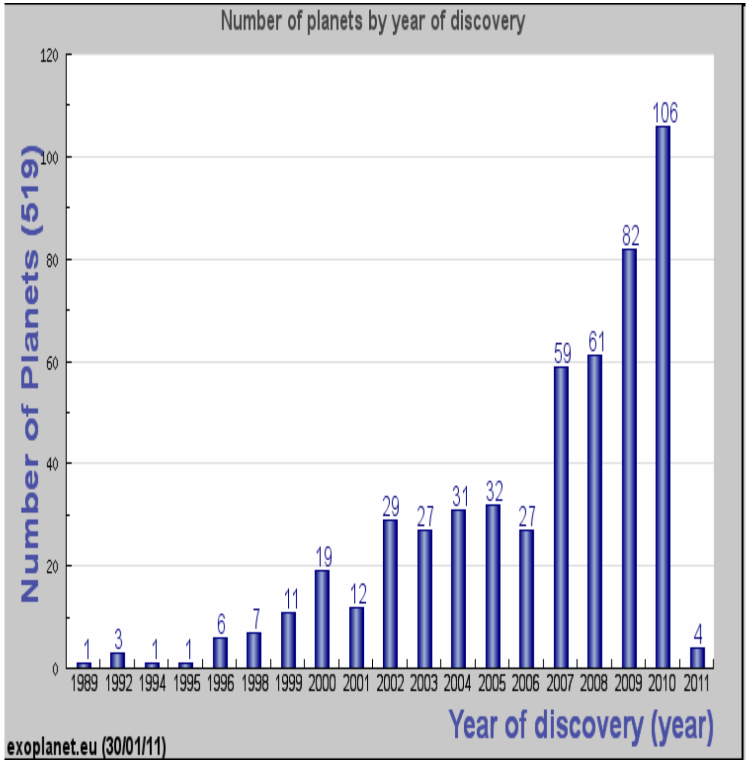
ОБ ОСОБЕННОСТЯХ МАГНИТОСФЕР ГОРЯЧИХ ЭКЗОПЛАНЕТ-ГИГАНТОВ

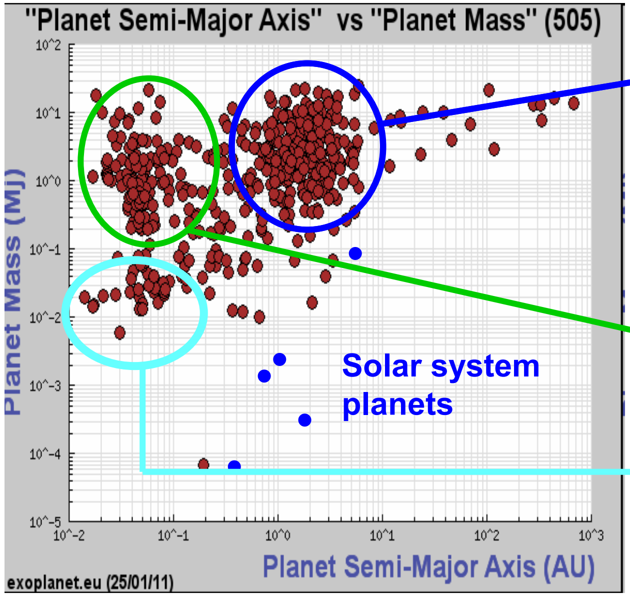
M. L. Khodachenko [1], I. I. Alexeev [2], H. Lammer [1],
E. Belenkaya [2], J.-M. Grießmeier [3]

(1) Space Research Institute, Austrian Academy of Sciences, Graz, Austria,
(2) Institute of Nuclear Physics, Moscow State University, Moscow, Russia,
(3) LPC2E Orleans France

➢ Exoplanet – Status Jan. 2011



- 435 Exoplanetary systems
- 519 Exoplanets
- 54 Multiple Planetary systems



usual Giants

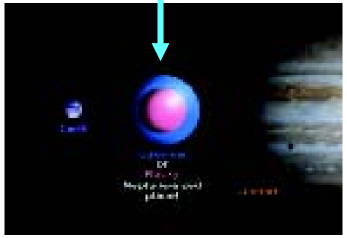
Hot Jupiters

$(0.5\text{-}1{,}75)M_J$

136 (27%)

