RADIO DIAGNOSTIC OF STAR-PLANET PLASMA INTERACTIONS

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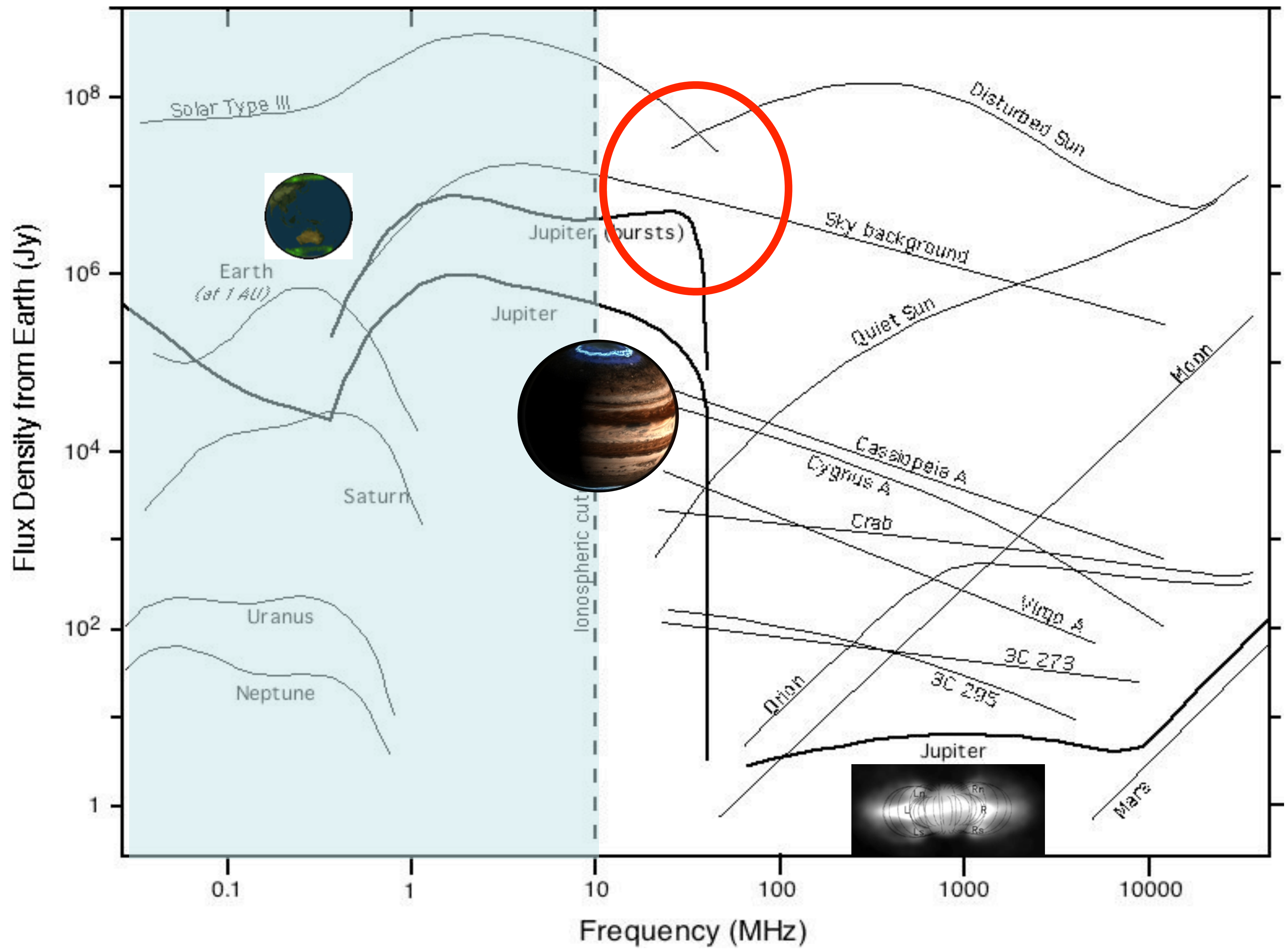
EXOPLANETS IN RADIO

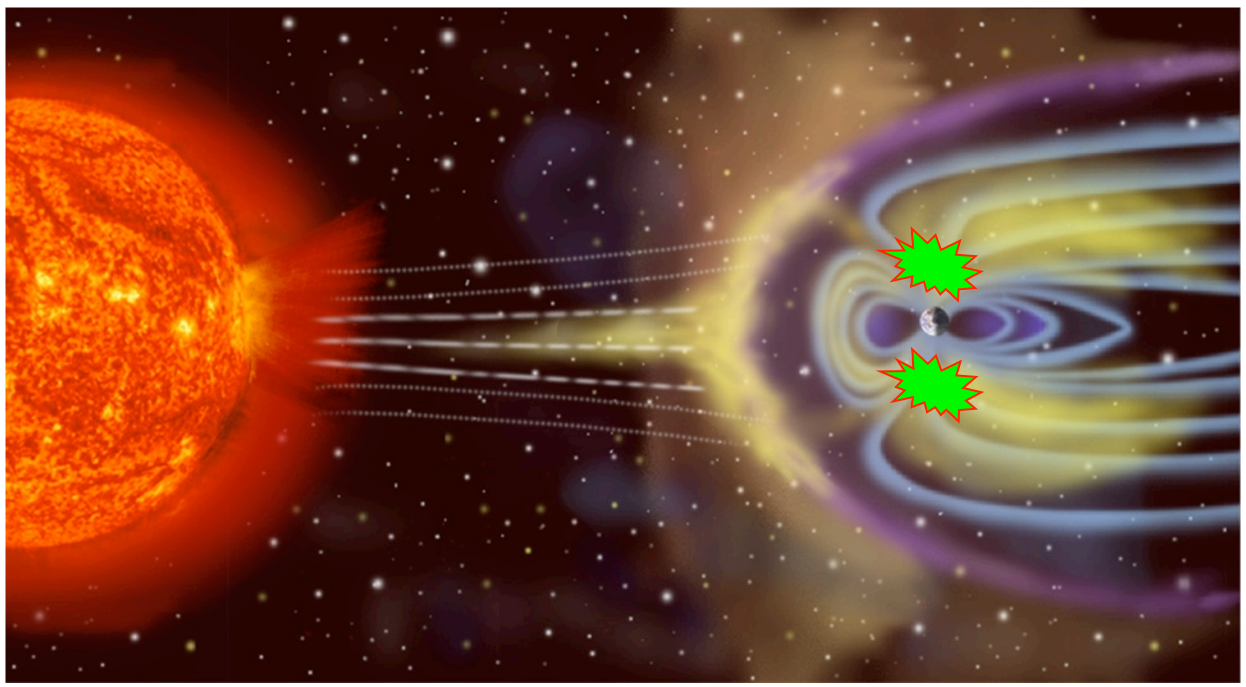
- Magnetized planets are strong radio sources (Jupiter ~ Sun)

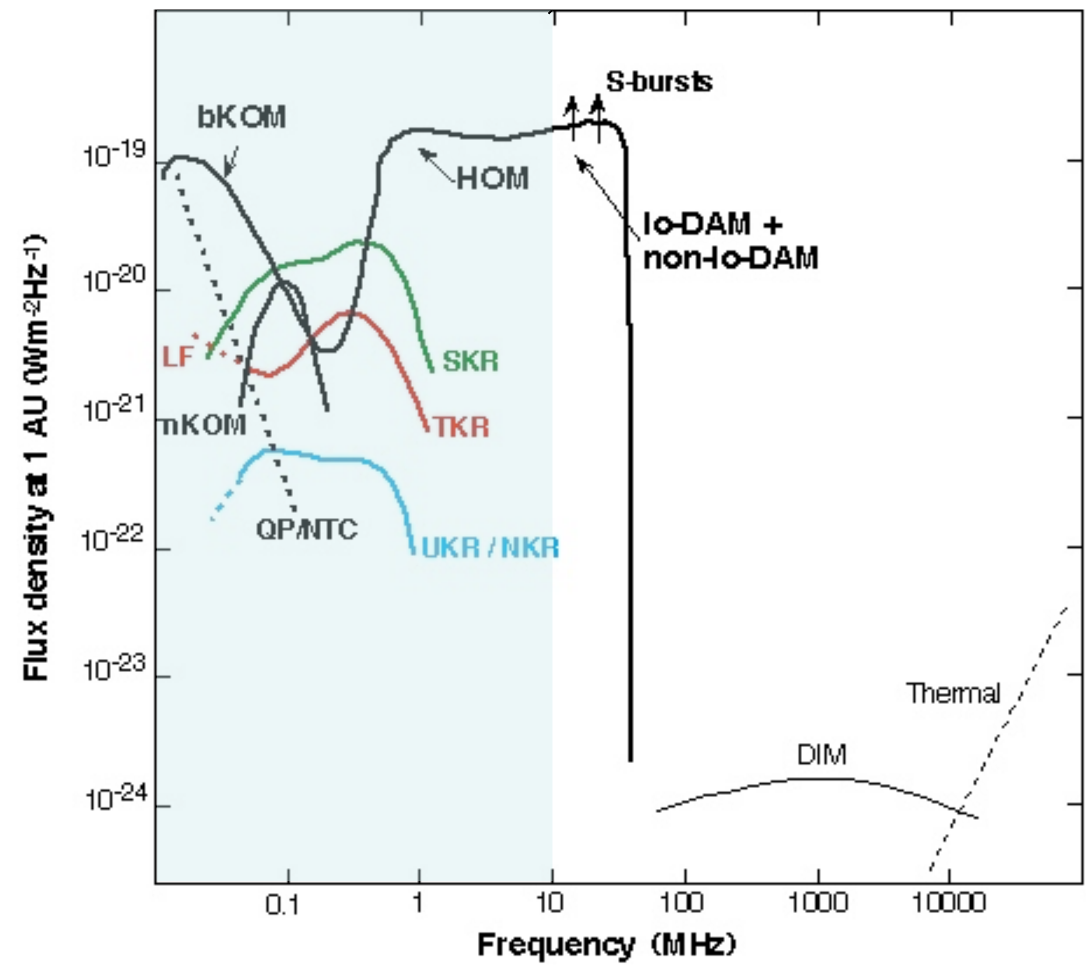


- Exoplanets in Radio ⇒ physical characterization & comparative studies with solar system planets

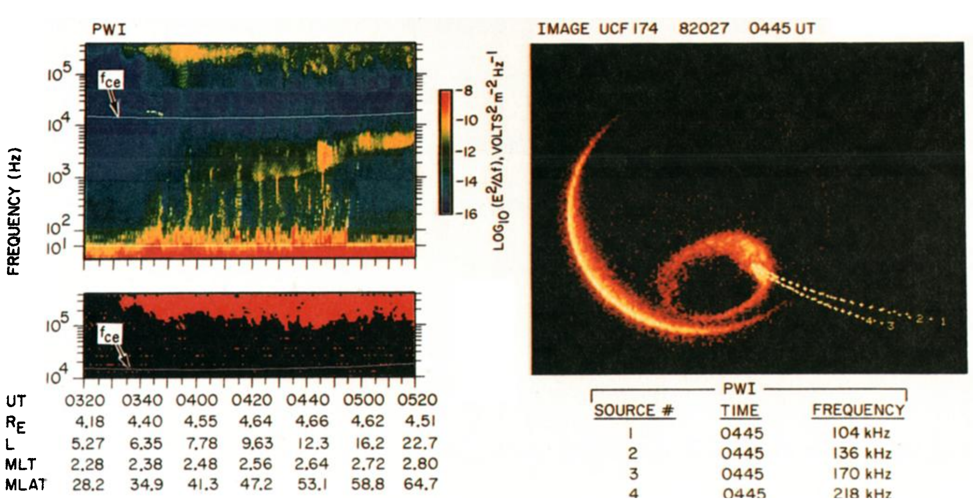
EXPERIENCE FROM SOLAR SYSTEM PLANETS + THEORY

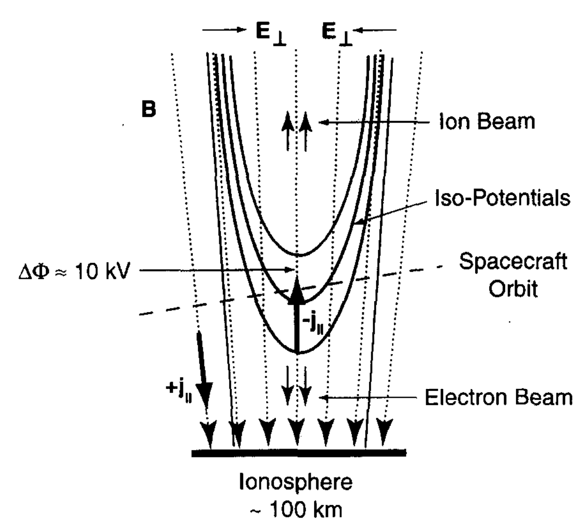
- 6 magnetized planets (M,E,J,S,U,N) with planetary-scale B field
  - → magnetospheres, accelerating keV-MeV electrons
  - → high-latitude (auroral) radio emissions
  - → radio sources studied remotely & in situ





[Zarka, 1998]





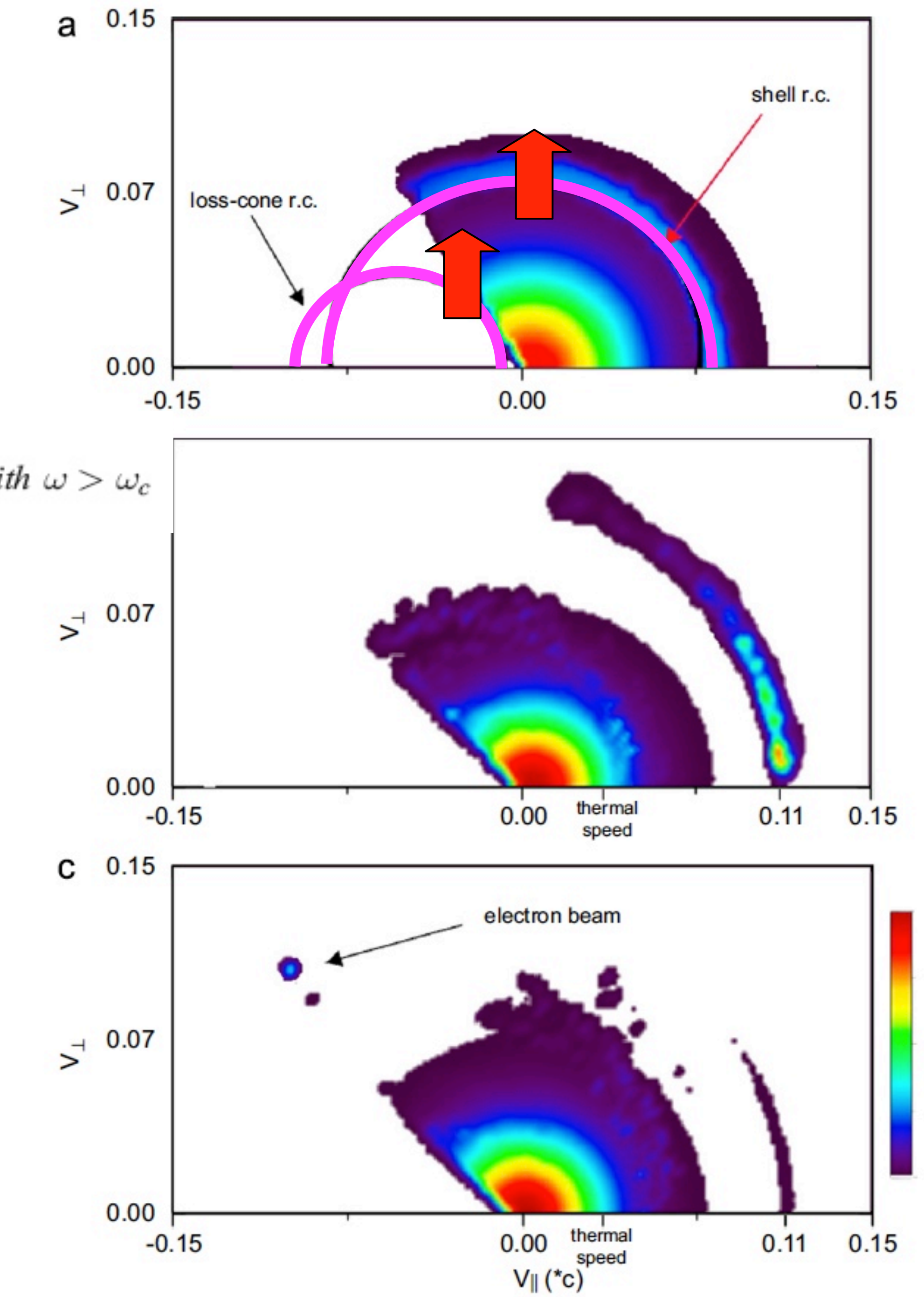
[Huff et al., 1988;
Treumann & Pottelette, 2002]

