Aeronomy of hot Jupiters

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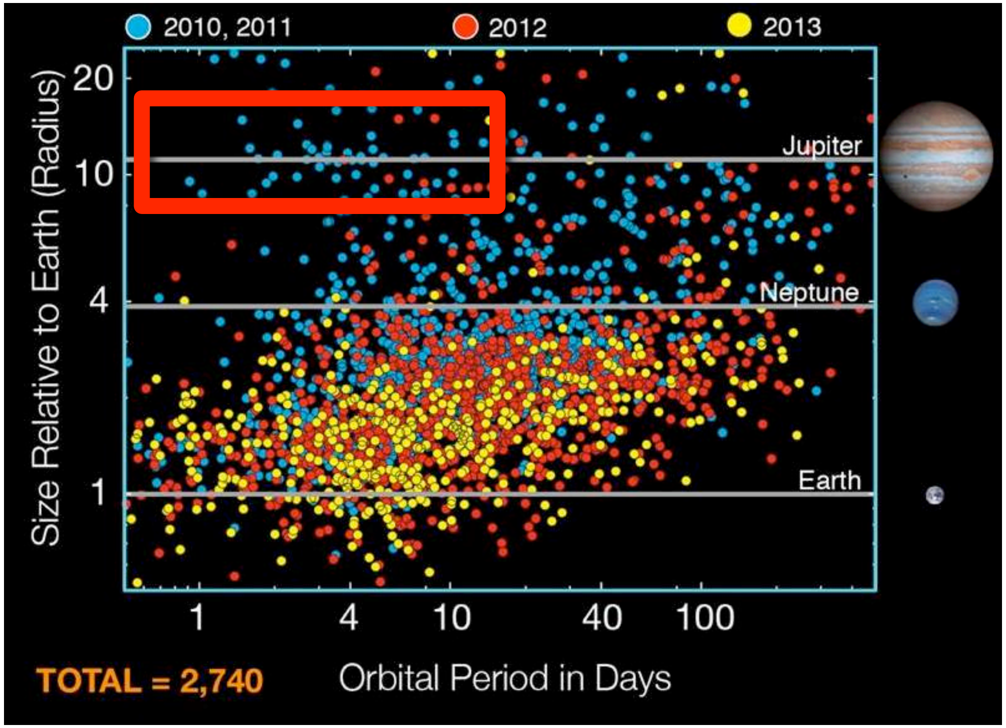
Hot Jupiters

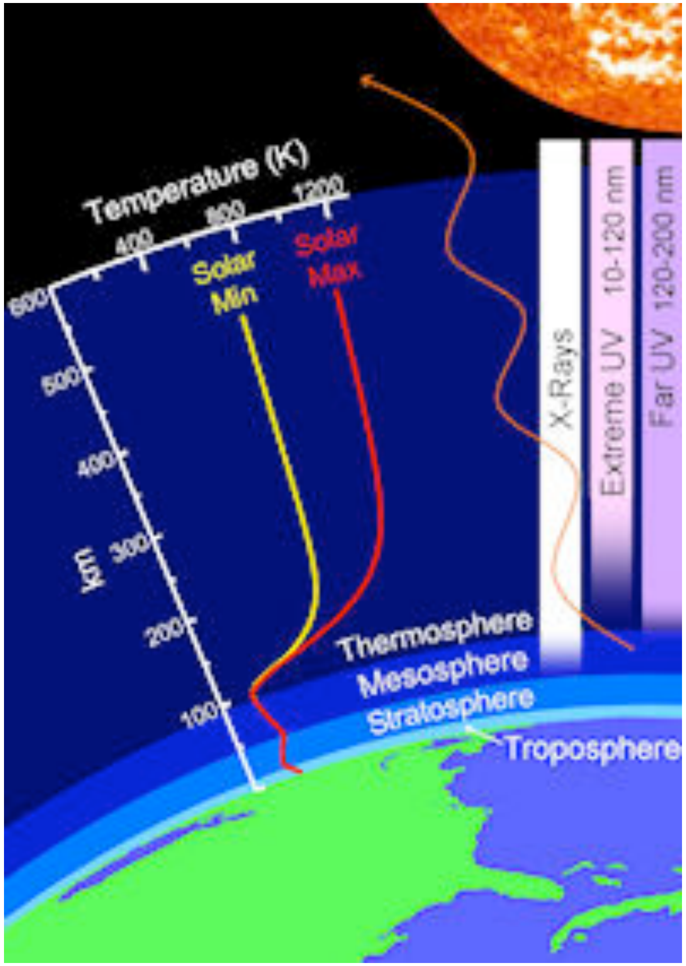


HJs are 'easy':

1) **to find (RV, transit)**
2) **to characterize**

HJs are 'pathfinders'

Aeronomy: Upper atmosphere physics & chemistry



credit: Science.nasa.gov

Scale height, H = k T / μ g

$p/p_0 \sim \exp(-z/H)$

Planet's in-transit size ~ H

On Earth:

Lower atm. (photosphere), H(z=0)~ 8 km

Upper atm., $H(z_{exosphere})$~ 5 x 8 km

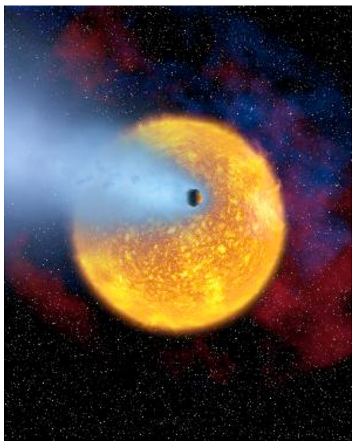
On Hot Jupiter

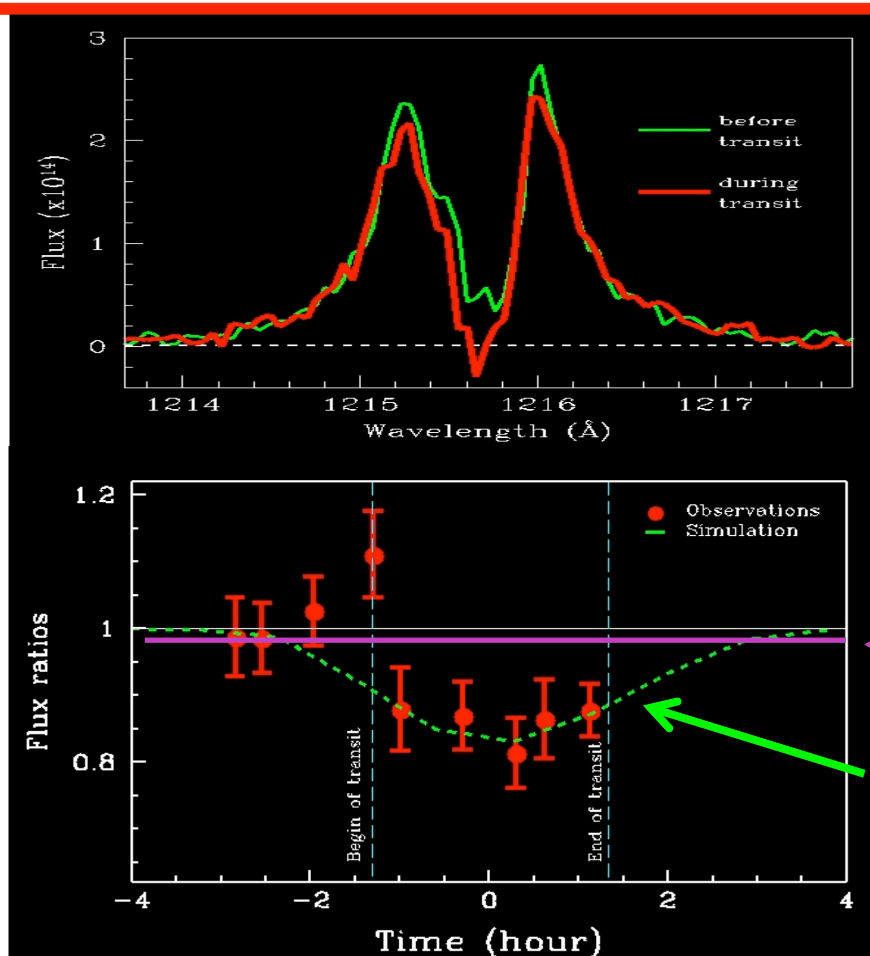
Lower atm., H(z=0)~ 700 km

Upper atm., $H(z_{exosphere})$~ (20-40) x 700 km

HD209458b's extended atmosphere

Optical thickness → Large σ:
Lyman-α: H(n=1) + hν (1215.67 Å) → H(n=2)





(Vidal-Madjar et al., 2003)

