STUDIUM EXPOLANET: JEDEN Z NEJRYCHLEJI SE ROZVIJEJICICH OBORU SOUCASNE ASTROFYZIKY

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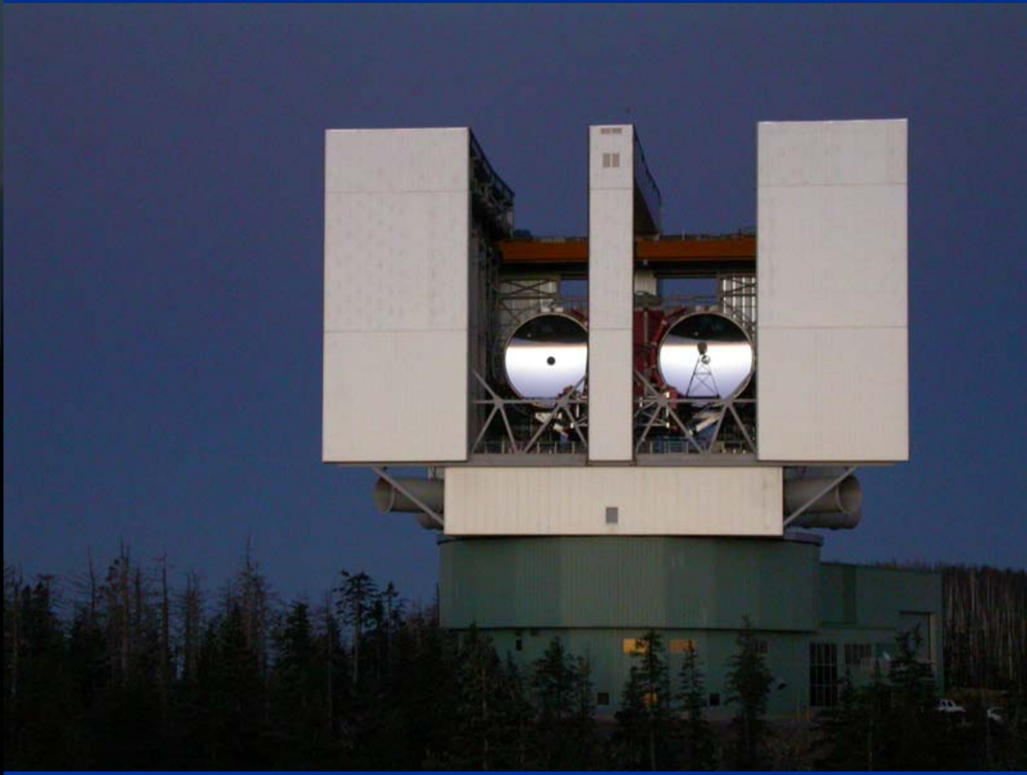


Obsah

- Uvod
- Detekce exoplanet
- Transitujici planety --> presne urceni hmoty a polomeru
- Vyvojove modely: souhlas mezi teoretickymi a zmerenymi hodnotami hmoty a polomeru?
- Modely atmosfer a teoreticka spektra
- Sekundarni zakryty --> prvni pozorovana spektra!
- Analyza spekter - existence exoplanetarnich stratosfer?
- Zaver

Exoplanety: Proc?

- Vrozena lidska zvedavost:
  - Jak vypadaji objekty mensi nez hvezdy?
  - Jsou podobne sluncenim planetam?
  - Kdyz ne, tak proc?
- Astronomicke duvody:
  - Pochopeni Vesmiru znamena pochopeni vsech jeho komponenet, tedy i malych
  - Studium exoplanet, jejich vzniku a vyvoje, dava dodatecnou informaci o protostelarnich a protoplanetarnich discich attedy i vniku hvezd
  - Jsou mimoslunceni planetarni systemy vzacne nebo bezne?
  - Exoplanety: vesmirne laboratore pro studium hmoty za jinak tezko realizovatelnych podminek
- Fundamentalni - filosoficke duvody:
  - EXISTUJE ZIVOT MIMO ZEMI/SLUNECNI SOUSTAVU?
  - Jak je mozne detekovat zivot na dalku?
  - Pokud ano, co je mozno rict o jeho vlastnostech?

EXOPLANETY: JAK?

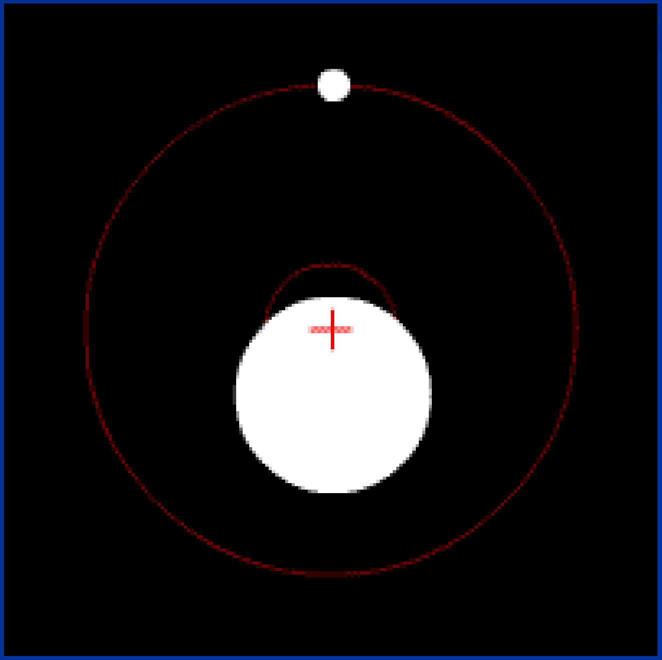
- Dynamicke jevy
  - Mereni indukovanych radialnich rychlosti materske hvezdy
- Fotometrie
  - Prechody planety pred hvezdou, snizeni svetla hvezdy
- Prime zobrazeni (narocne)
- Microlensing (gravitacni cocka)

Trochu historie

- Uz historicky nekteri lide predpokladali ze mimoslunceni planety existuji (napr. Giordano Bruno)
- 1992 - prvni telesa podobna planetam (obihajici okolo pulsaru) objevena (PSR B1257+12 b,c,d) (Wolsz**czan 1992)**
- **1995** - objevena prvni exoplaneta u hvezdy - **51 Peg b** (Mayor & Queloz) => POCATEK INTENZIVNIHO STUDIA EXOPLANET. Velke prekvapeni: hmotnost Jupitera, ale 100 x blize ke sve hvezde nez Jupiter!
- **1995** - (ten samy den) - ohlaseni prvniho hnedeho trpaslika - **Gliese 229b** (Nakajima et al., Oppenheimer et al.)
- **2000** - prvni pozorovani exoplanetarniho transitu - **HD 209458b** (Charbonneau et al., Henry et al.)
- **2002** - prvni detekce spektroskopicke informace pro exoplanetu - **cara Na I u HD 209458b**
- **2005** - prvni pozorovani sekundarniho zakrytu - **HD 209458b, TR-ES-1** ==> tedy prvni detekce spektra exoplanety (Charbonneau et al., Deming et al.)

DETEKCE POMOCI RADIALNICH RYCHLOSTI

Presne stejne jako spektroscopicke dvojhvezdy, pouze amplituda rychlostnich zmen daleko mensi, a tedy hure meritelna.



Pozorovane:
- amplituda zmen radialnich rychlosti
- perioda zmen
- hmotnost hvezdy (z jejiho spektra)

Z toho lze urcit (z Keplerovych zakonu):
- M_P sin i (spodni mez hmotnosti planety)
- a (velka poloosa drahy planety)
- e (excentricita drahy)

- ale nic dalsiho o jejich vlastnostech!

TRANSITUJICI PLANETY

HD 209458b

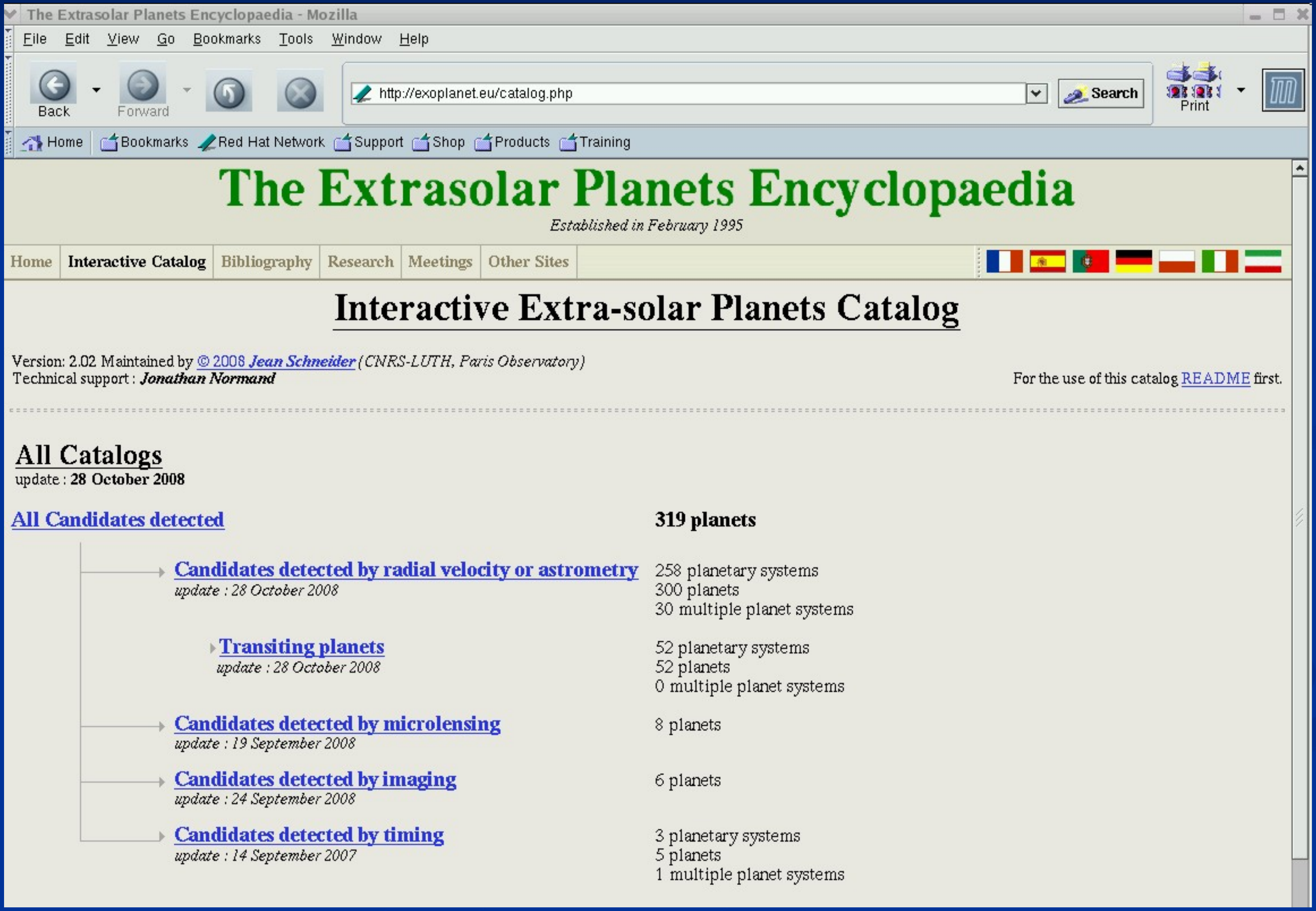
ve skutecne skale

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

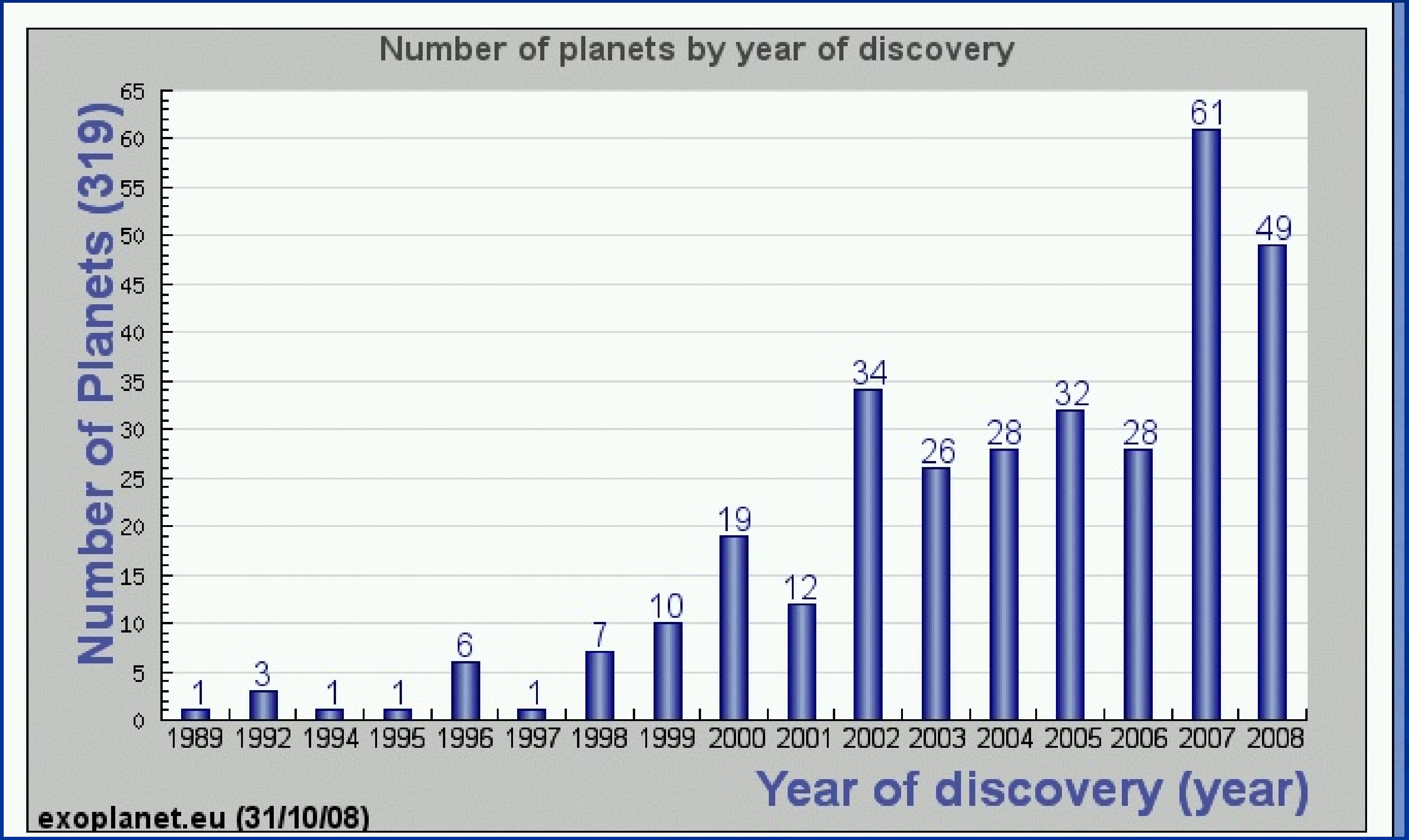
svetelna krivka
(vse co je k dispozici)
Zmena svetla *1.6%*
(pro HD 209458b)