EXPERIENCE FROM SOLAR SYSTEM PLANETS + THEORY

- Coherent cyclotron (Maser) radiation from keV electrons
  - → frequency ≤ a few 10's MHz ($f_{ce} \propto |B|$)
  - → intense (T_B~10^{15-20} K)
  - → sporadic (msec-hour)
  - → anisotropic
  - → circularly polarized

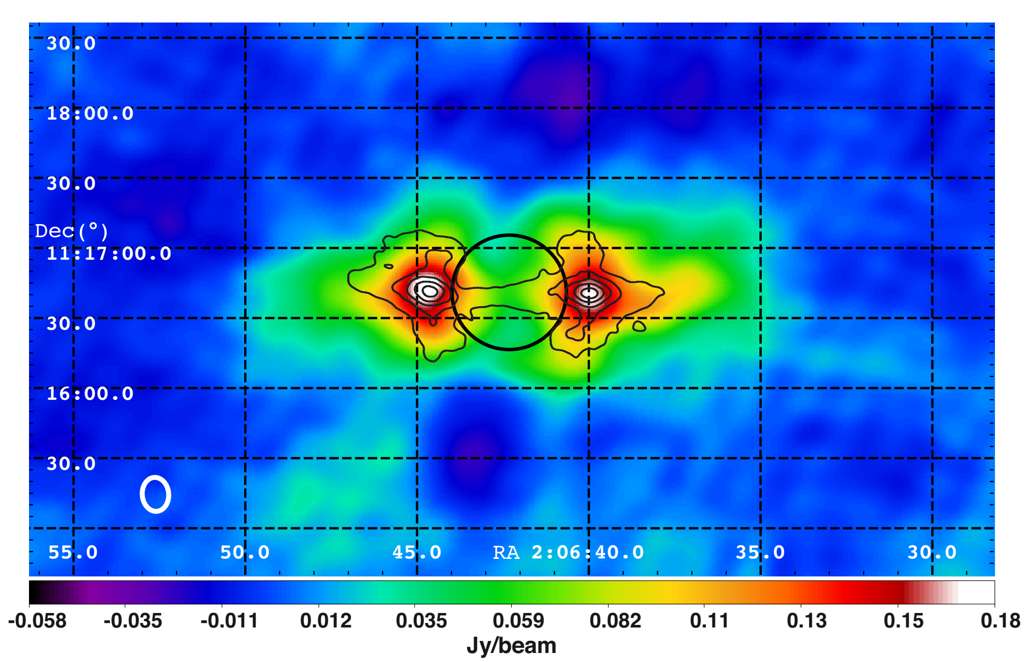
$$\omega = \omega_c/\Gamma - k_\parallel v_\parallel$$

$$\gamma = \frac{\omega_p^2 c^2}{8\omega_c} \int_0^{2\pi} v_\perp^2(\theta) \nabla_{v_\perp} f(\mathbf{v_0}, \mathbf{R}(\theta)) d\theta \text{ with } \omega > \omega_c$$



[Wu, 1985 ; Treumann, 2006 ; Hess et al., 2008]

- + weaker incoherent synchrotron emission from MeV e^- in radiation belts

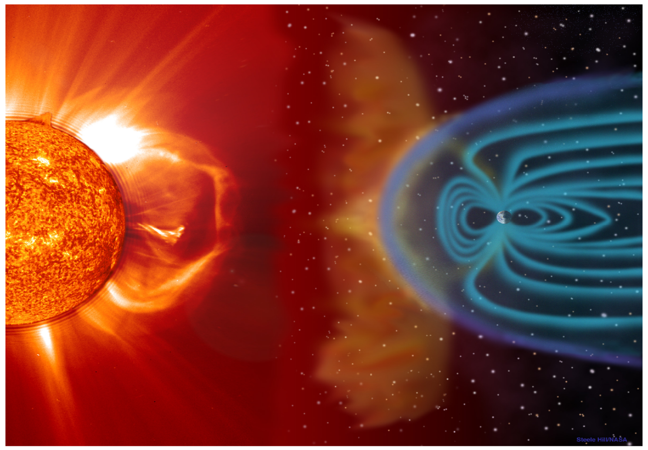


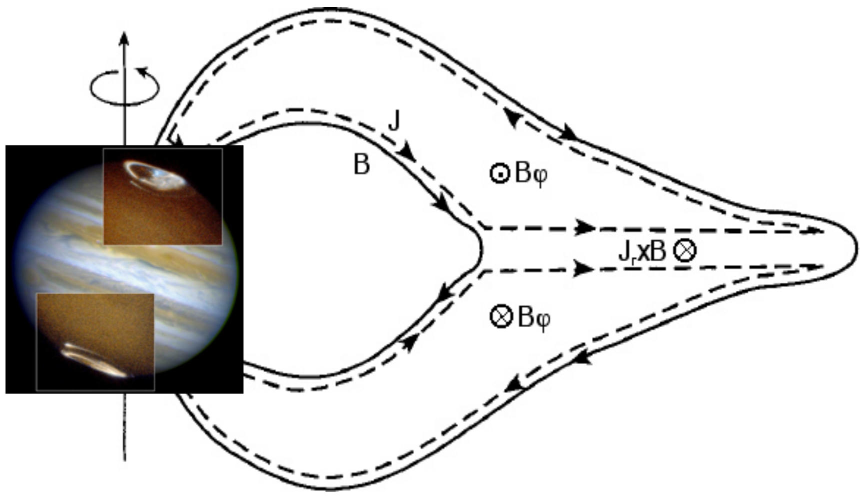
[Girard et al., 2012]

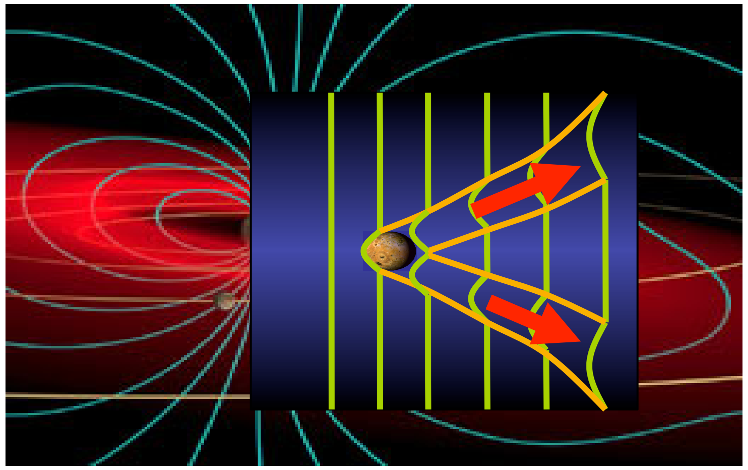
EXPERIENCE FROM SOLAR SYSTEM PLANETS + THEORY

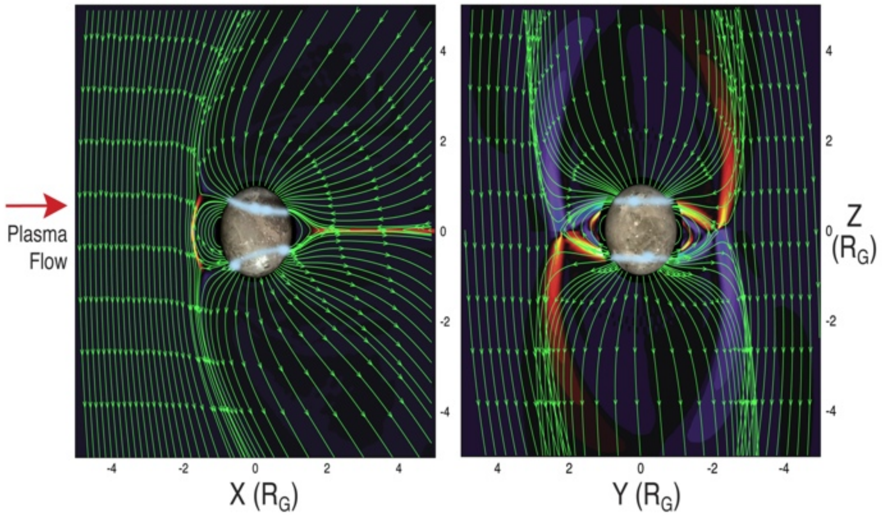
- Energy (keV electron acceleration) drivers

→ Stellar Wind-Magnetosphere interaction (super-Alfvénic, compression, reconnection)
→ Magnetosphere-Ionosphere coupling
→ Magnetosphere-Satellite coupling (sub-Alfvénic, reconnection, unipolar inductor)
→ Star-Planet Interaction (" " ")



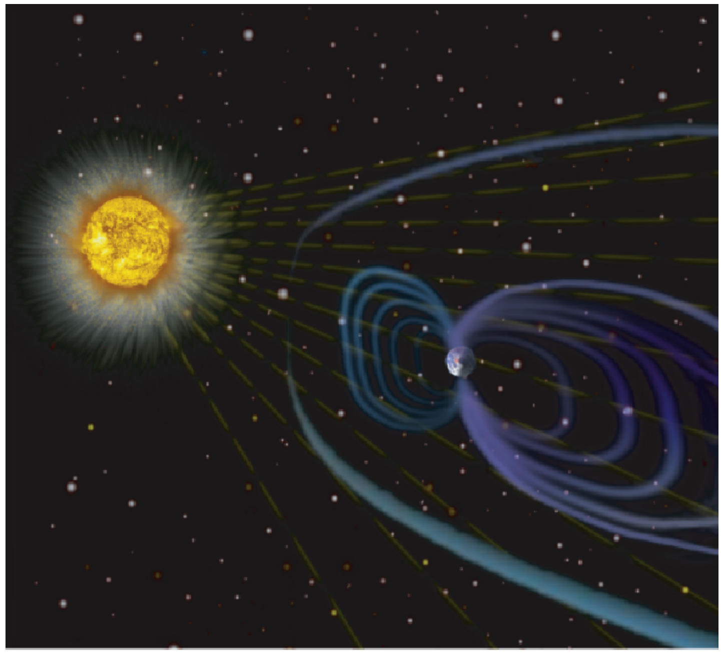






[Zarka et al., 2001 ; Zarka, 2007 ; Nichols, 2011]

→ Stellar Wind-Magnetosphere interaction

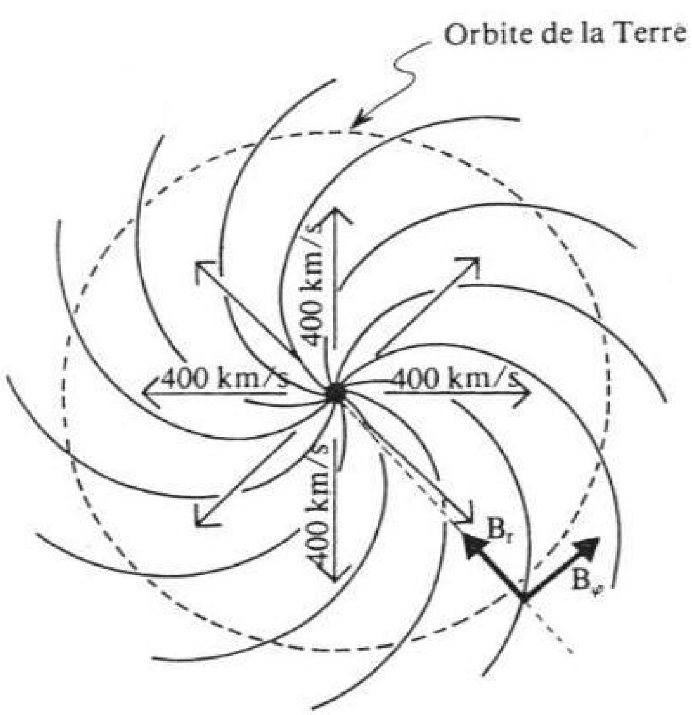


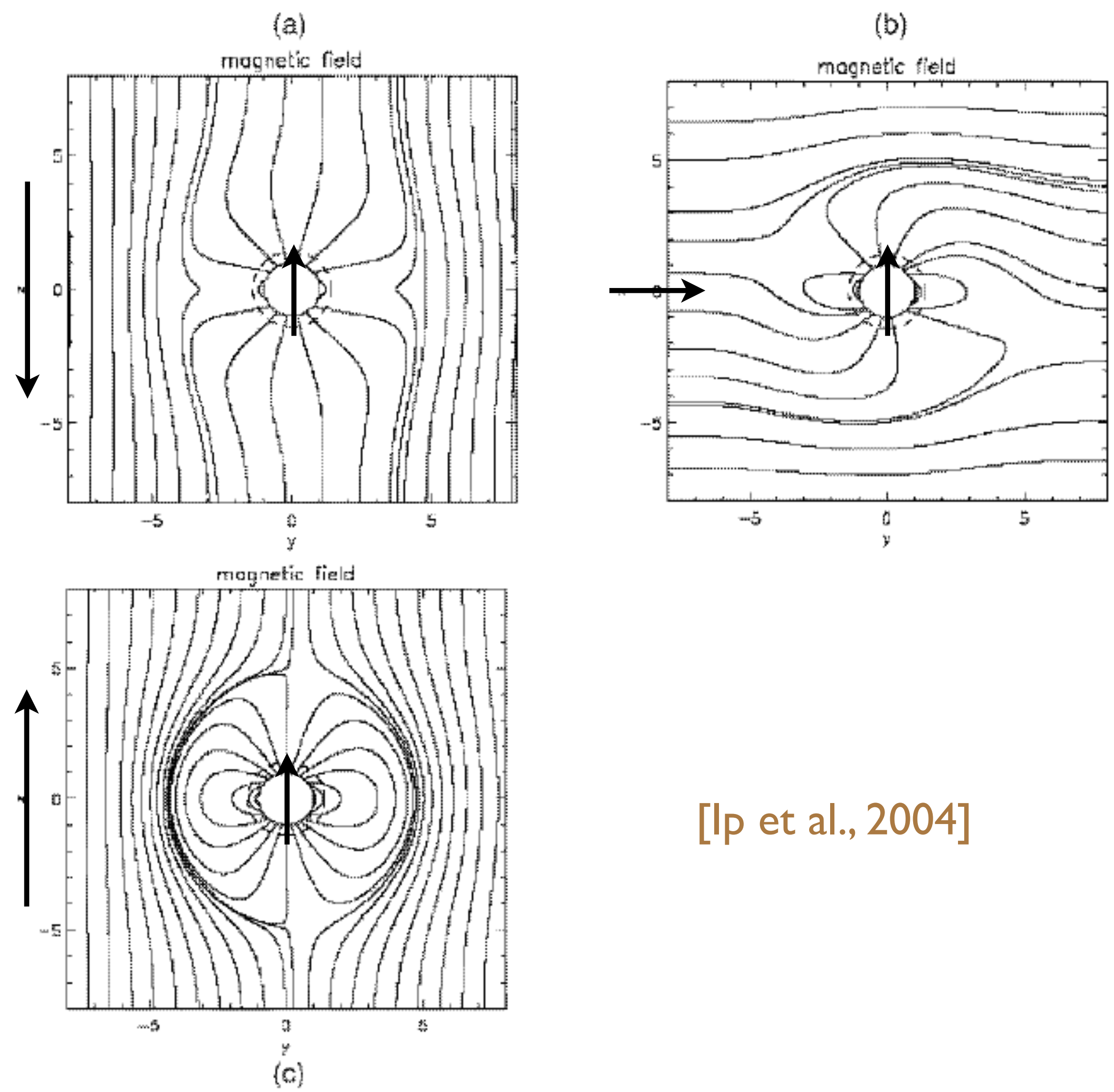
Poynting flux of B_{IMF} on obstacle :

$$P_m = B_\perp^2/\mu_o \, V \;\; \pi R_{obs}^2$$

Dissipated power :

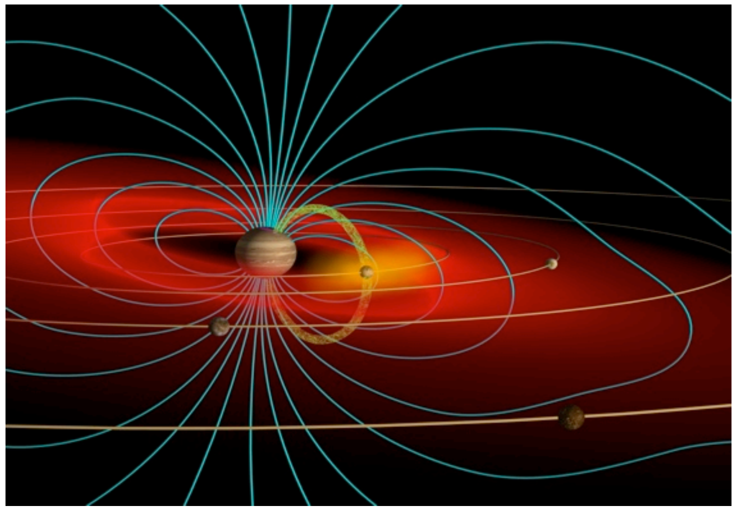
$$P_d = \varepsilon \, P_m \qquad (\varepsilon = 0.1 - 0.2)$$