? Evolution of planets

? Formation of terrestrial type worlds

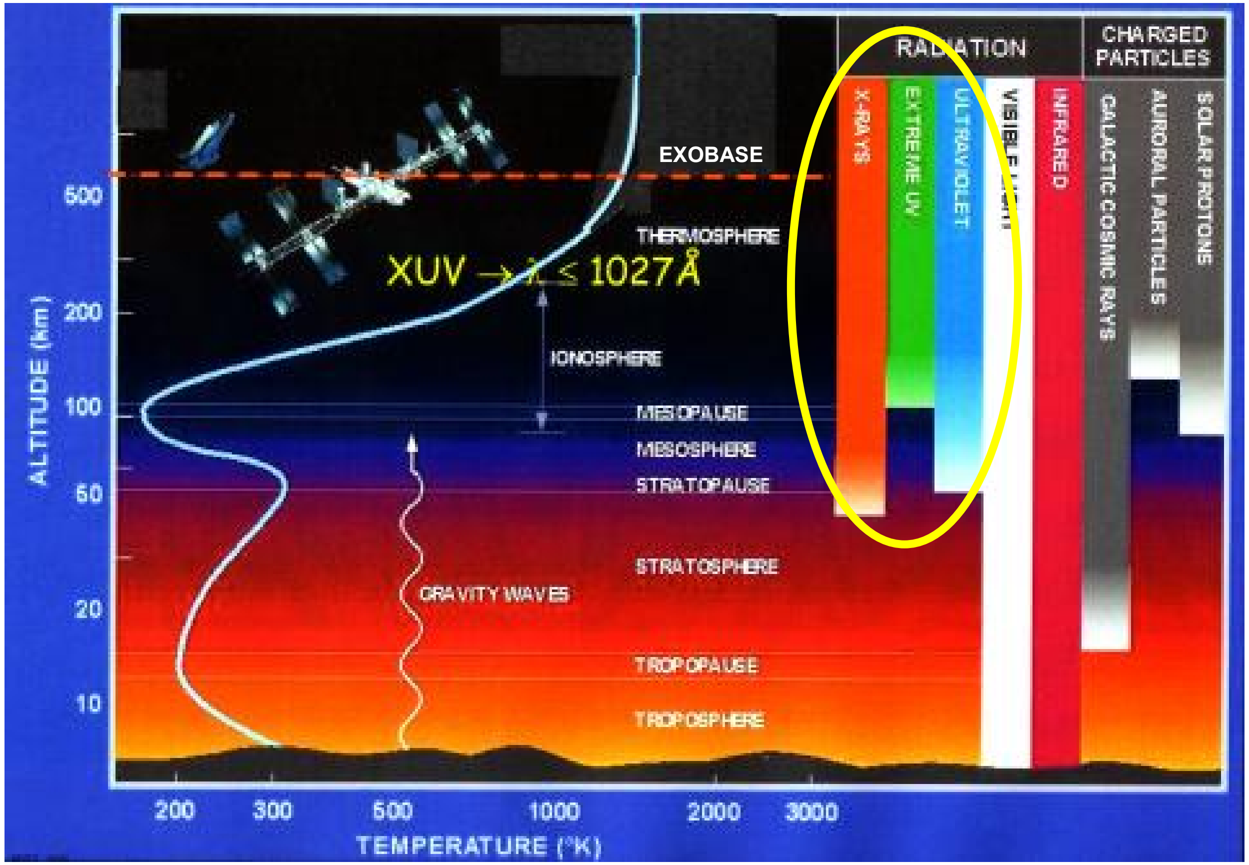


- 28 planets, $<10\ m_{\text{Earth}}$
- 9 planets, $<5\ m_{\text{Earth}}$

Super-Earths ?

➢ Exploplanet evolution – mass loss

- **Stellar X-ray and EUV induced expansion of the upper atmospheres**
  - ♦ Stellar XUV luminosity → **energy deposition to upper atmospheres**



➢ Exoplanet evolution – mass loss

- **Soft X-ray and EUV induced expansion of the upper atmospheres**

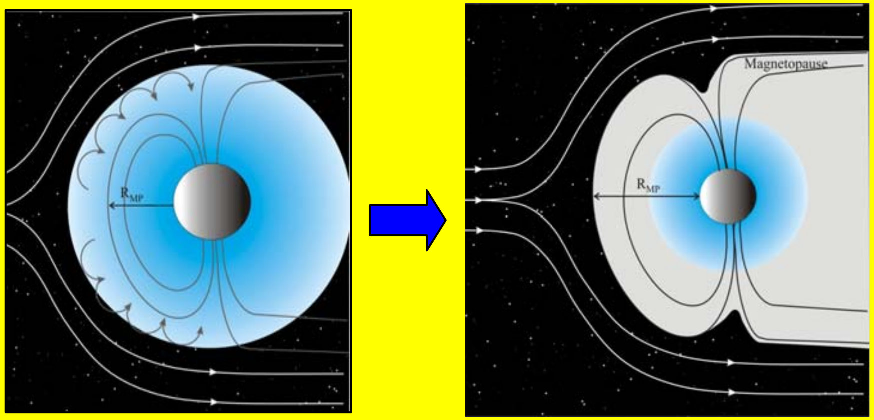
  ⇒ high ***thermal*** & ***non-thermal*** loss rates

  ♦ **Thermal escape:** particle energy > W_{ESC}

  → Jeans escape – particles from "tails"
  → hydrodynamic escape – all particles

The size of magnetosphere is a crucial parameter

Magnetically protected planet

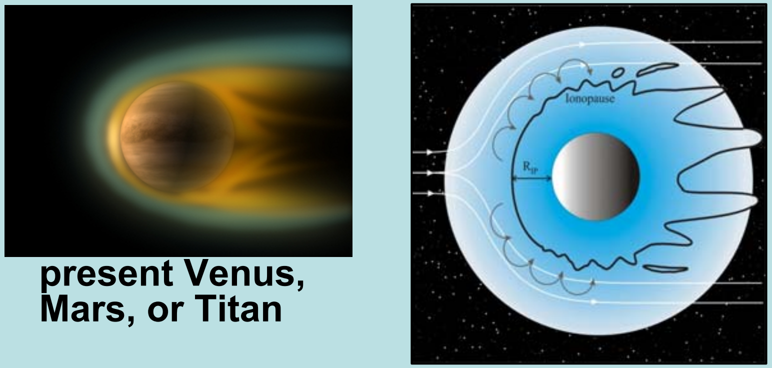


Early Earth **present Earth**

♦ **Non-thermal escape:**

→ Ion pick-up
→ Sputtering (S.W. protons & ions)
→ Photo-chemical energizing & escape
→ Electromagnetic ion acceleration

