Ultra-cool dwarf radio emissions: recent advancements and comparison with (extra-) solar system planets

J. D. Nichols

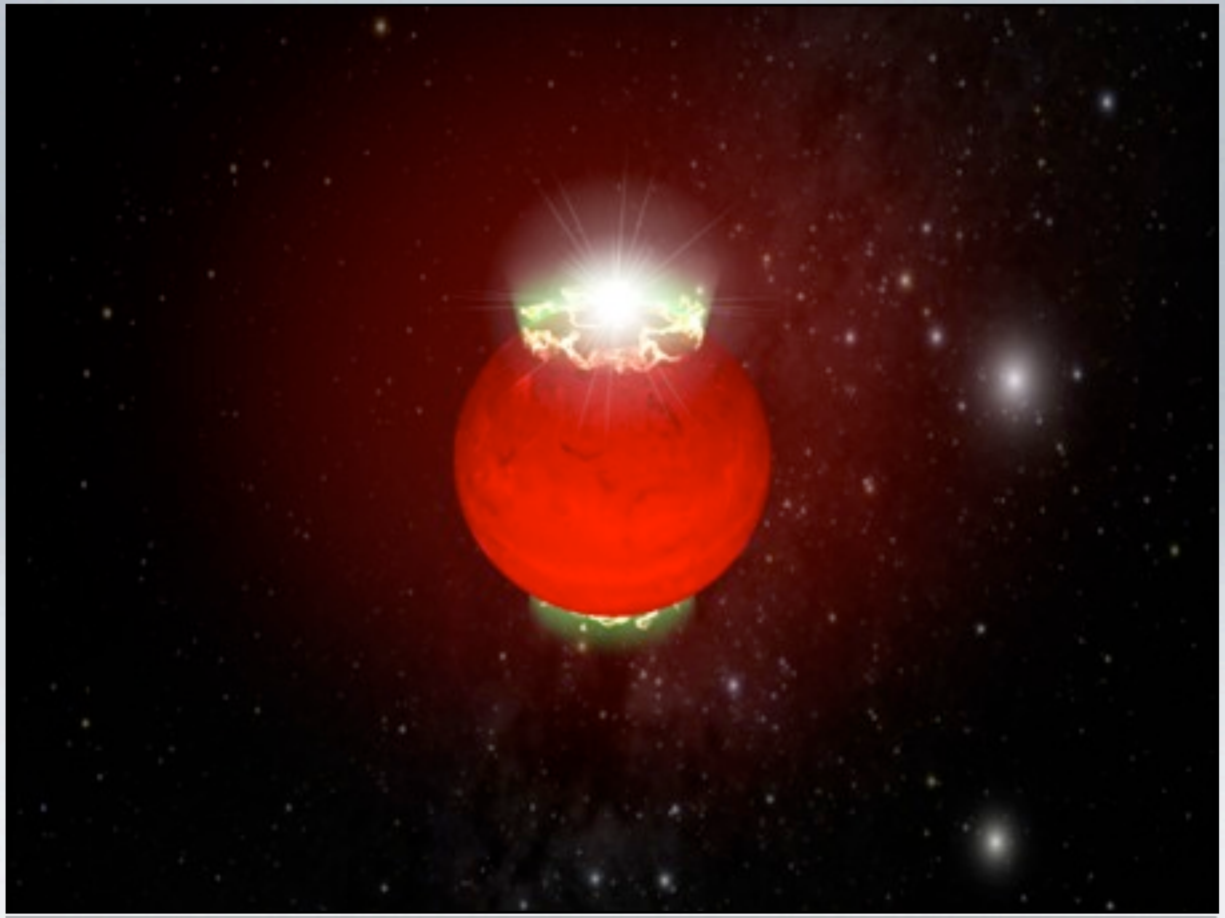


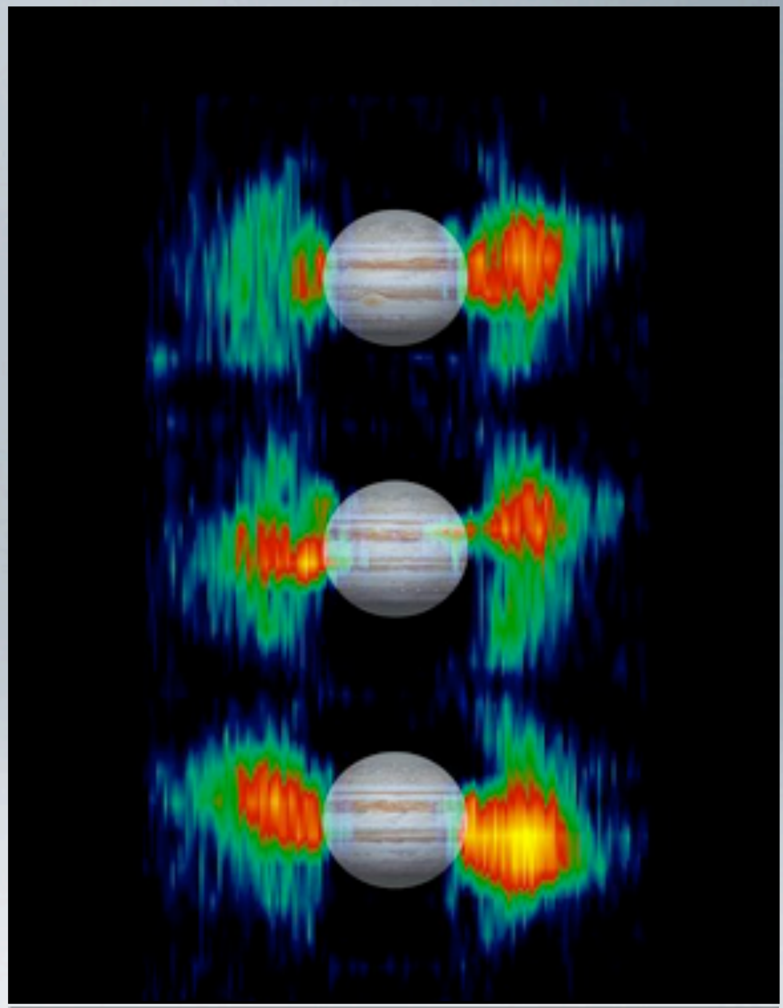
Image credit: Hallinan et al., NRAO/AUI/NSF

4 September 2013
Exoplanets and Brown Dwarfs: Mind the Gap
University of Hertfordshire

University of Leicester

Why the interest?

- Radio emissions = magnetosphere
- Magnetic field related to:
  - Formation, evolution and interior structure (e.g. Chabrier et al., 2007; MacDonald & Mullan, 2009)
  - Atmospheric dynamics, temperature and composition (e.g. Browning et al., 2008, Miller et al. 2013)
  - Interaction with primaries, satellites and space environment (e.g. Cuntz et al., 2000; Shkolnik et al., 2003; Nichols 2012; Noyola et al., 2013)
  - Detectability and photometry (e.g. Zarka et al., 2007, McLean et al., 2011)
  - Habitability (e.g. Lammer et al., 2009; Griessmeier et al., 2009)



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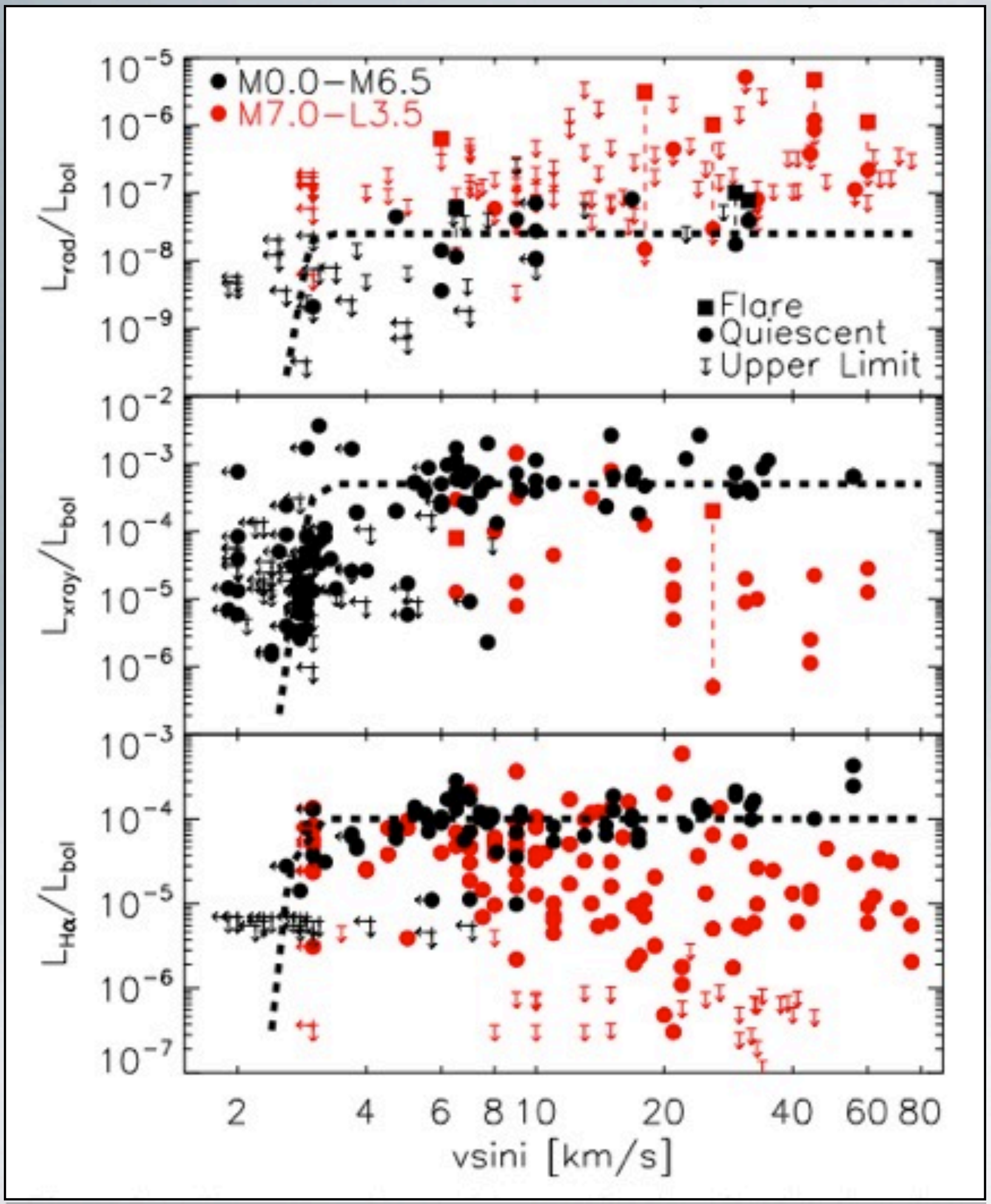
Relation to *v* sin *i*



McLean et al. 2012

Radio emission observational studies:

Berger et al., 2001, 2002, 2006, 2010
Hallinan et al., 2006, 2007, 2008
Phan-Bao et al., 2007
McLean et al., 2011, 2012
Burgasser et al., 2005, 2013
Antonova et al., 2008, 2013
Ravi et al., 2011
Route & Wolszczan, 2012, 2013...

Theoretical studies:

Schrijver, 2009
Yu et al., 2011, 2012
Kuzetsnov et al., 2012
Nichols et al., 2012...

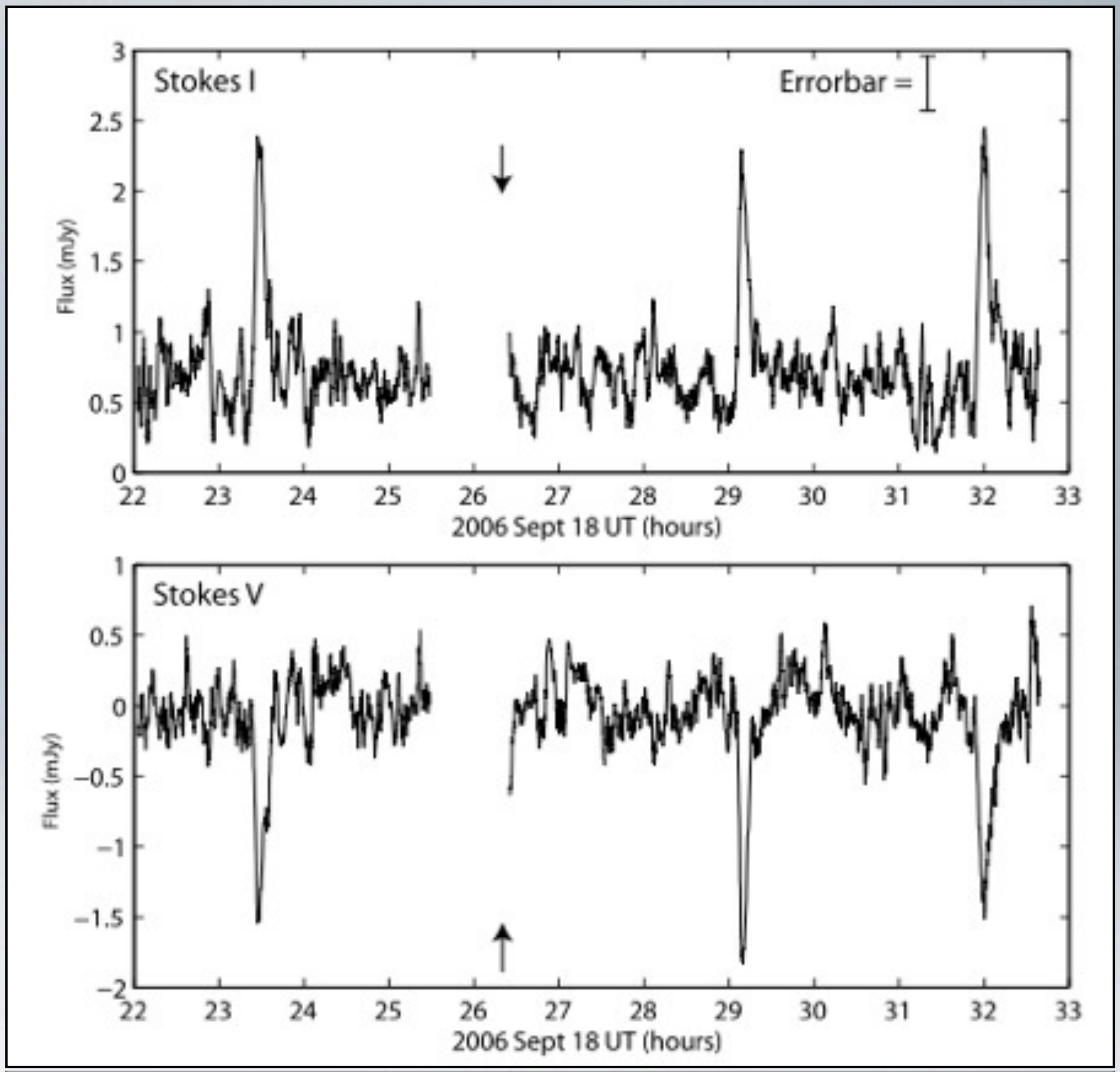
Quiescent and pulsed emission

~1 MW Hz^{-1} spectral luminosity

Quiescent: unpolarised, probably either synchrotron or depolarised maser emission

Spikes 75-100% circularly polarised, with <0.15 phase duty cycle, high ~10^8 K brightness temperature: maser emission

