Magnetospheres of “Hot Jupiters”:

formation of magnetodisk current system in the escaping plasma flow of an exoplanet

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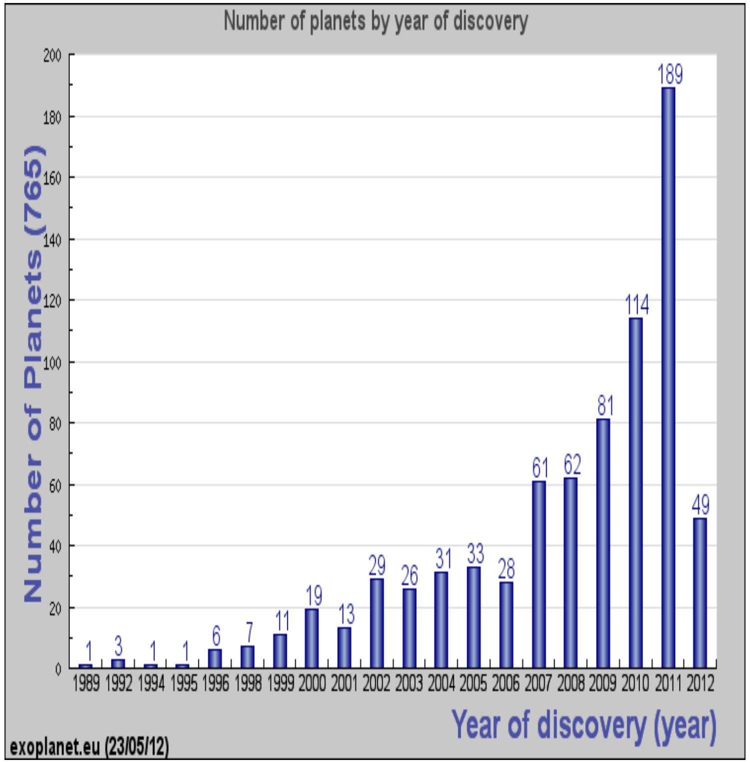
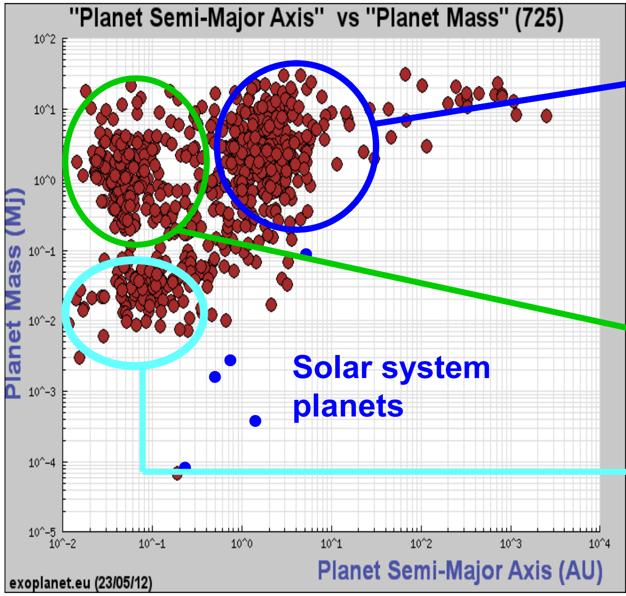
➢ Exoplanet – Status May 2012

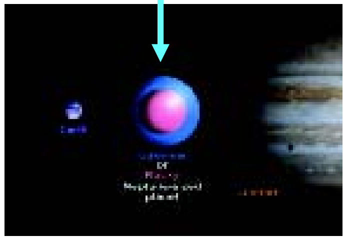




usual Giants

Hot Jupiters
$>0.2\ M_J$
< 0.3 AU
213 (28%)

? Evolution of planets
? Formation of terrestrial type worlds



Super-Earths ?

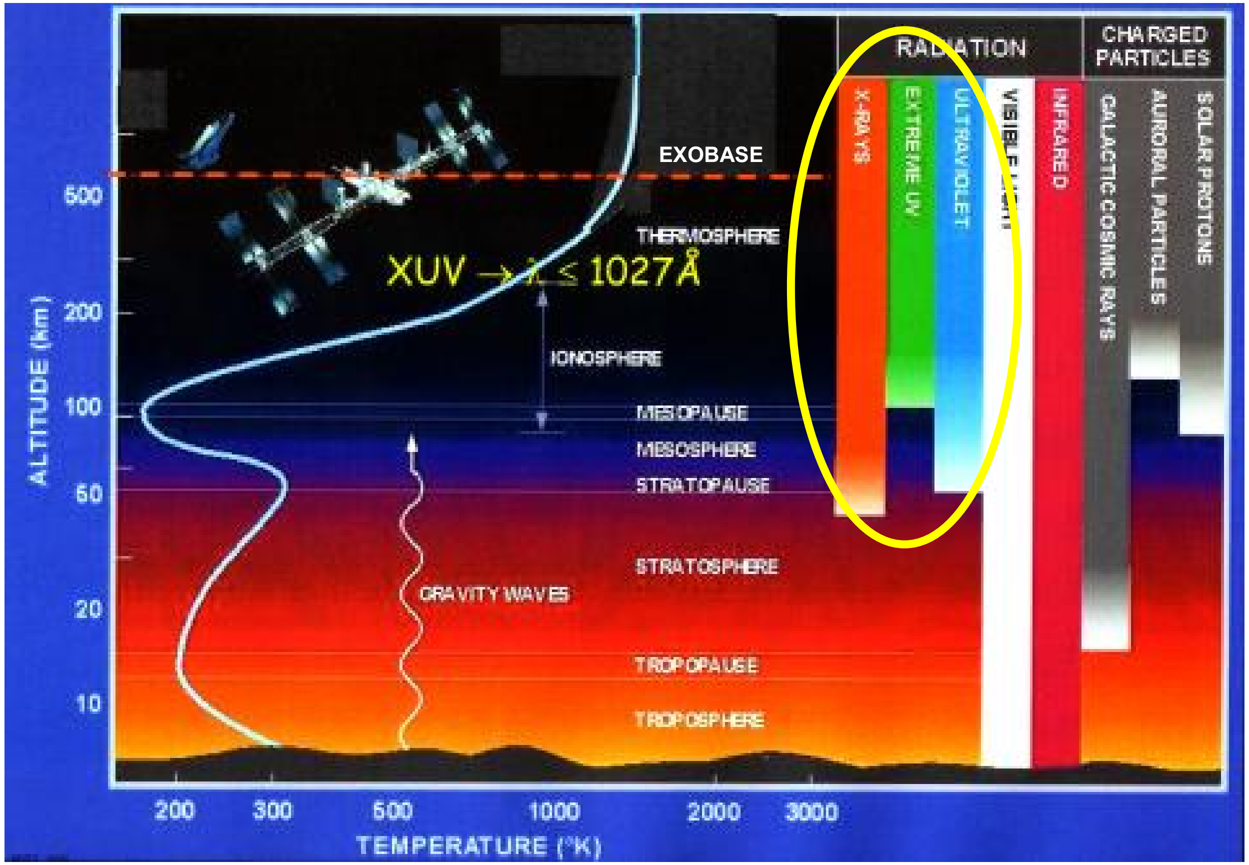
- 612 Exoplanetary systems
- 767 Exoplanets
- 102 Multiple Planetary systems

