Planet - Star
Plasma Interactions

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References :

• Zarka, P., Plasma interactions of exoplanets with their parent star and associated radio emissions, Planet. Space Sci., 55, 598-617, 2007.

• Griessmeier, J.-M., P. Zarka and H. Spreeuw, Predicting low-frequency radio fluxes of known extrasolar planets, Astron. Astrophys., 475, 359-368, 2007.

- Interest of LF radio observations of exoplanets

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

- Conclusion

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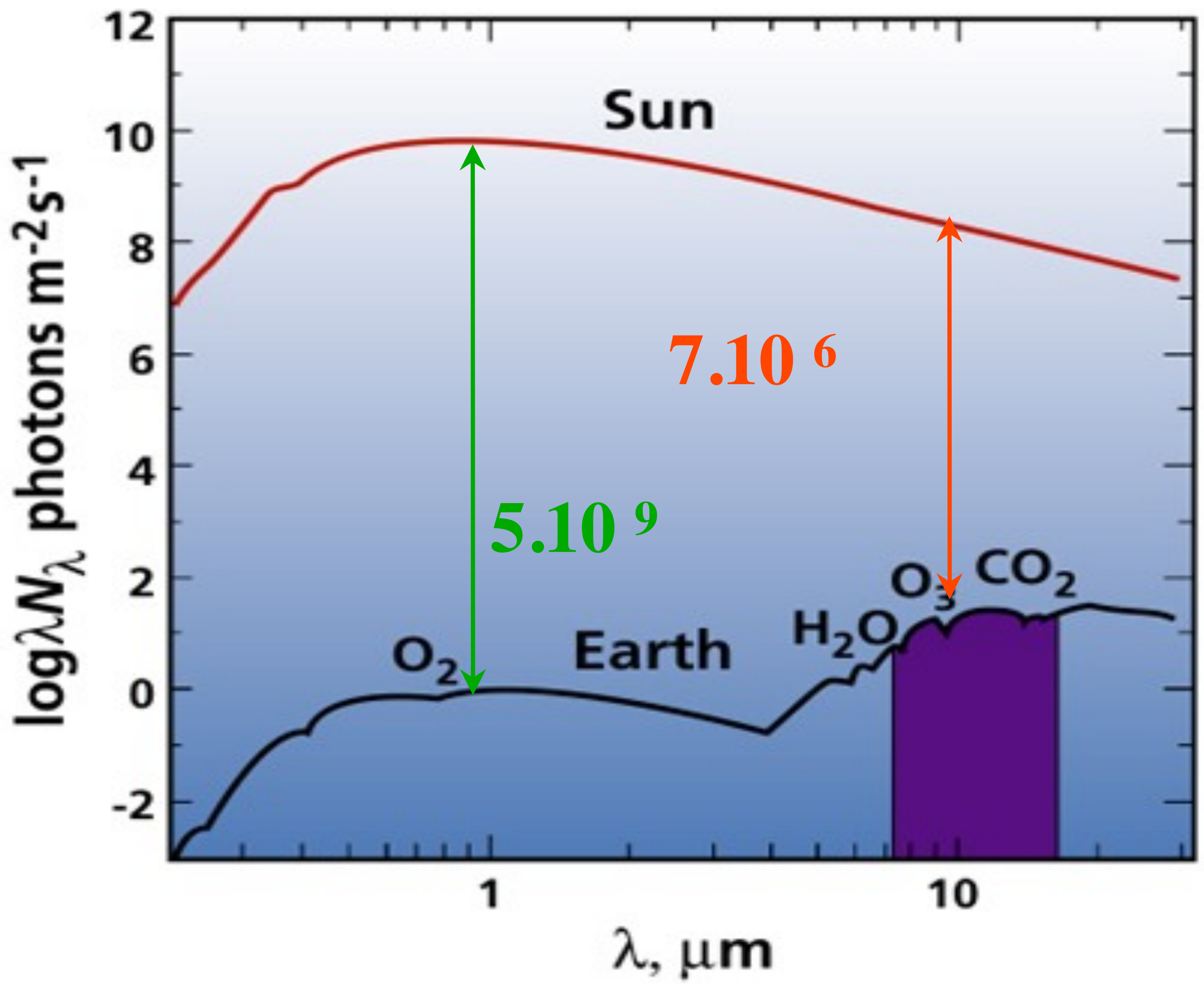
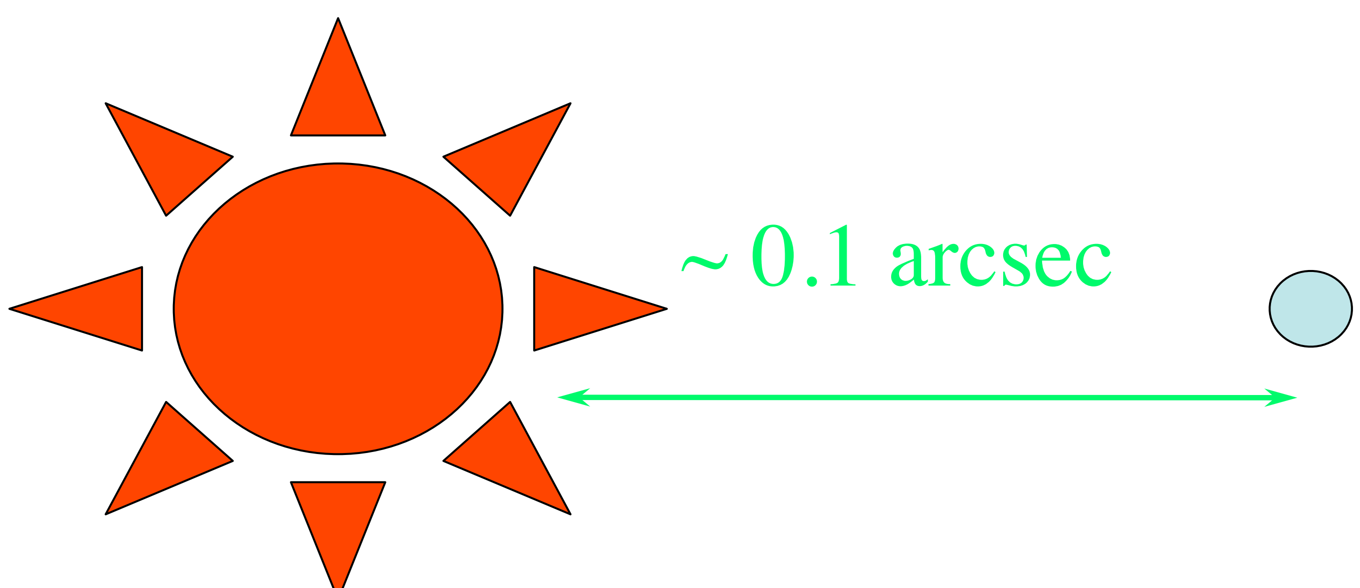
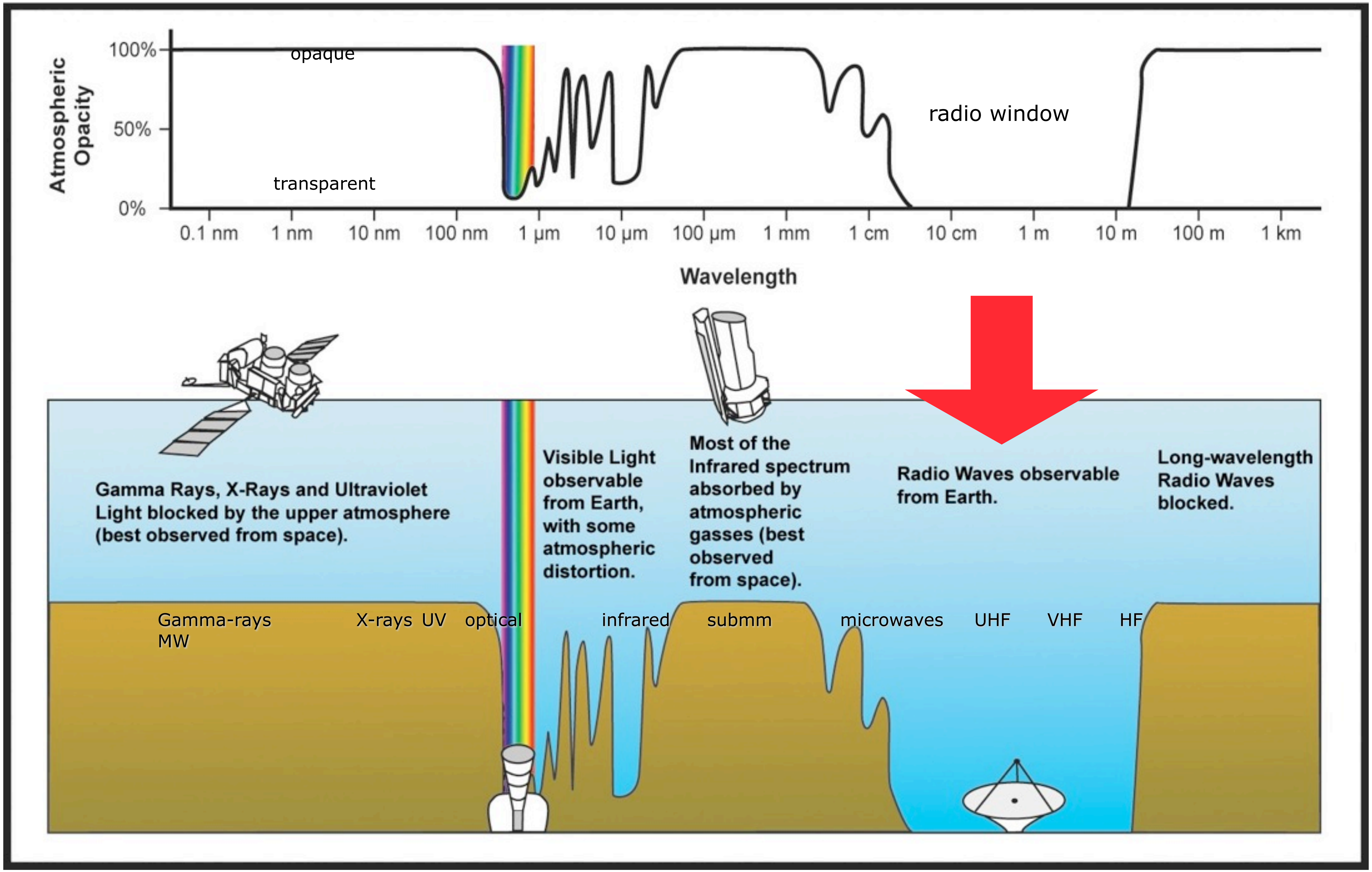
Obstacles to direct exoplanet detection

➔ contrast & proximity star/planet



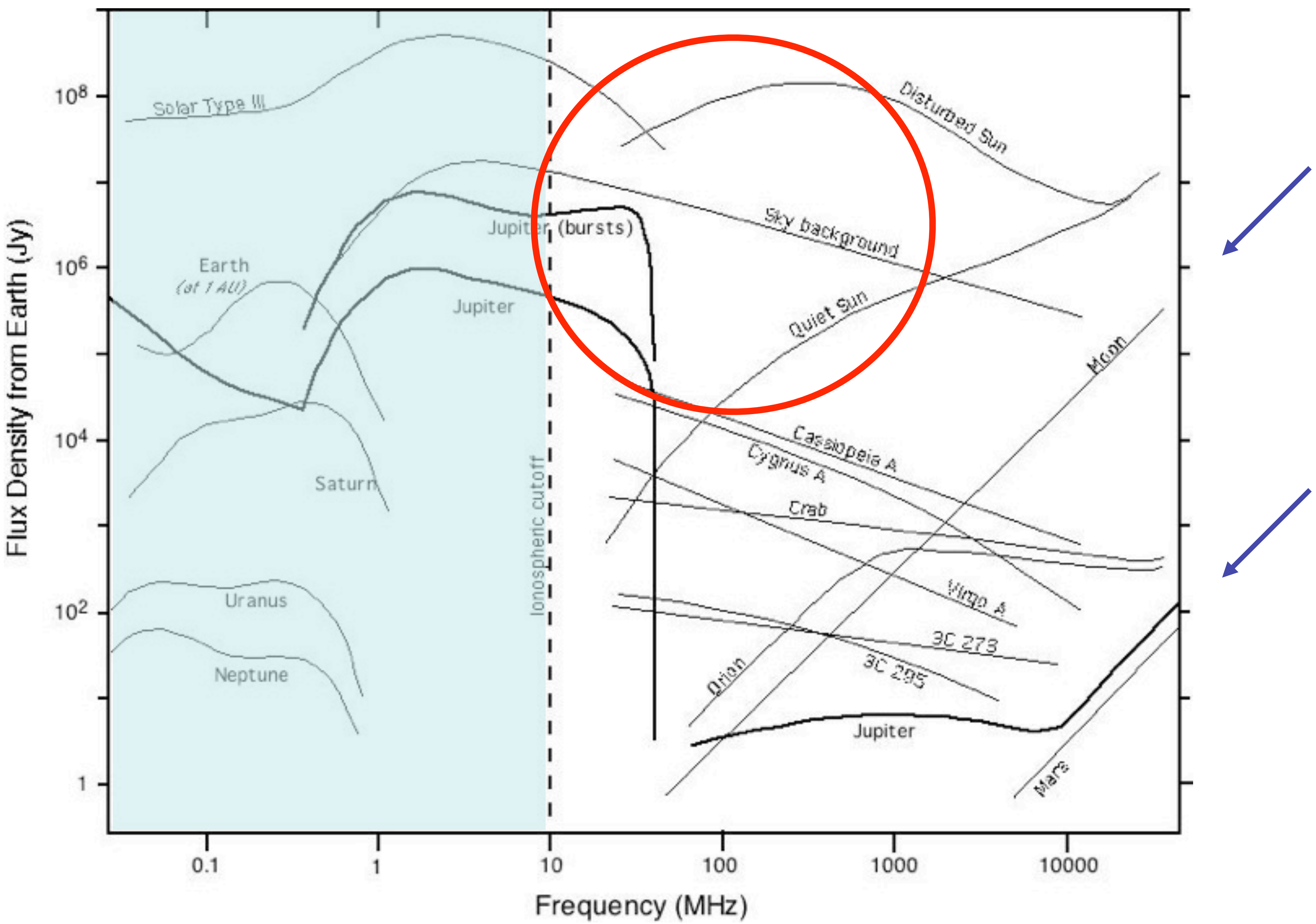


Atmospheric transparency



Interest of Radio observations

- A low frequencies, thermal spectrum in λ^{-2} (Rayleigh-Jeans)
- A very low frequencies, solar and planetary spectra ≠ thermal
- « Plasma » processes ➔ Contrast Sun/Jupiter ~1 !

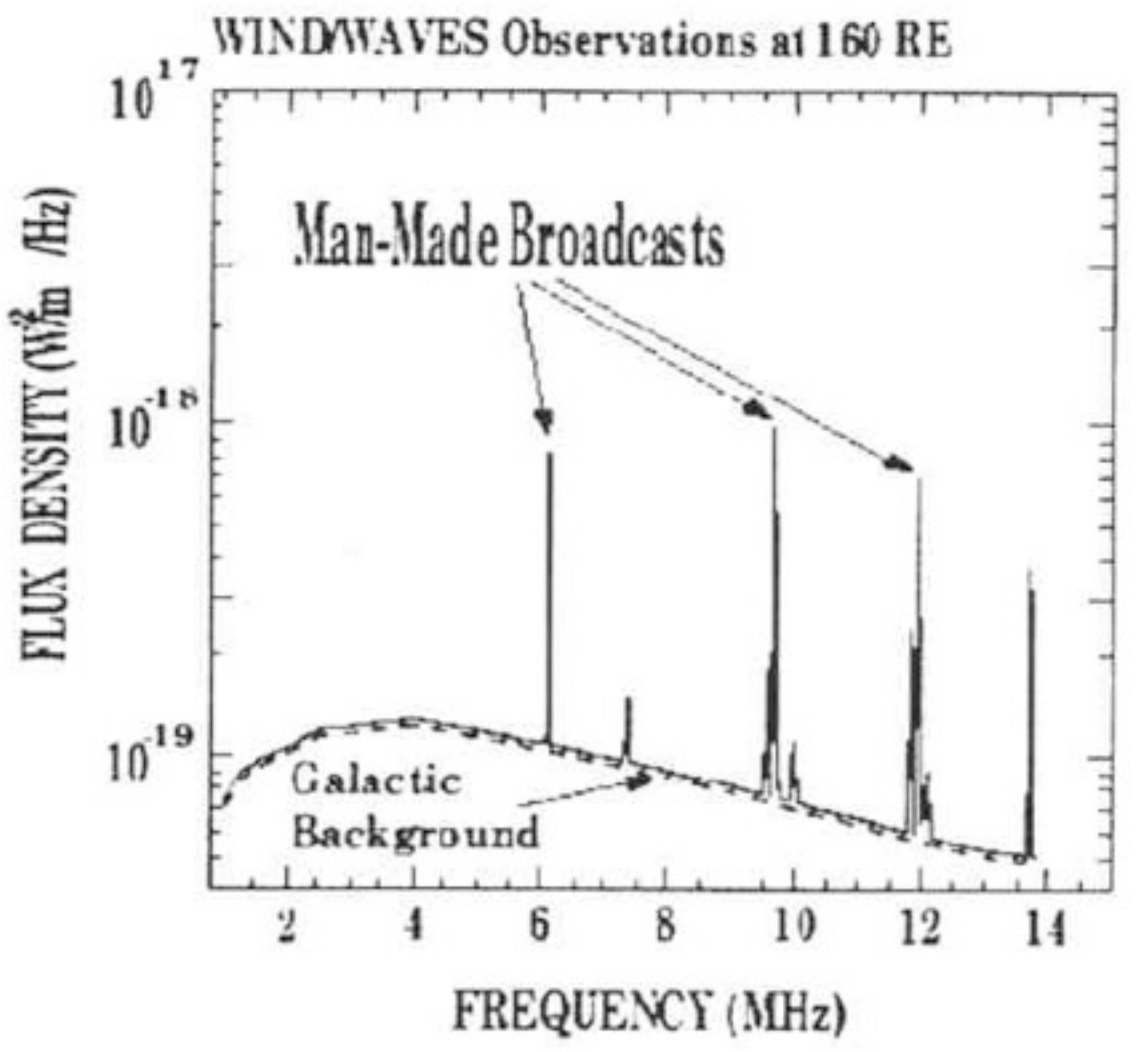


Limitations of Radio observations

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

  perturbations ≤30-50 MHz,

  scintillations IP/IS



Sensitivity of observations

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

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

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

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

- Maximum distance for $N\sigma$ detection of a source ζ x Jupiter :

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

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

$\Rightarrow \zeta = 1$

	$b\,\tau = 10^6$ (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)