Magnetically non-protected planet



present Venus, Mars, or Titan

➢ Exoplanet magnetic fields – role in planet protection

- **Magnetic moment estimation from scaling laws** → range for possible ***M***

$$M \propto \rho_c^{1/2}\, \omega r_c^4$$

$$M \propto \rho_c^{1/2}\, \omega^{1/2}\, r_c^3\, \sigma^{-1/2}$$

$$M \propto \rho_c^{1/2}\, \omega^{3/4}\, r_c^{7/2}\, \sigma^{-1/4}$$

$$M \propto \rho_c^{1/2}\, \omega^{1/2}\, r_c^3\, \sigma^{-1/2}$$

$$M \propto \rho_c^{1/2}\, \omega r_c^{7/2}$$

$\Rightarrow$

Interval of possible values for planetary magnetic dipole:

$$M_{max} \ldots M_{min}$$

J.-M. Grießmeier, A&A, 2004, 425, 753
J.-M. Grießmeier,Astrobiology, 2005,5

r_c - radius of the dynamo region (“core radius”): $r_c \sim M_P^{0.75} R_P^{-0.96}$

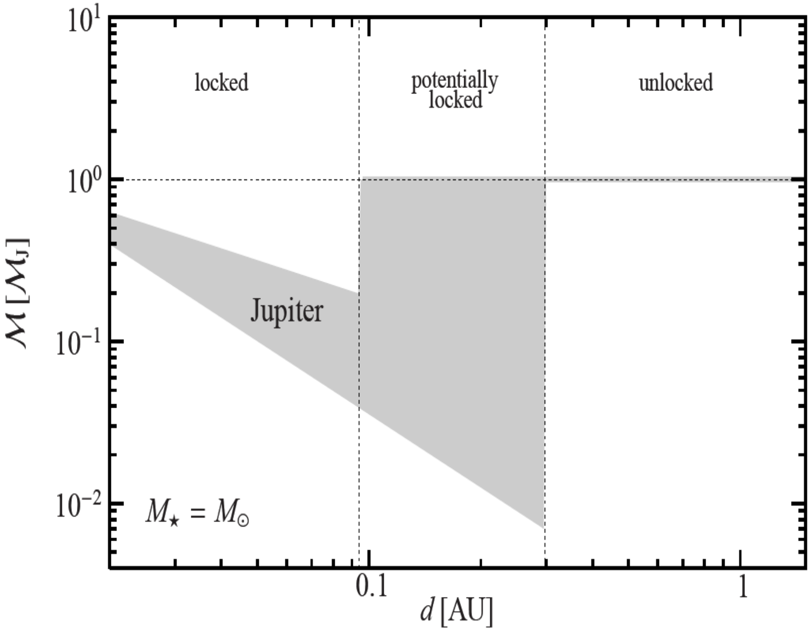
ρ_c - density in the dynamo region

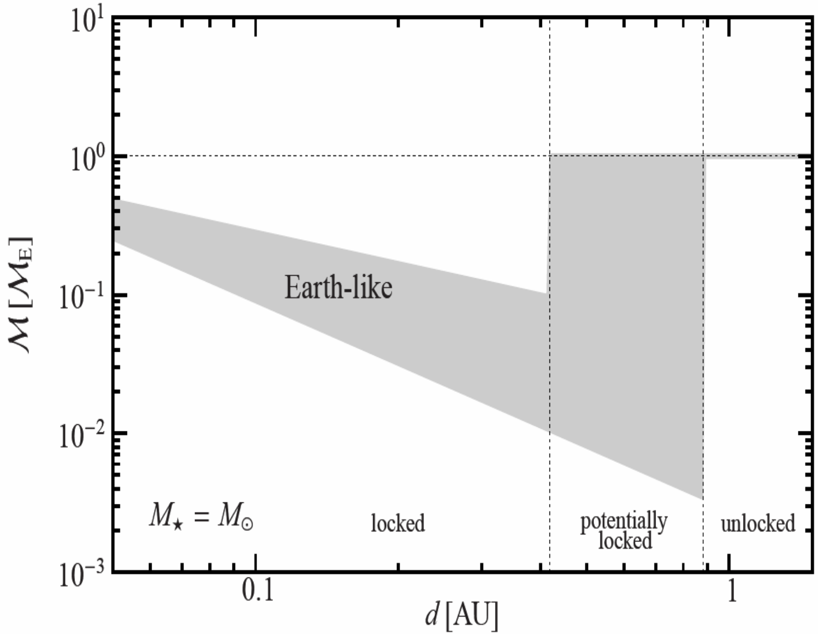
σ - conductivity in the dynamo region

ω - planet angular rotation velocity

➢ Exoplanet magnetic fields – role in planet protection

- **Magnetic moment estimation from scaling laws** → range for possible ***M***
  - ♦ Limitation of ***M*** by tidal locking [**Grießmeier, J.-M., et al., *Astrobiology*, 5(5), 587, 2005**]