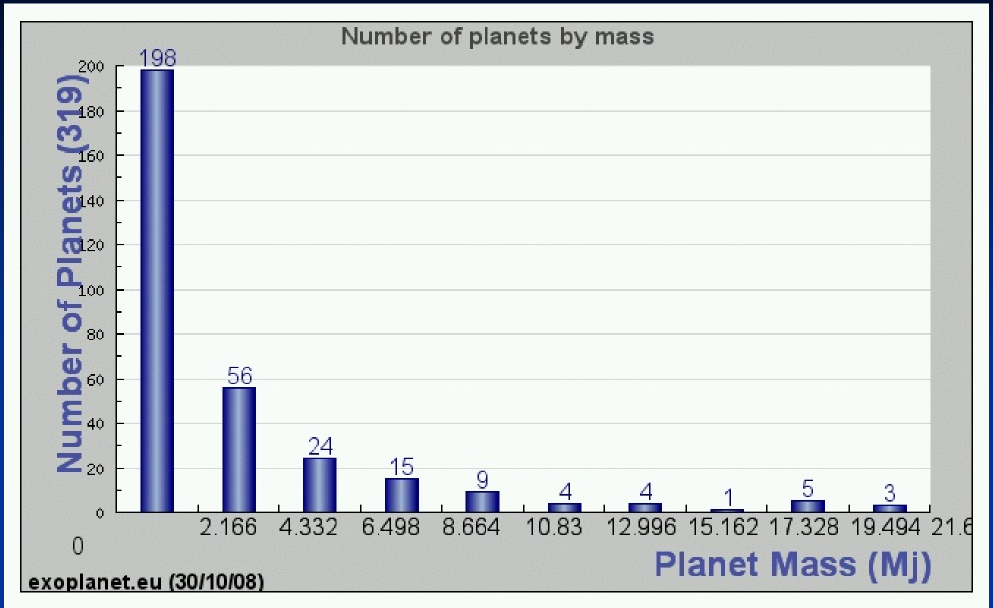
- presne urceni hmotnosti a polomeru planety!

Uzitecny website

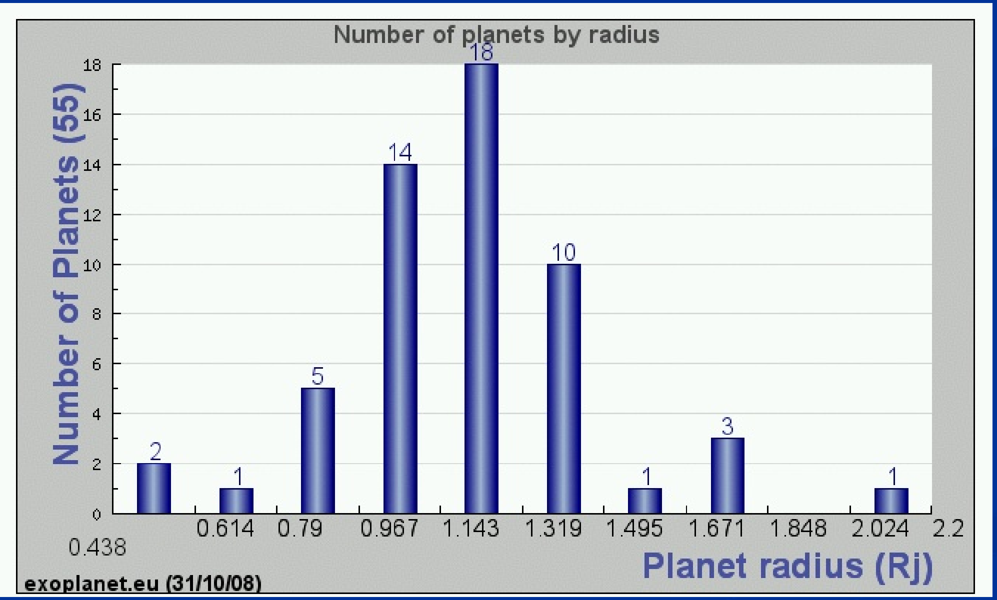


Historie objevovani exoplanet

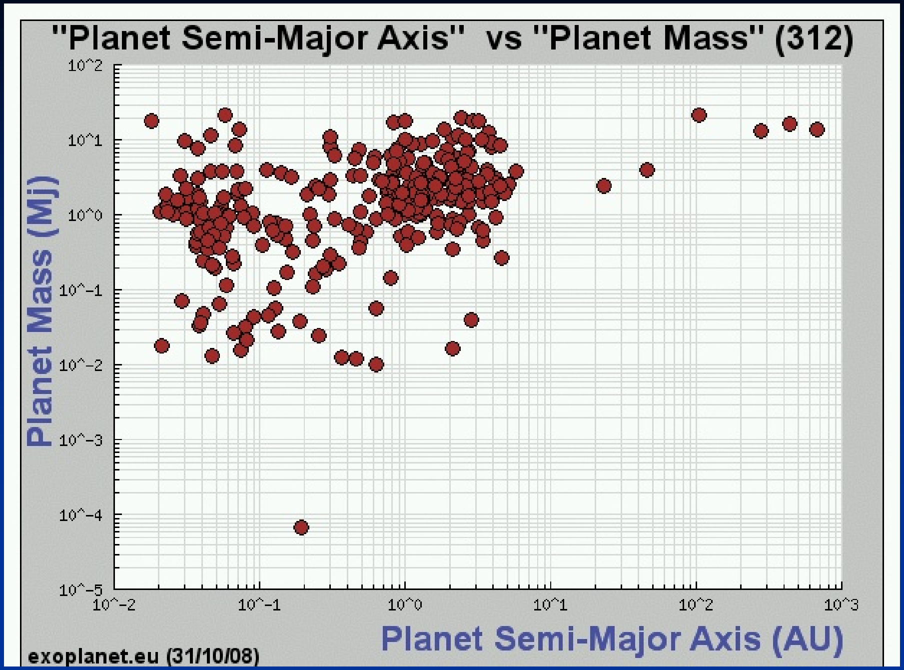




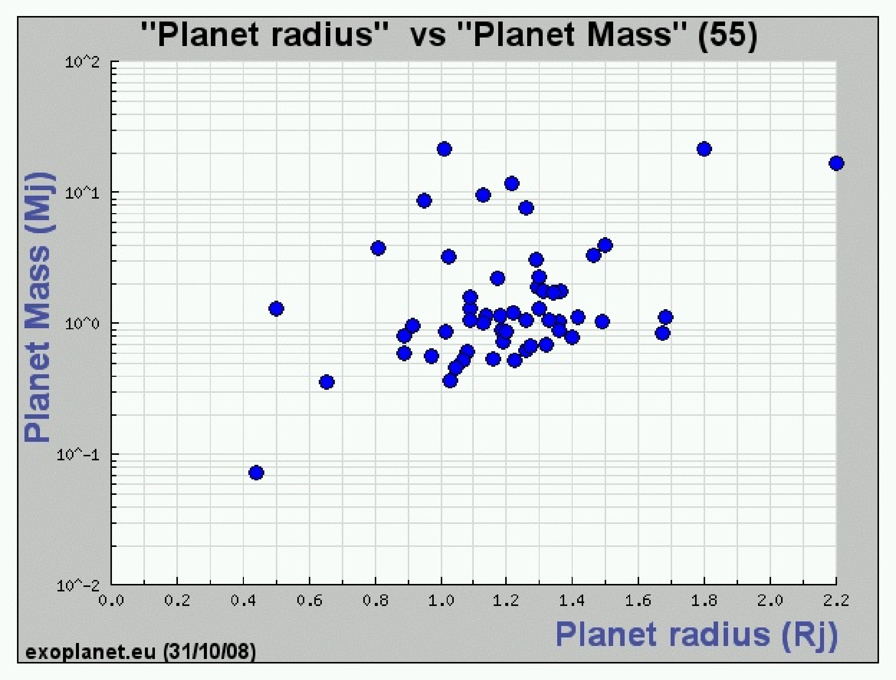
Histogram rozlozeni hmotnosti



Histogram rozlozeni polomeru



Korelace: velka poloosa-hmotnost



Korelace: polomer-hmotnost

Obri planety - zakladni fakta

- Vetsina objevenych planet podobna Jupiteru; nektere hmotnejsi, nekolik jako Saturn, a nekolik dokonce jako Neptun
- Pro odliseni od planet podobnych Zemi, jmeno Obri Exoplanety (Extrasolar Giant Planets - EGP)
- Planety jsou plynne, pripadne s velmi malym jadrem z materialu v pevne fazi (“rocky core” = “skalni jadro”)
- Chemicke slozeni planety je velmi podobne chemickemu slozeni materske hvezdy; obvykle blizke ke Slunecnimu slozeni
- Slunecni slozeni (dle poctu atomu): ~90% H; ~10% He; $\sim 10^{-3}$ O; $\sim 10^{-4}$ C, N, Ne; $\sim 10^{-5}$ Mg, Si, S, Fe, atd.
- Jupiter a Saturn - chemicke slozeni blizke slunecnimu
- Uran a Neptun - stale plynne, ale slozeni bohatsi na tezke prvky
- Extrasolarni obri planety - modely predpokladaji slozeni stejne jako jejich materska hvezda

Vyvoj planetarniho polomeru

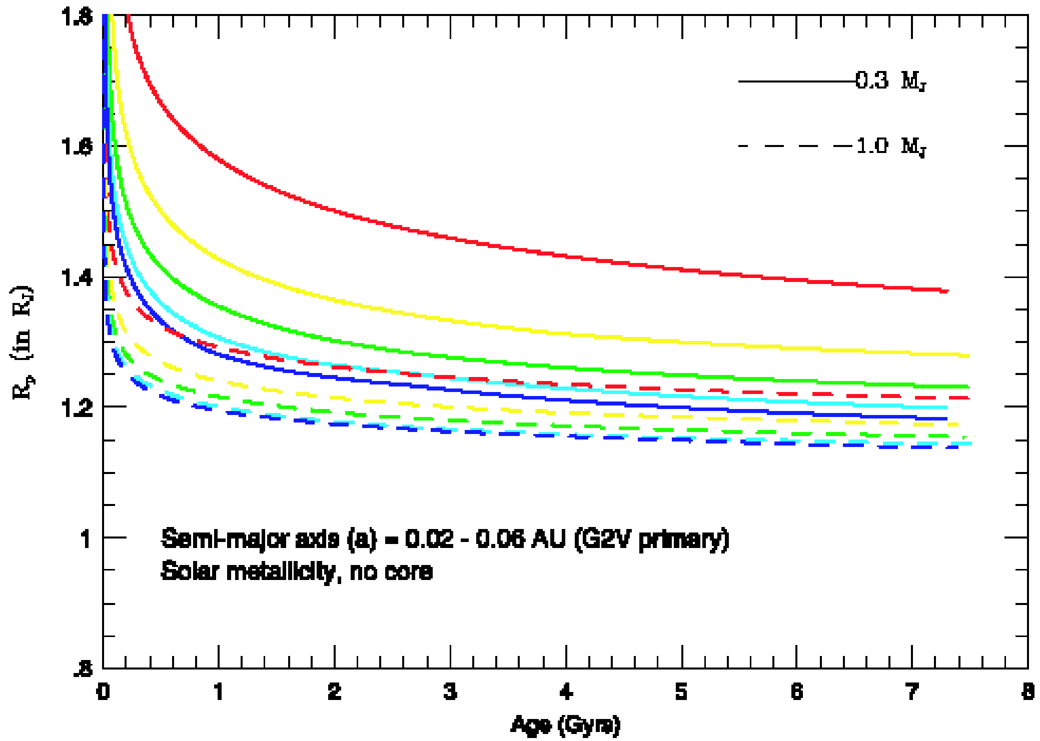


FIG. 3.—R_p (in R_J) vs. age (in Gyr) for model planets with masses of 1 M_J (*dashed lines*) and 0.3 M_J (*solid lines*) for different distances [0.02 (*red lines*), 0.03 (*yellow lines*), 0.04 (*green lines*), 0.05 (*aqua lines*), and 0.06 AU (*blue lines*)] from a G2 V primary. The models have no cores and assume solar metallicities when calculating the opacities. This plot portrays the systematic dependence of irradiated planet radii with orbital distance for different masses. See text in § 3 for a discussion.