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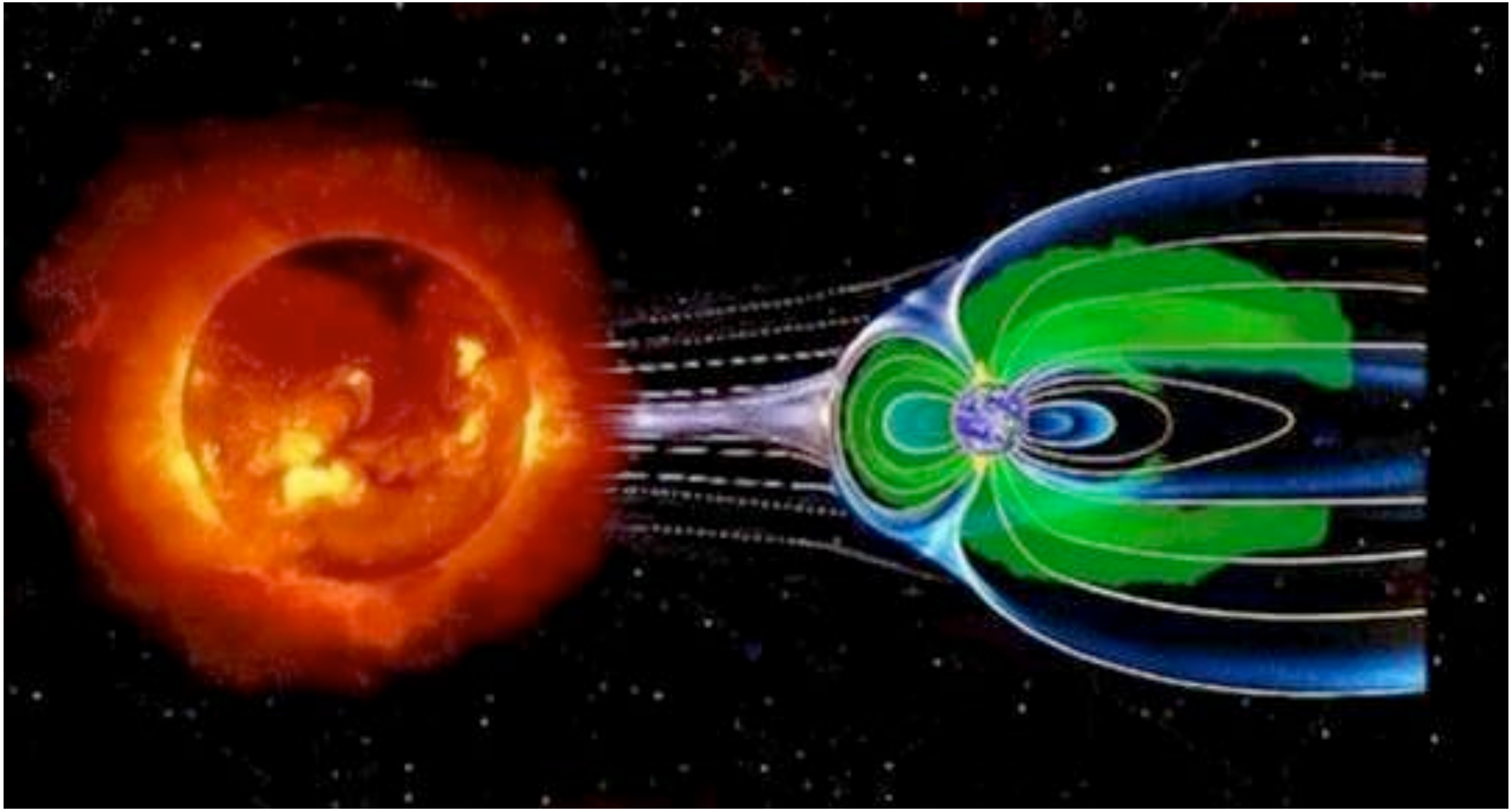
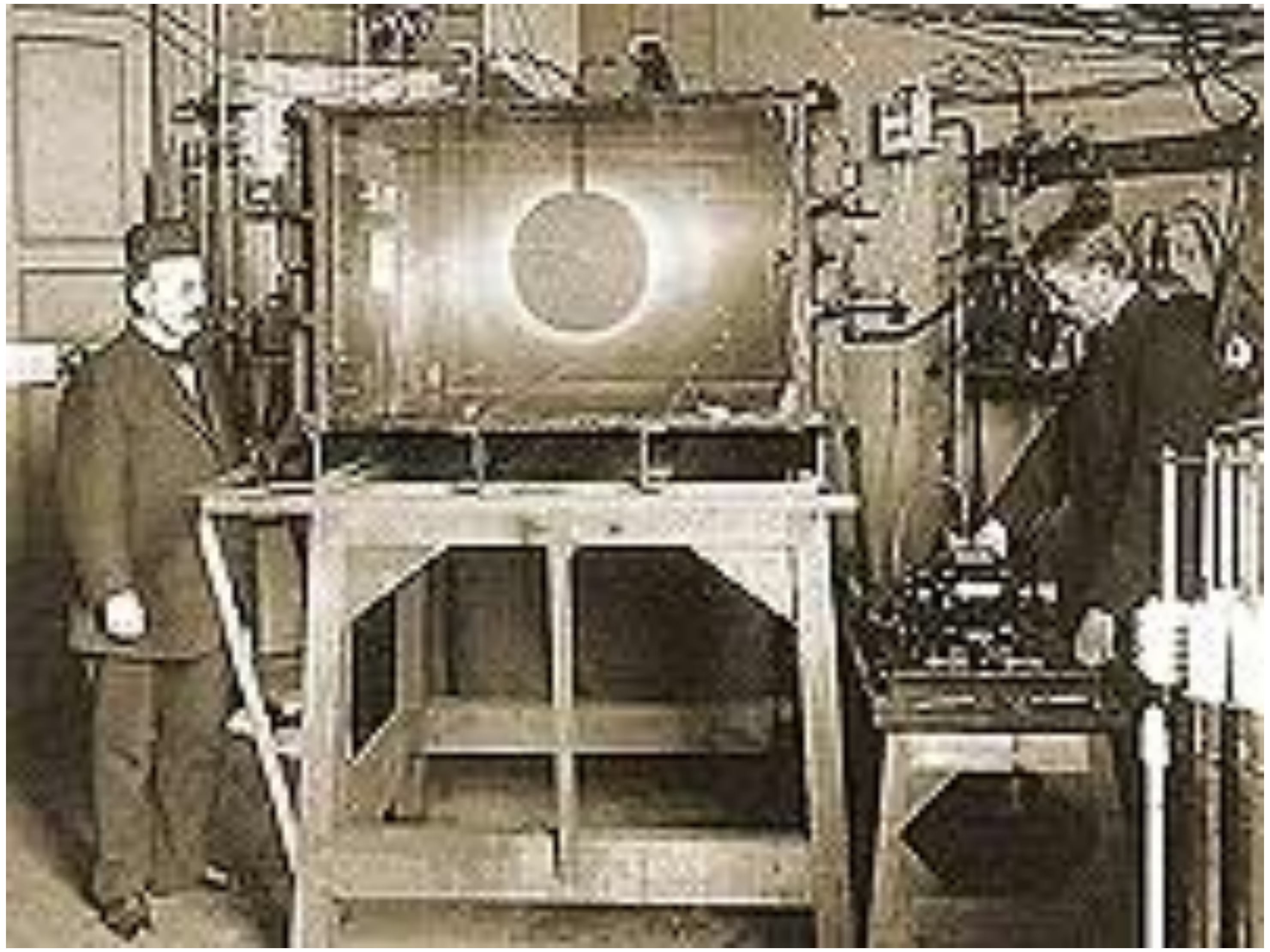
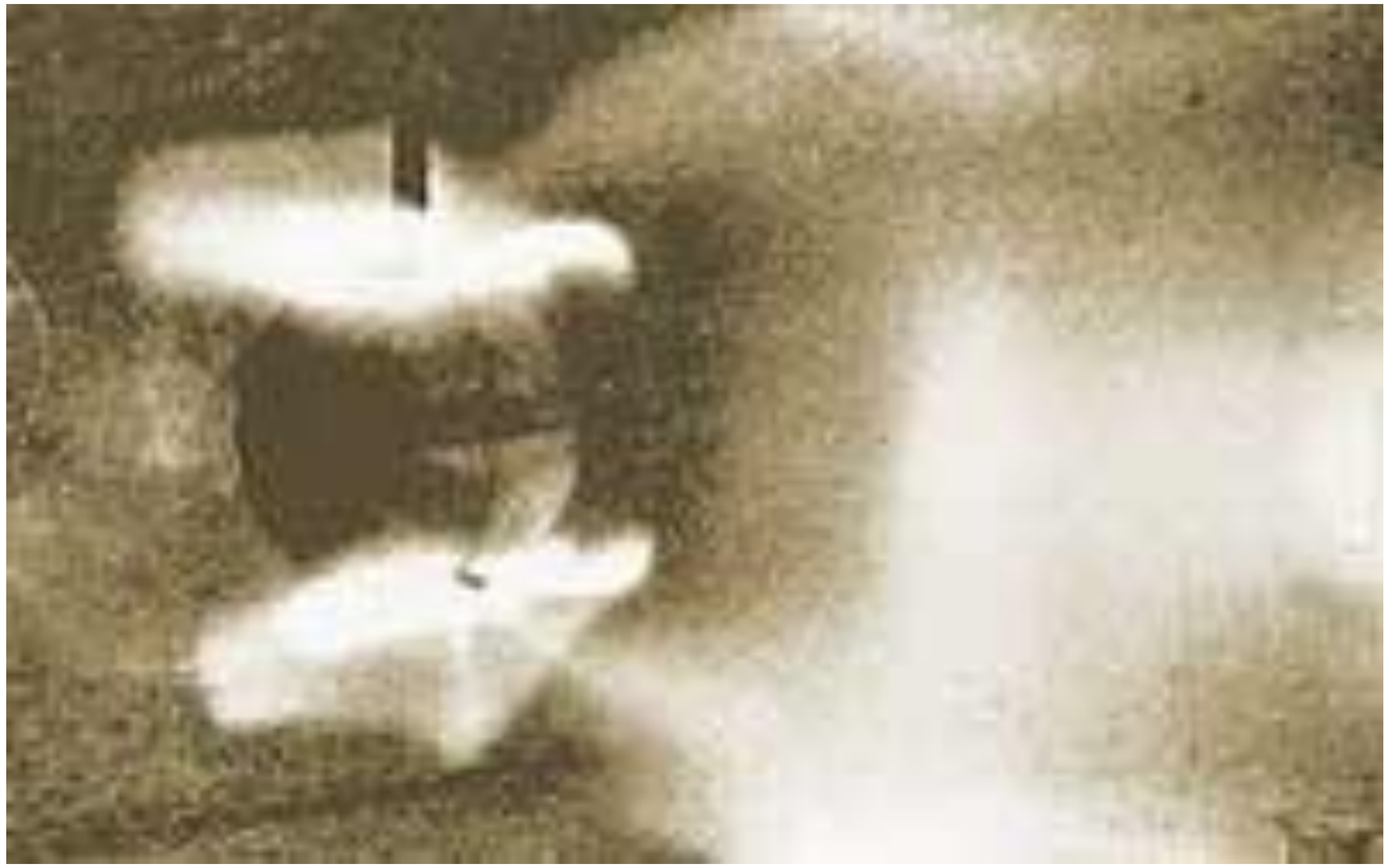
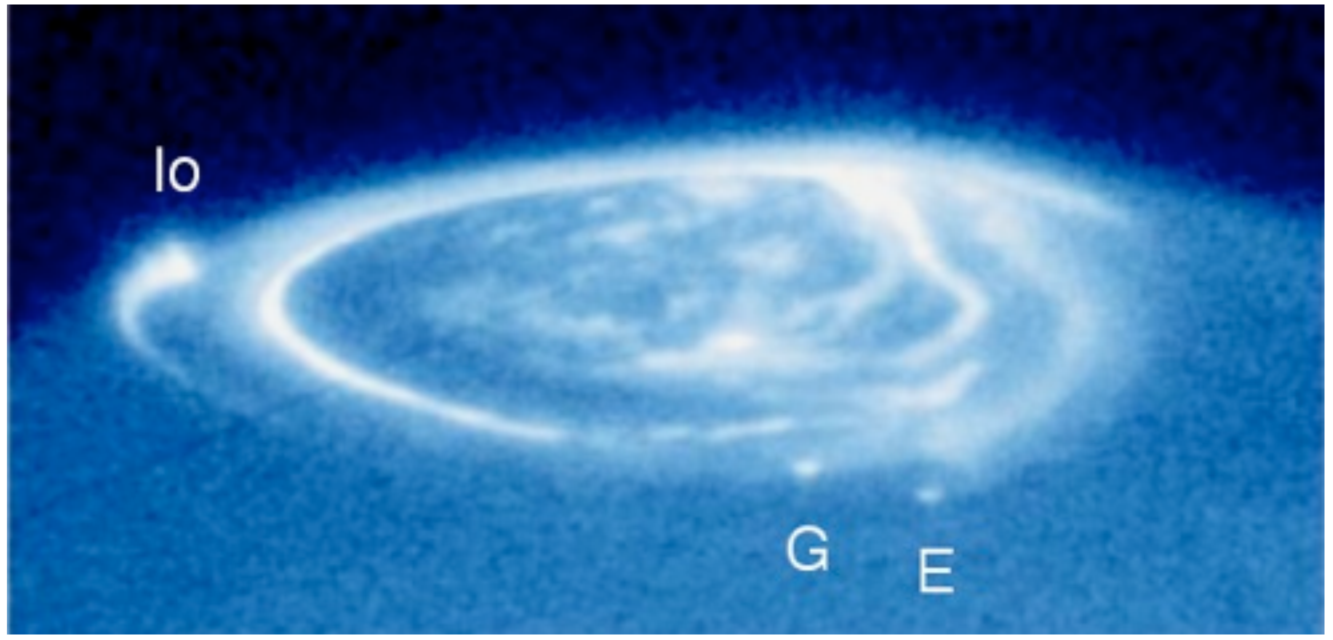
Solar Wind - Magnetosphere Interaction ...