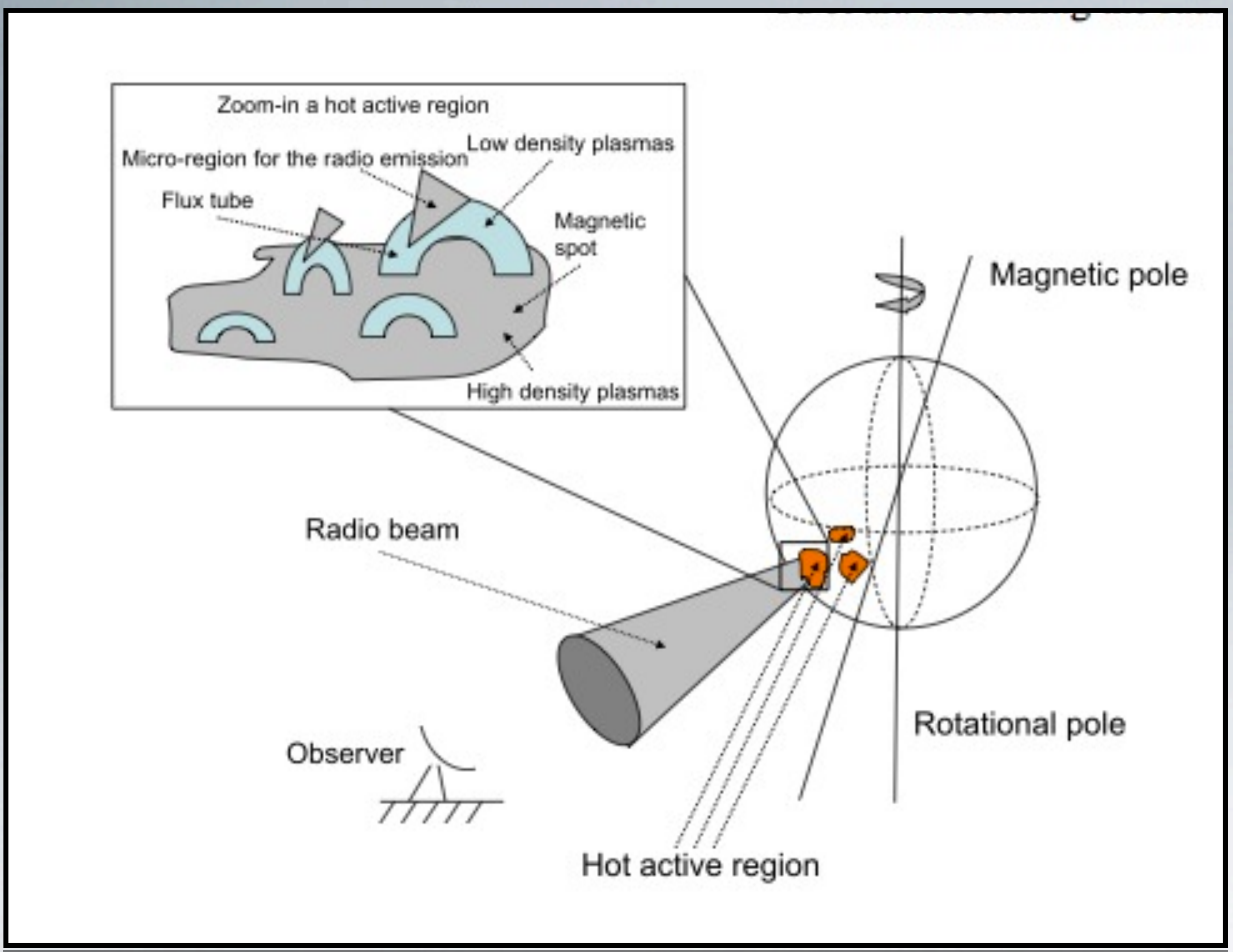
B~0.1 T (c.f. Jupiter ~1 mT)



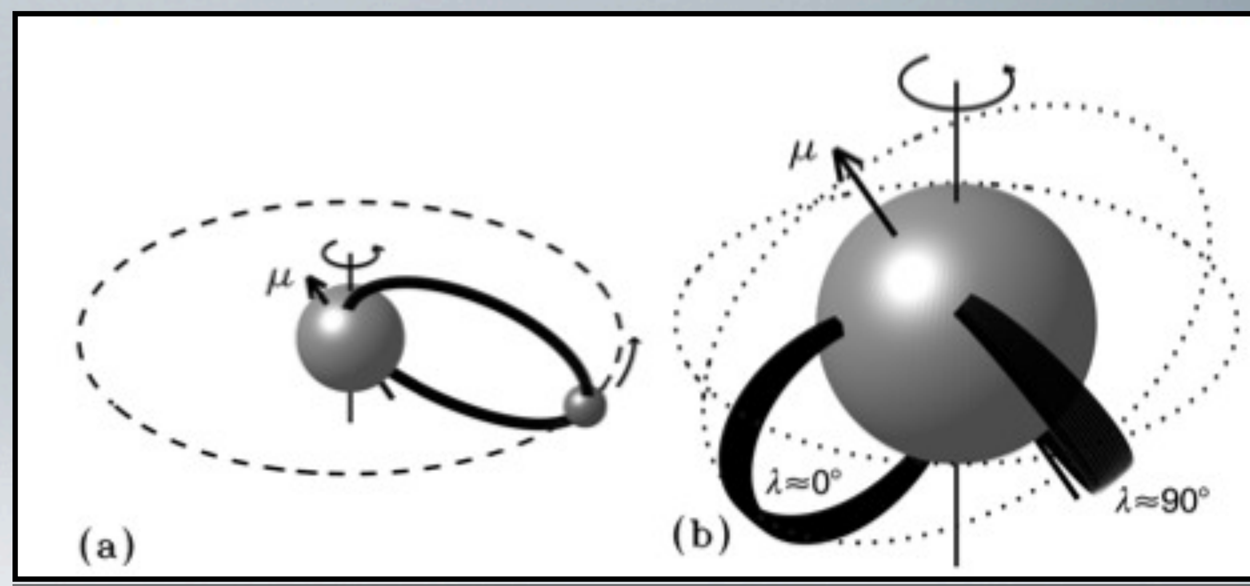
Hallinan et al., 2008

Stellar models: active regions

Yu et al. (2010)



Kuznetsov et al. (2011)



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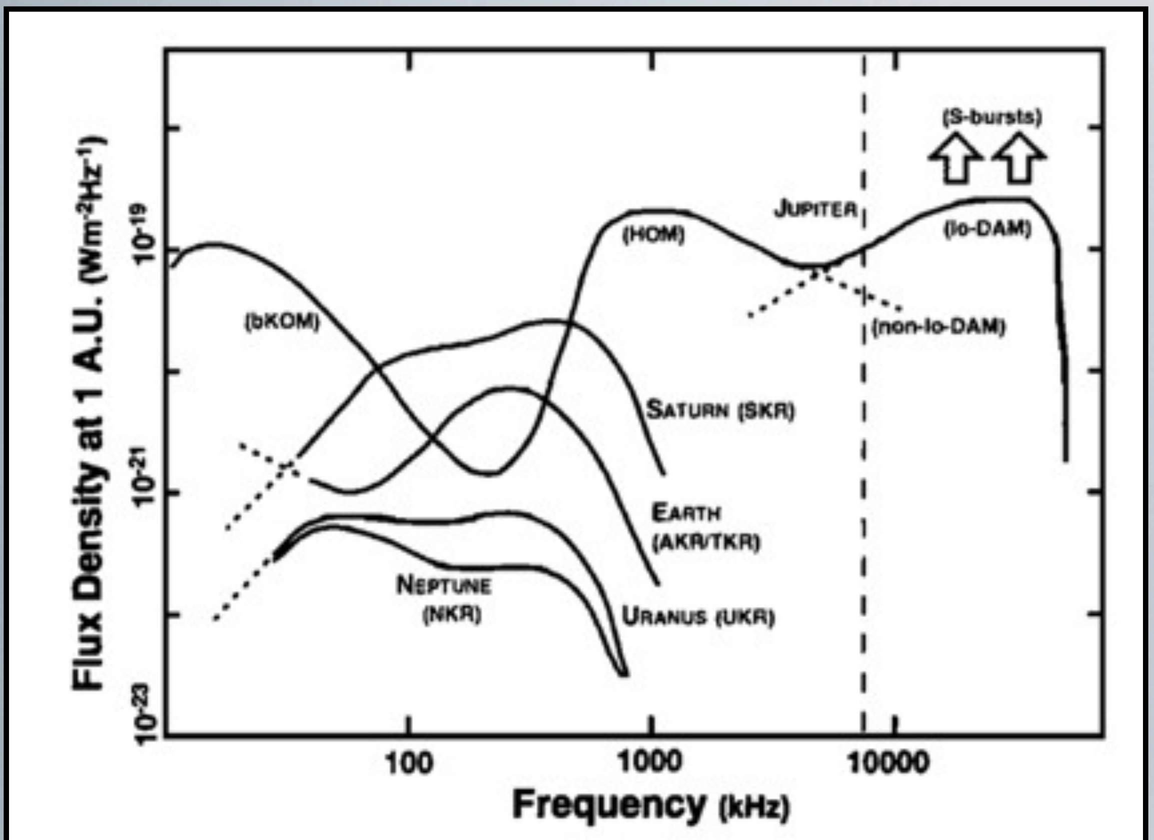
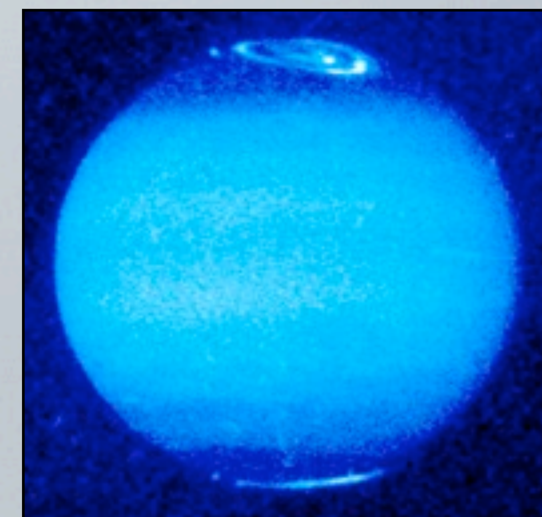
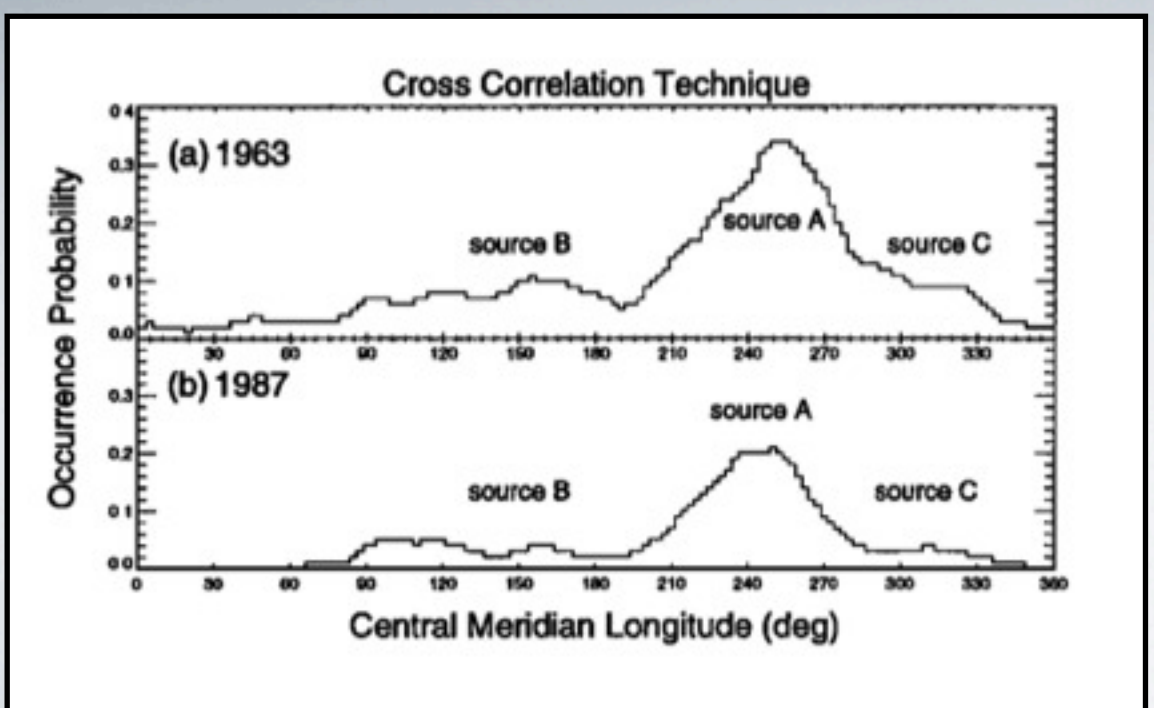
Jupiter: our own pulsar*

*OK a very weak pulsar



Zarka et al., 1998





Higgins et al. (1986)

Jupiter's DAM radio emission

FWHM ~50°

~0.14 duty cycle

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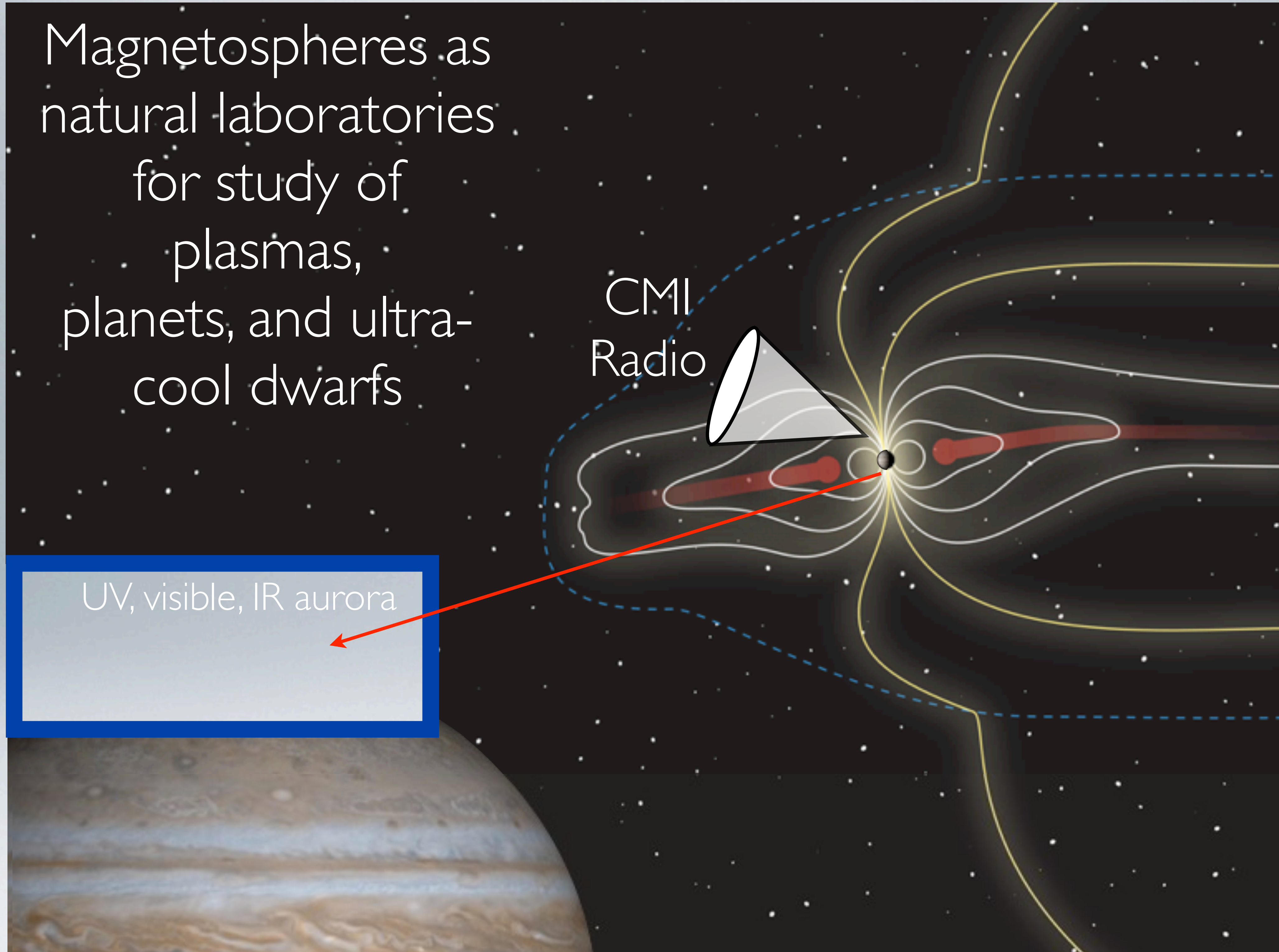
Magnetospheres as natural laboratories for study of plasmas, planets, and ultra-cool dwarfs



