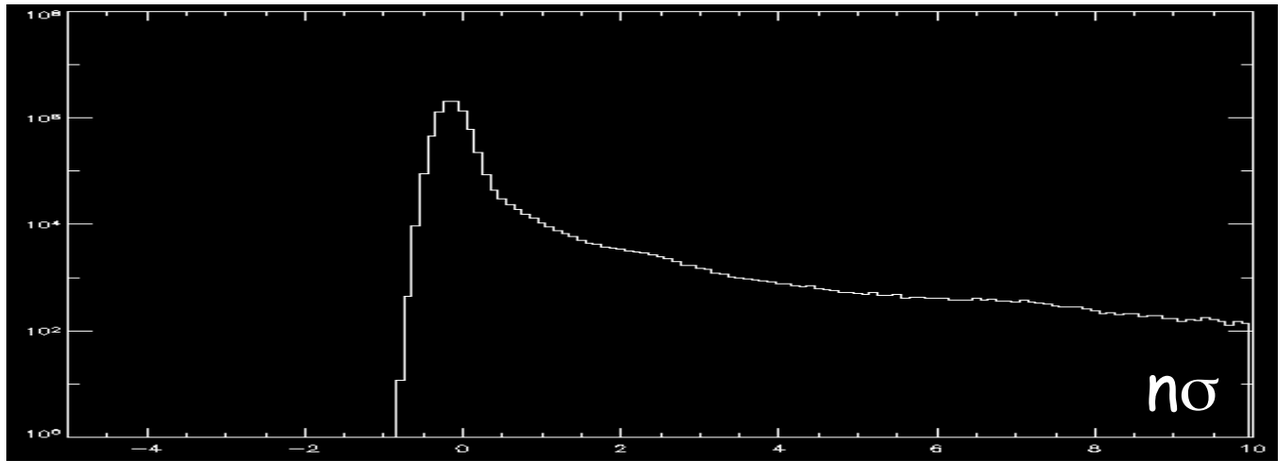


→ High temporal and spectral resolutions
+ large dynamic range required

[Zarka et al., 2004]

- RFI mitigation





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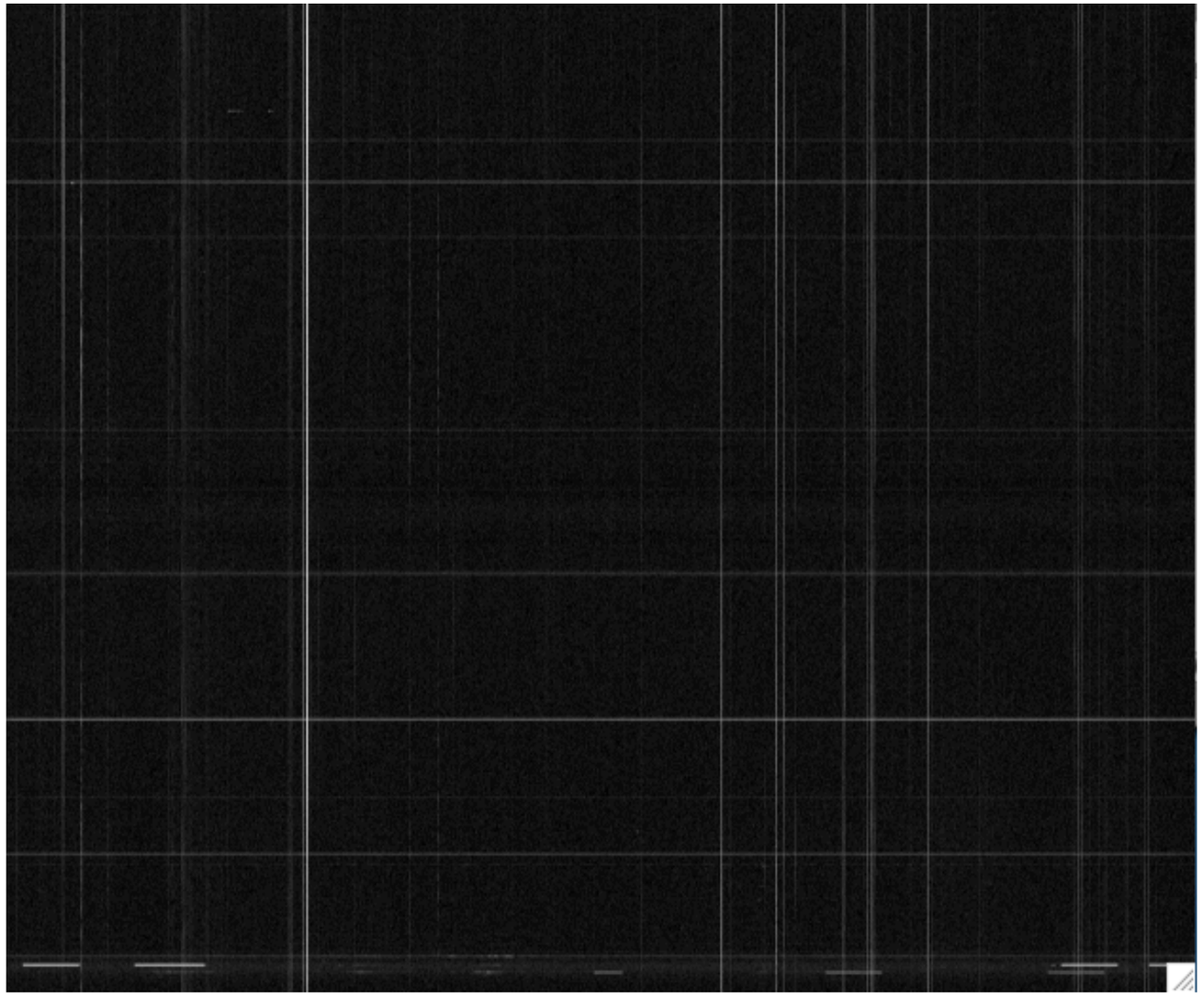

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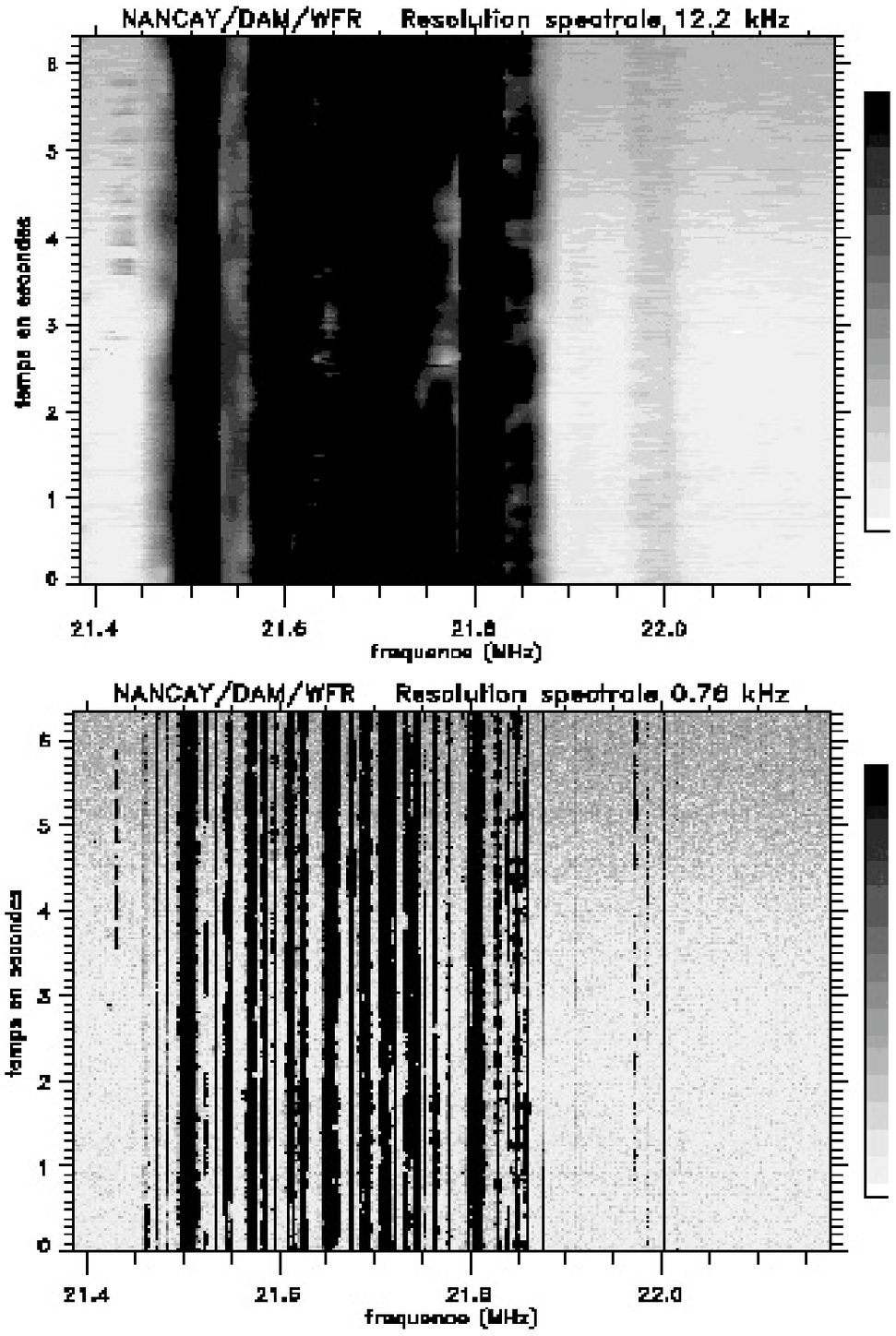

