Heat Redistribution in and Intrinsic Heat of a Hot Jupiter from TESS Phase Curve and Occultation Measurement

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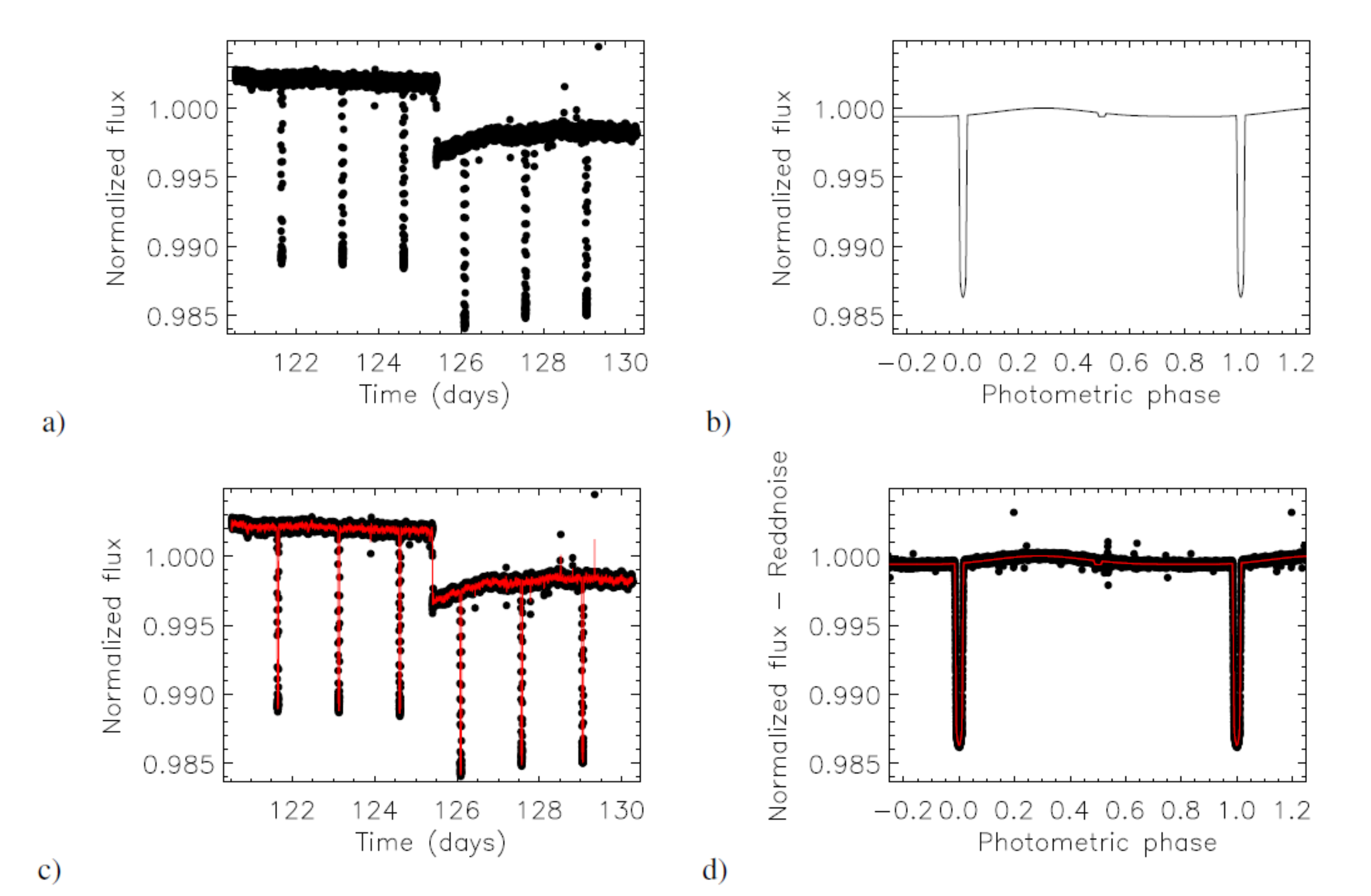
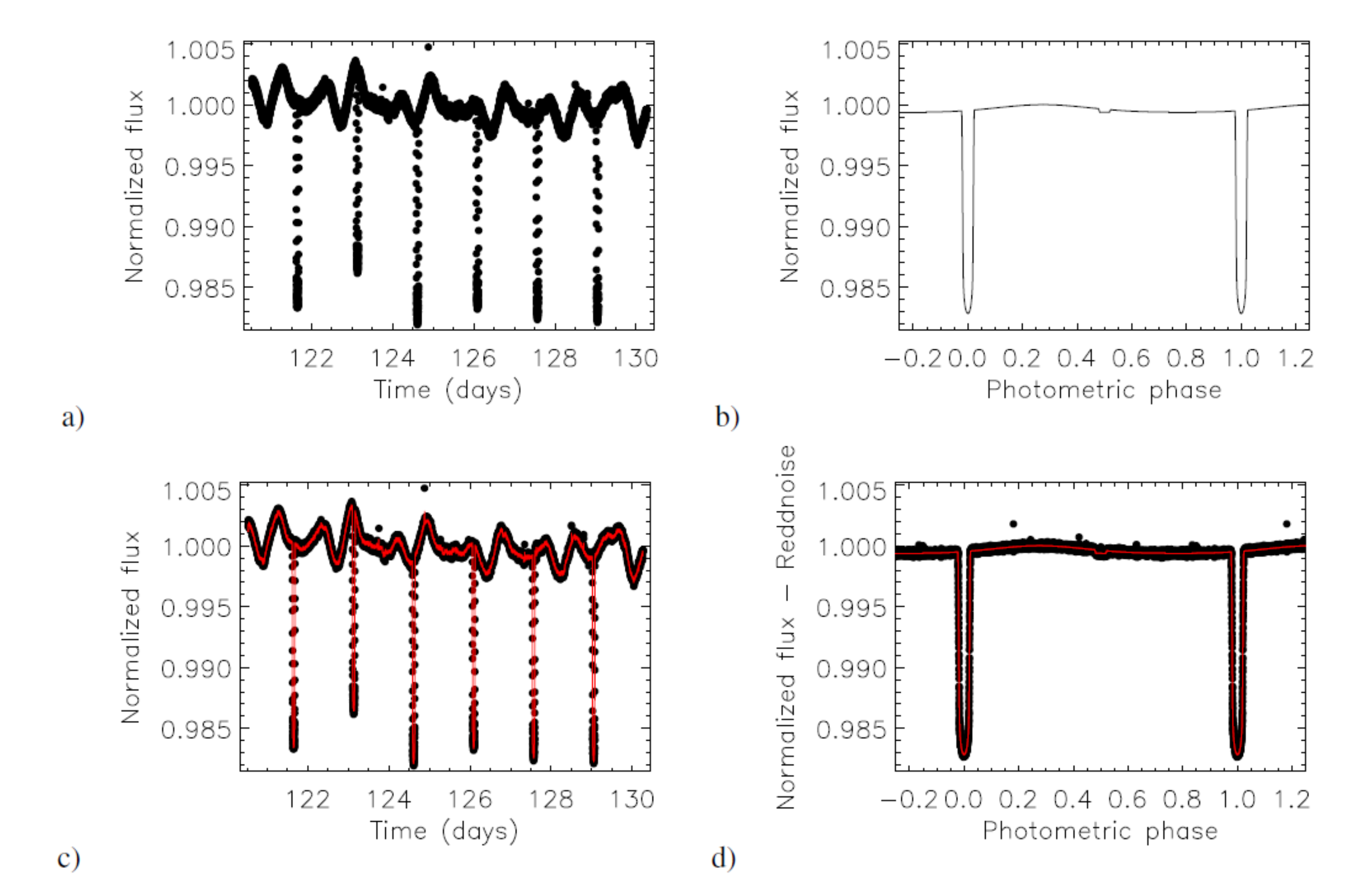
1. Power of wavelets in stellar variability and instrumental noise removal:

We use the formulation of Carter & Winn (2009, ApJ 704, 51).
We modified it in that way that we prescribe that the mean scatter of the residuals must be equal to the expected average noise level of the photometric data points and this is used as a prior:

$$\chi^2 \rightarrow \chi^2 + \frac{1}{2} N_{data} \left(\frac{MEAN\,(residuals)}{MEAN\,(\sigma_{obs})} - 1 \right)^2$$

Figures below show two examples out of the 1550 tests we carried out. We injected transit and phase curves into Kepler Q1 SC light curves and we modelled them with a joint fit of wavelet-based noise model plus a combined transit+occultation+ellipsoidal+reflection+bemaing effect model. The wavelet-based noise model is implemented into TLCM (Transit and Light Curve Modeller, Csizmadia 2020, MNRAS 496, 4442).





Left: a: the Kepler Q1 short-cadence light curve segment with the injected model
b: the injected model
c: red curve shows the model fit with the wavelet-based noise model
d: the phase-folded light curve with the derived red noise component. Red component is subtracted. Red curve is the transit+out of transit light curve model without the red noise component.

2. Application to KELT-9b

We used the S14 and S15 observations of KELT-9b obtained by TESS and modelled with TESS:

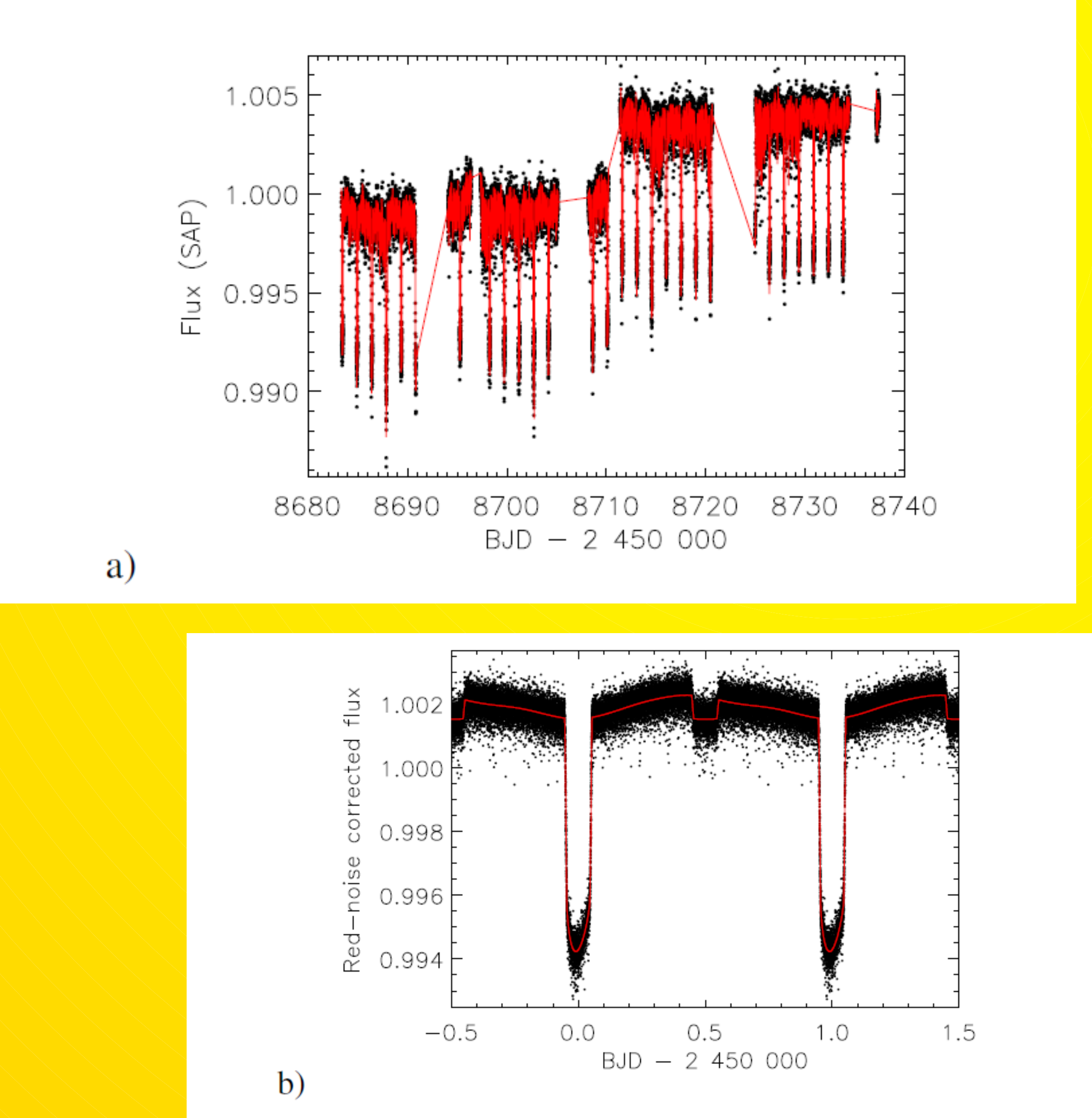


Fig. 2: a) The raw light curve (black dots) and the system+wavelet modelling best fit (red curve). b) The phase-folded, red noise corrected light curve (raw flux - wavelet based red noise, black dots) and the model fit (red line).

$$T_D^4 = T_{\rm int}^4 + \frac{1}{2} f (1 - A_B) T_{\rm star}^4 \left(\frac{R_{\rm star}}{a} \right)^2 \qquad (5)$$

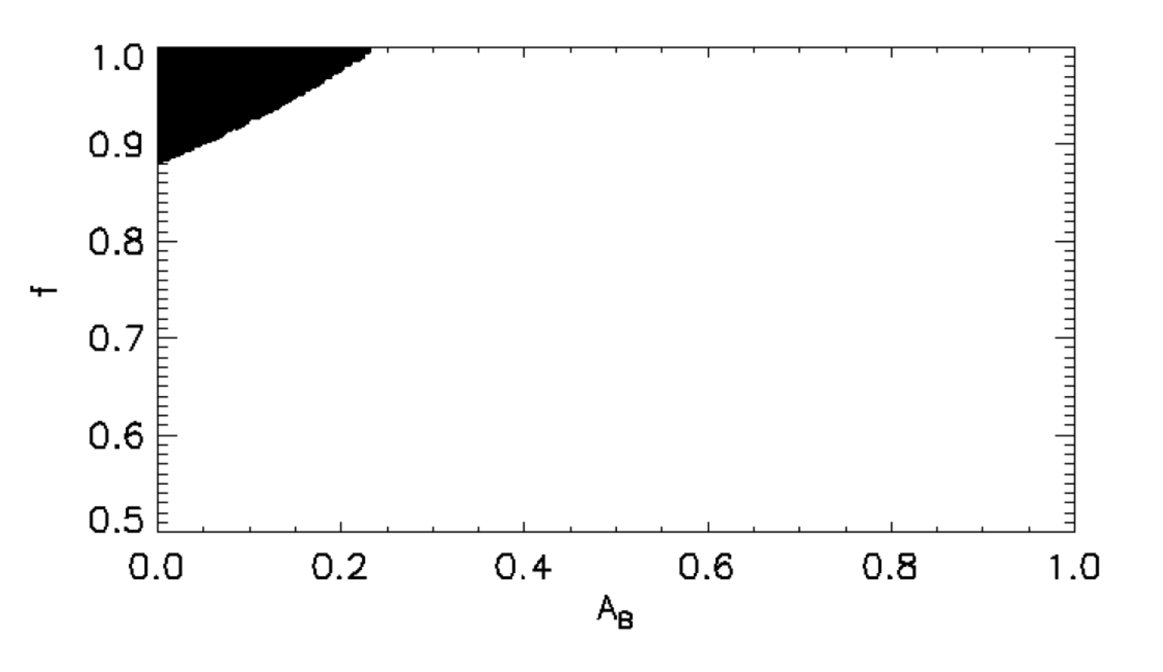
$$T_N^4 = T_{\rm int}^4 + \frac{1}{2} (1 - f)(1 - A_B) T_{\rm star}^4 \left(\frac{R_{\rm star}}{a} \right)^2 \qquad (6)$$