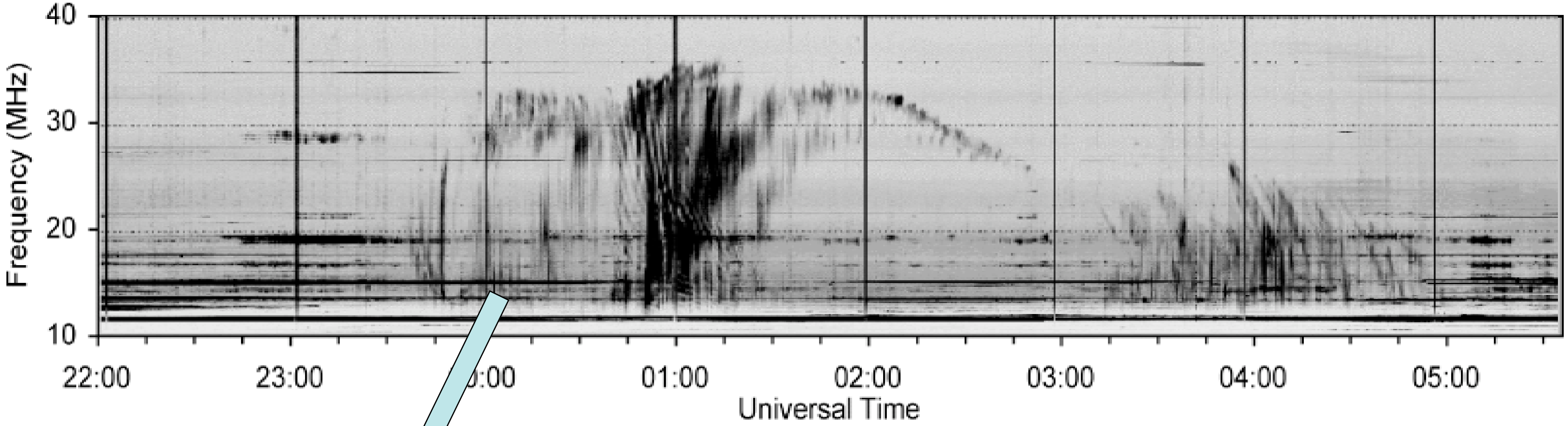
Aurorae

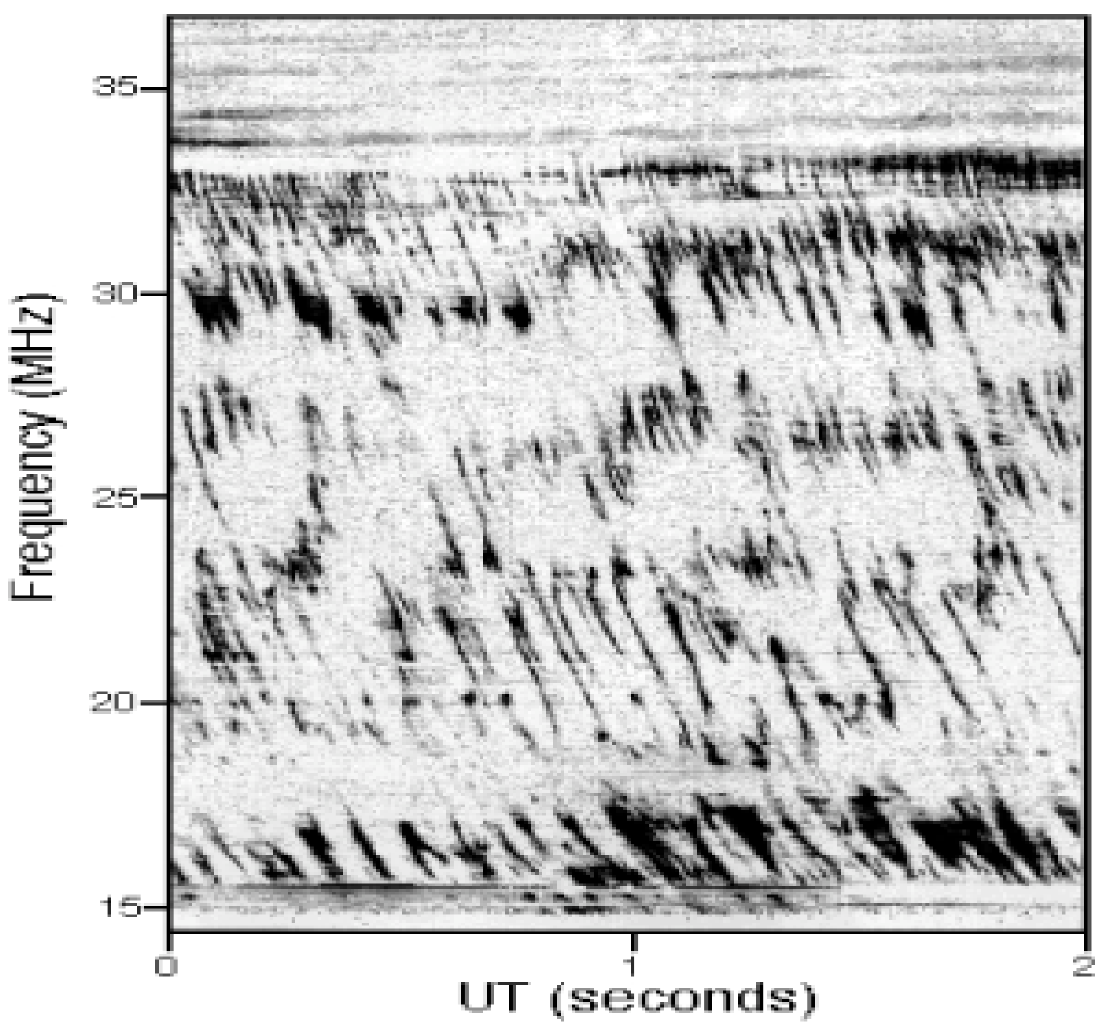


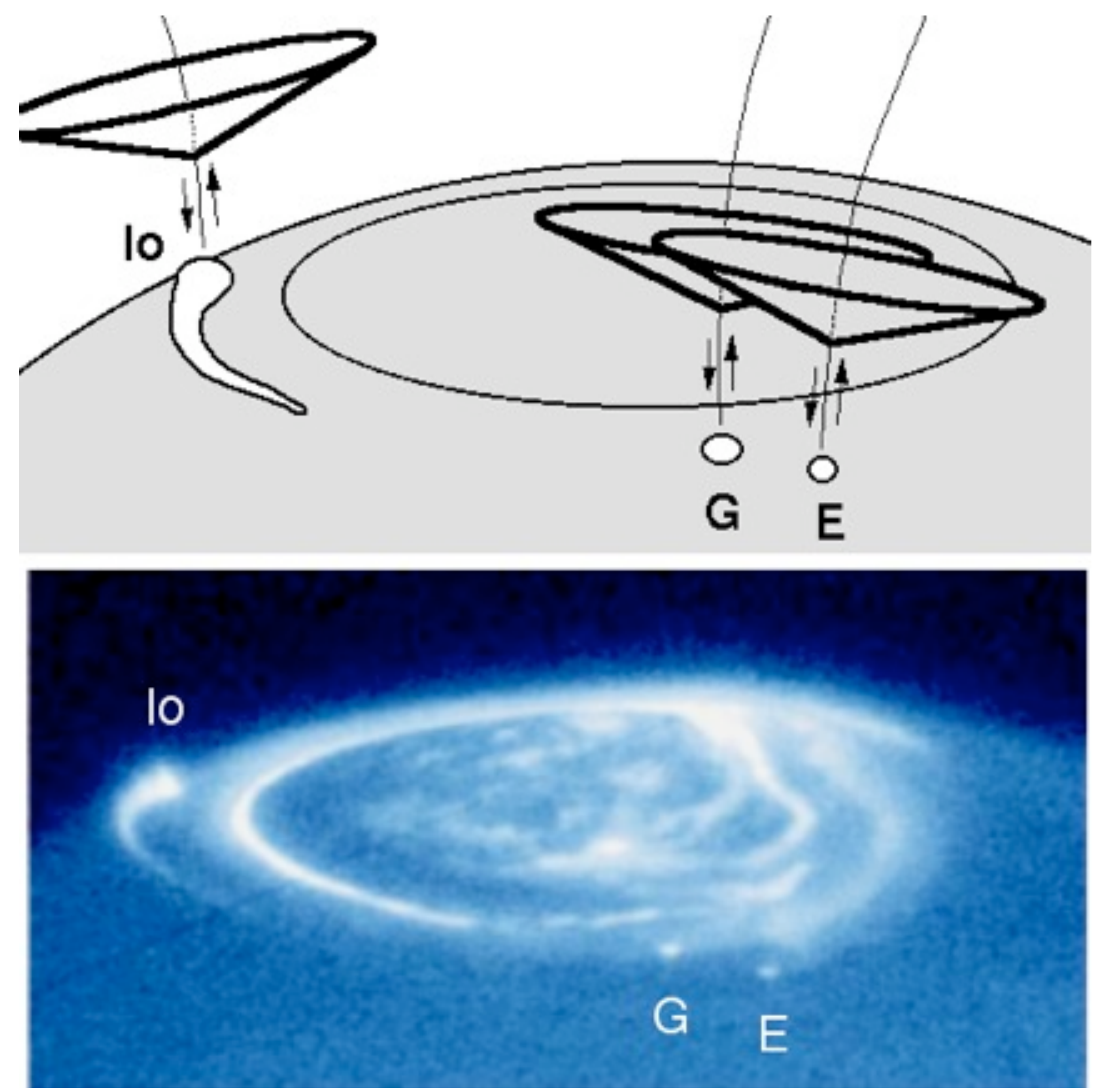




Radio emissions

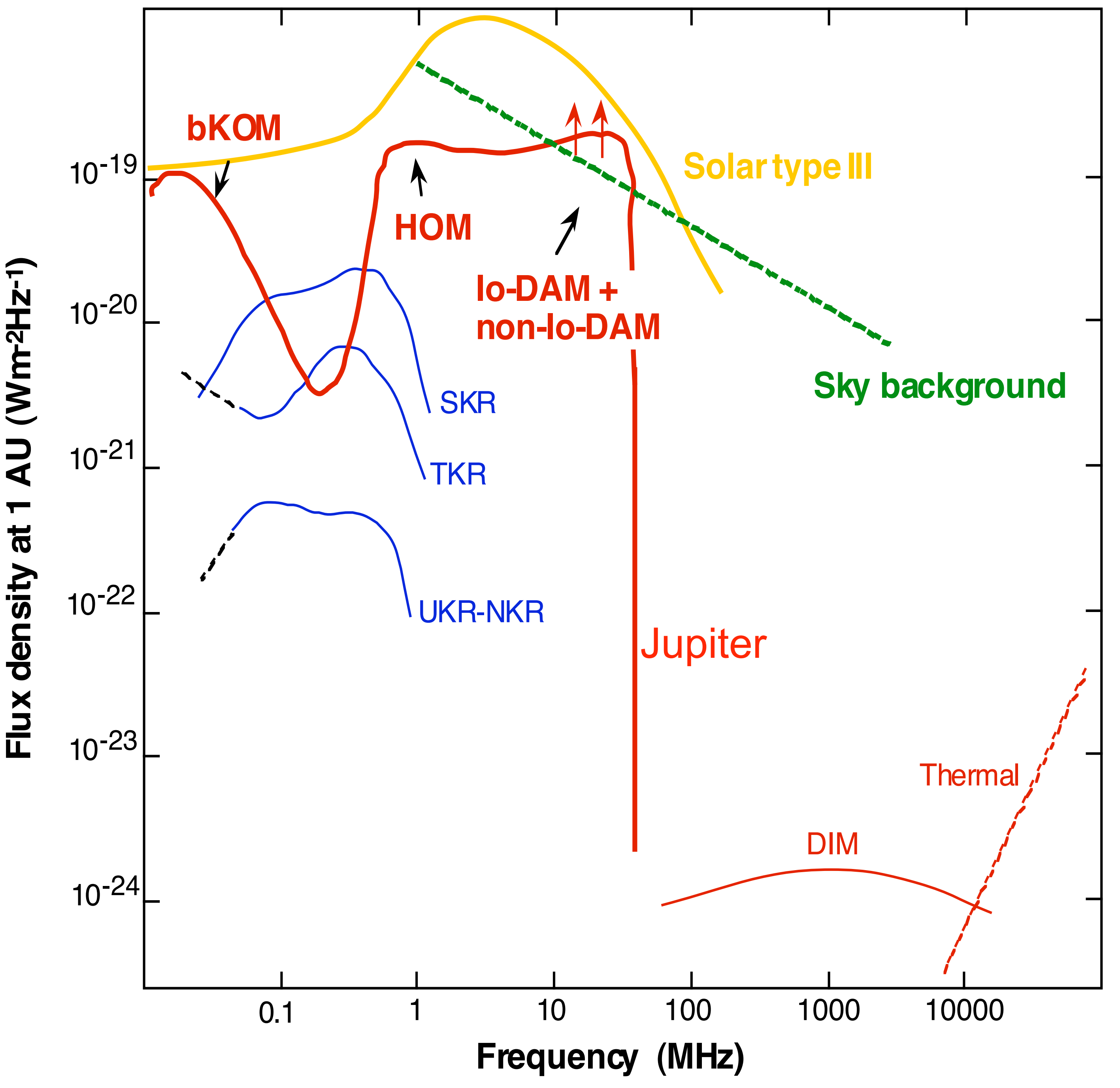






Properties of radio emissions

- $f \sim f_{ce}$, $\Delta f \sim f$
- $T_B > 10^{15}$ 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^{6-11} W



Generation of radio emissions

- Coherent cyclotron emission : 2 conditions within sources :

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

  - energetic electrons (keV) with non-Maxwellian distribution

  → high magnetic latitudes

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

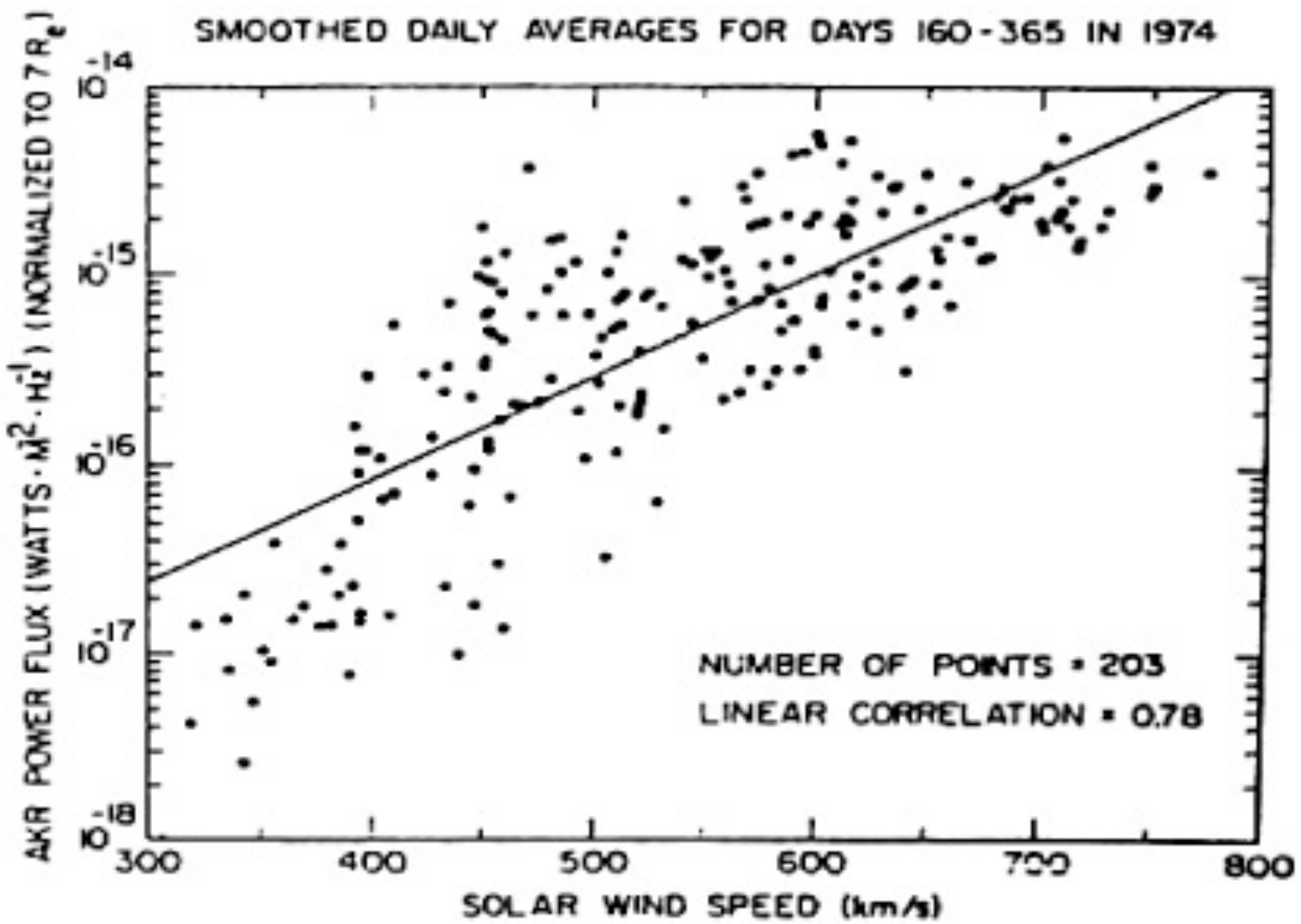
- Acceleration of electrons :

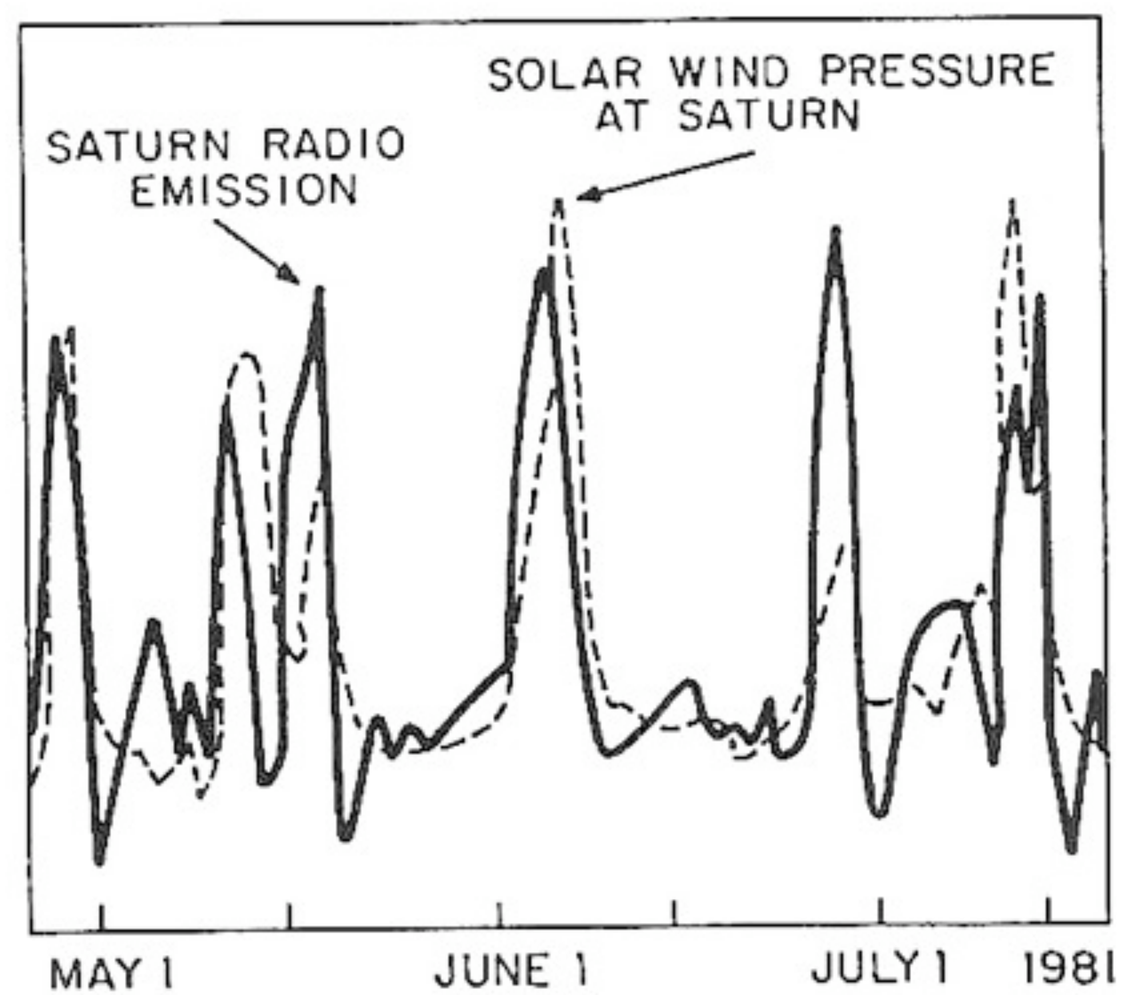
  - interactions B/satellites → $E_{//}$

  - MS compressions

  - magnetic reconnections

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





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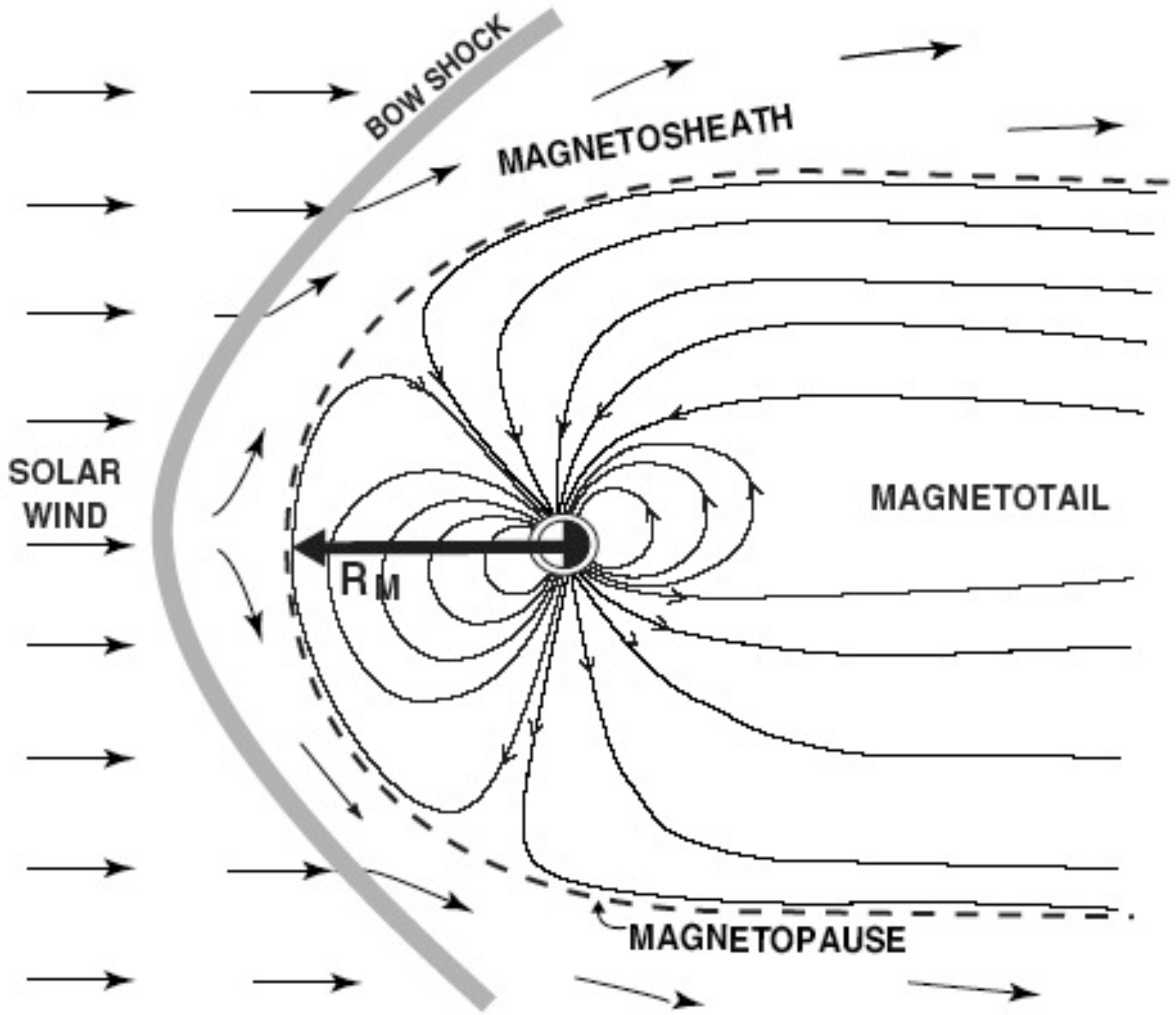


Magnetopause radius R_{MP} from pressure equilibrium :

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

$N=N_o/d^2 \quad N_o=5 \text{ cm}^{-3} \quad m \sim 1.1 \times m_p$

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

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

Solar Wind expansion

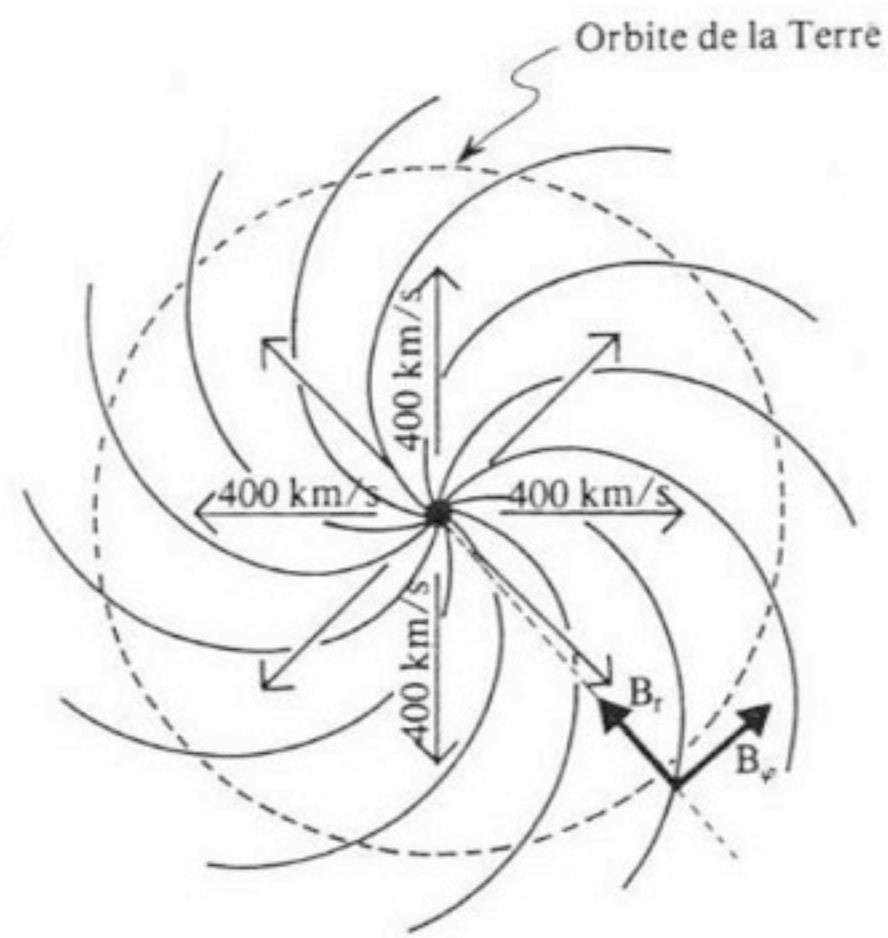
$V \sim c^{te}$

$N \sim d^{-2}$ (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, $B \sim B\varphi$)