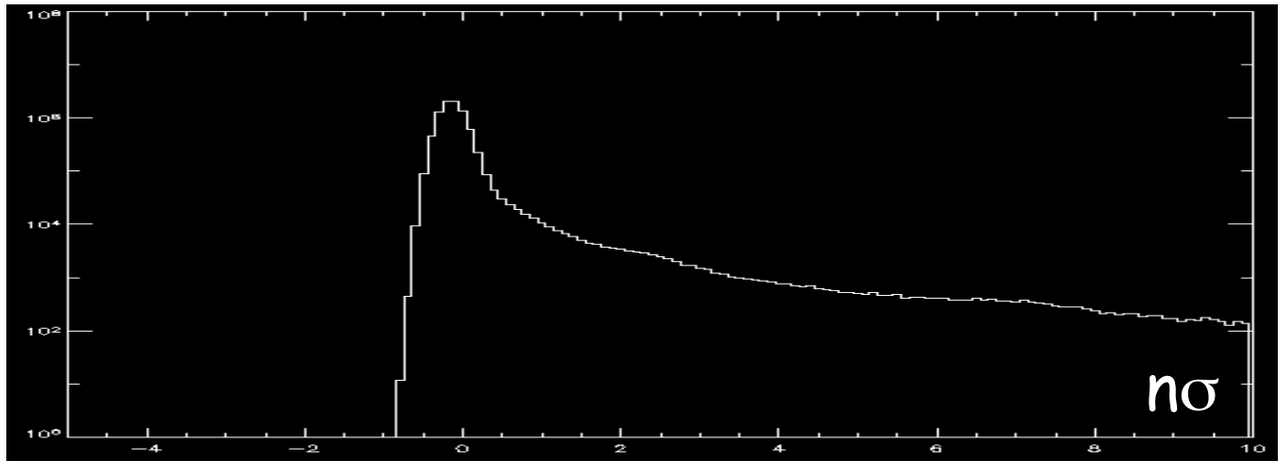

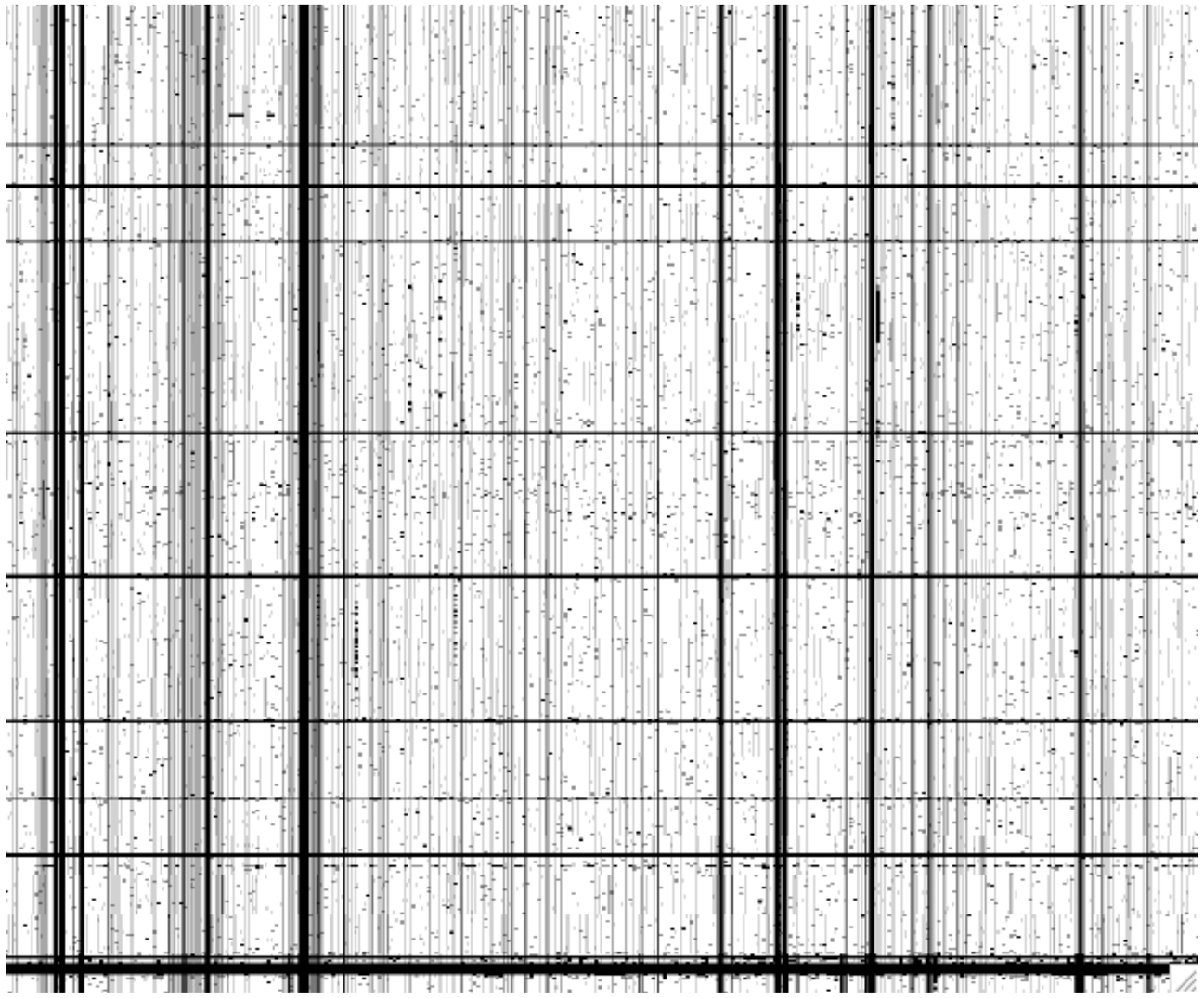

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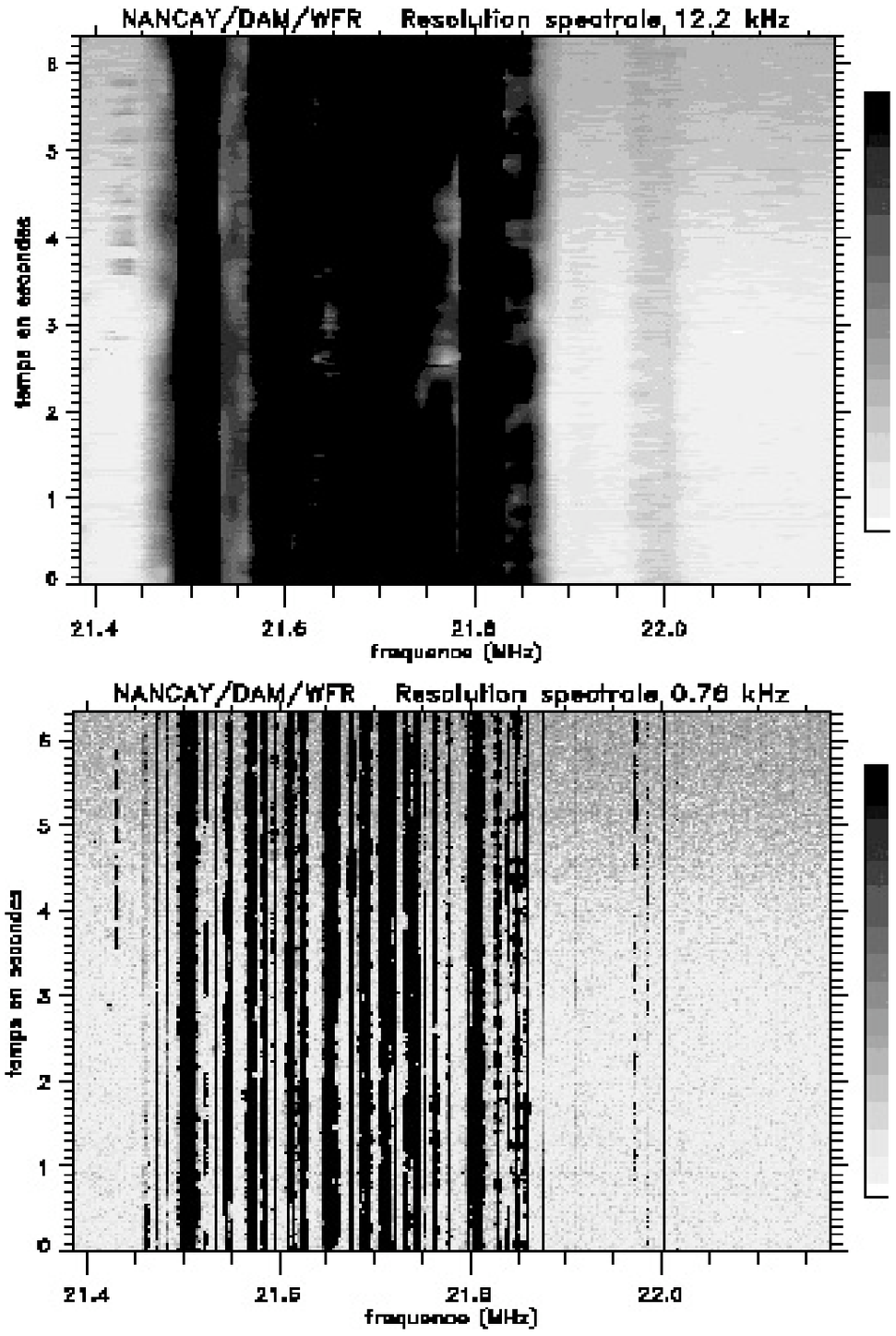