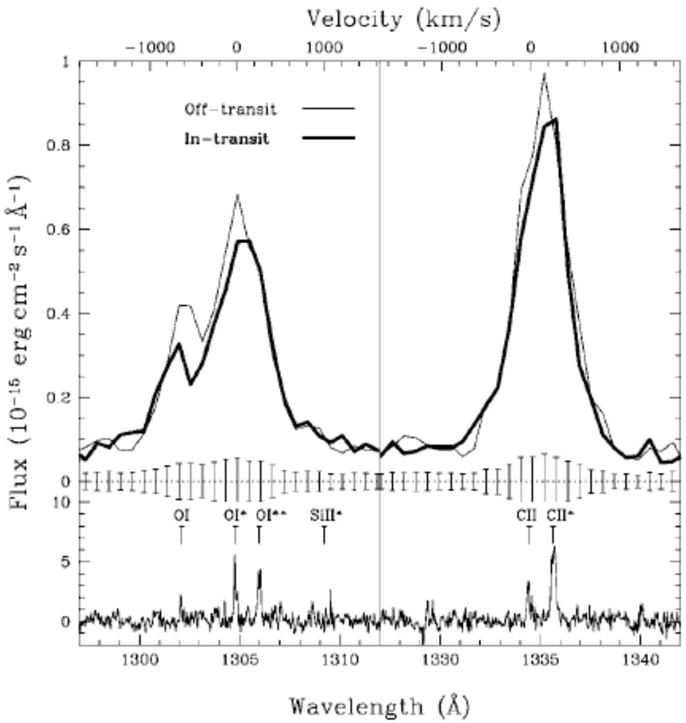
≈1.5% Dimming
→ $R_{visible}$

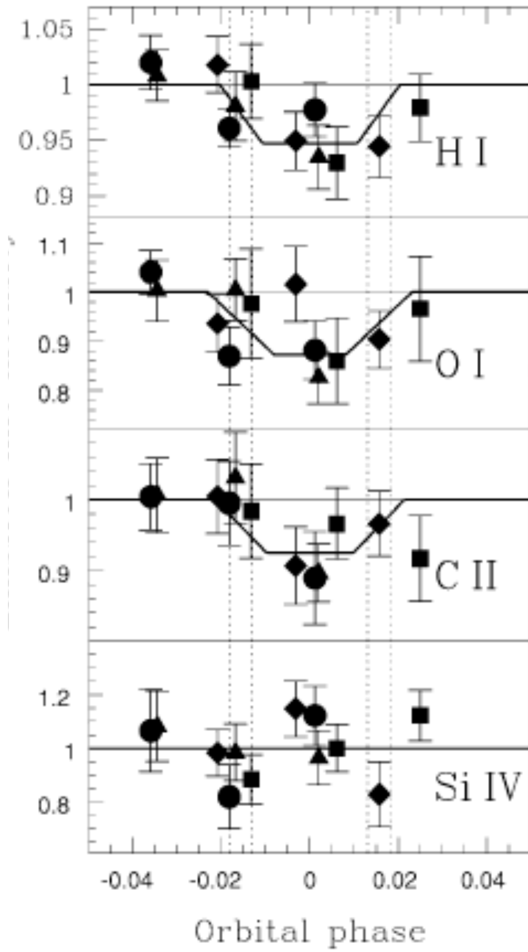
≈15% Dimming at Ly-α
→ $3R_{visible}$

HD209458b's extended atmosphere (+)

Confirmed H I; 1st evidence for O I & C II

(Vidal-Madjar et al., 2004)





Dimming:

H I: 5-15%

O I: 13%

C II: 7.5%

(i) Extended Atmosphere~3R_{vis}

(ii) Heavy atoms;

(iii) C II is ionized

Modeling HD209458b's atmosphere

Aeronomy models: e.g. Yelle, 2004; Tian et al., 2005, …
***García Muñoz, 2007…*, Koskinen et al., 2013**

Conservation Equations

Mass for all species

$$\frac{\partial(r^2\rho_s)}{\partial t}+\frac{\partial}{\partial r}(r^2\rho_s u)+\frac{\partial}{\partial r}(r^2\rho_s(u_s+v_s))=r^2\dot{\omega}_s,\quad s\in\mathcal{S},$$

Momentum

$$\frac{\partial(r^2\rho u)}{\partial t}+\frac{\partial}{\partial r}(r^2(\rho u^2+p))=r^2\rho f_{\mathrm{ext}}+2pr,$$

Energy

$$\frac{\partial(r^2\rho E)}{\partial t}+\frac{\partial}{\partial r}(r^2(\rho E+p)u)+\frac{\partial(r^2 q)}{\partial r}=\rho u r^2 f_{\mathrm{ext}}+r^2 Q.$$

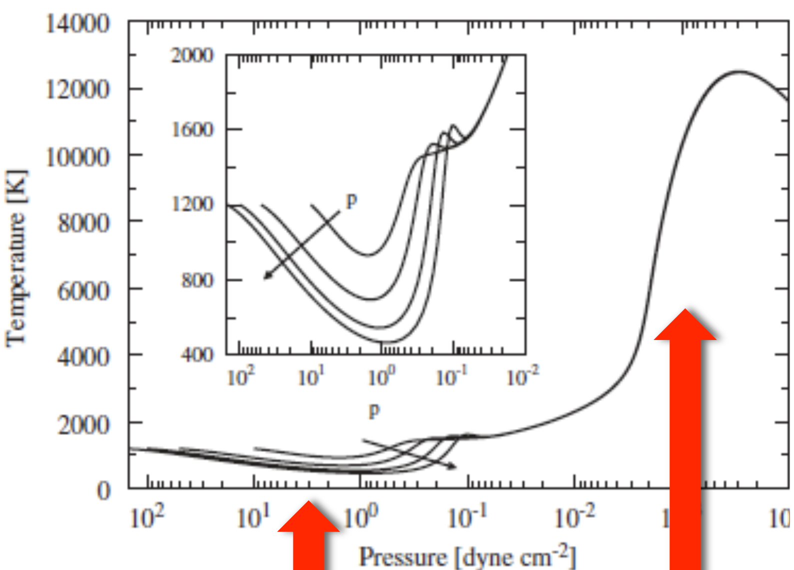
GM07: 46 species (*n-i-e;* >200 reactions) → 46+2 equations

Physical/chemical processes

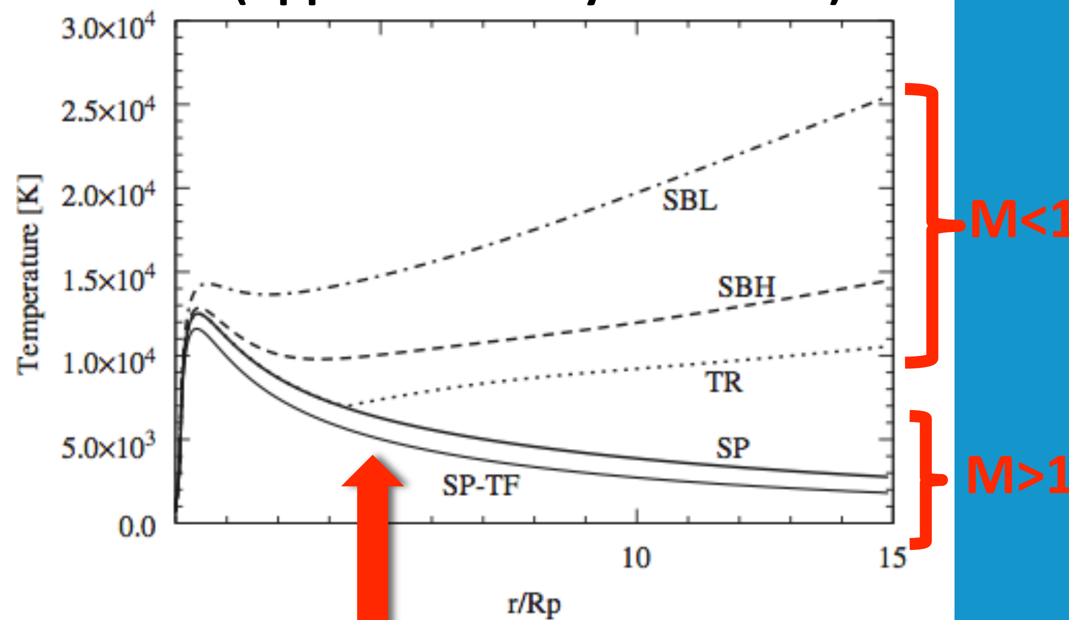
Compressible equations: *1-M^2 singularity* at sonic point