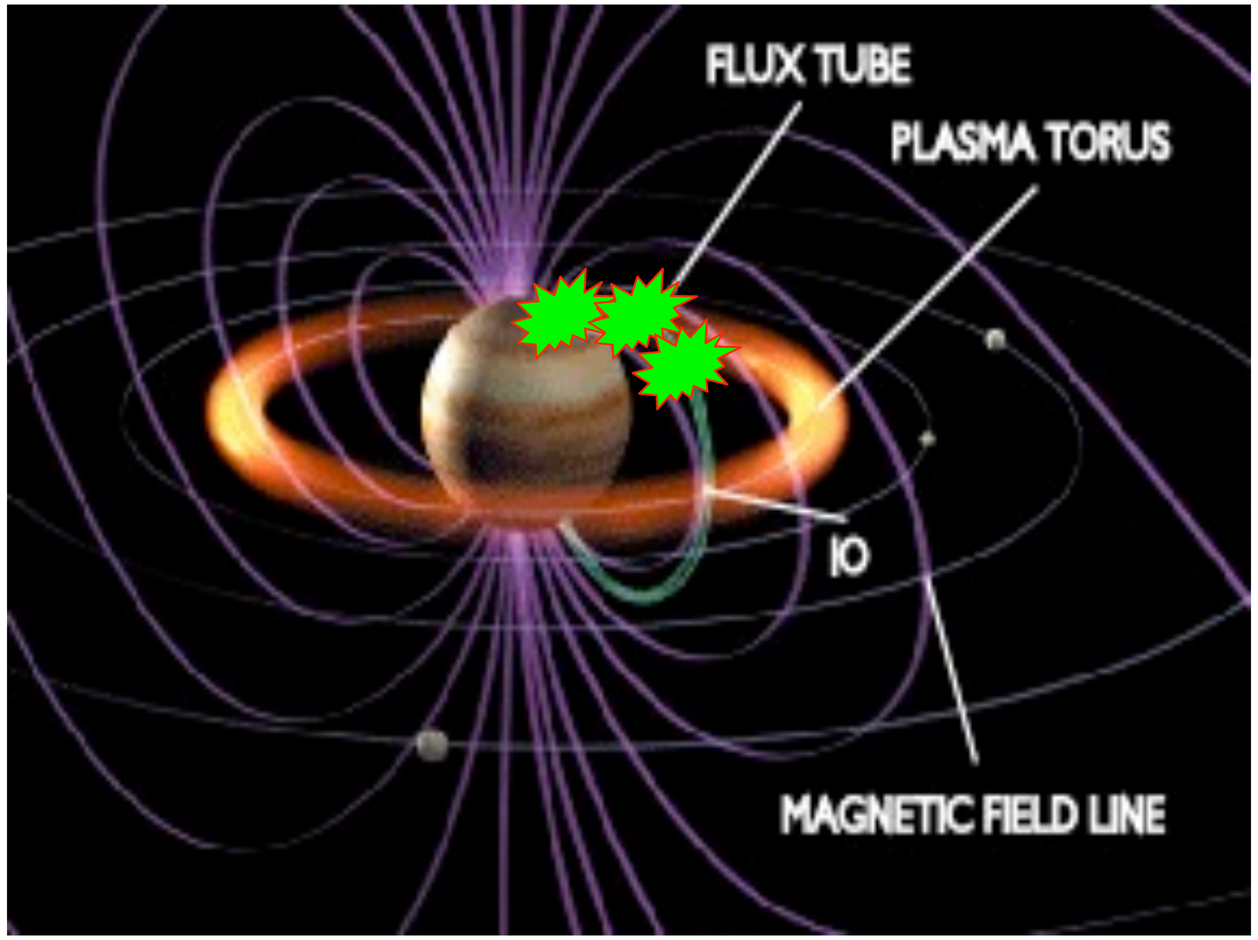


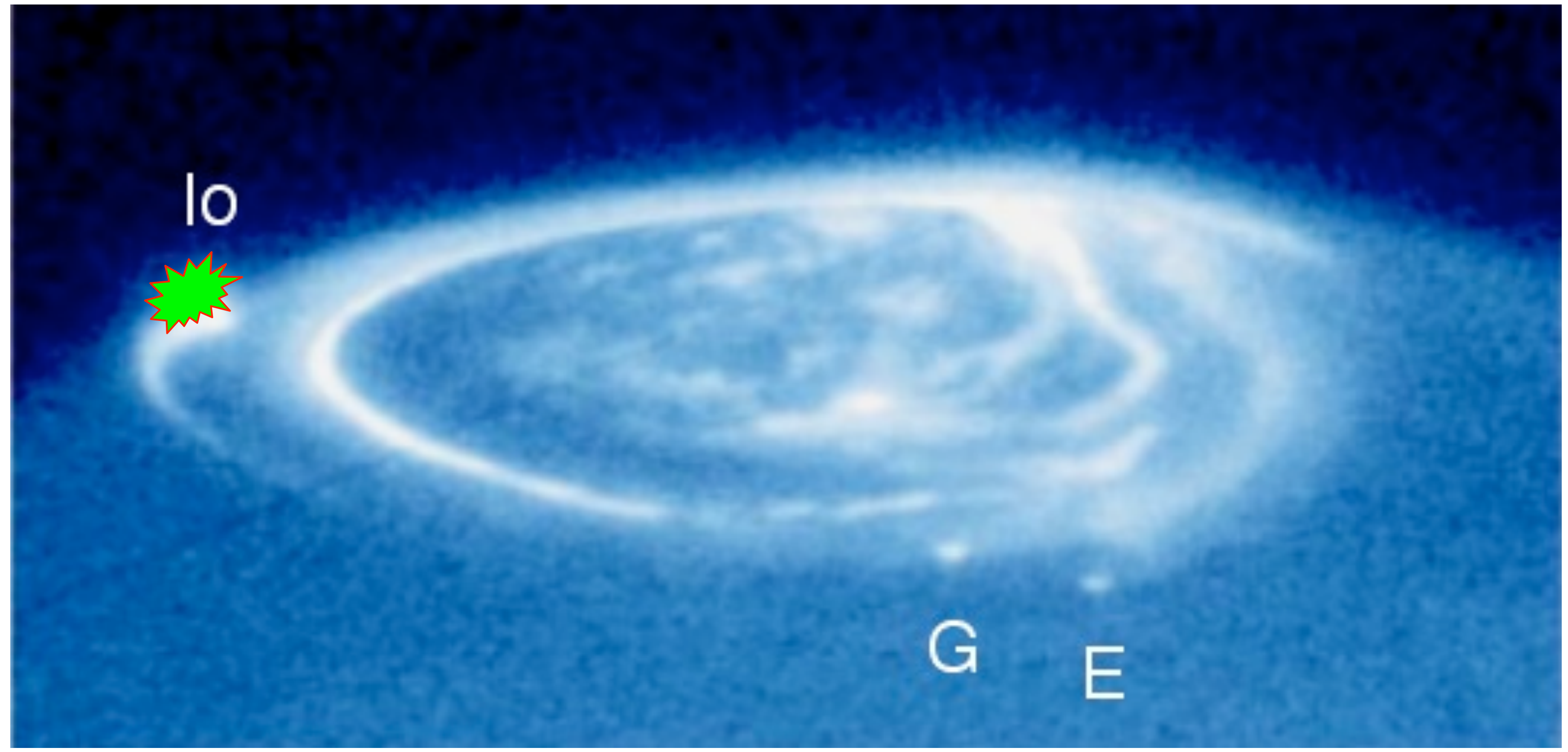
→ B^2 varies as NV^2 thus P_C varies as P_B

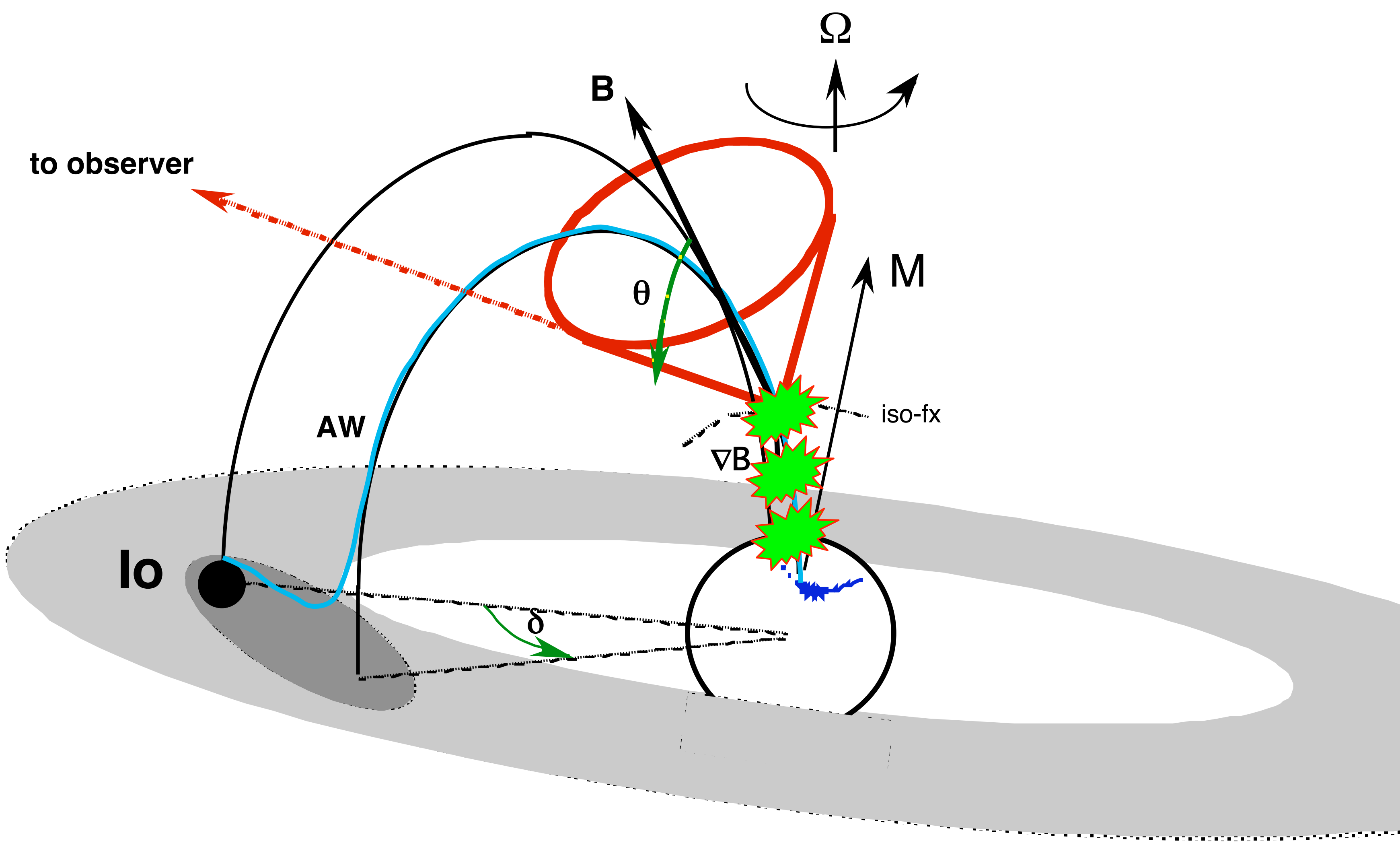
→ $P_C/ P_B \sim 170$ beyond 1 UA

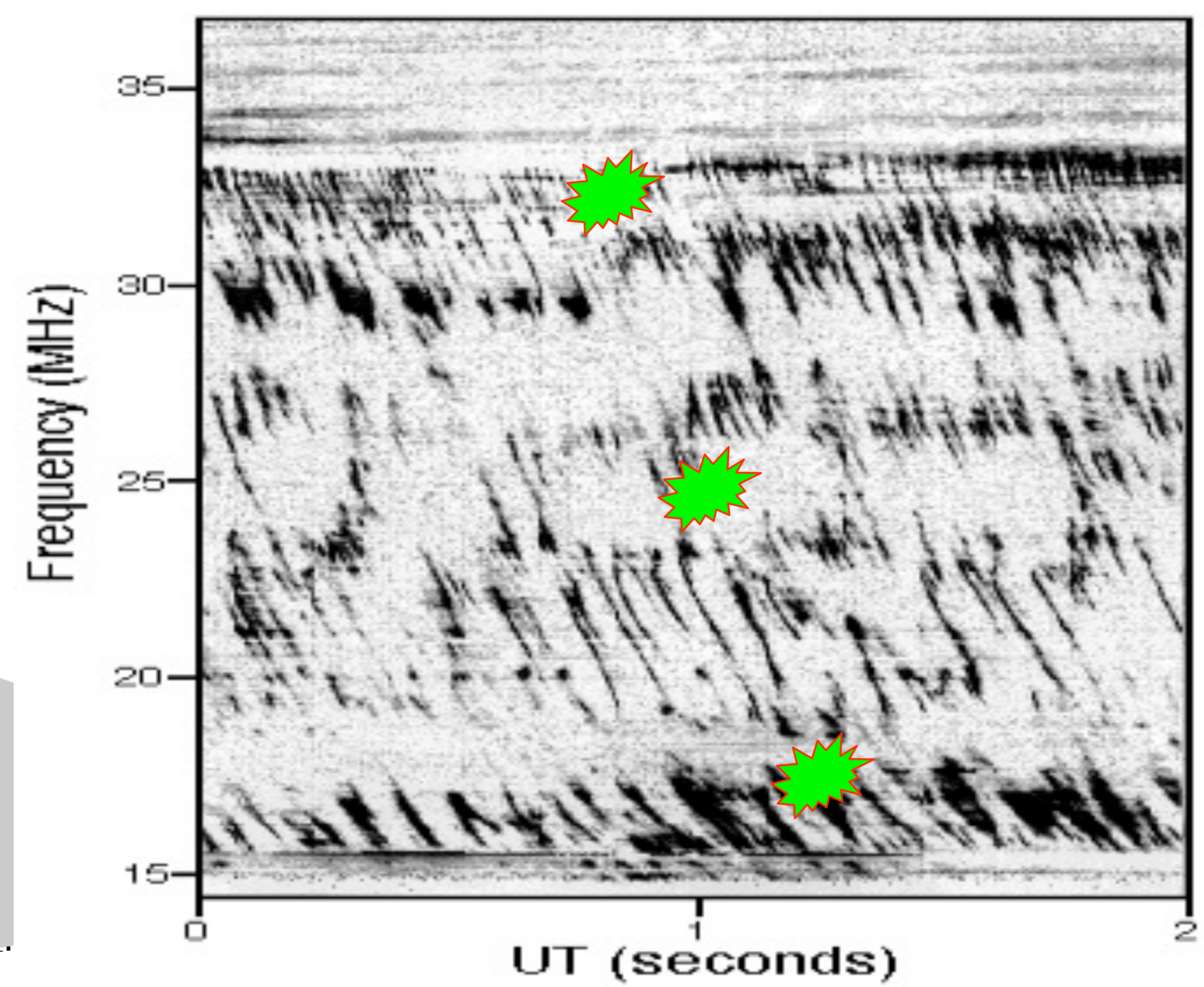
Obstacle \ Flow	Weakly/Not magnetized *(Solar wind)*	Strongly magnetized *(Jovian magnetosphere)*
Weakly/Not magnetized *(Venus, Mars, Io)*	No Intense Cyclotron Radio Emission	Unipolar interaction → Io-induced Radio Emission,
Strongly magnetized *(Earth, Jupiter, Saturn, Uranus, Neptune, Ganymede)*	Magnetospheric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

Satellite - $B_{Jupiter}$ interaction









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Dipolar interaction

- Magnetic reconnection

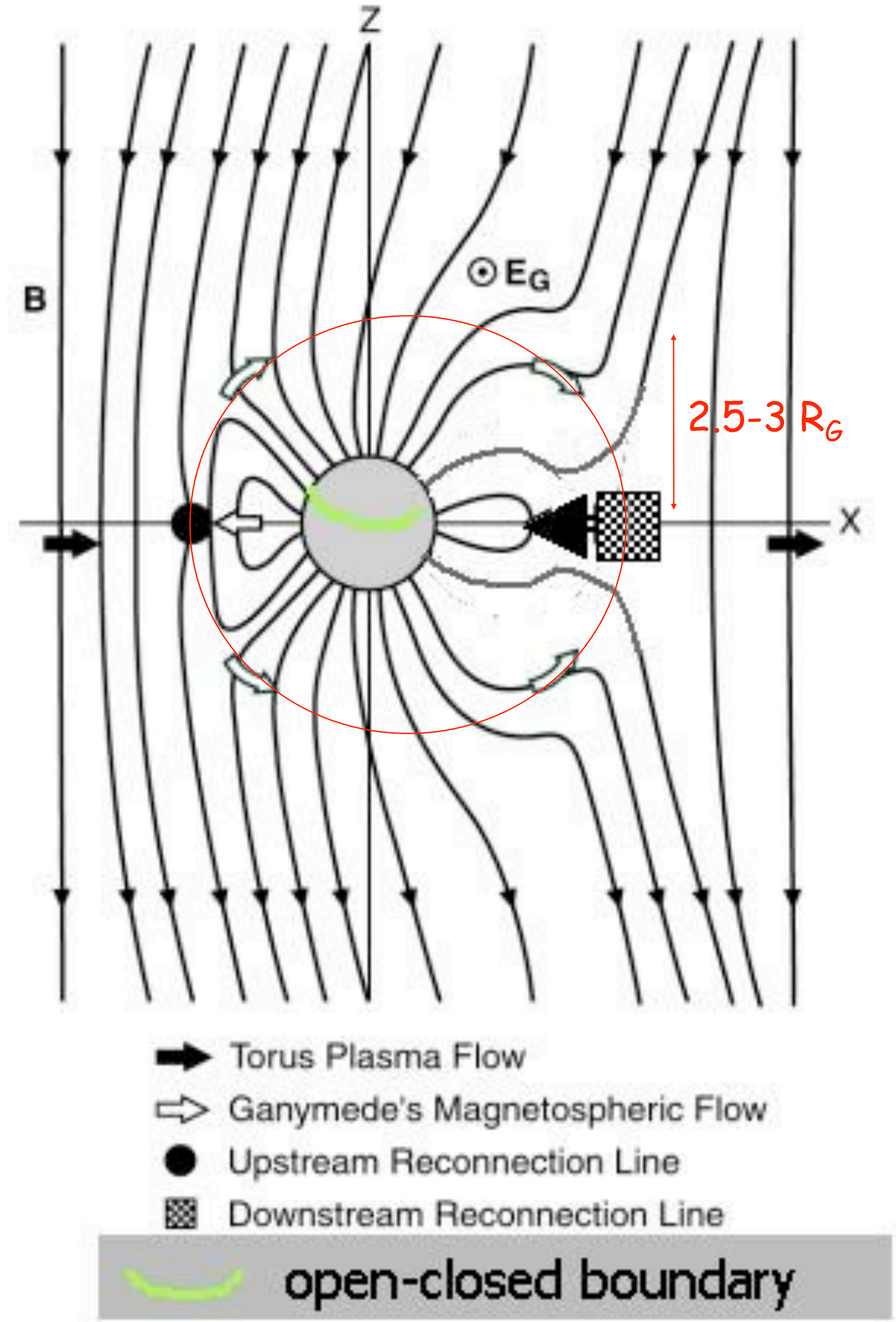
  (e.g. Ganymede-Jupiter)

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

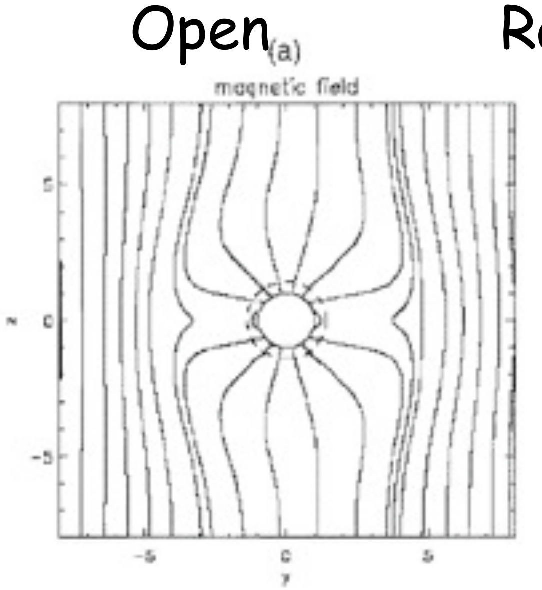
Efficiency $\varepsilon \sim 0.1\text{–}0.2$

