# Star-Planet Magnetic Interactions

A. F. Lanza
INAF-Osservatorio Astrofisico di Catania, Italy
nuccio.lanza@oact.inaf.it

Image Credit: NASA

*Toward Other Earths II – Porto – 15-19 September 2014*

# Introduction

- Stars interact with their planets through:
  - gravitation;
  - irradiation; and
  - magnetic fields;

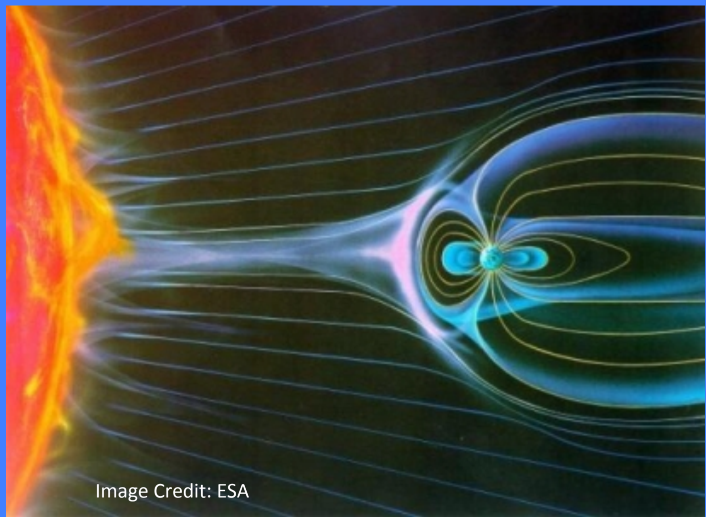
- I shall focus on the case of close-in planets (a < 0.15 AU) around main-sequence late-type stars;

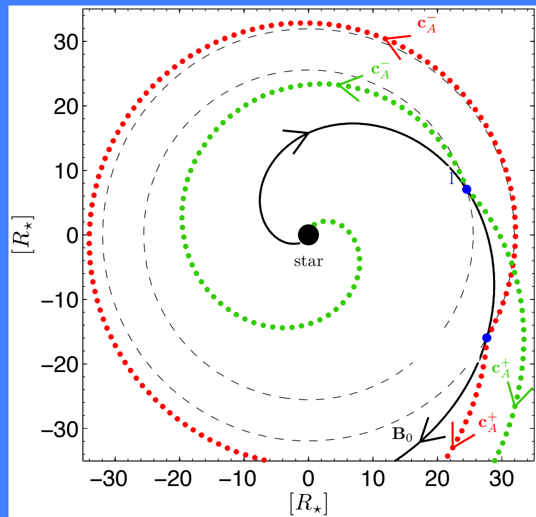
- I shall consider only some cases of interactions in which magnetic fields play a relevant role.

# Different MHD regimes

- In the Solar System, planets are in a region where the velocity of the solar wind $v_w$ is greater than the local Alfven velocity $v_A$ (super-Alfvenic regime):

=> Bow shock at the magnetospheric boundary as in the case of the Earth;




$$c_A^\pm = v \pm v_A,$$

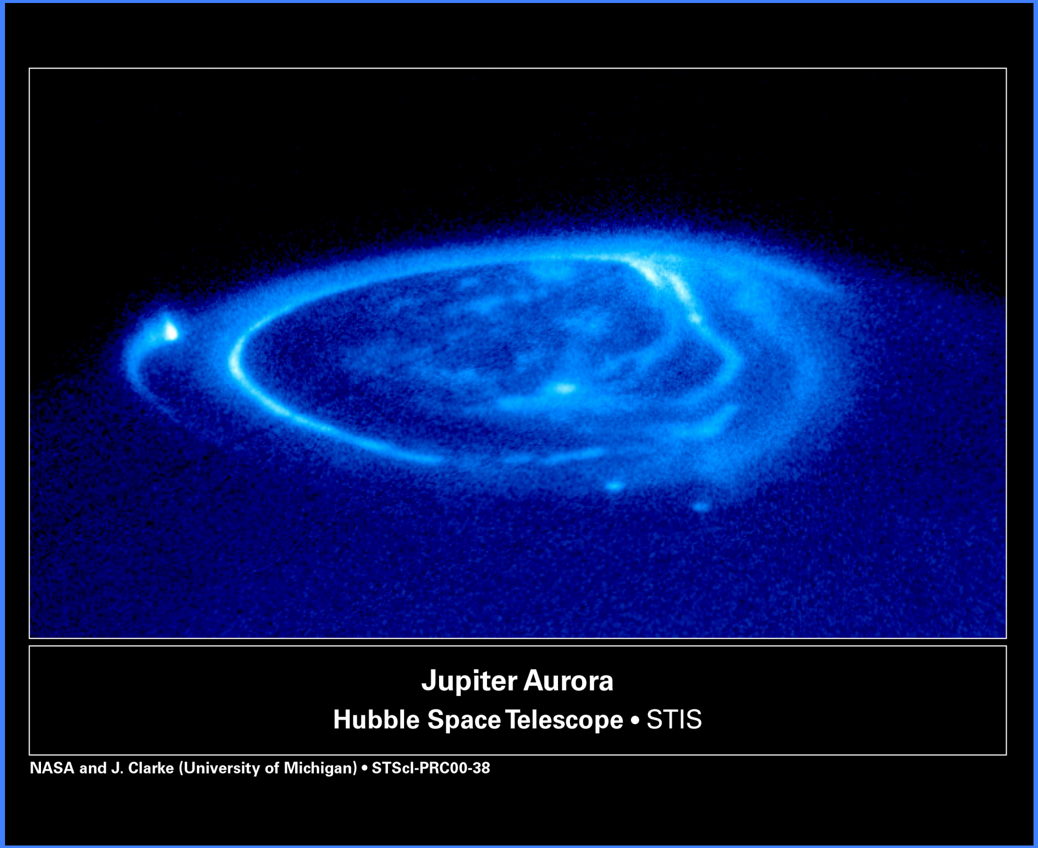
where $\mathbf{v}$ is the velocity of the plasma, $\mathbf{v}_A = \mathbf{B}/\sqrt{\mu\rho}$ the Alfven velocity, $\mu$ the permeability of the plasma, and $\rho$ its density.

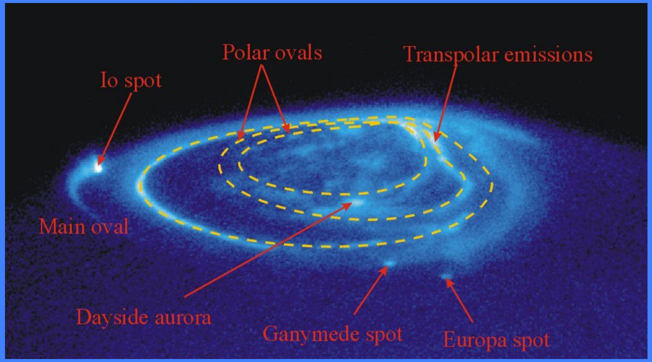
(Saur et al. 2013)

- In the case of close-in planets, the planet is likely to be inside the Alfven radius of the star where $v_w < v_A$ (e.g., Preusse et al. 2005);

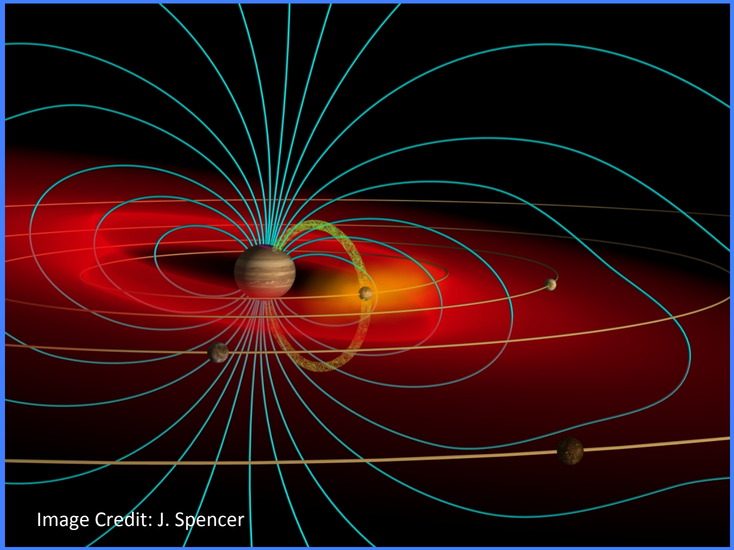
- Alfven waves excited by the planet orbital motion can travel down to the star (e.g., Preusse et al. 2006, 2007; Kopp et al. 2011; Saur et al. 2013).

# The Jupiter-Io analogy




The Alfven wing model
(e.g., Neubauer 1980; Saur et al. 2013)



# Star-Planet Magnetic Interactions (SPMI)

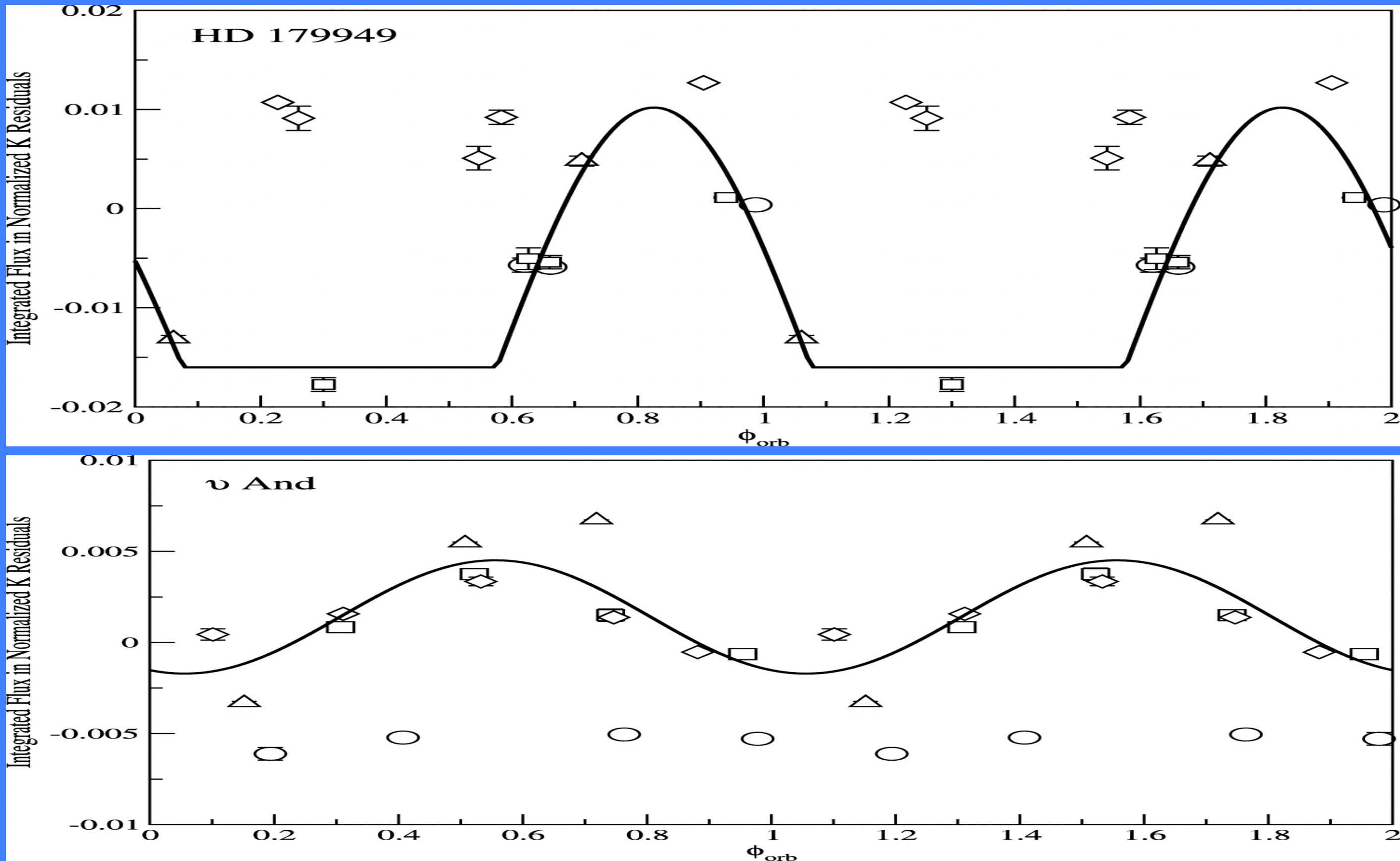
- I shall focus on a few observations:
  - chromospheric hot spots rotating in phase with a close-in planet;
  - low chromospheric emission levels in systems with HJs;