polomer mene hmotnych planet je citlivejsi na vzdalenst

Burrows, Hubeny, Budaj, Hubbard, 2007

Fitovani pro mensi planety

Dobry fit, ale spatne fyzikalni predpoklady

Lepsi fyzika, ale horsi fit

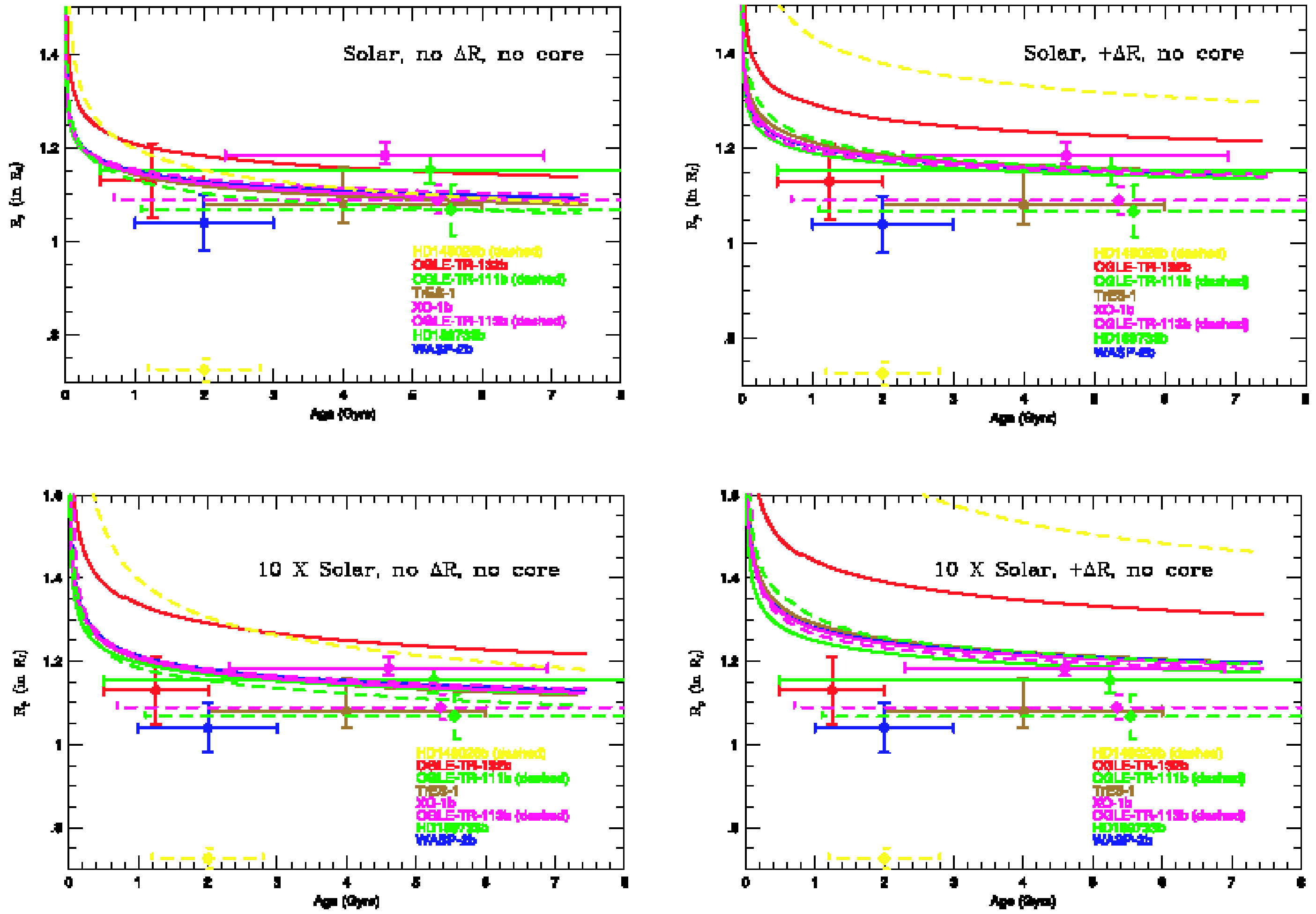


FIG. 6.— R_p (in R_J) vs. age (in Gyr) for a collection of no-core models for the smaller transiting EGPs. They include HD 149026b (*yellow dashed line*), HD 189744b (*green line*), OGLE-TR-113b (*purple dashed line*), OGLE-TR-111b (*green dashed line*), XO-1b (*purple line*), TrES-1 (*gold line*), WASP-2b (*blue line*), and OGLE-TR-132b (*red line*). The top left panel is for solar opacities and does not include the ΔR term. The top right panel is also solar, but does include the ΔR term. The bottom left panel is for 10×solar opacities, but does not include the ΔR term. The bottom right panel also assumes 10×solar opacities, but does include the ΔR term. This bottom right panel contains our default no-core/no-cloud models. The age of WASP-2b has been arbitrarily set at 2.0 ± 1.0 Gyr. The barely perceptible kinks near ~700 Myr in the curves for OGLE-TR-132b (*red line*) at the bottom left and right and for OGLE-TR-111b (*dashed green line*) at the bottom right are convergence glitches in the evolutionary tracks for those models. See discussion in § 5.

vetsi zastoupeni tezsich prvku nepomuze

Fitovani planetarniho polomeru na vyvojove modely (vetsi planety)

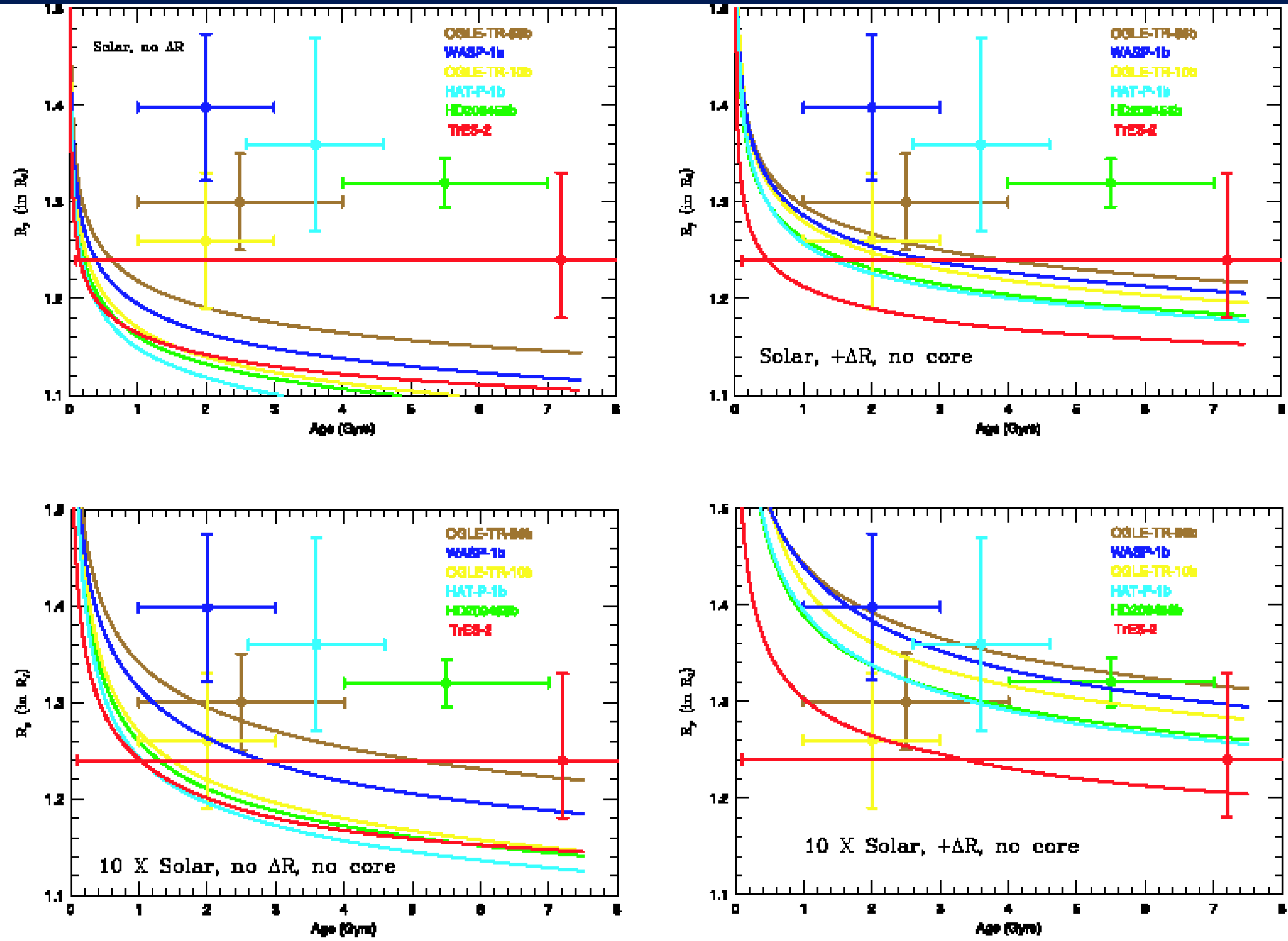
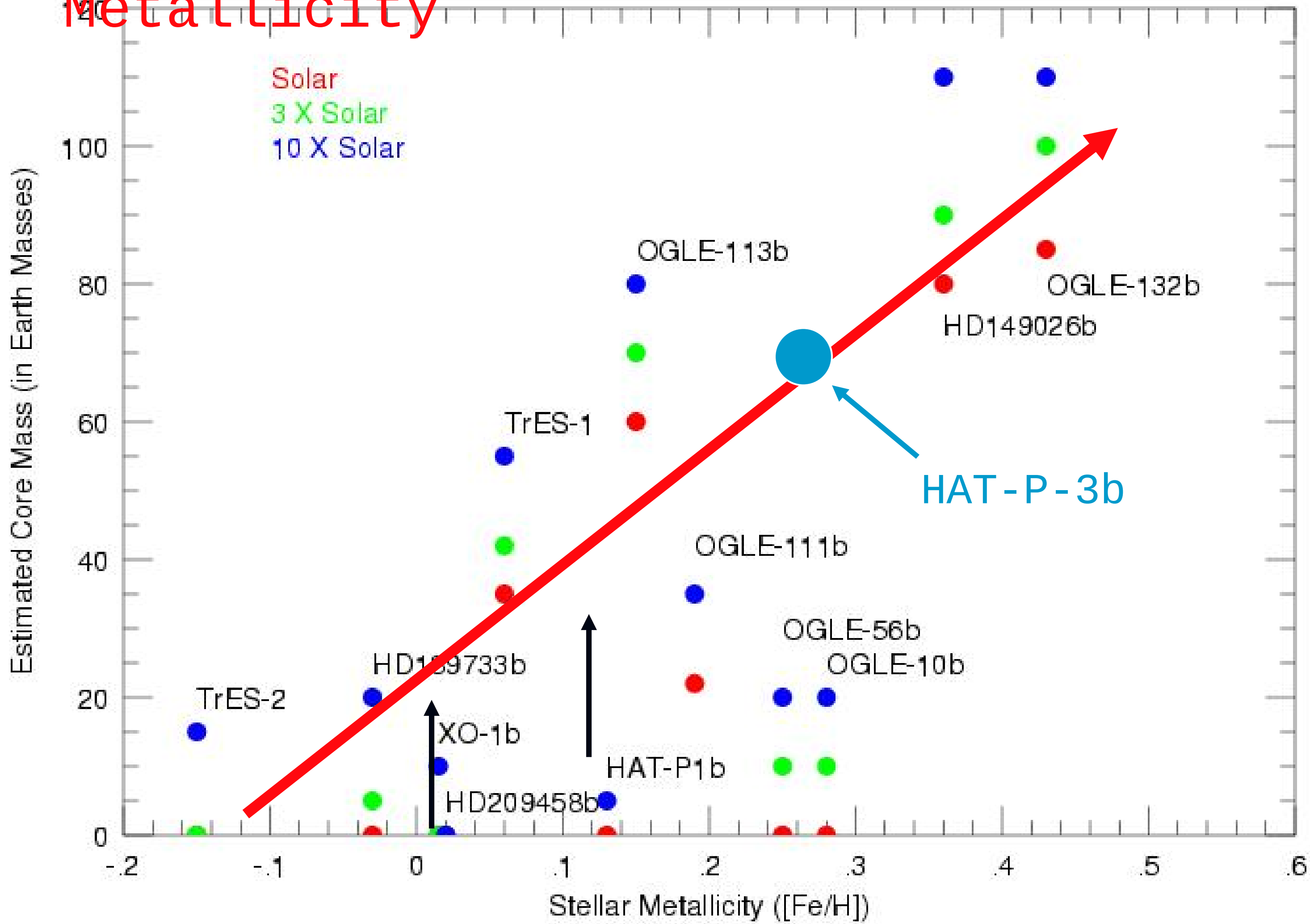


FIG. 7.— R_p (in R_J) vs. age (in Gyr) for a collection of no-core models for the larger transiting EGPs. They include WASP-1b (*blue line*), HATP-1b (*aqua line*), HD 209458b (*green line*), TrES-2 (*red line*), OGLE-TR-56b (*gold line*), and OGLE-TR-10b (*yellow line*). As in Fig. 6, the top left panel assumes solar opacities and does not include the ΔR term. The top right panel is also solar opacities, but does include the ΔR term. The bottom left panel is for 10×solar atmospheric opacities, but does not include the ΔR. The bottom right panel also assumes 10×solar opacities, but does include the ΔR term. This bottom right panel contains our default no-core/no-cloud models. The age of WASP-1b has been arbitrarily set at 2.0 ± 1.0 Gyr. See § 5 for a discussion.