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

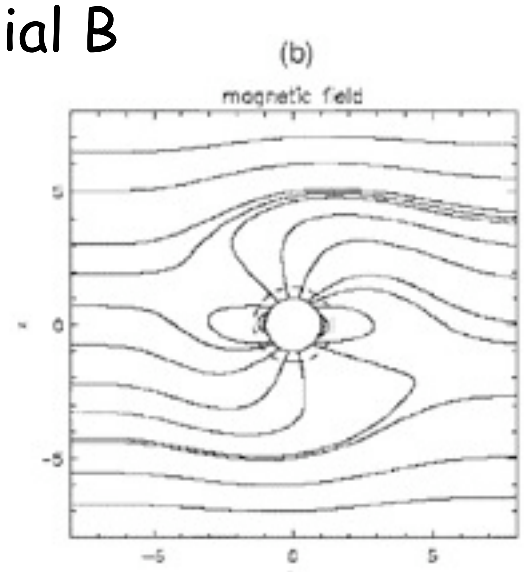
→ $P_d = \varepsilon\ P_B$



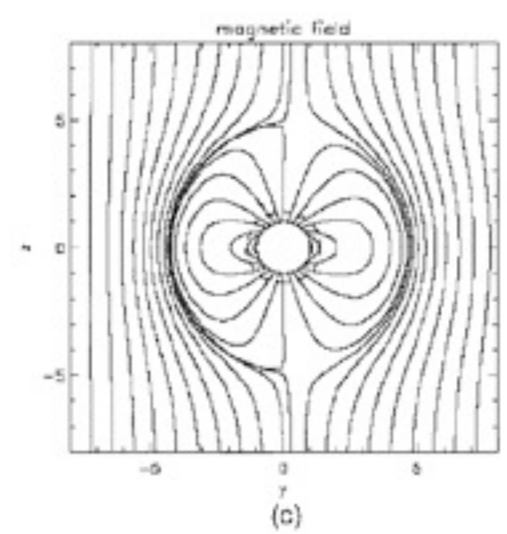
Open



Radial B



Closed



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Unipolar interaction

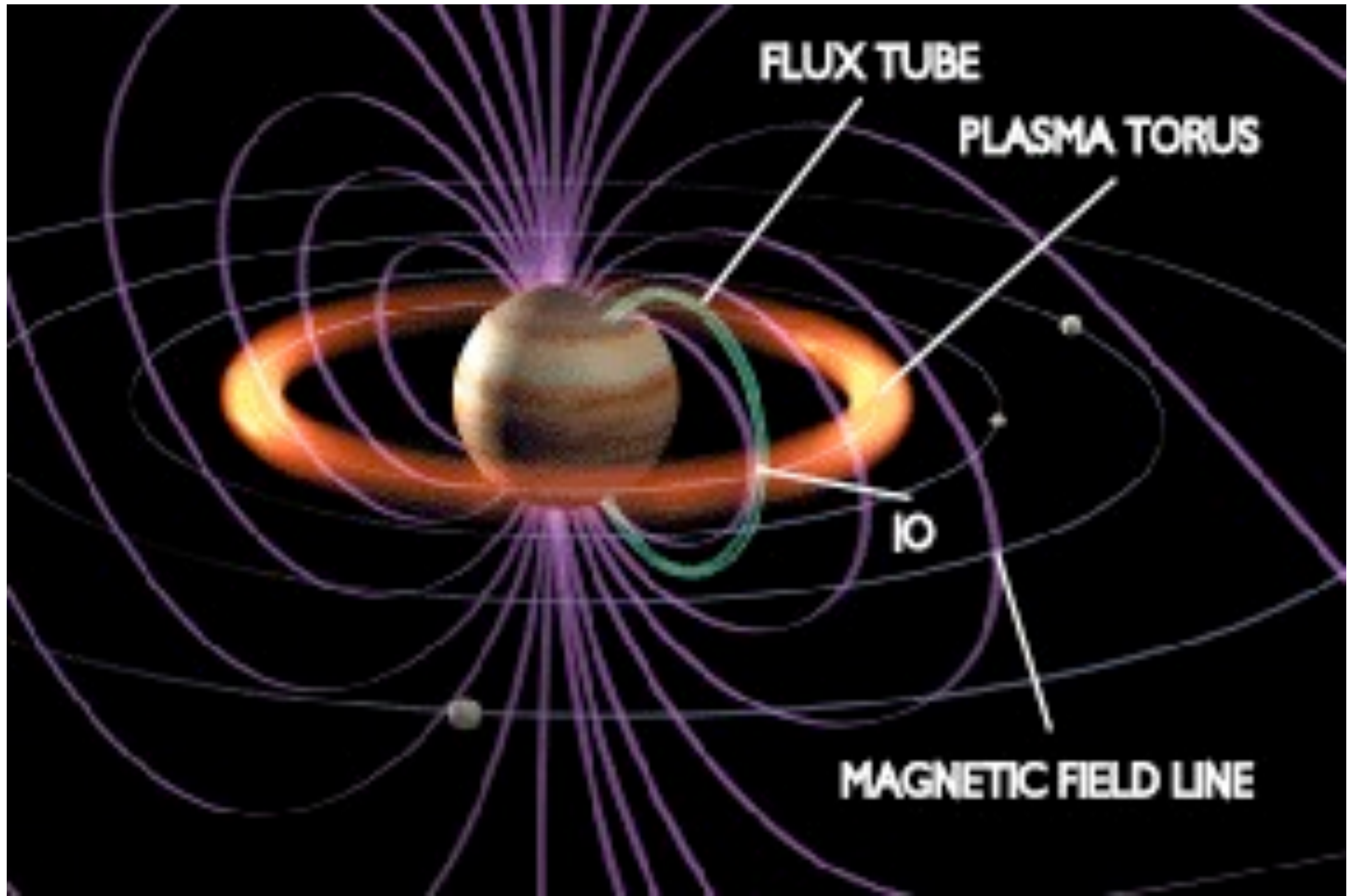
- Interaction via Alfvén waves & currents

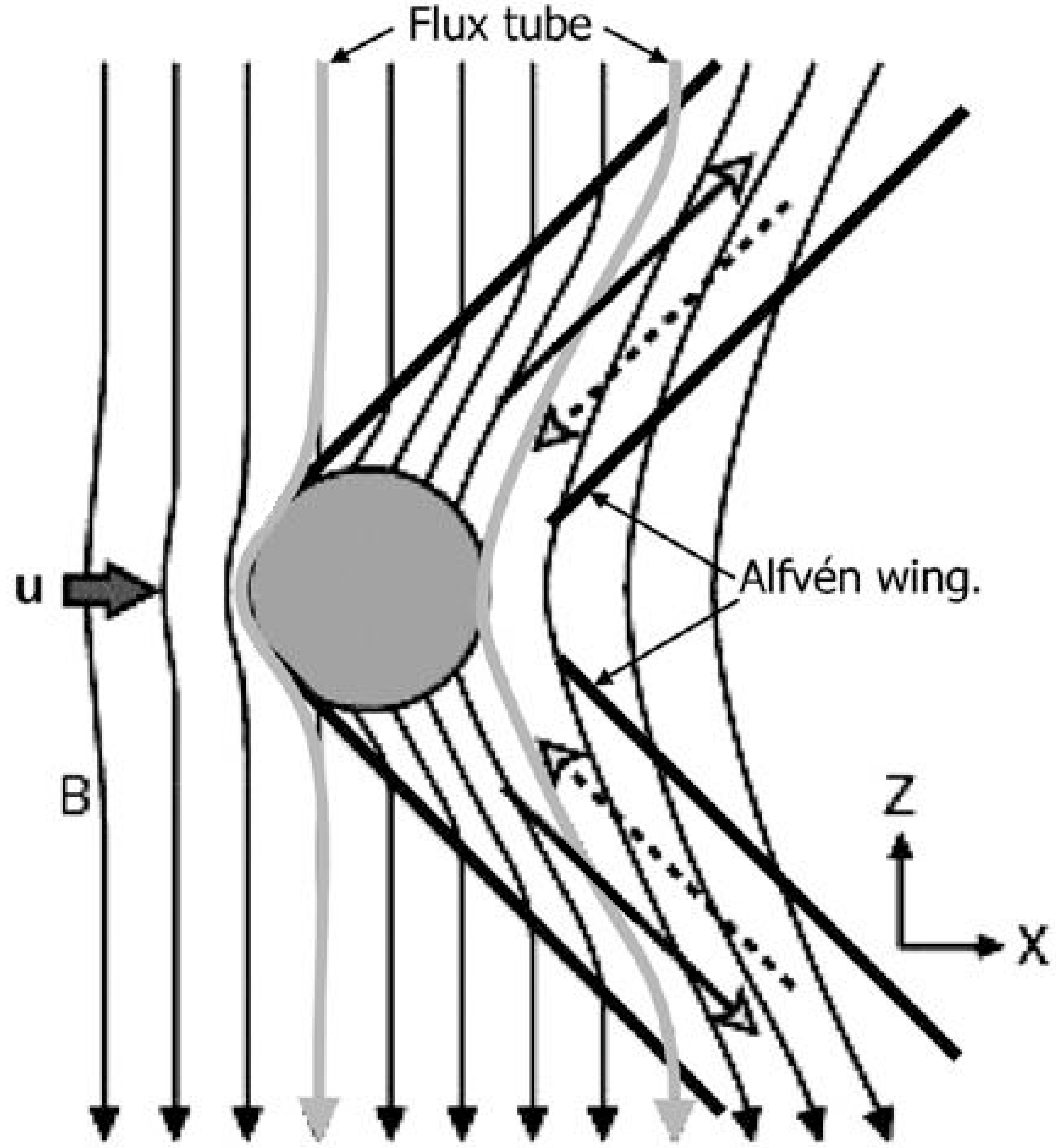
(e.g. Io-Jupiter) $\phi = E\times 2R_{obs} = V\times B_{\perp}\times 2R_{obs}$

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

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

→ $P_d = \varepsilon' P_B$





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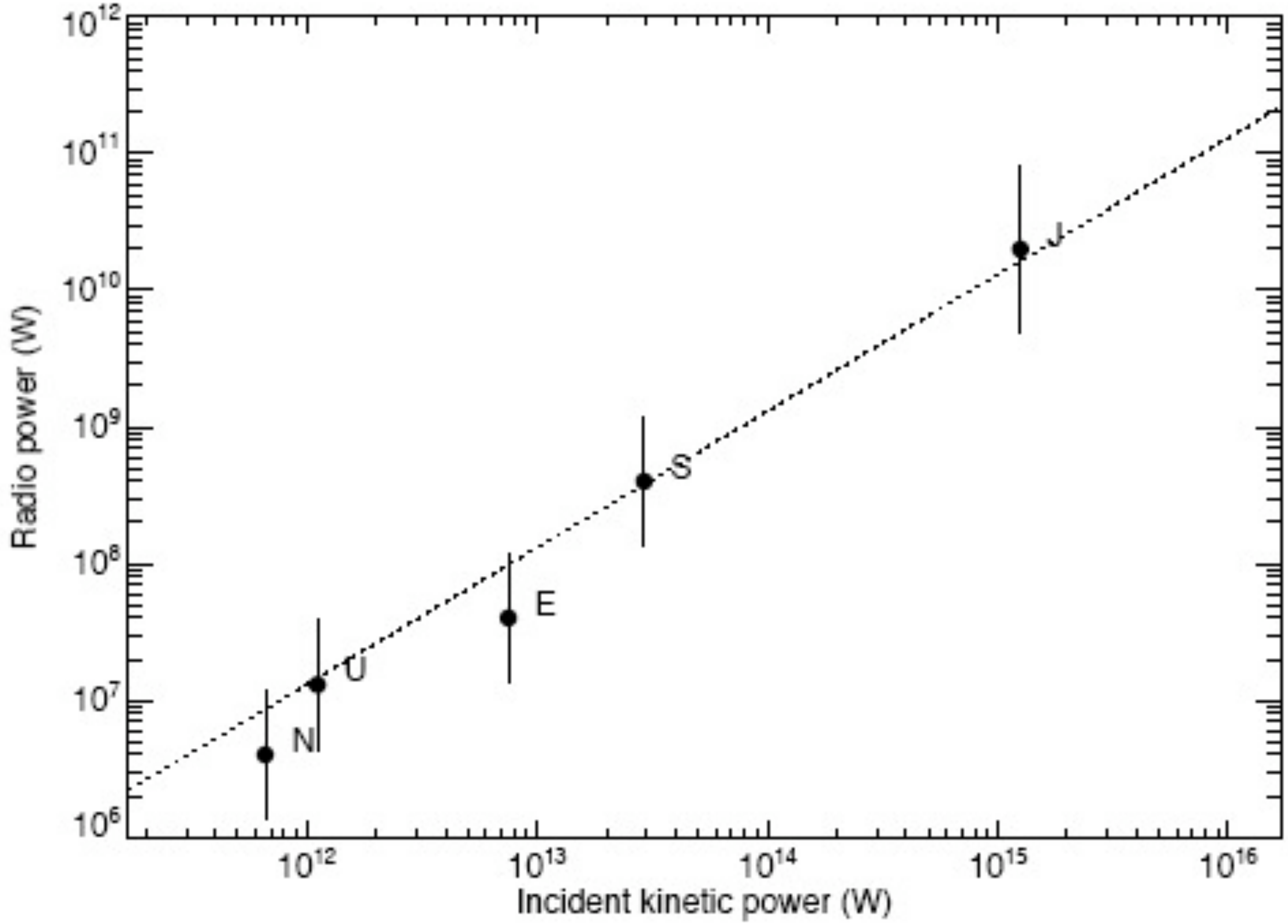
« Radio-kinetic Bode's law » (auroral emissions)

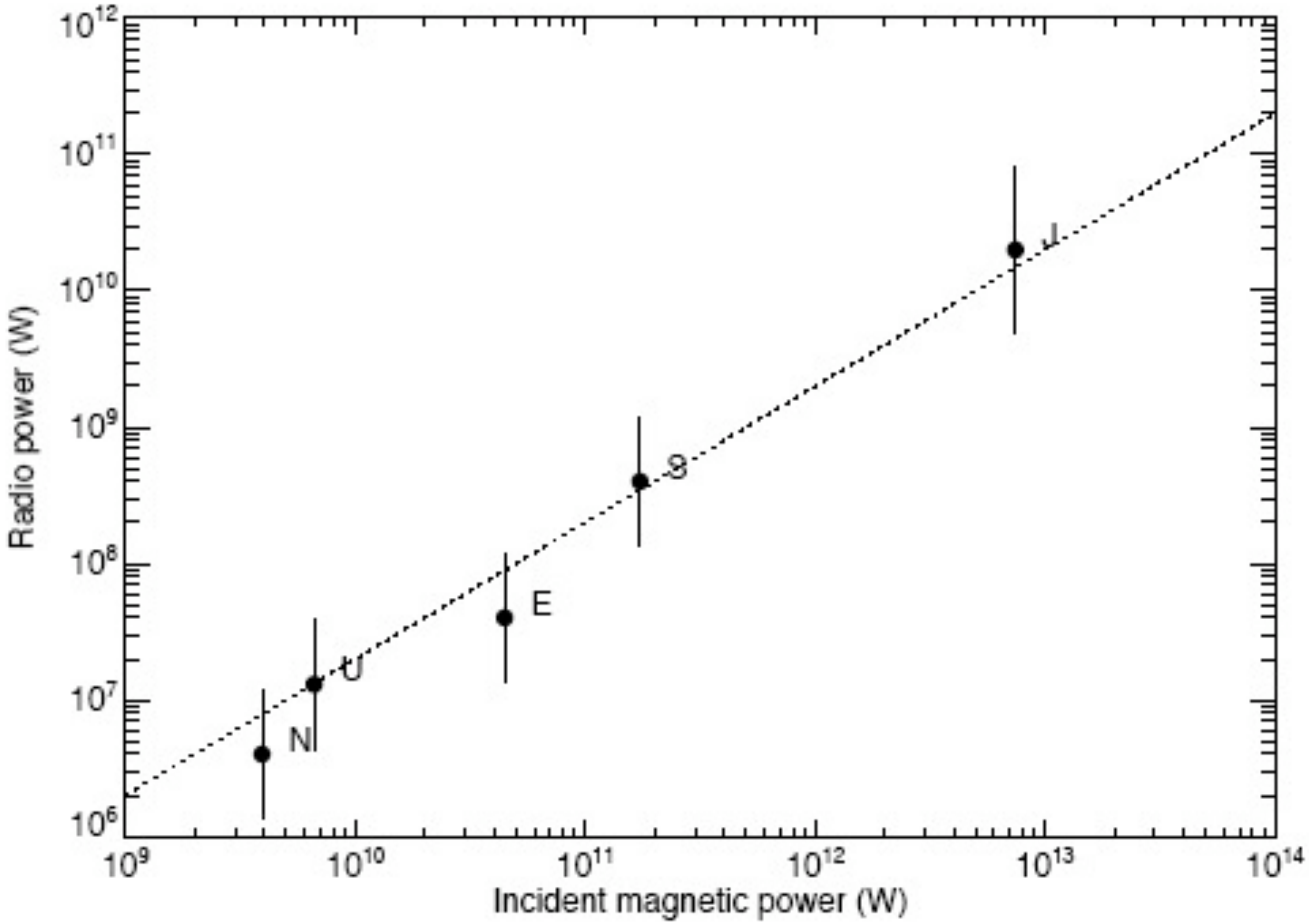
$P_{Radio} \sim \eta_1 \times P_C$ with $\eta_1 \sim 10^{-5}$



[Desch and Kaiser, 1984 ; Zarka, 1992]

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

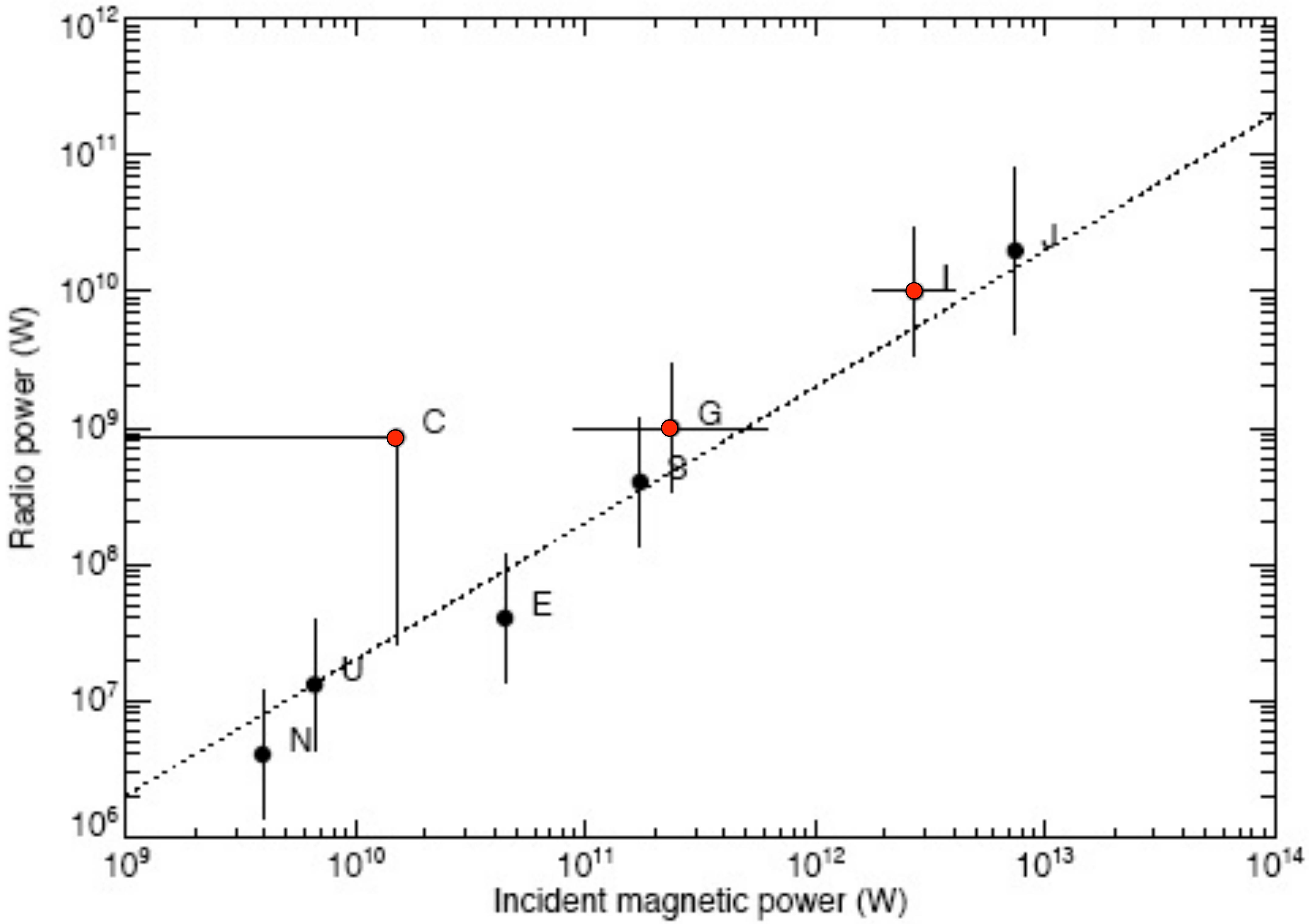
$P_{Radio} \sim \eta_2 \times P_B$ with $\eta_2 \sim 2\times10^{-3}$



[Zarka et al., 2001]

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

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



[Zarka et al., 2001, 2005]

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Planet & Star data

~250 exoplanets (in ~200 systems) 16% with $a \leq 0.05$ UA (10 Rs)

24% with $a \leq 0.1$ UA

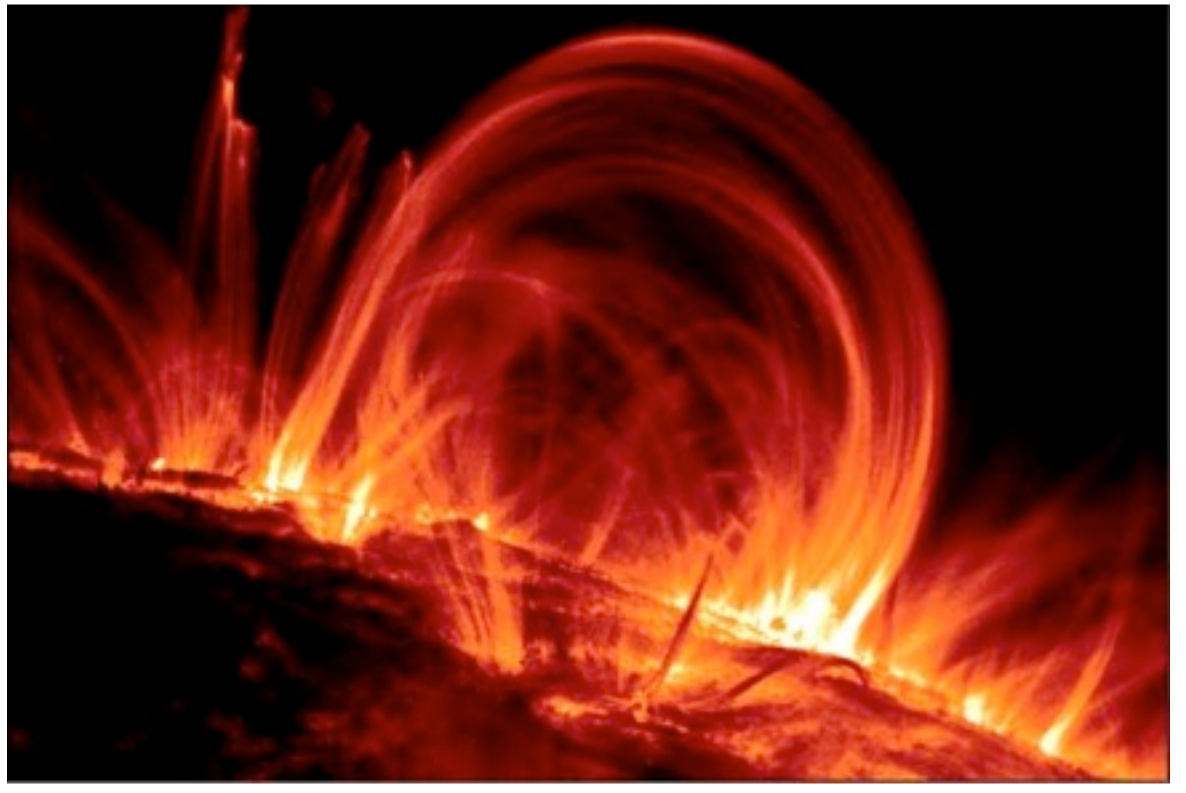
→ ~40 « hot Jupiters » with periastron @ ~5-10 R_S