and consider some models proposed for their interpretation;

finally, I shall consider

  - the possibility of photospheric activity phased to a close-in planet.

# SPMI in the chromospheres of HD 179949 and υ And

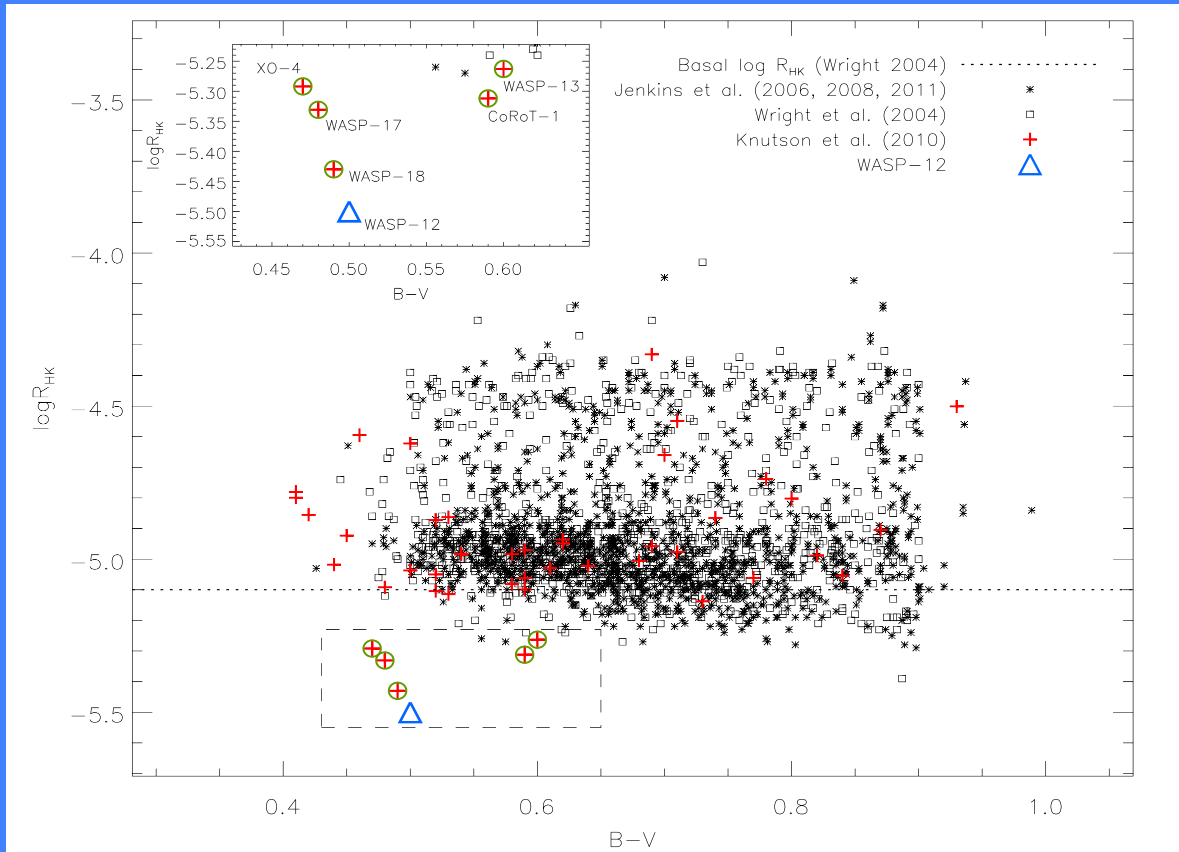



Different symbols refer to different epochs (Shkolnik et al. 2005; 2001 Aug: circles, 2002 Jul: squares; 2002 August: triangles; 2003 Sept: diamonds)

# Chromospheric hot spots

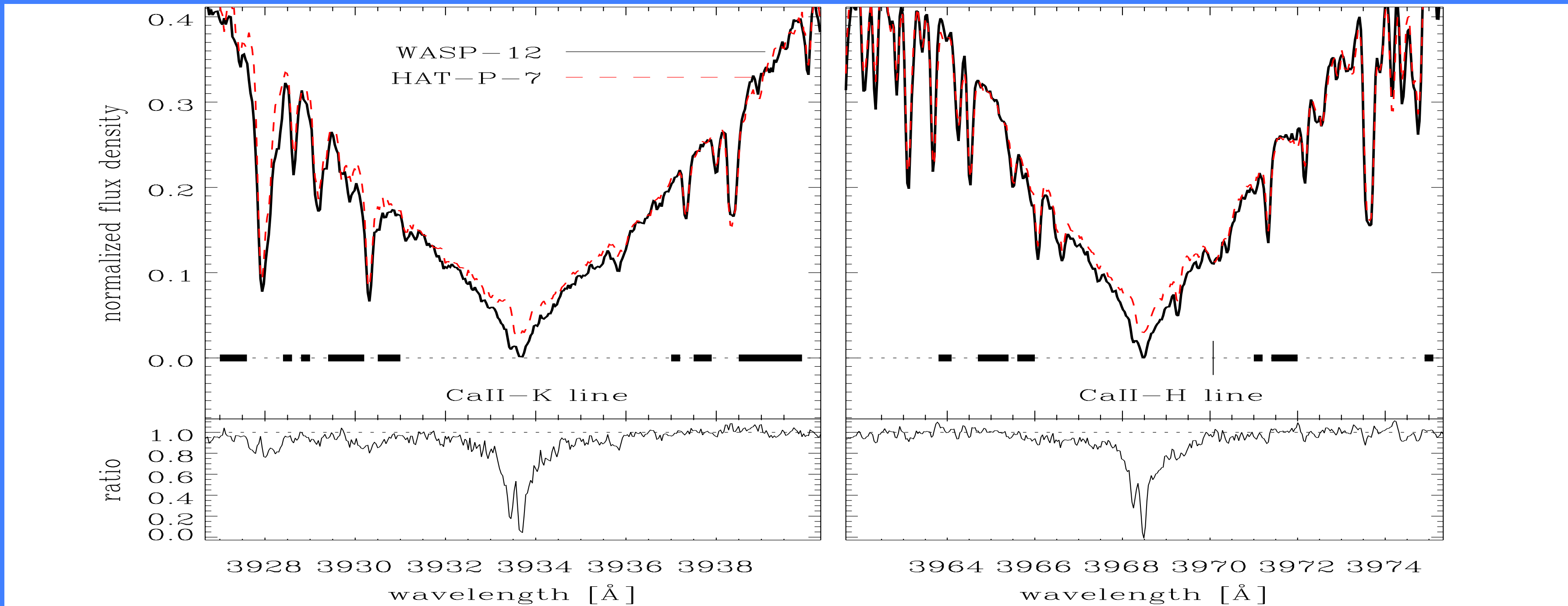
- Chromospheric hot spots rotating in phase with the planetary orbit have been reported (Shkolnik et al. 2003; 2005; 2008; Gurdemir et al. 2012):
  - The irradiated power is of the order of $10^{20} – 10^{21}$ W;
  - There is a phase lag between planet inferior conjuction and maximum hot spot visibility;
  - Planet-induced hot spots are not steady as they are observed only in ≈ 30-50 percent of the seasons (Shkolnik et al. 2008);
  - HD 179949 and $\upsilon$ And show the best examples (see, however, Poppenhaeger et al. 2011; Scandariato et al. 2013);
  - Some authors have questioned the reality of the phenomenon (e.g. Miller et al. 2012).

# Very low activity in some stars with transiting Hot Jupiters



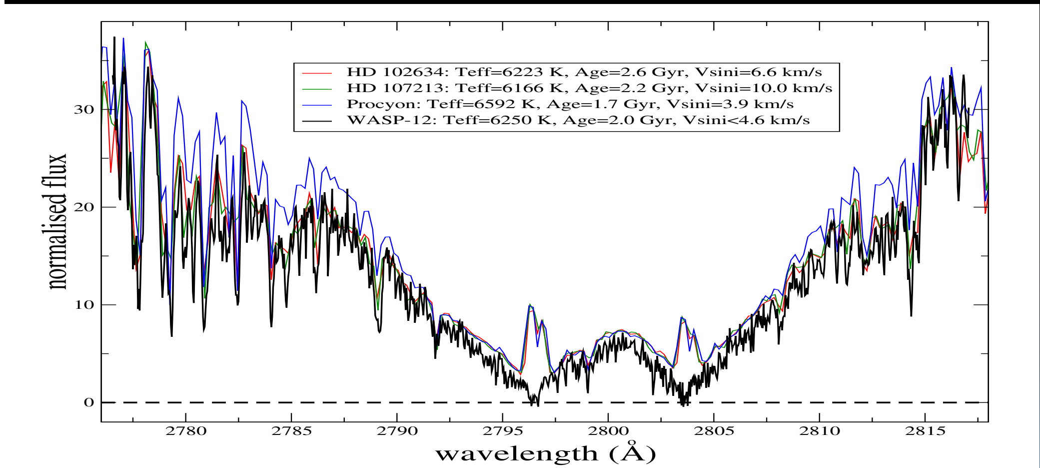

- Fossati et al. (2013) noticed the very low values of the chromospheric emission of some transiting HJs.