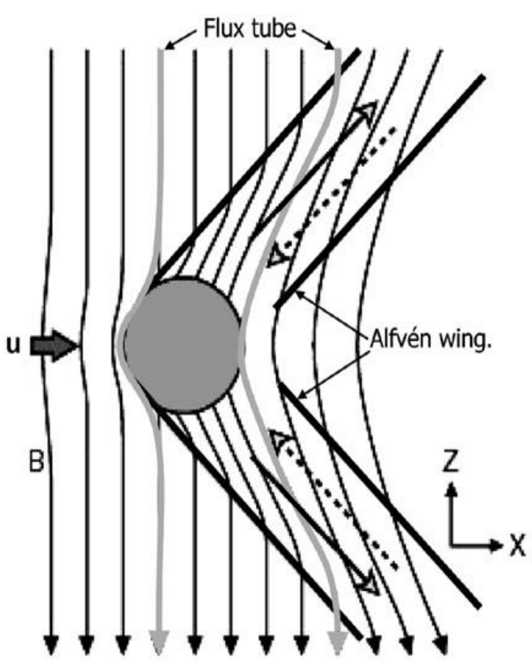




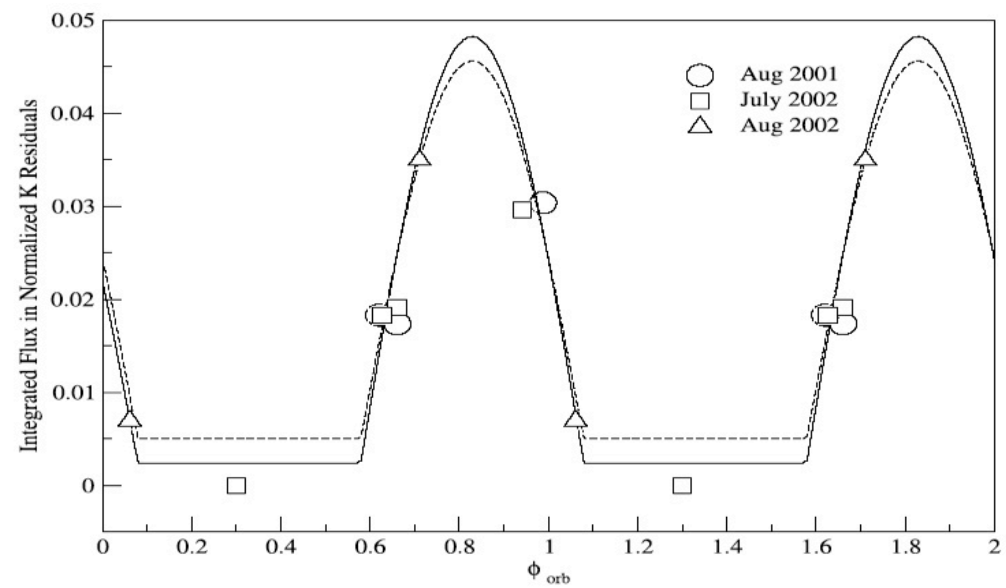
[Ip et al., 2004]

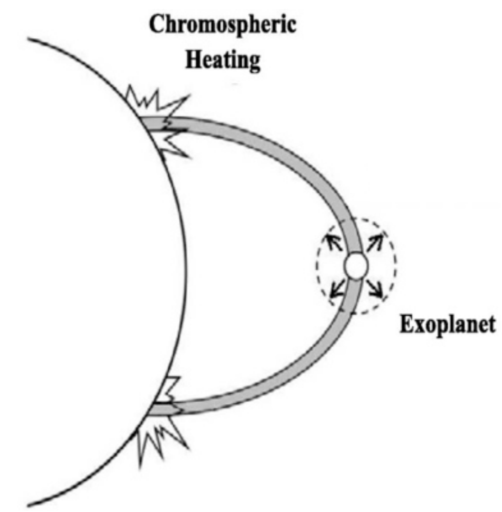
→ Magnetosphere-Satellite interaction (unipolar inductor)



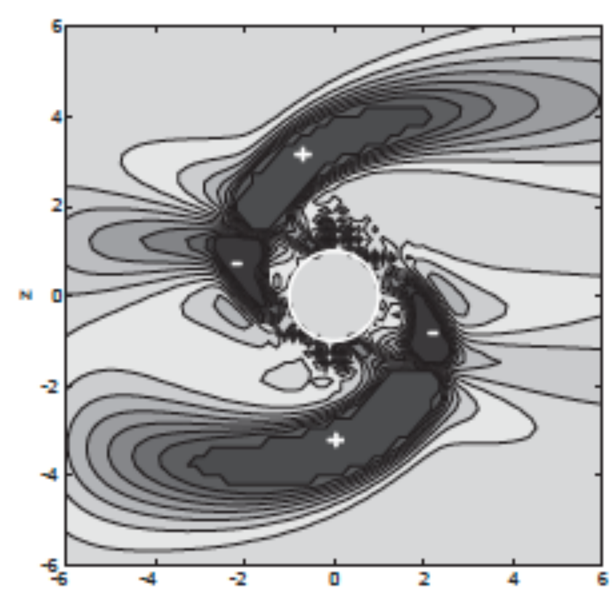


Chromospheric hot spot on HD179949 & υ And ?





[Shkolnik et al., 2005, 2008]



[Preusse et al., 2006]

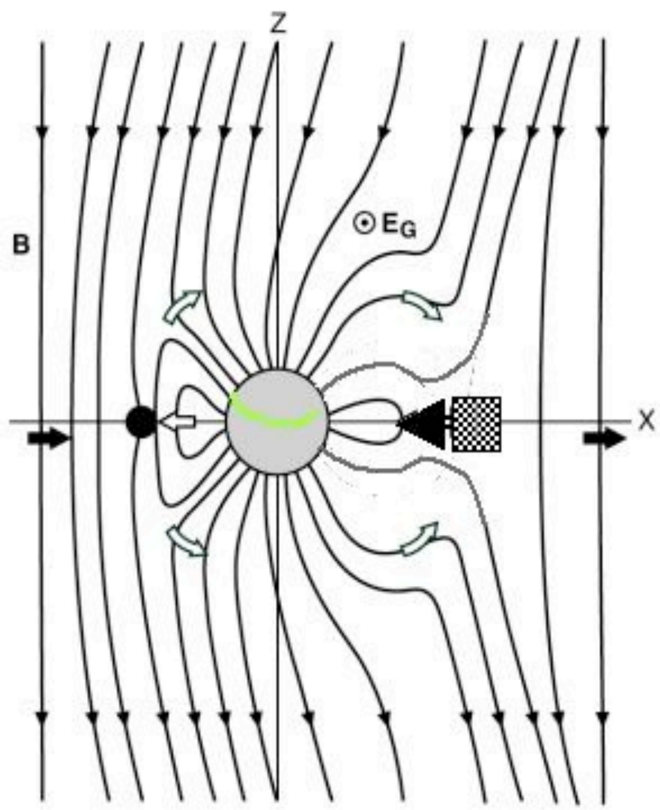
Dissipated power :

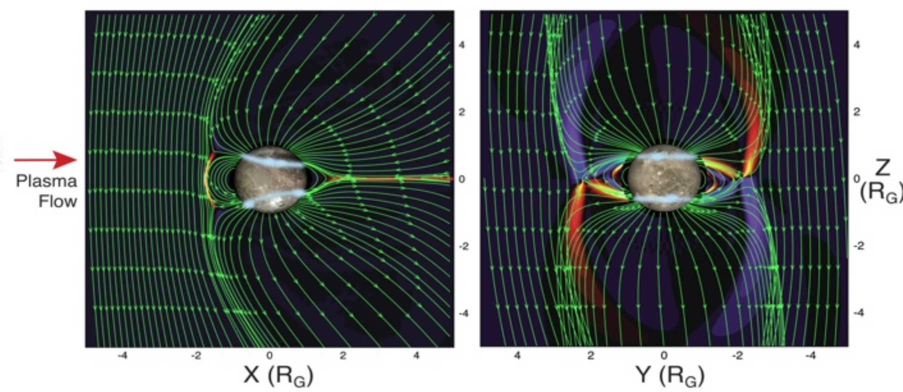
$P_d = \varepsilon\, V B_\perp^2/\mu_o\, \pi R_{obs}^2 = \varepsilon\, P_m$

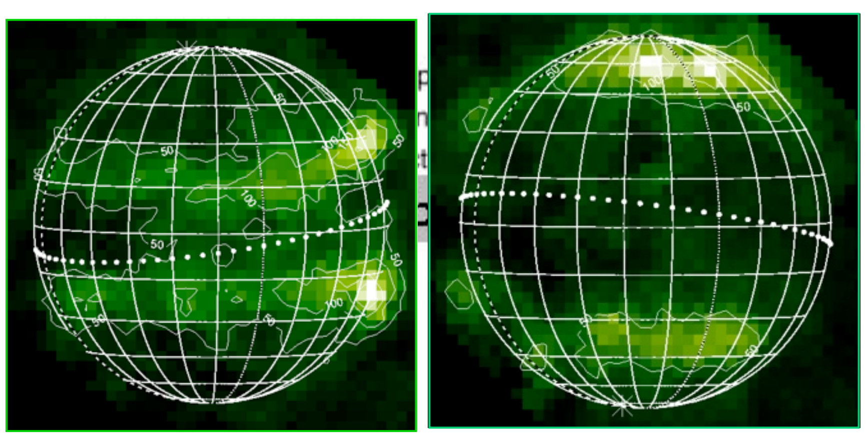
($\varepsilon \sim M_A = 0.1 - 0.2$)

→ Magnetosphere-Satellite interaction (reconnection)

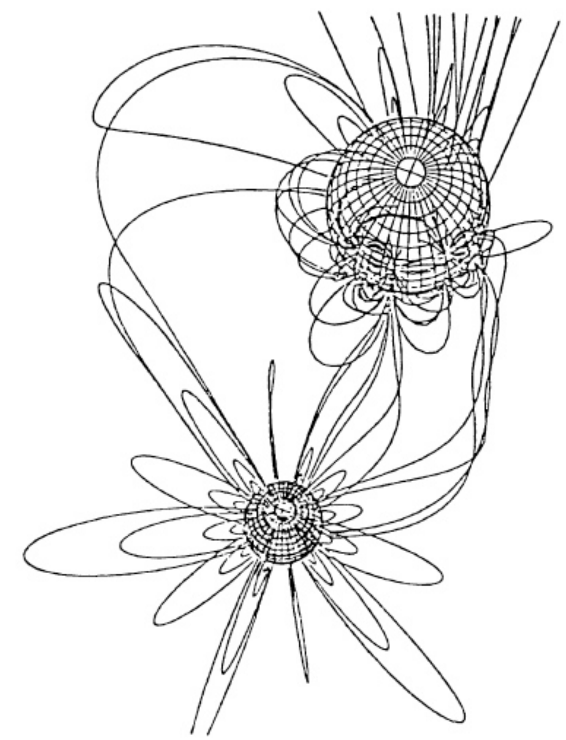
≈ Interacting magnetic binaries or star-planet systems







Downstream Upstream



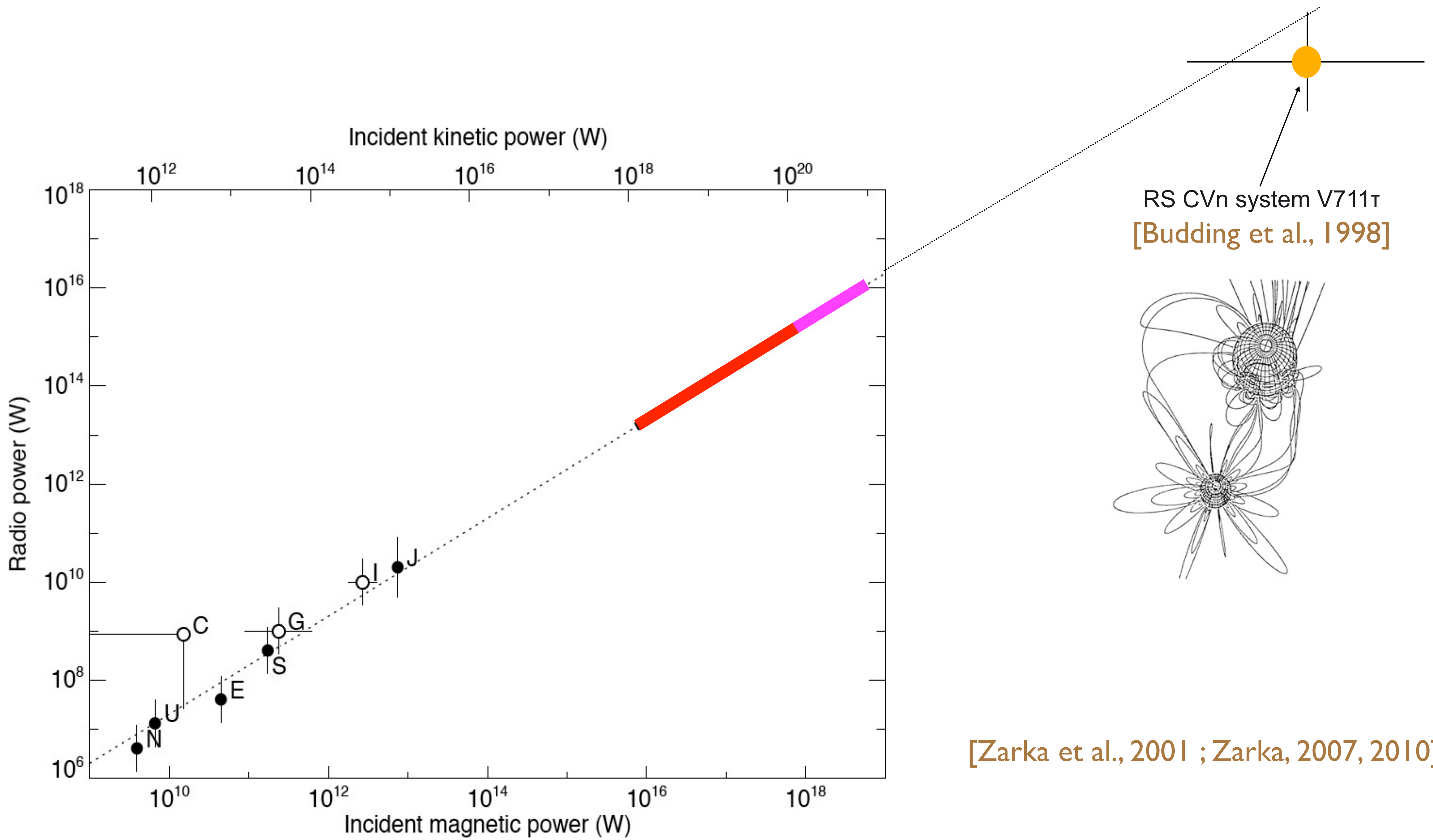
Dissipated power :

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

$(k = \cos^4(\theta/2) = 1\ ;\ \varepsilon = 0.1 - 0.2)$

PREDICTIONS FOR EXOPLANETS

- Jupiter detectable to <0.2 pc on the Galactic background
- Scaling laws & extrapolations :
  - → SW-M : LF radio output vs kinetic/CME/magnetic power inputs, up to 10^{3-5} x Jupiter's
  - → SPI : LF/HF radio output vs Poynting flux input, up to 10^{6} x Jupiter's



[Zarka et al., 2001 ; Zarka, 2007, 2010]

- **Magnetic field decay for hot Jupiters ?**

  - Spin-orbit synchronisation (tidal forces) $\Rightarrow$ $\omega\downarrow$

    but $M \propto \omega^{\alpha}$ with $½ \leq \alpha \leq 1$ $\Rightarrow$ $M\downarrow$ (B decay) ?