Approximate Core Mass vs. Stellar Metallicity



Note new measurement of HAT-P-3b

Burrows, Hubeny, Budaj, Hubbard 2007

Modely atmosfer

Motto:

Jeden obrazek ma hodnotu 1000 slov,

ale

jedno spektrum ma hodnotu 1000 obrazku!

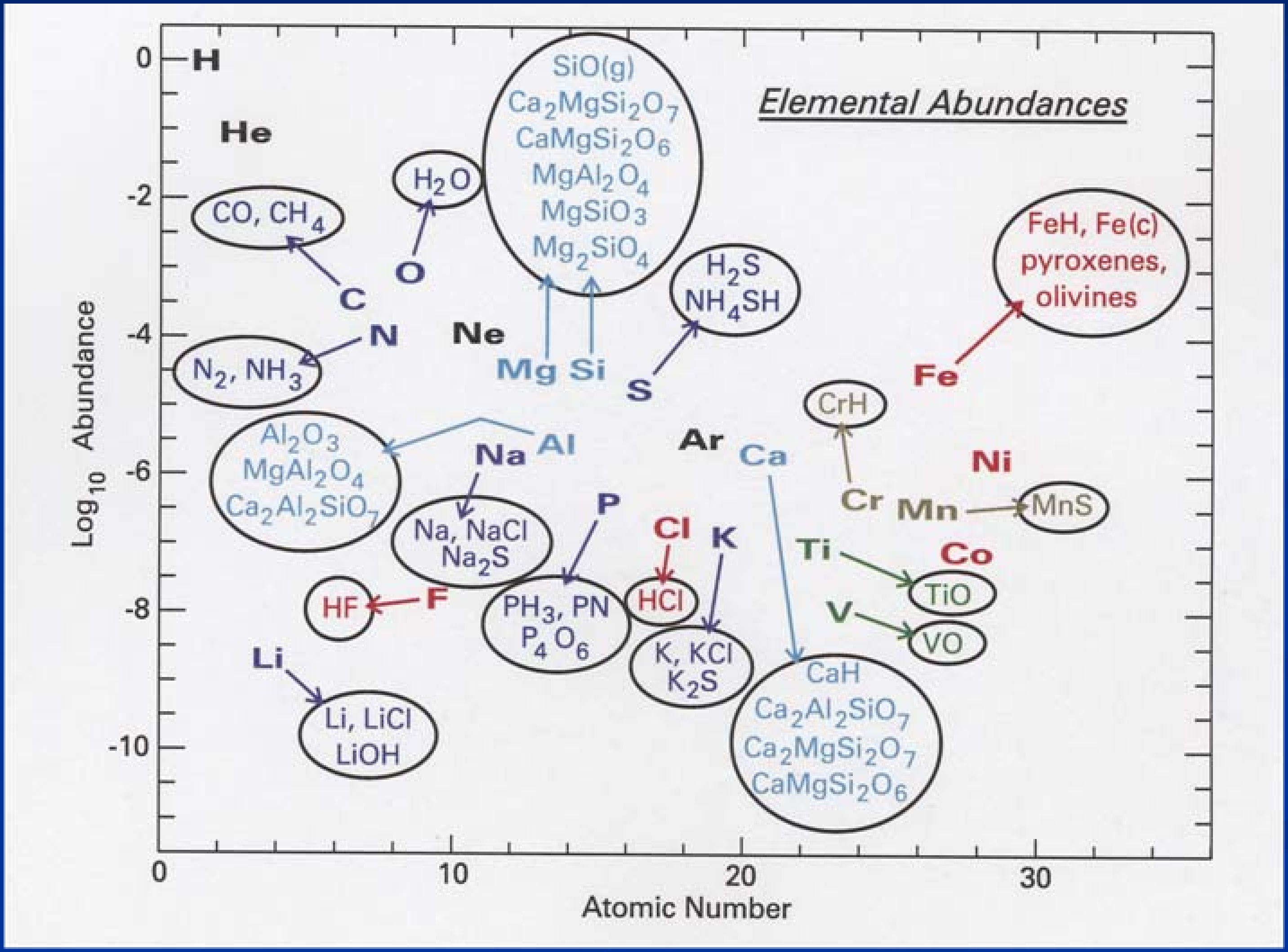
MODEL ATMOSFERY - DEFINICE

- Atmosfera (hvezdy nebo obri planety):
  - Oblast ze ktere prichazi pozorovane zareni
  - Obvykle tenka vrstva ve srovnani s polomerem
- Model atmosfery:
  - Spoctene zakladni strukturalni veliciny (teplota, hustota, tlak, koncentrace jednotlivych molekul a atomu, intensita zareni) v zavislosti na poloze
  - Nejdulezitejsi pro prakticke ucely: zareni na povrchu (pro srovnani s pozorovanim)
- Vypocet modelu atmosfery:
  - Reseni prislusnych strukturalnich rovnic (napr. hydrostaticka rovnovaha, energeticka bilance, chemicka rovnovaha, prenos zareni)
  - Diferencialni a integro-diferencialni rovnice, resene numericky

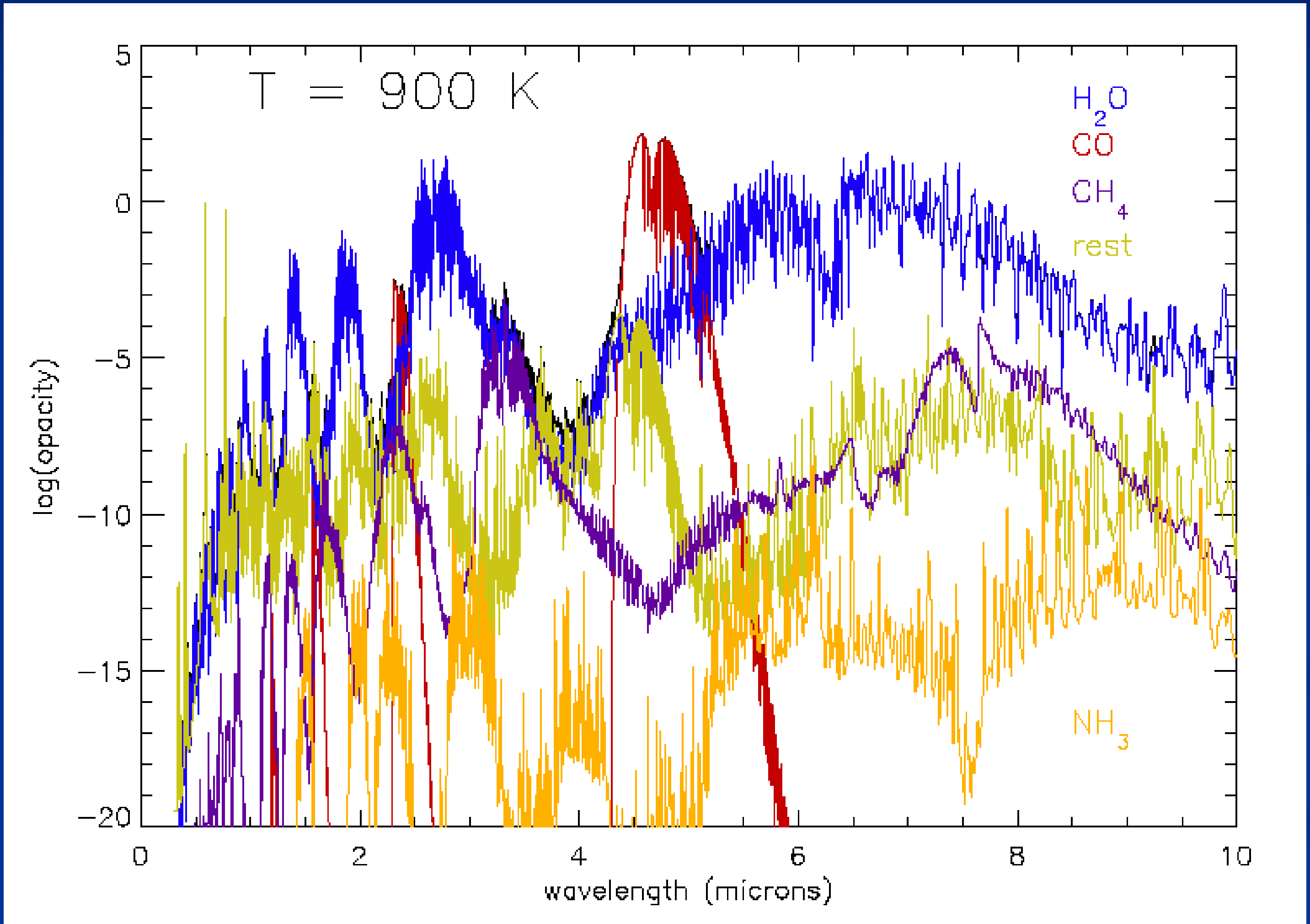
PROBLEMY

- Komplikovana chemie
- Molekularni data + opacity
- Formovani kondenzatu (oblaka)
- Opacita a rozptyl zareni na kondenzatech
- Sedimentace kondenzatu (dest)
- Prenos zareni
- Silne ozarovani od hvezdy
- Interakce mezi denni a nocni stranou

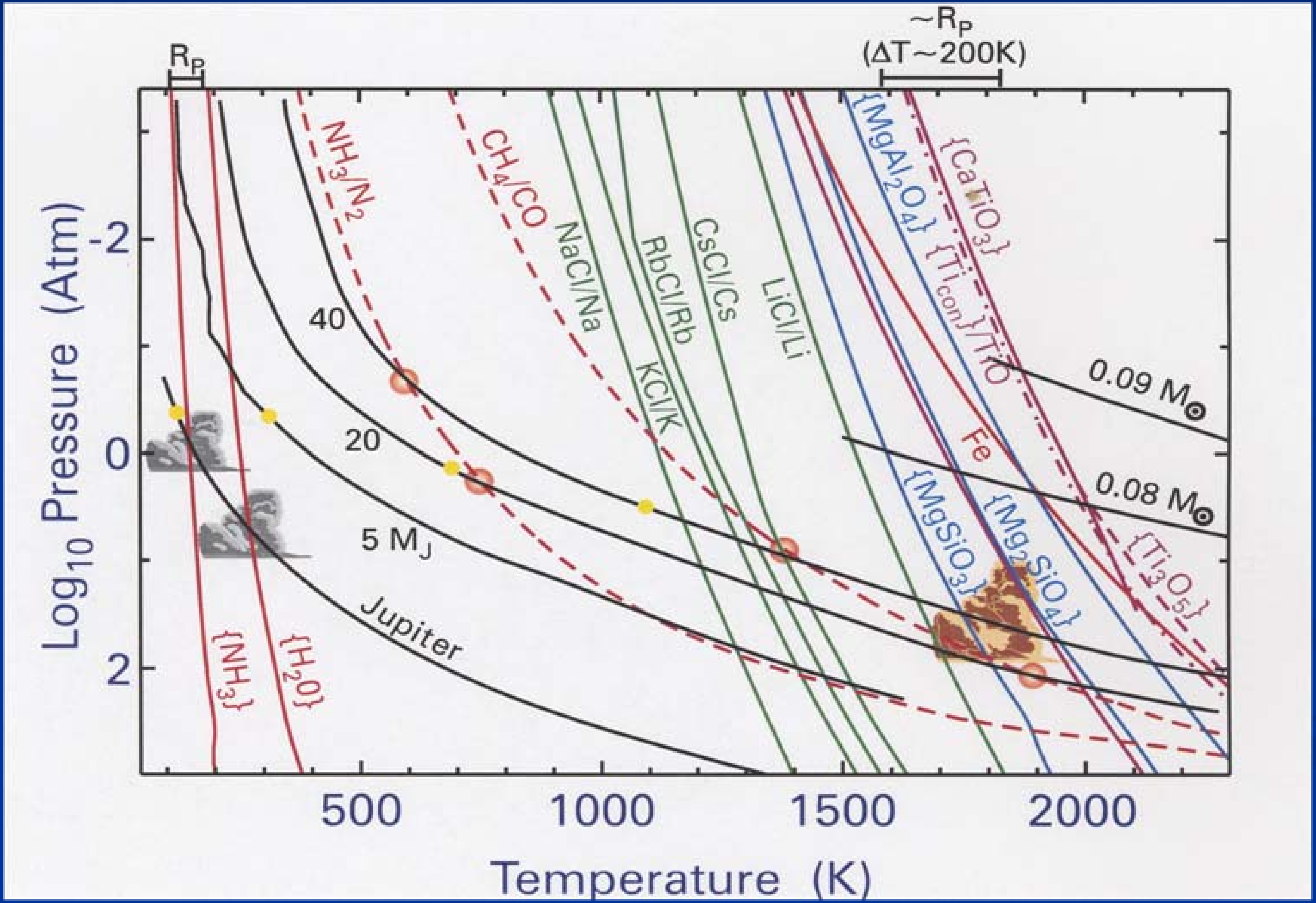
Chemie atmosfer obrich exoplanet



Opacita (absorpcni coefficient)



