Structure and evolution of the tidally heated hot-Jupiter KELT-9b

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Abstract

The ultra-hot Jupiter KELT-9b is observed to have a strong intrinsic heat flux characterized by T_{int} ~ 2400 +/- 800 K [1], and to be on a polar orbit around its parent star. Obliquity tidal heating can explain the observed high luminosity [1] suggesting parallel stellar and planetary rotation axes. Here, we investigate the possible thermal evolution and internal structure of KELT-9b. We find that its large radius of 1.9 R_E at a cooling time of 0.3-0.6 Gyrs requires a strong extra heat source with flat radius-evolution at present, consistent with obliquity tidal heating. However, adjusting the bulk metallicity to the observed planet radius requires that its interior follows a significantly colder adiabat characterized by T_{int} ~500 K. Merging both branches yields a tidal heat deposition zone at ~1 GPa and ~0.8 Rp, and consequently a low static Love number k_2 < 0.1 [2].

KELT-9b: high intrinsic luminosity (T_{int})

Param	G17	Cs21	used
$M_\star$ (M_{Sun})	$2.52^{+0.25}_{-0.20}$	2.26–2.82	2.52
$R_\star$ (R_{Sun})	$2.36^{+0.75}_{-0.63}$	2.28–2.54	2.362
$T_\star$ (K)	10170		10170
a (AU)	0.0346		0.0346
R_p (R_J)	$1.89^{+0.06}_{-0.05}$		1.89
M_p (M_J)	2.88 ± 0.84		2.88
A_B	—	0—0.23	0—0.25
T_{Day} (K)	—	4800±80	
T_{Night} (K)	—	2770±240	
T_{int}	—	2400± 820	800—1000

Table: Stellar and planetary parameters used here.

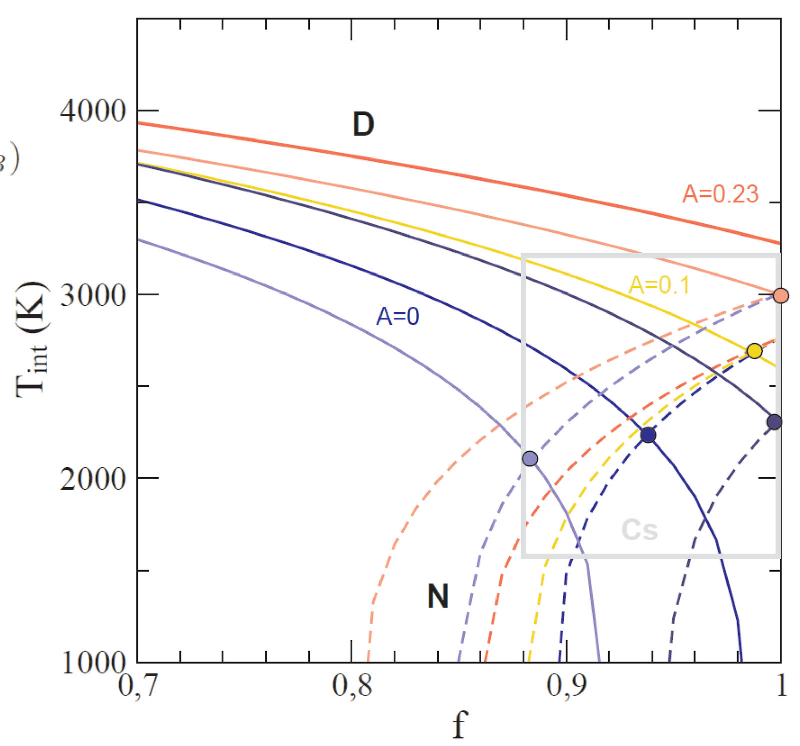
The energy balence equation used here (L_{eq}: planetary luminosity if in equilibrium with stellar irradiation, L_{int}: intrinsic luminosity, L_{sec}=cooling and contraction), $L_{tid,o}$: obliquity tidal heating [4]) is

$$L - L_{eq} = L_{int} = L_{sec} + L_{tid,o} + \ldots .$$

Using Stefan-Boltzman's law, luminosities are converted to temperatures.