# Absence of emission in the cores of chromospheric resonance lines



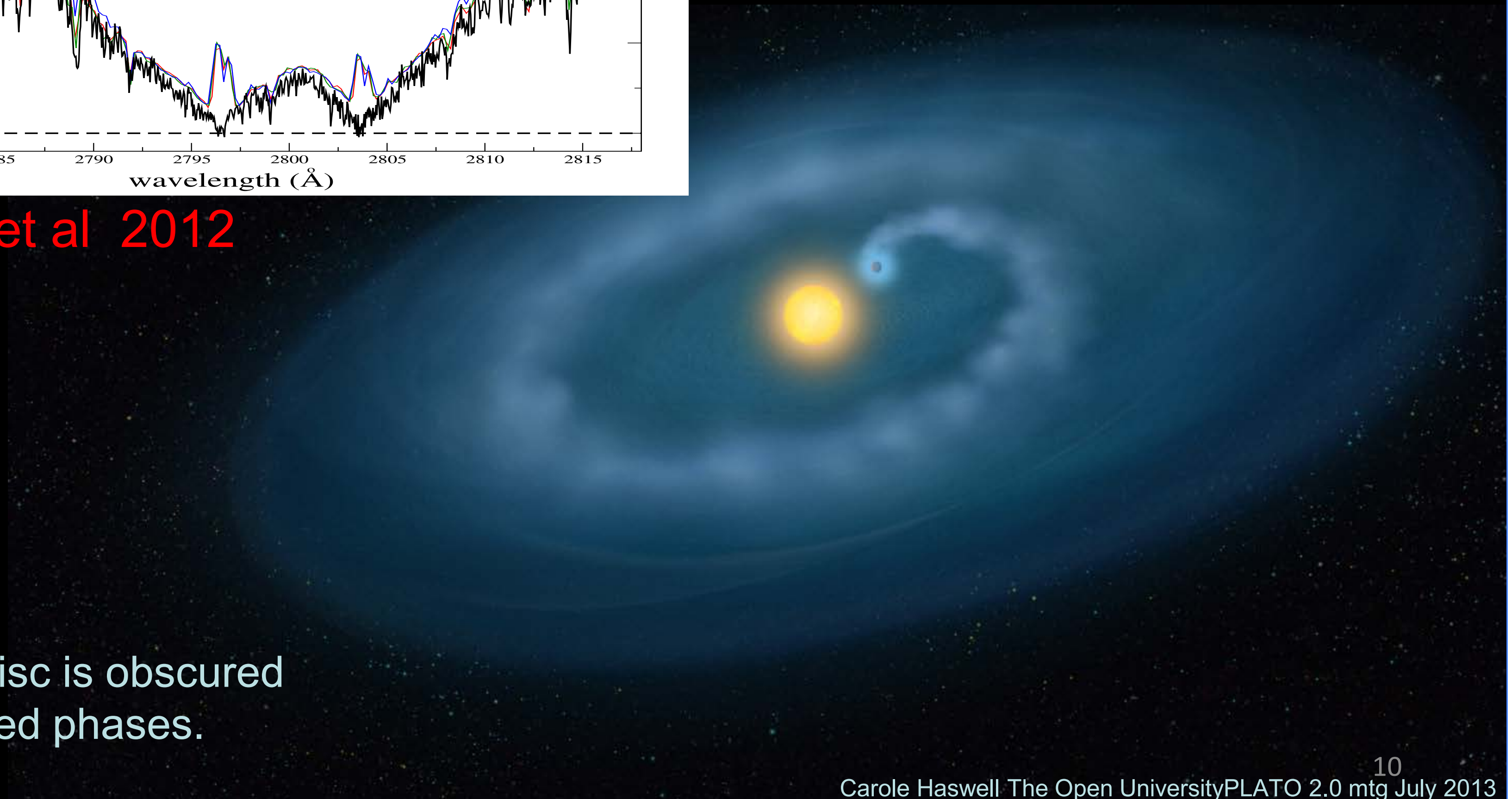

In WASP-12, the Ca II K line (and the Mg II h & k lines as well) have zero flux in the core. Interstellar absorption should be about one order of magnitude larger than generally found in the star direction to account for this (Haswell et al. 2012; Fossati et al. 2013).

# The WASP-12 system is shrouded in diffuse gas




Mg II h&k lines

Haswell et al 2012



The stellar disc is obscured at all observed phases.

# Open questions to be addressed by the models

- Why are chromospheric hot spots shifted with respect to the phase of planetary conjuction ?

- What is the physical process responsible for the energy dissipated in hot spots ?

- What is producing the low level of chromospheric emission in some stars with transiting HJs ? Is it circumstellar absorption or is the stellar activity level intrinsically very low (as found by Pillitteri et al. 2014b in WASP-18; see S.Wolk's talk) ?

# Simple magnetic field models

- Lanza (2008, 2009, 2012, 2013) has developed simple magnetic field models for stars with close-in planets;

- They assume that:
  a) gravity and plasma pressure are negligible in comparison to the Lorentz force;
  b) $v_{plasma} << v_{Alfven}$ (negligible ram pressure);
  c) the system is stationary ( => *force-free* fields).

# Force-free fields

$$\mathbf{J} = \mu^{-1}\nabla \times \mathbf{B}$$

(current density)

$$\mathcal{L} = \mathbf{J} \times \mathbf{B} = \mu^{-1}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

(Lorentz force per unit volume)

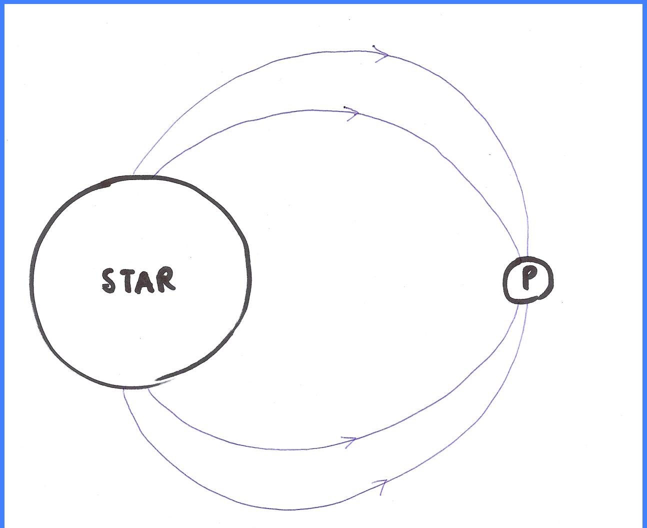
$$\text{If} \quad \mathcal{L} = 0 \quad \text{then} \quad \nabla \times \mathbf{B} = \alpha \mathbf{B}$$

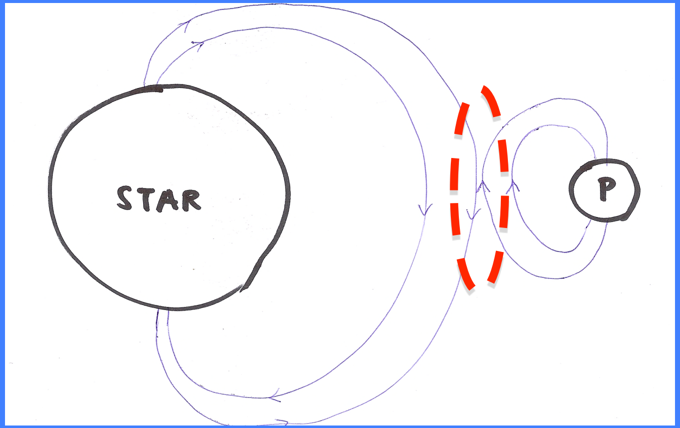
Taking the divergence of both sides of the above equation:

$$\mathbf{B} \cdot \nabla \alpha = 0$$

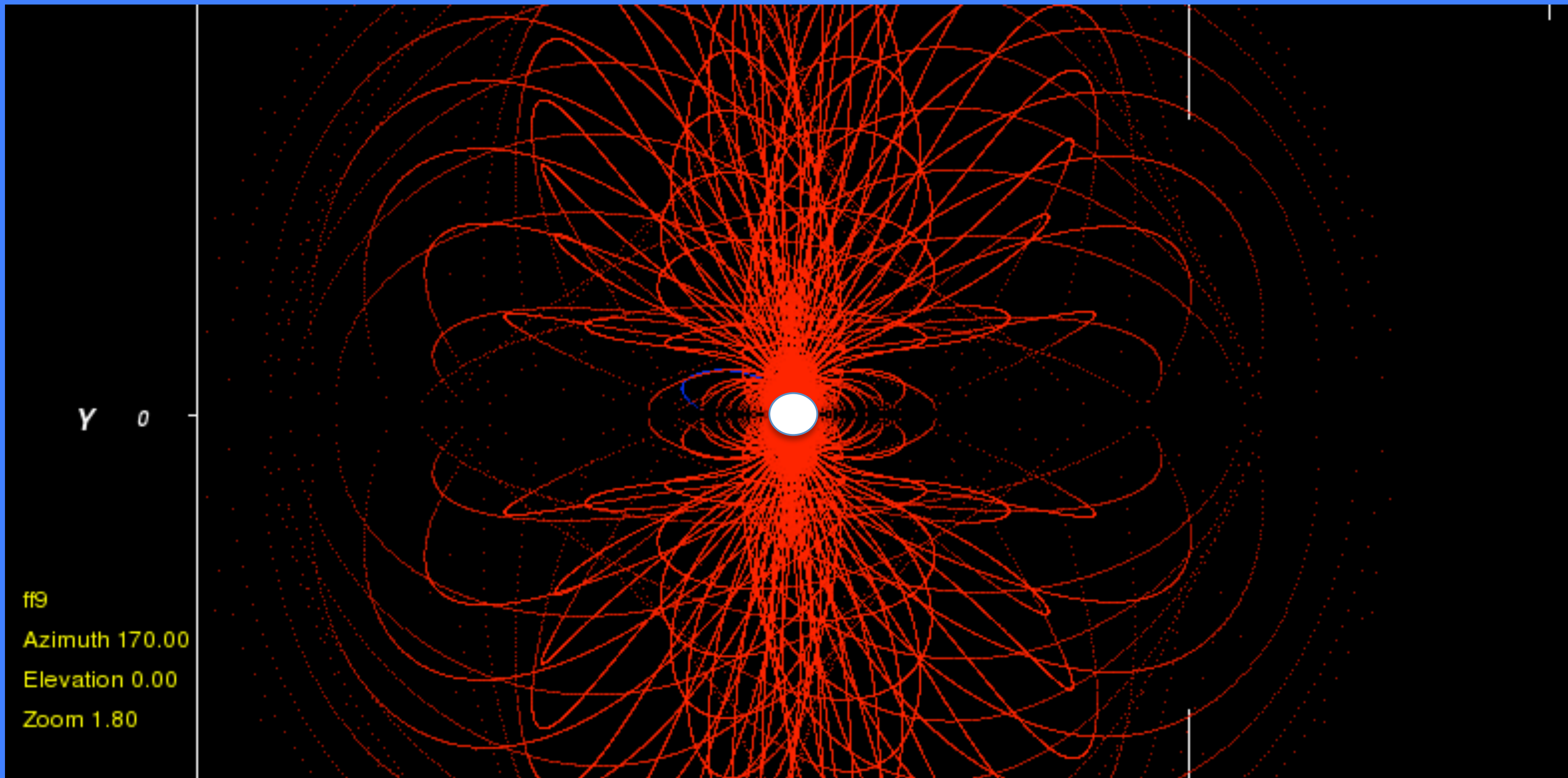
Therefore, α is *constant along each given field line*.