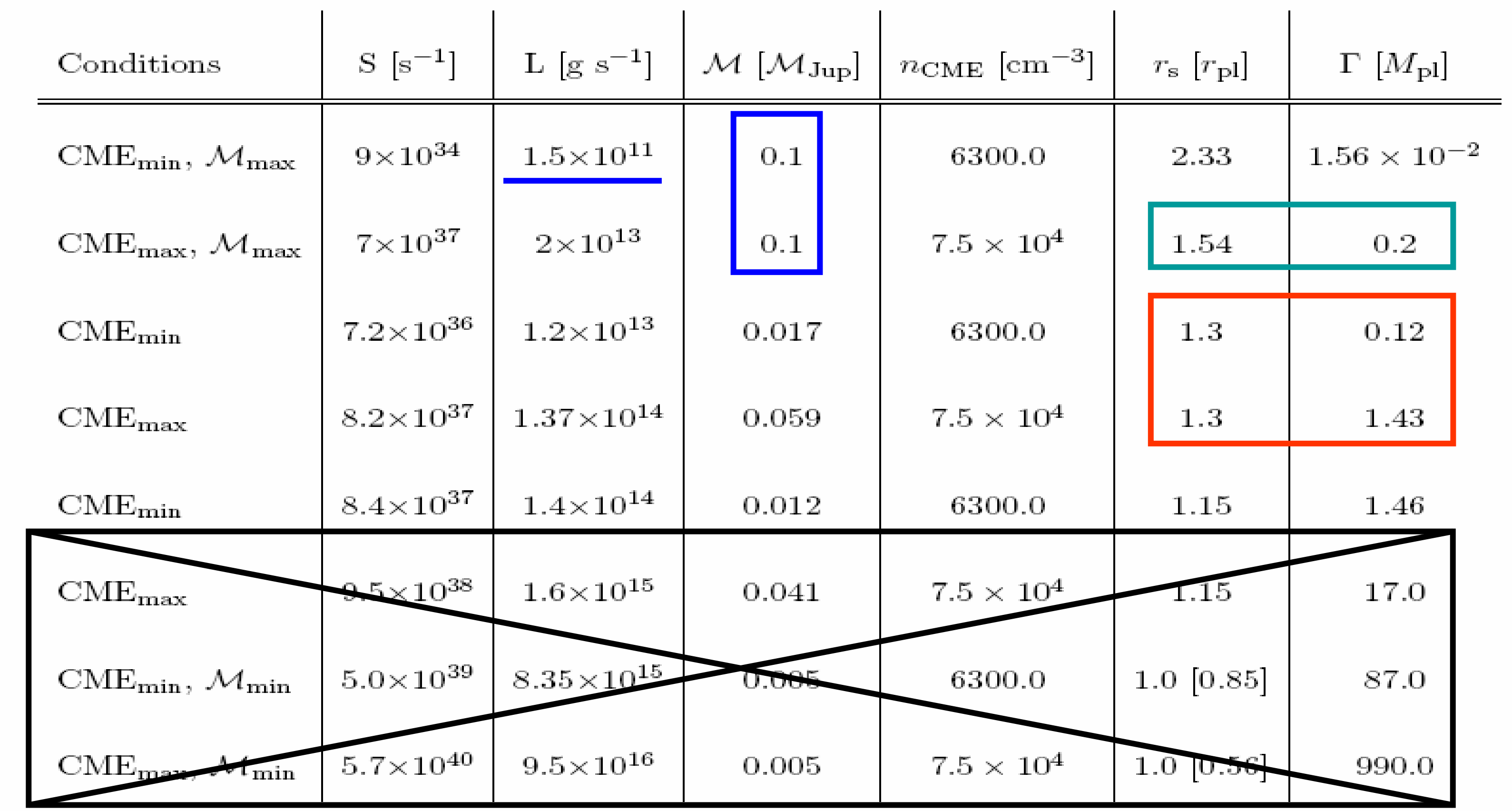
Tidal locking ⇒ strongly reduced magnetic moments

➢ Exoplanet magnetic fields – role in planet protection

- **Magnetospheric protection of evaporating/eroded planetary atmospheres**

Khodachenko et al., PSS, 55, 631, 2007; Khodachenko et al., Astrobiology, 7, 167, 2007

♦ CME induced H^+ ion pick-up loss at 0.05 AU for ‘Hot Jupiters’ → HD209458 b



Conditions	S [s^{-1}]	L [$g\ s^{-1}$]	$\mathcal{M}$ [$\mathcal{M}_{Jup}$]	n_{CME} [cm^{-3}]	r_s [r_{pl}]	Γ [M_{pl}]
CME_{min}, $\mathcal{M}_{max}$	9×10^{34}	1.5×10^{11}	0.1	6300.0	2.33	1.56×10^{-2}
CME_{max}, $\mathcal{M}_{max}$	7×10^{37}	2×10^{13}	0.1	7.5×10^4	1.54	0.2
CME_{min}	7.2×10^{36}	1.2×10^{13}	0.017	6300.0	1.3	0.12
CME_{max}	8.2×10^{37}	1.37×10^{14}	0.059	7.5×10^4	1.3	1.43
CME_{min}	8.4×10^{37}	1.4×10^{14}	0.012	6300.0	1.15	1.46
CME_{max}	9.5×10^{38}	1.6×10^{15}	0.041	7.5×10^4	1.15	17.0
CME_{min}, $\mathcal{M}_{min}$	5.0×10^{39}	8.35×10^{15}	0.005	6300.0	1.0 [0.85]	87.0
CME_{max}, $\mathcal{M}_{min}$	5.7×10^{40}	9.5×10^{16}	0.005	7.5×10^4	1.0 [0.56]	990.0

Mass loss ~10^{11} g/s even for weak CMEs & M_{max} ⇒ *strong magn. protection* in reality