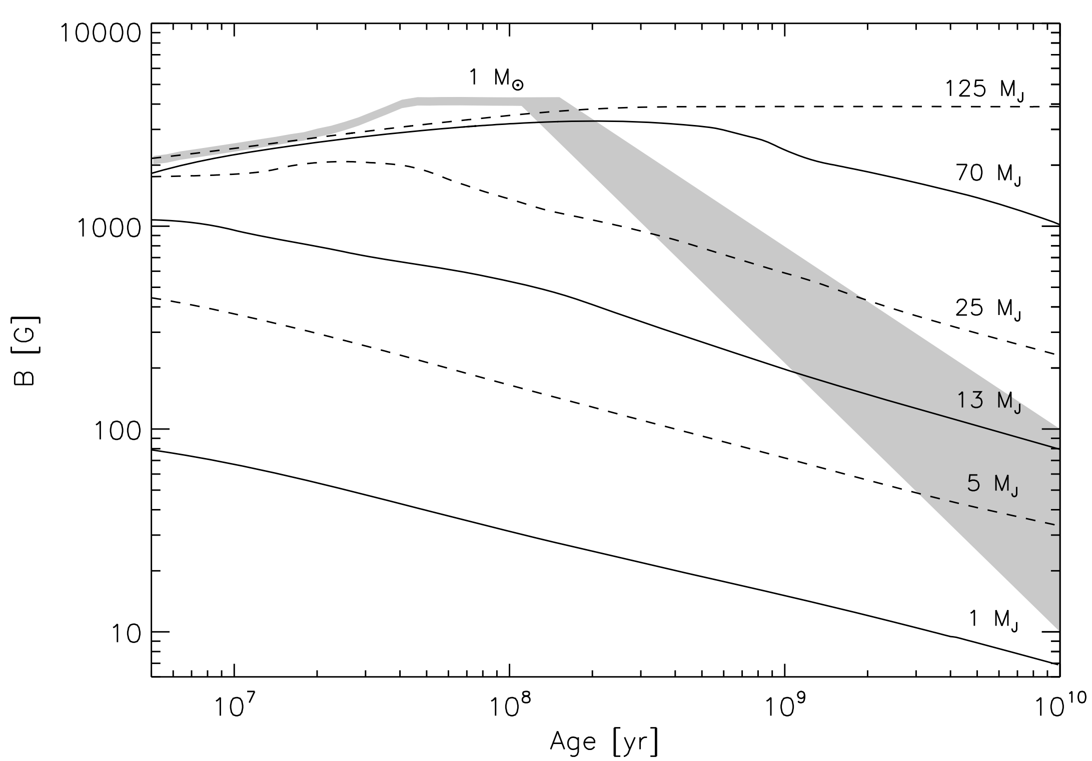
  - Internal structure + convection models

    $\Rightarrow$ self-sustained dynamo $\Rightarrow$ M could remain ≥ a few $G.R_J^3$

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]

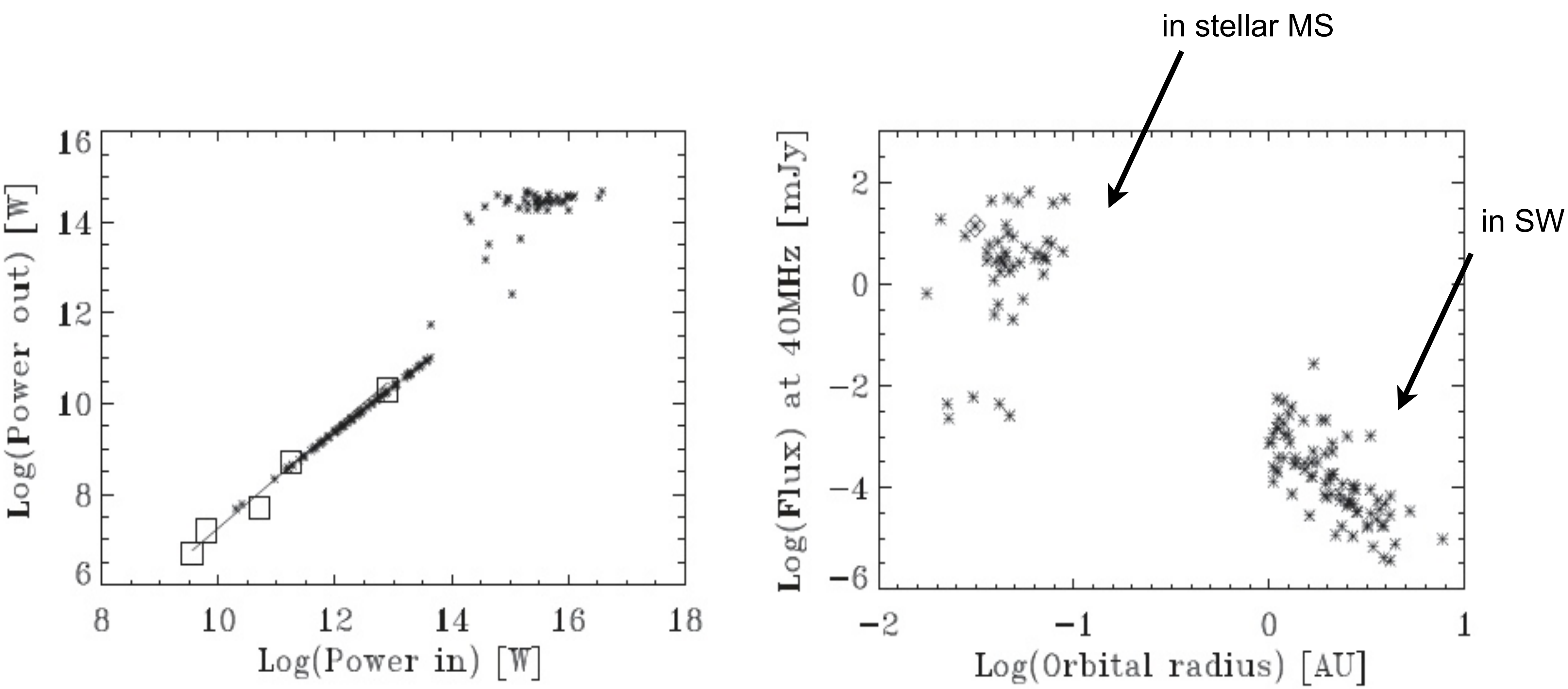


Planet name	Planet mass [M_{Jup} sin i]	a [AU]	d^1 [pc]	$\dot{M}$ [$\dot{M}_\odot$]	Age [Gyr]	B^{pol}_{dip} [G]
Jupiter	1.00	5.20		1.0	4.5	9
eps Eridani b	1.55	3.39	3.2	25.9	1.7	19
Gliese 876 b	1.93	0.21	4.7	0.1	2.4	23
Gliese 876 c	0.56	0.13	4.7	0.1	2.4	6
GJ 832 b	0.64	3.40	4.9	0.2	2.0	7
HD 62509 b	2.90	1.69	10.3	0.3	5.6	24
Gl 86 b	4.01	0.11	11.0	9.4	2.9	40
HD 147513 b	1.00	1.26	12.9	150.4	0.8	15
ups And b	0.69	0.06	13.5	20.2	1.4	10
ups And c	1.98	0.83	13.5	20.2	1.4	30
ups And d	3.95	2.51	13.5	20.2	1.4	58
gamma Cephei b	1.60	2.04	13.8	1.1	3.6	16
51 Peg b	0.47	0.05	14.7	0.2	6.2	3
tau Boo b	3.90	0.05	15.0	198.5	0.8	58
HR 810 b	1.94	0.91	15.5	103.9	0.8	30
HD 128311 b	2.18	1.10	16.6	39.9	0.9	33
HD 128311 c	3.21	1.76	16.6	39.9	0.9	48
HD 10647 b	0.91	2.10	17.3	22.9	1.4	14
GJ 3021 b	3.32	0.49	17.6	170.2	0.8	49
HD 27442 b	1.28	1.18	18.1	1.9	2.7	14
HD 87883 b	1.78	3.60	18.1	2.6	3.3	19
HD 189733 b	1.13	0.03	19.3	17.3	1.7	14
HD 192263 b	0.72	0.15	19.9	7.1	2.5	8

[Reiners & Christensen, 2010]

• **Magnetic reconnection and electron acceleration at the magnetopause ?**

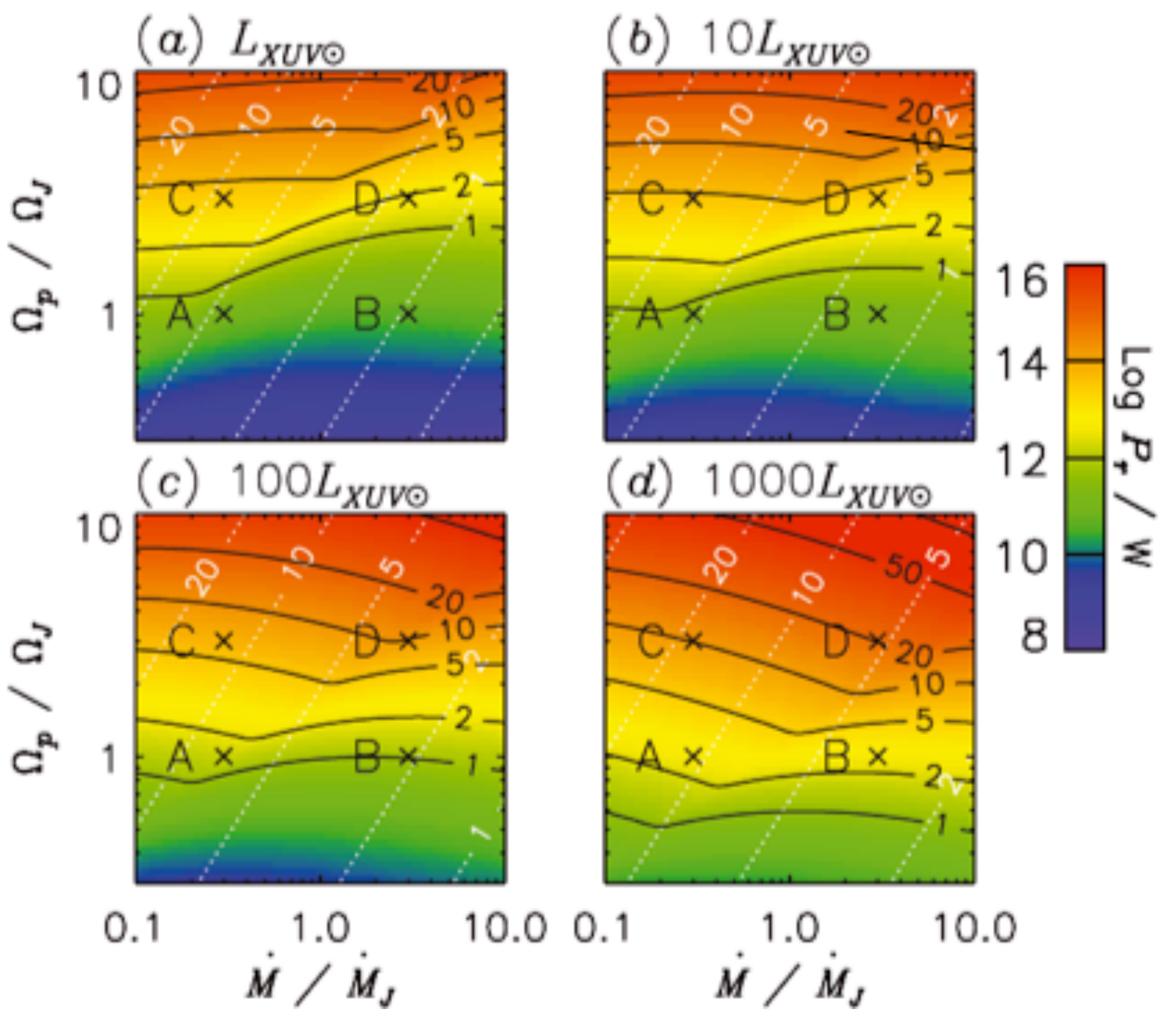
- Computation of parallel E field (assuming B_*=1G)
- Number and energy of runaway electrons
- Parametrization by "efficiency" η



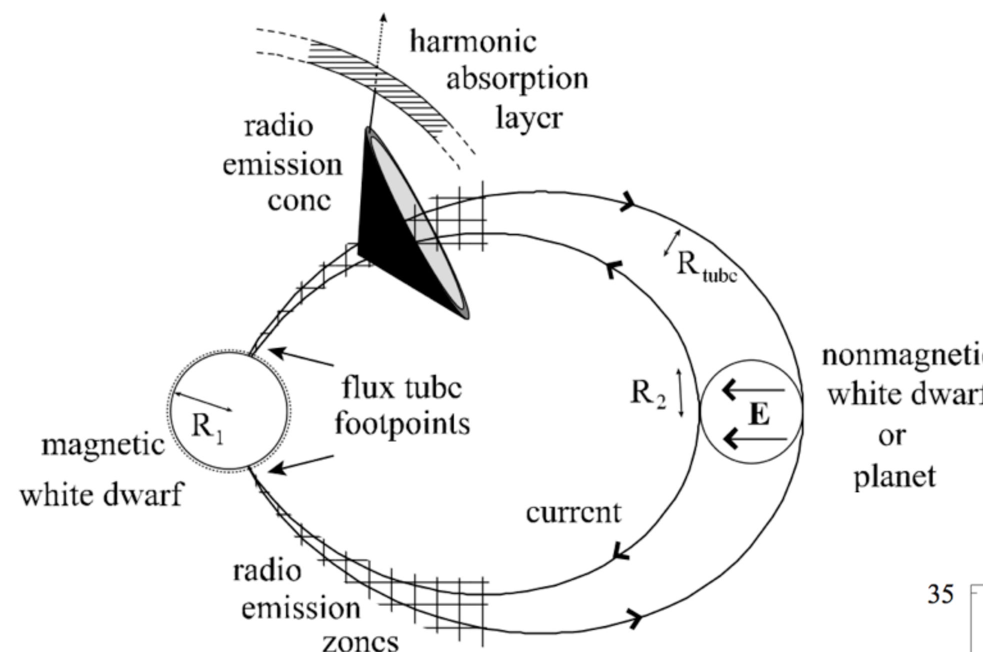
[Jardine & Cameron, 2008]

PREDICTIONS FOR EXOPLANETS

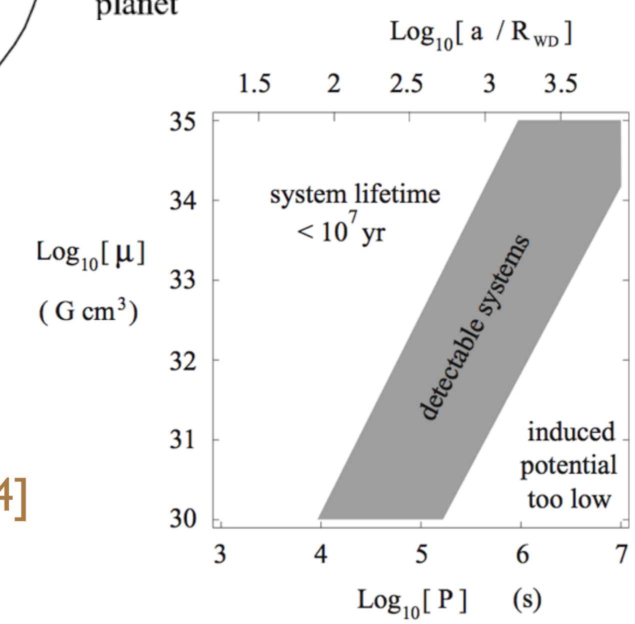
- Theoretical predictions :
  - → M-I : LF radio output vs M-I coupling (rotation), up to 10^4 x Jupiter's
  - → SPI : HF radio output from terrestrial planets around White Dwarfs



[Nichols, 2011, 2012]



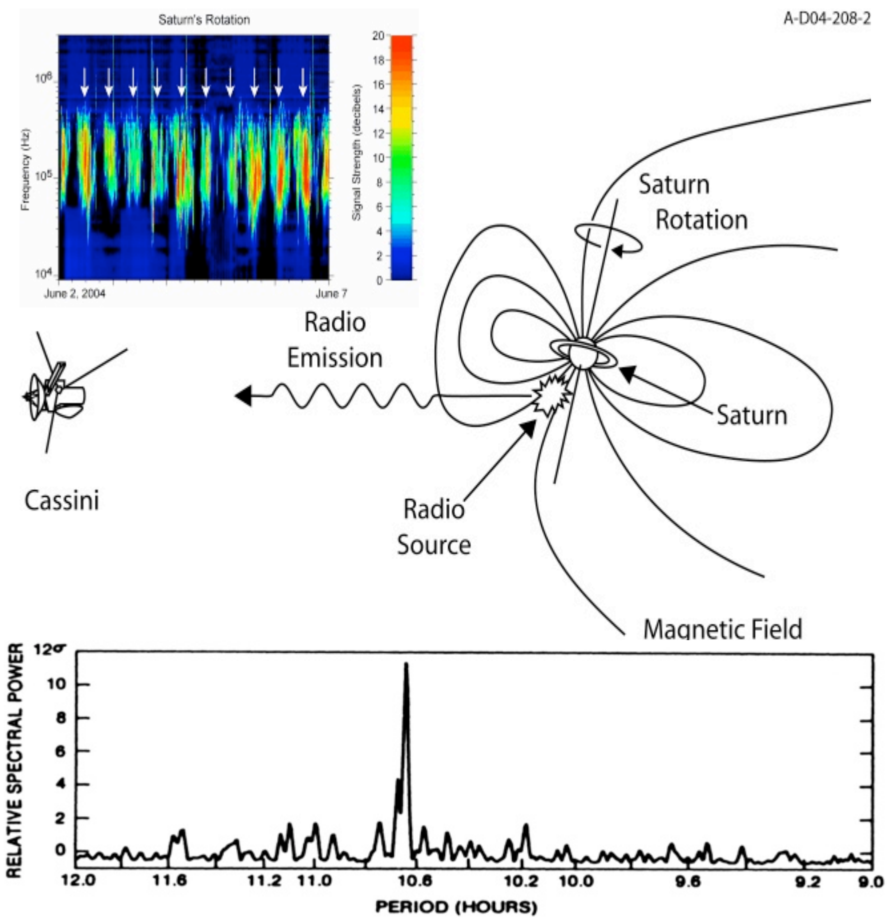
[Willes & Wu, 2004]