- There are two different possible configurations:
  - Interconnecting configurations (potential magnetic fields); [left]
  - Topologically separated star-planet flux systems (with possibility of magnetic reconnection); [right]



# A force-free field model



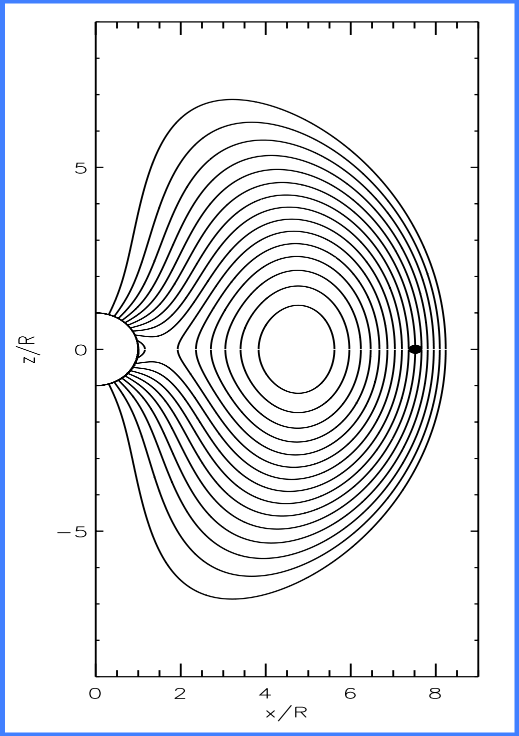

A linear force-free field model for HD 179949 with twisted field lines (Lanza 2008, 2009) that can account for the phase lag of the hot spot. Linear f-f fields (i.e., with constant α) are minimum-energy configurations for given magnetic helicity (e.g., Berger 1985).

# Some axisymmetric field configurations

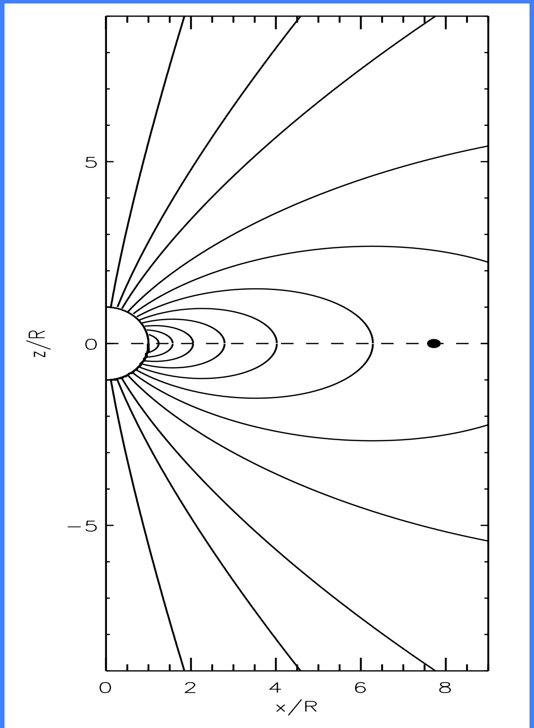
There are particular minimum-energy configurations that:

a) have field lines that do not connect the planet with the star => the energy dissipated by reconnection is not conveyed to the star; and

b) can store evaporated plasma in a torus around the star thus accounting for the absorption suggested by Fossati et al. (2013), at least qualitatively.

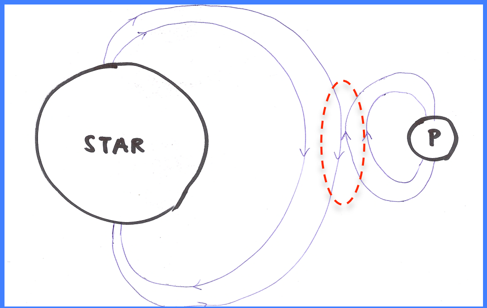



Meridional sections of HD 179949 model fields; Linear f-f field with an *azimuthal flux rope* (left); or non-linear f-f field (right; Lanza 2012).



# Magnetic reconnection power

$$P_\mathrm{d} \simeq \gamma \frac{\pi}{\mu} \left[ B\left(a, \frac{\pi}{2}\right) \right]^2 R_\mathrm{m}^2 v_\mathrm{rel},$$




where $0 < \gamma < 1$ depends on the relative angle between reconnecting field lines, $\mu$ is the permeability of the vacuum, and $v_{rel}$ the relative velocity between the interacting field lines;

- estimated dissipated powers $P_d \approx 10^{17}$-$10^{19}$ W for $B_{pl} = 10$ G, $B_* \approx 10$-$40$ G, $R_m \approx 4$-$5\, R_p$, $v_{rel} \approx v_{orb} \approx$ 100-200 km/s (Lanza 2009, 2012);

- similar powers are obtained with the Alfven wing model (e.g., Zarka 2007; Saur et al. 2013);

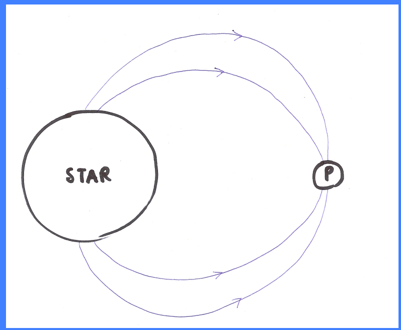
- They are short of 2-3 orders of magnitude to account for the hot spot emission.

# Interconnecting loops

- When the field of the star is close to a potential configuration (e.g., close to the minimum of the activity cycle), the formation of interconnecting loops between the planet and the star is favoured (e.g., Lanza 2013);

- The stress induced by the orbital motion of the planet makes a large power available, up to $10^{20}$-$10^{21}$ W:

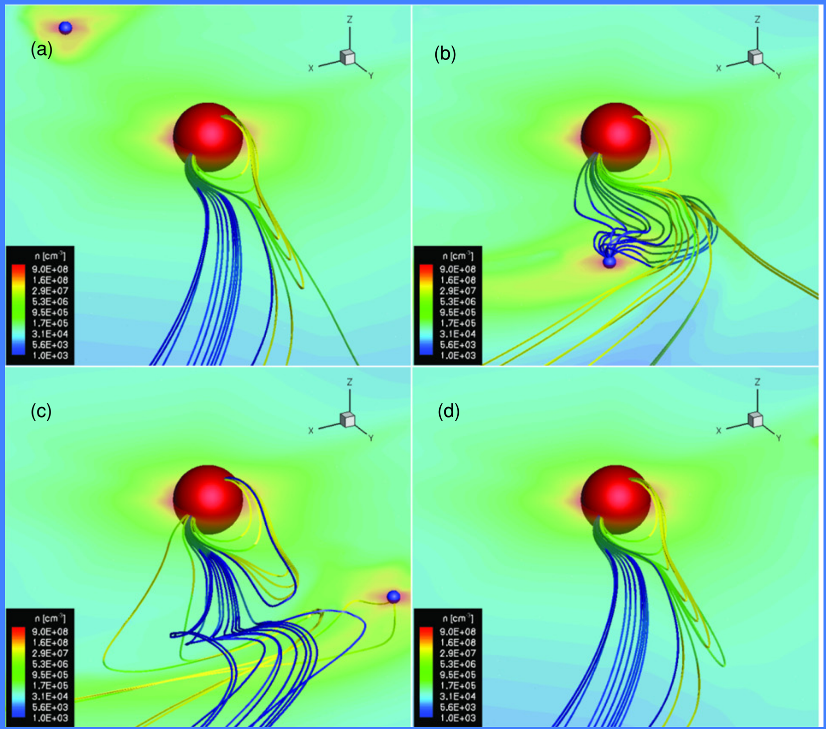
$$P \simeq \frac{2\pi}{\mu} f_{\rm AP} R_{\rm p}^2 B_{\rm p}^2 v_0.$$

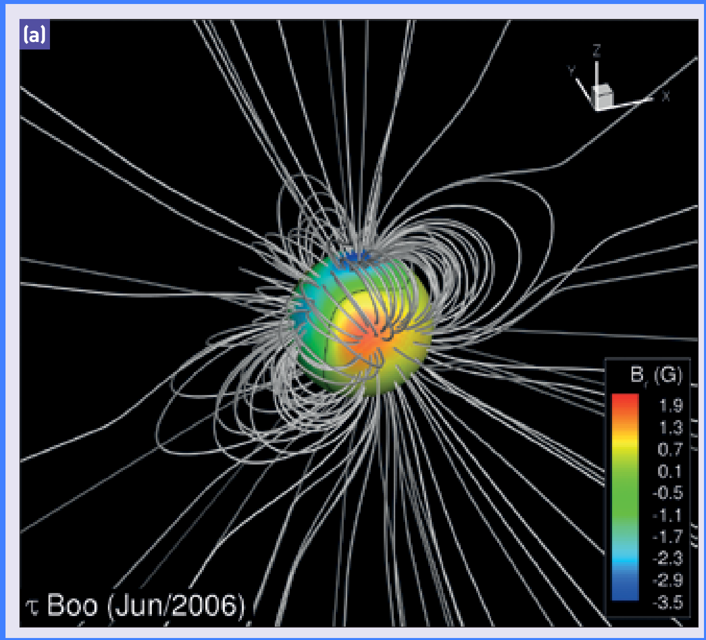



where $f_{AP}$ is the fraction of the planet surface covered by the interconnecting field lines (usually $f_{AP} \approx 0.1$-$0.2$; Adams 2011), $B_p$ the planet's polar field, and $v_0 \approx v_{orb}$ the relative velocity between the loop footpoints;

- In principle, the available power is enough to account for hot spot emission.

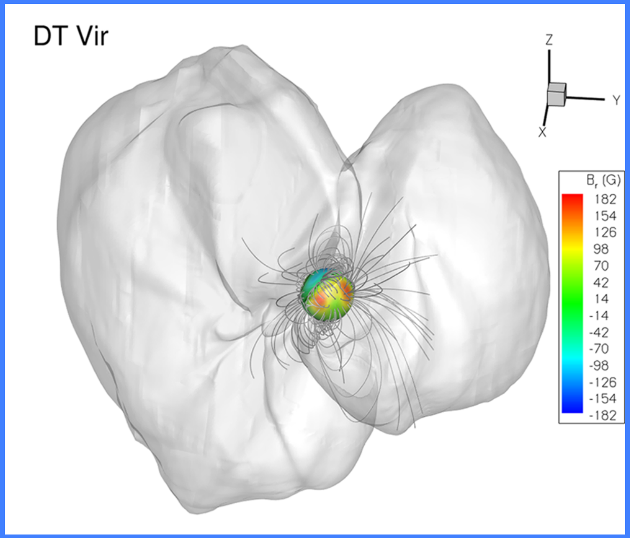
# MHD numerical models

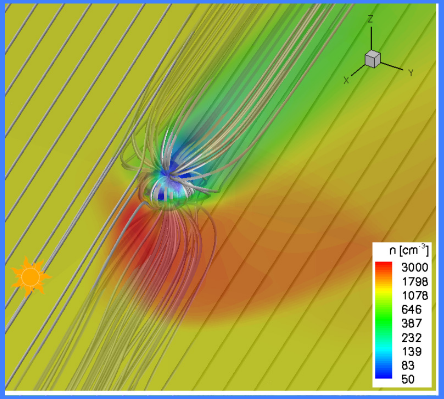


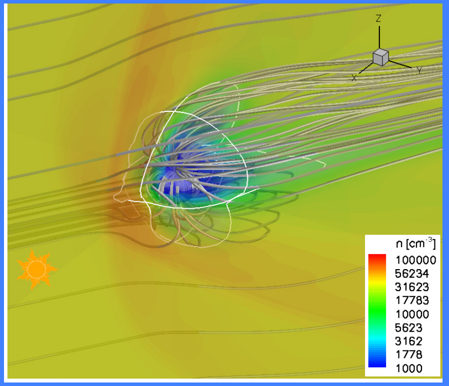

- Cohen et al. (2009, 2011) developed MHD numerical models also including the measured field at the photosphere (e.g., Moutou et al. 2007; Fares et al. 2010);
- They do include the effects of plasma pressure and gravity;
- They may account for the power released in hot chromospheric spots;
- Models of stellar winds and their interaction with close-in planets have been developed by, e.g., Vidotto et al. (2010, 2011, 2013); Cohen et al. (2014).