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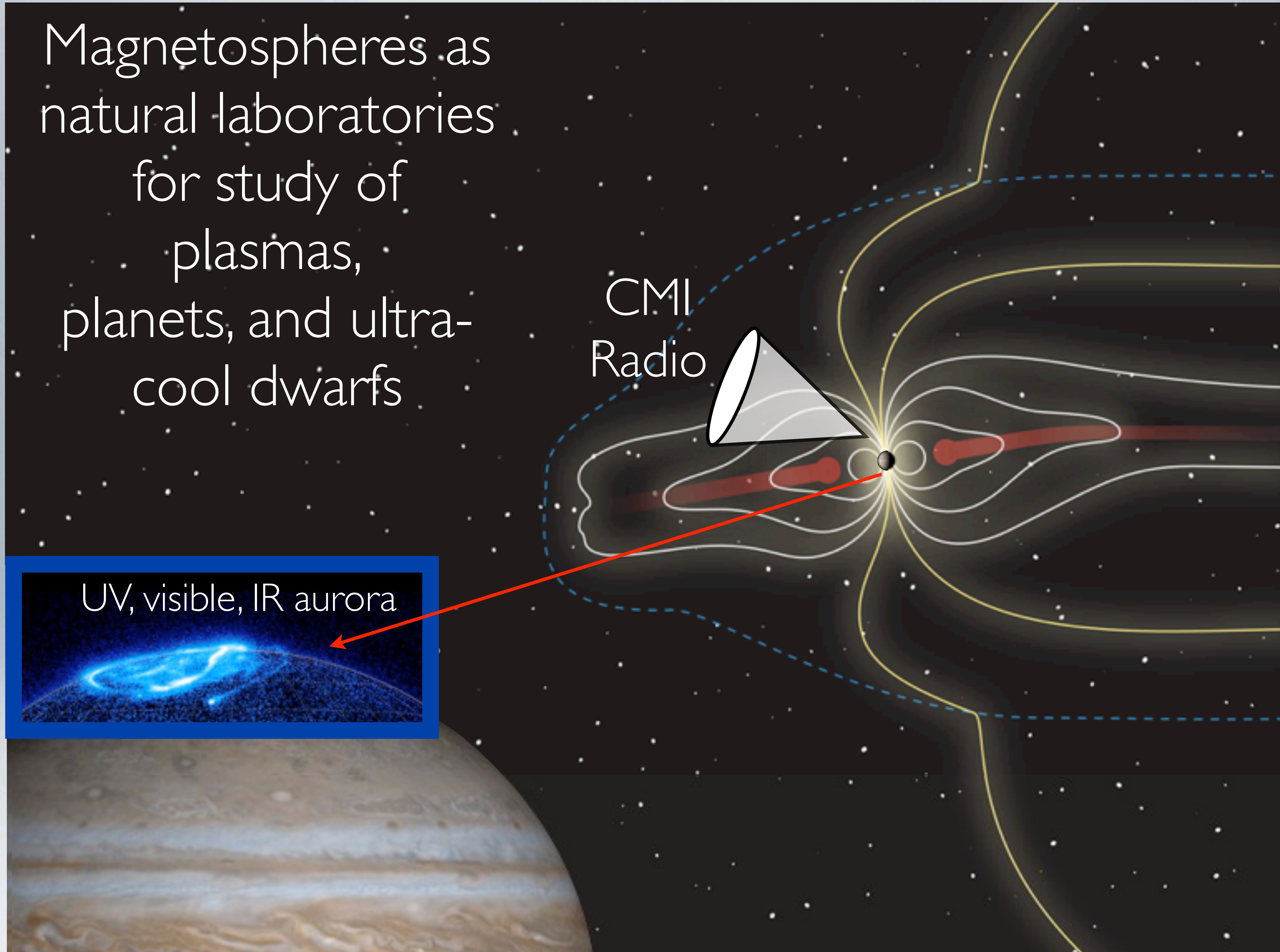

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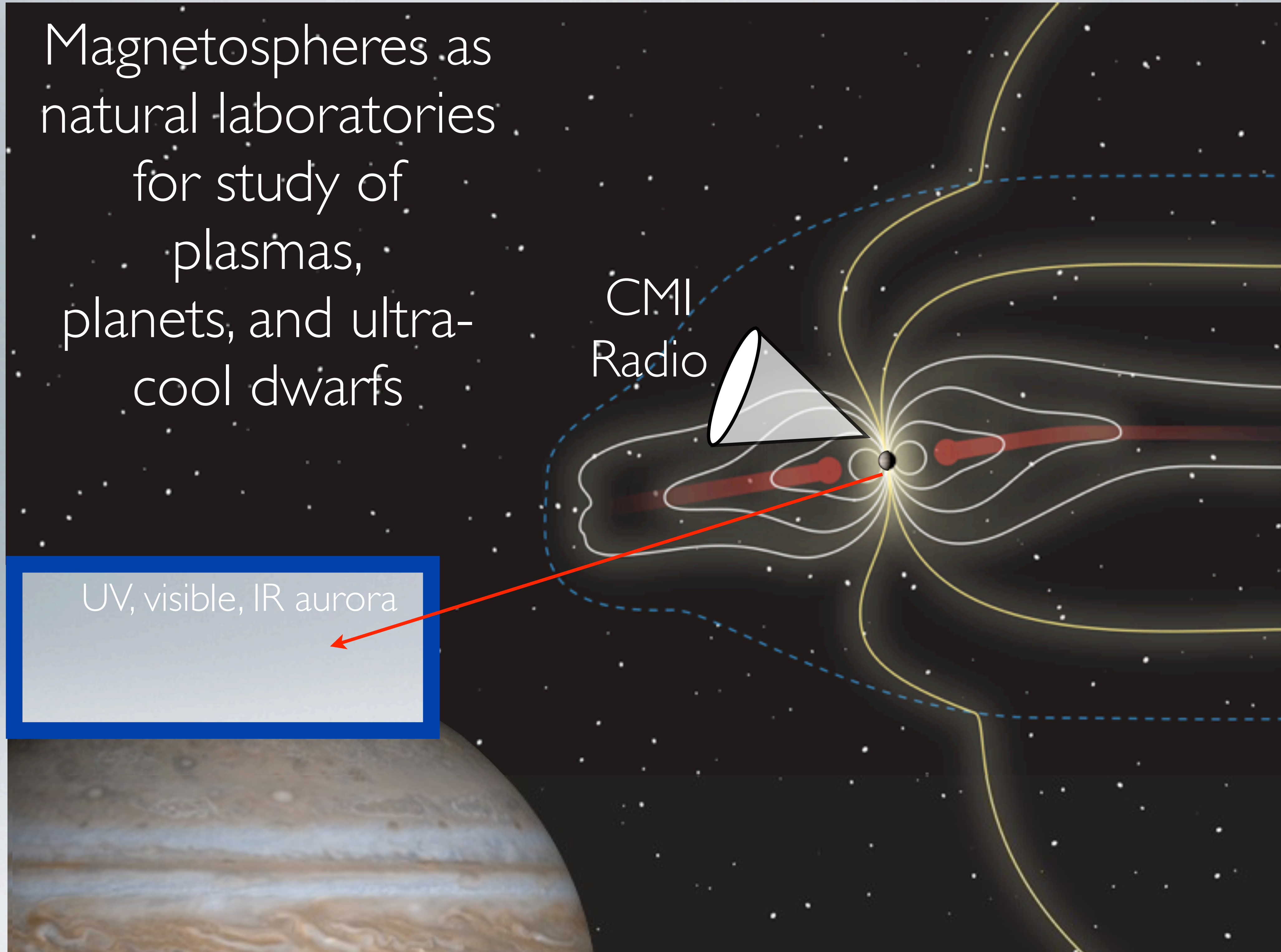
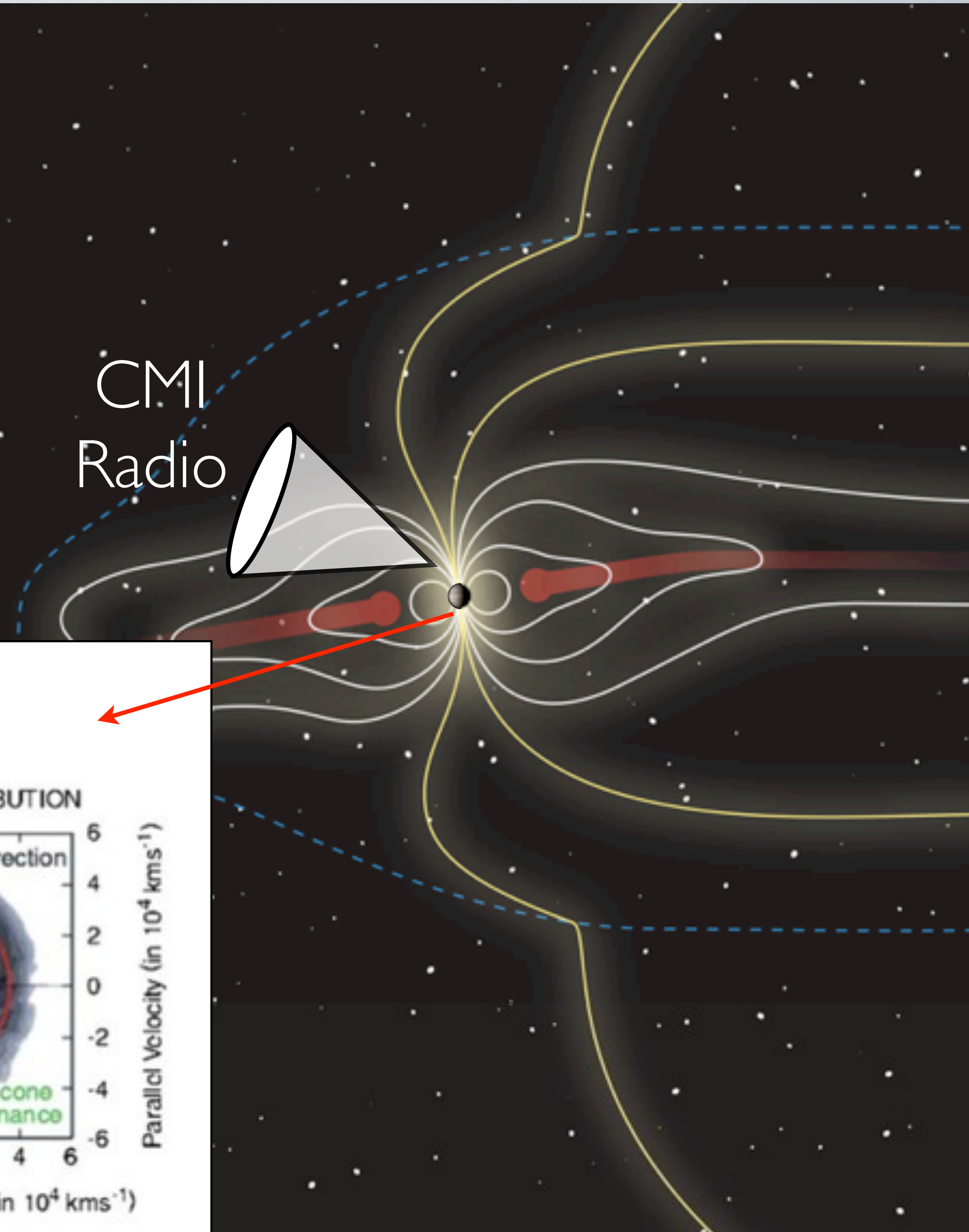
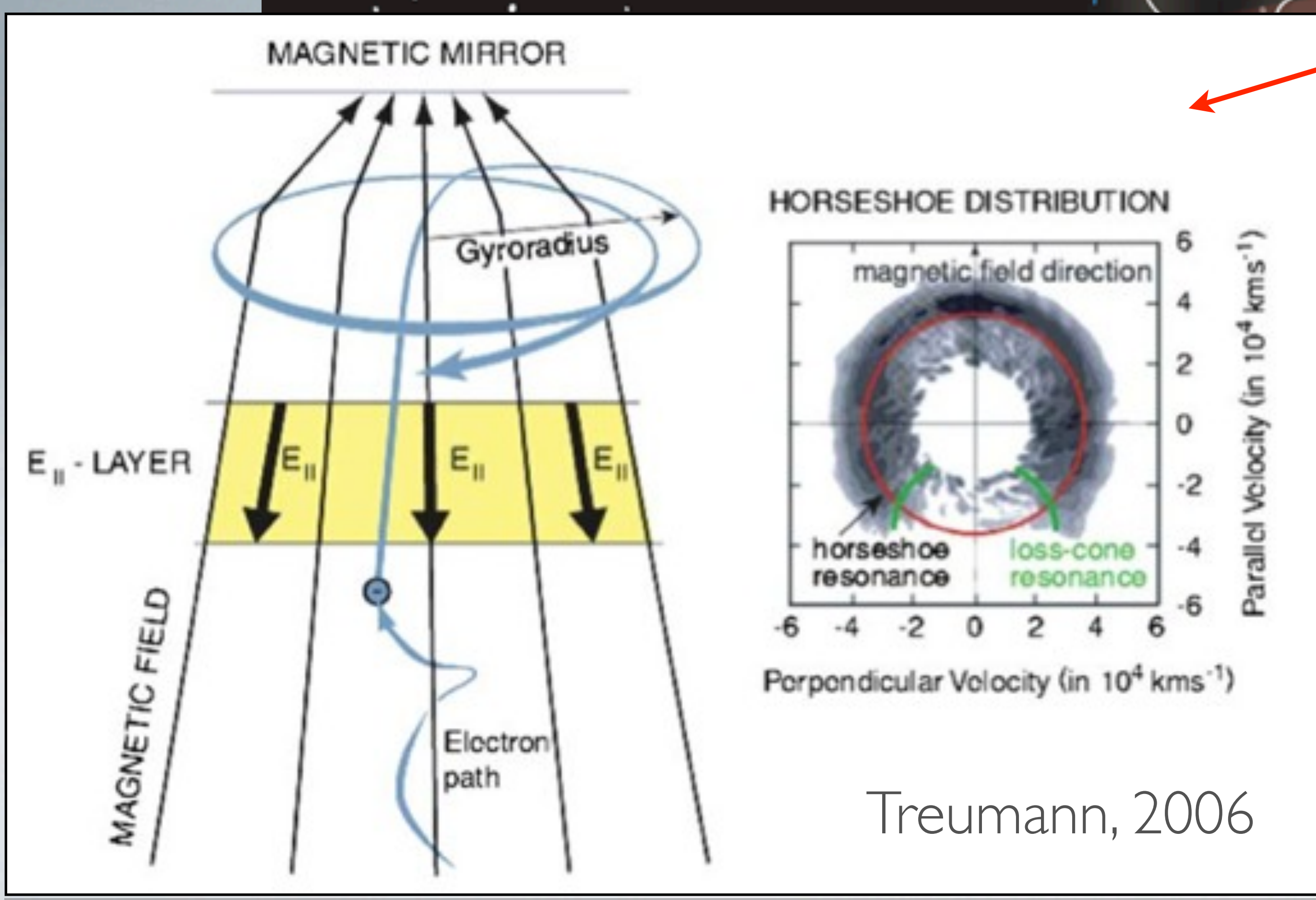

Magnetospheres as natural laboratories for study of plasmas, planets, and ultra-cool dwarfs
CMI Radio
UV, visible, IR aurora

Magnetospheres as natural laboratories for study of plasmas, planets, and ultra-cool dwarfs





Treumann, 2006

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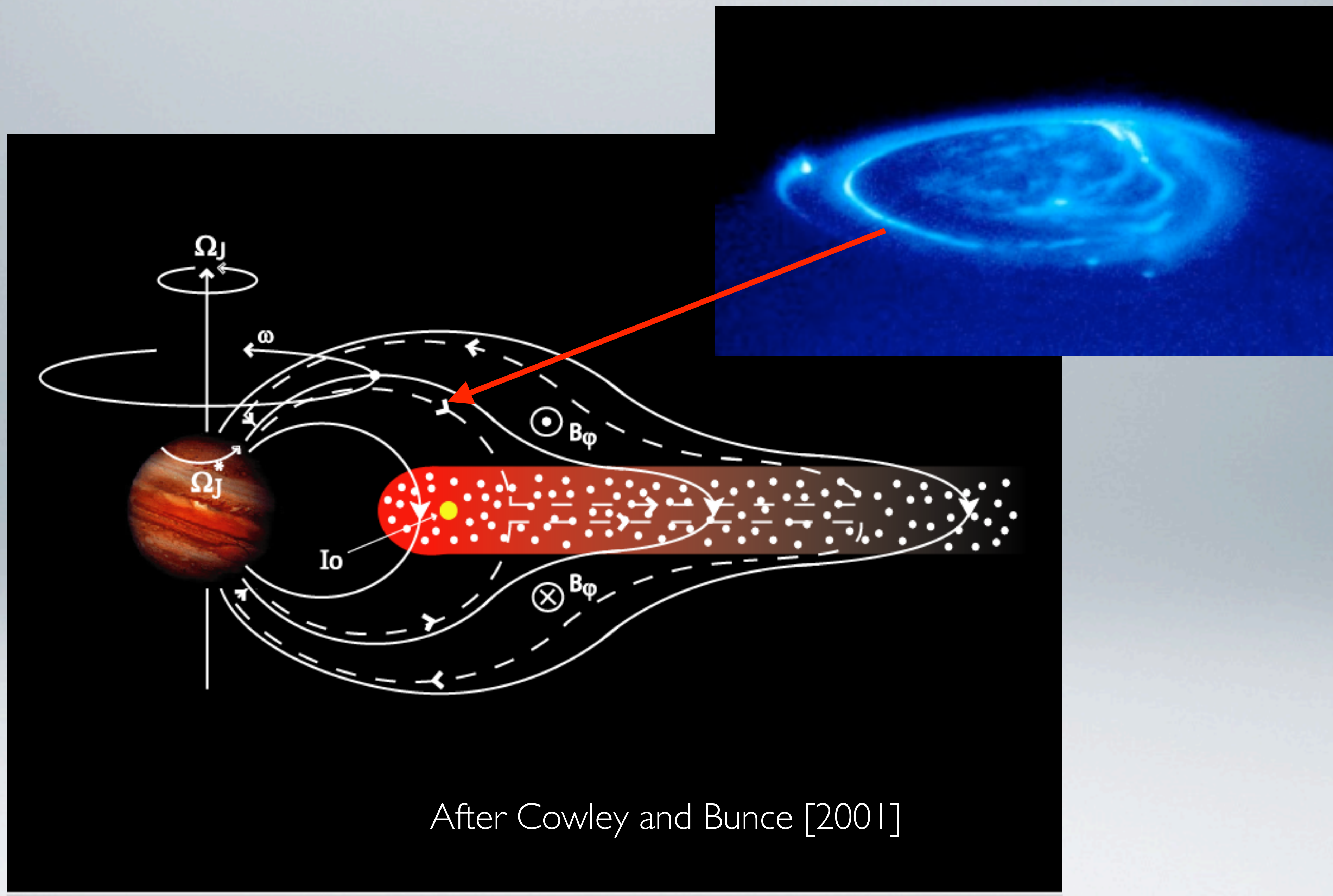
Magnetosphere-ionosphere coupling at Jupiter (1)