- 58 planets $<10\ m_{Earth}$
- 25 planets $< 5\ m_{Earth}$

➢ Exoplanet evolution – mass loss of "HJs"

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

  ♦ Stellar XUV luminosity → **energy deposition to upper atmospheres of "HJs"**



➢ Exoplanet evolution – mass loss of “HJs”

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

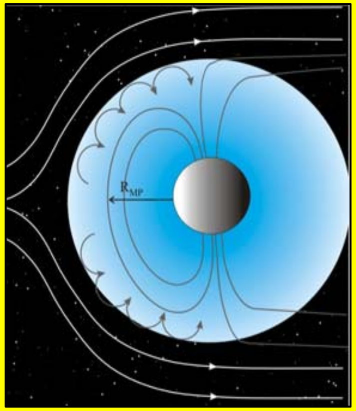
  ⇒ high ***thermal*** & ***non-thermal*** loss rates

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

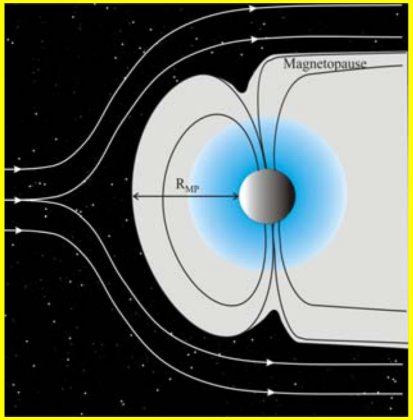
  → Jeans escape – particles from “tails”
  → hydrodynamic escape – all particles

The size of magneto-sphere is a crucial parameter

Magnetically protected planet



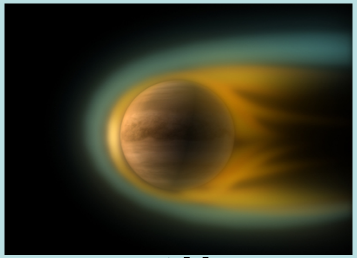
Early Earth



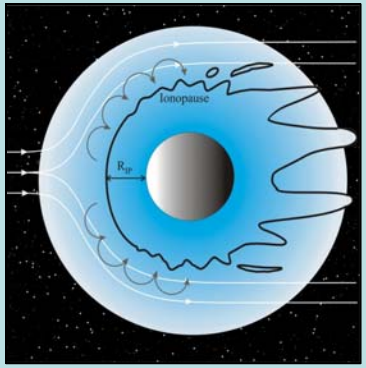
present Earth

♦ **Non-thermal escape:**

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



present Venus, Mars, or Titan



Magnetically non-protected planet

➢ 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:

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

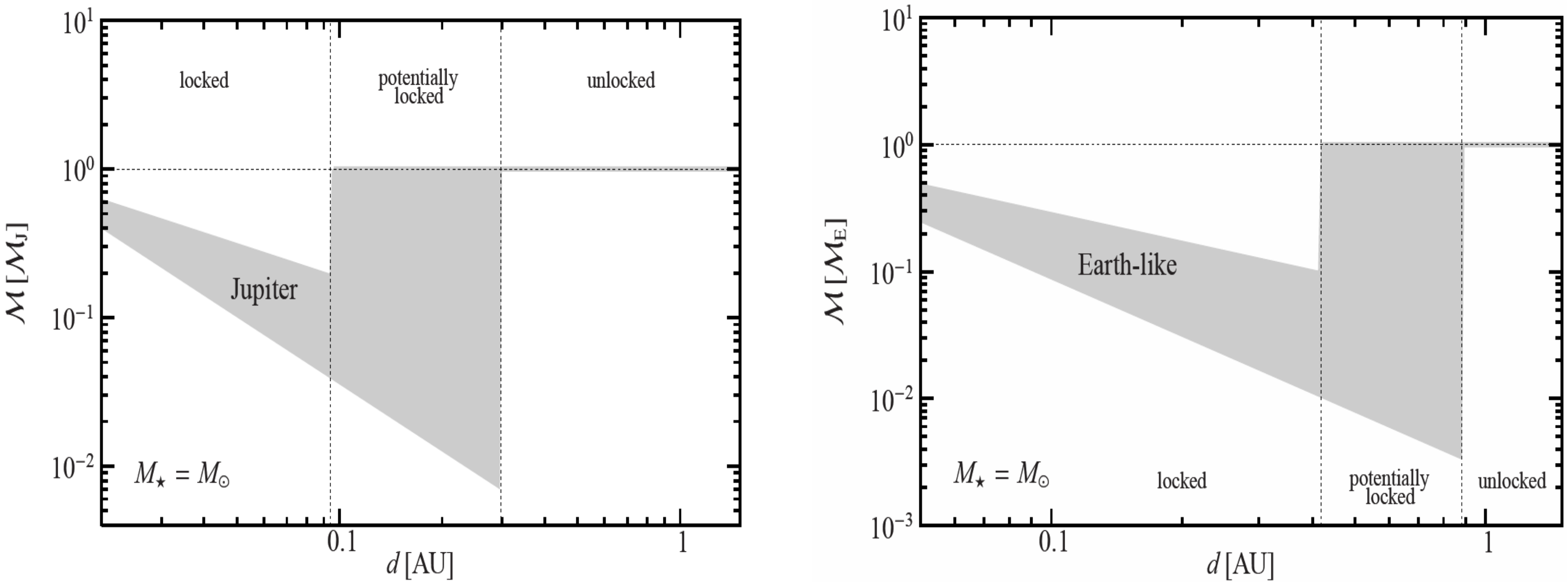
J.-M. Grießmeier, A&A, 2004, 425, 753
J.-M. Grießmeier,Astrobiology, 2005,5