# Numerical wind models and planetary magnetospheres




Sub-Alfvenic wind




Super-Alfvenic wind

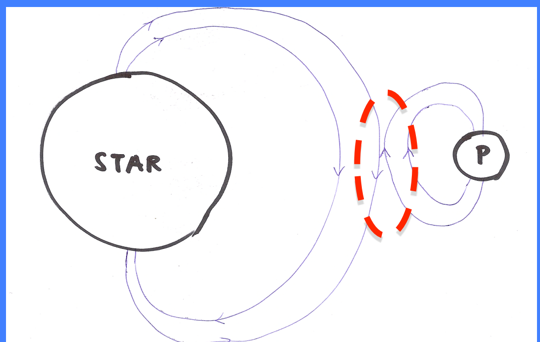
Left: Vidotto et al.'s (2014) model of the wind from an M-type dwarf star. Right: a planetary magnetosphere under different wind regimes (Cohen et al. 2014) [see also talk by V. See].

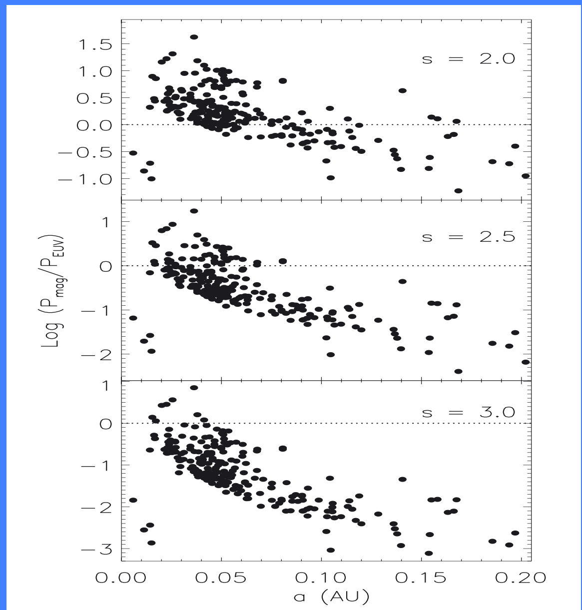
# Magnetically powered evaporation

- In stars with planets closer than about 0.05 AU, magnetic reconnection between the stellar and planetary fields may release a power exceeding that of the stellar EUV flux (Buzasi 2013; Lanza 2013);

- The induced evaporation is expected to be modulated with the stellar field strength;

- Accelerated electrons (and ions) can induce chemical reactions in the planet atmosphere (e.g., Rimmer, Helling et al. 2014, production of $C_2H_2$, $C_2H_4$, $NH_3$, $C_6H_6$, etc.).




($B(R_*) = 10$ G; $B_p = 10$ G)

$B(r) = B(R_*)\,(r/R_*)^{-s}$

where $2 \leq s \leq 3$,
$s = 2$: radial field
$s = 3$: dipole field

EUV fluxes from Lecevelier des Etangs (2007)

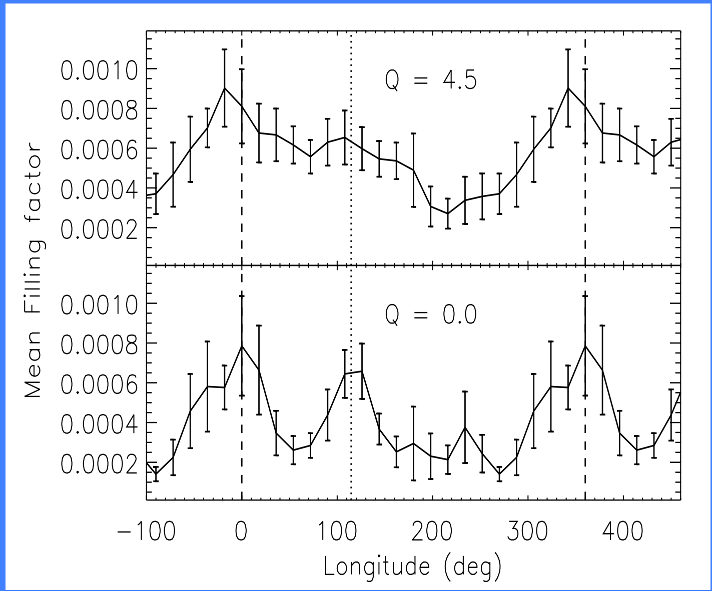
# Photospheric spots forming in phase with the planet ?

- For a general introduction to starspots in late-type main-sequence stars see, e.g., Berdyugina (2005); Strassmeier (2009); Kovari & Olah (2014);

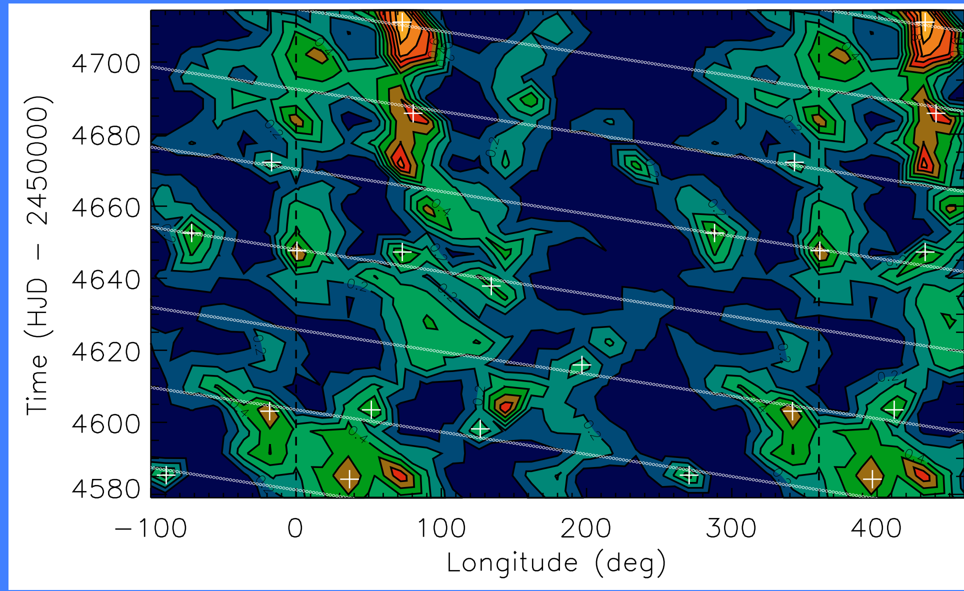
- Spots at the subplanetary longitude have been detected in the synchronized system CoRoT-4 (Lanza et al. 2009);

- Lanza et al. (2011b) suggested that some photospheric spots emerged at a constant phase lag with respect to the sub-planetary longitude in CoRoT-6;

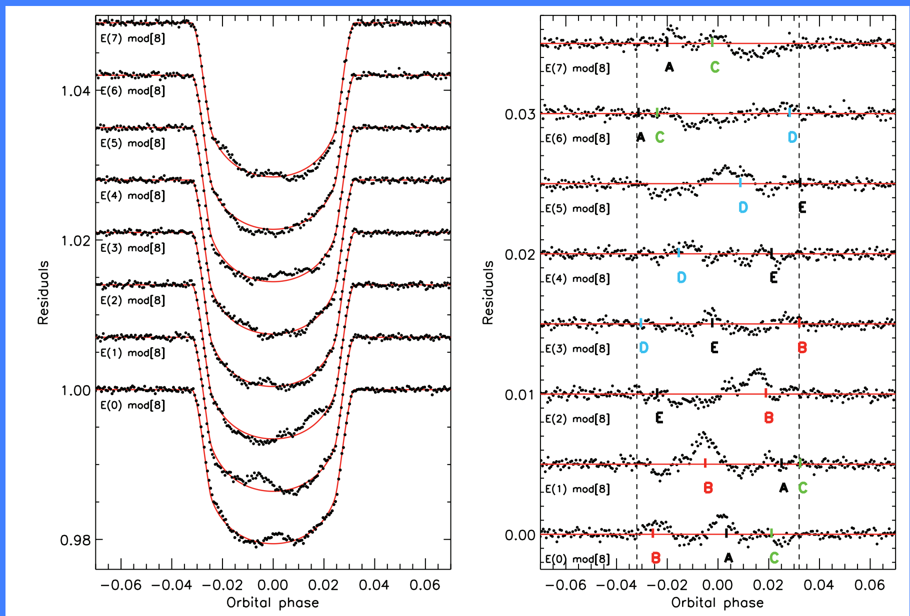
- Recently Beky et al. (2014) found a close commensurability between the rotation period of the spots occulted during transits and the orbital period of the planet in HAT-P-11 and confirmed a similar phenomenon in Kepler-17 (see Desert et al. 2011).




CoRoT-4 (Lanza et al. 2009)




CoRoT-6 (Lanza et al. 2011b)




Kepler-17 transits (Desert et al. 2011); Bonomo & Lanza (2012) found a mean rotation of the unocculted spots of 12.01 days, while that of the occulted spots is 11.89 days = 8 $P_{orb}$ ($P_{orb}$ = 1.4857 days).