Hill 1979, 2001; Pontius 1997; Cowley & Bunce 2001; Nichols & Cowley 2003, 2004, 2005, Cowley et al. (2007), Ray et al. (2010), Tao et al. (2010)

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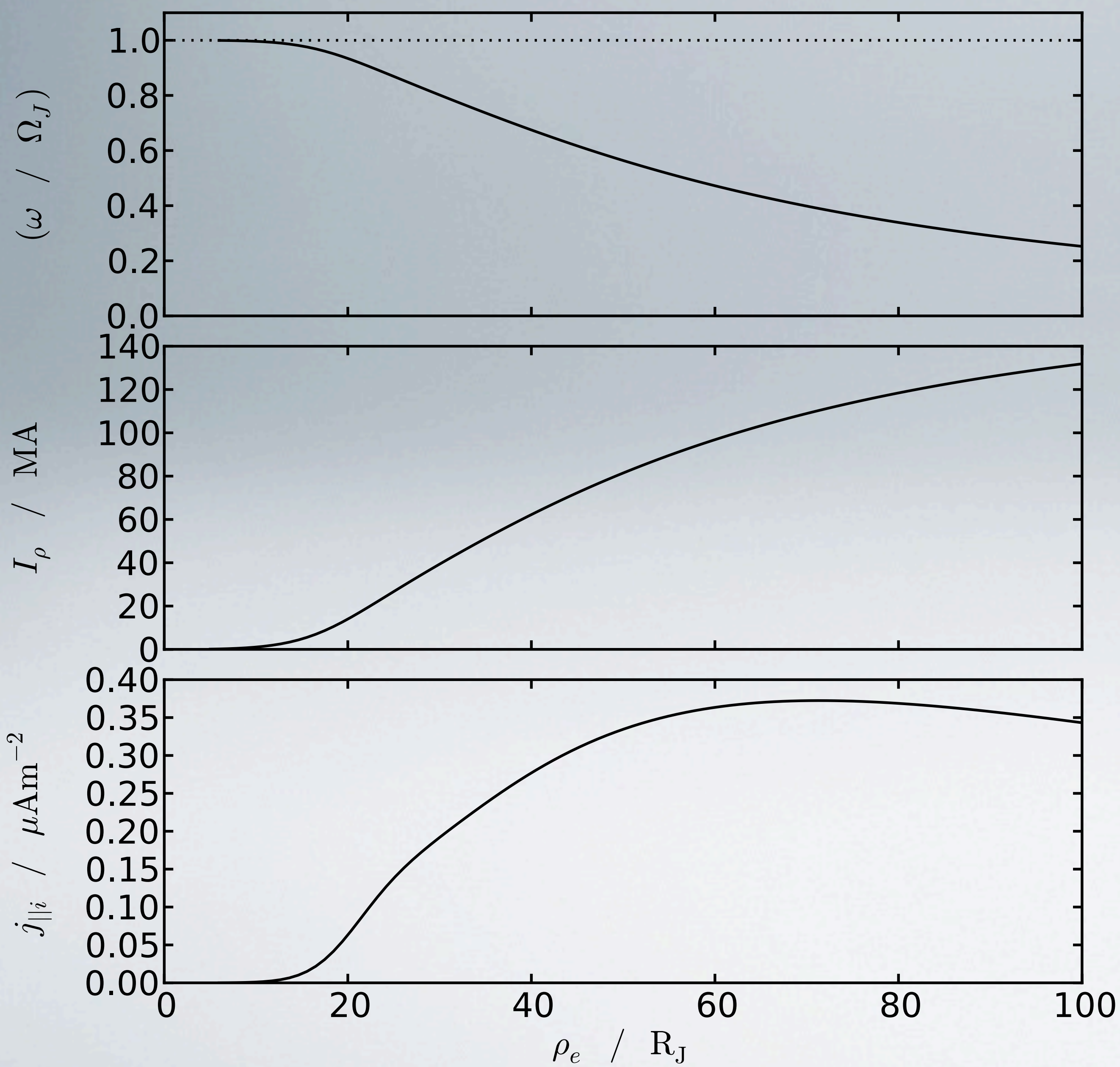
Magnetosphere-ionosphere coupling at Jupiter (I)

Momentum equation

$$\frac{\rho_e}{2}\frac{d}{d\rho_e}\left(\frac{\omega}{\Omega_J}\right)+\left(\frac{\omega}{\Omega_J}\right)=\frac{4\pi\Sigma_P^* F_e|B_{ze}|}{\dot{M}}\left(1-\frac{\omega}{\Omega_J}\right)$$



Equatorial radial current

$$I_\rho = 4\pi\Sigma_P^*\rho_i^2(\Omega_{UCD}-\omega)B_i$$

Field-aligned current

$$j_{\|i} = -\frac{1}{2\pi\rho_i^2\sin\theta_i}\frac{dI_p}{d\theta_i}$$

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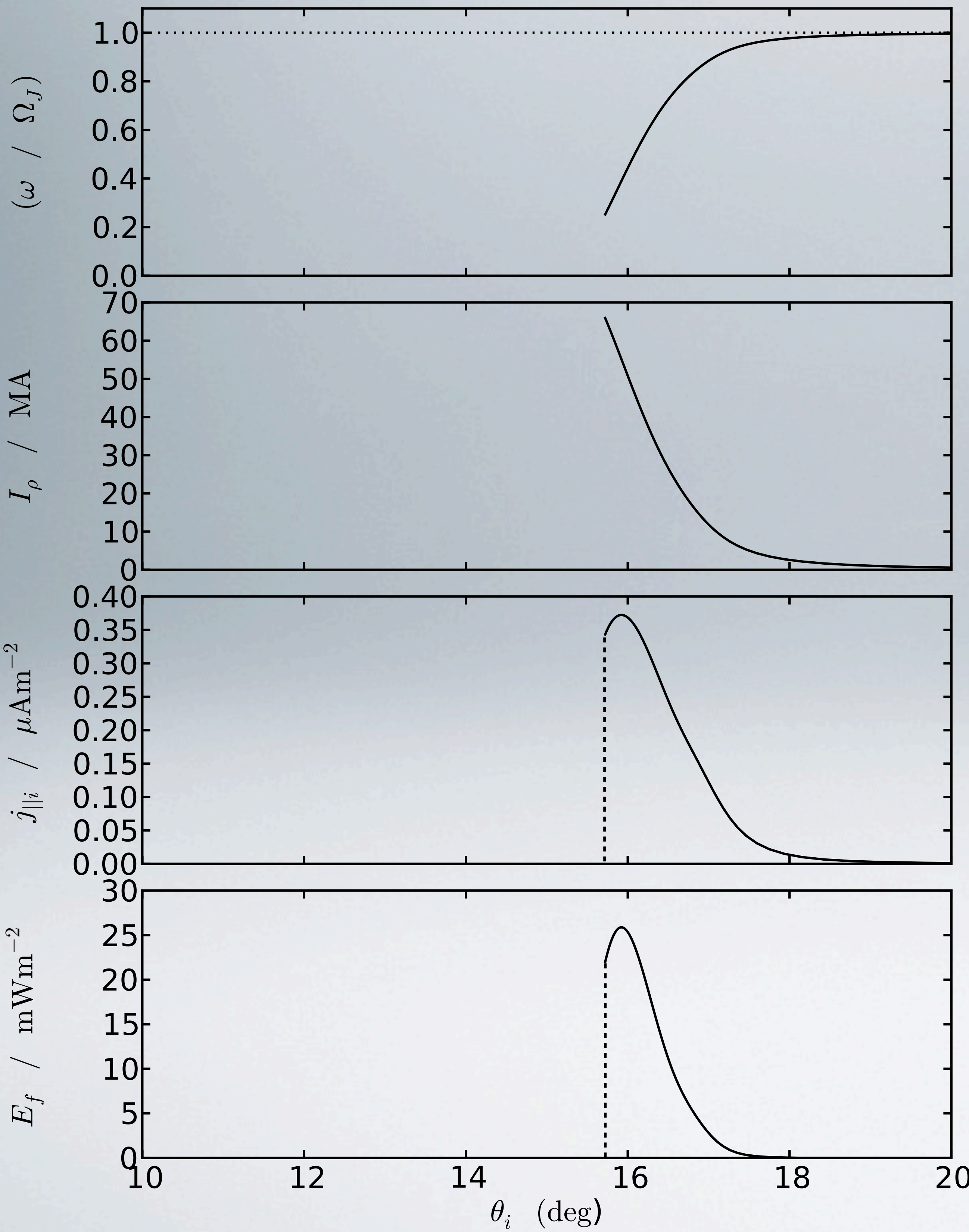
Magnetosphere-ionosphere coupling at Jupiter (I)



Pedersen current

$$I_P = 2\pi \Sigma_P^* \rho_i^2 (\Omega_{UCD} - \omega) B_i$$

Field-aligned current

$$j_{\|i} = -\frac{1}{2\pi\rho_i^2 \sin\theta_i} \frac{dI_p}{d\theta_i}$$

Electron energy flux

$$\left(\frac{E_f}{E_{f0}}\right) = 1 + \left(\frac{e\Phi}{W_{th}}\right) + \frac{1}{2}\left(\frac{e\Phi}{W_{th}}\right)^2$$

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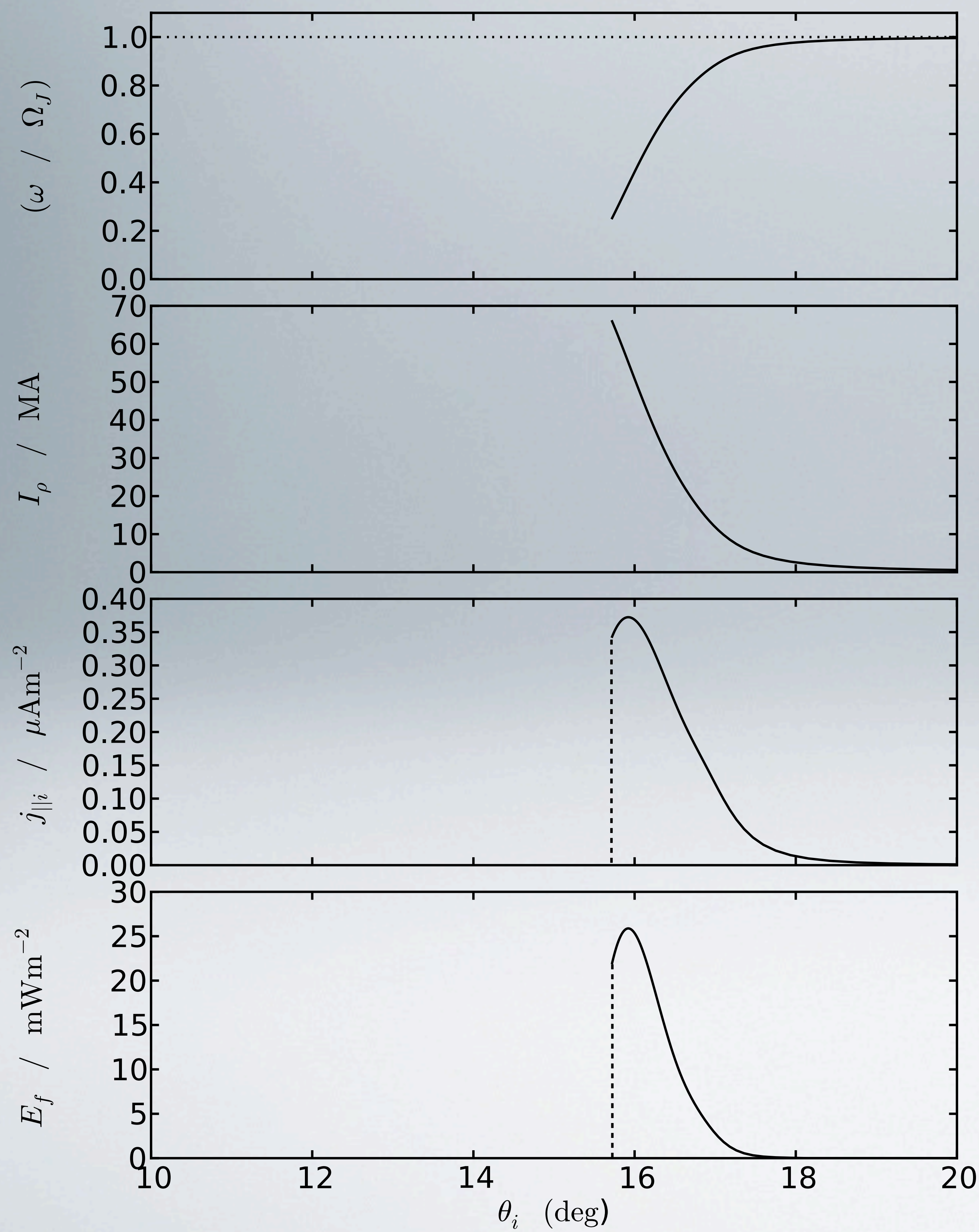
Magnetosphere-ionosphere coupling at Jupiter (I)



Total precipitating power

$$P_e = \int_0^{90} 2\pi R_{UCD}^2 \sin\theta_i \; E_f \; d\,\theta_i$$

Spectral luminosity

$$L_r = \frac{P_e}{100\,\Delta\nu}$$

Jupiter: ~10^{11} W

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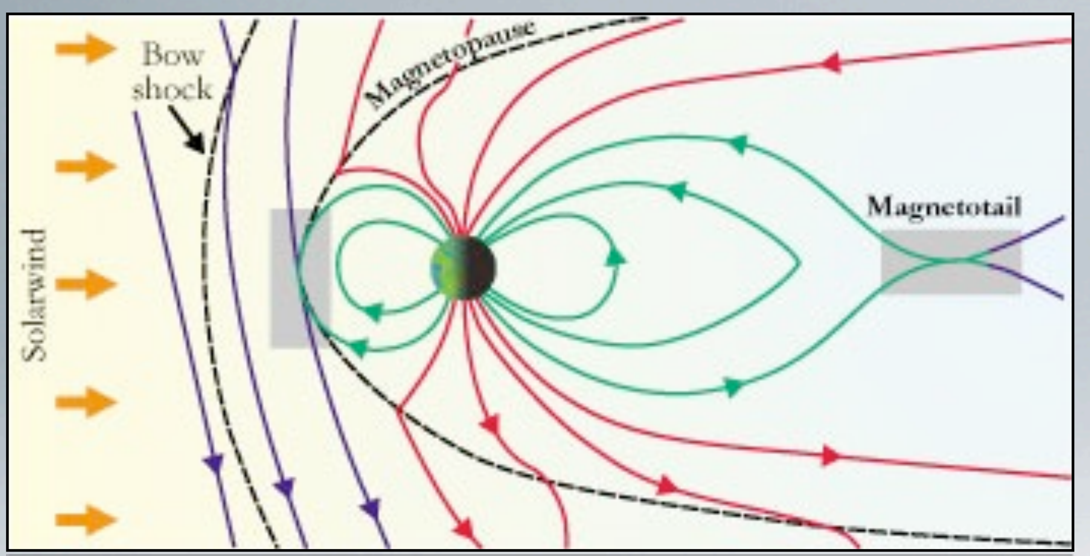
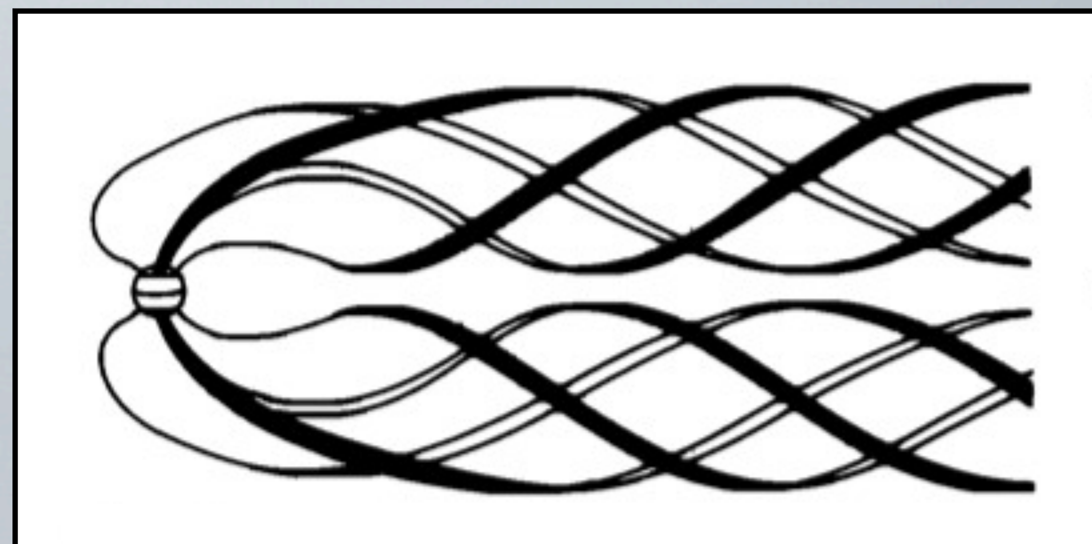
Magnetosphere-ionosphere coupling at Jupiter (2)