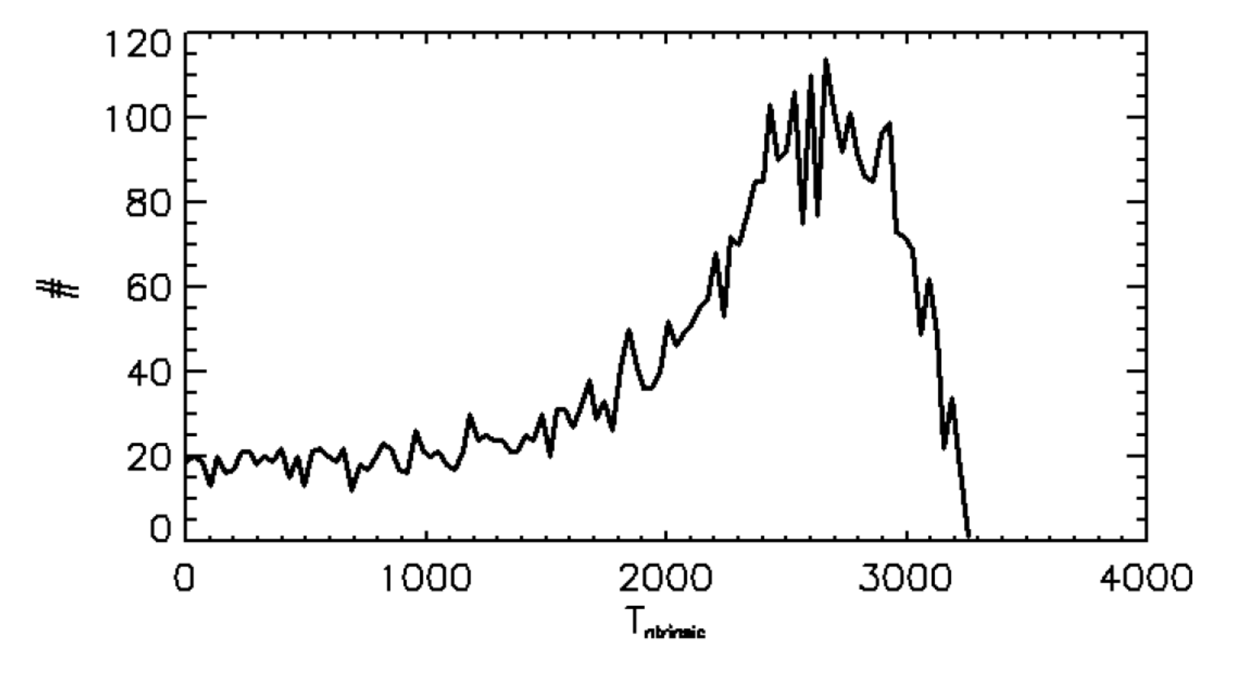
$$I_X = \int_0^\infty S(\lambda) B_\lambda (T_X) d\lambda \qquad (8)$$

Figures on the left and the quoted equations are from Csizmadia et al. (2022, A&A, under revision). Taking the response functions S(λ) of TESS and assuming a black-body emission of the exoplanet (possible flat etc atmosphere was not considered), we determined the dayside, nightside temperatures which are in good agreement (within 200 K) with results of Wong (2020, AJ 160, 88) and Mansfield (2020, ApJ 888, L15).

From Equations above we determined the possible values of the Bond-albedo A_B, heat redistribution factor f (1: all heat remains on the dayside, 0.5: half of incoming flux remains on dayside) and Intrinsic temperature. Because of three unkowns and with only two measured quantity (day- and nightside temperature) we can give only limits for these quantities, see the shadowed area and the distribution on the Figure left.

We concluded that under the assumption of black-body emission of the exoplanet, obliquity tides can explain the observed most likely intrinsic heat value, while gravitational contraction or ohmic
dissipation cannot.





Our results for KELT-9b based on TESS light curve:

- the dayside temperature is 4798 ± 80 K,
- the nightside temperature is 2767 ± 241 K,
- the intrinsic temperature is 2394 ± 817 K,
- the Bond-albedo is between 0.0 and 0.23,
- the heat-redistribution factor is between 0.88 and 1.0.