Discussion: Temperature

Reference T(p)



Interaction with environment (upper boundary condition)

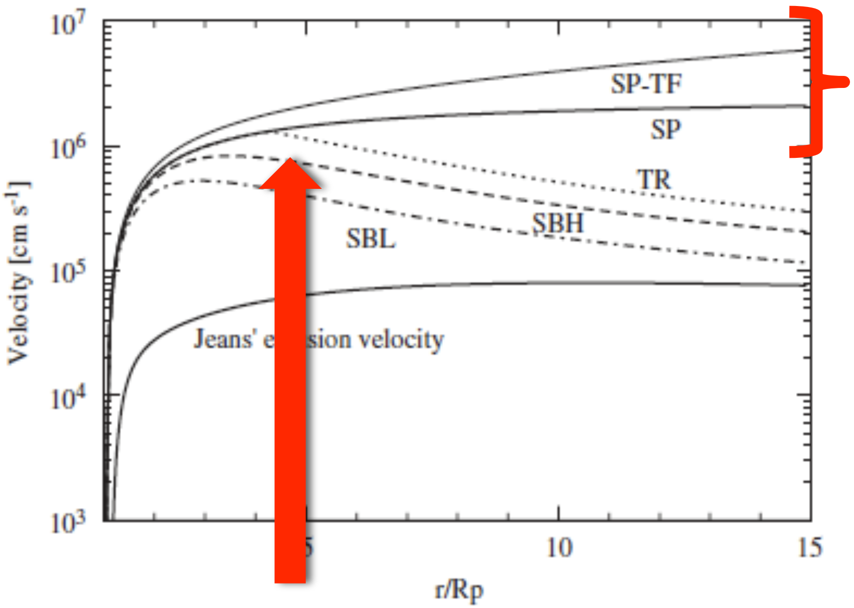


Energy deposition

Sonic point

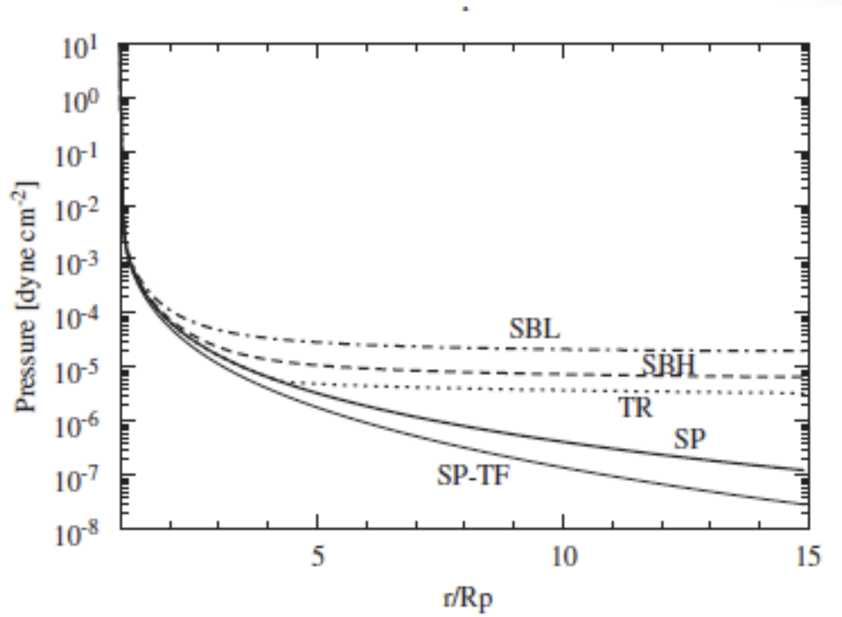
Energy-limited flow

Discussion: velocity & pressure

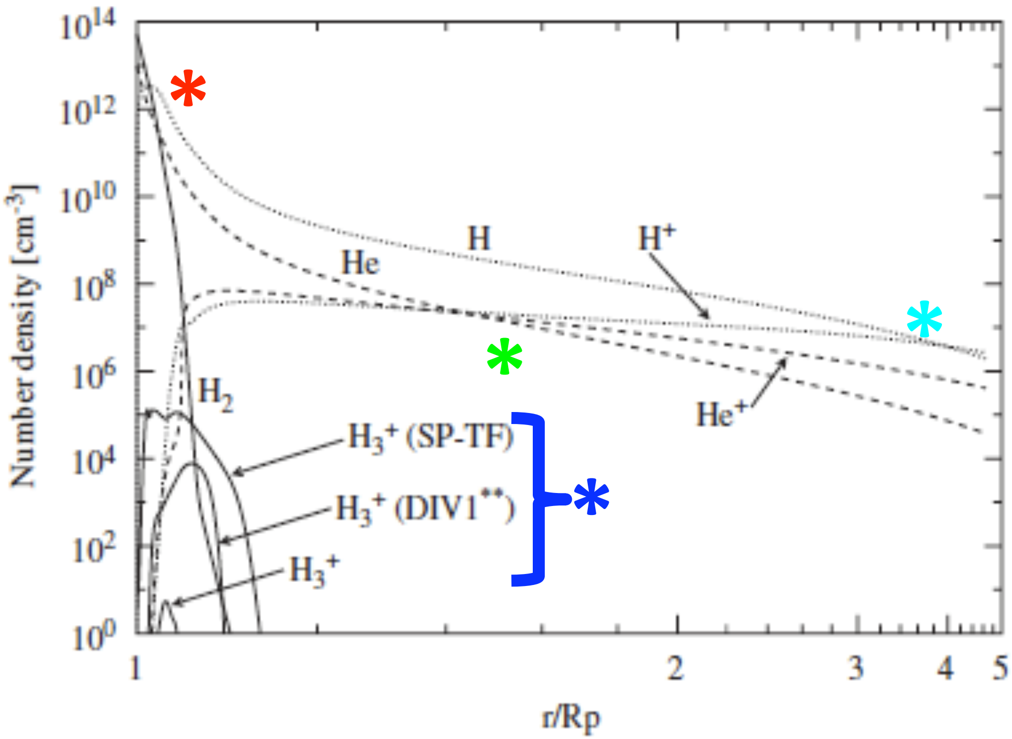


v ~ 10 km s^{-1}

Sonic point



Discussion: H & He chemistry



Highlights:

* H_2 → H @ 1.05 R_p