Isbell et al. (1984)

$$\left(\frac{\omega}{\Omega_p}\right) = \frac{\mu_0 \Sigma_P^* v_{sw}}{1 + \mu_0 \Sigma_P^* v_{sw}}$$

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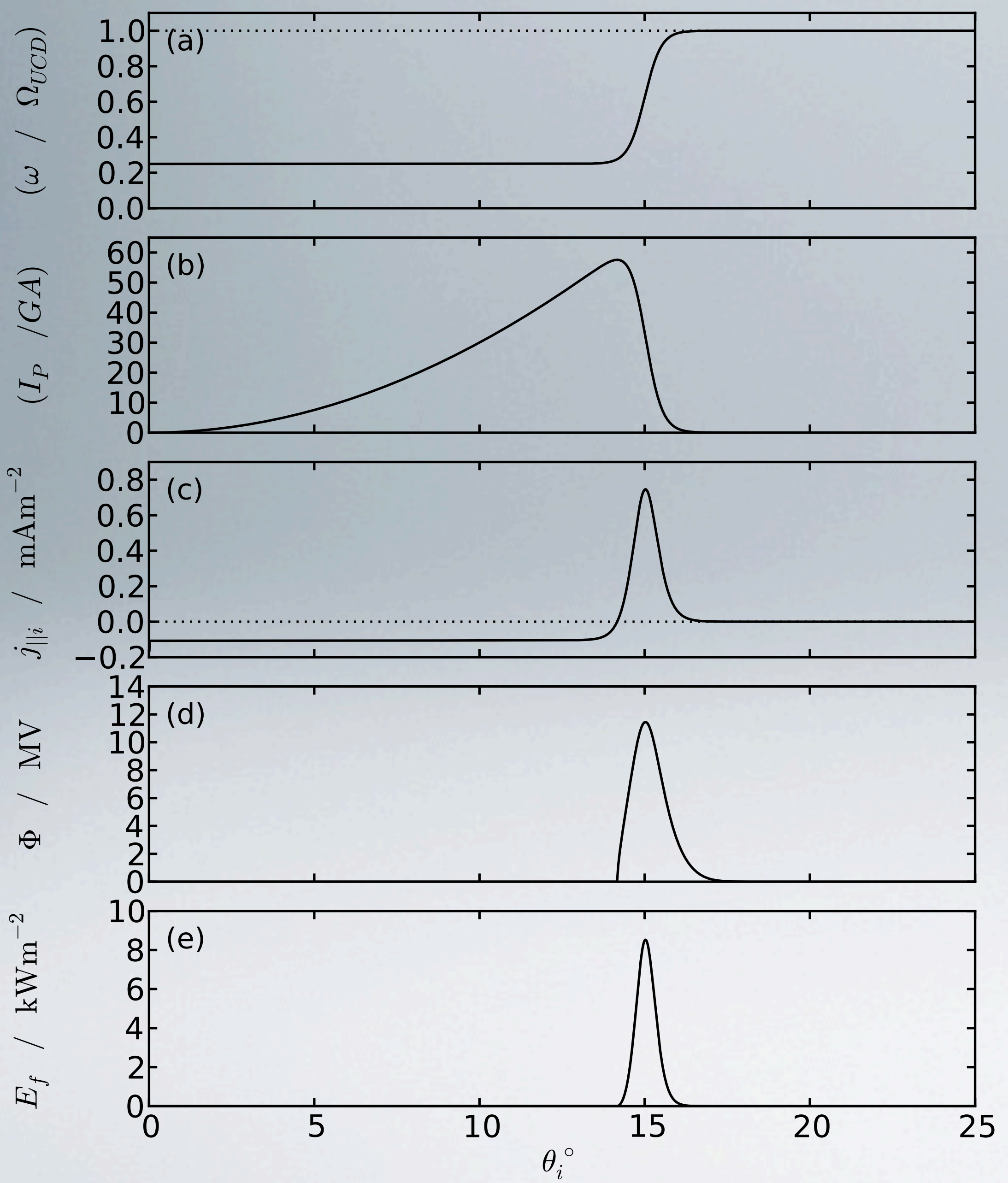
Ultra-cool dwarfs

Ionospheric field 0.3 T Rotation period 2 h



$$\left(\frac{\omega}{\Omega_p}\right) = \left(\frac{\omega}{\Omega_p}\right)_{\text{Open}} + \frac{1}{2}\left(1 - \left(\frac{\omega}{\Omega_p}\right)_{\text{Open}}\right)\left(1 + \tanh\left(\frac{\theta_i - \theta_{ic}}{\Delta\theta_i}\right)\right)$$

$$\left(\frac{j_{\|i}}{j_{\|io}}\right) = 1 + \left(\frac{e\Phi}{W_{th}}\right) + \frac{\left(\frac{e\Phi}{W_{th}}\right)^2}{2\left[\left(\frac{m_e c^2}{W_{th}}\right) + 1\right]}$$

$$P_e = \int_0^{90} 2\pi R_{UCD}^2 \sin\theta_i\ E_f\ d\theta_i$$

$P_r \sim 1.1$ MW Hz^{-1} at ~8 GHz

($\Longrightarrow 10^{16}$ W)

Nichols et al. (2012)

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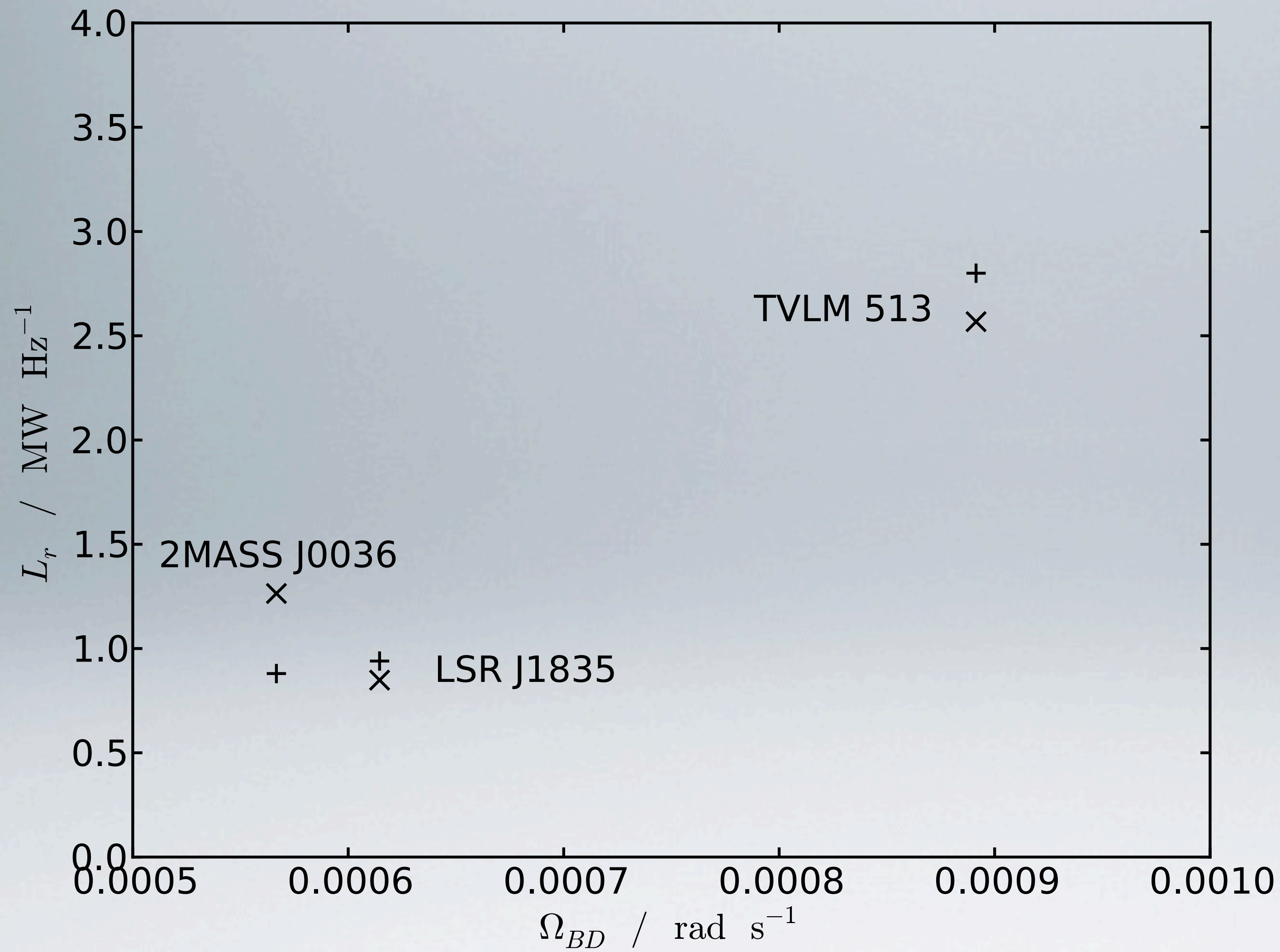
Comparison with observations



Solitary UCDs with confirmed CMI radio emissions and known rotation periods

Nichols et al. (2012)

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Thursday, 17 October 13

Causes for angular velocity shear

$$\left(\frac{\rho_H}{R_{UCD}}\right) = \left(\frac{2\pi\Sigma_P^* B_{eq}^2 R_{UCD}^2}{\dot{M}}\right)^{1/4} \simeq 775$$

$$\left(\frac{R_{mp}}{R_{UCD}}\right) = \left(\frac{k_m^2 B_{eq}^2}{2\mu_\circ(p_{th} + p_{dyn} + p_B)}\right)^{1/6} \simeq 713 - 820$$

$$\left(\frac{\omega}{\Omega_p}\right) = \frac{\mu_0 \Sigma_P^* v_{sw}}{1 + \mu_0 \Sigma_P^* v_{sw}}$$

~3% for 0.5 mho and 50 km/s

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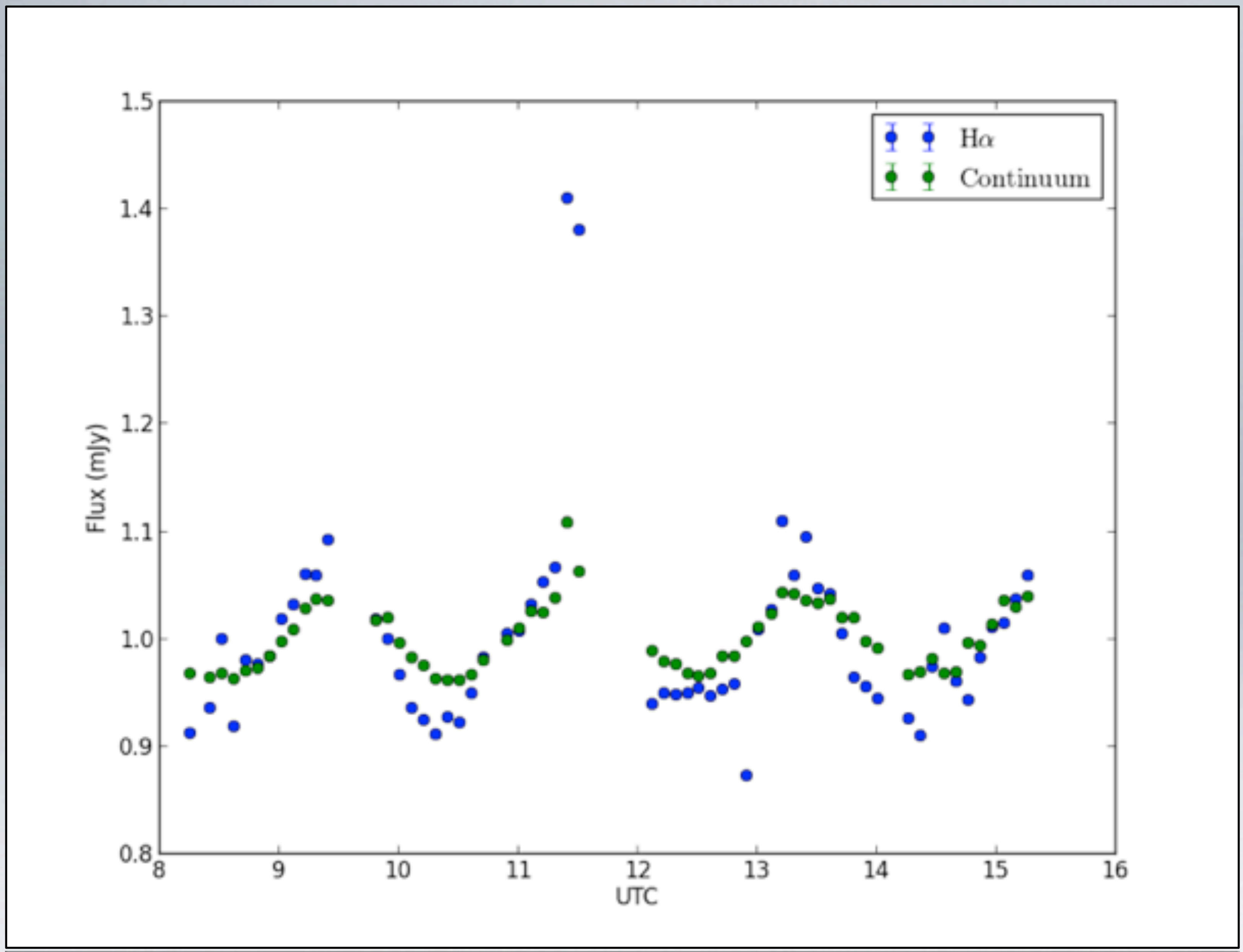
TVLM 513: comparison with H-α



Littlefair et al., this session

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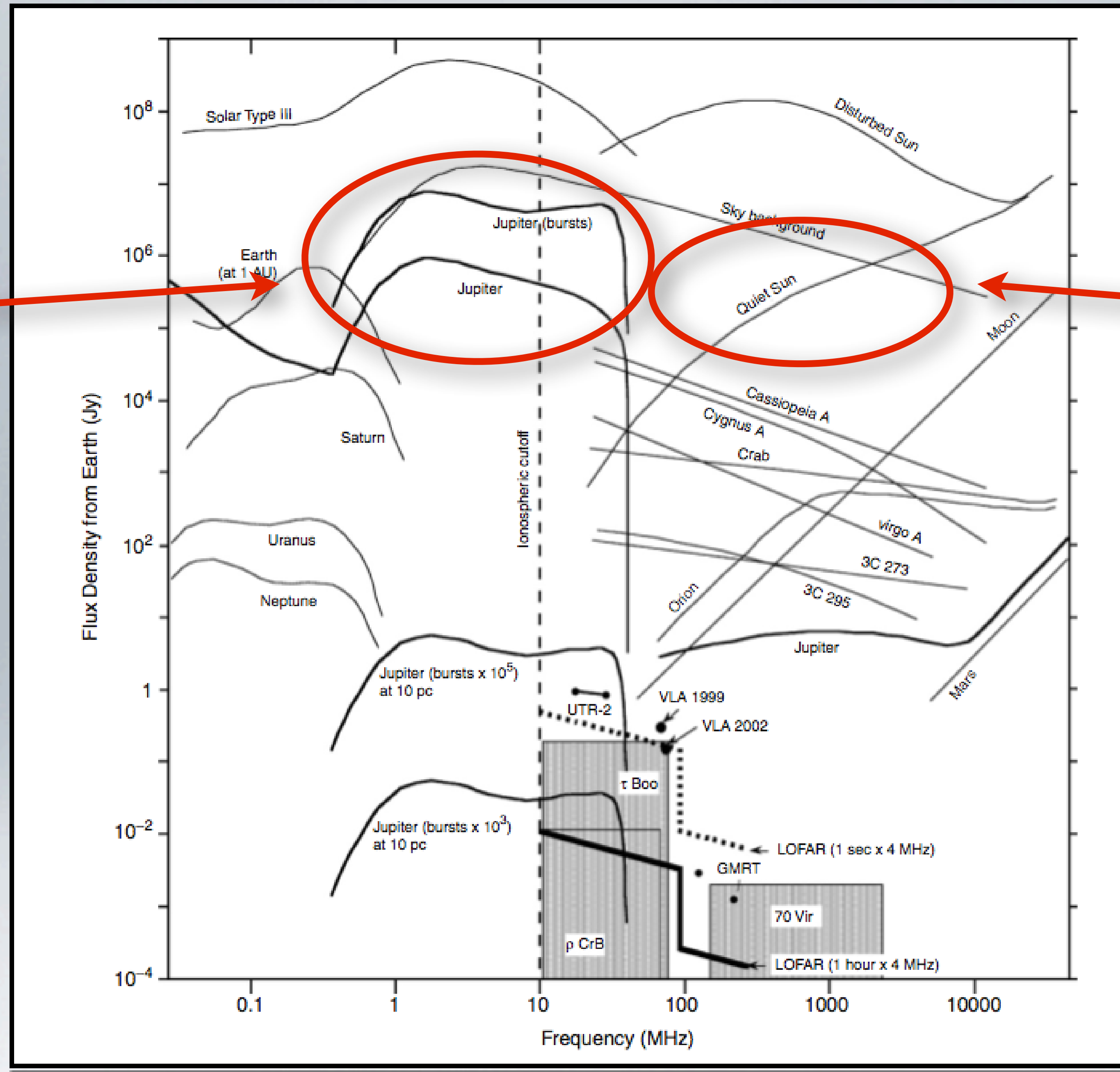
Exoplanets... radio observable?