# Conclusions and open questions

- Different regimes of magnetic interactions among stars and planets (sub-Alfvenic vs. super-Alfvenic); magnetospheric and coronal physics;

- Interconnecting loops may account for chromospheric hot spots;

- Other magnetic field configurations may provide support for *prominence-like condensations* in the outer stellar corona, leading to circumstellar absorption of chromospheric emission;
  - However, an intrinsically low level of activity cannot be excluded (cf. the case of WASP-18 studied by Pillitteri et al. 2014);

- Magnetic fields rule planetary evaporation and its time modulation (stellar EUV flux vs. energy released by magnetic reconnection);

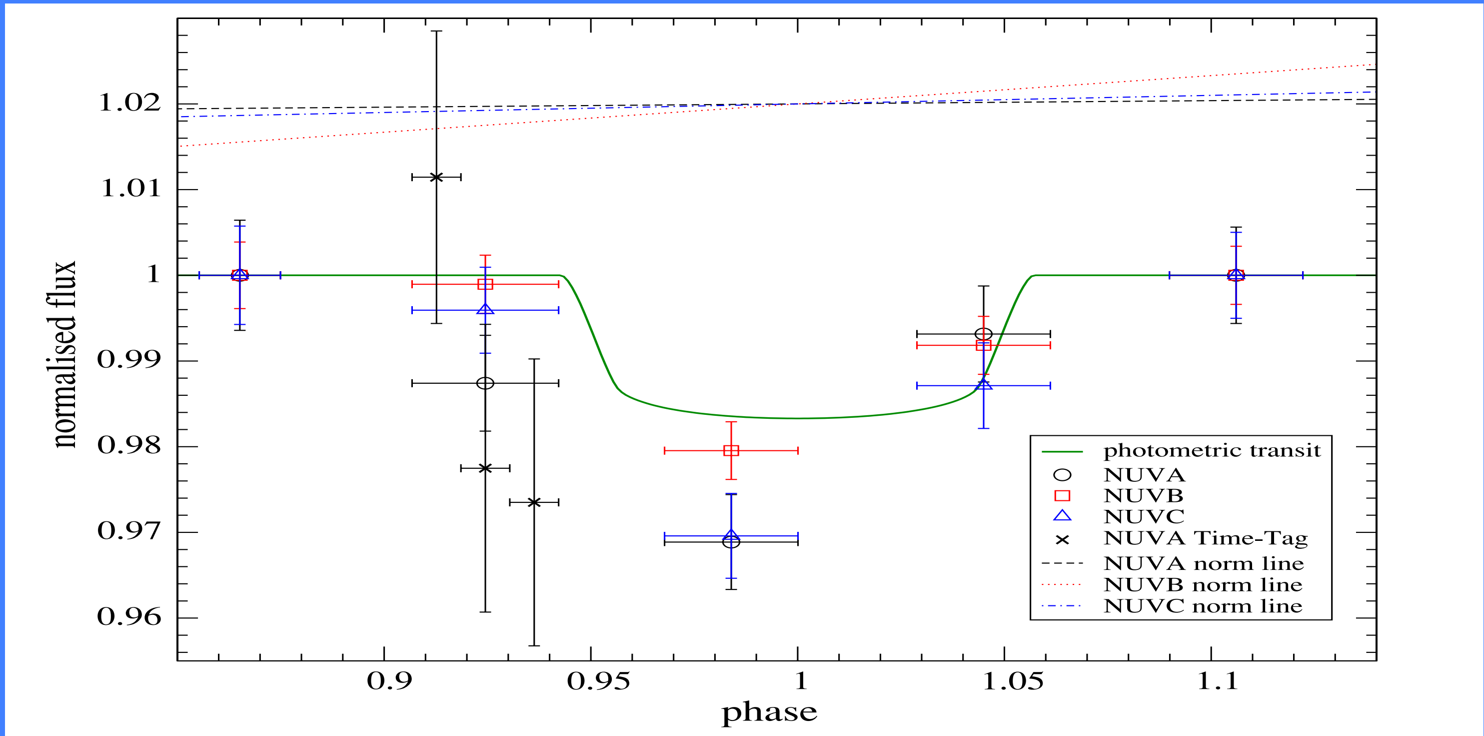
# Conclusions and open questions

- Exotic dynamo processes (starspots forming/rotating in phase or with a period commensurable with a close-in massive planet) ?
- Photospheric features phased to the planets can affect the RV modulation thus impacting on planet confirmation and their parameter determination (e.g., the case of HD 192263, Santos et al. 2003);
- The TESS and PLATO missions will open new perspectives by discovering bright planetary systems;
- New theoretical work with MHD numerical models (Cohen et al.; Mathis, Brun et al.; Strugarek 2014).

Thank you for your attention

# Additional material

# Transit of WASP-12 in UV



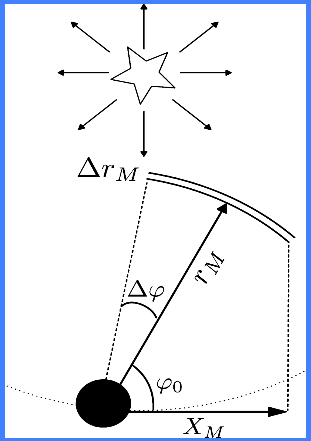

Passbands: NUVA: 253.9-258.0 nm; NUVB: 265.5-269.6 nm; NUVC: 277.0-281.1 nm (Fossati et al. 2010; see also Haswell et al. 2012).

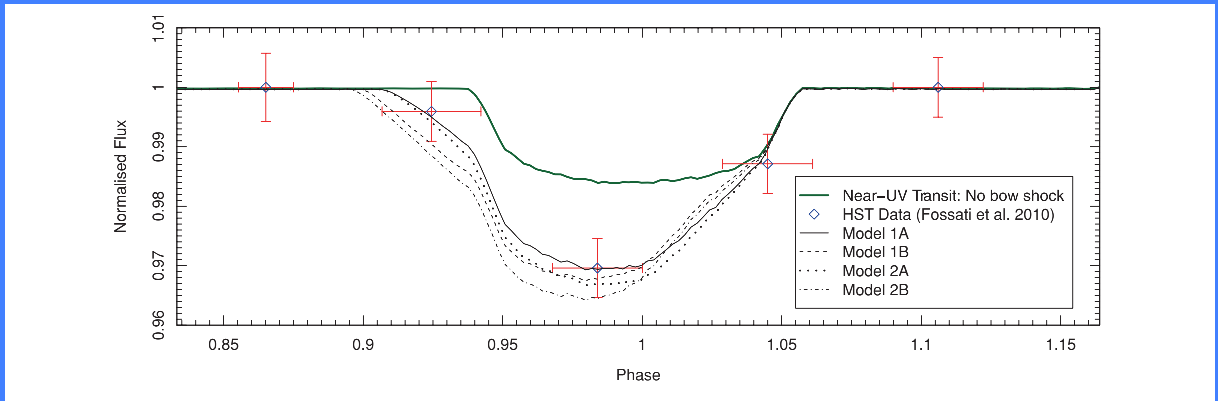
- BenJaffel & Ballester (2013) found hints of an early ingress in the transit of HD 189733 as observed in the C II 133.5 nm line, but it needs to be confirmed;

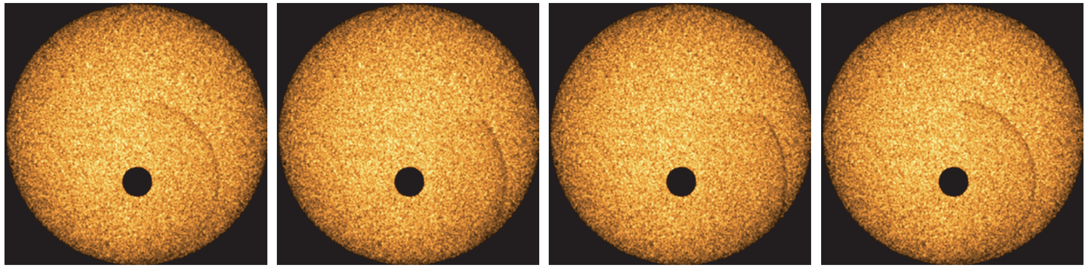
- Czesla et a. (2012) reported a longer transits (by ≈ 15%) in the Ca II H&K lines in CoRoT-2.

# Models of transit of WASP-12 in NUV

Asymmetric accrection stream or magnetopause (Lai et al. 2010)



Observations by Fossati et al. (2010; mainly in the range ≈ 254-258 nm) and bow-shock models (Vidotto et al. 2010; Llama et al. 2011);

Ben-Jaffel & Ballester (2014) proposed that the occulting material comes from an evaporating exomoon orbiting the hot Jupiter.

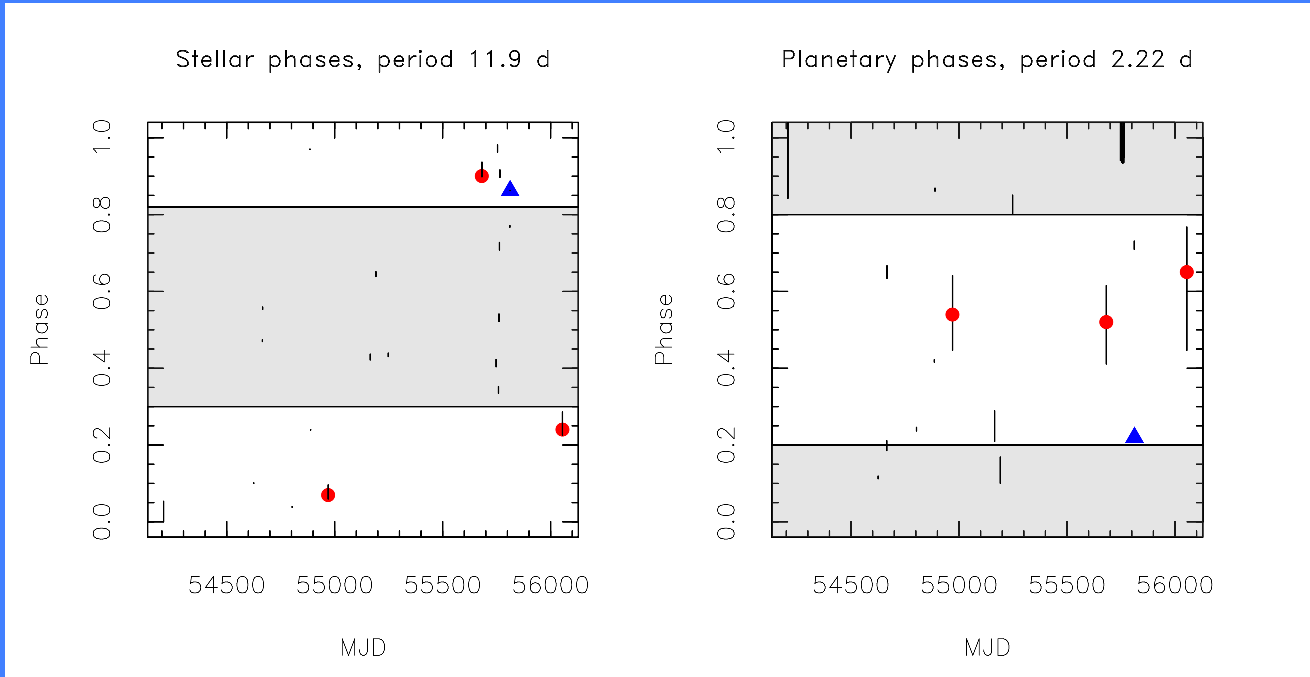
# Star-Planet Magnetic Interactions (SPMI)

- I shall focus on a few observations:
  - Chromospheric hot spots rotating in phase with the planet;
  - Low chromospheric emission level in systems with HJs;
  - Transits in the EUV (WASP-12);
  - Preferential orbital phases for stellar flares (HD 189733);
  - Possible photospheric activity phased to a close-in planet.
- Then I shall briefly consider some simple models.