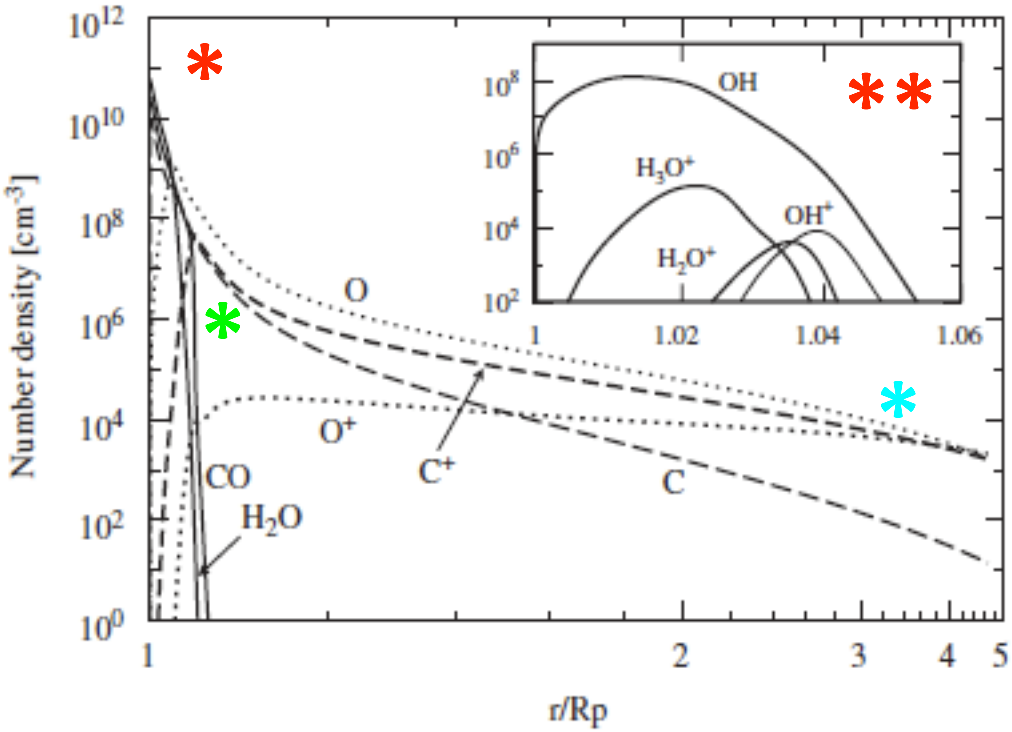
* H → H^+ + e^- @ >3 R_p

* He → He^+ @ 1.5 R_p

* H_3^+ : IR radiator; aurora

H_3^+ Loss: Reaction with CO & H_2O

Discussion: C & O chemistry



Highlights:

* H_2O, CO → O @ 1.05 R_p

** H_2O [CO]: complex in the *heavier* atmosphere.

* O → O^+ + e^- @ >3 R_p
(H^+ + O ←→ O^+ + H)

* C → C^+ @ 1.05 R_p

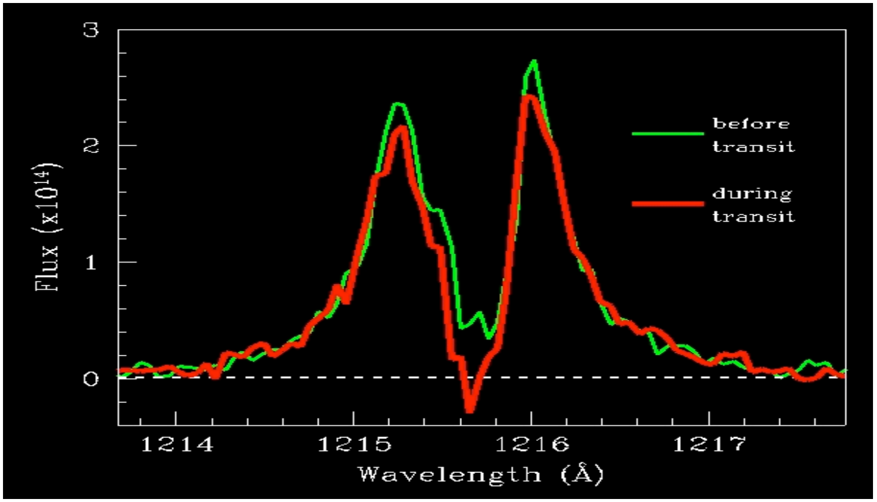
Discussion: H I, O I & C II chemistry

Aeronomy models (1D):