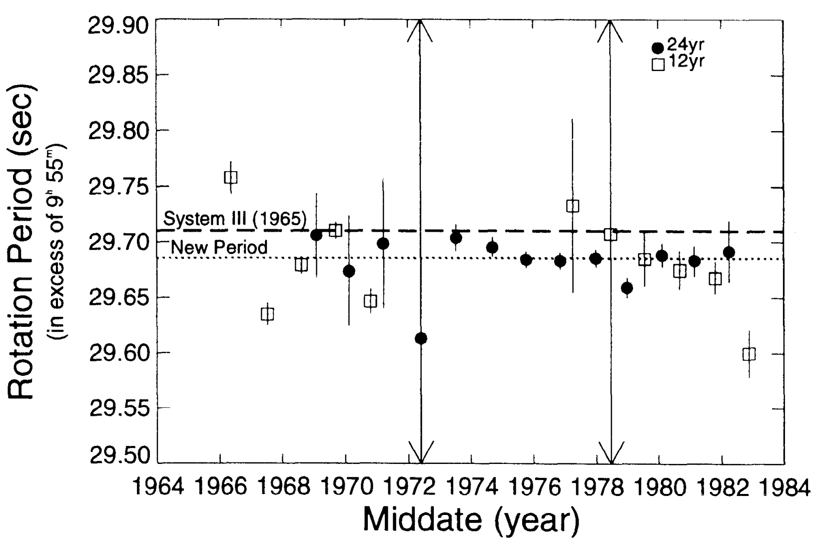
- Star-Planet discrimination : polarization (circular) + periodicities (rotation, orbital)

MOTIVATIONS FOR STUDYING EXOPLANET'S RADIO EMISSIONS

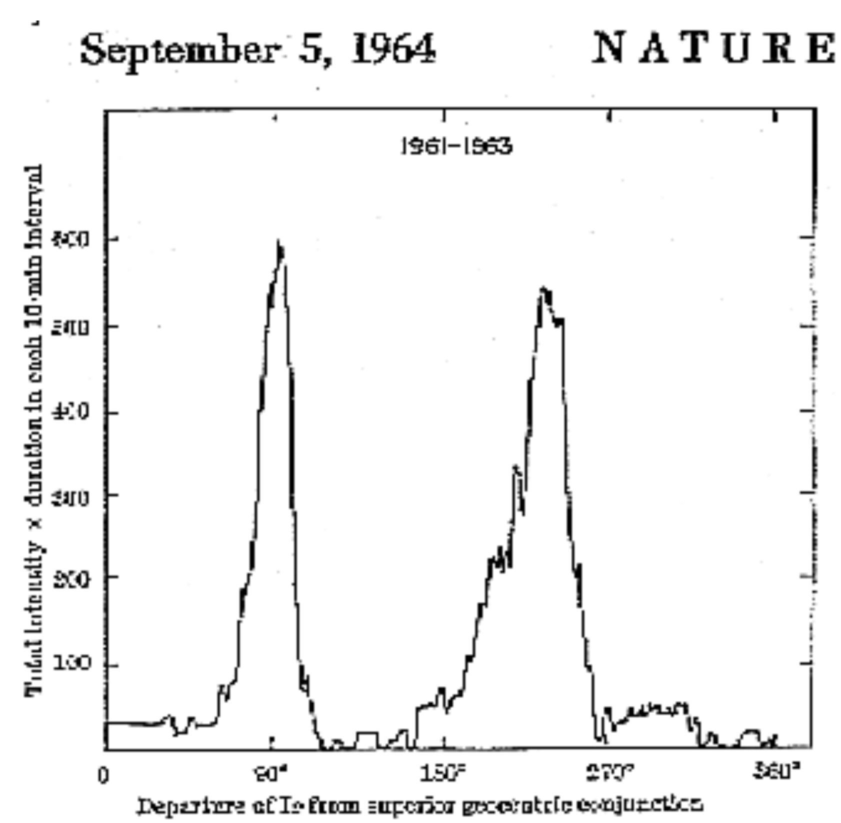
- Planetary |B| & tilt (e.g. Jupiter) ⇒ dynamo
  ⇒ planetary interior structure
- Planetary rotation (J, S, U, N) ⇒ spin-orbit locking ?
- Presence of satellites (e.g. Io)



[Desch & Kaiser, 1981]



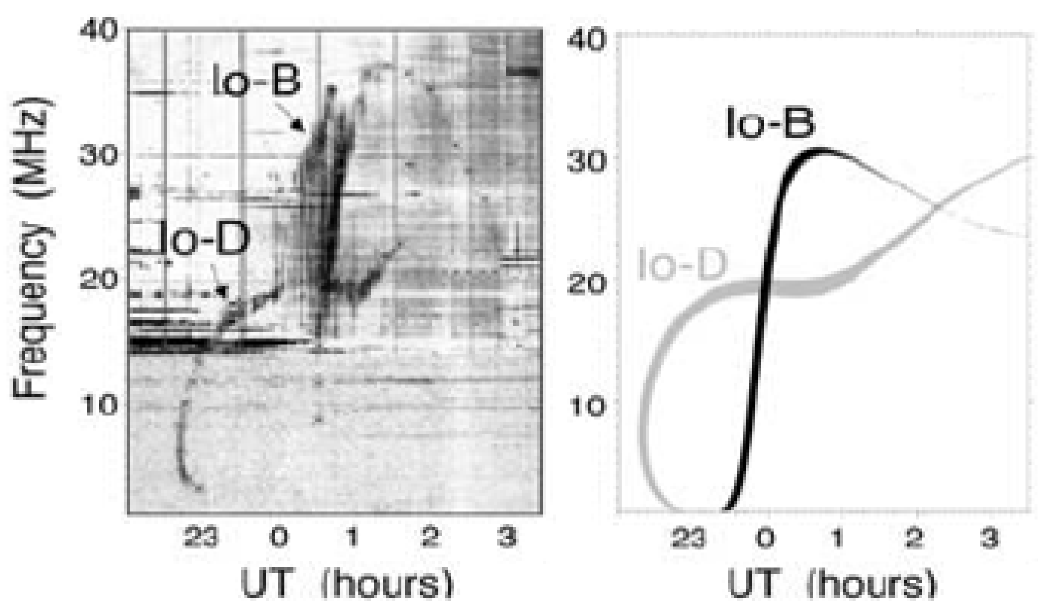
[Higgins et al., 1997]

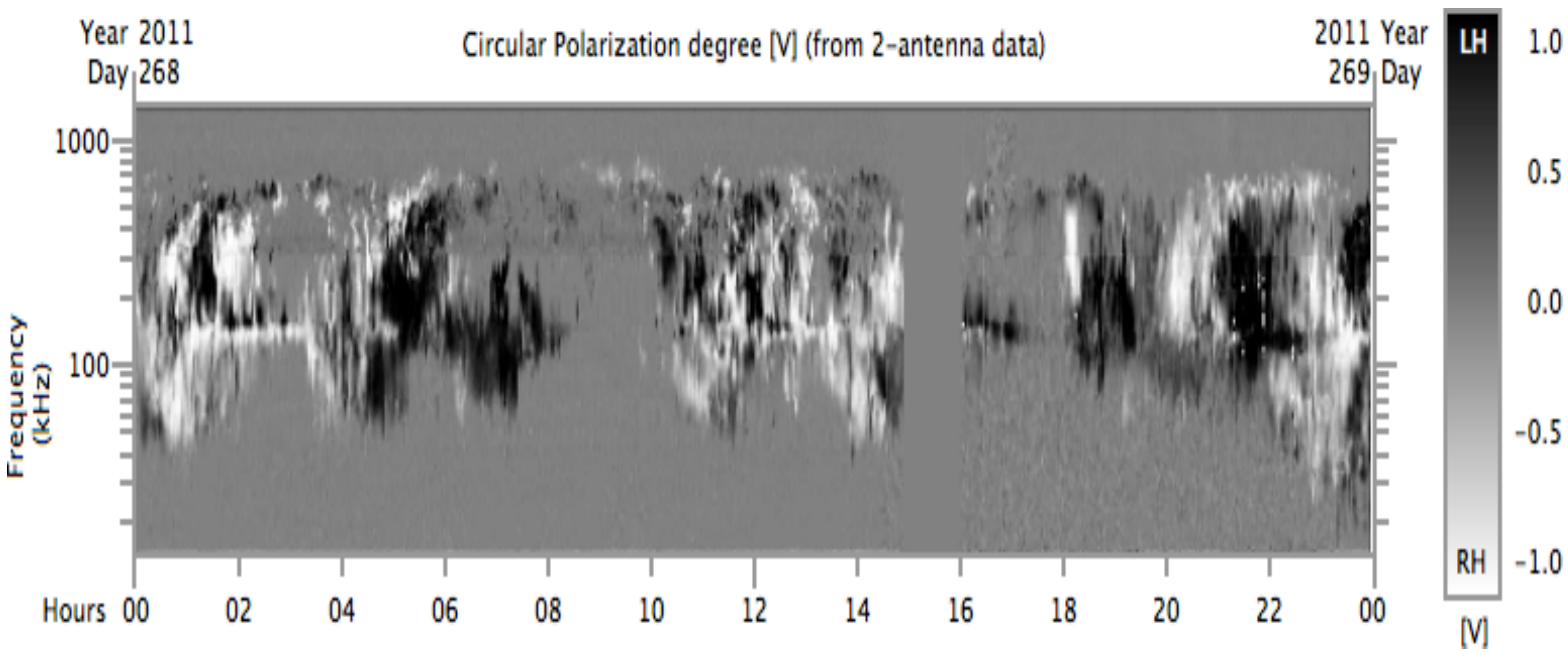


[Bigg, 1964]

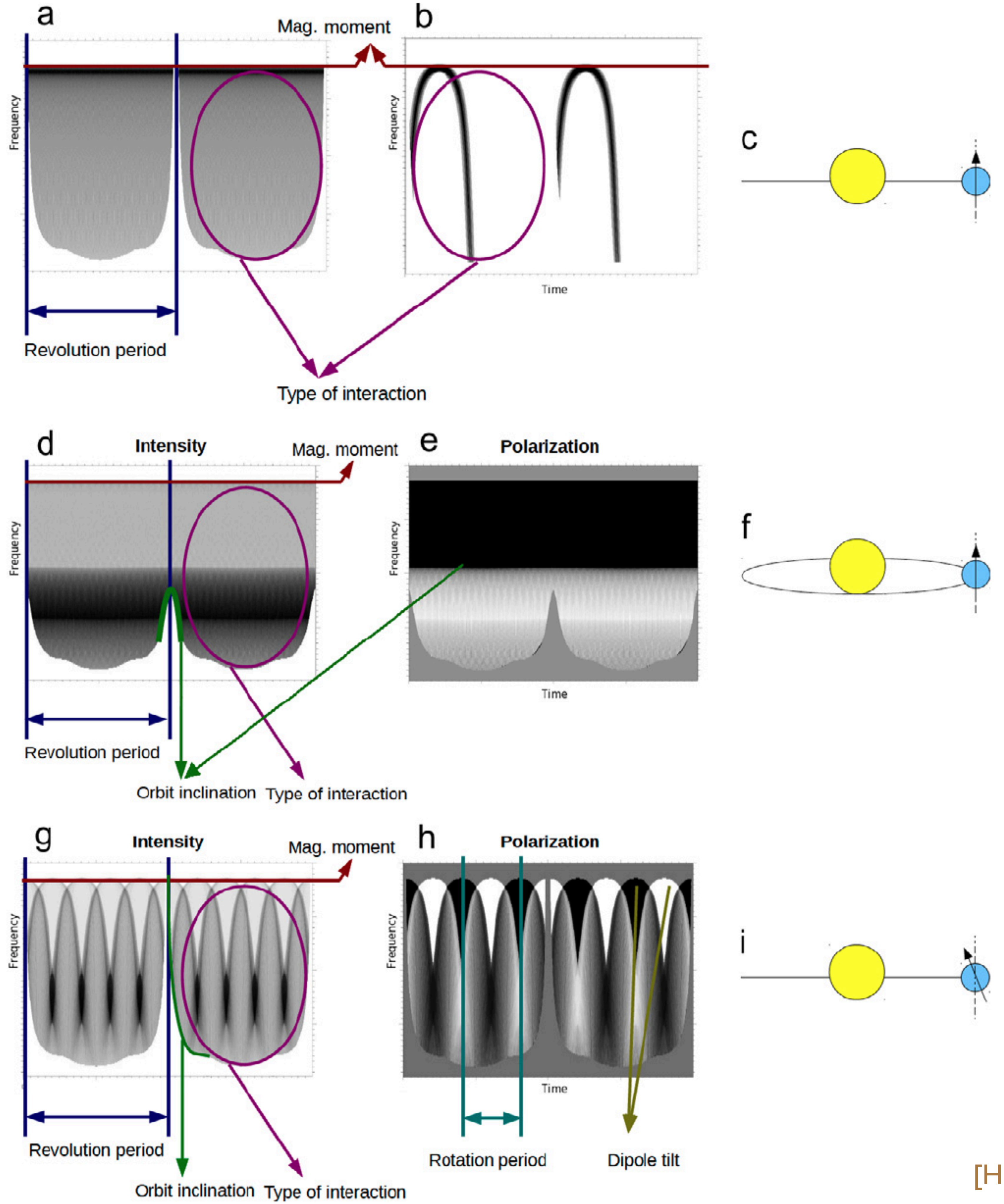
MOTIVATIONS FOR STUDYING EXOPLANET'S RADIO EMISSIONS

- Planetary |B| & tilt (e.g. Jupiter) ⇒ dynamo
  ⇒ planetary interior structure
- Planetary rotation (J, S, U, N) ⇒ spin-orbit locking ?
- Presence of satellites (e.g. Io)
- SPI energetics, magnetospheric dynamics, M-I coupling
- Orbit inclination





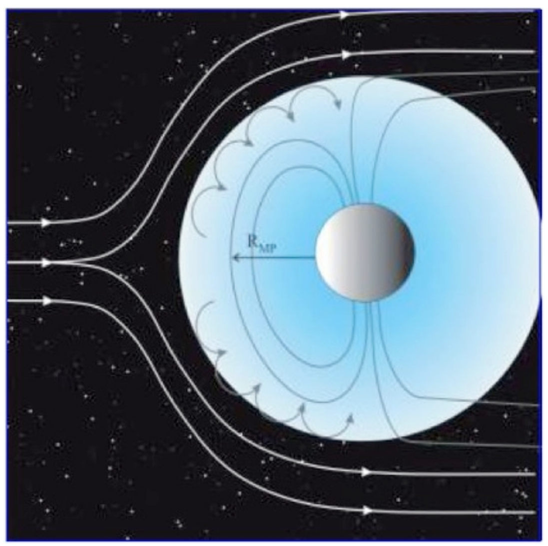
[Hess et al., 2008 ; Lamy et al., 2008]