FORMACE KONDENZATU (OBLAK)

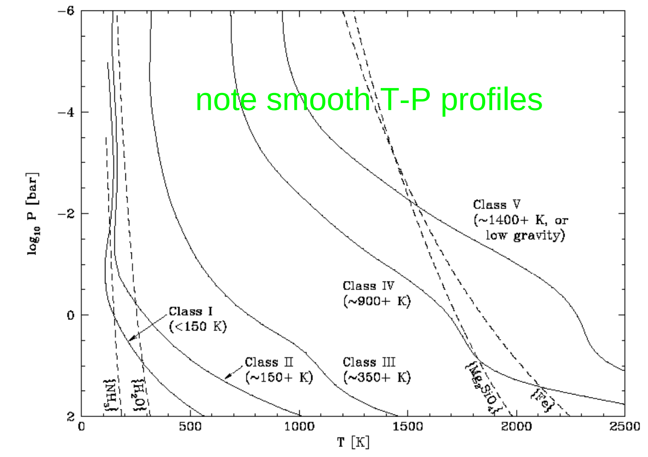


VYPOCETNI PROCEDURA

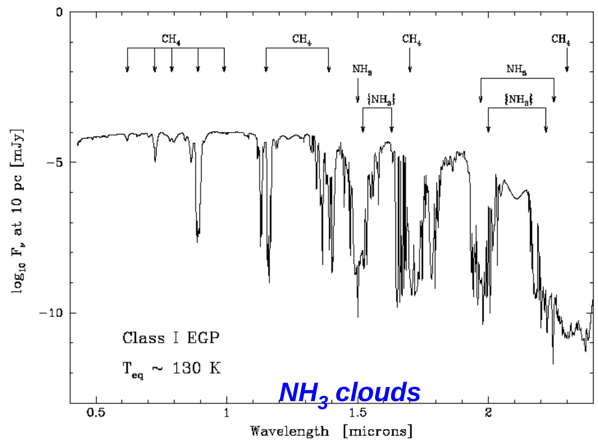
- ***CoolTLUSTY*** - varianta univerzalniho programu pro vypocet modelu hvezdnych atmosfer ***TLUSTY*** (Hubeny 1988; Hubeny & Lanz 1995; Hubeny, Burrows, Sudarsky 2003)
- TLUSTY:
  - Aplikabilita: od 50-100 K az 10^9 K; ale s mezerou 3000-5000 K
  - Pocita hvezdne atmosfery a akrecni disky
  - Odchylky od lokalni termodynammicke rovnovahy
- CoolTLTUSTY:
  - Navic: modifikovana chemicka rovnovaha, s pripadnymi odchylkami
  - Formace kondenzatu a oblak
  - Molekularni opacity (tabelovane) nekolik 10^9 spektralnich car
  - Mie rozptyl na kondenzatech
  - Zariva + konvektivni rovnovaha

Pet trid obrich planet

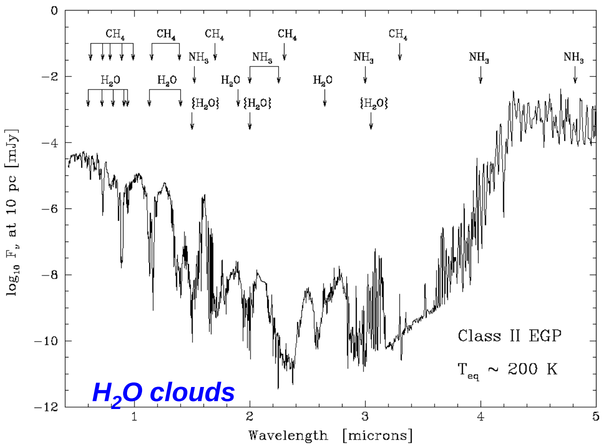
Sudarsky, Burrows, & Hubeny 2003



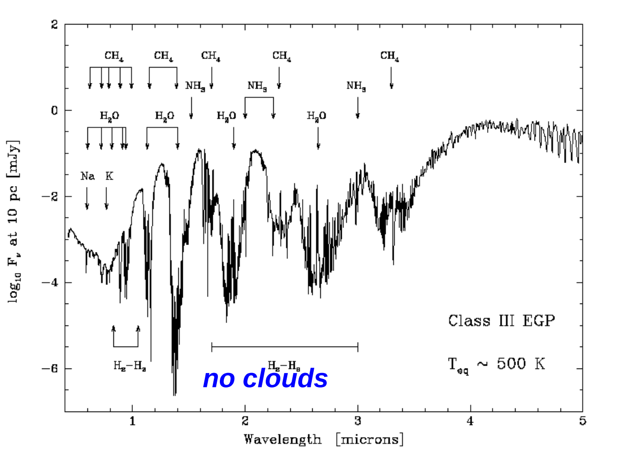
Class I - Jovian



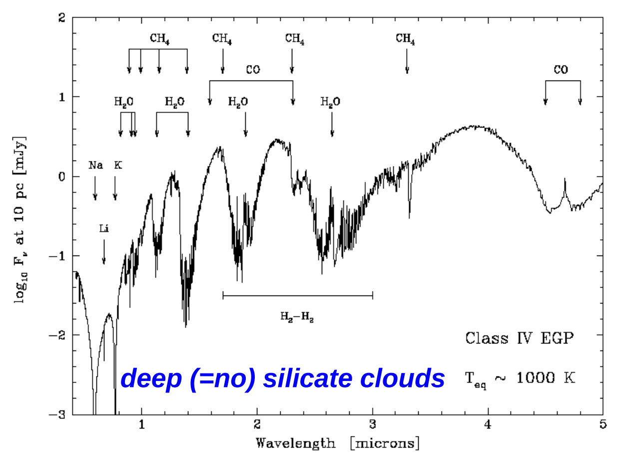
Class II - Water class



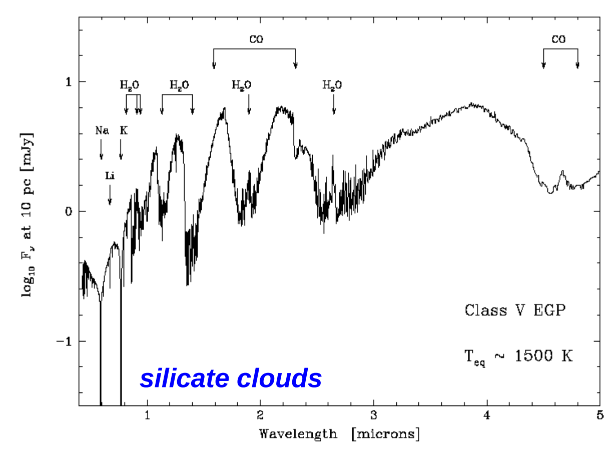
Class III - clear



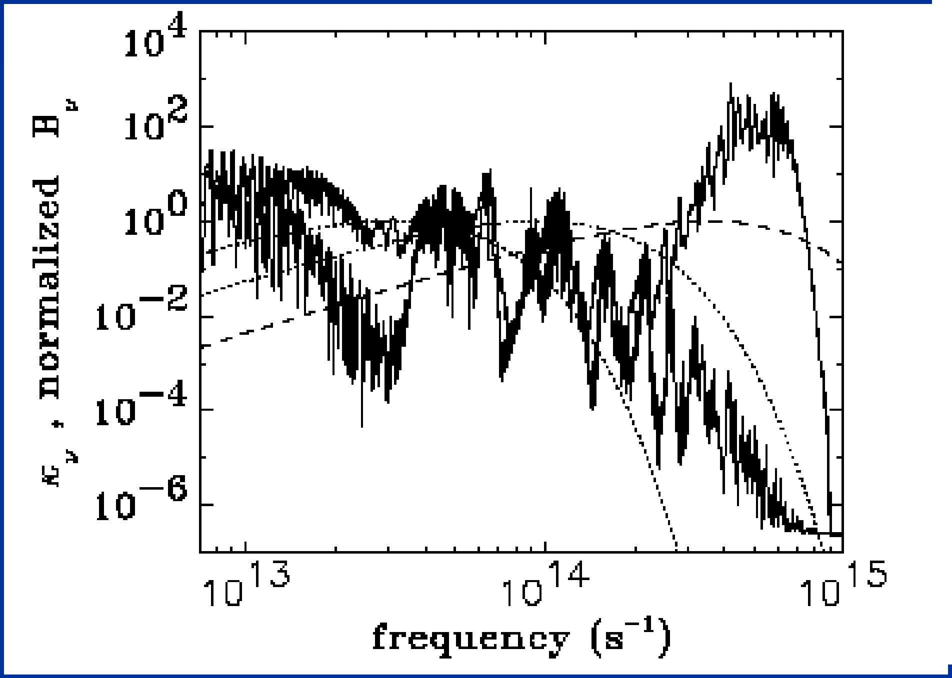
Class IV - close in

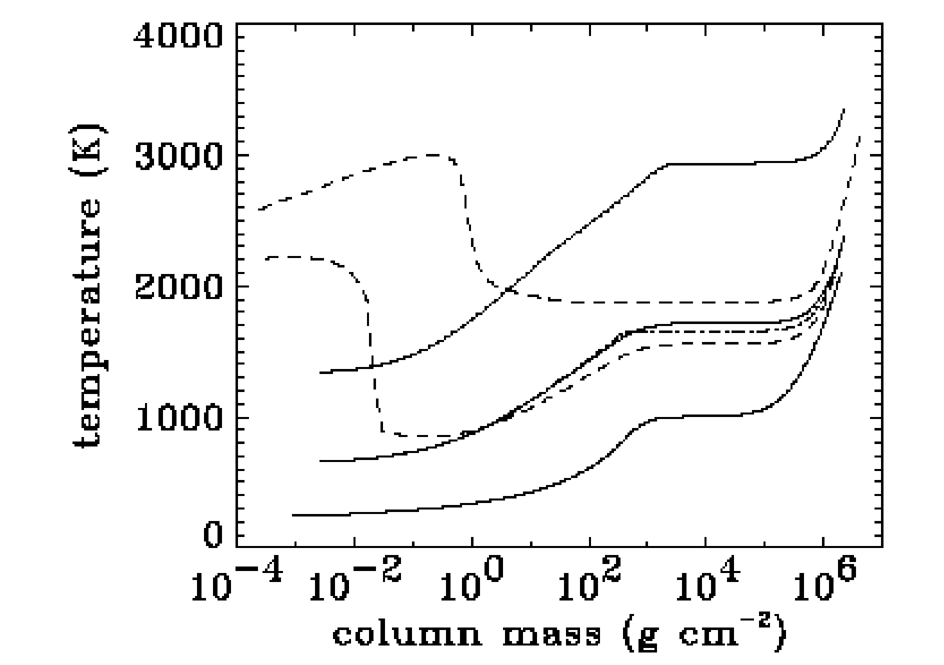


Class V - roasters



Bifurkace modelu pri silne iradiaci; moznost stratosfer





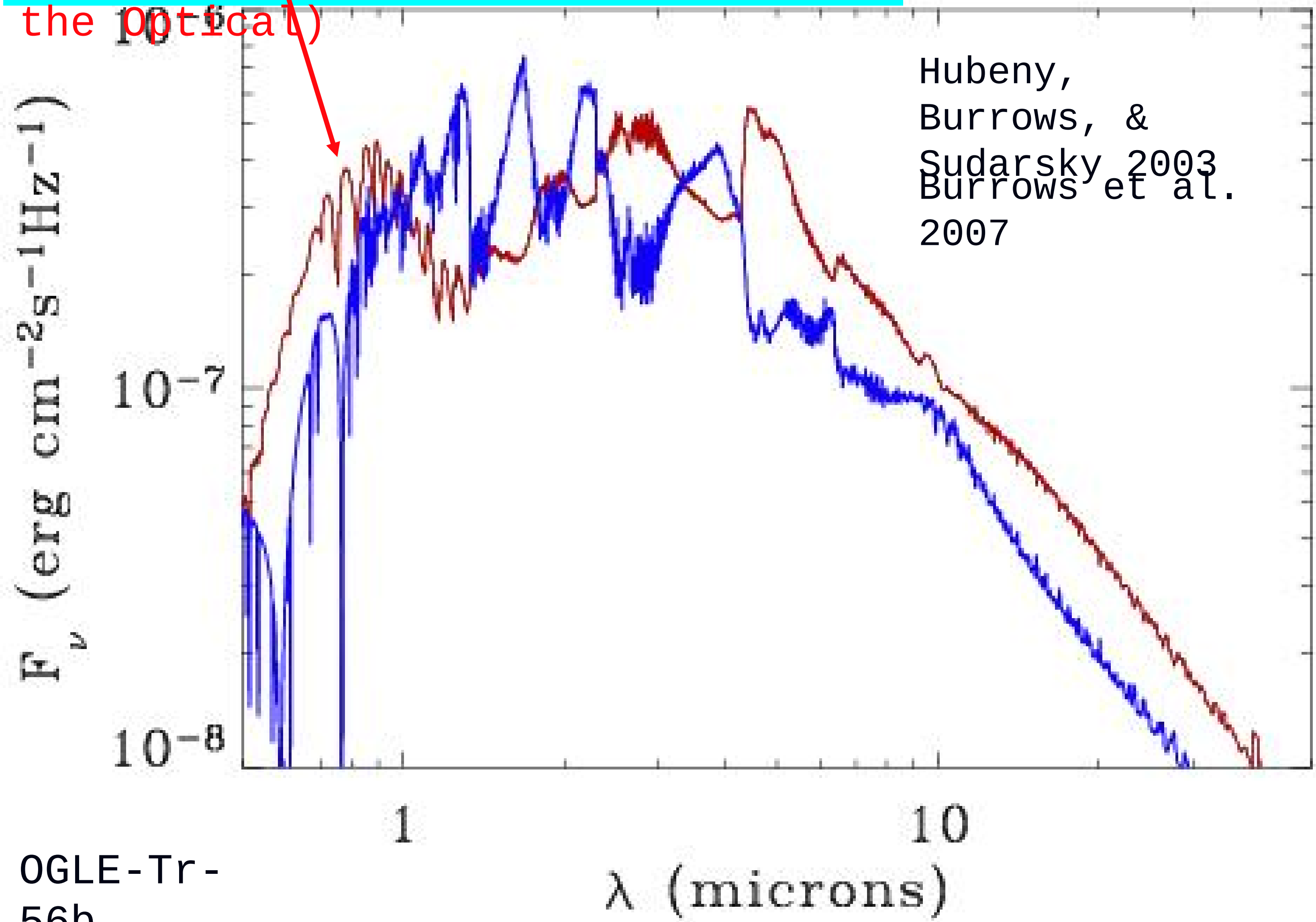
Hubeny, Burrows, Sudarsky 2003

Termalni inverze: Cary vody v Emisi (!)