H, O, C^+ atoms dominate at ~$3R_p$ ✓

They do not reproduce line absorption shape ✗

$\Delta V_{thermal} + \Delta V_{natural}$ ~ 10-20 km s^{-1} << 100 km s^{-1}



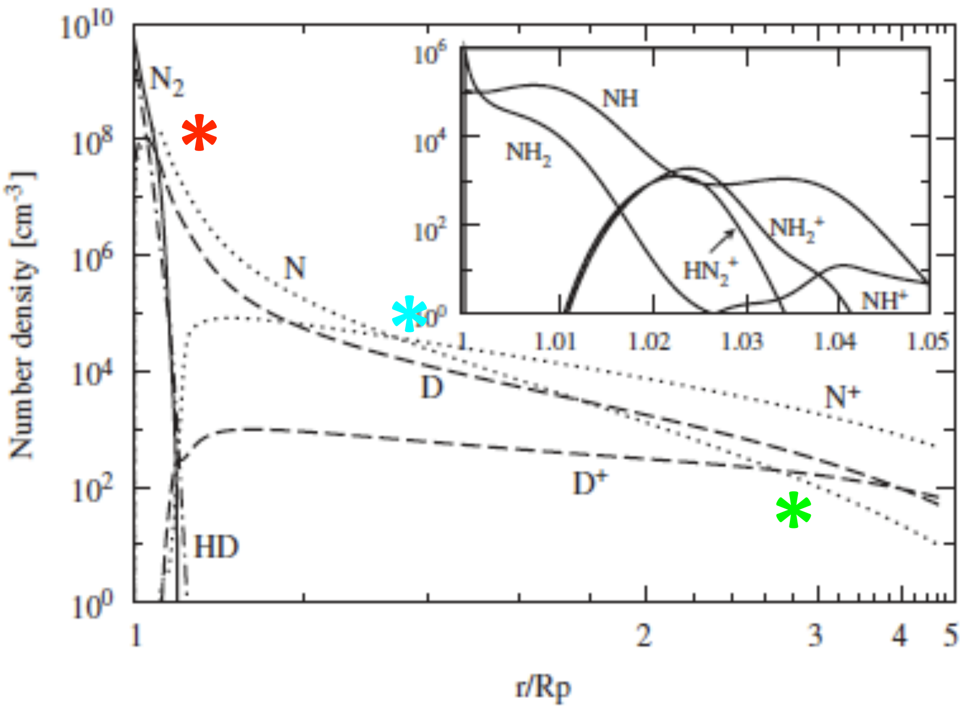
(Vidal-Madjar et al., 2003)

Other mechanisms invoked

- H I acceleration by radiation pressure & ENAs (Kislyakova et al. 2015)
- Magnetohydrodynamics (Trammell et al., 2014)

3D effects simulated only for H I

Discussion: N & D chemistry



Highlights:

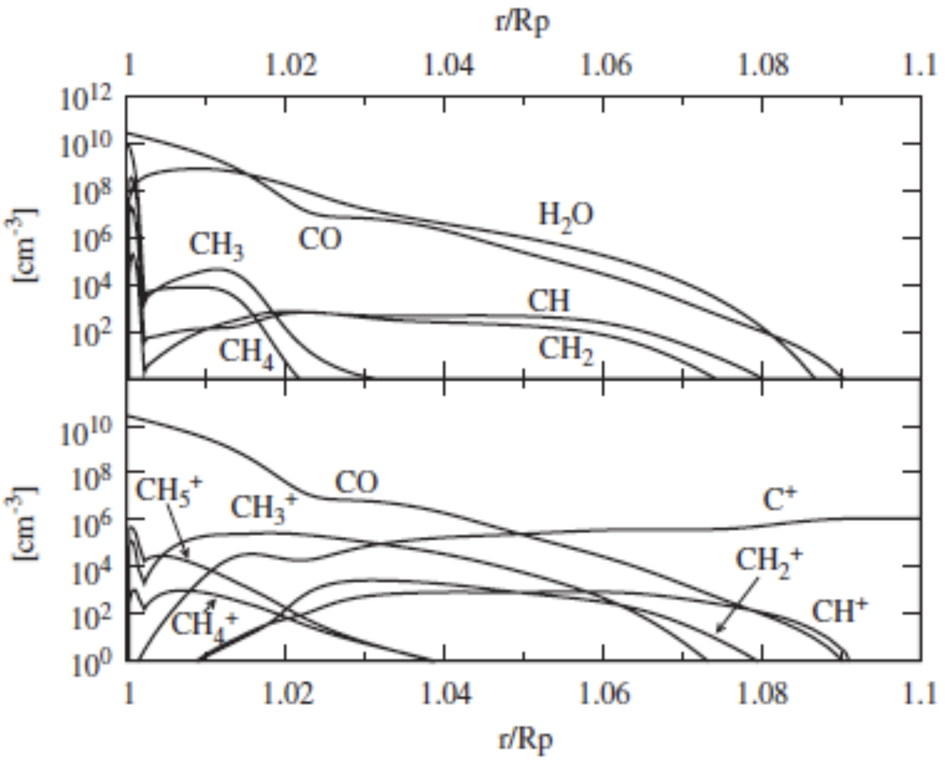
* $N_2 \rightarrow N$ @ 1.05 R_p

* $N \rightarrow N^+ + e^-$ @ 1.5 R_p

* $D \rightarrow D^+$ @ 3 R_p
($H^+ + D \leftrightarrow D^+ + H$)