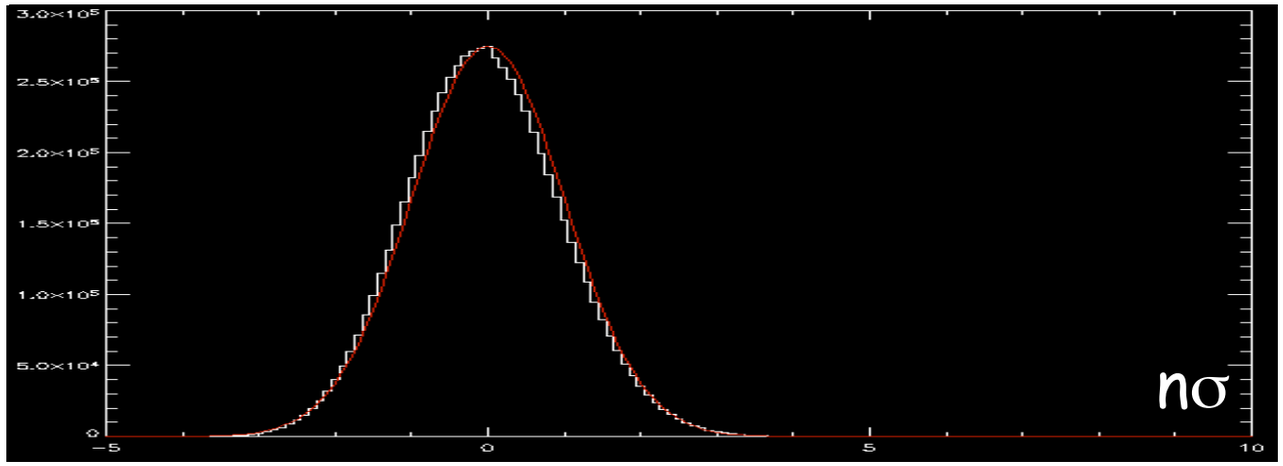

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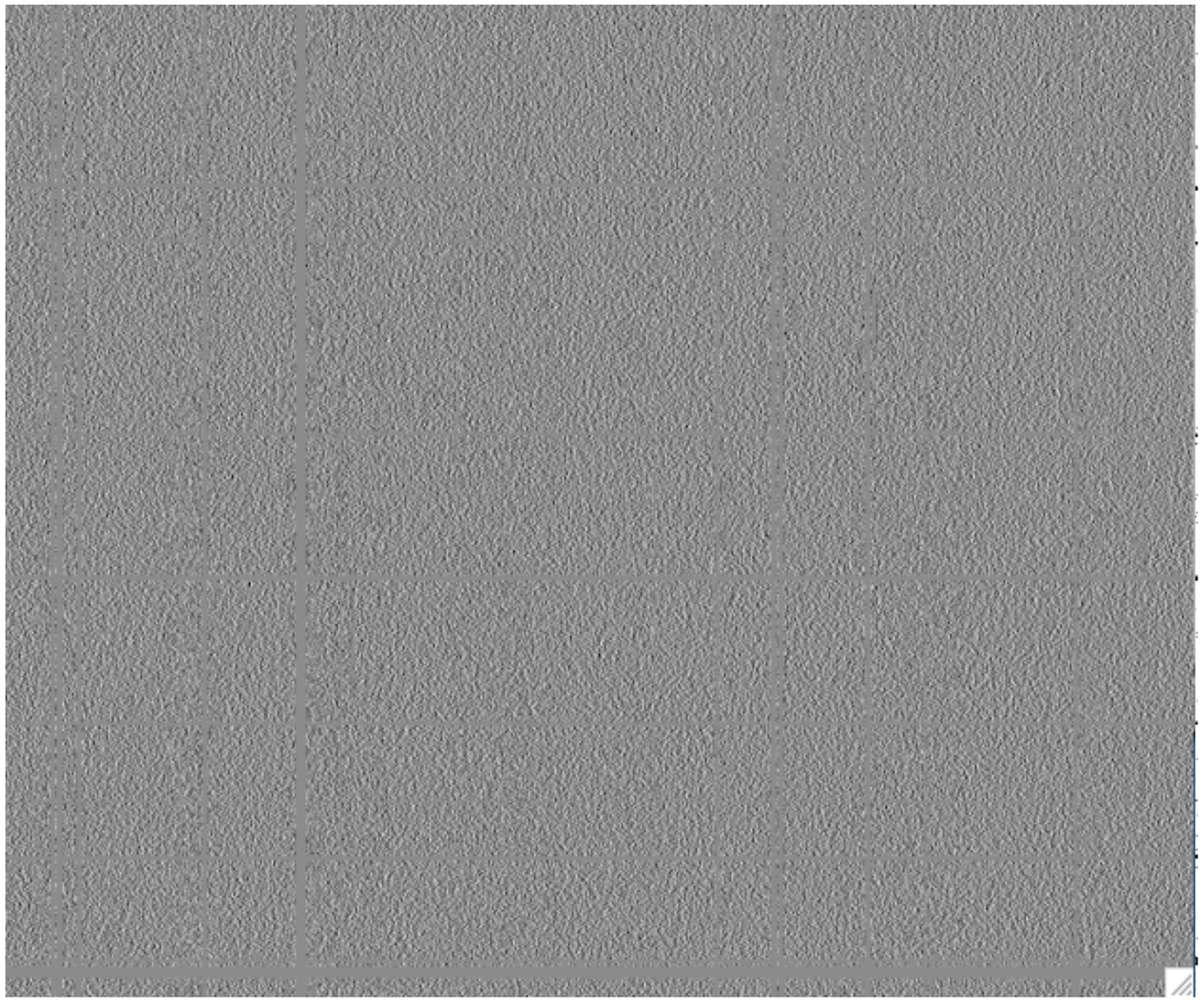
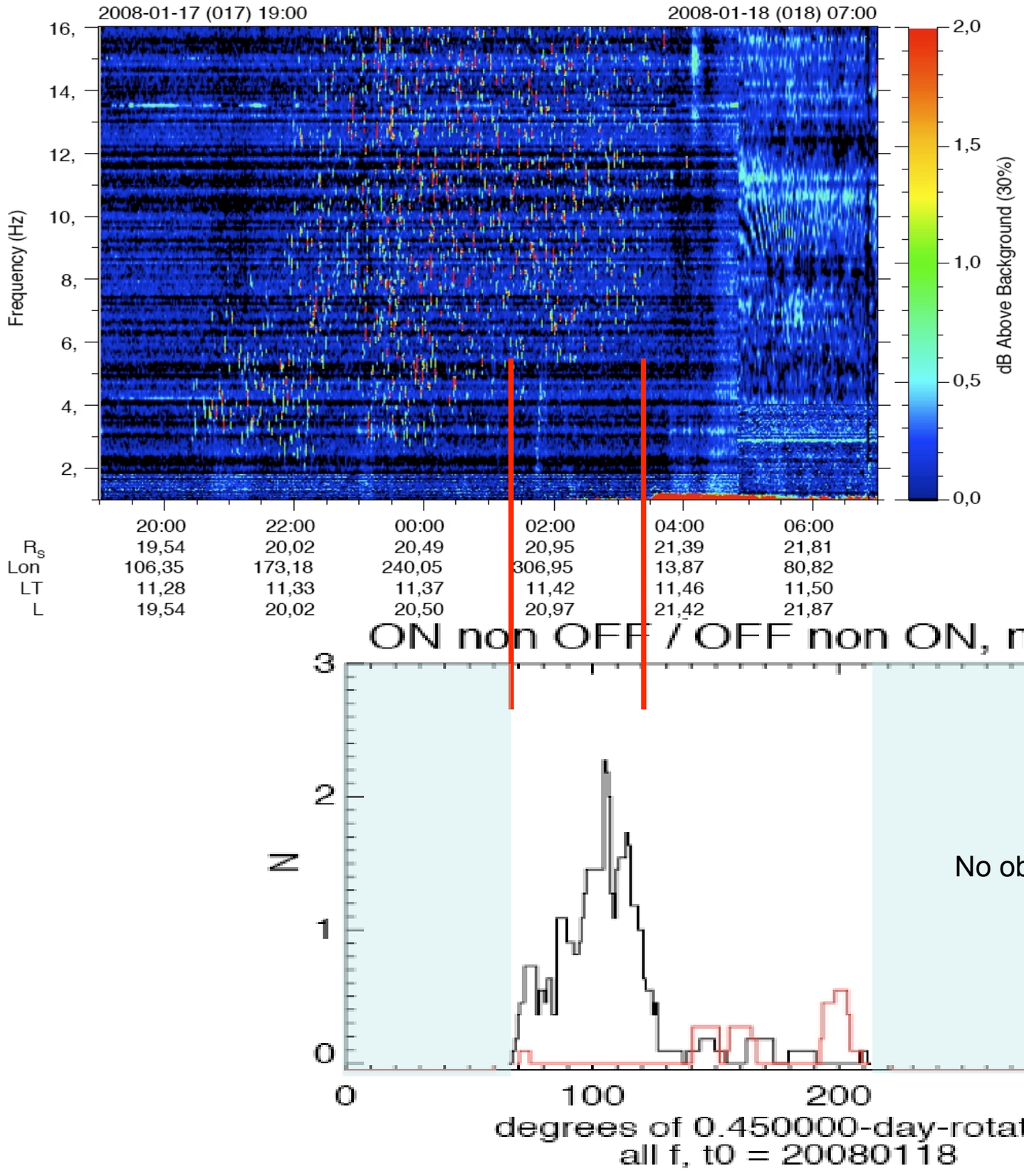


