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 $T_{\text{int}} \approx 2400 \pm 800$ K \cite{1}, and to be on a polar orbit around its parent star. Obliquity tidal heating can explain the observed high luminosity \cite{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 $1.9 R_{\oplus}$ at a cooling time of $0.3-0.6$ Gyr 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 $T_{\text{int}} \approx 500$ K. Merging both branches yields a tidal heat deposition zone at $\sim 1$ GPa and $\sim 0.8 R_{\oplus}$, and consequently a low static Love number $k_{2} < 0.1$ \cite{2}.

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

<table>
<thead>
<tr>
<th>Param</th>
<th>G17</th>
<th>Ca21</th>
<th>used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_*$ ($M_{\odot}$)</td>
<td>2.52</td>
<td>2.52</td>
<td></td>
</tr>
<tr>
<td>$R_*$ ($R_{\odot}$)</td>
<td>2.30-2.56</td>
<td>2.30-2.56</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>10170</td>
<td>10170</td>
<td></td>
</tr>
<tr>
<td>$a$ (AU)</td>
<td>0.0346</td>
<td>0.0346</td>
<td></td>
</tr>
<tr>
<td>$R_p$ ($R_\oplus$)</td>
<td>2.88 $\pm$ 0.84</td>
<td>2.88</td>
<td></td>
</tr>
<tr>
<td>$M_p$ ($M_\oplus$)</td>
<td>0-0.23</td>
<td>0-0.25</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{top}}$ (K)</td>
<td>4800</td>
<td>2770-240</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{bot}}$ (K)</td>
<td>2400+820</td>
<td>800-1000</td>
<td></td>
</tr>
</tbody>
</table>

Table: Stellar and planetary parameters used here.

The energy balance equation used here ($L_{\text{eq}}$: planetary luminosity if in equilibrium with stellar irradiation, $L_{\text{sec}}$: intrinsic luminosity, $L_{\text{tid},o}$: obliquity tidal heating \cite{4}) is

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

Using Stefan-Boltzmann’s law, luminosities are converted to temperatures.

$$T_{\text{sec}} = \frac{L_{\text{sec}}}{4\pi R_p^2}$$

$$T_{\text{tid},o} = \frac{L_{\text{tid},o}}{4\pi R_p^2}$$

$$T_{\text{tot}} = \frac{T_{\text{sec}}^4 + T_{\text{tid},o}^4}{2}$$

Using the observed $T_{\text{dd}}$ and $T_{\text{N}}$ values \cite{1}, we can solve for $T_{\text{玎}}$ as a function of heat distribution factor $f$ and adjusted $A_{\text{dd}}$. Results are consistent with Csizmadia \cite{1}.

Thermal evolution

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

Heavy element enrichment (Z)

ADIABATIC MODELS (grey): possible $T_{\text{top}}$ values range from $\sim 800$ K (zero Z) to $\sim 1600$ K (Z=100%), inconsistent with observations.

MODELS W SHELL HEATING (color):

- $P_{\text{bot}}$ = 1 GPa yields $\sim 20\%$ (good) models with $T_{\text{玎}} = 2000$ K are possible, while $>>2000$ K still too hot (too high Z).

Structure models with tidal heating in a shell

ASSUMPTIONS:

i) outer P-T profile above $P_{\text{bot}}$ follows solution for $T_{\text{玎}}=1600-2000$ K

ii) interior P-T profile below $P_{\text{bot}}$ follows cool adiabat for $T_{\text{玎}} < 500$ K

RESULT:

$P_{\text{top}}$ = 1 GPa $P_{\text{bot}}$ = 1 Mbar (near maximum of static tidal response, dashed) low $k_2 < 0.1$

References

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

Acknowledgement

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