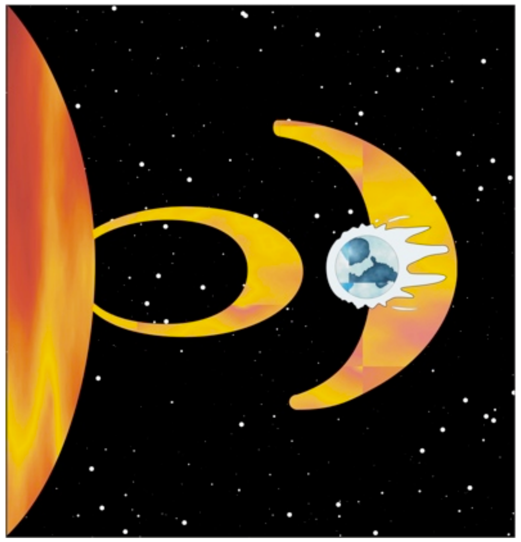


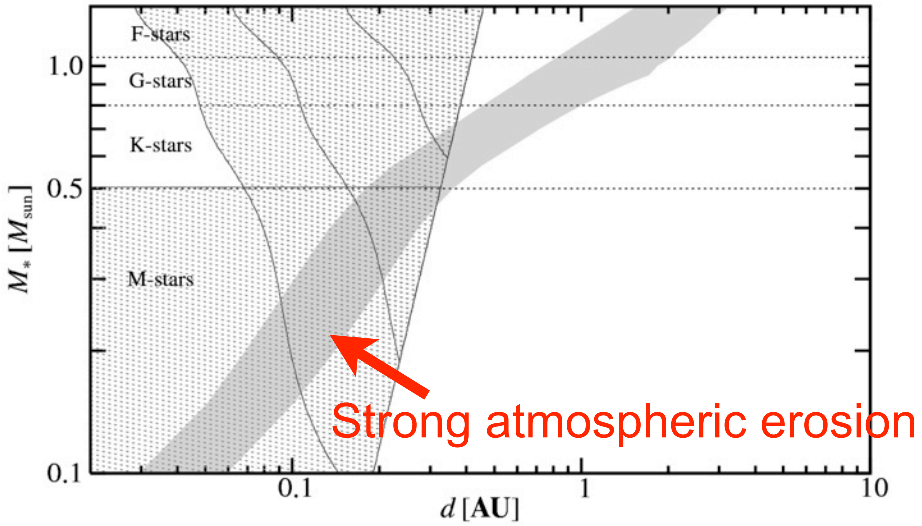
[Hess & Zarka, 2011]

MOTIVATIONS FOR STUDYING EXOPLANET'S RADIO EMISSIONS

→ Conditions for life (shielding planet's atmosphere and surface vs CR/SW/CME, O3 destruction, atmospheric erosion/escape)





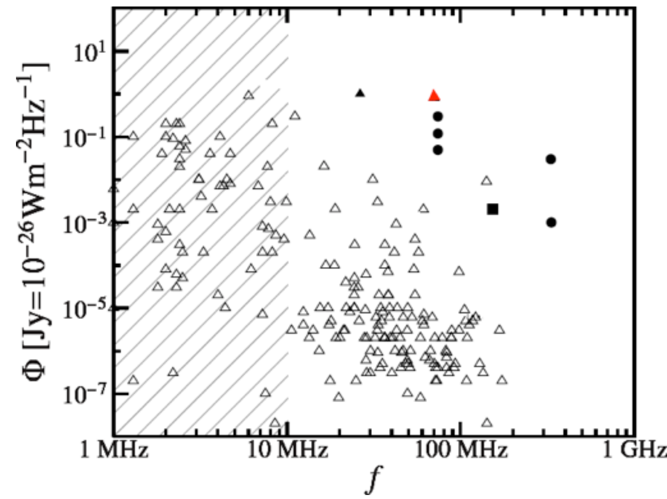


[Griessmeier et al., 2004; Khodachenko et al., 2006...]

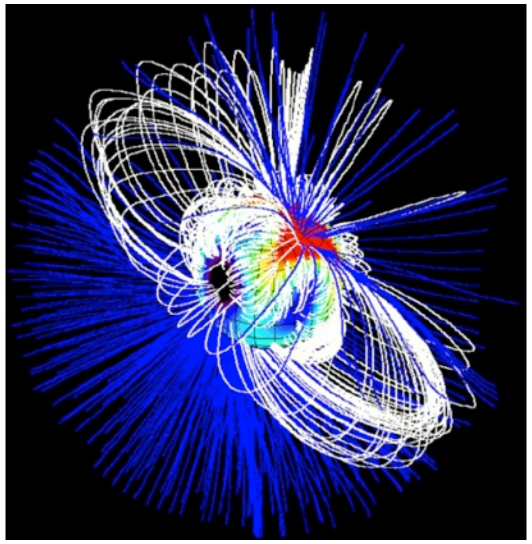
+ Independent discovery tool ? (planets around active, magnetic or variable stars)

PAST AND ONGOING OBSERVATIONS AND RESULTS

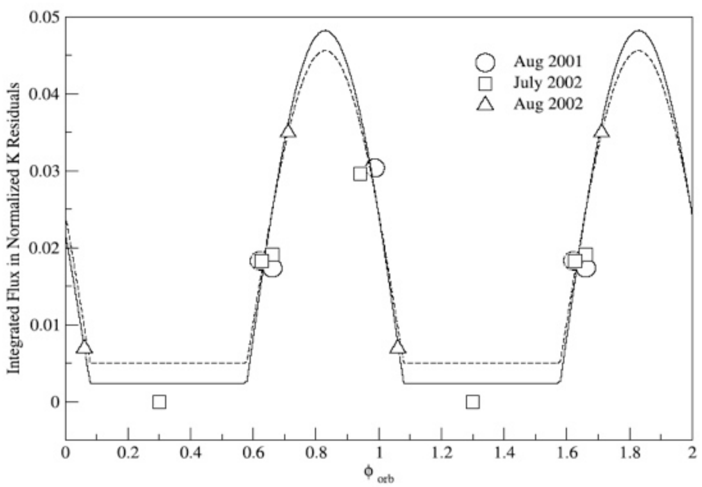
- Targeted searches
  - theory/scaling laws applied to exoplanet census ⇒ τ Boo, υ And, 55 Cnc …
  - strongly magnetized stars ⇒ HD 189733 …
  - planets with very elliptical orbit and close-in periastron ⇒ HD 80606
  - optical SPI signatures

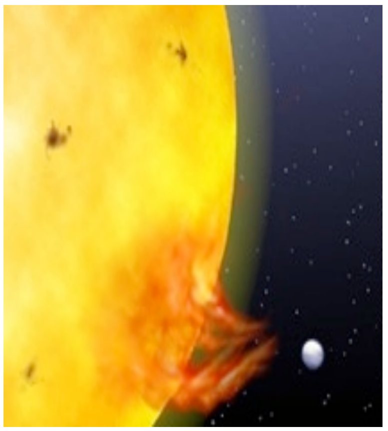


[Lazio et al., 2004 ; Griessmeier et al., 2007]

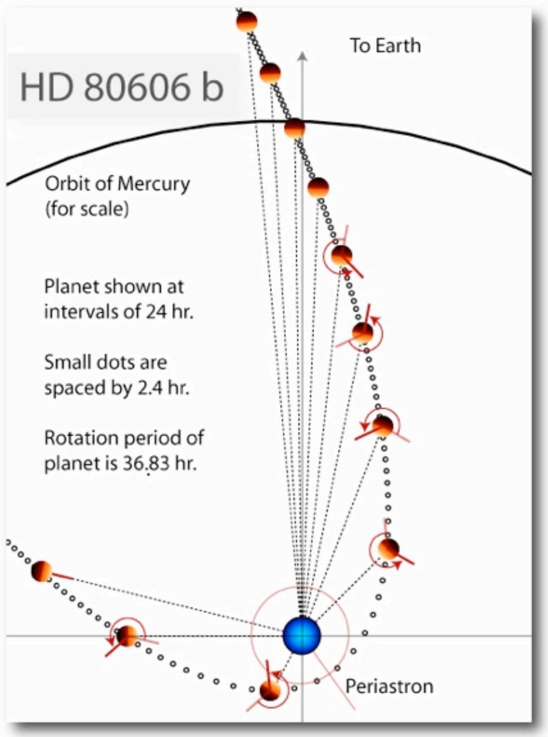


[Donati et al., 2006]

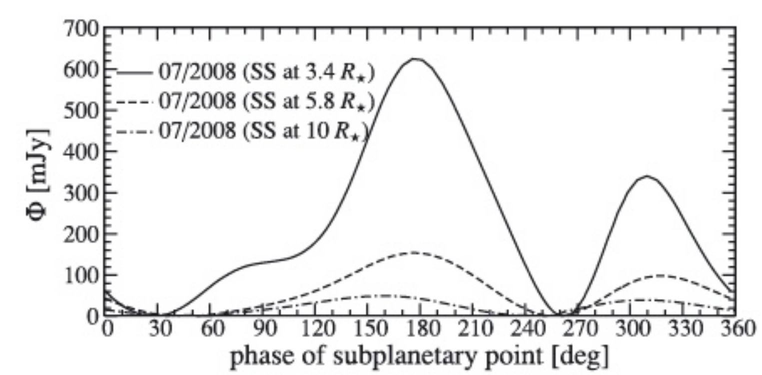




[Shkolnik et al., 2003, 2005, 2008]



[Lazio & Farrell, 2007 ; Lazio et al., 2010]



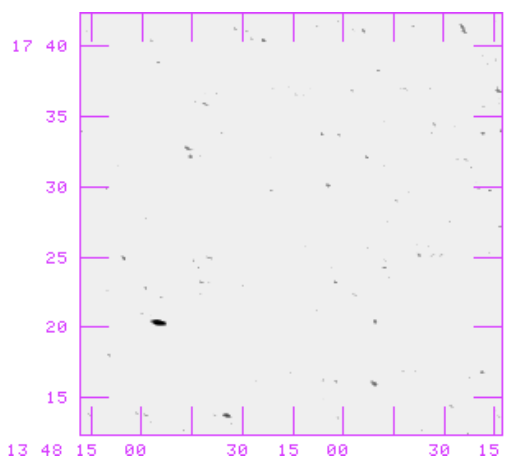
[Farès et al., 2010]

PAST AND ONGOING OBSERVATIONS AND RESULTS

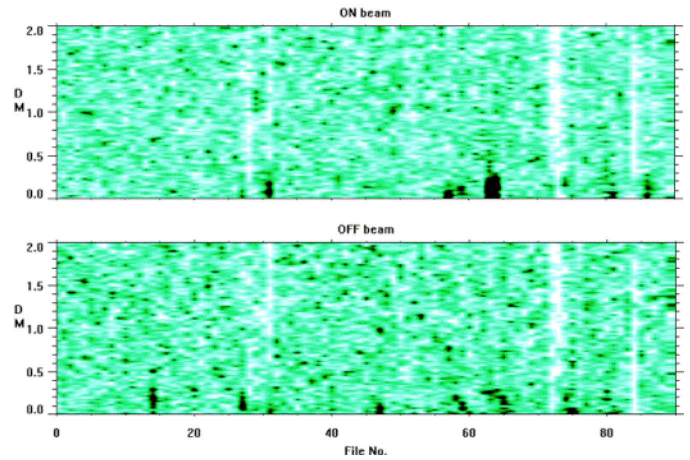
- Past observations

  VLA 74+ MHz, UTR-2 10-32 MHz, GMRT 150+ MHz

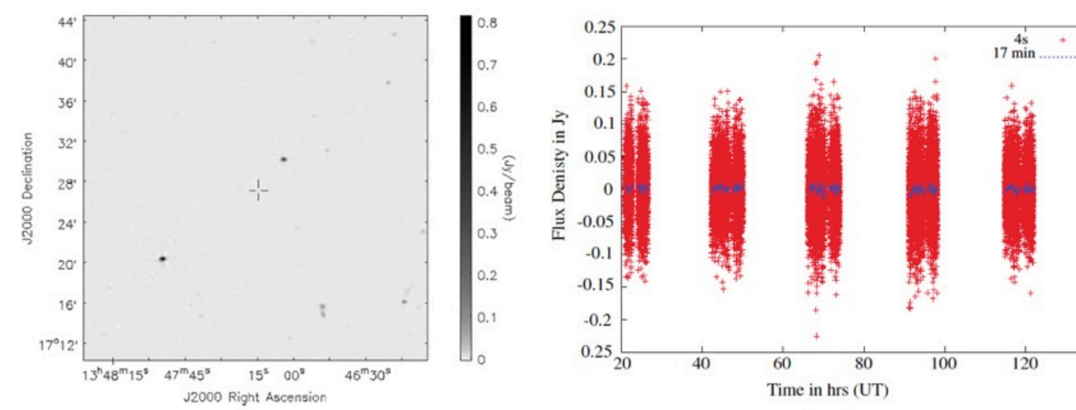
τ Boo, 74 MHz, 100 mJy



ρ Cr, 160 mJy (On / Off)

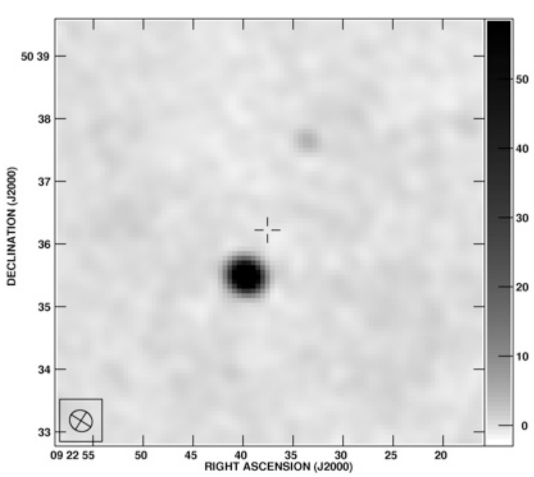


τ Boo, 150 MHz, 1 mJy



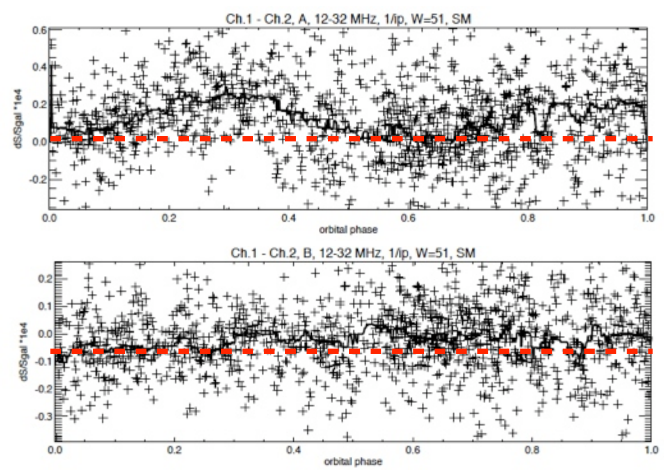
[Hallinan et al., 2013]

HD80606, 330 MHz, 1.7 mJy



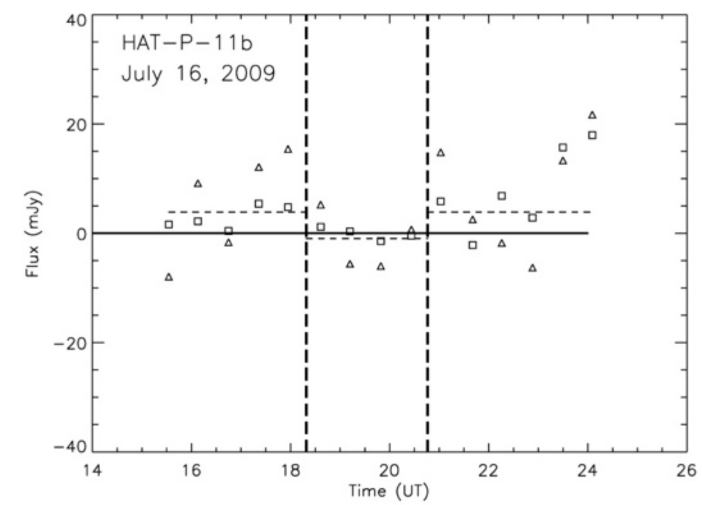
[Farrell et al., 2003, 2004 ; Lazio & Farrell, 2007]

Corot 7, ~1 Jy (On / Off)



[Ryabov et al., 2004 ; Zarka et al., in prep.]

Hat-P-11, 150 MHz, 3.9 mJy



[Lecavelier et al., 2013]

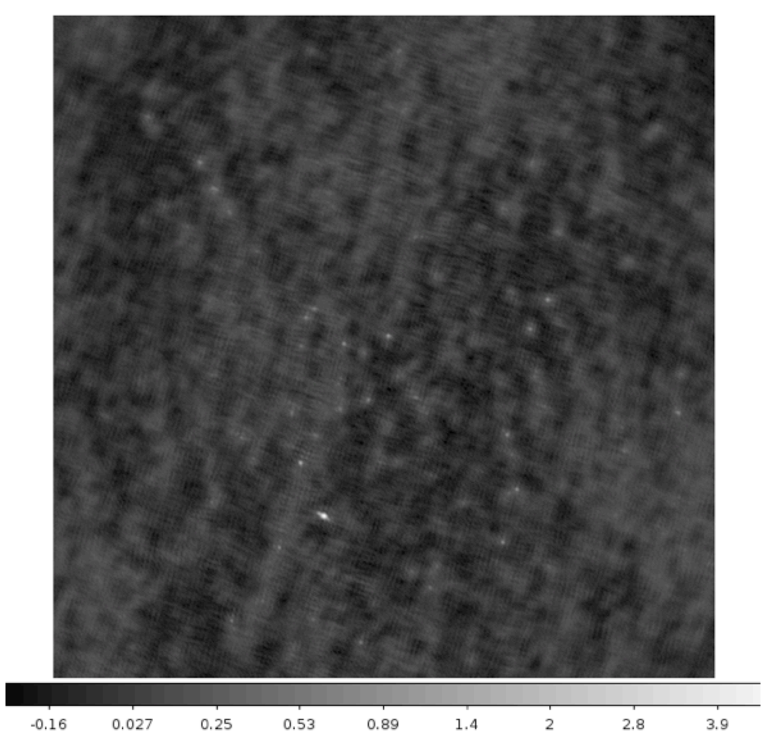
→ no confirmed detection : |B|, beaming, flux density ?