→ High temporal and spectral resolutions
+ large dynamic range required

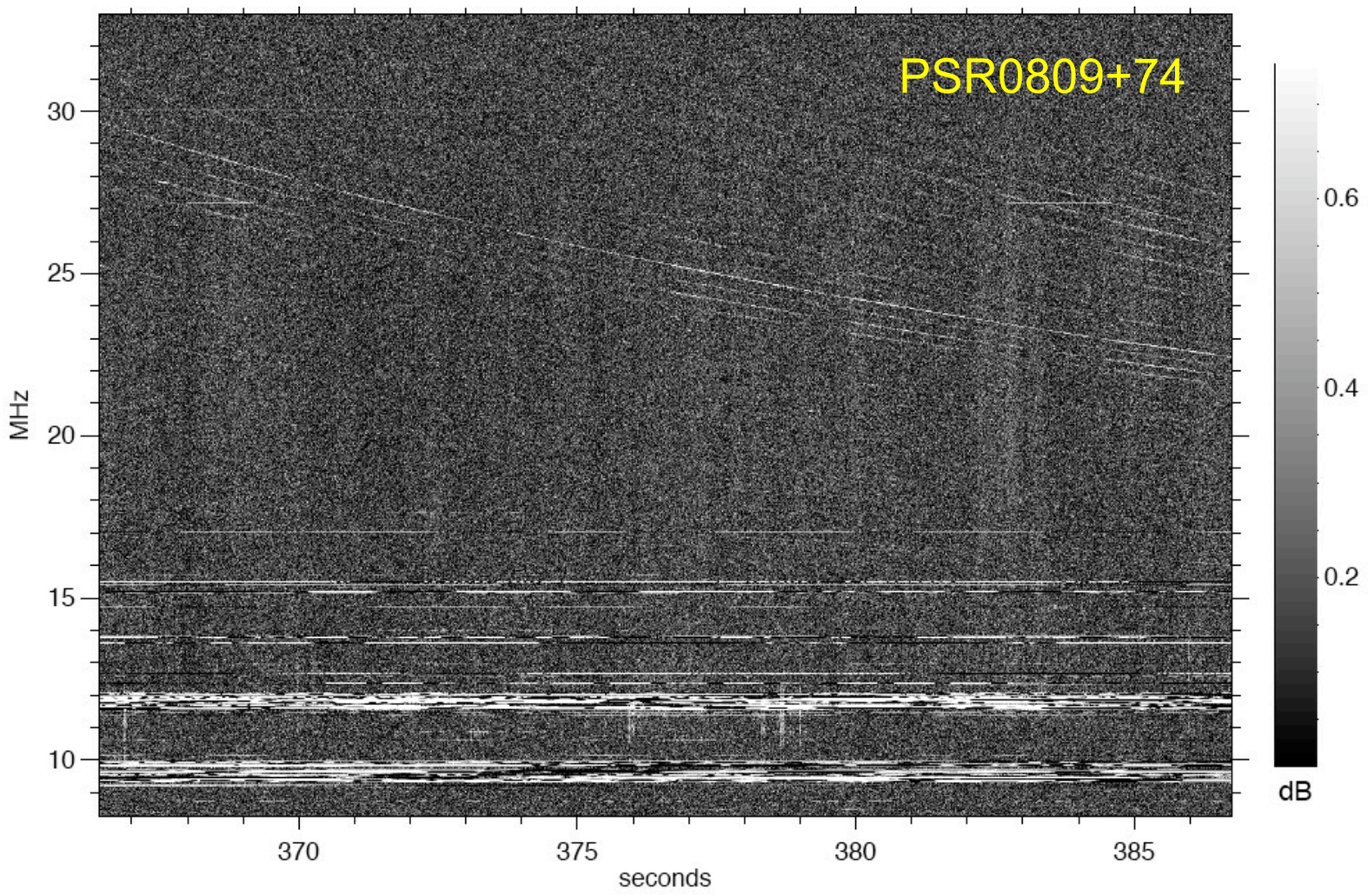
[Zarka et al., 2004]

- UTR-2 : detection of Saturn's lightning



[Zarka et al., 2009]

- De-dispersion & temporal broadening



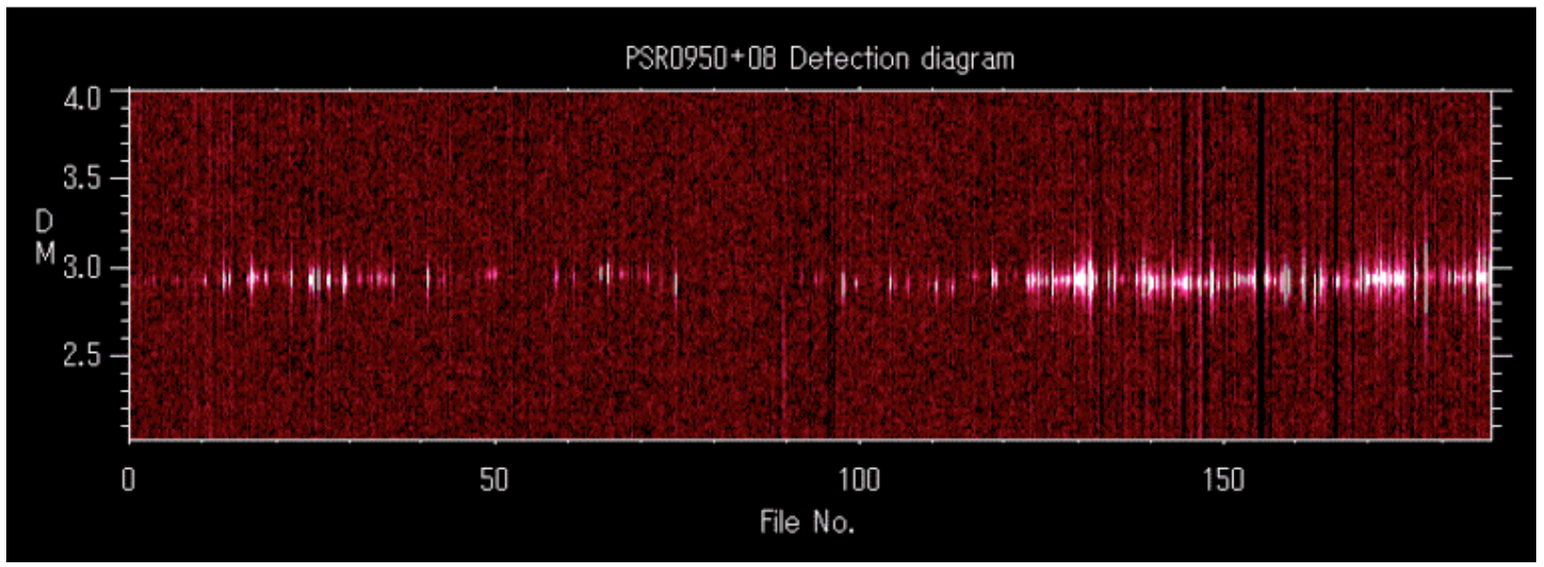
- Dispersion : $\Delta t(\mathrm{sec}) = 4150\ [\mathrm{DM}] / f^2$ (f in MHz)
  → typically 1 - 100 sec