New Scientist

Exoplanets... radio observable?

Jupiter

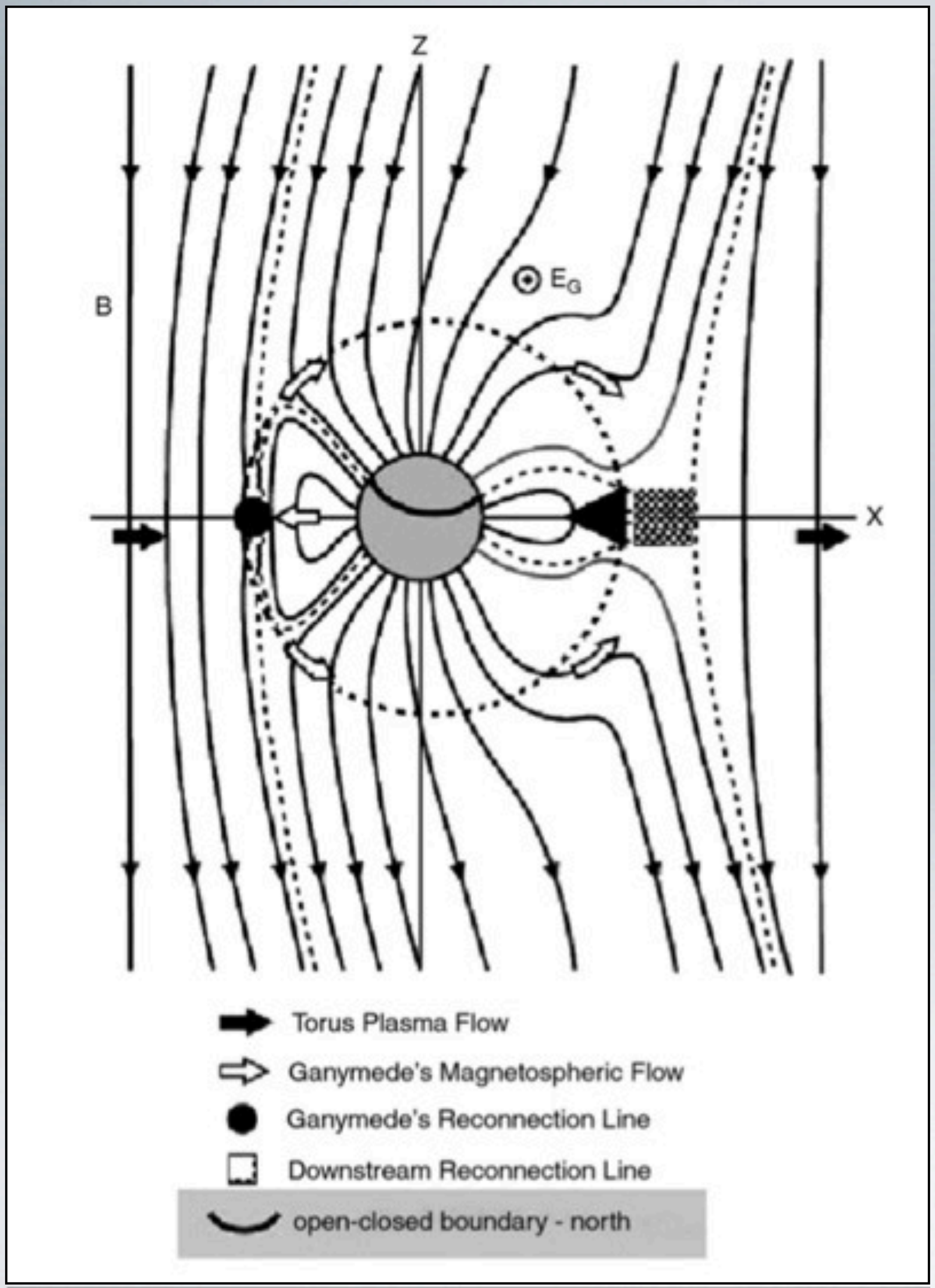


Sun

Zarka et al. 2007

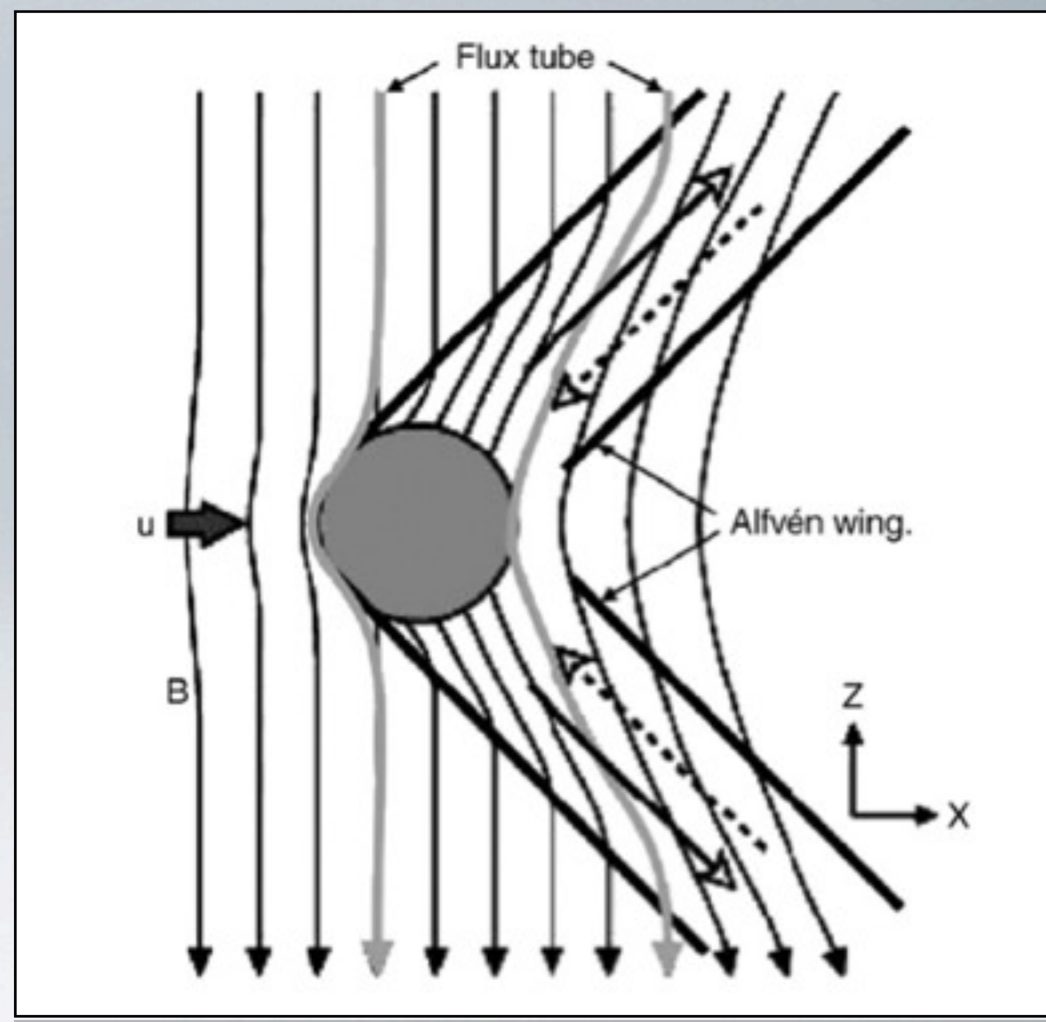
Thursday, 17 October 13

Two hot Jupiter mechanisms



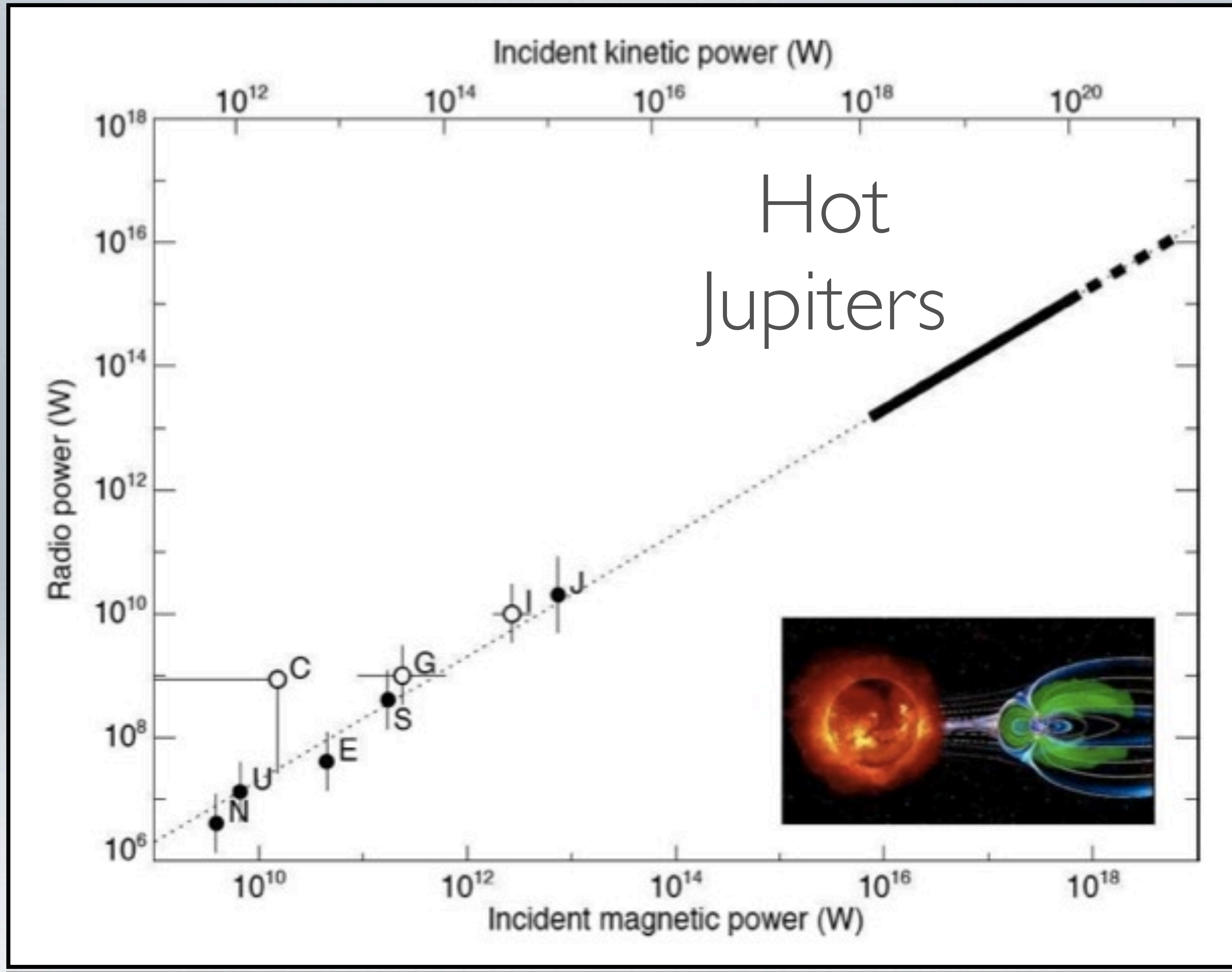
Ganymede-like

Io-like



Zarka et al., 2007

‘Radiometric Bode’s Law’



Farrell et al. 1999, 2004; Zarka et al. 2001, 2007; Lazio et al. 2004; Grießmeier et al. 2005, 2007; Jardine & Cameron 2008; Fares et al. 2010)

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‘Radiometric Bode’s Law’

Radio emission observational studies:

Bastian et al. 2000
Ryabov et al. 2004
Winterhalter et al. 2005
George & Stevens 2007
Lazio & Farrell 2007
Smith et al. 2009
Lecavelier des Etangs et al. 2009, 2011, 2013
Lazio et al. 2010a, 2010b...

Theoretical studies:

Zarka et al., 2001, 2007
Farrell et al.. 2004
Lazio et al, 2004
Greissmeier et al., 2005, 2007
Jardine & Cameron, 2008
Hess & Zarka, 2011
Nichols, 2011, 2012
Noyola et al., 2013...

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'Radiometric Bode's Law'

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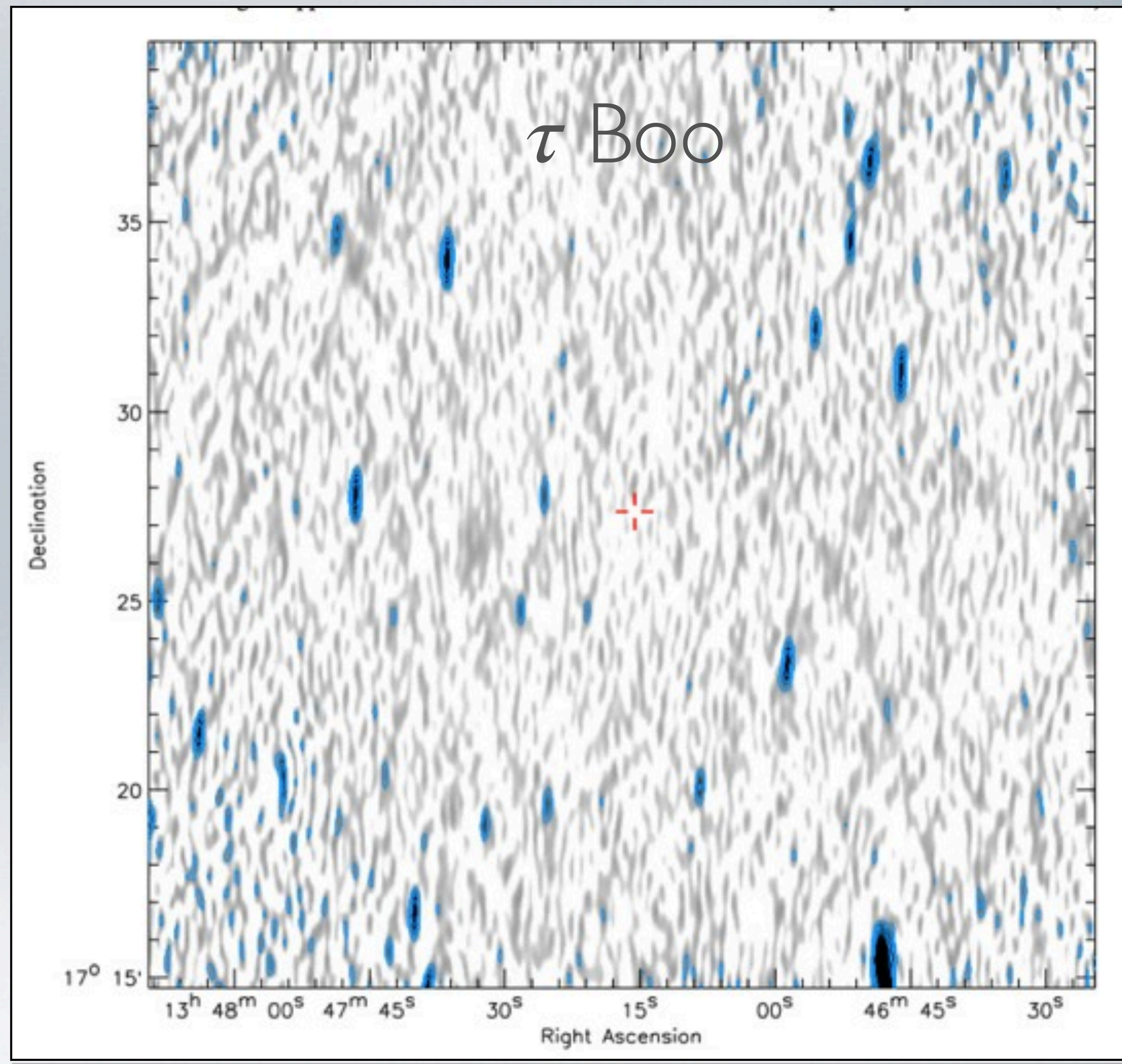
Noyola et al., 2013...