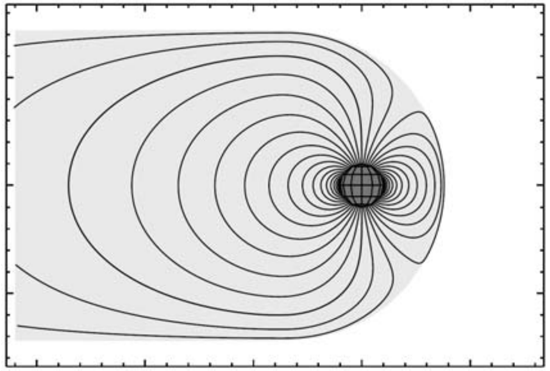
➢ Exoplanet magnetospheres – importance of magnetodisk

- **Relatively large amount of observed Hot Jupiters (27%):**
  ”survival” of close-in giants indicates their efficient protection against of extreme plasma and radiation conditions

- **All estimations were based on too simplified model**
  Magnetospheric protection of exoplanets was studied assuming a simple planetary dipole dominated magnetosphere

  → dipole mag. field $\mathbf{B} = \mathbf{B}_{dip} \sim M / r^3$ balances stellar wind ram pressure

  → big ***M*** are needed for the efficient protection (but tidal locking → small ***M*** → small $\mathbf{R}_s$)



J.-M. Grießmeier, A&A, 2004, 425, 753

- **Specifics of close-in exoplanets → new model**

  → strong mass loss of a planet should lead to *formation of a plasma disk* (similar to Jupiter and Saturn) → Magnetodisk dominated magnitosphere

  → more complete planetary magnetosphere model, including the whole complex of the magnetospheric electric current systems

➢ Exoplanet magnetospheres – importance of magnetodisk

- **Paraboloid Magnetospheirc Model (PMM) for 'Hot Jupiters'**
  Semi-analytical model. Key assumption: magnetopause is *approximated by* <u>*paraboloid of revolution*</u> along planet-star ($\boldsymbol{V}_{SW}$) line

  ♦ **PMM considers mag. field of different current systems** on the boundaries and within the boundaries of a planetary magnetopause:

  → planetary ***magnetic dipole***;

  → current system of ***magnetotail***;

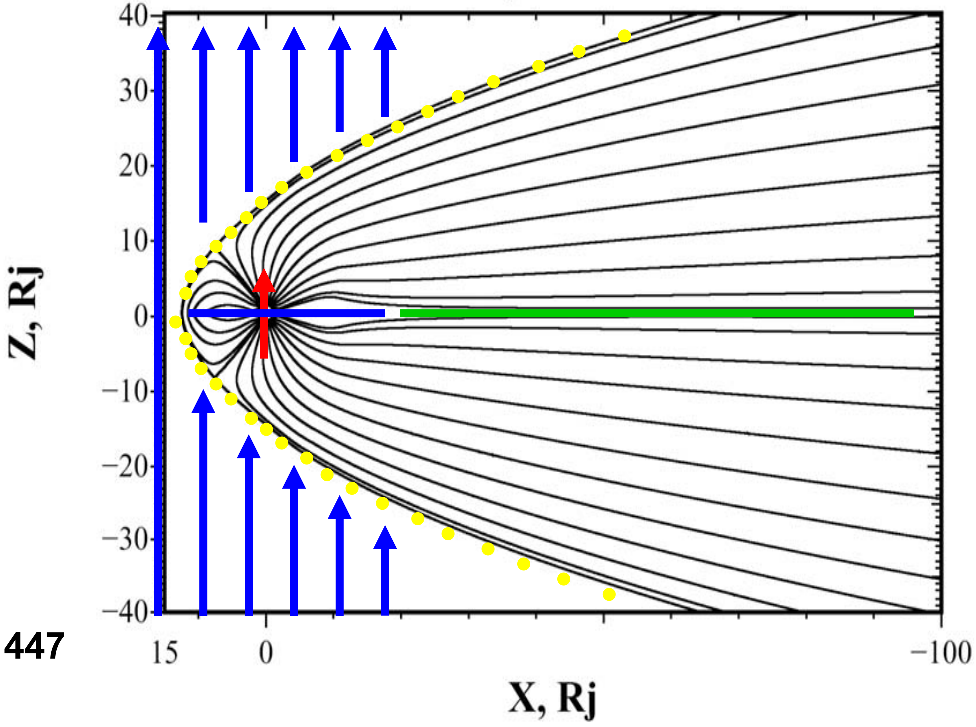
  → ***magnetodisk***;

  → ***magnetopause*** currents;

  → ***magnetic field of stellar wind***, partially penetrated into the magnetospheric obstacle.