# Open questions to be addressed by the models

- Why are chromospheric hot spots shifted with respect to the phase of planetary conjuction ?
- What is the physical process responsible for the energy dissipated in hot spots ?
- What is producing the low level of chromospheric emission in some stars with transiting HJs ? Is it circumstellar absorption or is the stellar activity level intrinsically very low (as found by Pillitteri et al. 2014b in WASP-18; see S.Wolk's talk) ?
- What is producing the asymmetric transit profile in the UV in WASP-12 ?

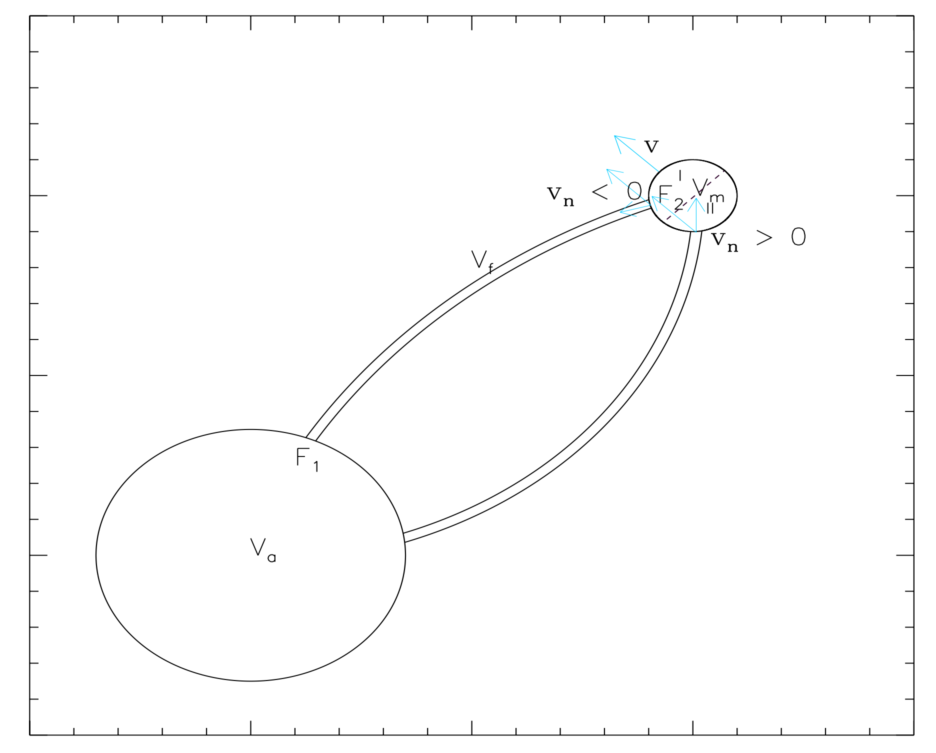
# Preferential orbital phases for flares in HD 189733



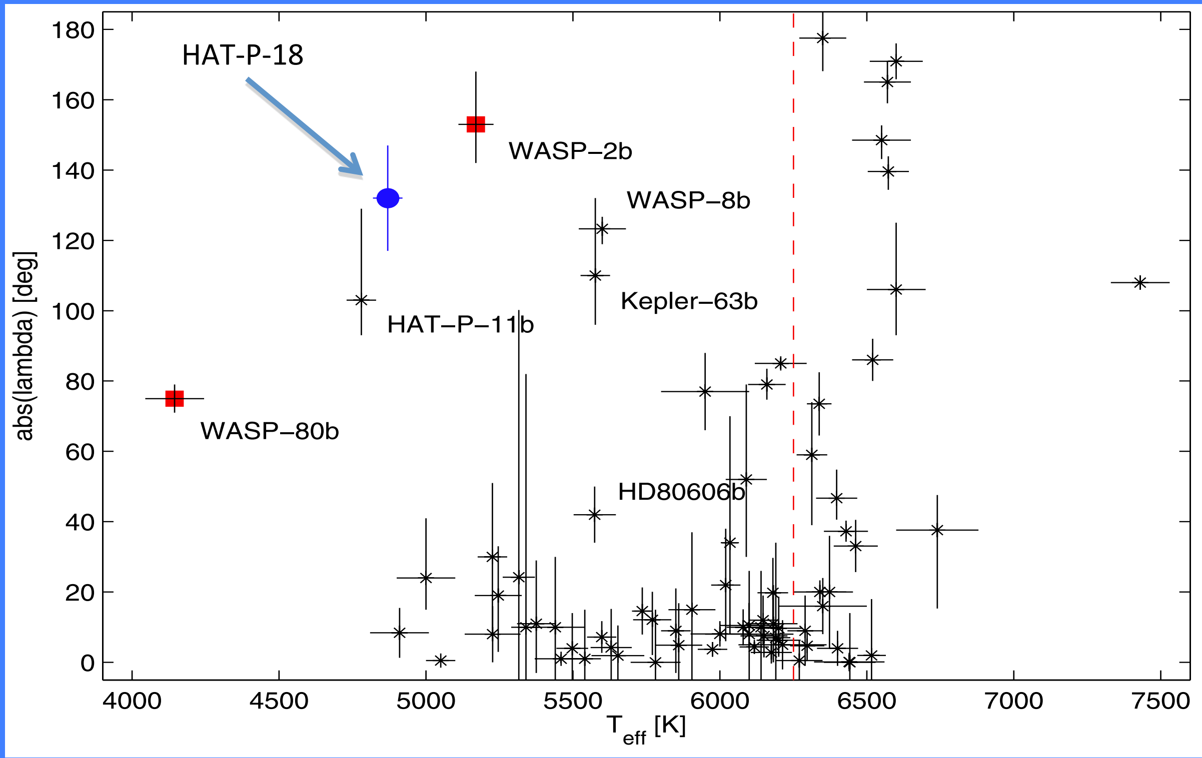

- Pillitteri et al. (2014a) studied the X-ray emission of HD 189733. Three coronal flares were observed close to the egress of the planetary transits (orbital phase range 0.55-0.65).

# Helicity modulation and flares

- The passage of the planetary magnetosphere across an extended stellar loop modulates its magnetic helicity and may trigger a flare (Lanza 2012);
- If an extended coronal loop is present in HD 189733 at an approximately constant longitude, then it can produce recurrent flares when it is perturbed by the planetary magnetosphere moving across its top (cf. Pillitteri et al. 2011, 2014a).



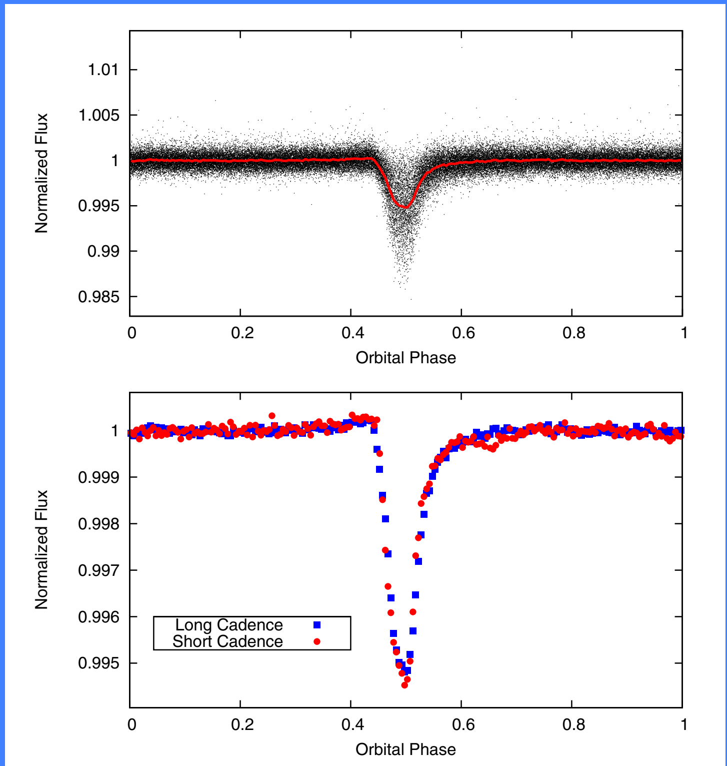
# Stellar obliquities

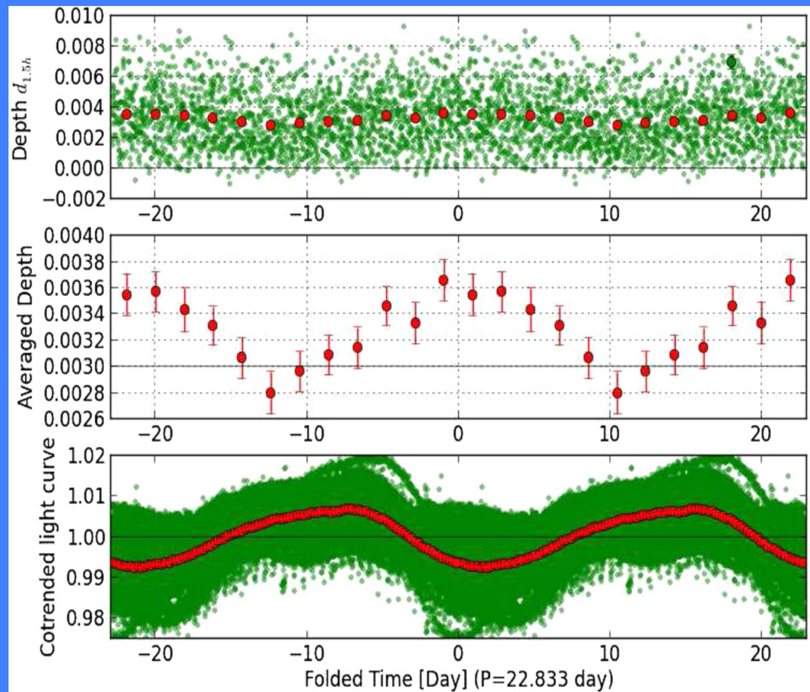



- Measuring tidal dissipation efficiency in stars of different $T_{eff}$ is crucial also to understand the distribution of the measured projected stellar obliquity (lambda) in planetary systems (picture from Esposito et al. 2014; see also Winn et al. 2010);
- Large body of theoretical investigations on this topics (e.g. Lai 2012; Albrecht et al. 2012; Rogers & Lin 2013).

# Magnetically modulated evaporation ?

- Kawahara et al. (2013) suggested that in the case of the very low-mass transiting planet KIC 12557548 (Rappaport et al. 2012; Croll et al. 2014), the transit depth of its cometary tail may change in phase with the modulation of the stellar light curve induced by starspots.




($P_{orb}$ = 15.685 hrs; a ≈ 0.013 AU; Croll et al. 2014)

(Kawahara et al. 2013)

# Linear force-free fields

- Force-free fields: $\nabla \times \mathbf{B} = \alpha \mathbf{B}$
- Taking the divergence of both sides: $\mathbf{B} \cdot \nabla \alpha = 0$
- Therefore α is constant along each magnetic field line;
- A *linear force-free* field is one whose α is the same along all the field lines;
- For a fixed magnetic helicity *H* and boundary conditions, it is the minimum energy field [REF.];

$$H = \int_V \boldsymbol{A} \cdot \boldsymbol{B} \, \mathrm{d}V,$$

  where **A** is the vector potential of the field, i.e. $\mathbf{B} = \nabla \times \mathbf{A}$
- When *H=0,* the minimum energy configuration for assigned boundary conditions is the potential field (α = 0).