Magnetic field at Solar surface :

→ large-scale ~1 G (10^{-4} T)

→ magnetic loops ~10^3 G,

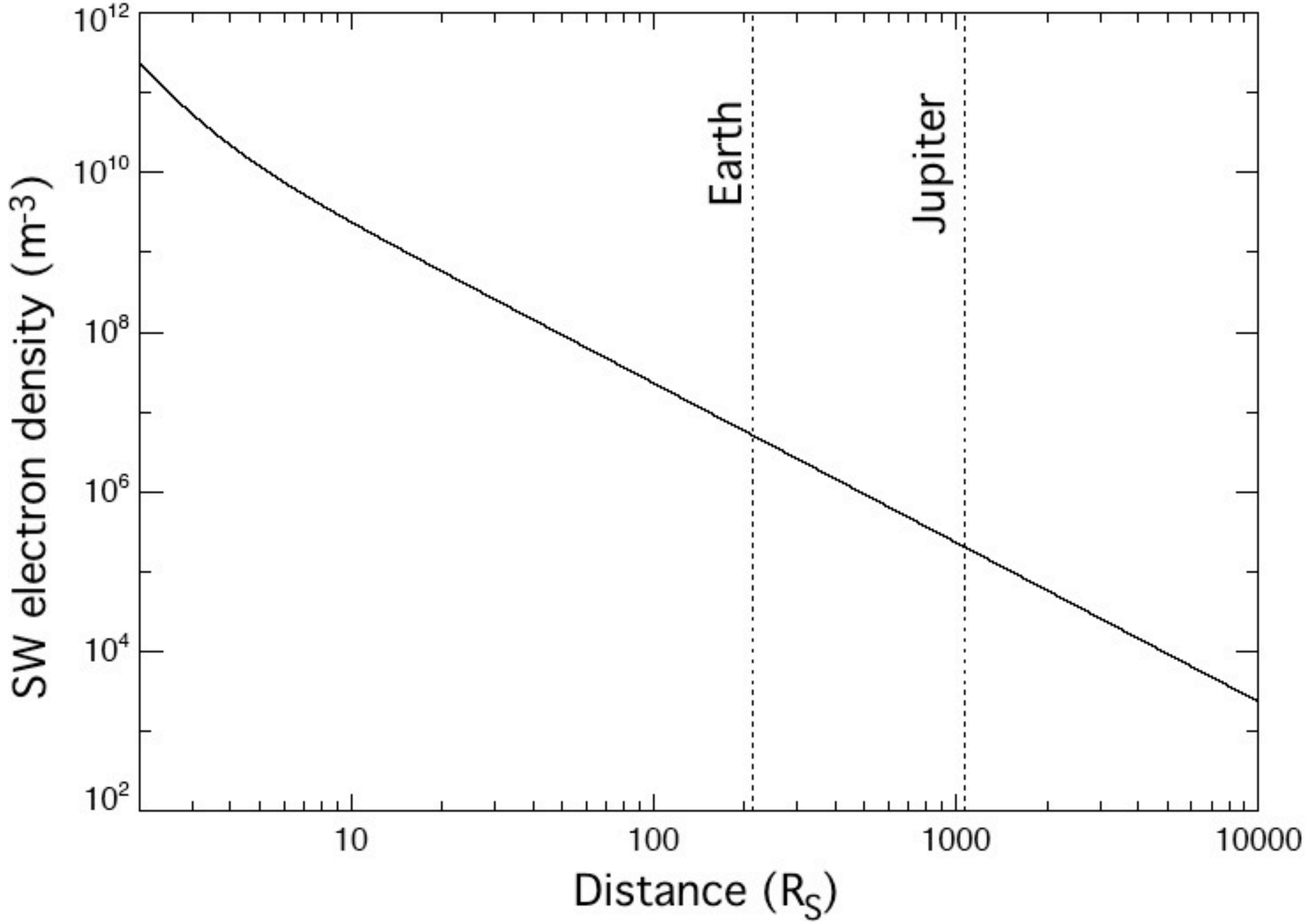
over a few % of the surface



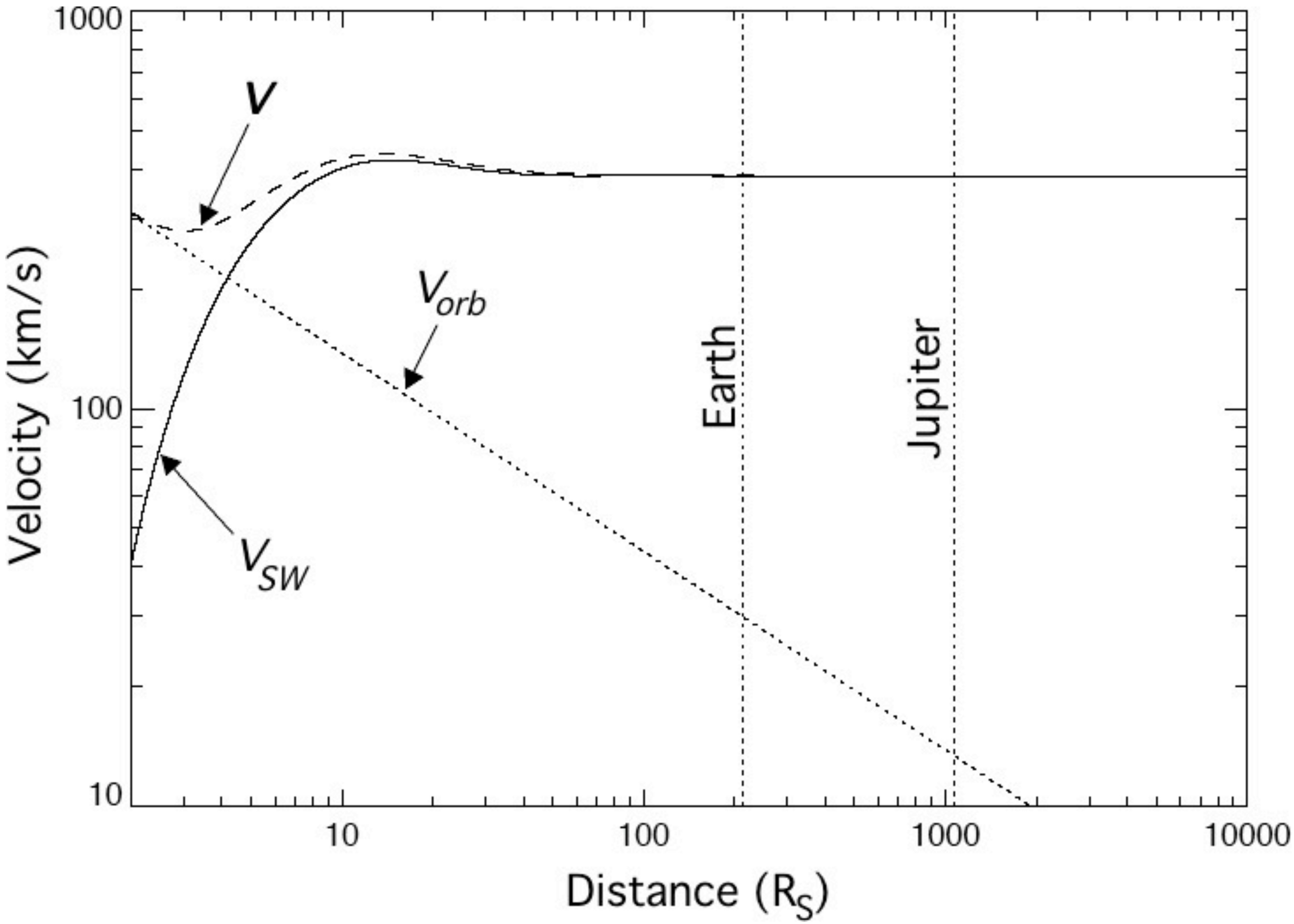
Magnetic stars : > 10^3 G

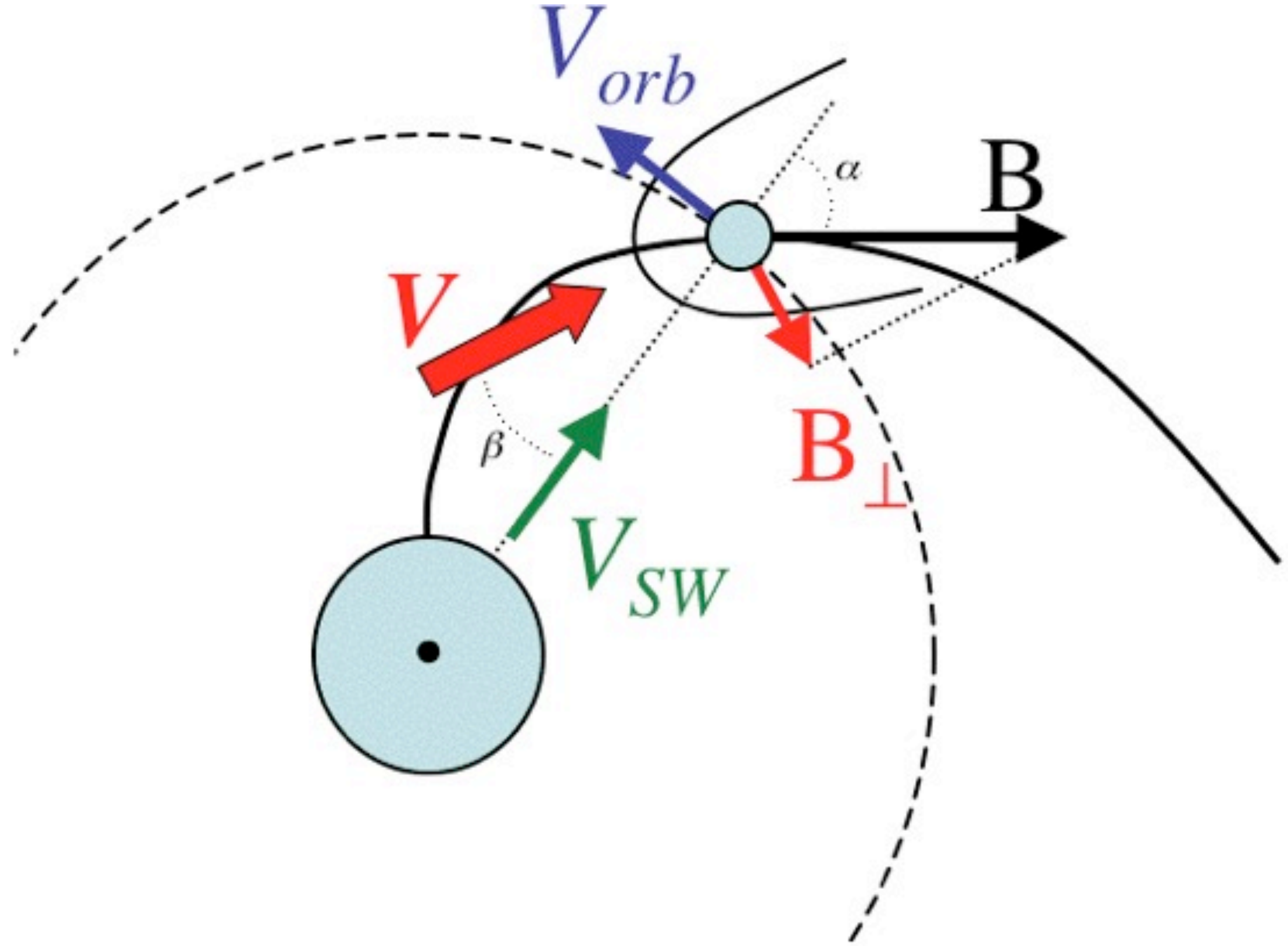
Modelling of a hot Jupiter (magnetized) orbiting a Solar type star