I.Alexeev, Geomag.&Aeronomia, 1978, 18, 447

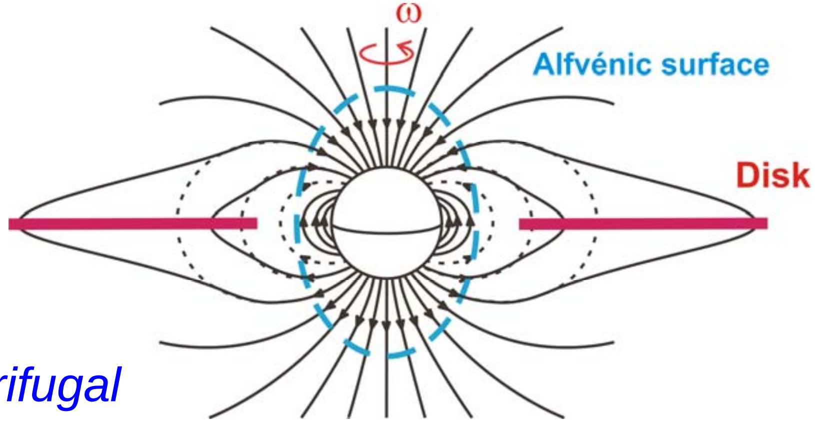
M.Khodachenko et al., ApJ, 2010 (submitted)



➢ Exoplanet magnetospheres – importance of magnetodisk

- **Paraboloid Magnetospheirc Model (PMM) for 'Hot Jupiters'**

♦ **Formation of magnetodisk**



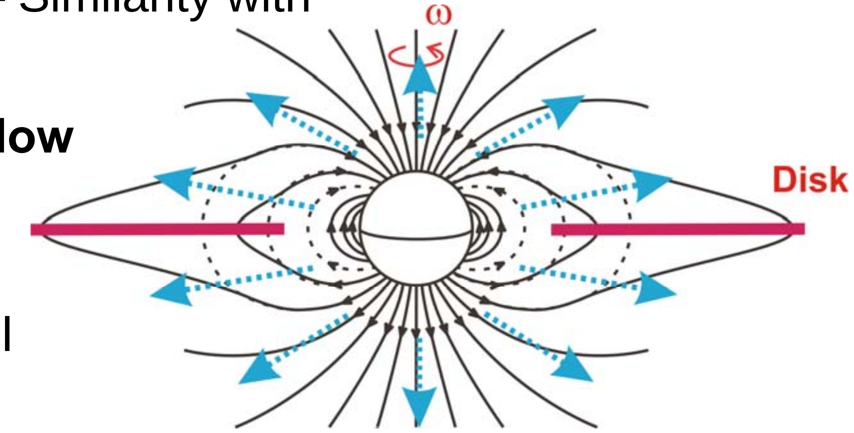
→ **"*sling" model*:**

dipole mag. field can drive plasma
in co-rotation regime only inside
"Alfvenic surface" **($r < R_A$);** → *Centrifugal*
escape of plasma

→ **"material-escape driven" *models*:** → Hydrodynamic escape of plasma

(a) Fully ionized plasma outfow – Similarity with
heliospheric current sheet (disk)

(b) Partially ionized material outflow



Background magn.field (dipole),
charge separation electric field,
ambipolar diffusion, azimuth.Hall
current in equator.plane

➢ Exoplanet magnetospheres – importance of magnetodisk

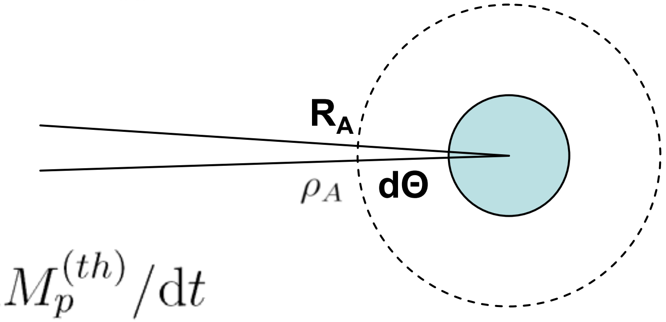
- **Paraboloid Magnetospheirc Model (PMM) for 'Hot Jupiters'**

  - **Formation of magnetodisk – "*sling" model*** (analogy with the Jupiter):

→ ***"Alfvénic surface"*** radius $\mathbf{R_A}$

Co-rotation until $\varepsilon_p = \dfrac{\rho_A \omega_p^2 R_A^2}{2} = \varepsilon_B = \dfrac{M_d^2}{2\mu_0 R_A^6}$, $M_d = \mu_0 \mathcal{M}/(4\pi)$

$\Rightarrow$ ***R_A*** : $\boxed{R_A = \left(\dfrac{M_d^2}{\mu_0 \rho_A \omega_p^2}\right)^{1/8}}$



→ ρ_A is estimated from thermal mass loss $\mathrm{d}M_p^{(th)}/\mathrm{dt}$

$$\rho_A = \frac{\mathrm{d}M_p^{(th)}/\mathrm{dt}}{2\pi R_A^3 \omega_p \delta\theta} \quad \Rightarrow \quad \boxed{\frac{R_A}{r_p} = \left(\frac{2\pi\delta\theta B_{d0}^2 r_p}{\mu_0 \omega_p (\mathrm{d}M_p^{(th)}/\mathrm{dt})}\right)^{1/5}}$$

Increase of ω_p and $\mathrm{d}M_p^{(th)}/\mathrm{dt}$ → decrease of ***R_A***

➢ Exoplanet magnetospheres – importance of magnetodisk

● Paraboloid Magnetospheirc Model (PMM) for ‘Hot Jupiters’

♦ Magnetic field structure in PMM with magnetodisk

→ **r < R$_A$:** magnetic field of dipole (**~*R*$^{-3}$**)

$$\mathbf{B}(r, z = 0) = B_\theta(r)\boldsymbol{\theta}_0 = B_{d0} r_p^3 / r^3 \boldsymbol{\theta}_0$$

→ **r > R$_A$:** conservation of m.flux reconnected across the disc

⇒ m.field of the disk (and current density) **~*R*$^{-2}$**

$$\mathbf{B}(r, z \sim 0) = B_r(r)\, \mathbf{r_0} = B_{d0} r_p^3 / (R_A r^2)\, \mathbf{r_0}$$