→ hint on HAT-P-11 @ GMRT

PAST AND ONGOING OBSERVATIONS AND RESULTS

- Ongoing observations
  - UTR-2 10-32 MHz (100+ h) [Zarka et al.]
  - LOFAR 20-80 MHz (~100 h) [Lazio, Zarka et al.]
  - LWA/HJUDE (~5000 h) [Hartman, Hallinan, et al.]

LOFAR-LBA : Ups And



A volume-limited survey of known HJs

distance: $d < 50$ pc

semi-major axis: $a < 0.5$ AU

projected mass: $M \sin i > 0.5\ M_J$

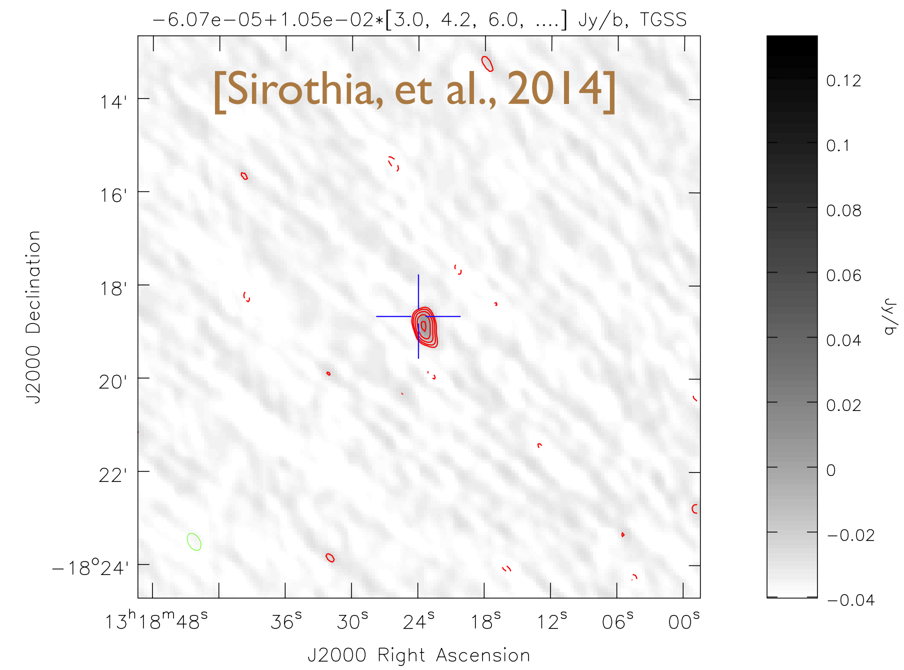
location: northern sky

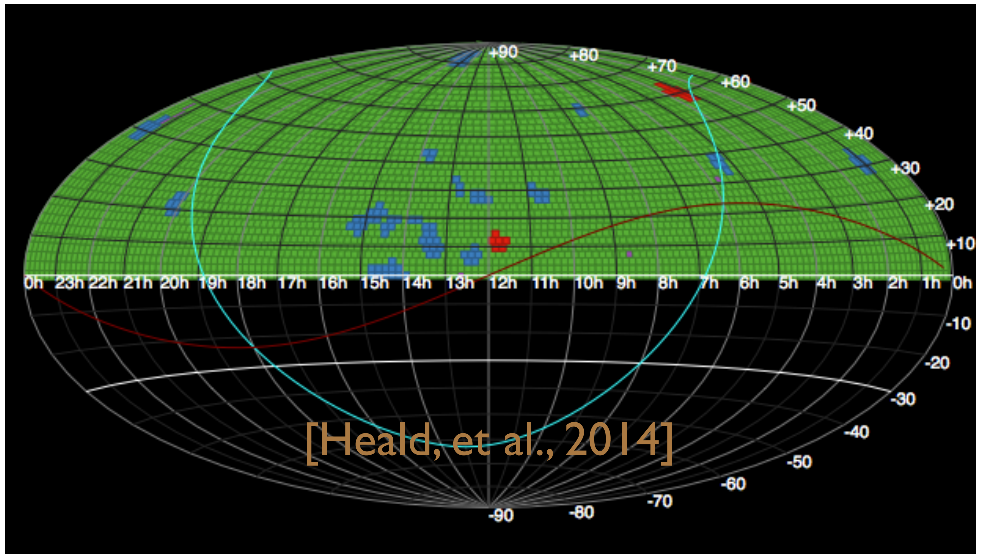
Planet	d (pc)	a (AU)	P_{orb} (d)	M (M_J)	Coordinates (J2000)	Best month	Num. days
Hot Jupiters likely to be tidally locked:							
υ And b	13.49	0.059	4.62	1.4	01^h37^m $+41°24'$	Sep	37
τ Boo b	15.62	0.048	3.31	6.5	13^h47^m $+17°27'$	Mar	43
HD 189733 b	19.45	0.031	2.22	1.13	20^h01^m $+22°43'$	Jun	29
HD 187123 b	48.26	0.042	3.10	> 0.51	19^h47^m $+34°25'$	Jun	31
HD 209458 b	49.63	0.047	3.52	0.69	22^h03^m $+18°53'$	Aug	32
Hot Jupiters less likely to be tidally locked:							
55 Cnc b	12.34	0.116	14.65	> 0.84	08^h53^m $+28°20'$	Dec	30
ρ CrB b	17.24	0.226	39.84	> 1.06	16^h01^m $+33°18'$	Apr	30
70 Vir b	17.99	0.484*	116.69	> 7.46	13^h28^m $+13°47'$	Mar	30
HD 195019 b	38.52	0.137	18.20	> 3.58	20^h28^m $+18°46'$	Jun	30
HD 114762 b	38.65	0.363*	83.89	>11.68	13^h12^m $+17°31'$	Mar	30
HD 38529 b	39.28	0.131*	14.31	> 0.86	05^h47^m $+01°10'$	Nov	30
HD 178911 Bb	42.59	0.345*	71.48	> 7.29	19^h09^m $+34°36'$	Jun	30
HD 37605 b	43.98	0.261*	54.23	> 2.86	05^h40^m $+06°04'$	Nov	30

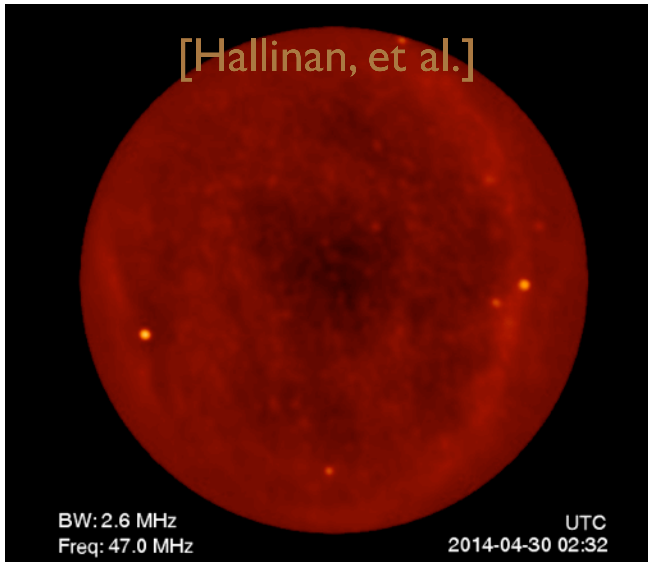
* Sources with eccentricities greater than 0.1.

PAST AND ONGOING OBSERVATIONS AND RESULTS

- Surveys-Catalogs correlations
  - TGSS 150 MHz
    → 4 candidates out of 175 exoplanetary systems
    (61 Vir, 1RXS1609, HD 86226, HD 164509) 18-120 mJy
    + 171 3σ upper limits 8.7 - 136 mJy
  - LOFAR MSSS
    → HBA : 120-160 MHz (≤120", ≤5 mJy/b)
    → LBA : 30-75 MHz (≤100", ≤15 mJy/b)
  - OLWA

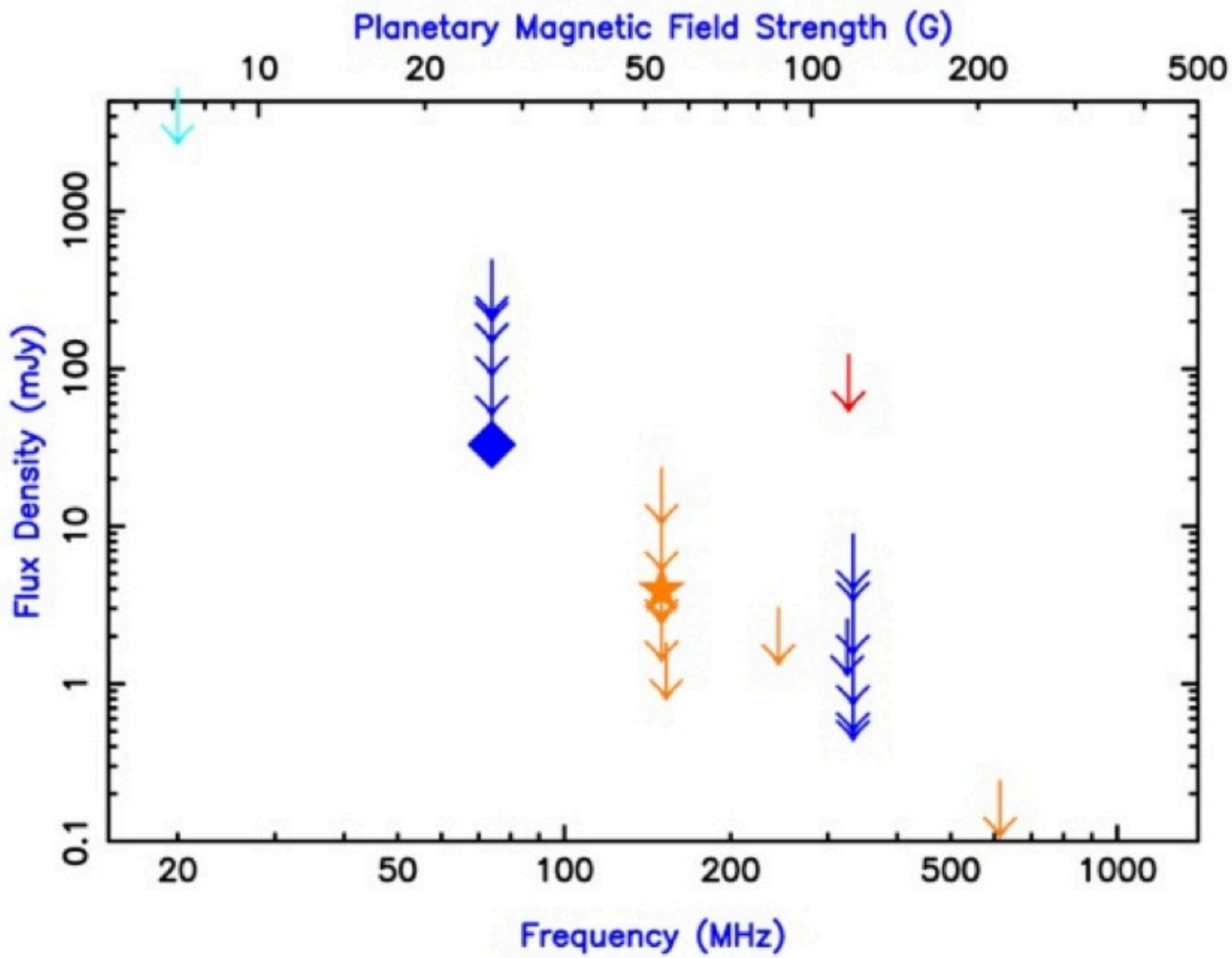






PAST AND ONGOING OBSERVATIONS AND RESULTS

- Radio emissions much stronger than Jupiter's at frequencies ≥150 MHz is rare ?



[Lazio]

SCIENCE OUTCOME ENABLED BY SKA

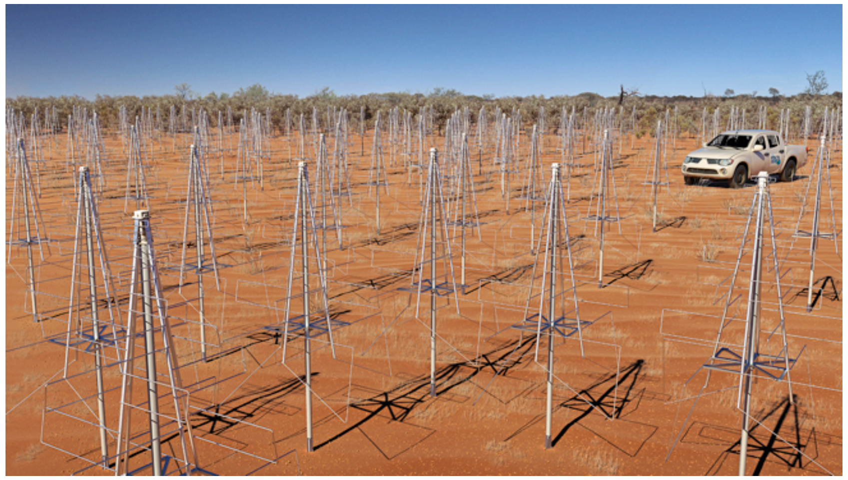
- Radio emissions much stronger than Jupiter's at frequencies ≥150 MHz is rare ? |B| to low, narrow beaming, low flux density

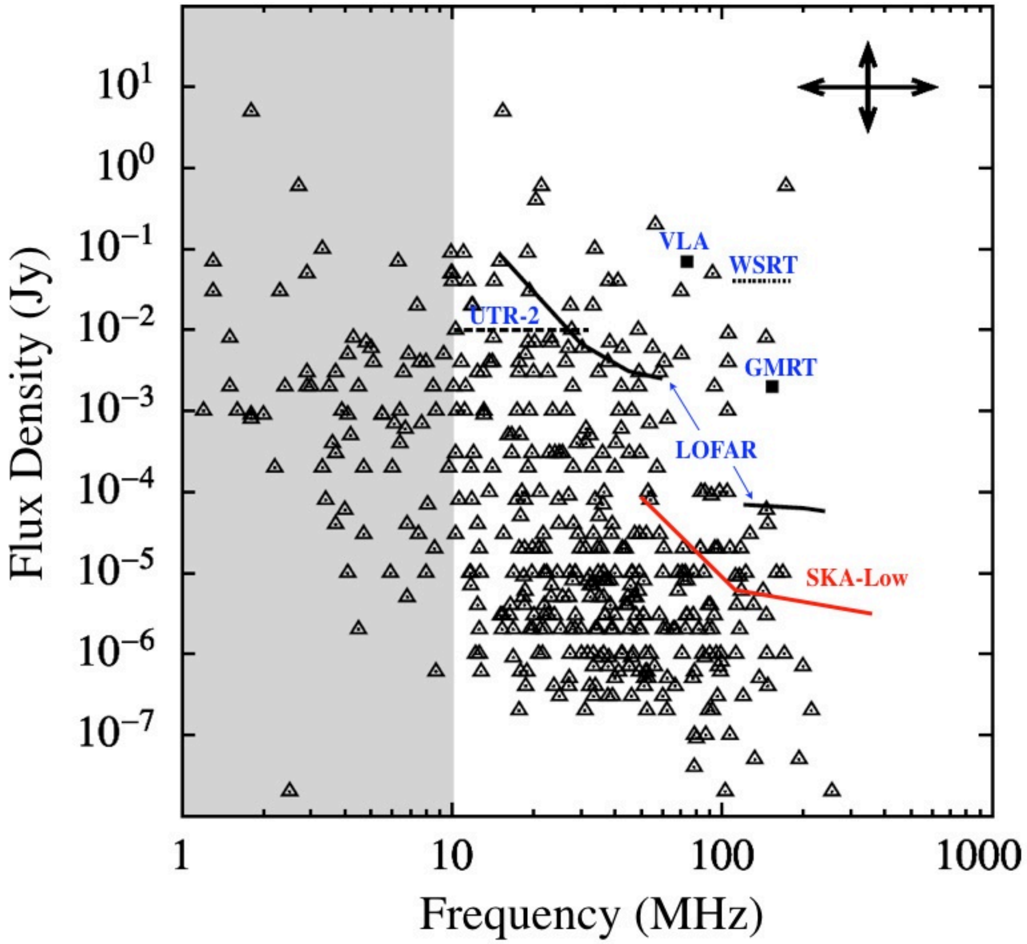
→ Need to explore a large sample of targets with highest possible continuum sensitivity, LF, circular/full Stokes