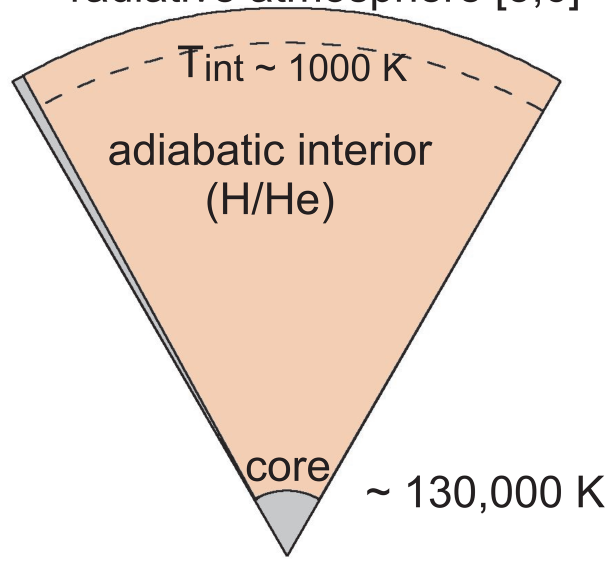
$$L = L_{Day} + L_{Night}$$
$$L_D = 2\pi R_p^2\,\sigma_B T_D^4$$
$$L_N = 2\pi R_p^2\,\sigma_B T_N^4$$
$$L_{eq} = 4\pi R_p^2\,\sigma_B T_\star^4 (R_\star/2a)^2\,(1-A_B)$$

Using the observed T_D and T_N values [1], we can solve for T_{int} as a function of heat distribution factor f and Albedo A Results are consistent with Csizmadia [1]..