- Pulse temporal broadening : $\tau_B \propto f^{-4.4}$ (Kolmogorov)
  → typically 1 - 100 msec

- UTR-2 : parametric dedispersion of pulsar signals

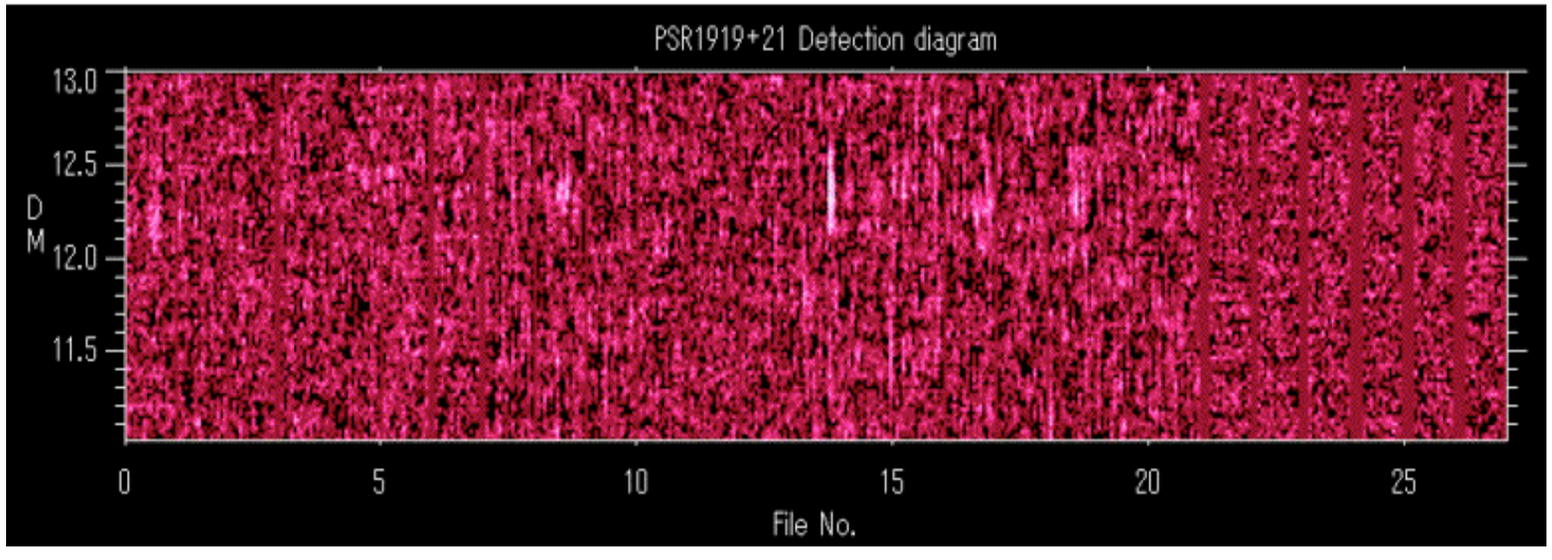
Example of pulse detection: strong signal

PSR0950+08 DM=2.95



Example of pulse detection: weak signal

PSR1919+21 DM=12.4



[Ryabov et al., 2004]

Optical observations

Optical observations

- Super-flares ?

[Rubenstein & Schaefer, 2000 ; Schaefer et al., 2000]

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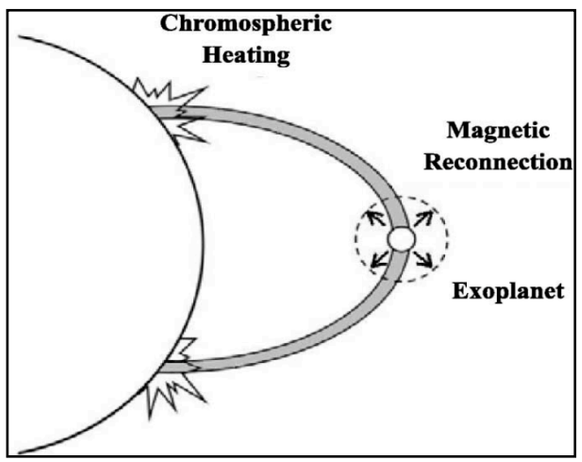

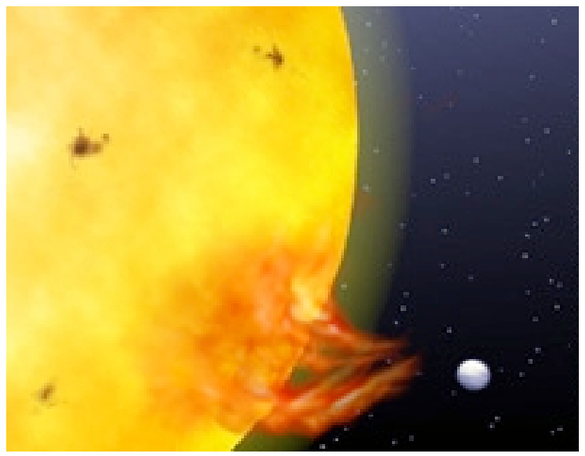

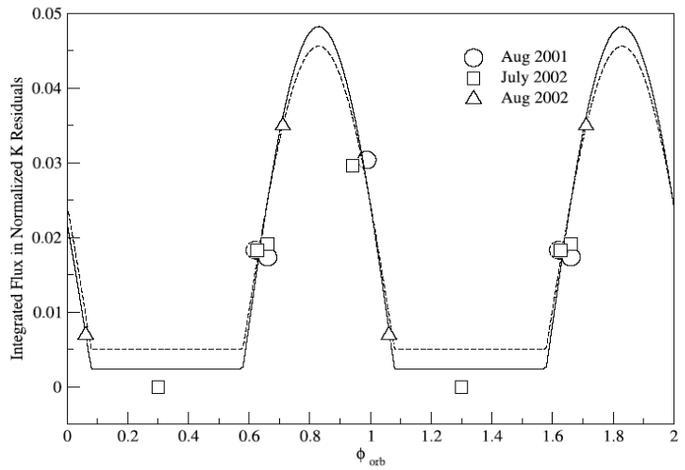

➡ unipolar or dipolar interaction ?

Optical observations

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[Rubenstein & Schaefer, 2000 ; Schaefer et al., 2000]

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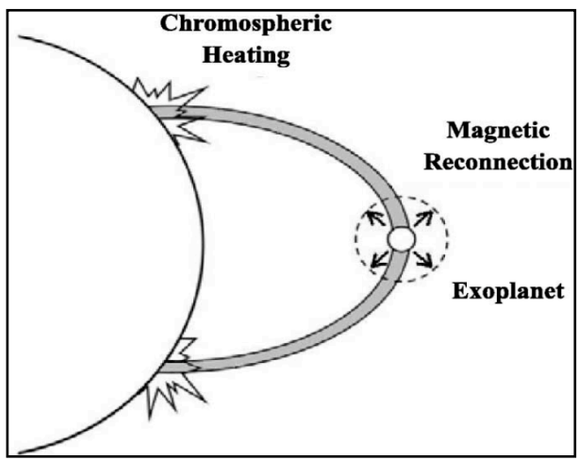

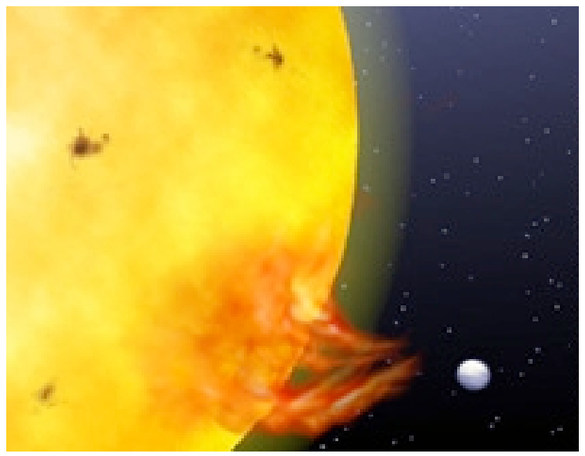

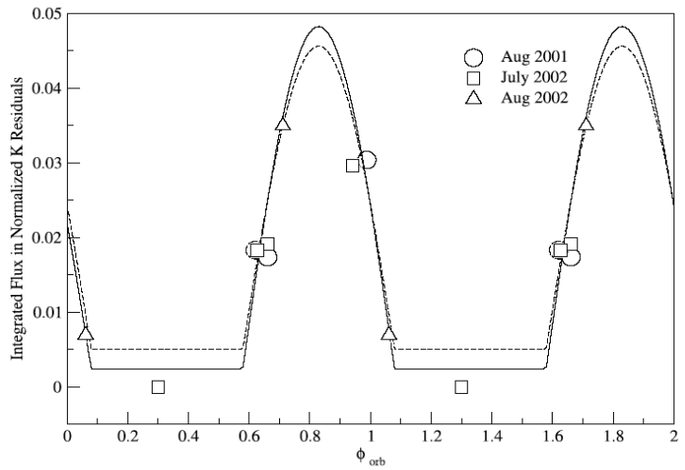

➡ unipolar or dipolar interaction ?