Strong Absorber at Altitude (in the Optical)

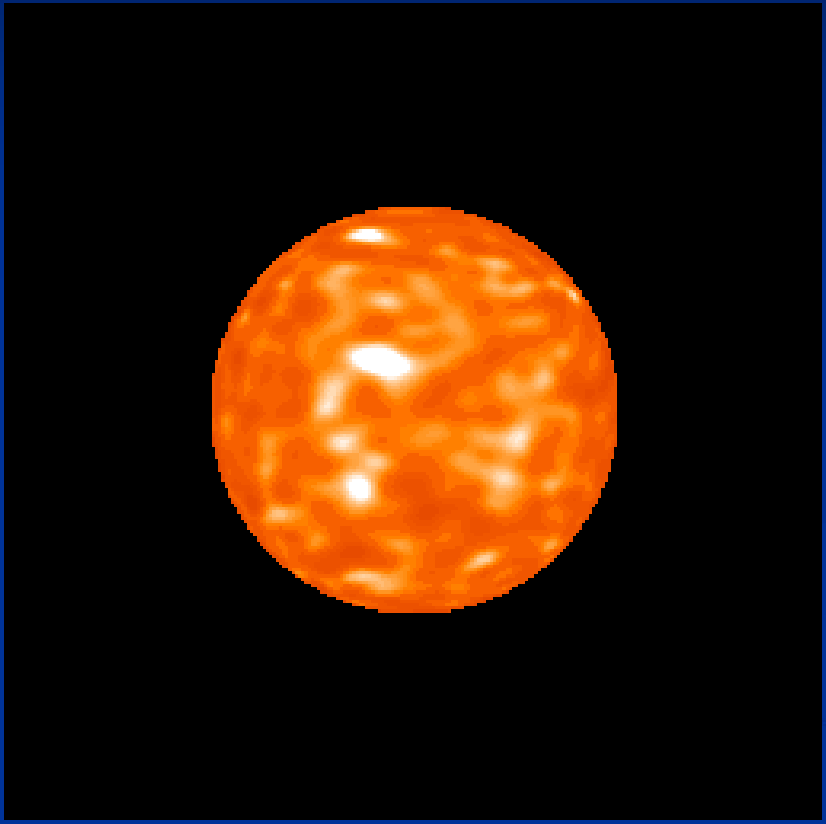
Hubeny, Burrows, & Sudarsky 2003

Burrows et al. 2007



OGLE-Tr-56b

Sekundarni zakryty; svetelne krivky, spektra



1) spektrum(planeta) = spektrum(hvezda + planeta) - spektrum(hvezda)

2) mereni svetelne krivky behem celeho orbitu ==> informace o nocni strane

Sekundarni zakryty: Prvni pozorovana spectra exoplanet!

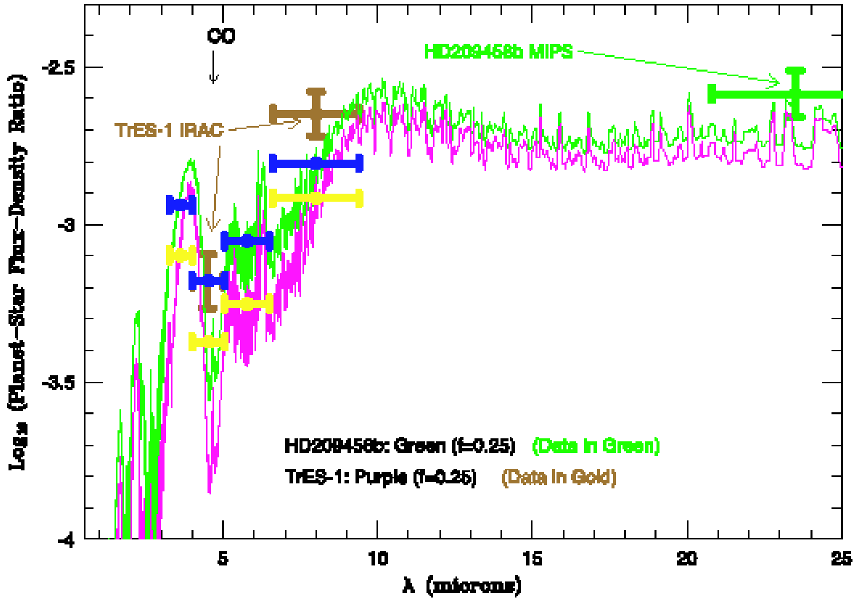


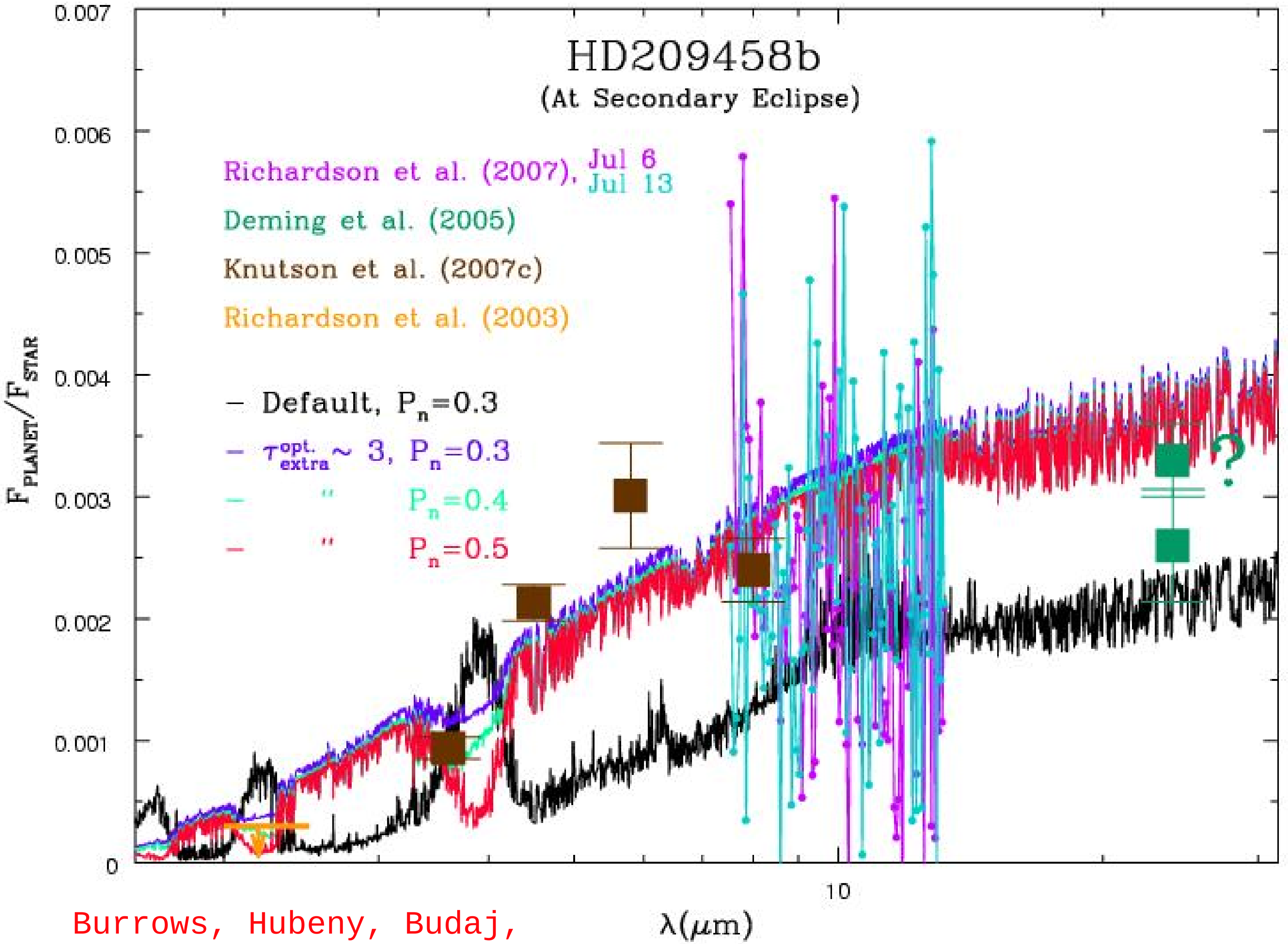
FIG. 1.—The logarithm base 10 of the planet-to-star flux density ratio as a function of wavelength (λ, in microns) for our baseline models of TrES-1 and HD 209458b (for $f = 0.25$). The model for TrES-1 is purple, and that for HD 209458b is green. Superposed are the secondary eclipse data: the gold circles with corresponding error bars are the TrES-1 IRAC data from Charbonneau et al. (2005), while the green circle with error bars is the HD 209458b MIPS 24 μm datum from Deming et al. (2005). Also included are the band-averaged detected electron/"flux" ratios for the TrES-1 (*yellow circles*) and HD 209458b (*blue circles*) models in the four IRAC bands. Note that coincidently the blue circle at 4.5 μm overlaps the gold TrES-1 data point. The position of the strong CO absorption feature at ~4.67 μm is indicated and clearly coincides with the ~4.5 μm IRAC band flux. See text for a discussion and details.

TR-ES-1 : Charbonneau et al. 2005, ApJ 626, 523

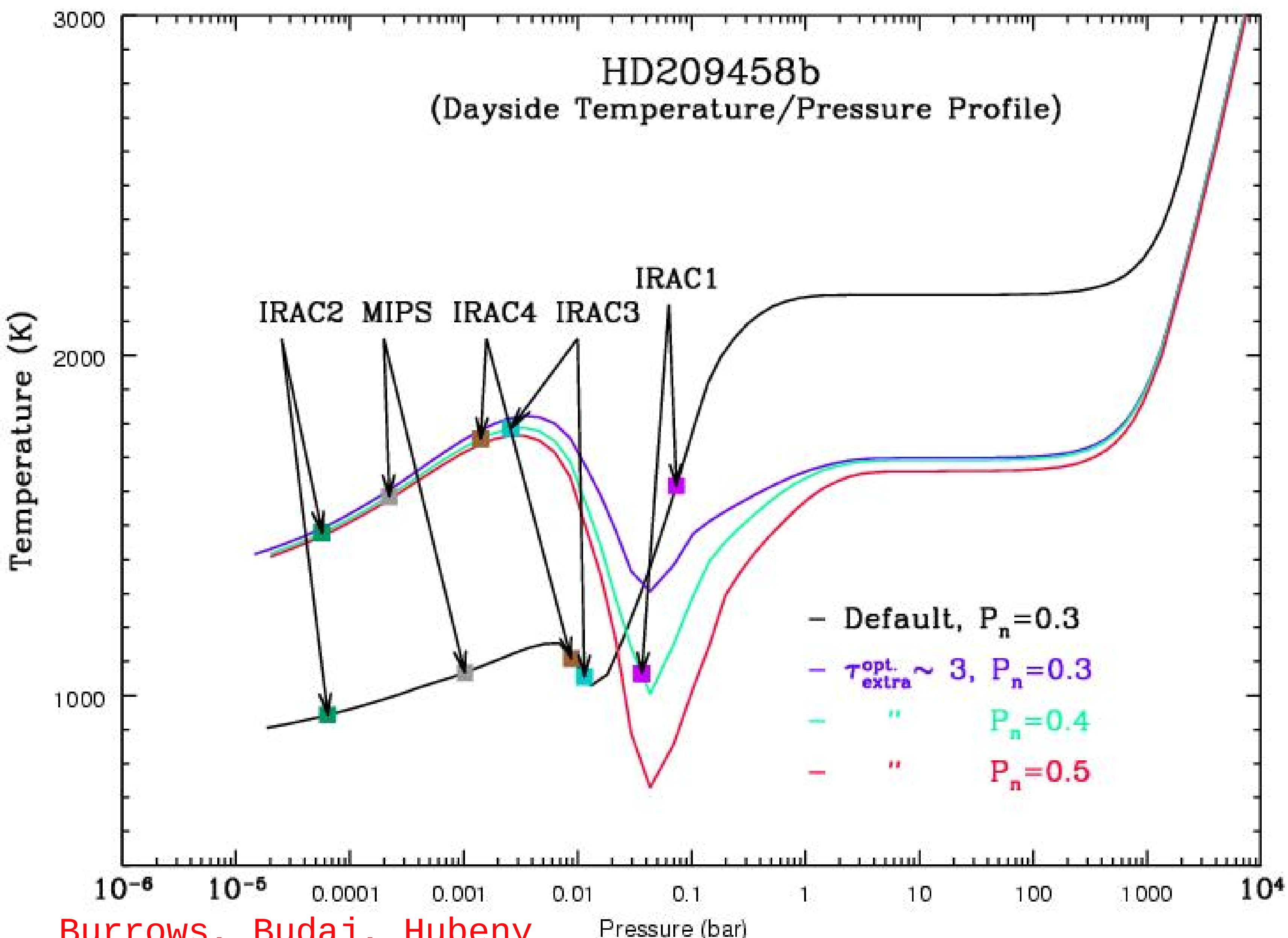
HD 209458b: Deming et al. 2005, Nature 434, 740