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

- **Non-thermal mass loss of a Hot Jupiter with a dipole type magnetosphere (a problem of protection against of strong atm. erosion)**

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 $[g\ s^{-1}]$	$\mathcal{M}\ [\mathcal{M}_{Jup}]$	$n_{CME}\ [cm^{-3}]$	$r_s\ [r_{pl}]$	$\Gamma\ [M_{pl}]$
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

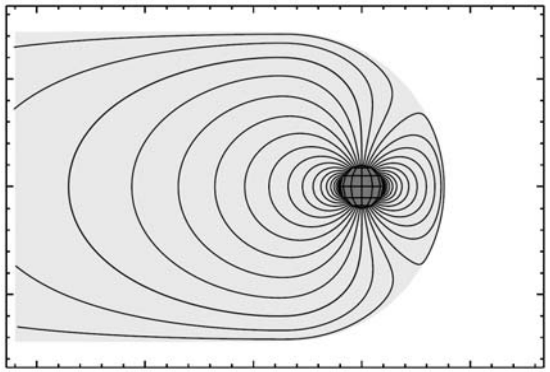
➢ Exoplanet magnetospheres – importance of magnetodisk

- **Relatively large amount of observed Hot Jupiters (28%):**
  ”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 <u>planetary dipole dominated</u> magnetosphere

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

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



J.-M. Grießmeier, A&A, 2004, 425, 753

- **Specifics of close-in exoplanets → <u>new model</u>**

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

  → 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* *paraboloid of revolution* 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***;

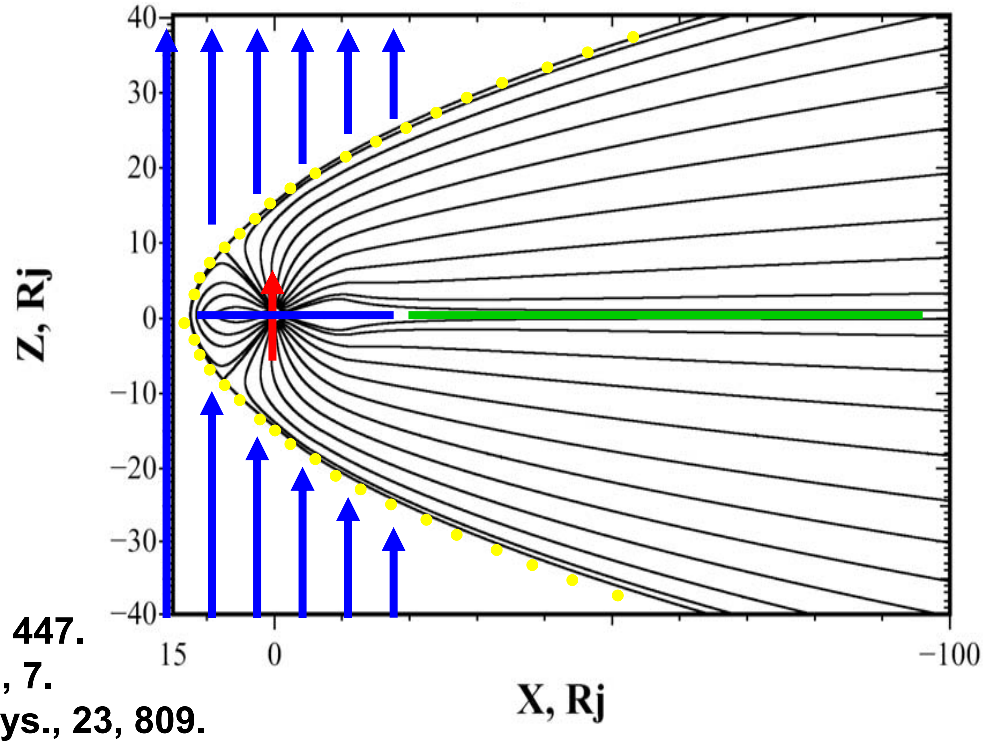
    → current system of ***magnetotail***;

    → ***magnetodisk***;

    → ***magnetopause*** currents;

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

M.Khodachenko et al., ApJ, 2011 (submitted)

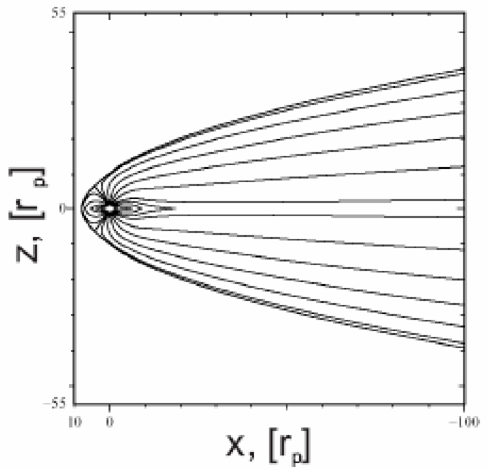


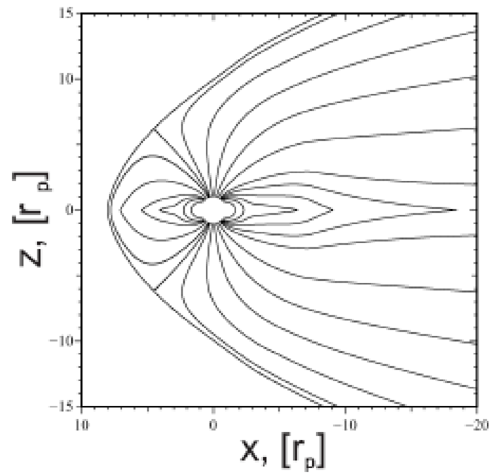
I.Alexeev, 1978, Geomag.&Aeronomia, 18, 447.
I.Alexeev et al., 2003, Space Sci. Rev., 107, 7.
I.Alexeev, E.Belenkaya, 2005, Ann. Geophys., 23, 809.