Stroe et al., 2012

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‘Radiometric Bode’s Law’

Radio emission observational studies:

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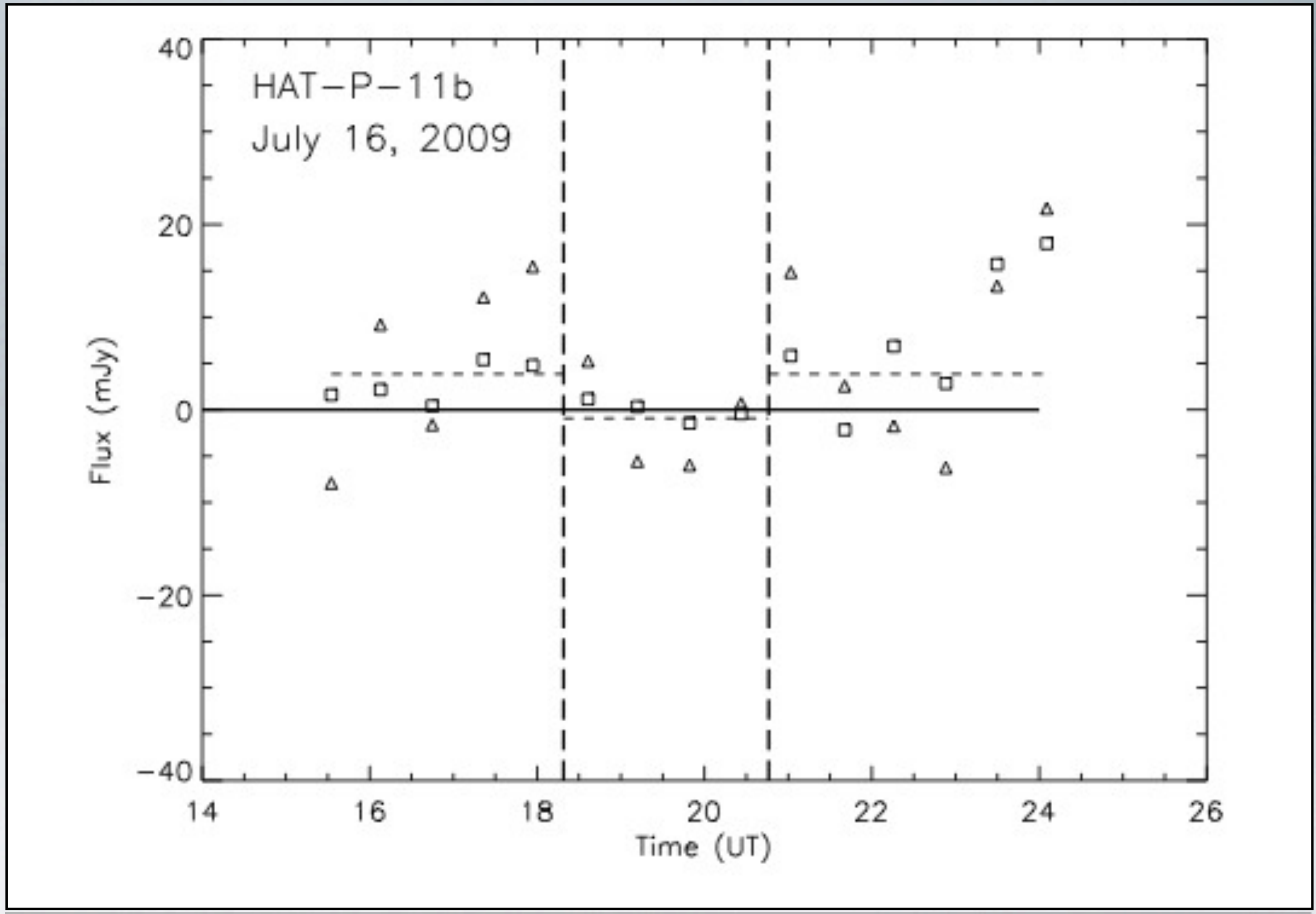
Hess & Zarka, 2011
Nichols, 2011, 2012
Noyola et al., 2013...

HAT-P-11b

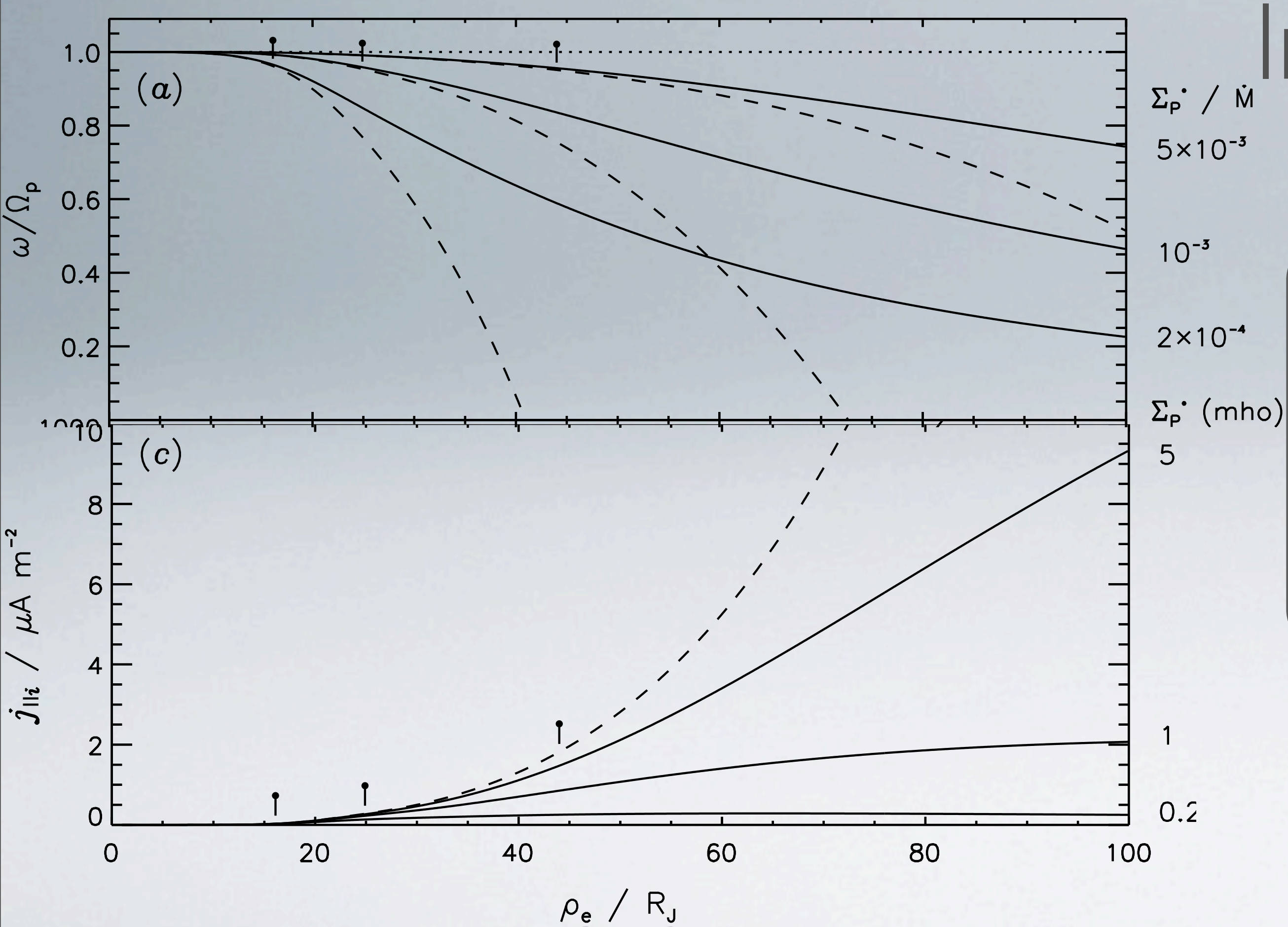


Lecavelier des Etangs et al., 2013

A third mechanism: rotation

Momentum equation

$$\frac{\rho_e}{2}\frac{d}{d\rho_e}\left(\frac{\omega}{\Omega_J}\right)+\left(\frac{\omega}{\Omega_J}\right)=\frac{4\pi\Sigma_P^{*}F_e|B_{ze}|}{\dot{M}}\left(1-\frac{\omega}{\Omega_J}\right)$$



Inner region approximations:

$$\left(\frac{\omega}{\Omega_J}\right)_S = 1-\frac{1}{2}\left(\frac{\rho_e}{R_{CSe}}\right) \qquad R_{CSe}=\left(\frac{2\pi\Sigma_P^{*}B_{\circ}F_{\circ}}{\dot{M}}\right)^{\frac{1}{m}}$$

$$j_{\|i\,S}=-\frac{\dot{M}\Omega_p B_{eq}}{\pi\rho_e|B_{ze}|^3}\frac{d|B_{ze}|}{d\rho_e}$$

From Nichols and Cowley [2003]

High conductance = near-rigid corotation

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Computation of radio flux density

Limiting conductance required for rigid corotation

$$\Sigma^*_{P\ lim} \approx 0.956 \frac{\dot{M}}{B_\circ F_\circ} \left(\frac{R_{mp}}{R_p}\right)^m$$

How does conductance depend on distance from the star?

$$\Sigma^*_P = \left(\frac{L_{EUV\ \mathrm{star}}}{L_{EUV\ \mathrm{sun}}}\right)^{1/2} \frac{2.6}{R_{orb}} + 3$$

Precipitating electron energy flux converted to beamed radio power output with bandwidth equal to the electron cyclotron frequency

$$E_{fS} = \frac{E_{f\circ}}{2} \left(\frac{j_{||i}}{j_{||i\circ}}\right)^2$$

$$P_e = \int_0^{90} 2\pi {R_J}^2 \sin\theta_i \; E_f \; d\,\theta_i$$

$$P_r = \frac{P_e}{100}$$

$$F_r = \frac{P_r}{1.6 s^2 \Delta\nu} \qquad \Delta\nu = \frac{e B_{eq}}{\pi m_e}$$

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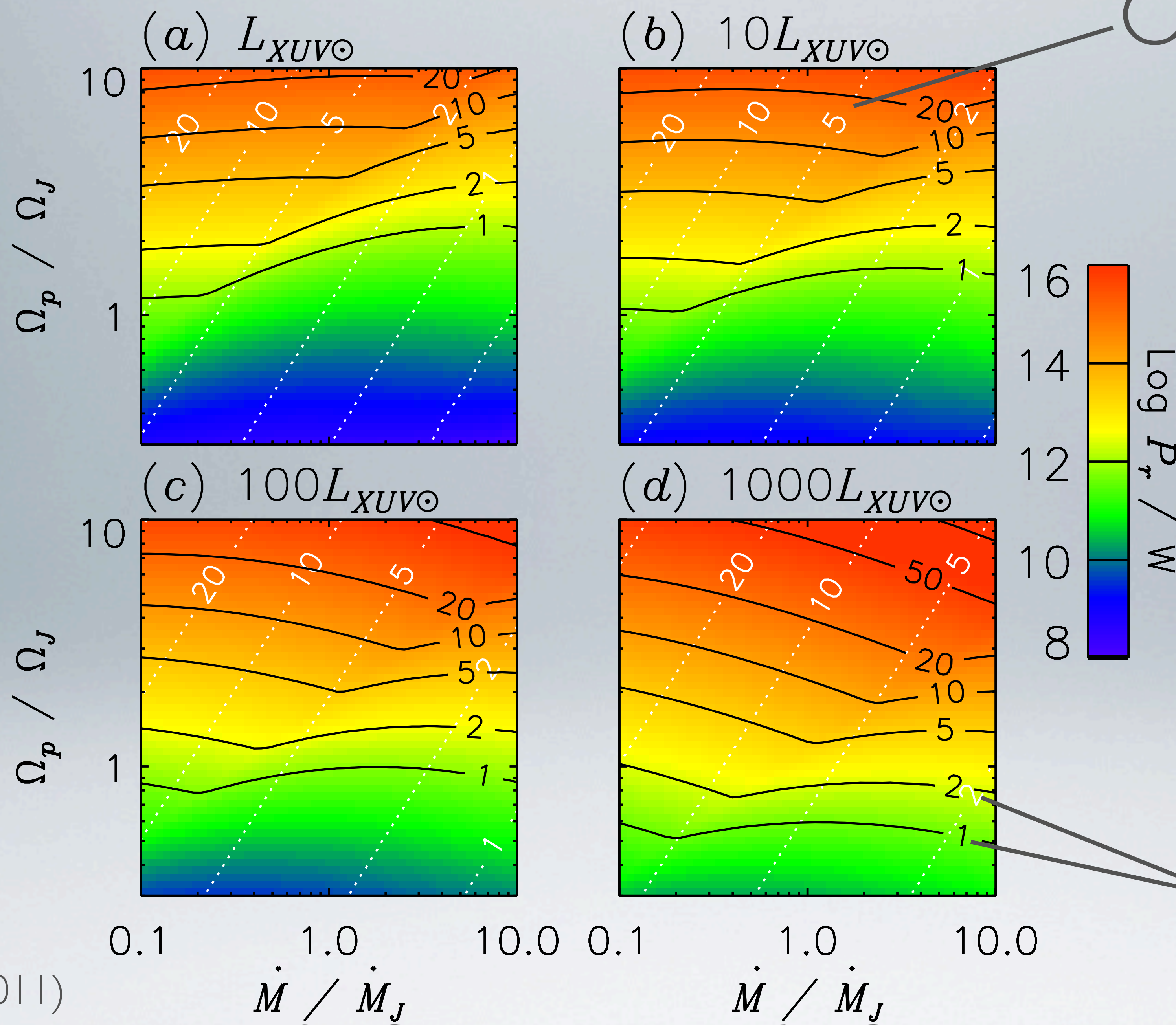
Results over larger parameter space



Orbital radius in AU

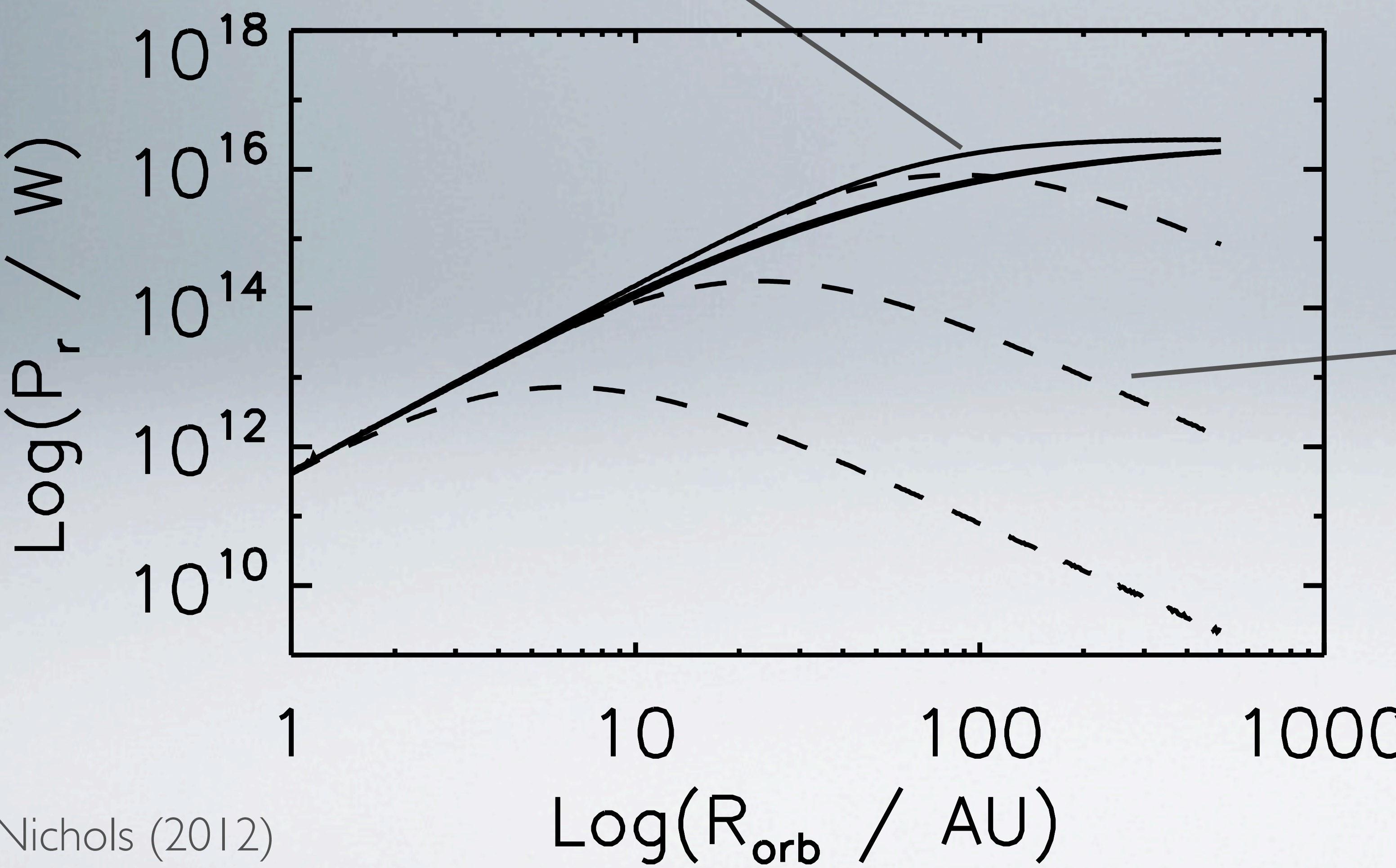
Maximum observable distance in pc

Nichols (2011)