# Magnetic field configurations

- The planet's magnetic field is potential (α=0), so a stationary magnetic field line connecting the surface of the star to the planet belongs to a potential field;

- On the other hand, the domains of the stellar field that are not potential cannot be stationarily connected to the planet's field because α is constant along a given field line;

- In that case, the two flux systems (planetary and stellar) are topologically separate from each other and interact only at a discontinuity surface where there is magnetic reconnection and energy release.

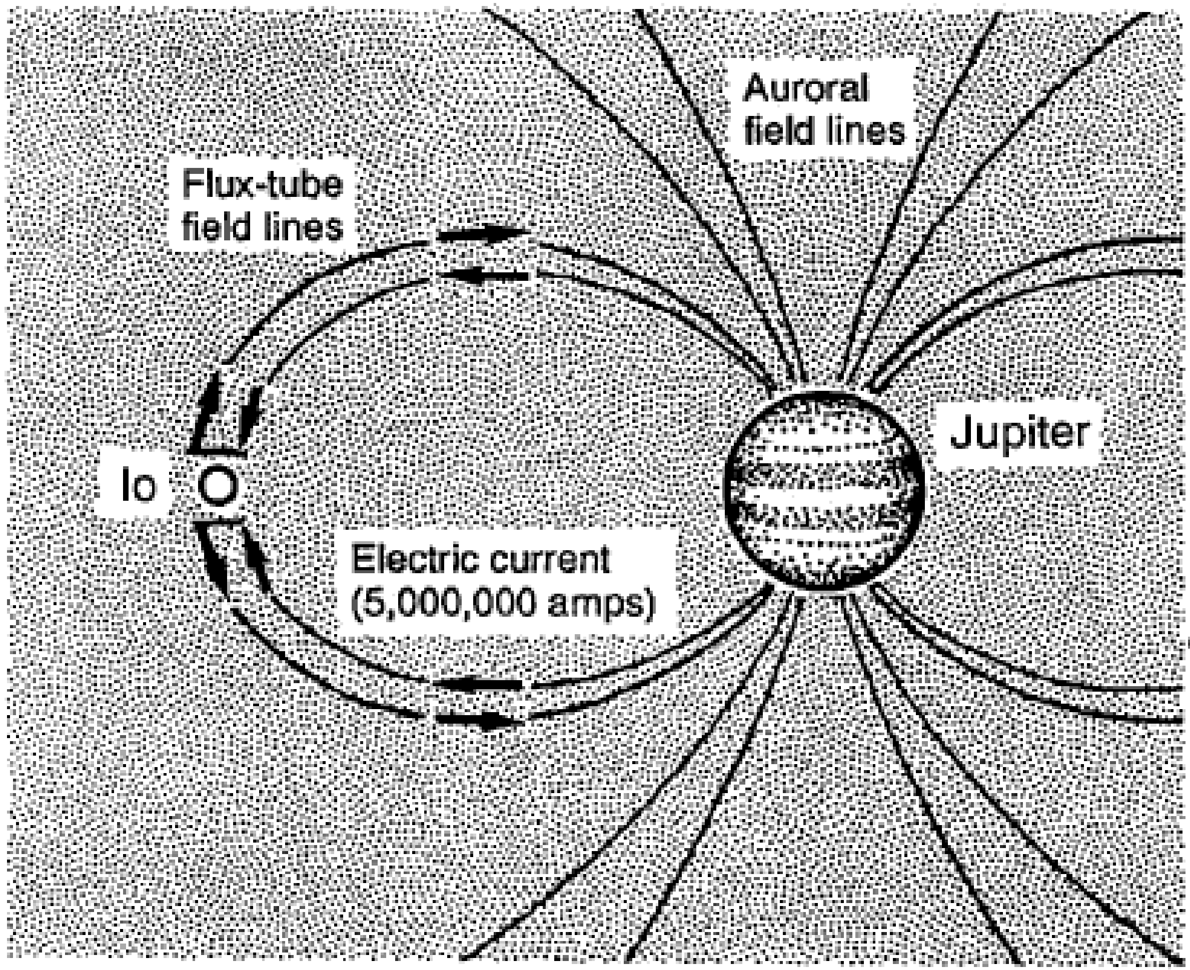



*Fig. 2. The electrical circuit model of the Io-Jupiter interaction. A few million amperes of electrical current flows through the circuit in the direction indicated by the arrows [after Goldreich and Lynden-Bell, 1969]. Note that the scale is distorted for clarity; the circuit path in Jupiter's ionosphere is of order 0.001 $R_J$ long.*

# Evaporation of planetary atmospheres

- Vidal-Madjar et al. (2003, 2004, 2008), Linsky et al. (2010), and others found evidence of deeper transits in Lyα and other FUV lines (e.g. Si III, C II) with depths 2-3 times larger than in the optical band in HD 209458, HD 189733, and WASP-12;
- A remarkable time variability has been found (e.g., Lecavelier des Etangs 2012);
- The absorbing material extends beyond the planet's Roche lobe and has velocities ranging from several tens of km/s up to ≈ 100-150 km/s;
- These observations are interpreted as evidence of evaporation of planetary atmospheres;
- Haswell et al. (2012) extended the approach to NUV lines in the case of WASP-12.

# What powers atmospheric evaporation ?

- The stellar EUV flux (≈ 1-100 nm) has been identified as the main source of energy to power evaporation;
- It depends on the stellar $T_{eff}$ and rotation rate;
- It can vary remarkably along the activity cycle (at least by a factor of 2-3 in the Sun) and be enhanced during flares;
- Due to interstellar H absorption, it is difficult to estimate (e.g., Ribas et al. 2005; Lecavelier des Etangs 2007; Sanz-Forcada et al. 2011; Linsky et al. 2013).

# The intriguing cases of CoRoT-2 and HD 189733

- CoRoT-2 and HD 189733 have visual M-type dwarf star companions whose age can be estimated from the level of their X-ray emission;
- Values of several Gyr are derived (e.g. Guinan 2013);
- The same method, or gyrochronology, can be applied to estimate the age of their primaries that host hot Jupiters;
- The ages of CoRoT-2 and HD 189733 are thus estimated to be ≈ 0.5 Gyr and ≈1-1.5 Gyr, respectively;
- Therefore, there is a remarkable discrepancy between these age estimates and those derived for the companions (Schröter et al. 2011; Pillitteri et al. 2014; Poppenhaeger & Wolk 2014);

- Is the presence of the HJ affecting stellar rotation ?
  - Pont (2009) proposed that close-in massive planets may spin up their hosts through tidal interaction;
  - Lanza (2010) and Cohen et al. (2010) proposed that the planet may reduce the stellar angular momentum loss rate by perturbing/modifing the stellar magnetized wind.

# References


- Beky et al. 2014, ApJ, 788, 1
- Ben-Jaffel & Ballester 2014, ApJL 785, L30
- Birkby et al. 2014, MNRAS, 440, 1470
- Bonomo & Lanza 2012, A&A, 547, A37
- Brown 2104, MNRAS 442, 1844
- Buzasi 2013, ApJL, 765, L25
- Cohen et al. 2009, ApJL, 704, L85
- Cohen et al. 2010, ApJL, 723, L64
- Cohen et al. 2011, ApJ, 733, 67
- Cohen et al. 2014, ApJ, arXiv:1405.7707
- Desert et al. 2011, ApJS, 197, 14
- Fares et al. 2010, MNRAS, 406, 409
- Fossati et al. 2010, ApJL. 714, L222
- Fossati et al. 2013, ApJL, 766, L20
- Guinan 2013, JAVSO, 41, 153
- Haswell et al. 2012, ApJ, 760, 79
- Kopp et al. 2011, ApJ, 729, 116
- Lai et al. 2010, ApJ, 721, 923
- Lanza 2008, A&A, 487, 1163
- Lanza 2009, A&A, 505, 339
- Lanza 2010, A&A, 512, A77
- Lanza 2012, A&A, 544, A23
- Lanza 2013, A&A, 557, A31
- Lanza & Shkolnik 2014, MNRAS, in press, arXiv: 1405.7245

# References


- Lanza et al. 2009, A&A, 493, 193
- Lanza et al. 2011a, A&A, 529, A50
- Lanza et al. 2011b, A&A, 525, A14
- Laskar 2008, Icarus, 196, 1
- Lecavelier des Etangs 2007, A&A, 461, 1185
- Lecavelier des Etangs et al. 2012, A&A, 543, L4
- Linsky et al. 2010, ApJ, 717, 1291
- Linsky et al. 2013, ApJ. 766, 69
- Linsky et al. 2014, ApJ, 780, 61
- Llama et al. 2011, MNRAS, 416, L41
- McQuillan et al. 2013, ApJL, 775, L11
- Meibom & Mathieu 2005, ApJ, 620, 970
- Miller et al. 2012, ApJ, 754, 137
- Moutou et al. 2007, A&A, 473, 651
- Ogilvie & Lin 2007, ApJ, 661, 1180
- Pillitteri et al. 2011, ApJL, 741, L18
- Pillitteri et al. 2014a, ApJ, 785, 145
- Pillitteri et al. 2014b, A&A 567, A128
- Pont 2009, MNRAS, 396, 1789
- Poppenhaeger et al. 2011, A&A, 528, A58
- Poppenhaeger & Wolk 2014, A&A, 565, L1
- Preusse et al. 2005, A&A, 434, 1191
- Preusse et al. 2006, A&A, 460, 317

# References


- Ribas et al. 2005, ApJ, 622, 680
- Sanz-Forcada et al. 2011, A&A, 532, A6
- Saur et al. 2013, A&A, 552, A119
- Schröter et al. 2011, A&A, 532, A3
- Shkolnik et al. 2003, ApJ, 597, 1092
- Shkolnik et al. 2005, ApJ, 622, 1075
- Shkolnik et al. 2008, ApJ, 676, 628
- Strugarek 2014, Presentation at Cool Stars 18, Flagstaff; https://d8cf70b1753ce8f714241f1c2851eb374d3d8933.googledrive.com/host/0BxBaqwiaesNkY2FVVkxOdEpoaEk/Strug_CS2014.pdf
- Strassmeier 2009, A&ARv, 17, 251
- Teitler & Konigl 2014, ApJ, 786, 139
- Vidal-Madjar et al. 2003, Nature, 422, 143
- Vidal-Madjar et al. 2004, ApJL, 604, L69
- Vidal-Madjar et al. 2008, ApJL, 676, L57
- Vidotto et al. 2010, ApJ, 720, 1262
- Vidotto et al. 2011, MNRAS, 411, L46
- Vidotto et al. 2013, A&A, 557, A67
- Vidotto et al. 2014, MNRAS, 438, 1162
- Walkowicz & Basri 2013, MNRAS, 436,1883
- Wu & Lithwick 2011, ApJ, 735, 109
- Zarka 2007, P&SS 55, 598