NB: ~11" resolution at 110 MHz → no star-planet resolution

- Imaging down to thermal (confusion) noise + beamformed observations (time variations)

SCIENCE OUTCOME ENABLED BY SKA

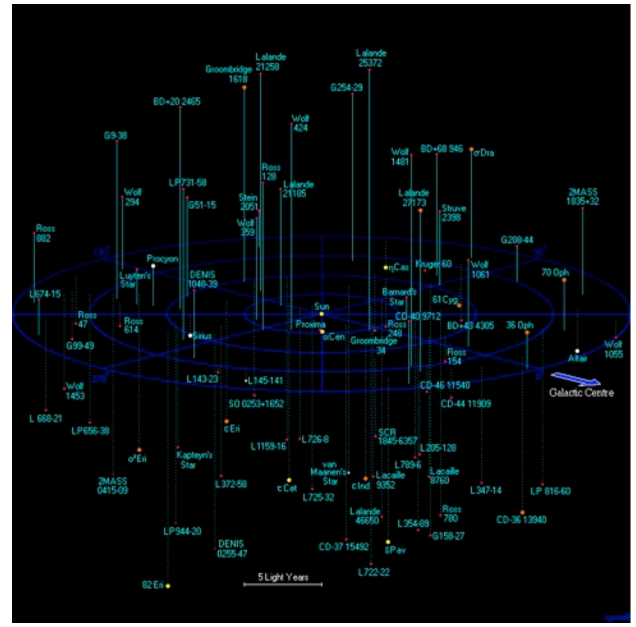


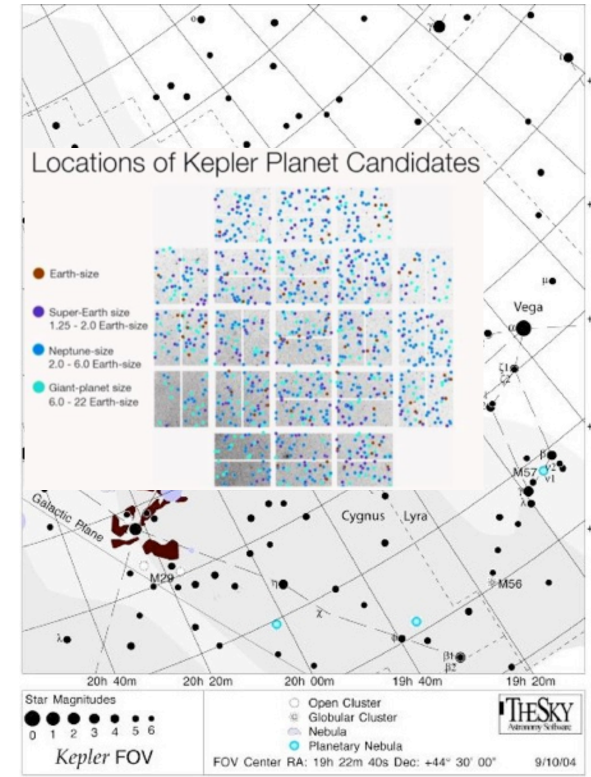


- Jupiter bursts at 30-40 MHz : ~40 μJy at 10 pc range

- SKA-Low 50-350 MHz : sensitivity ~10-17 μJy (20 MHz × 1 hour), 10-30 x better than LOFAR
  → Jupiter ~detectable at a few parsecs
  (~independent on high power / high B extrapolations)
  → highly likely that SKA-Low will
  detect exoplanetary radio signals

SCIENCE OUTCOME ENABLED BY SKA





- Targets

  → exhaustive survey up to 10(30) pc

  ~400(2500) stars/WD/BD within 10(30) pc, with ~35(200) known exoplanets

  → targeted SPI, bright XUV stars, high B stars, Kepler fields …

  → surveys, commensal analyses

- Observations

  → several epochs x several hours (phase effects/variability) [multi-beam]

  → circular / full Stokes

⇒ many detections expected, with higher S/N

⇒ quantitative interpretations

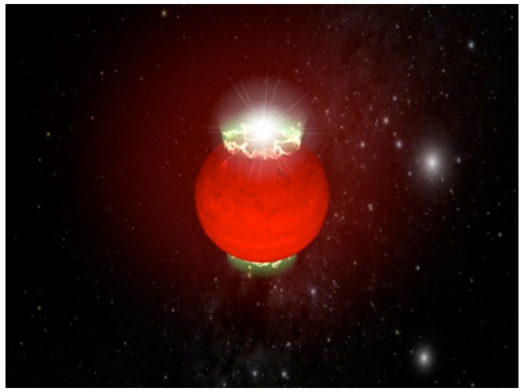
⇒ **opening new field of comparative exo-magnetospheric physics**

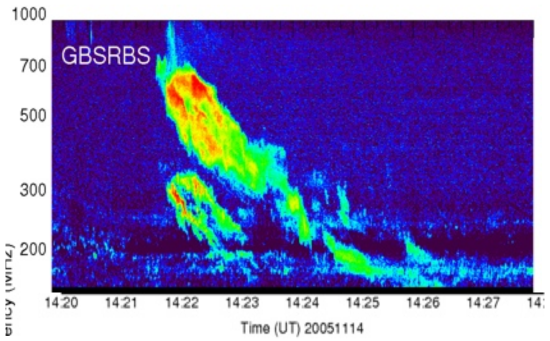
SYNERGIES

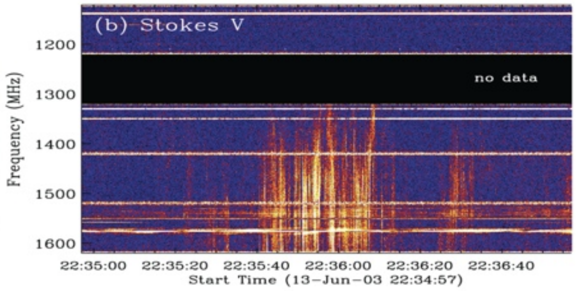
- With other SKA observations

  → solar-like bursts

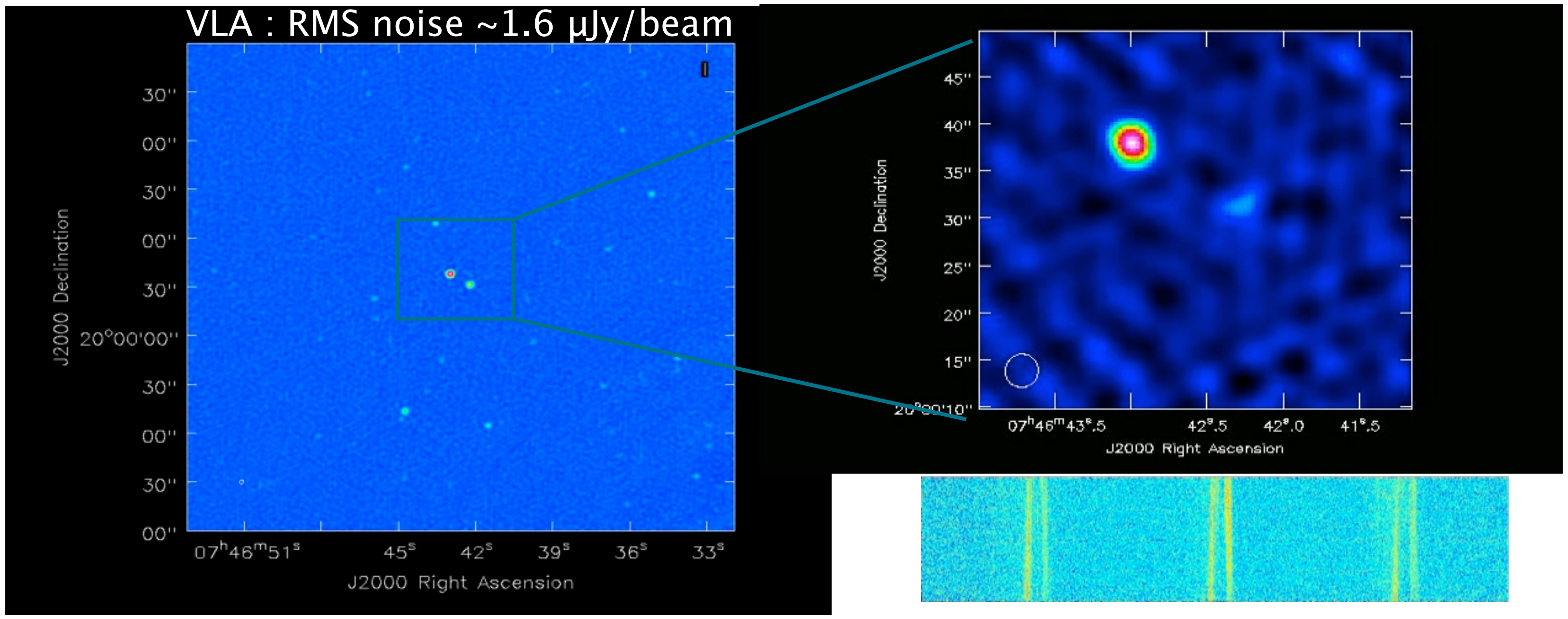
  → stellar flares : planet induced, cool stars cyclotron Maser

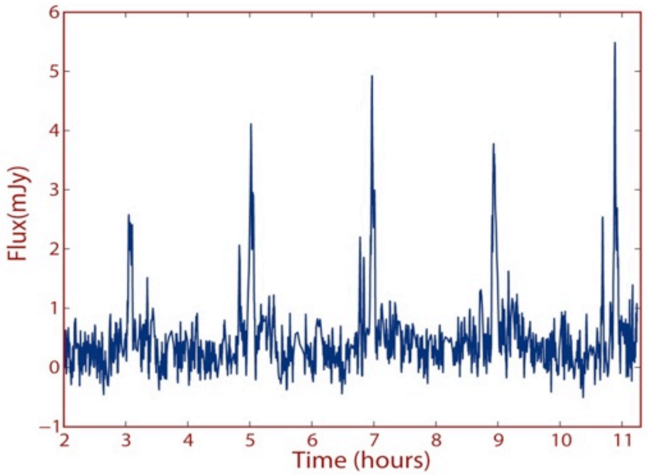






[Osten, Hallinan, et al.]





[Hallinan et al., 2007, 2008]

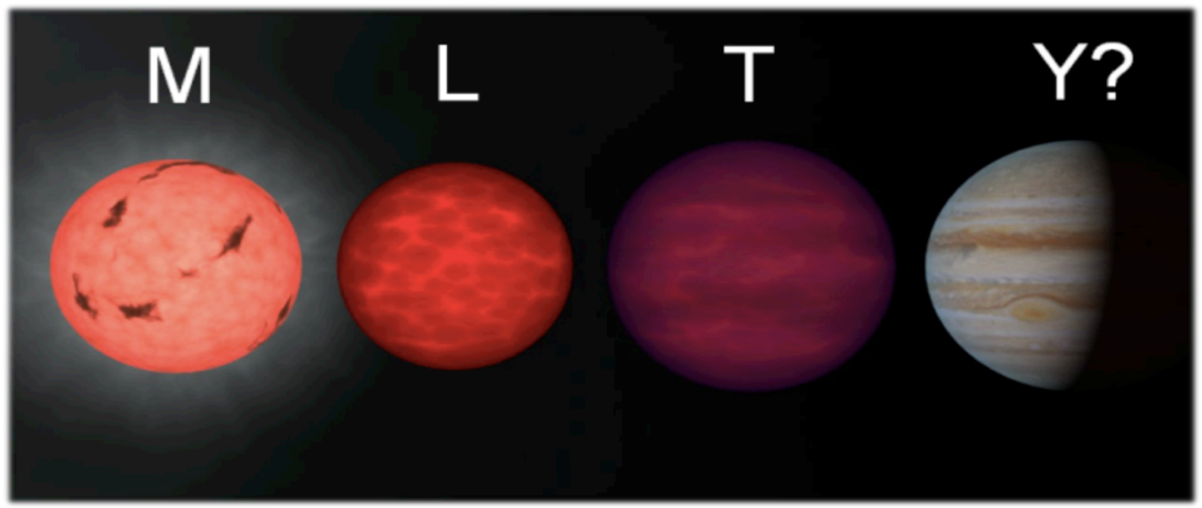
→ Brown dwarfs pulses discovered at GHz frequencies

→ Periodic pulses (~2 h), 100% circularly polarized, $T_B > 10^{15}$ K, |B| ~2 kG

SYNERGIES

- With other SKA observations

→ from brown dwarfs to exoplanets (decreasing Prot, cooler & more neutral atmosphere, larger-scale stable B topologies, weaker |B|)



[Hallinan]

→ tracing B and radio flux densities from brown dwarfs to planets will bring unique constraints for dynamo theories & radio emission scaling laws

→ lower mass planets more frequent around M dwarfs, close-in planets in habitable zone

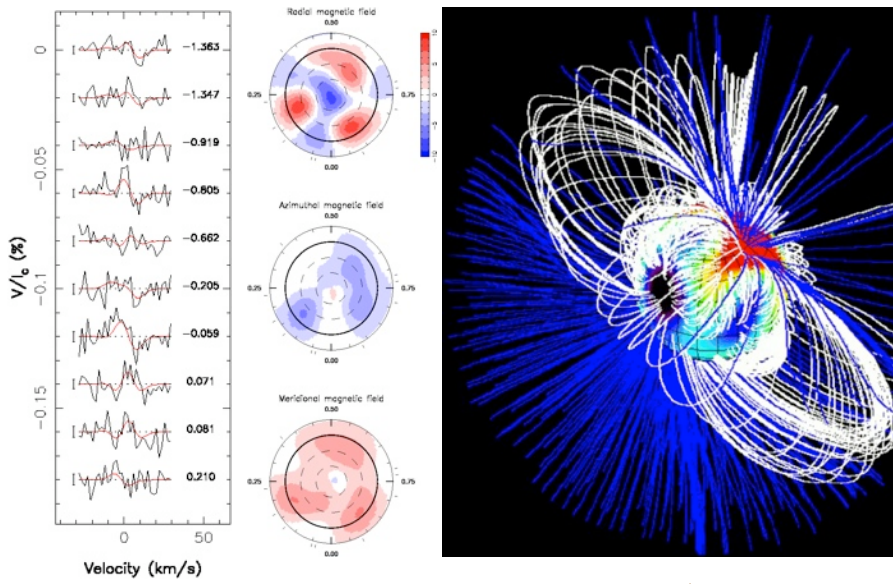
→ commensal SETI searches (if beamformed raw voltages can be exported in // to imaging or BF spectral data)

SYNERGIES

- With other wavelengths

  → ZDI (CFHT/Espadon, TBL/Narval, CFHT/Spirou)

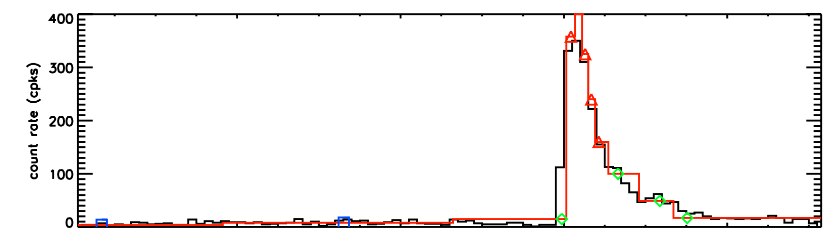
  ⇒ stellar B, planets around M dwarfs



[Donati et al., 2006+]

  → UV-X observations (HST, JWST, XMM, Chandra, Athena)

  ⇒ stellar flares, atmospheres



[McCleary & Wolk, 2011]

  → PLATO, TESS ⇒ more nearby exoplanets

  → ESO-VLT/NGTS, ESPRESSO, GAIA ...

  ⇒ 10's exoplanets per SKA-Low FoV

  → UTR-2, OLWA, NenuFAR ⇒ f ≤ 50 MHz, follow-up

RADIO DIAGNOSTIC OF STAR-PLANET PLASMA INTERACTIONS

- Broad New Field to Explore
- Theoretical Frame ~Ready
- Optimistic Prospects with SKA