➢ Exoplanet magnetospheres – importance of magnetodisk

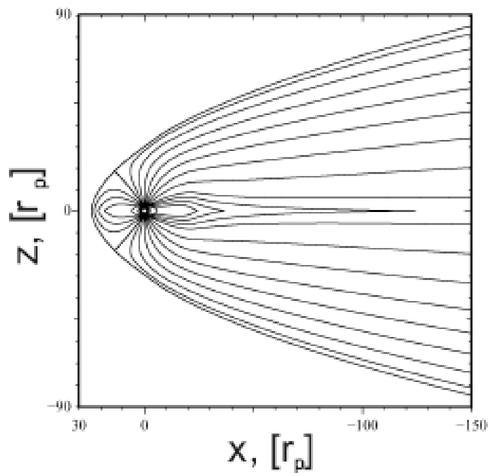
- **Paraboloid Magnetospheirc Model (PMM) for a hypothetic "Hot Jupiter"**

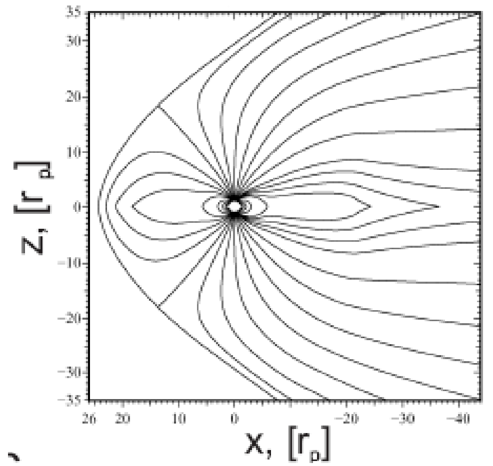
  - **Magnetosphere at 0.045 AU, R_S = 8.0 R_J** (tidally locked)





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





➢ Exoplanet magnetospheres – importance of magnetodisk

- **Paraboloid Magnetospheirc Model (PMM) for a hypothetic "Hot Jupiter"**

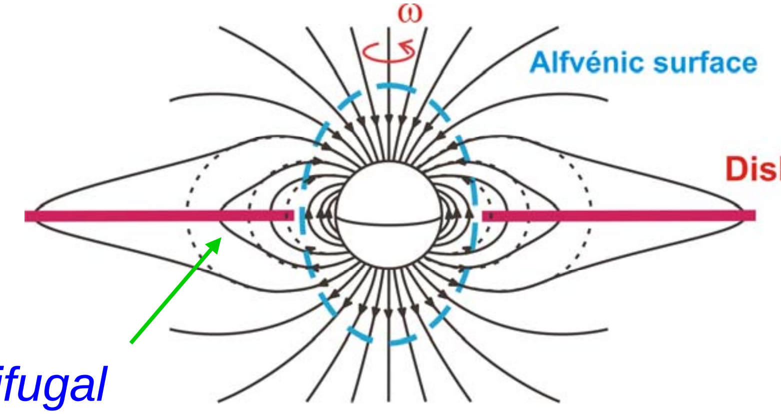
  - **magnetospheric parameters (estimated and calculated)**

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 $[\omega_J]$	$\frac{dM_p^{(th)}}{dt}$ [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}

➢ Exoplanet magnetospheres – importance of magnetodisk

- **Formation of magnetodisk for 'Hot Jupiters'**



♦ **"*sling" model*:**

dipole mag. field can drive plasma in co-rotation regime only inside

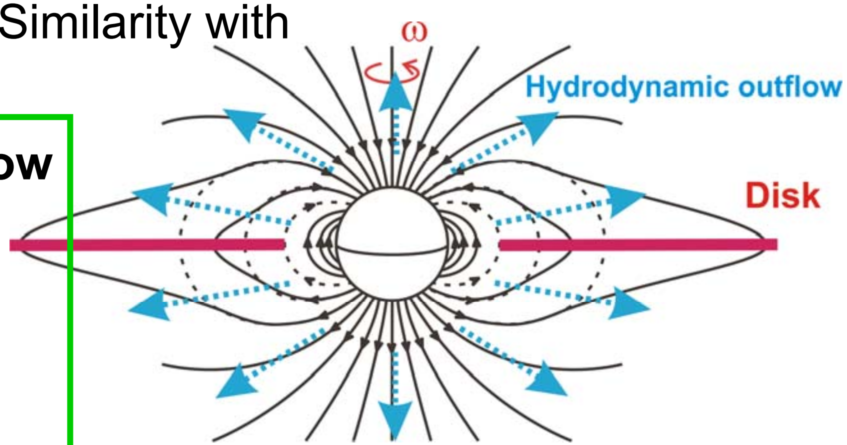
***"Alfvenic surface"* (r < R_A);** → *Centrifugal inertial escape of plasma for $r>R_A$*