Conclusion: Complex NH_3 chemistry at ~1.05 R_p

Discussion: CH_x chemistry

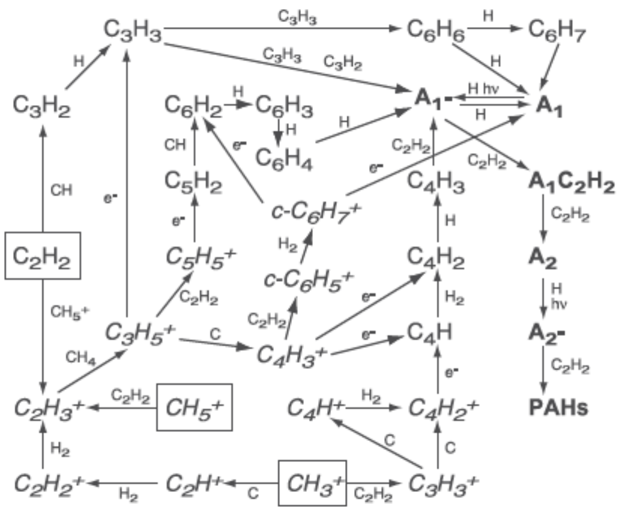


Complex CH_x chemistry in dense atmosphere

Largest CH_x in scheme: CH_5^+

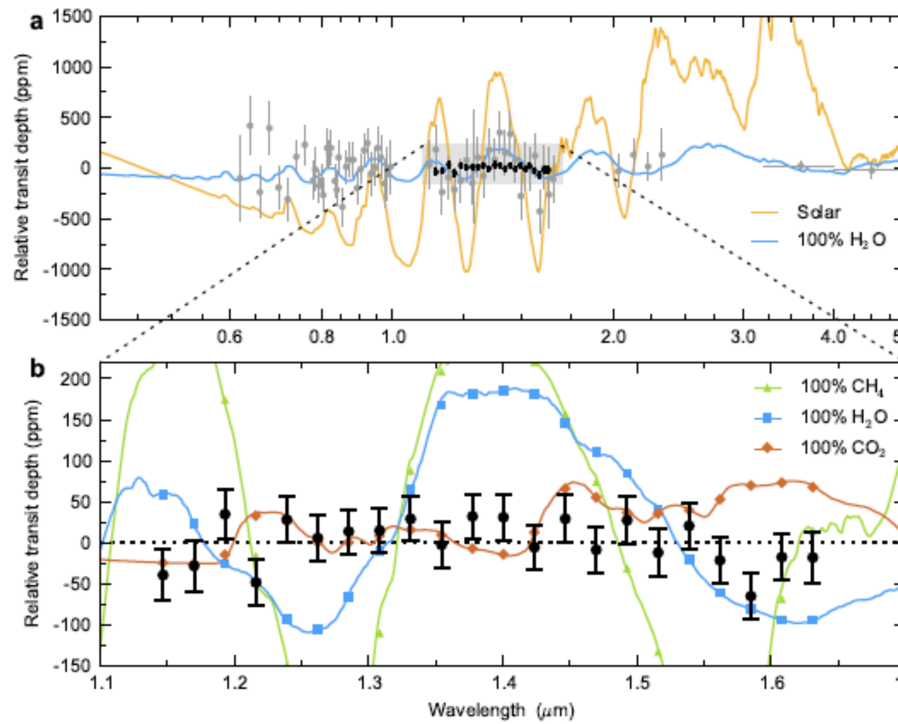
CH_x^+ chemistry → PAH → *Titan-like haze??*

Discussion: CH_x chemistry



(Wong et al., 2003)

Transmission spectrum of super-Earth GJ 1214b



(Kreidberg et al., 2014)

Predicting haze is key for transmission spectroscopy!!!

Chemistry summary

HD 209458b : H I, O I, C II, Mg I, Si II **(Linsky et al. 2010)**

HD 189733b : H I, O I, C II (??) **(Lecavelier des Etangs et al. 2010; Ben Jaffel & Ballester, 2013)**