- Electron density in Solar corona

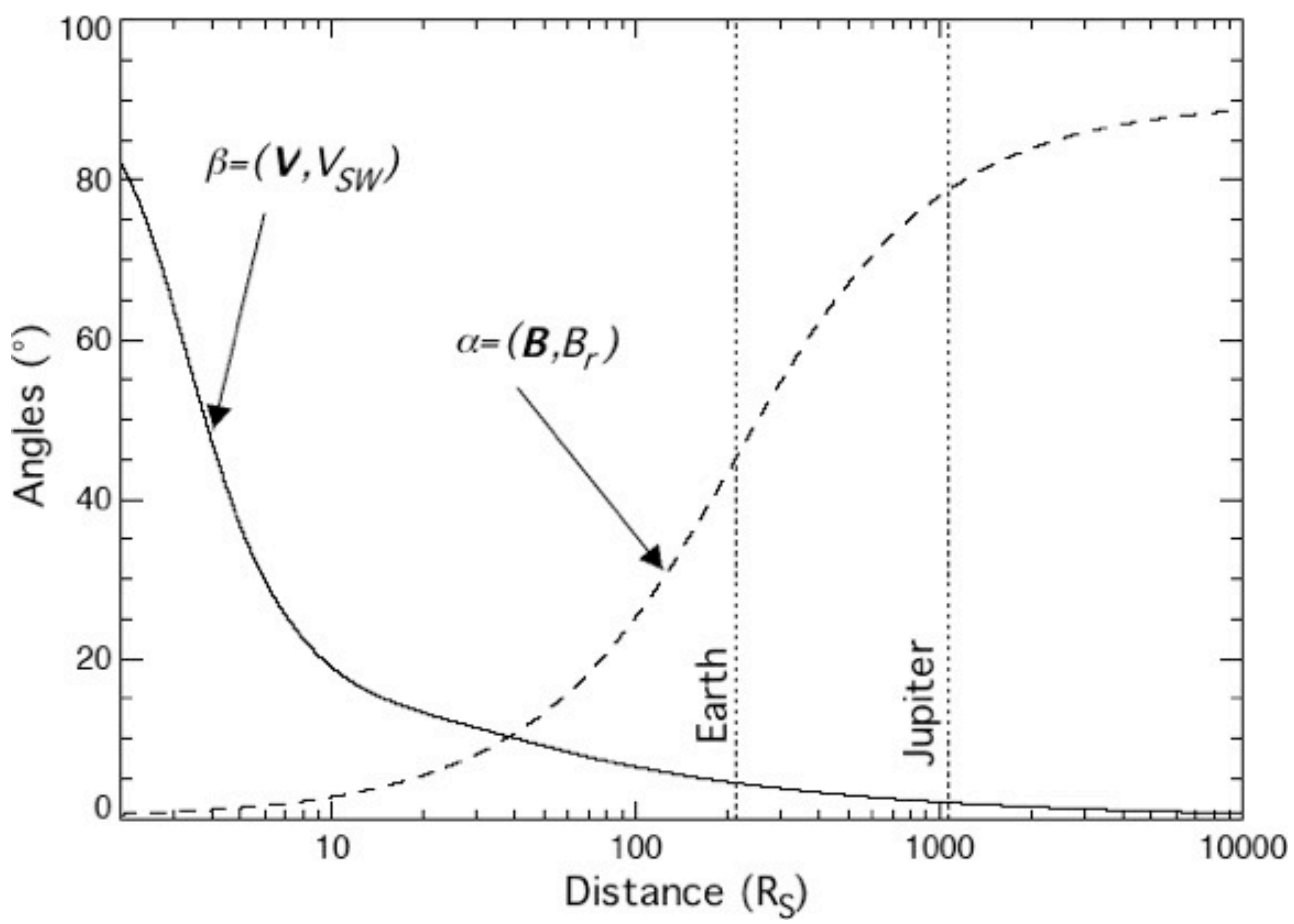


• Solar wind speed in the planet's frame



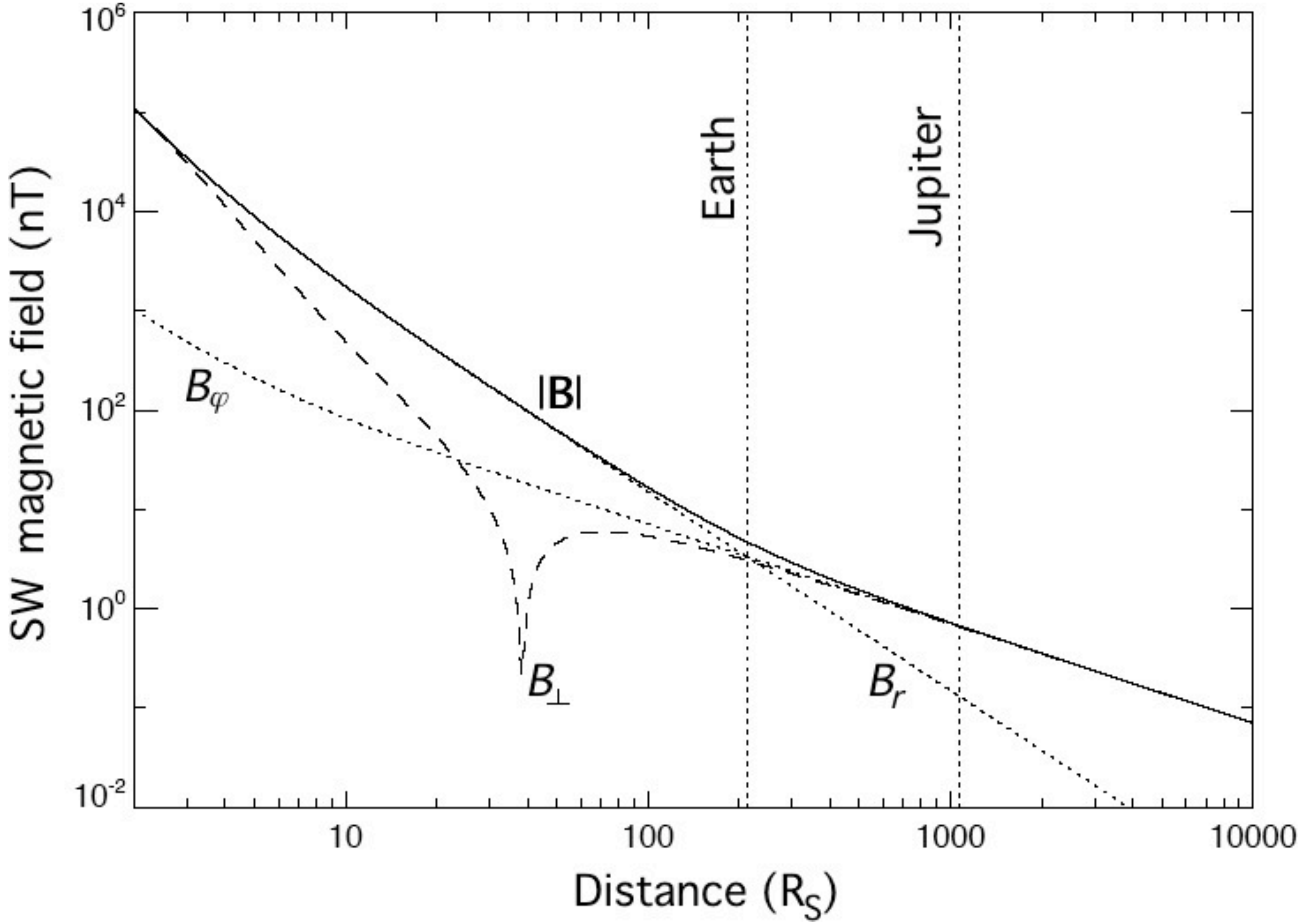


V_{orb}
α
B
V
β
$B_\perp$
V_{SW}

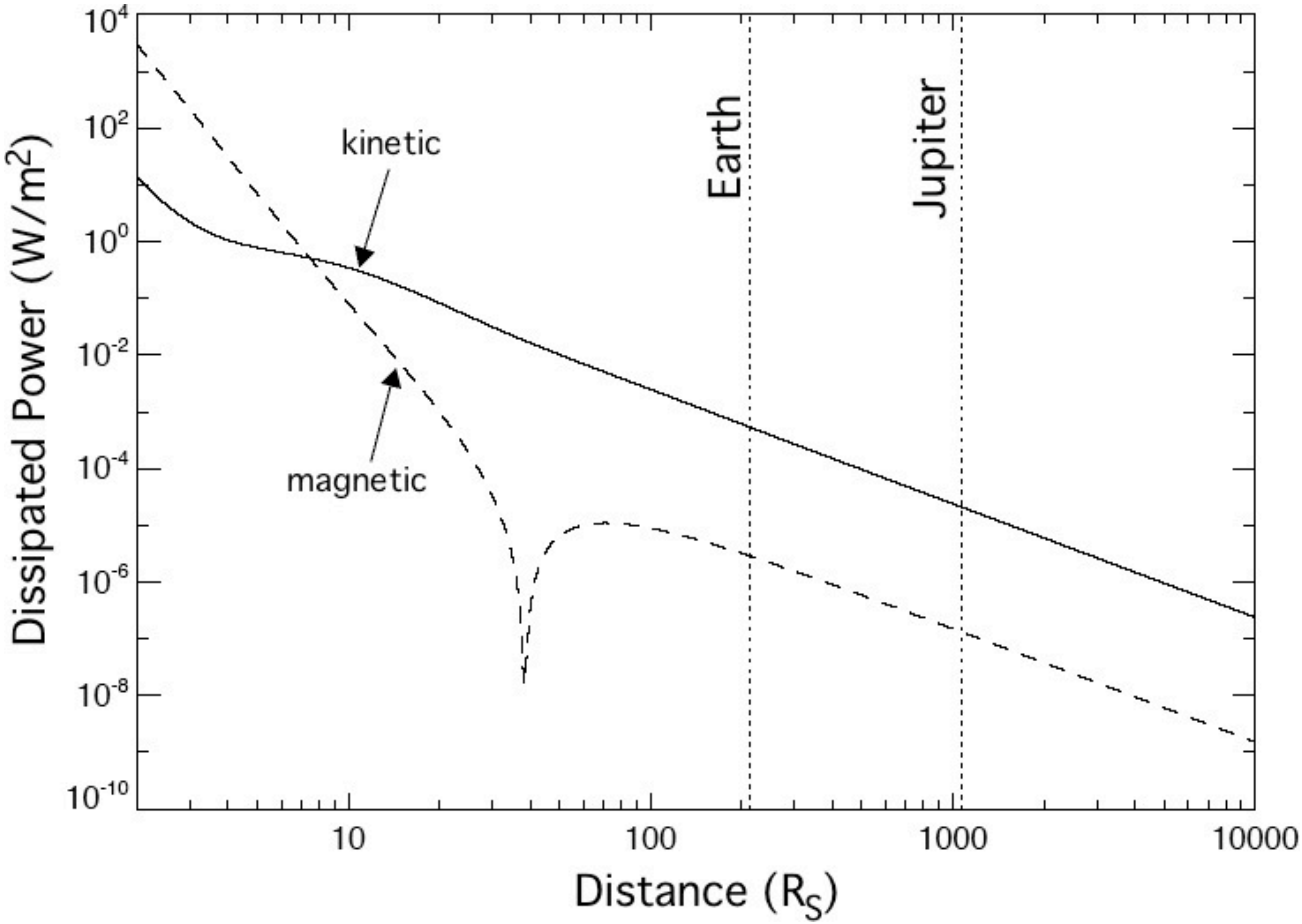


β=(**V**,V_{SW})
α=(**B**,B_r)
Earth
Jupiter
Angles (°)
Distance (R_S)
0
20
40
60
80
100
10
100
1000
10000

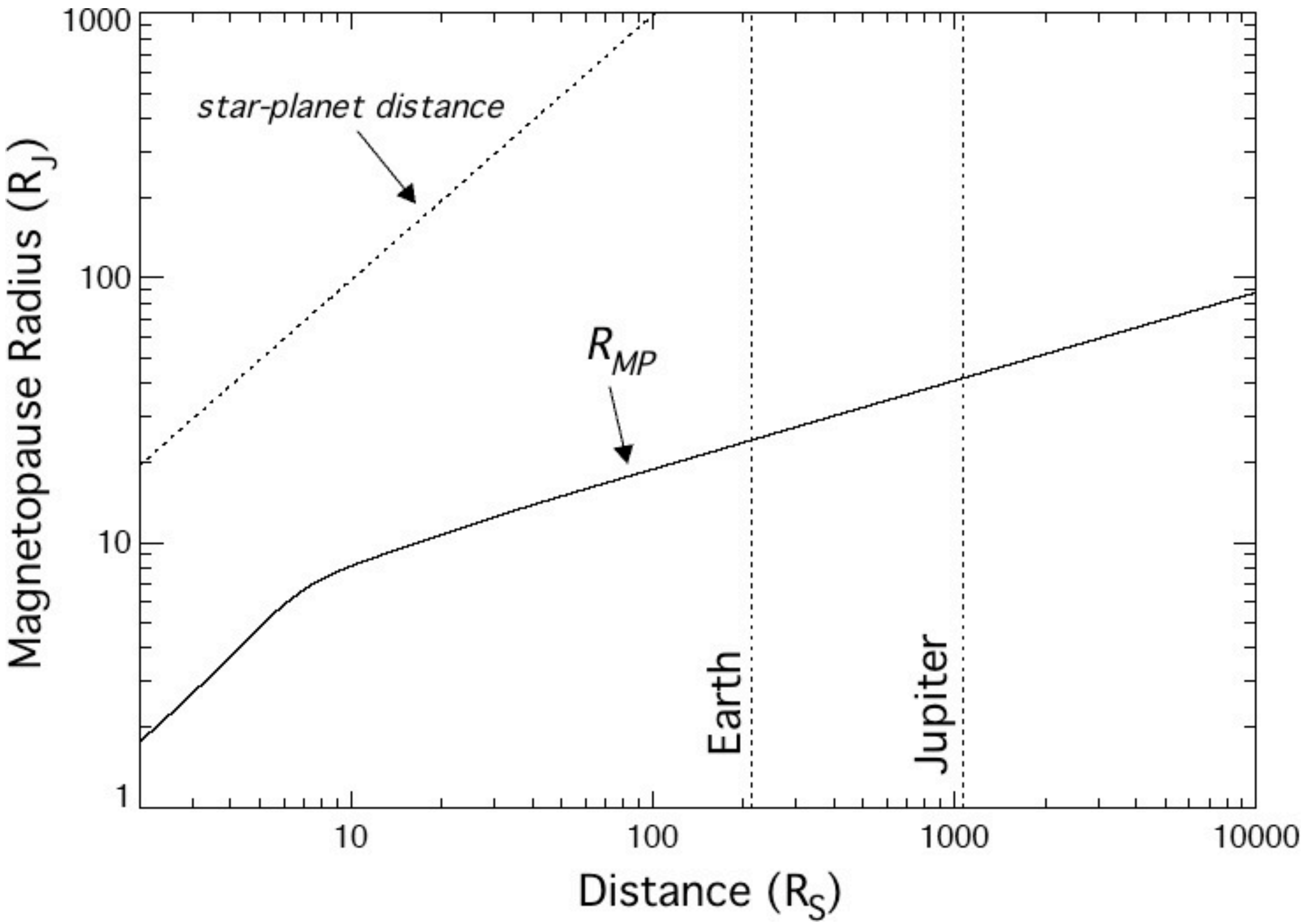
• Interplanetary magnetic field



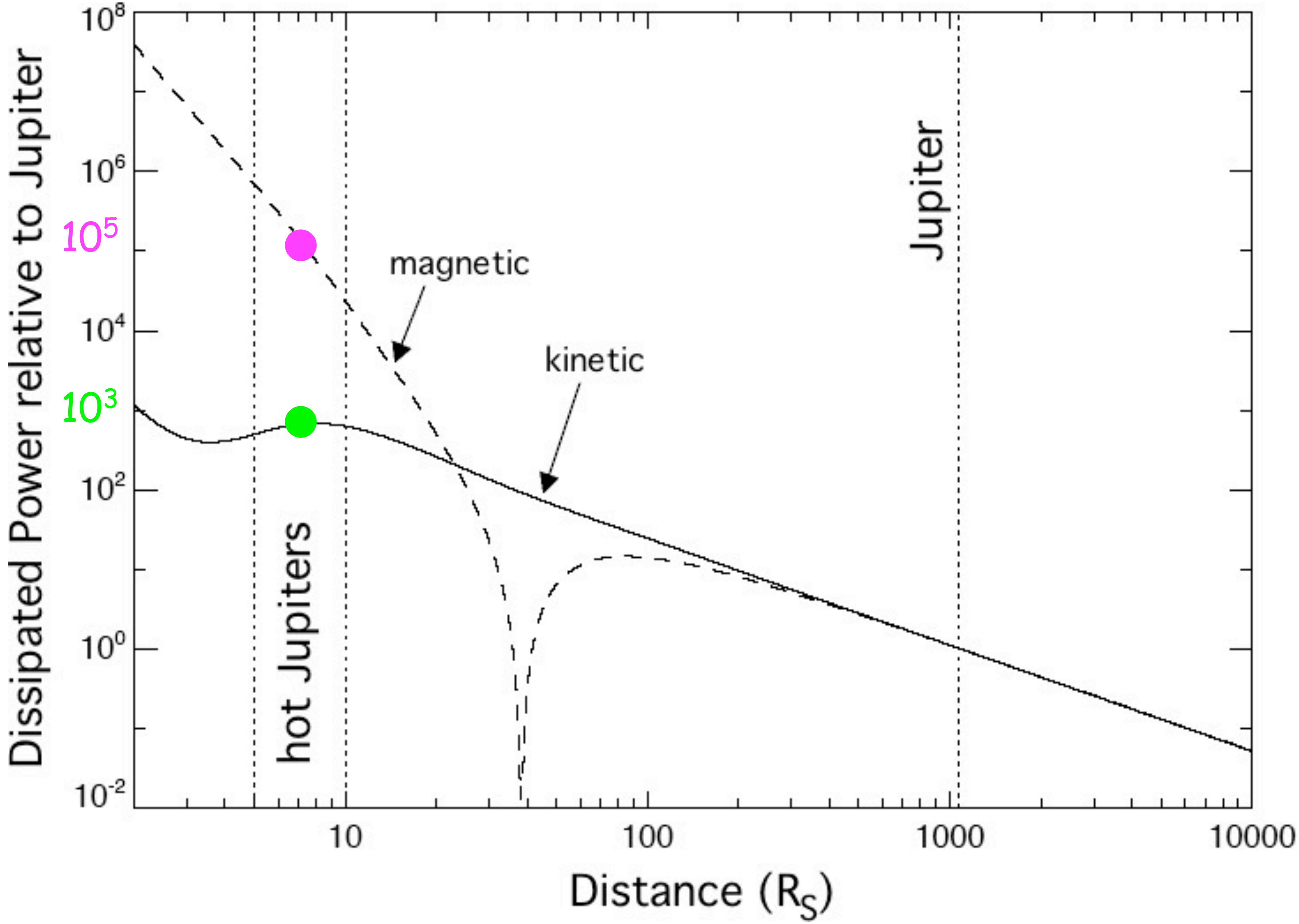
• Dissipated power per unit area of the obstacle

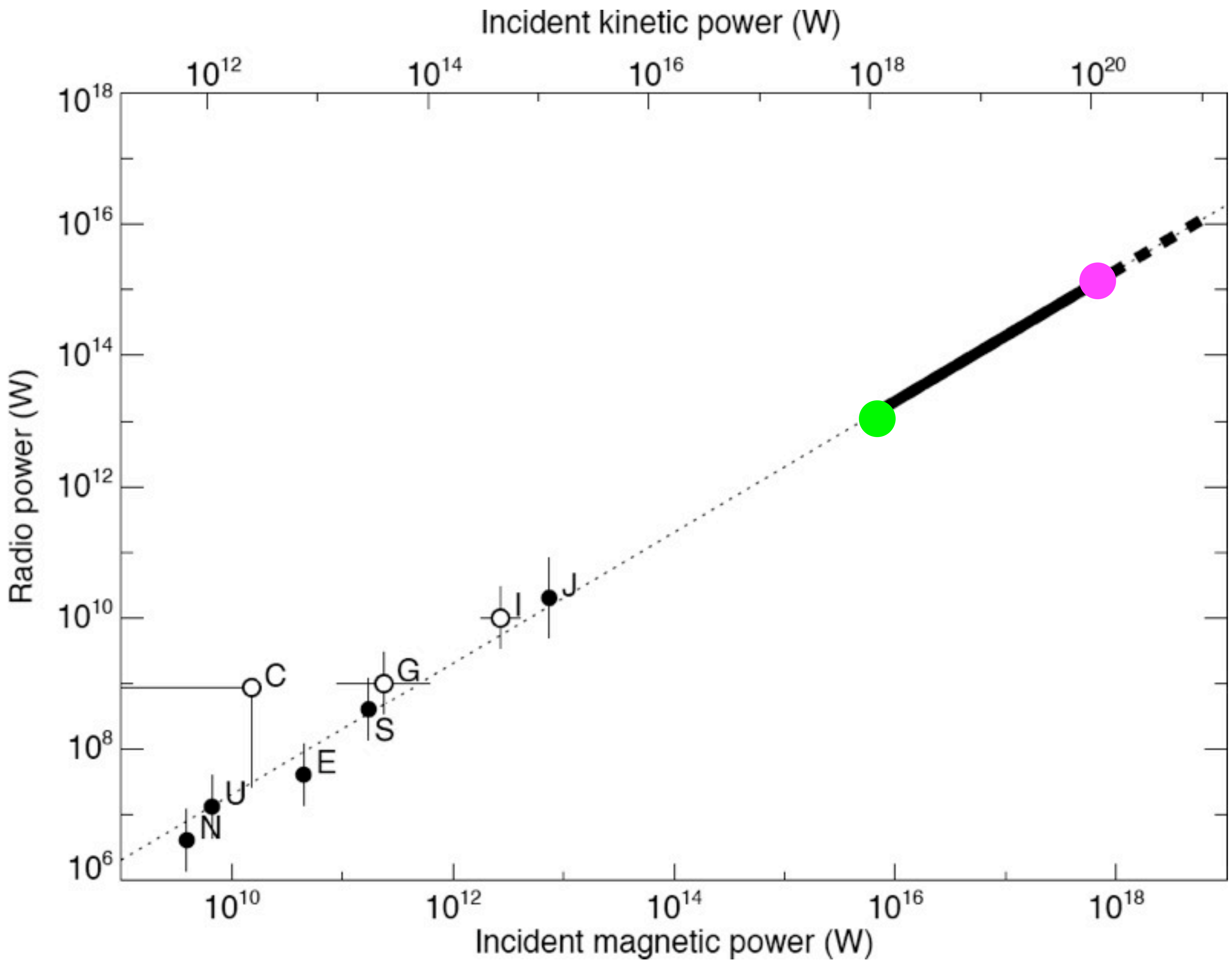


• Magnetospheric compression



• Total dissipated power on obstacle





- Extrapolation / Radio-kinetic Bode's law → $P_{Radio} = P_{Radio\text{-}J} \times 10^3$

[Farrell et al., 1999, 2004]

- Extrapolation / Radio-magnetic Bode's law → $P_{Radio} = P_{Radio\text{-}J} \times 10^5$

[Zarka et al., 2001, 2005]

except if there is a « saturation » mechanism

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) → ω↓
- But $\mathcal{M} \propto P_{sid}^{\alpha}$ $-1 \leq \alpha \leq -\frac{1}{2}$ → $\mathcal{M}$↓   (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

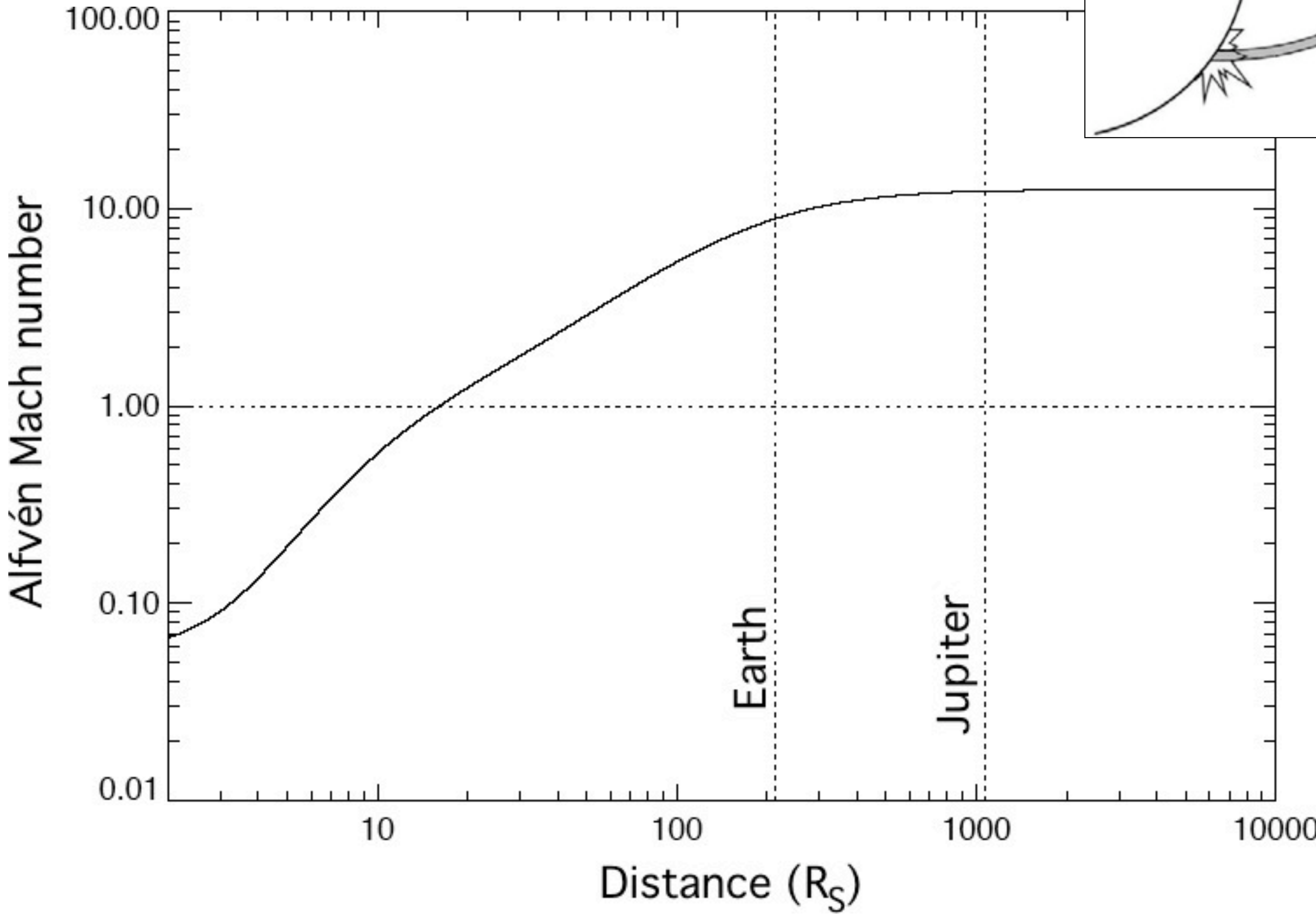
- Internal structure + convection models

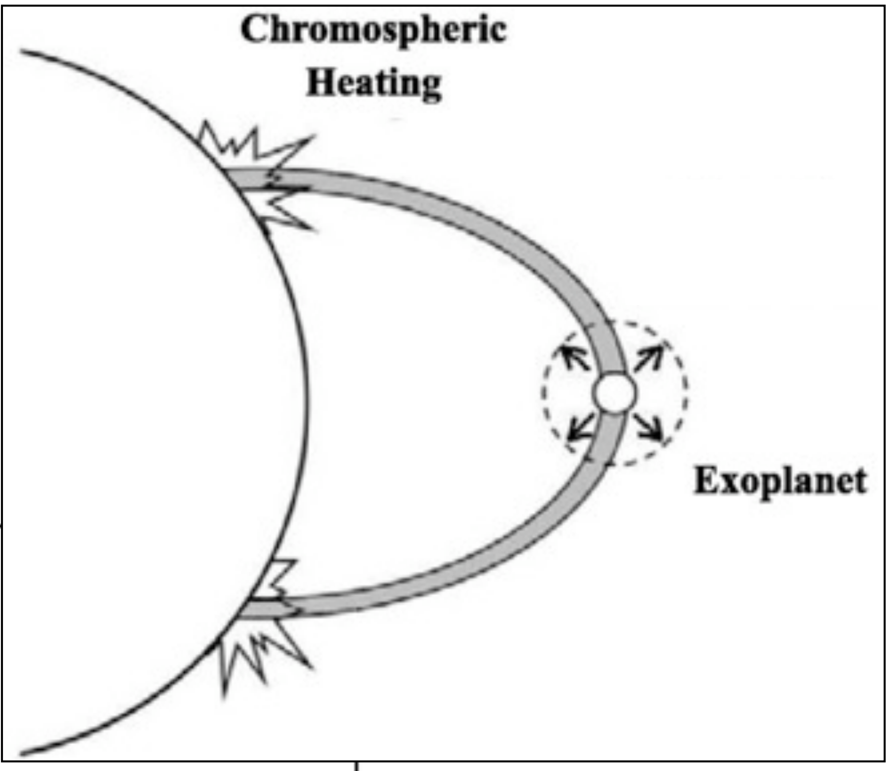
  → self-sustained dynamo   → $\mathcal{M}$ could remain ≥ a few G.R_J^3