♦ **"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

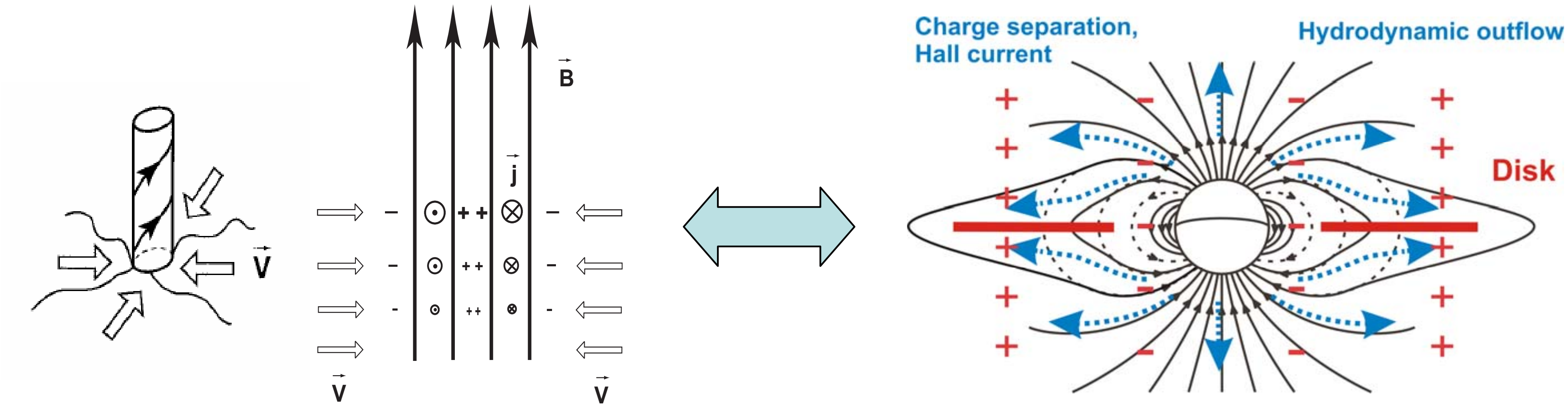


➢ Magnetodisk – plasma outflow as a driver

- **Partially ionized plasma case:**

  - ♦ m.Field (planetary intrinsic m.dipole) is not frozen into plasma
  - ♦ neutral gas slips through m.Field and plasma → charge separation Electr.field $\boldsymbol{E_{cs}}$, ambipolar diffusion
  - ♦ Strong anisotropy of conductivity
  - ♦ Strong magnetic tension forces acting on the expanding plasma

- **Similarity with intense m.tube formation in solar photosph.conv.flow:**



- Hall current $\mathbf{J_H \sim [B \times E_{CS}]}$ distorts the background m.field

➢ Magnetodisk – plasma outflow as a driver

- **Partially ionized plasma case:**

  ♦ **Generalized Ohm's law:**

$$\boxed{\mathbf{E} + \frac{1}{c}[\mathbf{V}\times\mathbf{B}] = \frac{\varepsilon\mathbf{G} - \nabla p_e}{en} + \frac{\mathbf{j}}{\sigma} + \frac{(1-2\varepsilon\xi_n)}{enc}[\mathbf{j}\times\mathbf{B}] - \frac{\xi_n}{c\alpha_n}\left\{\xi_n\frac{[[\mathbf{j}\times\mathbf{B}]\times\mathbf{B}]}{c} - [\mathbf{G}\times\mathbf{B}]\right\}}$$

where $\mathbf{V} = \xi_n\mathbf{v}_n + \xi_i\mathbf{v}_i$ - velocity of the center of mass

$\mathbf{G} = \xi_n\nabla(p_e + p_i) - \xi_i\nabla p_n$ - pressure function

$\xi_n = \dfrac{m_n n_n}{m_n n_n + m_i n_i}$ and $\xi_i = \dfrac{m_i n_i}{m_n n_n + m_i n_i}$ - relative densities

$\sigma = \dfrac{n_e e^2}{m_e(\nu'_{ei} + \nu'_{en})}$ - conductivity

$\alpha_n = m_e n_e \nu'_{en} + m_i n_i \nu'_{in}$ - momentum due to collisions with neutrals

$\varepsilon = \dfrac{n_e m_e \nu'_{en}}{\alpha_n} = \dfrac{\nu'_{en}}{\nu'_{en} + (m_i/m_e)\nu'_{in}}$ usually << 1

➢ Magnetodisk – plasma outflow as a driver

- **Partially ionized plasma case:**
  - look for a m.field configuration (***B_r, B_θ, B_φ=0***), co-existing with (***V_r, V_θ=0, V_φ=0***)
  - assume axial symmetry, i.e. ***$d/d\varphi = 0$*** ; ***$p(r)$***

projection of the Generalized Ohm's Law on φ-axis $\Rightarrow$

$$\boxed{\tilde{Re}_m \tilde{V}_r(\tilde{r}\tilde{B}_\theta) = \left(\frac{\partial}{\partial\tilde{r}}(\tilde{r}\tilde{B}_\theta) - \frac{\partial\tilde{B}_r}{\partial\theta}\right)\left[\frac{\sigma_C}{\sigma - \sigma_C} + (\tilde{B}_\theta^2 + \tilde{B}_r^2)\right] + \beta(\tilde{r}\tilde{B}_\theta)\left[\frac{\partial\tilde{P}_\Sigma}{\partial\tilde{r}} - \frac{\zeta_n}{\xi_n}\frac{\partial\tilde{P}_n}{\partial\tilde{r}}\right]}$$

where

$$\tilde{r} = r/R_0 \quad ; \quad \tilde{P}_\Sigma = P_\Sigma/P_\Sigma^0 \quad ; \quad \tilde{B}_r = B_r/B_0$$

$$\tilde{V}_r = V_r/V_0 \quad ; \quad \tilde{P}_n = P_n/P_0 \quad ; \quad \tilde{B}_\theta = B_r/B_0$$

normalized variables

$$\xi_n = \frac{\rho_n^0}{\rho_\Sigma^0} \quad ; \quad \zeta_n = \frac{P_n^0}{P_\Sigma^0} \quad ; \quad \beta = \frac{4\pi P_\Sigma^0}{B_0^2}$$

plasma characteristic parameters

$$\tilde{Re}_m = \frac{4\pi V_0 R_0}{c^2}\frac{\sigma\sigma_C}{\sigma - \sigma_C}$$

magnetic Reinolds number in partially ionized plasma

➢ Magnetodisk – plasma outflow as a driver

- **Partially ionized plasma case:**
  - ♦ express ***B*** via vector-potential ***A*** (***A****$_r$* **=*0***, ***A****$_\theta$* **=*0***, ***A****$_\varphi$*), :

$$\mathbf{B} = [\nabla \times \mathbf{A}]$$

$$(\triangle \mathbf{A})_\varphi = -\frac{4\pi}{c} J_\varphi$$

  - ♦ exclude ***J****$_\varphi$* from the Generalized Ohm's Law projection on φ-axis

$$\Rightarrow \quad \left[\frac{\partial^2(\tilde{r}\tilde{A})}{\partial^2\tilde{r}} + \frac{1}{\tilde{r}^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial(\tilde{r}\tilde{A})}{\partial\theta}\right) - \frac{\tilde{r}\tilde{A}}{\tilde{r}^2\sin^2\theta}\right] =$$