Burrows, Hubeny, Sudarsky 2005, ApJ 625, L135

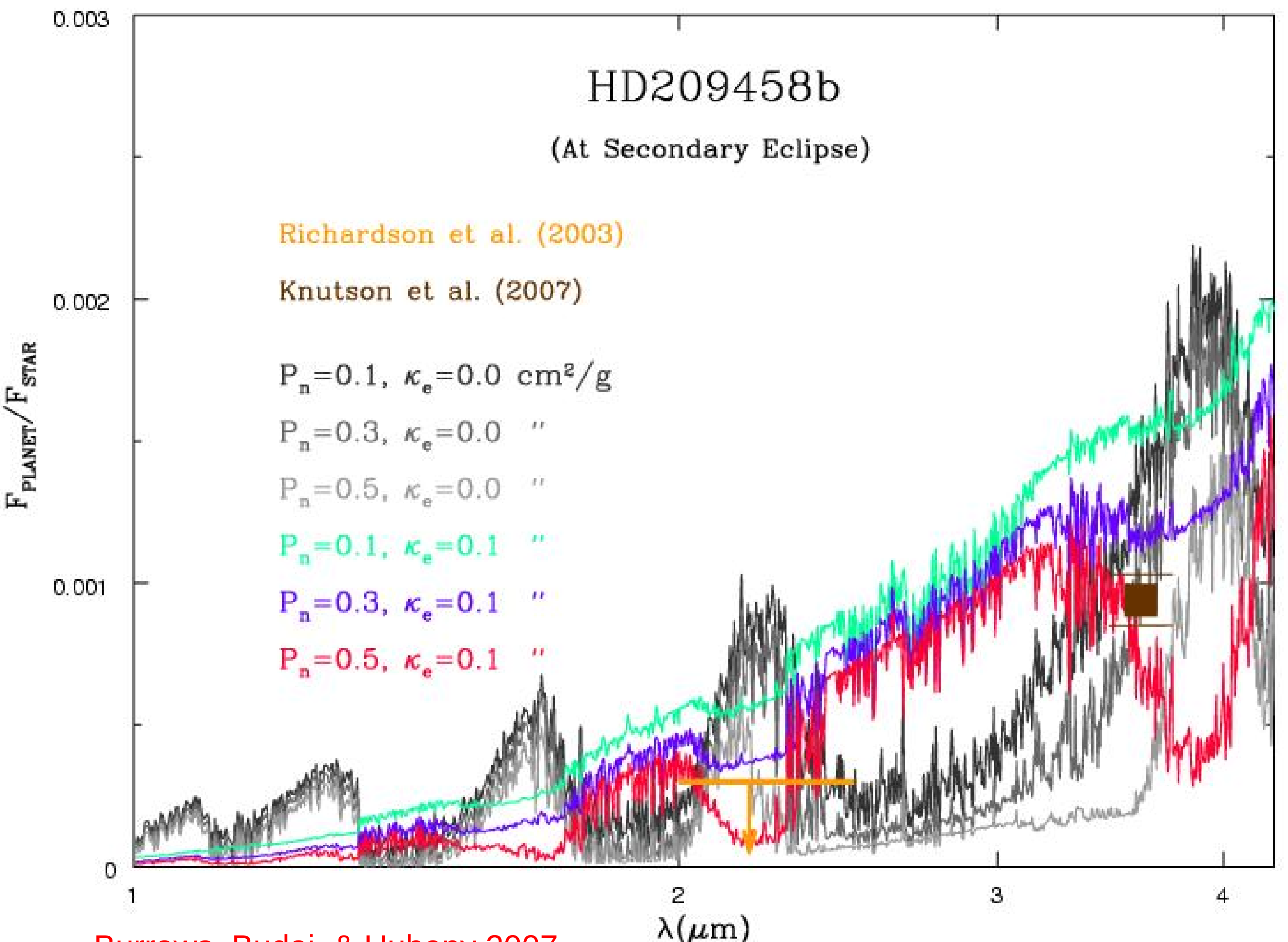
Fortney et al. 2005, ApJ 627, L69



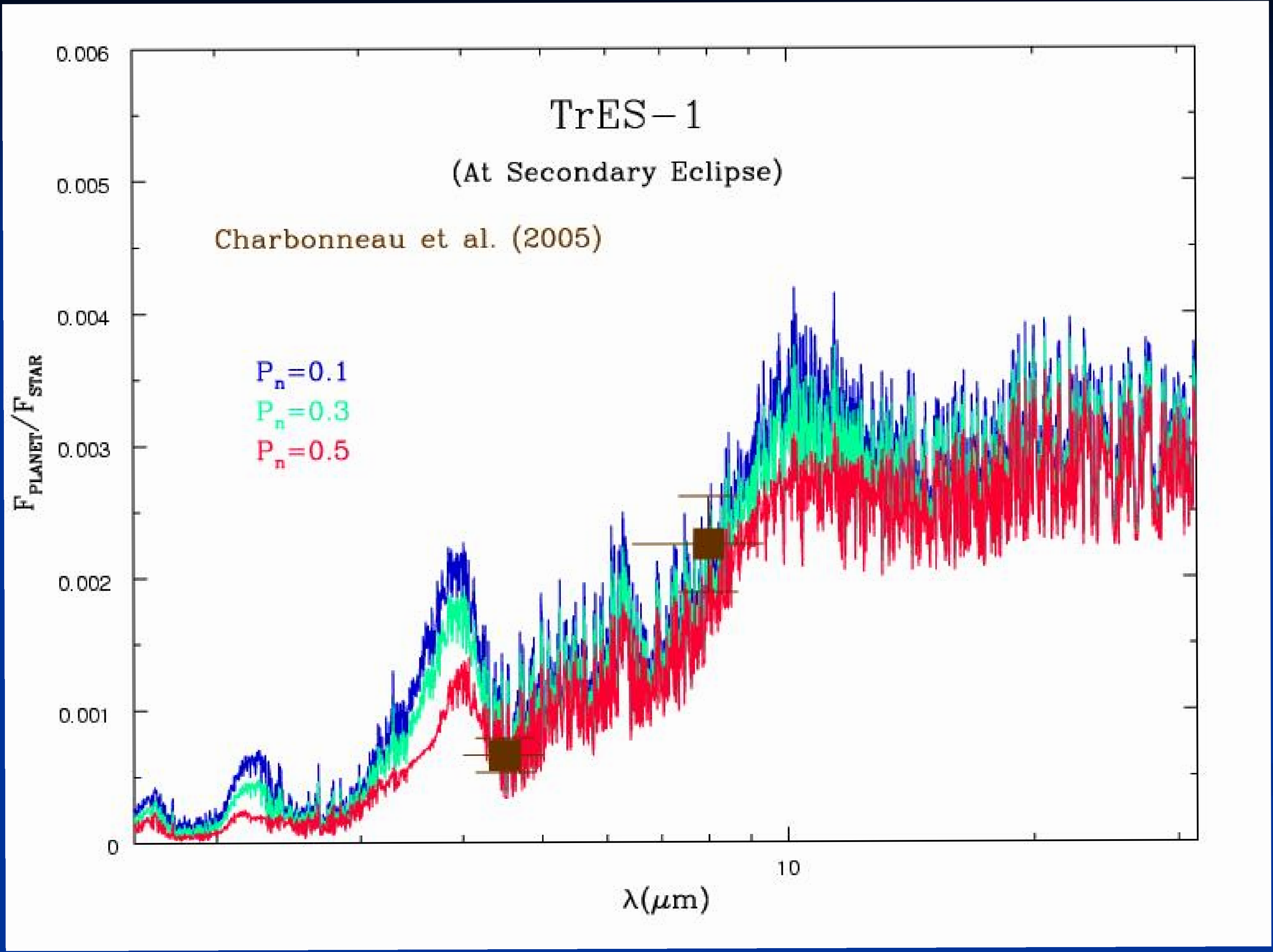
Burrows, Hubeny, Budaj, Knutson, & Charbonneau 2007