[Sanchez-Lavega, 2004]

• Unipolar inductor in sub-Alfvénic regime

(as for Io-Jupiter)

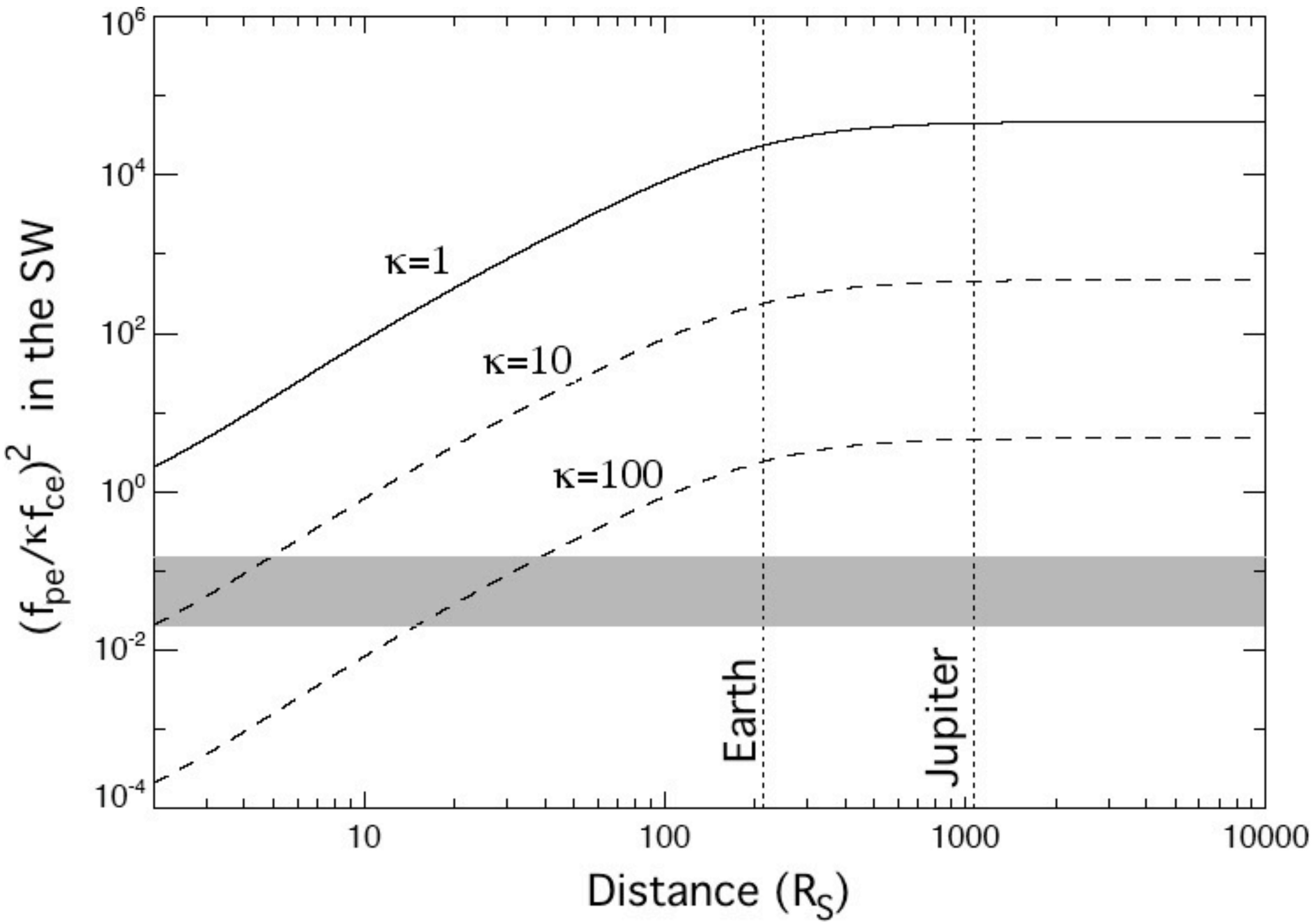




- But radio emission possible only if $f_{pe}/f_{ce} \ll 1$

  → intense stellar B required (κ = 10-100 × B_{Sun})

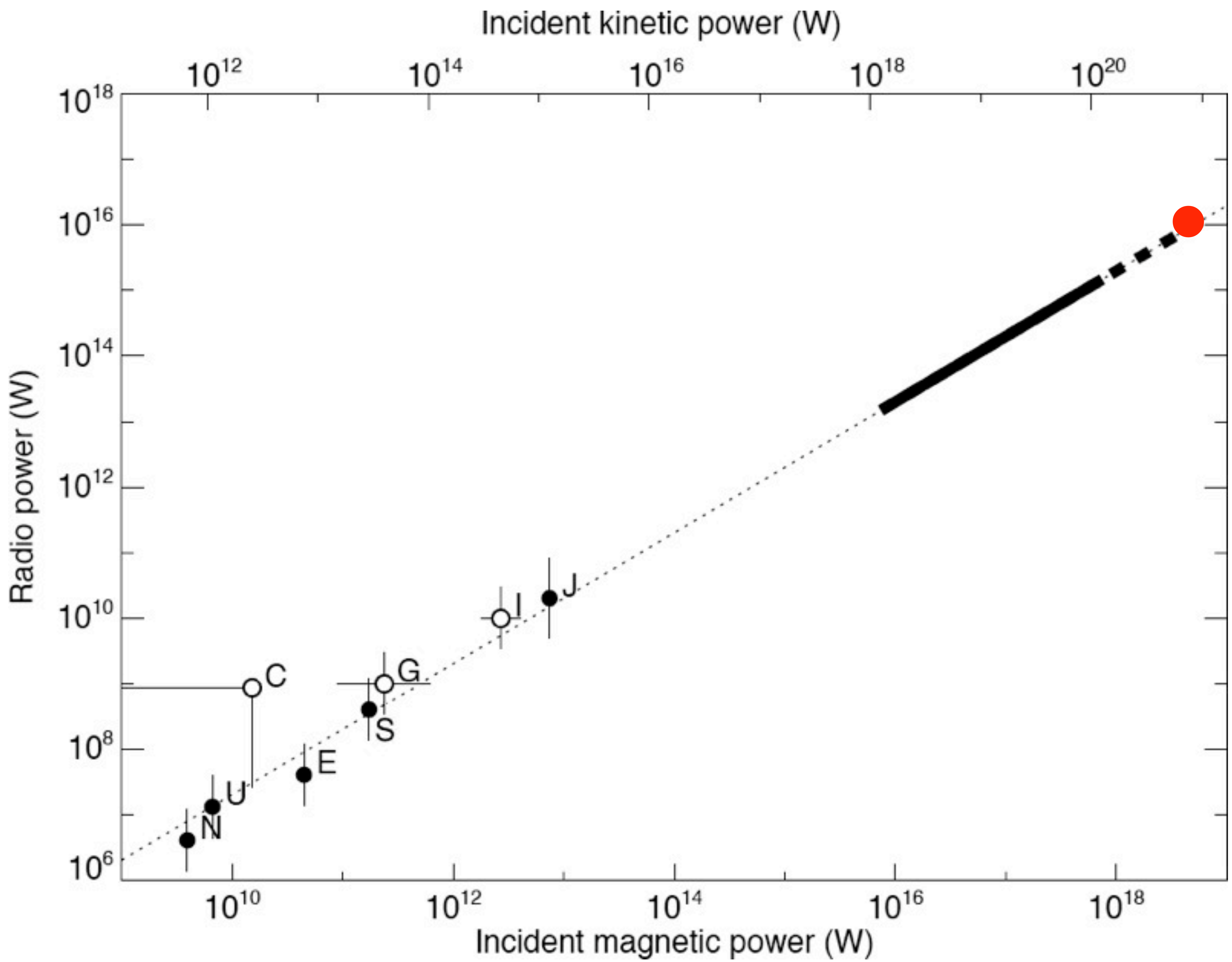
  → emission ≥ 30-250 MHz from 1-2 R_S



- Extrapolation / Radio-magnetic Bode's law [Zarka , 2005]

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

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



$\Rightarrow \zeta = 10^5$

	$b\tau = 10^6$ (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)

Other published studies …

- Possibilities for radio scintillations $\Rightarrow$ burts $P_{radio} \times 10^2$

[Farrell et al., 1999]

- Estimates of exoplanetary $\mathcal{M}$ (scaling laws - large planets better) → f_{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]

- Role of (frequent) Coronal Mass Ejections

[Khodachenko et al., 2006]

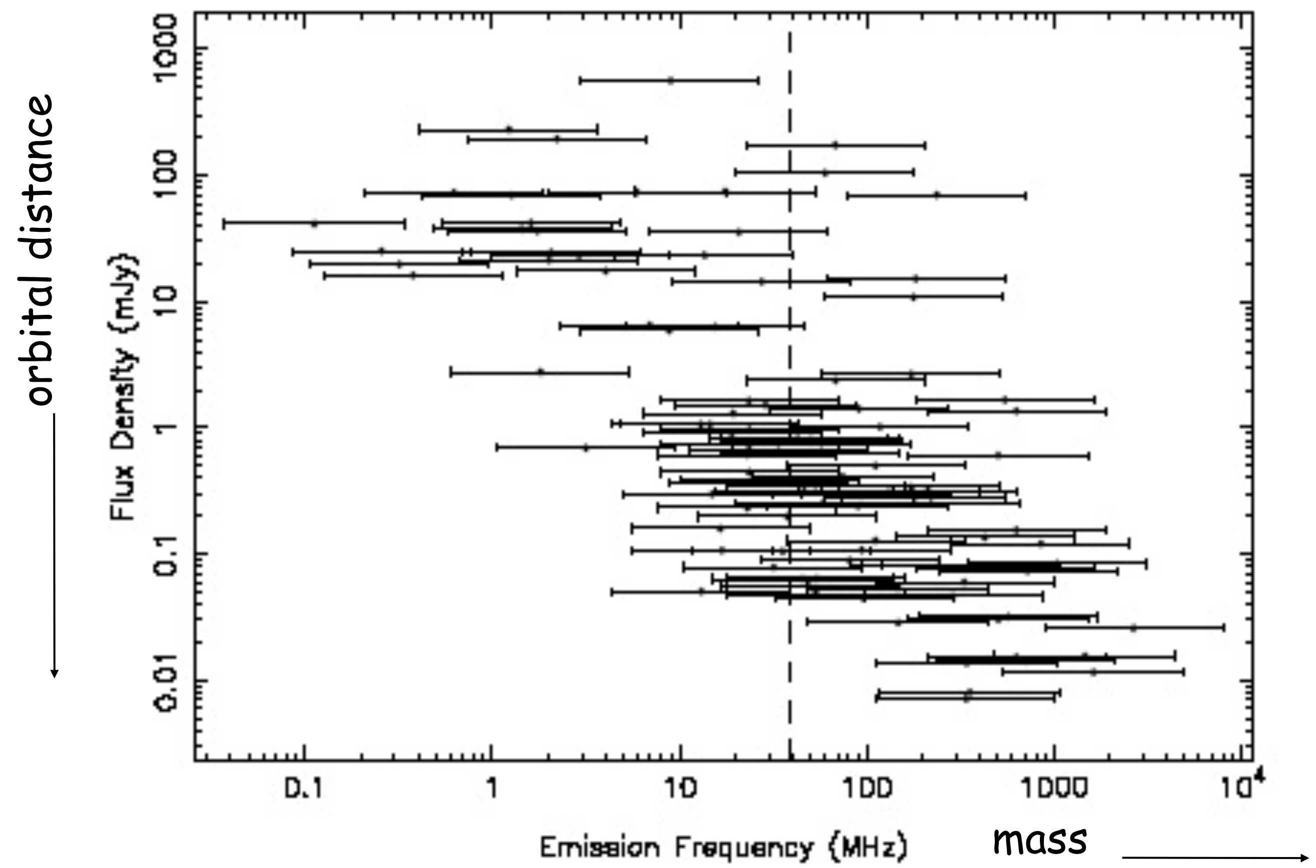
- Application of unipolar inductor model to white dwarfs systems

[Willes and Wu, 2004, 2005]

• Predictions for the whole exoplanet census

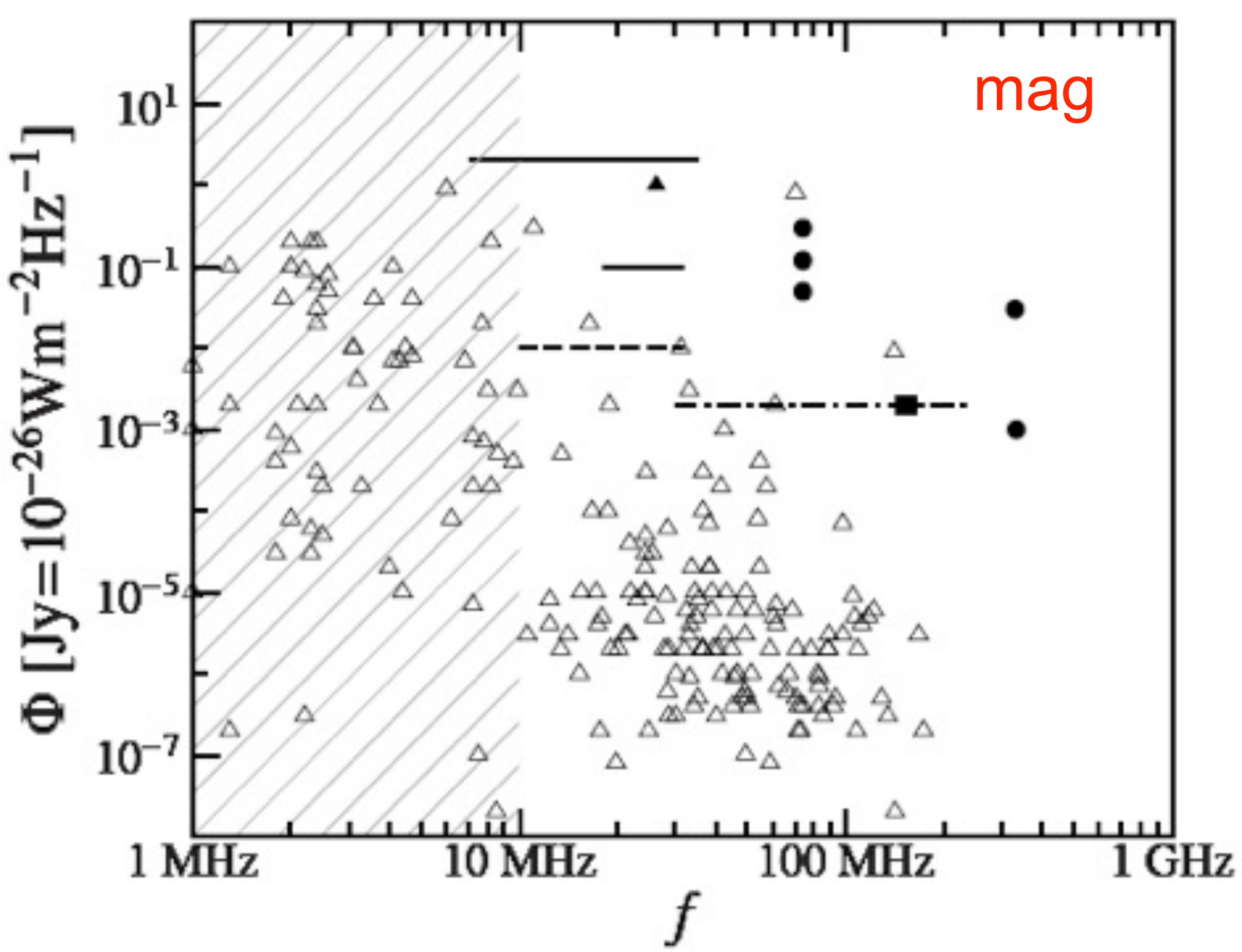
➡ radio-kinetic extrapolation

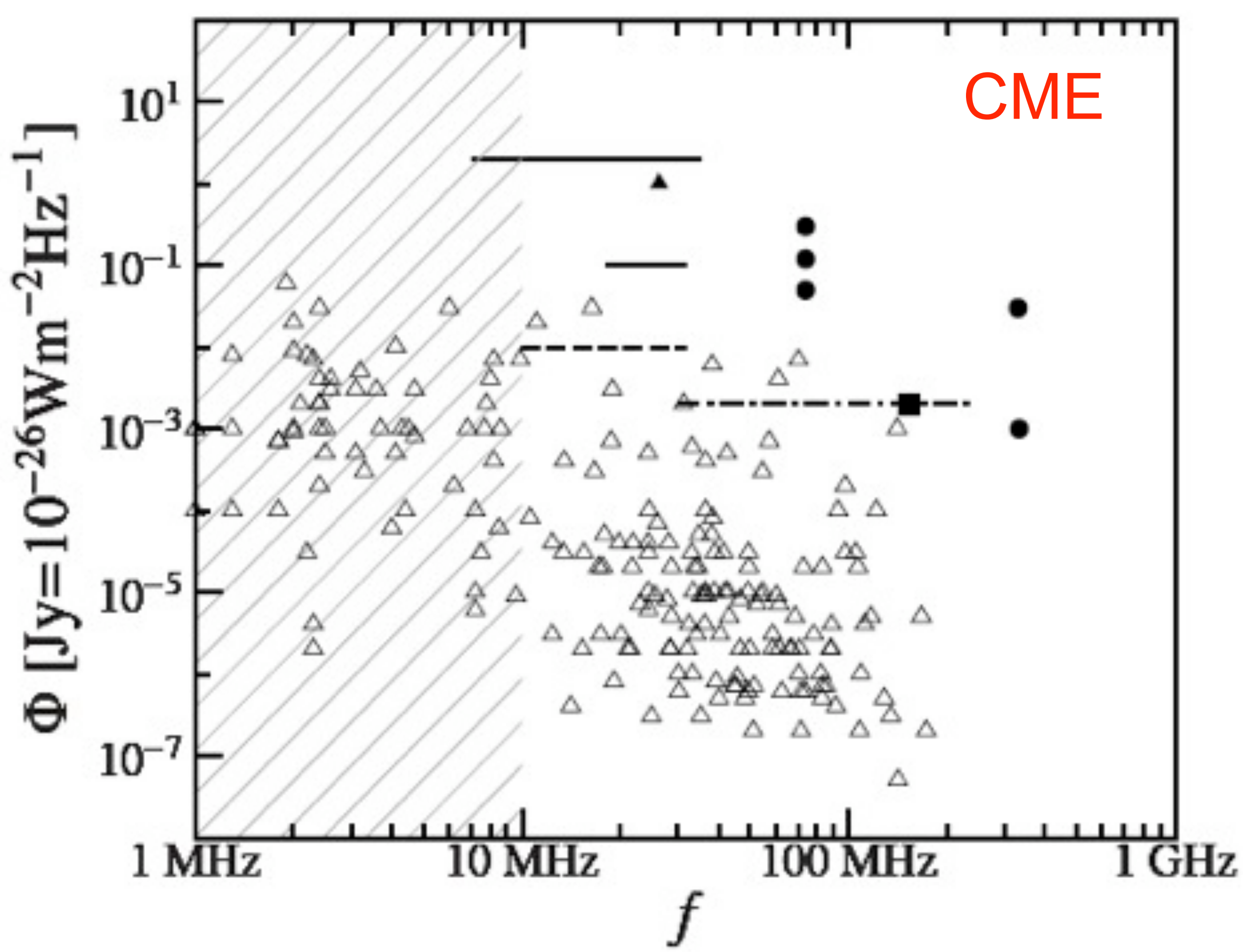
[Lazio et al., 2004]



➡ radio-magnetic + CME extrapolations

[Griessmeier , Zarka, Spreeuw, 2007]





- Interest of LF radio observations of exoplanets

- Theoretical predictions

  - planetary radio emissions

  - energy sources

  - scaling laws

  - extrapolation to exoplanets

- Conclusion

- The Radio Search for Extrasolar Planets is worth pursuing !

- Objectives

  → Direct detection (planet-star distinction via polarization & periodicity)

  → Planetary rotation period

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

  → Comparative magnetospheric physics (star-planet interactions)

  → Discovery tool (eventually) ?

- Ongoing observations at UTR-2, GMRT, VLA

- Future observations with : LOFAR, ALMA, SKA ... and from the Moon ?