$$\frac{\partial}{\partial\tilde{r}}(\tilde{r}\tilde{A})\left(\tilde{Re}_m\tilde{V}_r - \cancel{\beta\left[\frac{\partial\tilde{P}_\Sigma}{\partial\tilde{r}} - \frac{\zeta_n}{\xi_n}\frac{\partial\tilde{P}_n}{\partial\tilde{r}}\right]}\right)\left[\frac{\sigma_C}{\sigma - \sigma_C} + [\tilde{B}_\theta^2 + \tilde{B}_r^2]\right]^{-1} \Rightarrow$$

$$\boxed{\left[\frac{\partial^2(\tilde{r}\tilde{A})}{\partial^2\tilde{r}} + \frac{1}{\tilde{r}^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial(\tilde{r}\tilde{A})}{\partial\theta}\right) - \frac{\tilde{r}\tilde{A}}{\tilde{r}^2\sin^2\theta}\right] = \tilde{Re}_m\tilde{V}_r\frac{\partial}{\partial\tilde{r}}(\tilde{r}\tilde{A})\boxed{\left[\frac{\sigma_C}{\sigma - \sigma_C} + [\tilde{B}_\theta^2 + \tilde{B}_r^2]\right]^{-1}}}$$

can be ~ or < *1*

usually << *1*

denote as $\eta(r)$

➢ Magnetodisk – plasma outflow as a driver

- **Partially ionized plasma case:**

♦ look for a solution in the form $\boldsymbol{rA_\varphi = \Phi(r,\theta) = \Phi(r)\ Sin\ \theta}$

$$\Rightarrow \boxed{\frac{\partial^2\tilde{\Phi}}{\partial^2\tilde{r}} - \frac{\partial\tilde{\Phi}}{\partial\tilde{r}}\cdot[\tilde{Re}_m\eta(\tilde{r})\tilde{V}_r] - \frac{2\tilde{\Phi}}{\tilde{r}^2} = 0}$$

♦ asymptotic case $\boldsymbol{r \longrightarrow \infty}$ (**>>** $\boldsymbol{R_0}$) : $\cancel{\frac{2\tilde{\Phi}}{\tilde{r}^2}}$, $[\tilde{B}_\theta^2 + \tilde{B}_r^2] \longrightarrow \boldsymbol{0}$,

$$\tilde{Re}_m\eta(\tilde{r}) \longrightarrow \tilde{Re}_m\left[\frac{\sigma_C}{\sigma - \sigma_C}\right]^{-1} = Re_m^0$$

$$\Rightarrow \boxed{\frac{\partial^2\tilde{\Phi}}{\partial^2\tilde{r}} - \frac{\partial\tilde{\Phi}}{\partial\tilde{r}}\cdot[Re_m^0\tilde{V}_r] = 0}$$

♦ assume incompr.flow, i.e. $\tilde{V}_r(\tilde{r}) = 1/\tilde{r}^2$

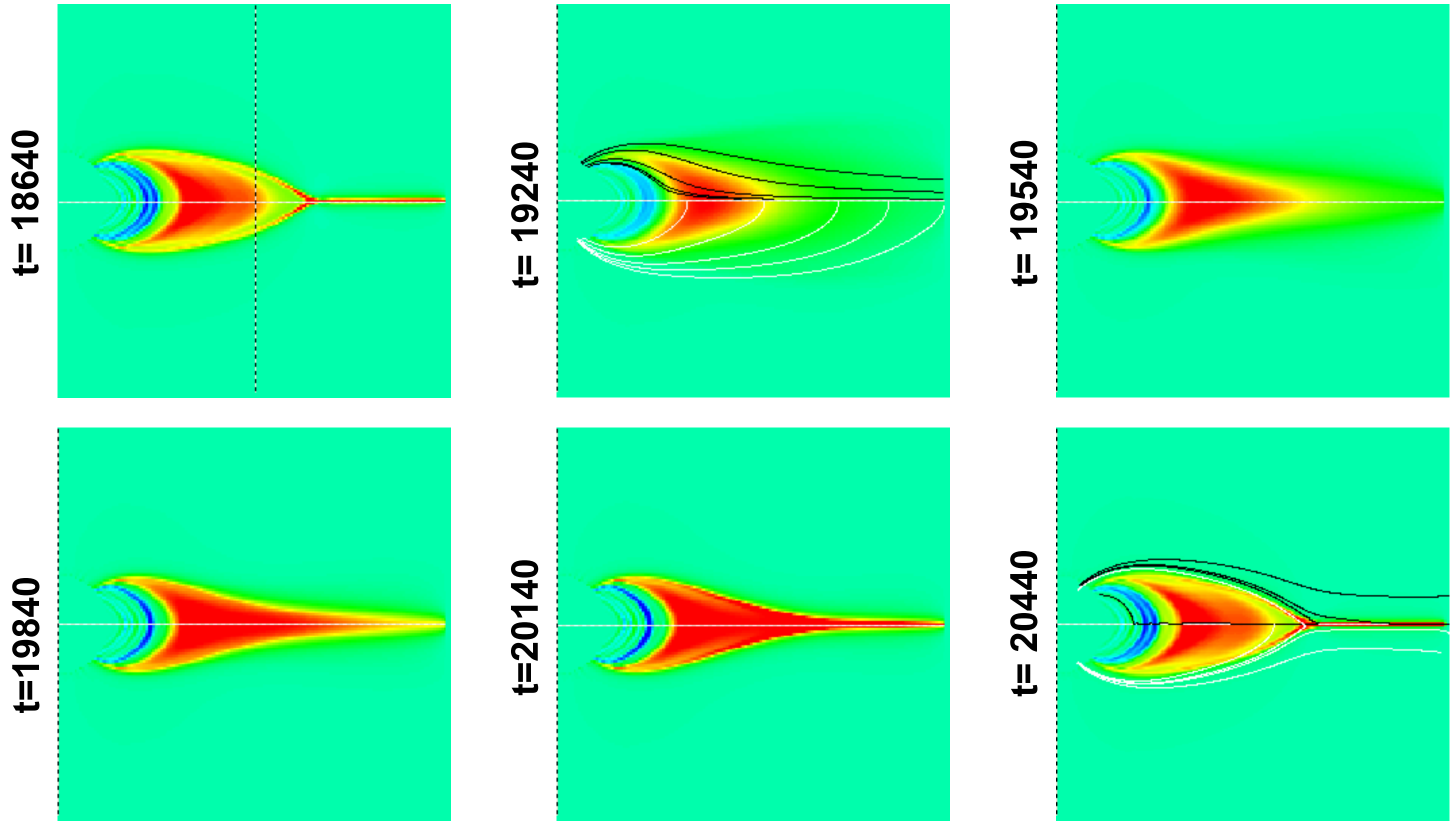
solutions: **1)** $\tilde{\Phi}(\tilde{r})$ = Const