University of Leicester

Mass 10 M_J, Angular velocity Ω_J

Including auroral precipitation-induced conductivity



Stellar XUV-induced conductivity only

Nichols (2012)

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Results

<u>40</u> stars within 25 pc, which have planets and measured or estimated values of Lx

					$\mathcal{F}$ / mJy							
					B_{eq} Nichols (2011)				B_{eq} Reiners et al. (2010), $10M_J$			
					$p_{sw\odot}$		$100p_{sw\odot}$		$p_{sw\odot}$		$100p_{sw\odot}$	
Alias	Sp. Type	s/pc	dec	$\mathrm{Log}(L_X/\mathrm{W})$	$\Omega_p/\Omega_J =$ 1	3	$\Omega_p/\Omega_J =$ 1	3	$\Omega_p/\Omega_J =$ 1	3	$\Omega_p/\Omega_J =$ 1	3
V* eps Eri	K2V	3.2	-9.5	21.32 (R)	0.61	18.21	0.49	11.63	31.43	282.87	5.10	45.93
HIP 85523	M2+V	4.5	-46.9	20.53 (R)	0.30	9.04	0.24	5.78	15.62	140.56	2.55	22.95
V* IL Aqr	M3.5V	4.7	-14.3	19.49 (R)	0.28	8.38	0.23	5.37	14.49	130.42	2.37	21.35
LHS 3685	M2/3V	4.9	-49.0	19.77 (R)	0.25	7.59	0.21	4.86	13.13	118.19	2.15	19.33
LHS 349	G5V	8.5	-18.3	19.87 (R)	0.08	2.55	0.07	1.64	4.42	39.75	0.72	6.50
HR 7722	K3V	8.8	-27.0	20.23 (R)	0.08	2.39	0.06	1.53	4.13	37.15	0.67	6.07
LHS 311	G3/5V	9.2	-40.5	19.78 (R)	0.07	2.17	0.06	1.39	3.75	33.78	0.61	5.53
LHS 310	M3V	10.2	26.7	19.84 (R)	0.06	1.77	0.05	1.13	3.06	27.56	0.50	4.51
LHS 3257	M1V	10.3	25.7	19.25 (S)	0.06	1.74	0.05	1.11	3.00	27.03	0.49	4.43
HD 13445	K1V	10.9	-50.8	20.61 (R)	0.05	1.57	0.04	1.00	2.71	24.36	0.44	3.98

Nichols (2012)

University of Leicester

Results

51 stars within 25 pc, which have measured or estimated values of Lx > 100 x solar

Alias	Sp. Type	s/pc	dec	Log(L_X/W)	$\mathcal{F}$ / mJy							
					B_{eq} Nichols (2011)				B_{eq} Reiners et al. (2010), $10M_J$			
					$p_{sw\odot}$		$100p_{sw\odot}$		$p_{sw\odot}$		$100p_{sw\odot}$	
					$\Omega_p/\Omega_J =$		$\Omega_p/\Omega_J =$		$\Omega_p/\Omega_J =$		$\Omega_p/\Omega_J =$	
					1	3	1	3	1	3	1	3
CPD-28 332	F9-V	8.7	-28.2	22.66 (R)	0.19	3.31	0.07	1.71	4.64	41.77	0.73	6.54
V* FF And	M0VEP	8.6	-20.6	22.38 (R)	0.15	2.84	0.07	1.69	4.59	41.34	0.73	6.56
V* AT Mic	M1VE	9.9	-31.3	22.74 (R)	0.15	2.55	0.06	1.32	3.57	32.14	0.56	5.03
V* AK Pic	M4.0V	10.2	-32.4	22.55 (R)	0.13	2.25	0.05	1.23	3.34	30.03	0.52	4.72
V* BY Dra	M0VP	11.5	-43.8	22.60 (R)	0.10	1.78	0.04	0.97	2.64	23.72	0.41	3.73
V* V834 Tau	G0V	12.8	47.7	22.70 (R)	0.09	1.55	0.03	0.80	2.17	19.51	0.34	3.05
HIP 61941B	F1V+F0	11.8	-1.4	22.42 (R)	0.08	1.51	0.04	0.90	2.45	22.05	0.39	3.50
V* OU Gem	G0V	21.7	33.9	23.66 (R)	0.10	1.36	0.01	0.33	0.92	8.24	0.13	1.17
V* V775 Her	K4Vke	13.5	20.9	22.57 (R)	0.07	1.29	0.03	0.71	1.92	17.27	0.30	2.72
* tet Boo	F8V	14.6	51.9	22.63 (R)	0.06	1.11	0.03	0.61	1.64	14.80	0.26	2.33

Nichols (2012)

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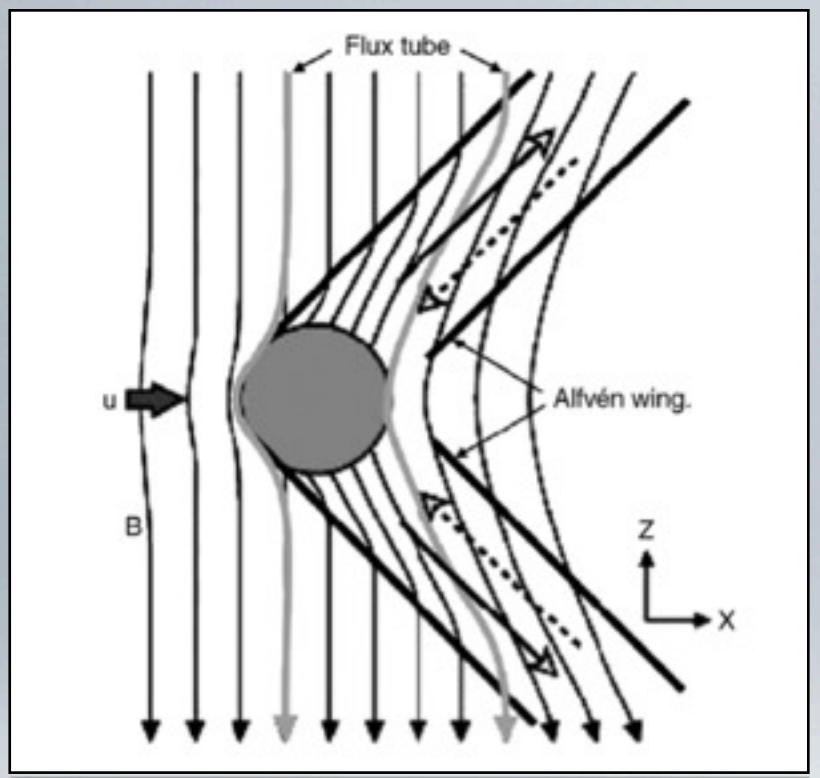
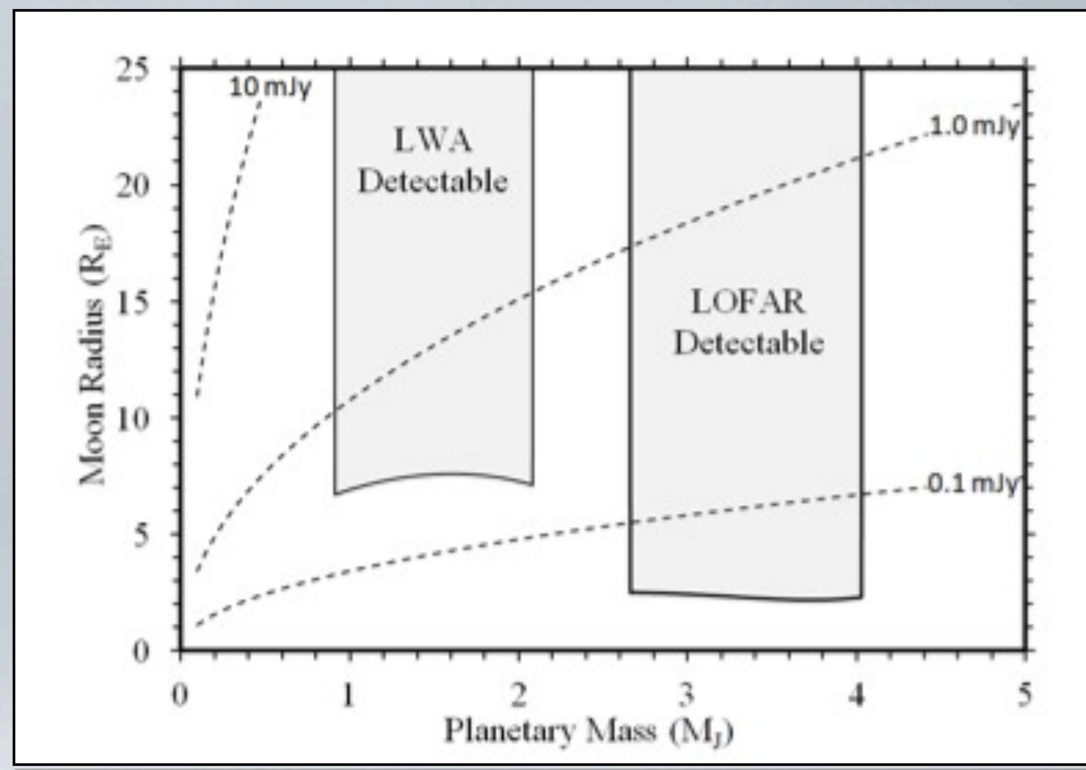
Io-Jupiter-type interaction





Noyola et al., 2013

Nichols (2012)

LOFAR observations underway...

Ups Andromeda
Eps Eridani
Tau Bootes
HAT-P-11
HD 189733
Corot-7

Watch this space...

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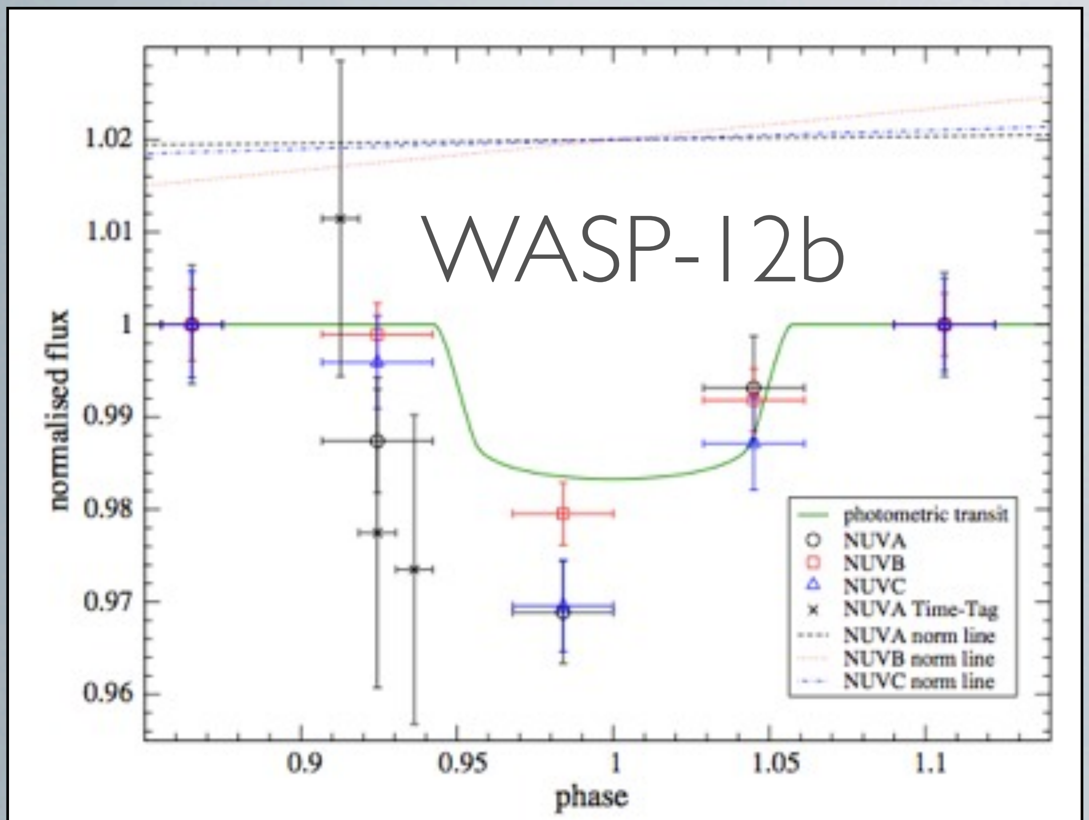
NUV transits may also reveal B field



Fossati et al., 2010

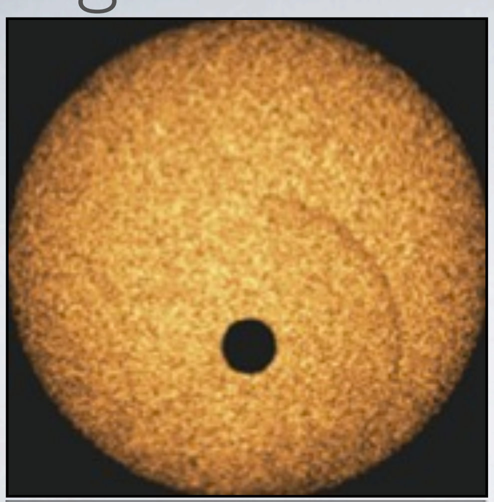
Excited much discussion...

Lai et al., 2010
Vidotto et al., 2010, 2011
Llama et al., 2011
Haswell et al., 2012
Bisikalo et al., 2013
Turner et al. ,2013

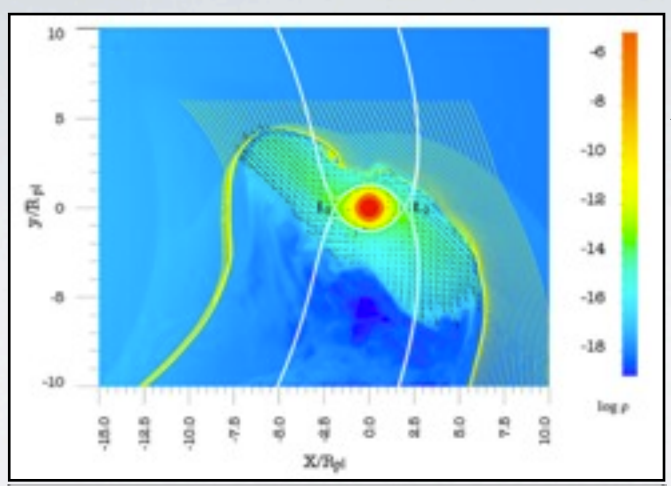
Magnetosheath

Outflow

Llama et al., 2011



vs.



Bisikalo et al., 2013

This October: 20 HST/COS orbits scheduled to observe 4 NUV transits of WASP-12b.

Again, watch this space...

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Summary

- Ultra-cool dwarfs are magnetised, with myriad implications.
- ~10% exhibit radio emissions. Most quiescent (synchrotron or depolarised CMI emission), some bursty (CMI). Fast rotation is important.
- Showed that a Jupiter-like M-I coupling current system is consistent with observations. Indicates interaction with ISM or satellite plasma source.
- Close-orbiting, or fast rotating more distant orbiting exoplanets may exhibit detectable emissions. LOFAR search underway.
- Auroral emission or asymmetric transits may offer further clues.

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