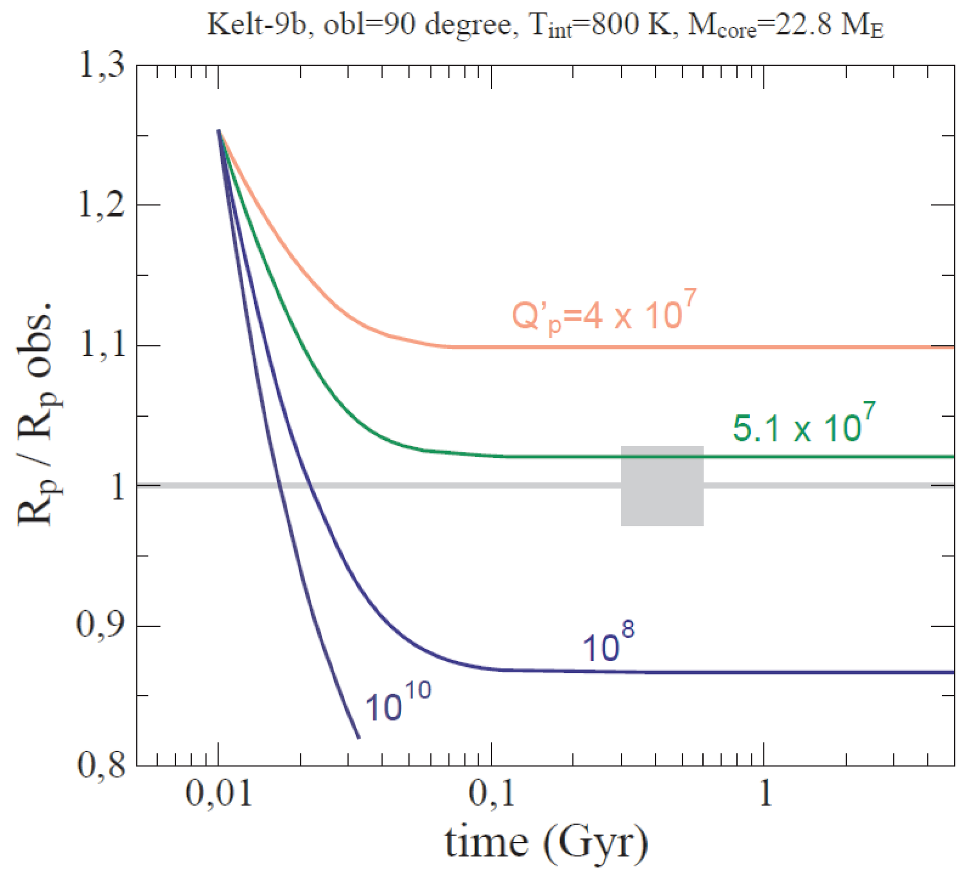


$$T_D^4 = T_{int}^4 + 2f\,T_\star^4 (R_\star/2a)^2\,(1$$
$$T_N^4 = T_{int}^4 + 2(1-f)\,T_\star^4 (R_\star/2a)^2\,(1-A_B)$$