2) $\frac{\partial\tilde{\Phi}}{\partial\tilde{r}} = \Phi_0 \exp\left\{Re_m^0\int\tilde{V}_r d\tilde{r}\right\}$ $\Rightarrow$

$$\boxed{\begin{aligned}\tilde{B}_r(\tilde{r}) &= \frac{\cos\theta}{\tilde{r}^2}\\ \tilde{B}_\theta(\tilde{r}) &= \frac{\sin\theta}{\tilde{r}}\exp\left\{-\frac{Re_m^0}{\tilde{r}}\right\}\end{aligned}}$$

➢ Magnetodisk – plasma outflow as a driver

- **Fully ionized plasma case (preliminary study case):**
  - numerical simulation with ***MHD*** (Inst.of Lasr Phys. Russ.Acad. of Sciences)
    - pressure P_0 and density ρ_0 in the inner boundary
    - initial dipole magnetic field



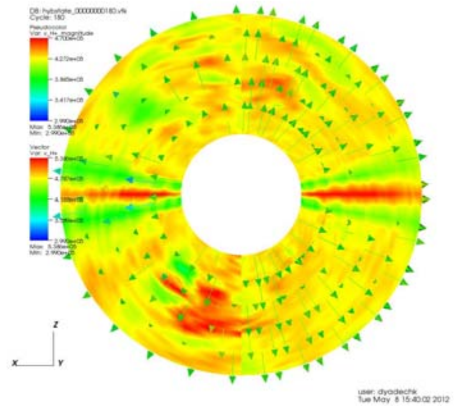
J_φ dynamic for $\beta = 10^{-2}$

Qusiperiodic Reconnection Regime !!!

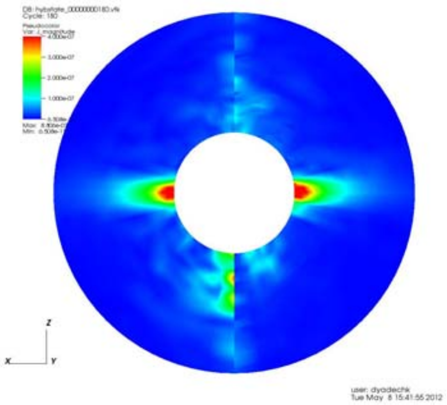
➢ Magnetodisk – plasma outflow as a driver

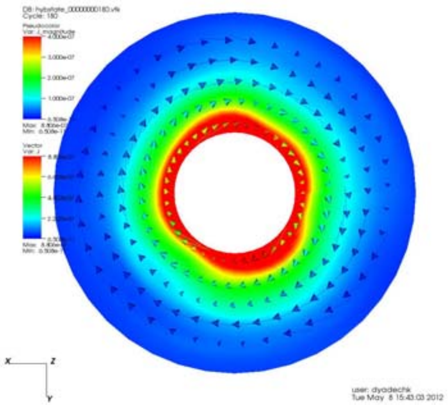
- **Fully ionized plasma case (preliminary study case):**
  - <u>numerical simulation</u> with ***HYB*** (hybride code from Finnish Meteorological Inst.)
    - expanding H-plasma (***V = V$_r$ r$_0$***)
    - initial dipole magnetic field