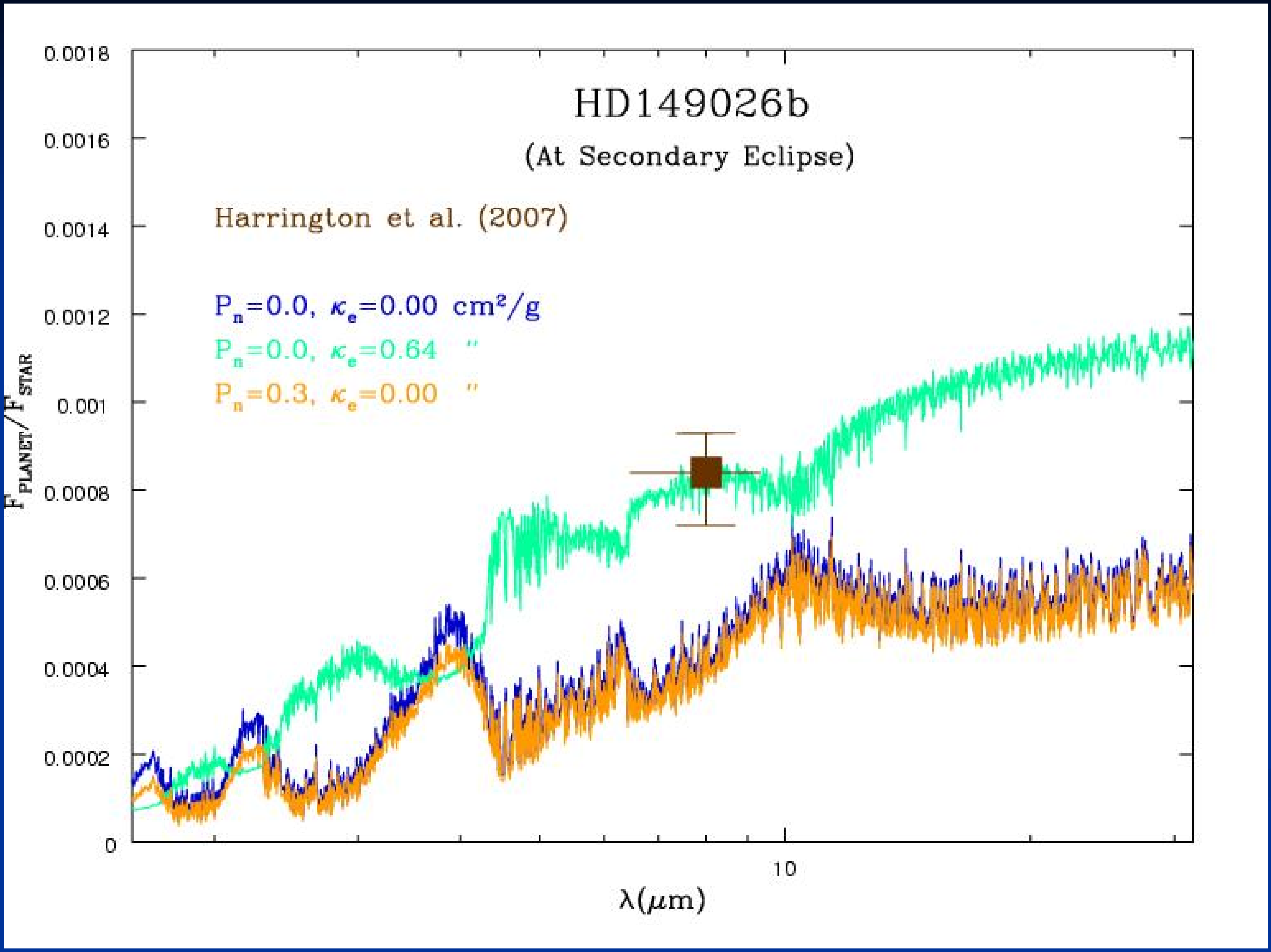
Burrows, Budaj, Hubeny 2007



Burrows, Budaj, & Hubeny 2007

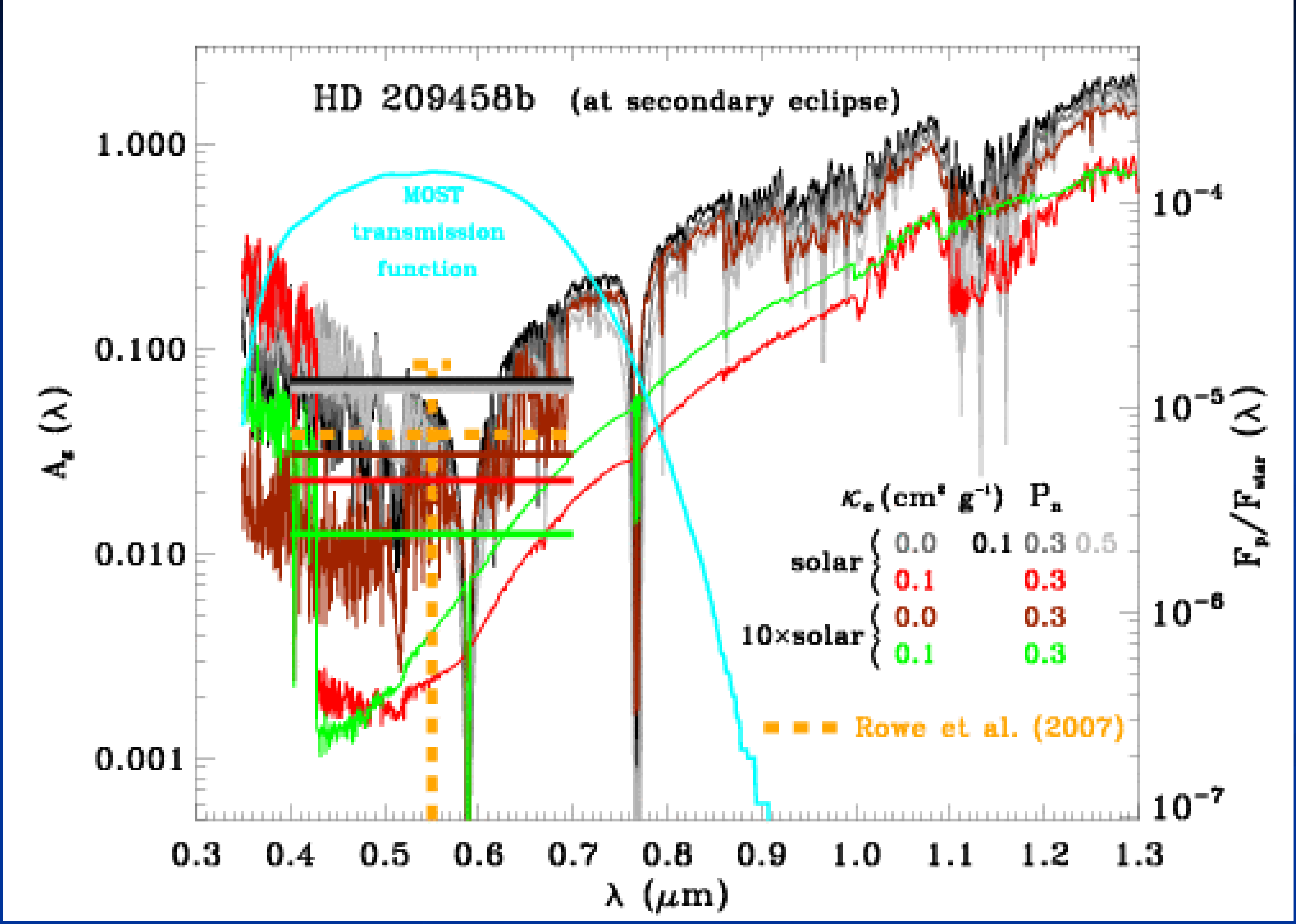


TrES−1
(At Secondary Eclipse)
Charbonneau et al. (2005)
P_n=0.1
P_n=0.3
P_n=0.5
F_{PLANET}/F_{STAR}
0.006
0.005
0.004
0.003
0.002
0.001
0
10
$\lambda(\mu m)$



HD149026b
(At Secondary Eclipse)
Harrington et al. (2007)
P_n=0.0, κ_e=0.00 cm^2/g
P_n=0.0, κ_e=0.64 "
P_n=0.3, κ_e=0.00 "
F_{PLANET}/F_{STAR}
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
10
λ(μm)

MOST HD 209458b Albedo: Burrows, Ibgui, &



Phase-dependent spectra of HD 189733b

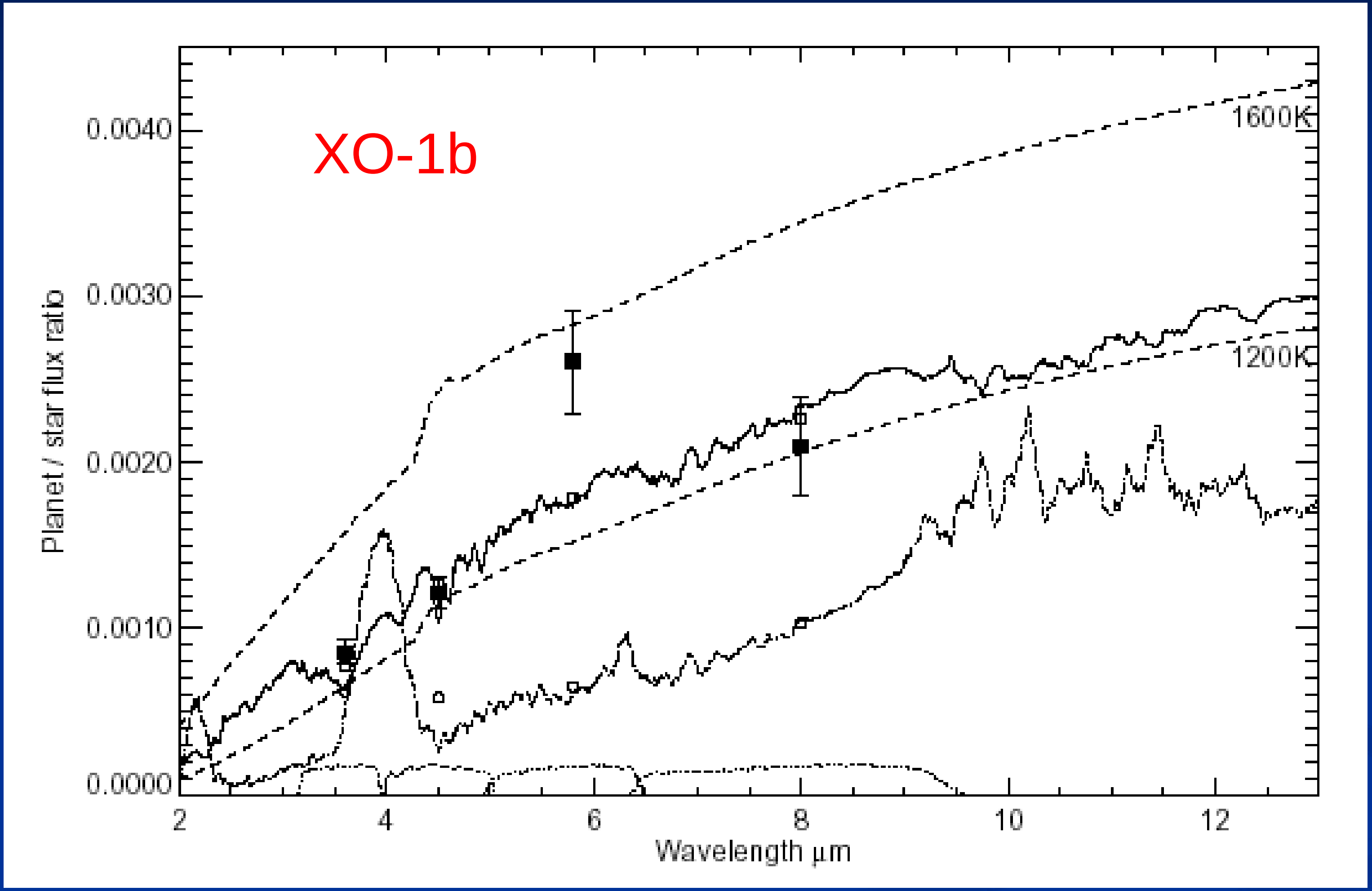
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- P_n= 0 - no energy redistribution to the night side
- P_n= 1/2 - half of energy emitted to the night side

Existence of a stratosphere

Planet	Star	a	F	Stratosphere
HD 149026b	G0 IV	0.042	2.089	yes
HD 209458b	G0 V	0.045	1.074	yes
HD 189733b	K1.5	0.031	0.468	no (?)
TrES-1	K0 V	0.039	0.428	no

New measurements: Machalek et al 2008



F = **0.485**

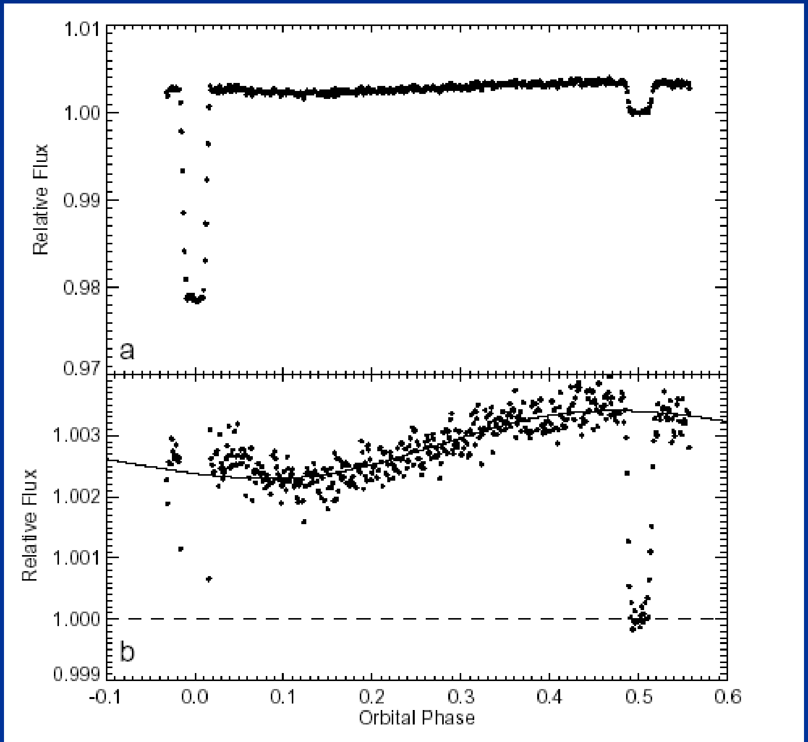
Exoplanetarni meteorologie

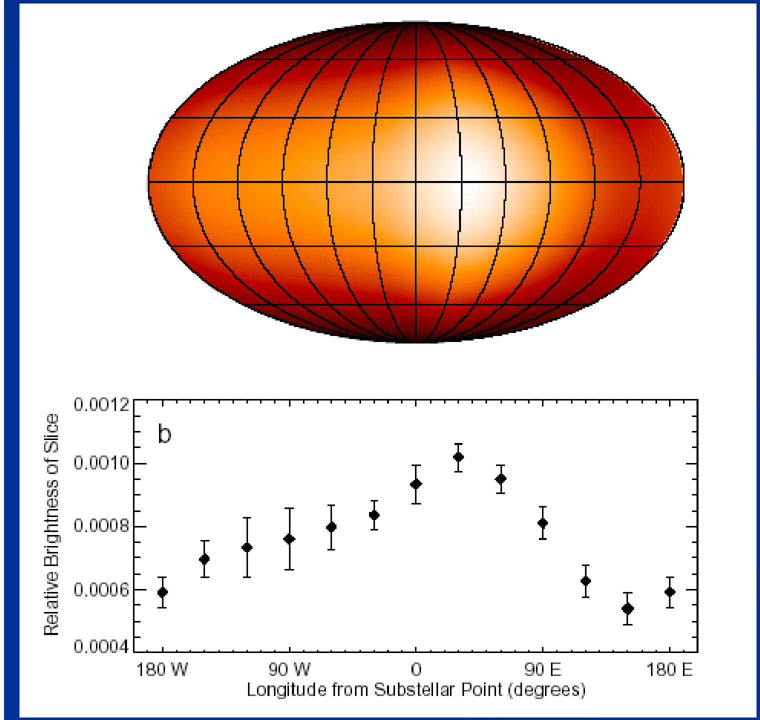
- Z pozorovani vyplyvaji kvantitativni indikace o mire prenosu energie z denni na nocni stranu
- Zariva energie z hvezdy staci byt prenesena pomoci cirkulaci (vetru) z denni na nocni stranu driv nez se staci vyzarit ==> rika neco o povaze a rychlosti cirkulaci
- Analyza cele svetelne krivky - lze v principu rekonstruovat rozlozeni “zarive” teploty na povrchu planety
- Existuji prvni dynamicke modely globalni cirkulace a dynamickych efektu v exoplanetarnich atmosferach (zatim pouze v pocatcich)

Mapovani povrchu ze svetelne krivky

HD 189733 b

Knutson et al. 2007, Nature 447, 173





ZAVER: CO SE UDALO ZA 13 LET?

- Objeveno celkem pres 300 exoplanet
- Z toho pres 50 transitujicich
- U ctyrech transitujicih planet obdrzena prvni spektroskopicka data

- Teoreticke predpovedi struktury atmosfer i nitra
- Spocteny vyvojove modely s prihlednutim k ozarovani od hvezdy
- Zmerene polomery transitujicih planet (zvlaste u vetsich planet) dobre souhlasi s vyvojovymi modely
- Pro mensi planety je indikace ze centralni jadro je slozeno z tezsiho materialu, tim vice ciz je materska hvezda bohata na tezke prvky
- Pozorovana spektra planet souhlasi s teoreticky prepovedenymi
- Teorii predpovedela existenci stratosfer; observacne overeno

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