♦ Determination of sub-stellar magnetopause distance:

pressure balance condition

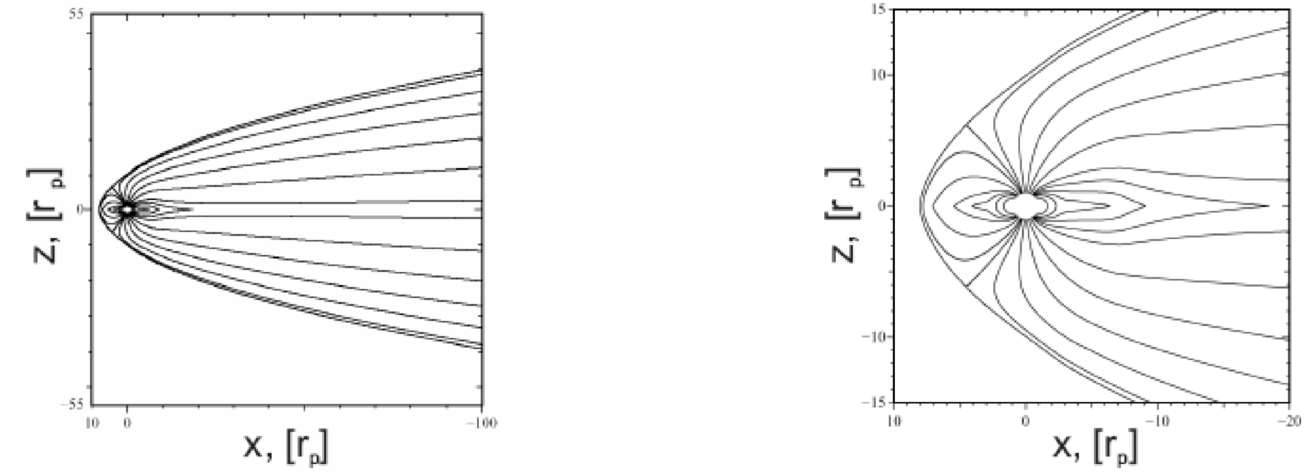
$$\rho_{sw}\tilde{v}_{sw}^2 = \frac{\kappa^2 (B_{ds} + B_{MDs})^2}{2\mu_0} + p_{mp} \Rightarrow \boxed{R_s \sim \frac{B_{d0}^{1/2} r_p^{3/2}}{(2\mu_0 p_{sw})^{1/4} \boxed{R_A^{1/2}}} (1 + \kappa^2)^{1/4}}$$

→ **Decrease of *R*$_A$** ⇒ **increase of *R*$_S$**

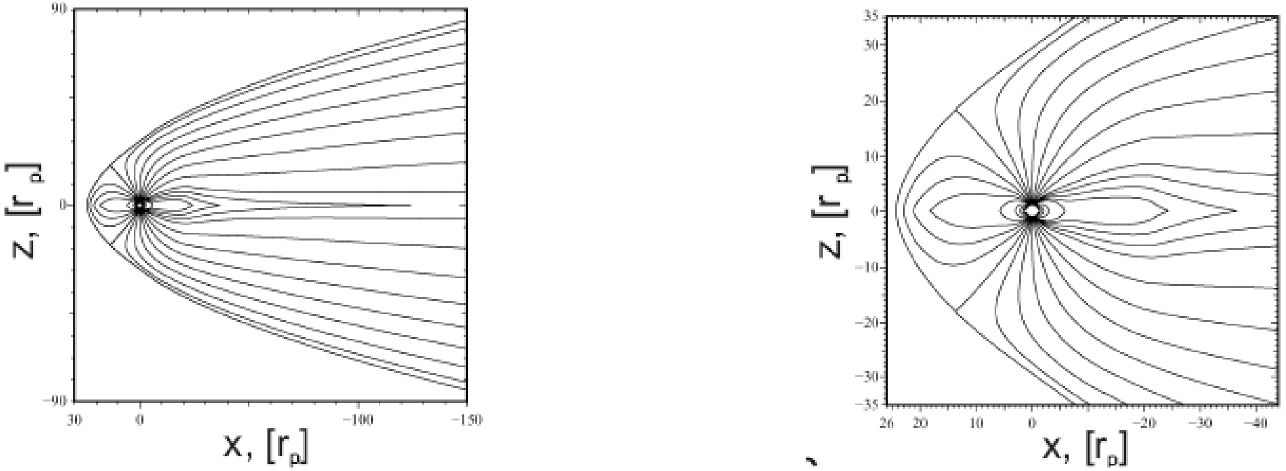
➢ Exoplanet magnetospheres – importance of magnetodisk

- **Paraboloid Magnetospheirc Model (PMM) for 'Hot Jupiters'**

  - **Magnetosphere at 0.045 AU, R_S = 8.0 R_J** (tidally locked)



  - **Magnetosphere at 0.3 AU, R_S = 24.2 R_J** (tidally un-locked)



➢ Exoplanet magnetospheres – importance of magnetodisk

- **Paraboloid Magnetospheirc Model (PMM) for 'Hot Jupiters'**
  - **magnetospheric parameters (estimated and calculated)**