Adiabatic models

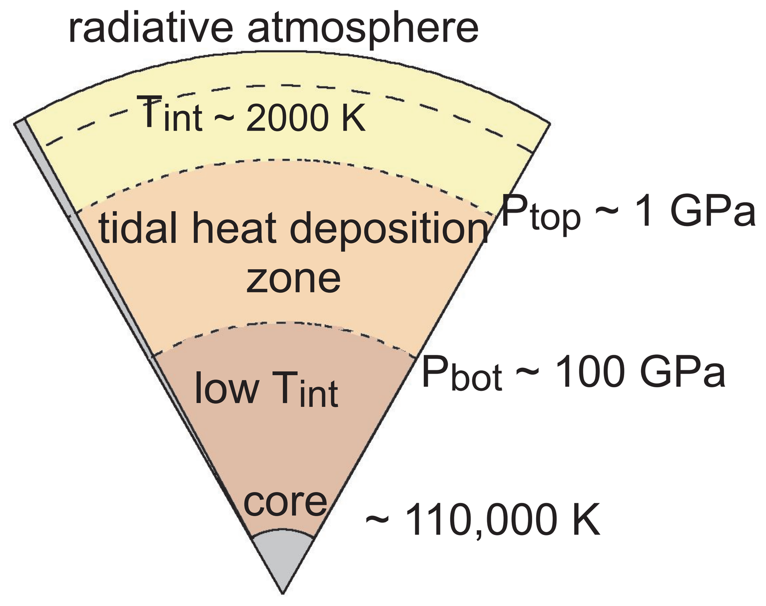


Thermal evolution

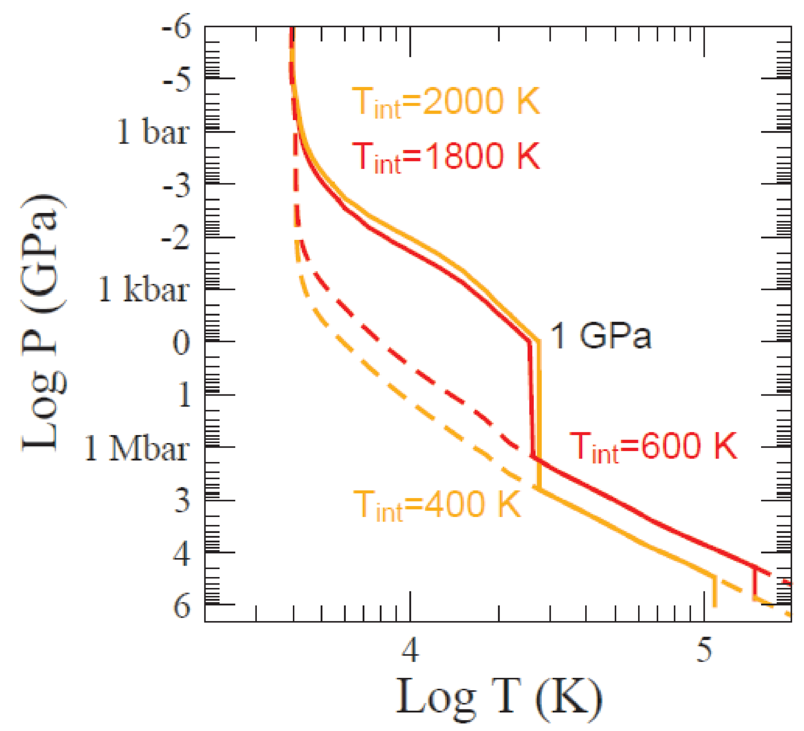


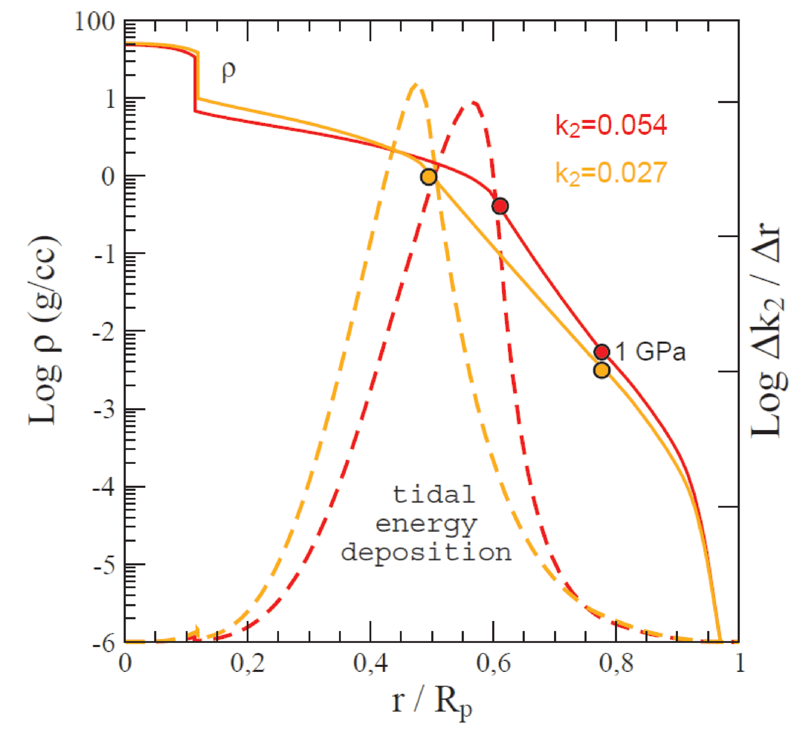
Strong extra heating that is required to obtain the observed radius after ~300 Mio cooling (grey box), leading to halted contraction (flat R_p (time)).

Structure models with tidal heating in a shell



ASSUMPTIONS:
i) outer P-T profile above "P_{top}" follows solution for T_{int}=1800-2000 K
ii) interior P-T profile below "P_{bottom}" follows cool adiabat for T_{int} ~ 500 K
RESULT:
P_{top} ~ 1 GPa
P_{bottom} ~ 1Mbar
(near maximum of static tidal response, dashed)
low k_2 < 0.1