➡ hot spot 60° ahead of sub-planetary point (P=3.1d)

→ Ok wrt "backwards" Alfén waves propagation in the stellar wind [Preusse et al., 2006]

Optical observations

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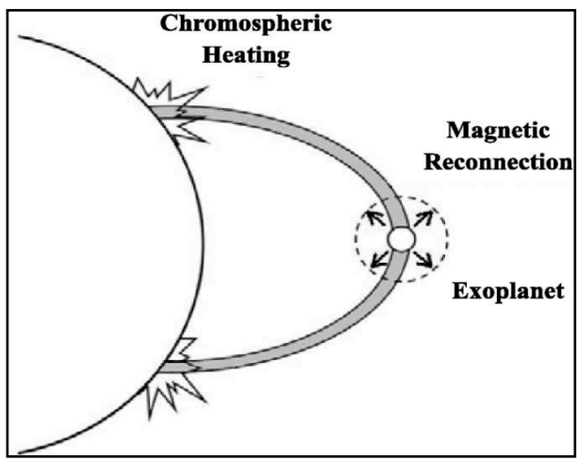

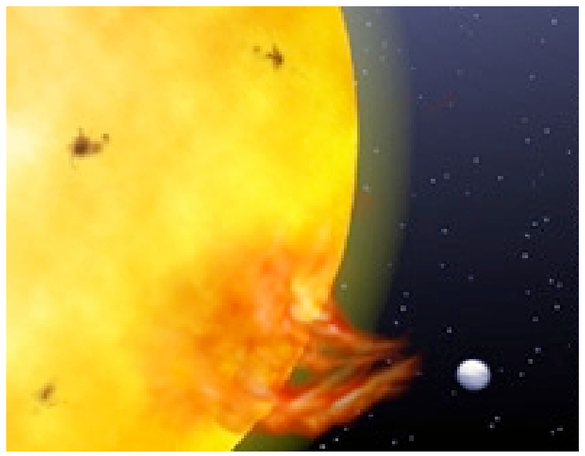

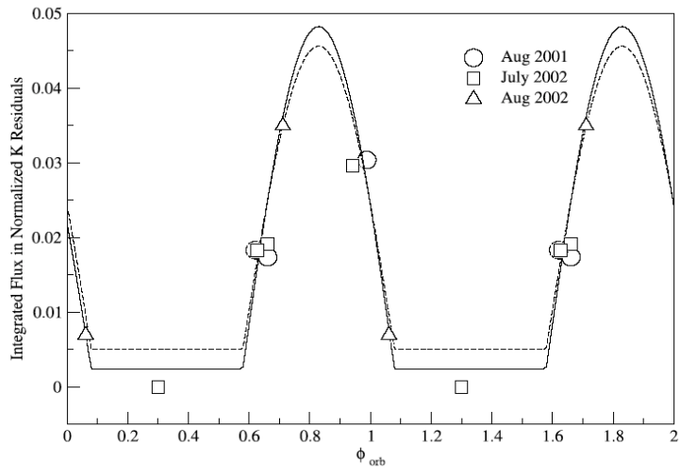

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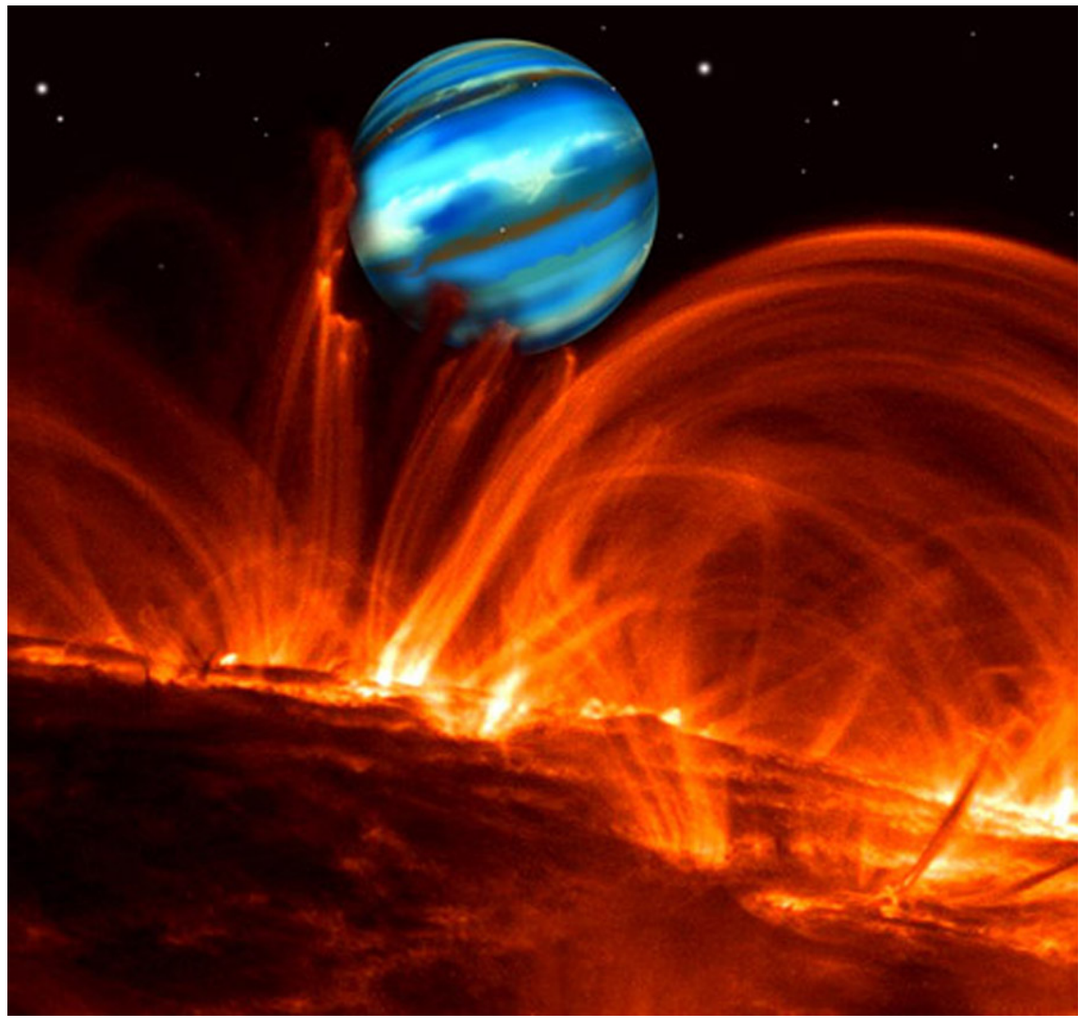
➡ $P_{spot} > 10^{19}$ W but $P_d = 0.15 \times 10^{15} \times \pi R_J^2$ W → energy crisis ?