but no detection of H I in another run !! **(LdE et al. 2012)**

GJ 436b (hot Neptune) : H I **(Kulow et al., 2014)**

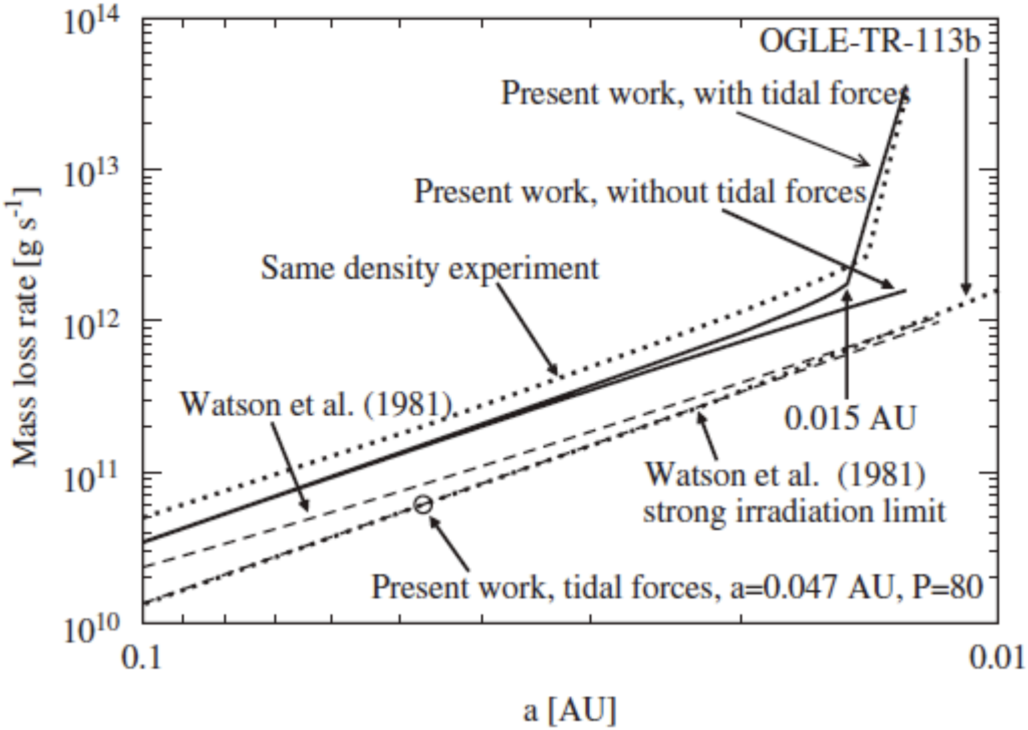
Very active field. Upper atmosphere connects planetary environment and lower atmosphere.

UV region depends on HST. Replacement?
World Space Observatory-UV (launch date 2017-2018?)

Atmospheric mass loss rates

$$\dot{m} = \boldsymbol{\rho}\ \mathbf{u}\ \mathbf{v}$$

HD 209458b's lifetime: $M_p/\dot{m}$~ 100 Gigayears

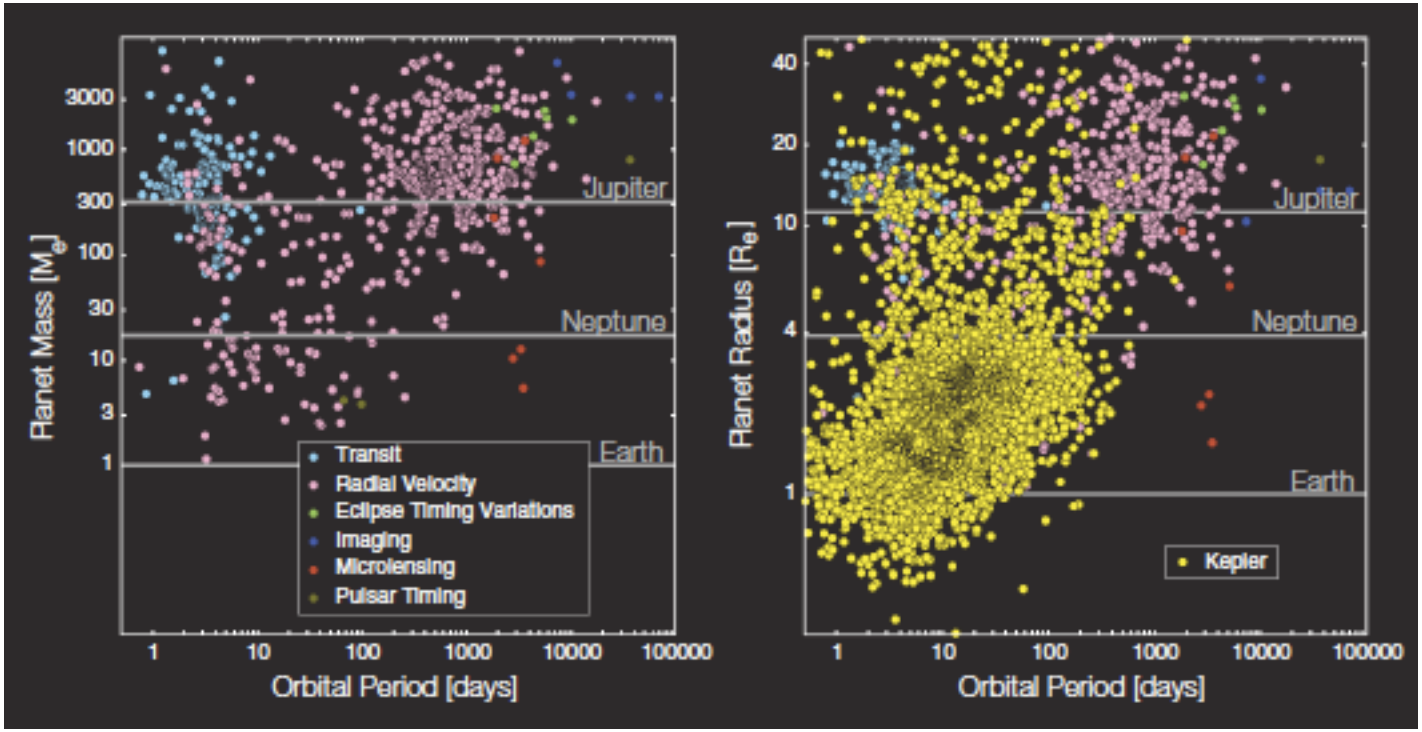


Shorter lifetime if:

- Planet is lighter
- Planet is much closer-in

Atmospheric mass loss rates (+)

$M_p - R_p$ picture formed by Kepler:



(Batalha et al., 2014)

To be completed by CHEOPS (2017), TESS (2018), PLATO (2024)

Chemistry is part of a larger problem

Thanks!

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