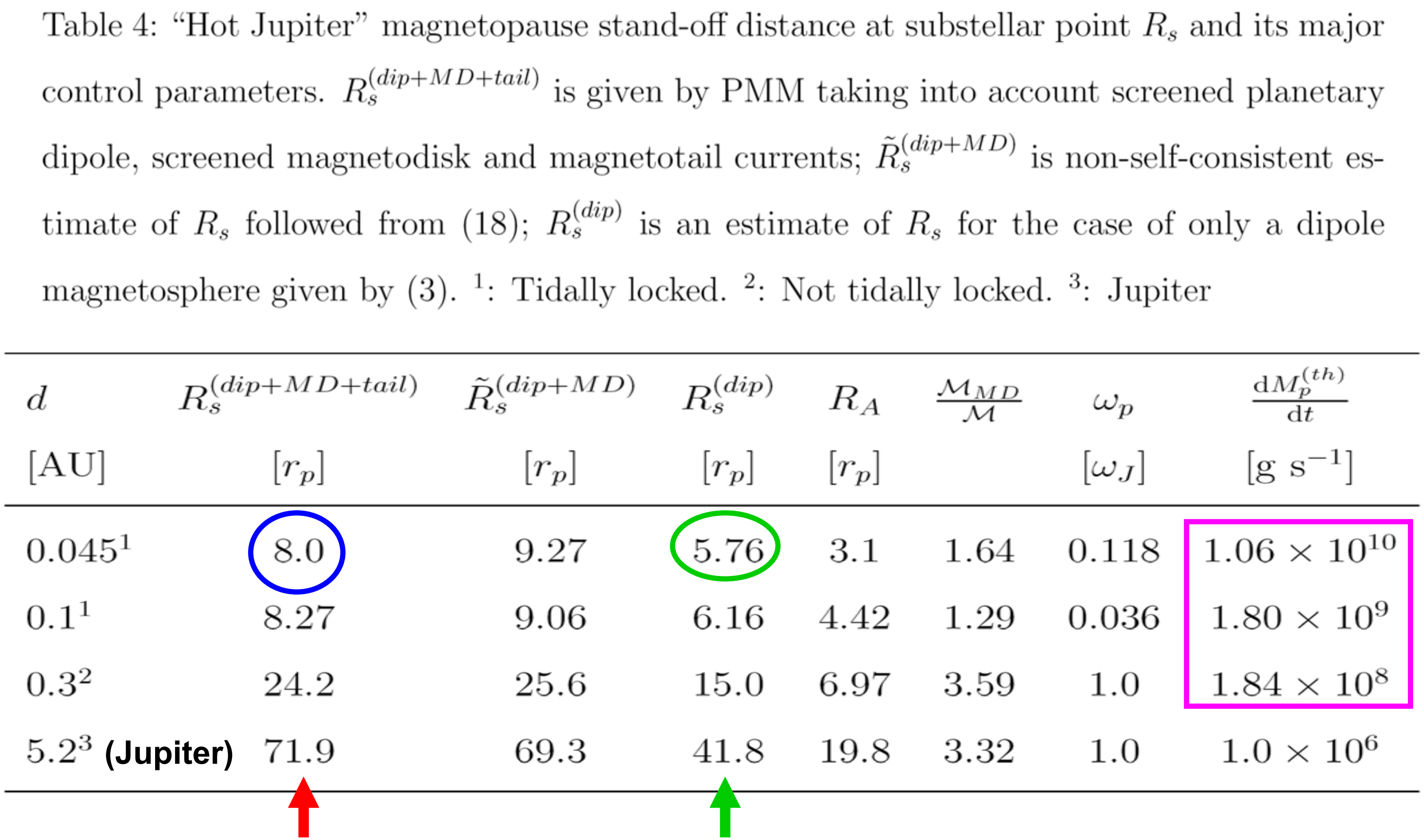


Table 4: "Hot Jupiter" magnetopause stand-off distance at substellar point R_s and its major control parameters. $R_s^{(dip+MD+tail)}$ is given by PMM taking into account screened planetary dipole, screened magnetodisk and magnetotail currents; $\tilde{R}_s^{(dip+MD)}$ is non-self-consistent estimate of R_s followed from (18); $R_s^{(dip)}$ is an estimate of R_s for the case of only a dipole magnetosphere given by (3). ^{1}: Tidally locked. ^{2}: Not tidally locked. ^{3}: Jupiter

d [AU]	$R_s^{(dip+MD+tail)}$ [r_p]	$\tilde{R}_s^{(dip+MD)}$ [r_p]	$R_s^{(dip)}$ [r_p]	R_A [r_p]	$\frac{\mathcal{M}_{MD}}{\mathcal{M}}$	ω_p [ω_J]	$\frac{dM_p^{(th)}}{dt}$ [g s^{-1}]
0.045^1	8.0	9.27	5.76	3.1	1.64	0.118	1.06×10^{10}
0.1^1	8.27	9.06	6.16	4.42	1.29	0.036	1.80×10^{9}
0.3^2	24.2	25.6	15.0	6.97	3.59	1.0	1.84×10^{8}
5.2^3 **(Jupiter)**	71.9	69.3	41.8	19.8	3.32	1.0	1.0×10^{6}

➢ Conclusions

Magnetodisks of close-in giant exoplanets (Hot Jupiters) influence the structure and character of their manetospheres, leading to a new type of „*magnetodisk dominated*“ magnetosphere.

Extended up to (40 – 70) % magnetodisk magnetospheres, as compared the to dipole type ones, may efficiently protect planetary environments, even close to a host star.