→ larger obstacle or wind strength + stellar B ? (F_X ~10× solar)

[Shkolnik et al., 2005 ; Zarka, 2007]

ESPaDOnS spectropolarimeter @ CFHT

- Magnetic field of Tau Bootes



[Catala et al., 2007]

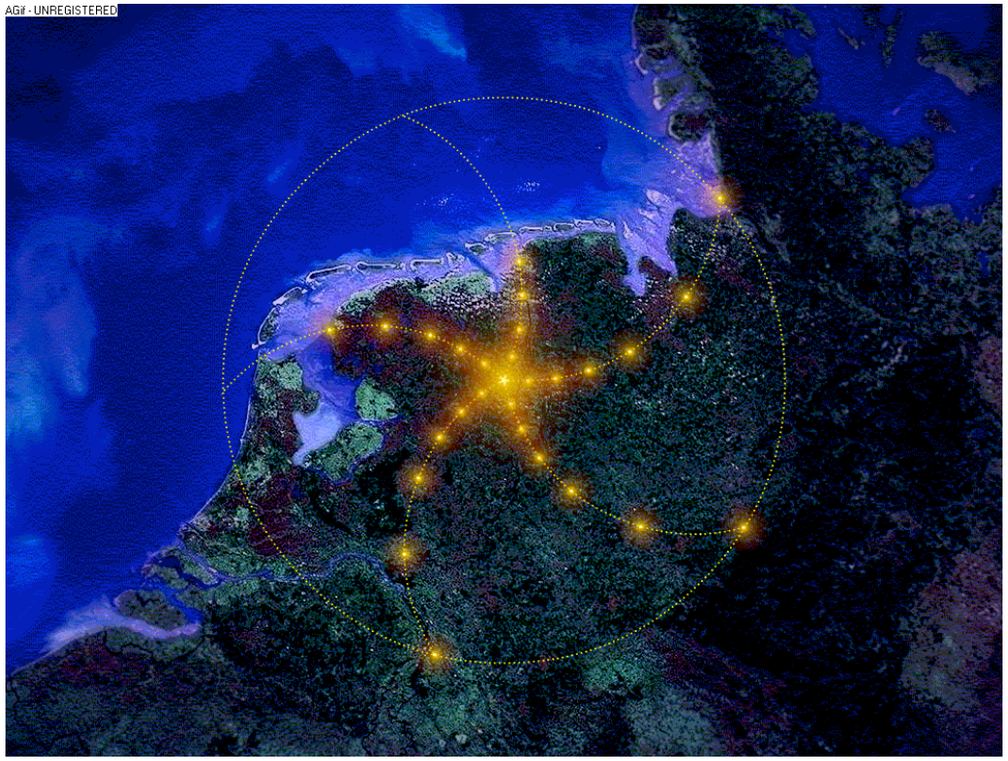
- Low-frequency radio observations of exoplanets

- Theoretical predictions
  - planetary radio emissions
  - energy sources
  - scaling laws
  - extrapolation to exoplanets

- Ongoing observations

- Future observations

- LOFAR



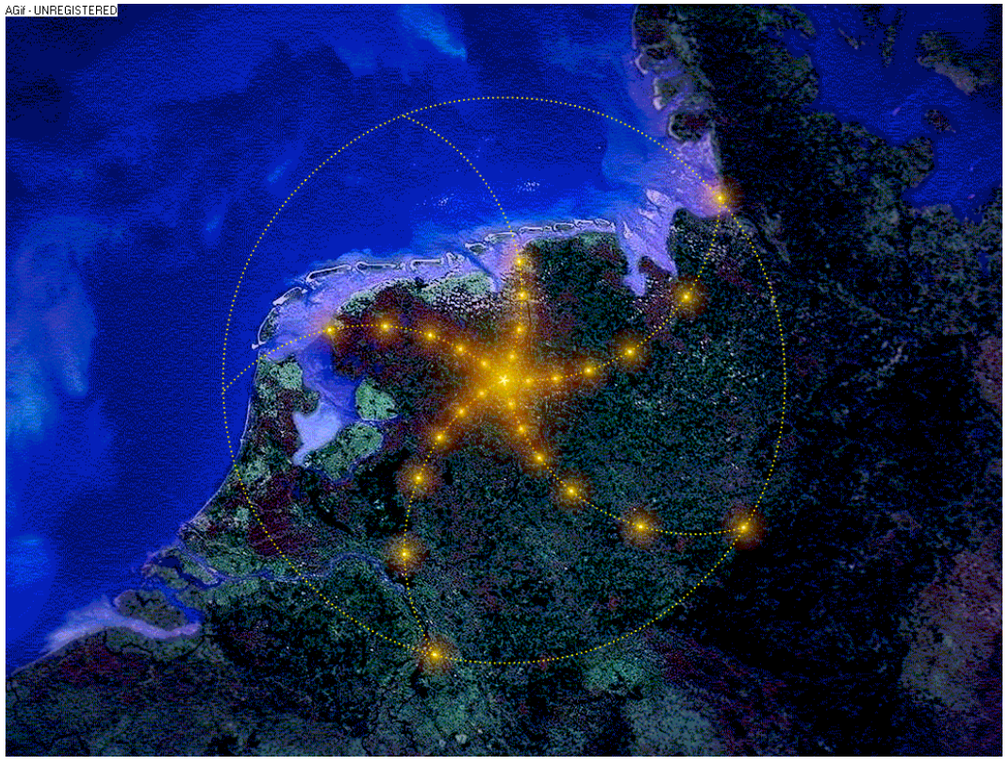
www.lofar.org

- 30-250 MHz
- Epoch 2009+ (solar max. !)
- Sensitivity ≤ mJy
- Imaging + tied array modes
- Built-in RFI mitigation & ionospheric calibration

➔ Exoplanet search part of "Transients" KP

➔ Candidate exoplanets + all close-by stars

- LOFAR



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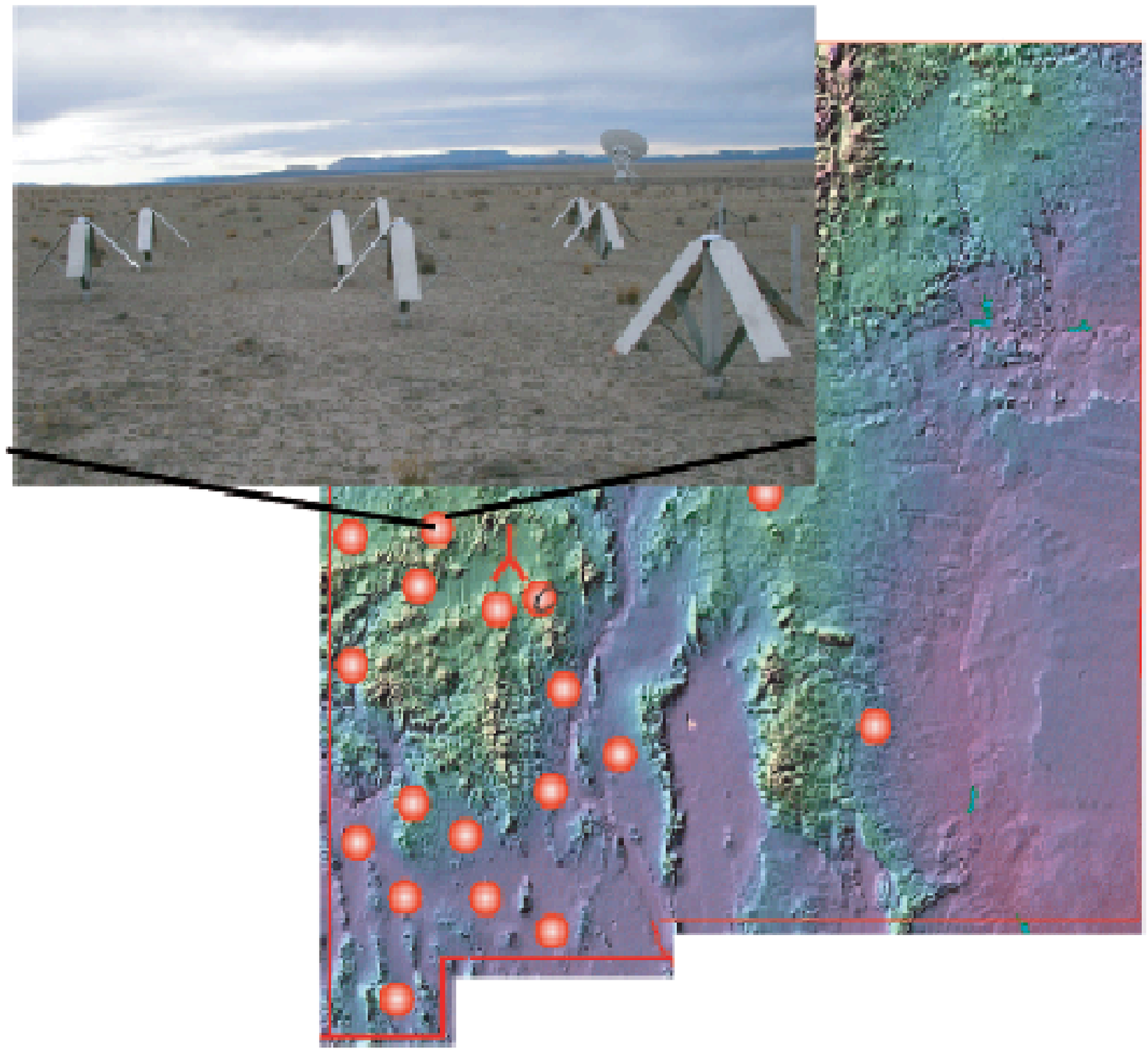
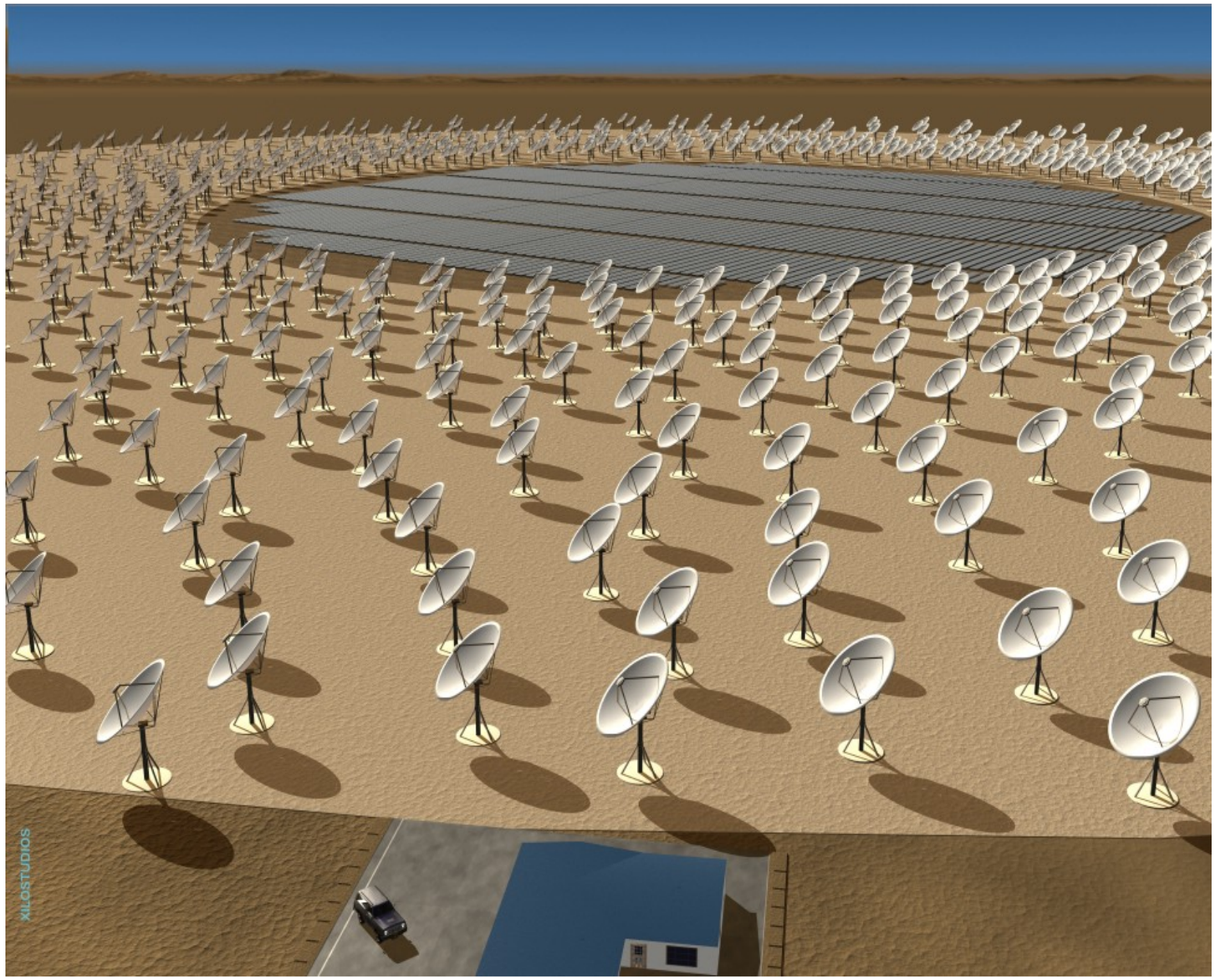