vVelocity field

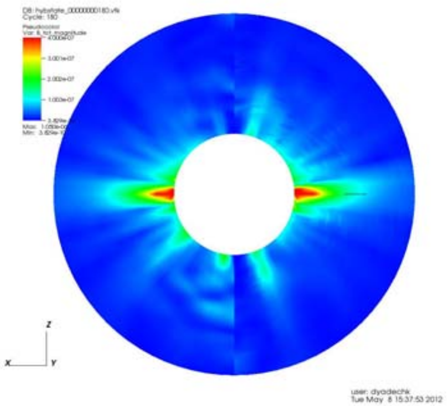


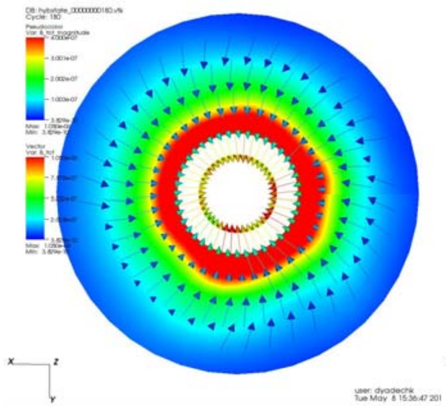
el.current

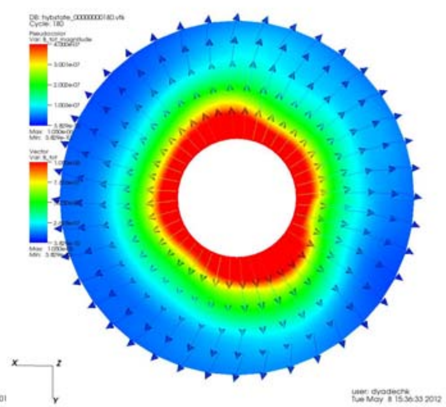




magn.field

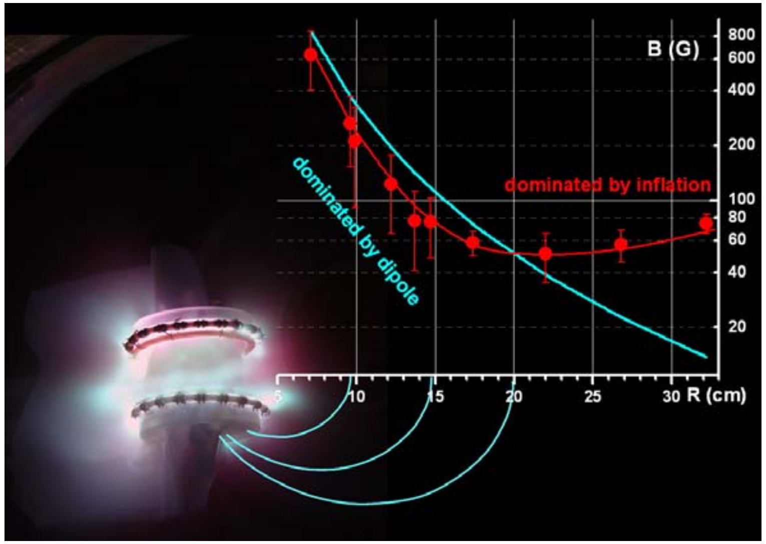


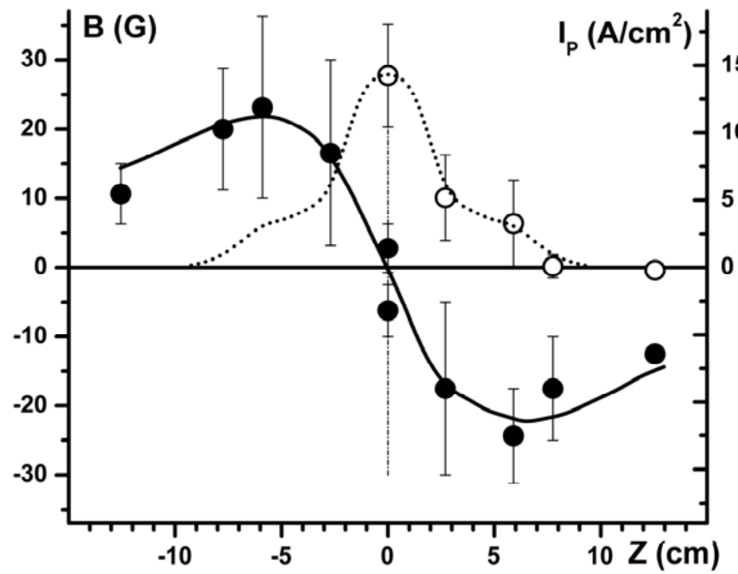




➢ Magnetodisk – plasma outflow as a driver

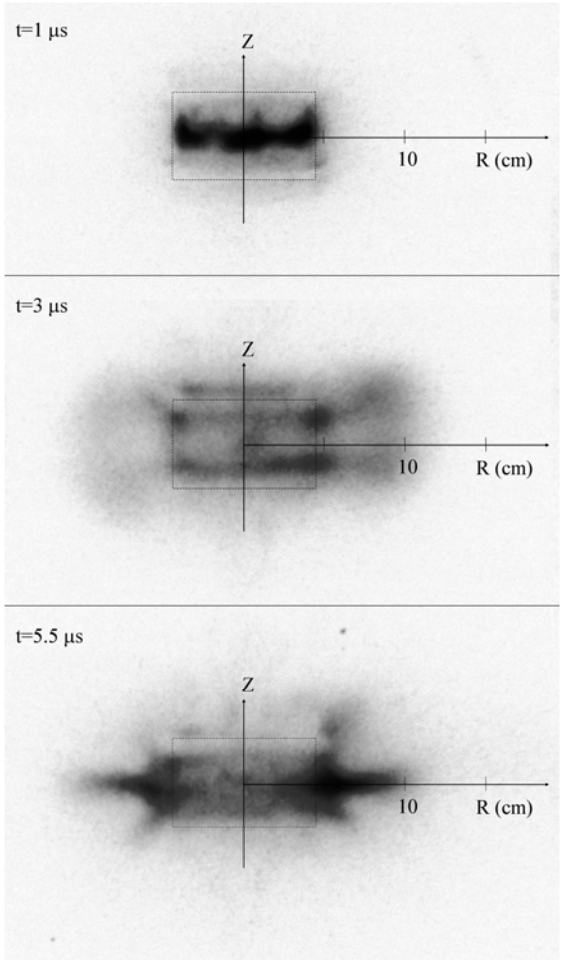
- **Fully ionized plasma case (preliminary study case):**
  - ♦ laboratory plasma experiment (Inst.of Laser Phys., Russ.Acad.Sci. Novosibirsk)
    - vacuum chambers (***120x500 cm***; ***100x55 cm***)
    - dipole magnetic field (***5x5 cm***, $M_d = 3 \times 10^5$ G cm^3); discharge plasma injectors
    - diagnostics with 1) Langmuire probe (charge dens.); 2) Faraday cap (ion flux); 3) Rogovskii coil (electric current). All sensors are movable.
    - sequence of pulses ($V = 50, 40, 30$ km/s, $n = 10^{12} - 10^{13}$ cm^{-3}), C^+ & 2 H^+





➢ Magnetodisk – plasma outflow as a driver

- **Fully ionized plasma case (preliminary study case):**
  - laboratory plasma experiment (Inst.of Laser Phys., Russ.Acad.Sci. Novosibirsk)



Parameter	Experiment	Hot Jupiter
planet radius R_p, cm	4.5	$\sim 10^{10}$
magnetic moment, $A \cdot m^2$	$3 \cdot 10^3$	10^{26}-10^{27}
temperature T_e, eV	~5	1-10
plasma velocity V, km/s	30-50	≥ 10
gravitational escape velocity	0	~50
rotation velocity at R_p	0	1-10
Alfvenic radius R_A/R_p	~3	5-10
Reynolds number $4\pi\sigma R_A V/c^2$	~30	>>1
Hall parameter $4\pi e n_e R_A V/cB$	1.5	>>1
gyroradius R_L/R_A	~1	<<1

➢ 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.**

  Khodachenko, M.L., Alexeev, I.I., Belenkaya, E.S., Leitzinger, M., Odert, P., Grießmeier, J.-M., Zaqarashvili, T.V., Lammer, H., Rucker, H.O., Magneto-spheres of 'Hot Jupiters': The importance of magnetodisks for shaping of magnetospheric obstacle, Astrophys. Journal, 2012, 744, 70. (doi:10.1088/0004-637X/744/1/70).

- **Expanding plasma flow leads to deformation of the background m.dipole field and formation of an equatorial ring current system of magnetodisk**

- **Fundamental astrophysical object (Hot Jupiters, Heliosph.current sheet)**