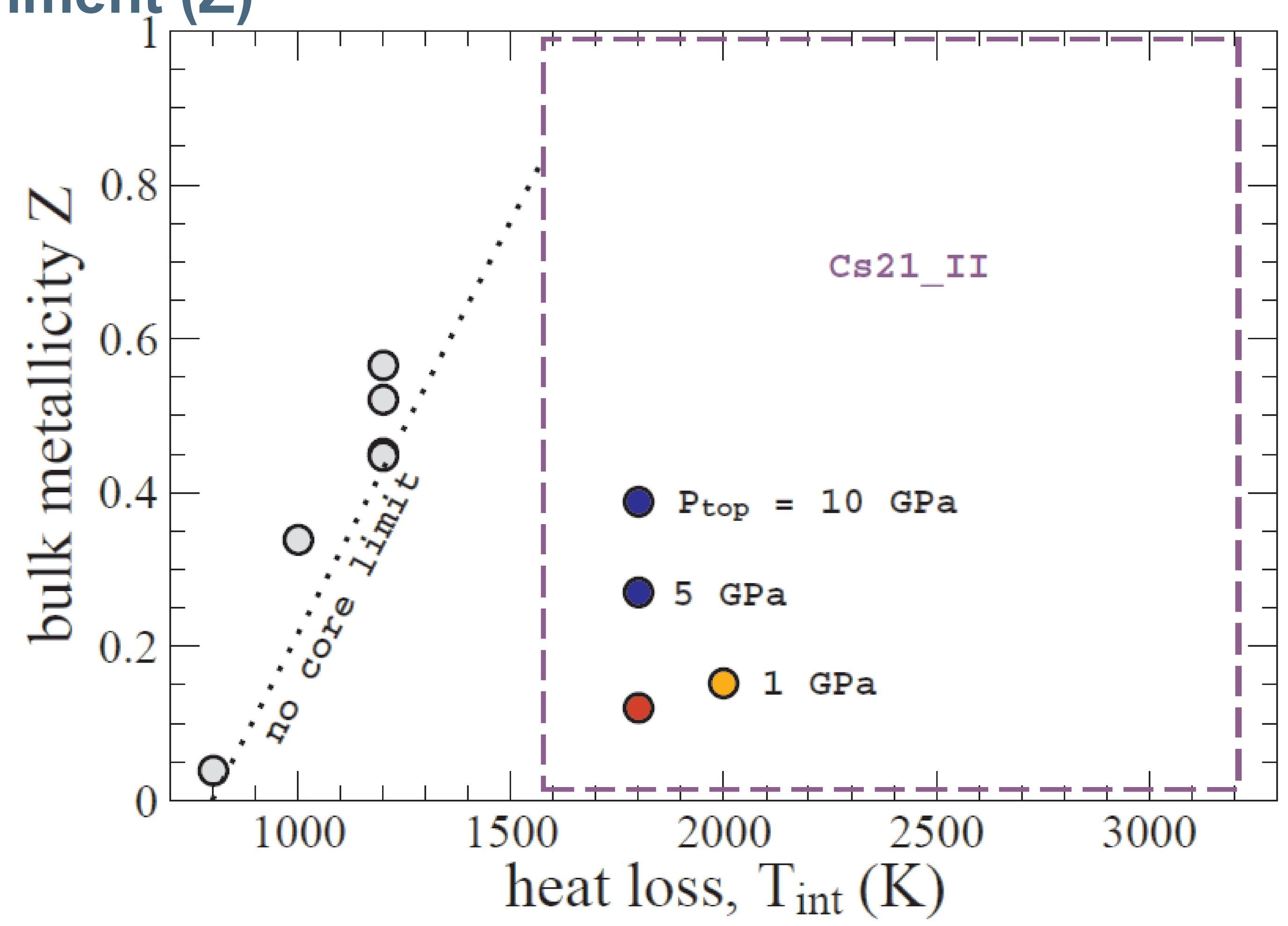
Heavy element enrichment (Z)

ADIABATIC MODELS (grey):
possible T_{int} values range from ~800 K (zero Z) to ~1600 K (Z=100%), inconsistent with observations.

MODELS w SHELL HEATING (color):

P_{top} <= 1 GPa yields Z<= 20% (good!)

models with Tint ~ 2000 K are possible, while >>2000 K still too hot (too high Z!)



References

[1] Csizmadia, Smith, et al (submitted)
[2] Nettelmann, et al (in prep)
[3] Gaudi BS et al (2017), Nature Astr.
[4] Millholland S (2019), ApJ
[5] Guilot T (2010), A&A
[6] Poser AJ et al (2019), Atmosphere

Acknowledgement

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