Long Wavelength Array

[Lazio et al., 2008]

- SKA



- High frequencies (0.2-20 GHz)
- ≥2015-20
- Sensitivity down to μJy ?

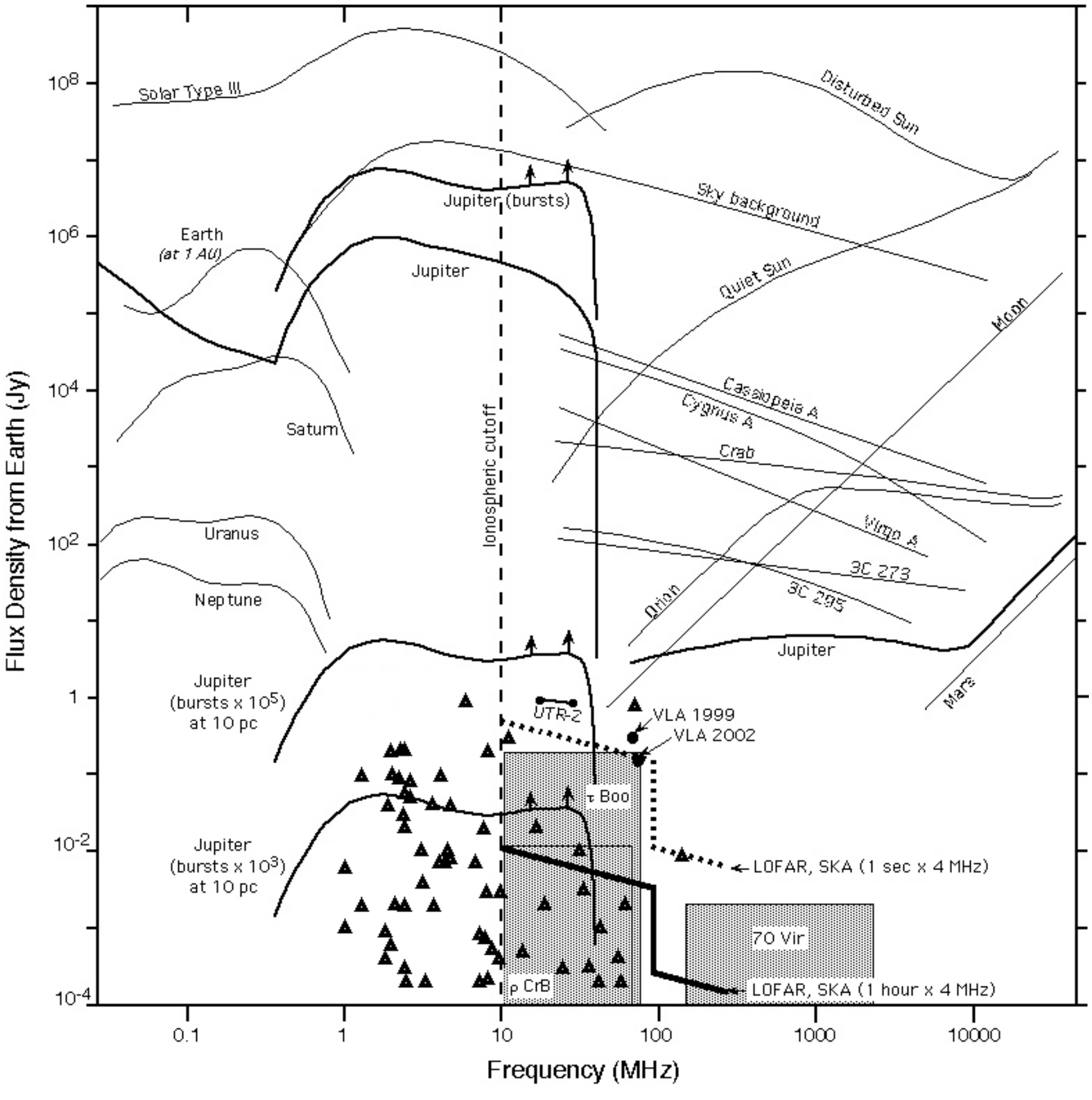
➔ Unipolar inductor systems

(e.g. hot Earths around White dwarfs)

➔ Detection of artificial emissions ?

➔ Astrometry (planets around M dwarfs)

www.skatelescope.org


Flux Density from Earth (Jy)
Frequency (MHz)
Solar Type III
Disturbed Sun
Sky background
Jupiter (bursts)
Earth
(at 1 AU)
Jupiter
Quiet Sun
Moon
Saturn
Cassiopeia A
Cygnus A
Crab
Virgo A
3C 273
3C 295
Orion
Uranus
Neptune
Jupiter
Mars
Ionospheric cutoff
Jupiter
(bursts x 10^5)
at 10 pc
UTR-2
VLA 1999
VLA 2002
τ Boo
Jupiter
(bursts x 10^3)
at 10 pc
LOFAR, SKA (1 sec x 4 MHz)
70 Vir
ρ CrB
LOFAR, SKA (1 hour x 4 MHz)

[Zarka, 2004]

- LOFAR-on-the-Moon ?