Characterization of KOI-94 system with photometric light curves and transit timing variation analysis: implication for the planet-planet eclipse

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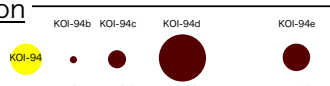
Introduction

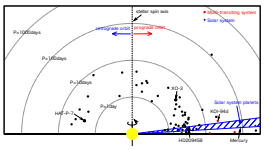
❖ KOI-94

- Multiple-transiting planetary system discovered by the Kepler space telescope
- Four transiting planets in the proximity of the central star



Spin-orbit angle measurement

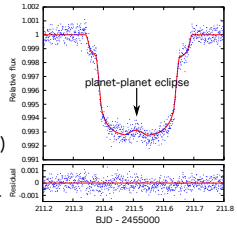
- Many hot Jupiters reside in misaligned orbits
  → How about multiple-transiting systems ?
- Rossiter-McLaughlin effect of KOI-94d
  → Orbital axis of KOI-94d is aligned with the stellar spin axis



Planet-planet eclipse (PPE)

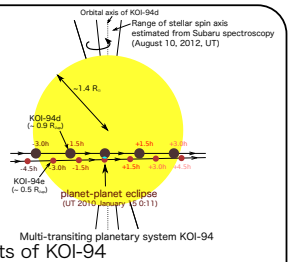
- Two planets (d and e) overlap with each other during their double-transit phase
- Shape of the "bump" (increase in the relative flux)
- → Orbital axes of KOI-94d and KOI-94e are well aligned

Hirano et al. (2012) →



❖ Motivation of this research

- Two close-in giant planets with well-aligned orbital axes
  → quiescent disk migration ?
- Important sample to understand the formation of multiple systems



Characterization of KOI-94

- Weiss et al. (2013): RV measurements of KOI-94
- Mass of KOI-94d is well constrained (m_d = 106 ± 11 M_E), but the detection of the other planets are marginal
- → Analysis of TTV can improve their estimates

Detailed study of PPE

- Mutual inclination can be precisely constrained
- No detailed modeling/discussion of multi-body effect

	KOI-94c	KOI-94d	KOI-94e
m (M_E)	$15.6^{+13.4}_{-12.6}$	106 ± 11	31^{+18}_{-16}
e	0.43 ± 0.23	0.022 ± 0.038	0.019 ± 0.23

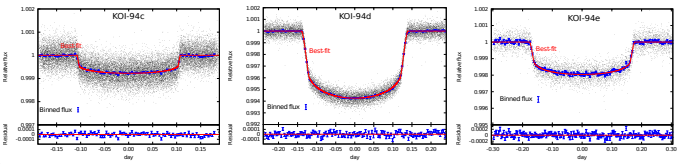
Best-fit parameters by Weiss et al. (2013)

⇒ Direct N-body analysis of TTV
Evaluation of the multi-body effect on PPE

Analysis of transit light curves

❖ Phase-folded transit light curve

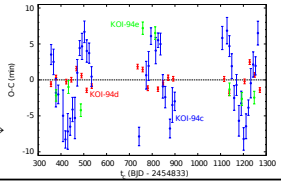
- Fix the transit parameters (a/R_s, R_p/R_s, b + limb darkening coefficients) based on the phase-folded transit light curves



❖ TTV signal

- Fit for the transit times (t_c) of KOI-94c, KOI-94d, and KOI-94e
- Deviation from the exact periodicity (= TTV: transit timing variation) was extracted by the linear fit
- Amplitude, phase, shape of TTV
  → planetary mass & eccentricity

Observed TTV signals of KOI-94c, KOI-94d, & KOI-94e →



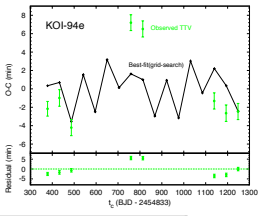
TTV analysis

❖ Method

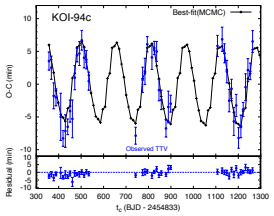
- Orbit integration using the fourth-order Hermite scheme
  → positions & velocities of the planets
- Transit center = minimum of the star-planet distance
  → simulated TTV → compared with the observed signal
- Fit for m (mass), e (eccentricity), ϖ (longitude of periastron)
- KOI-94b was neglected (negligible contribution to the TTVs of the other three)

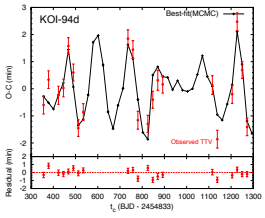
❖ Result

TTV of KOI-94e → poor best-fit
(not used to constrain system parameters)
★ outer non-transiting planet ?



TTVs KOI-94c & KOI-94d
(fitted simultaneously)





→ Solution with relatively small masses & eccentricities

❖ Comparison with RV result

- Eccentricity of KOI-94c: 1.8 σ smaller than RV best-fit (e_c = 0.43 ± 0.23)
- Mass of KOI-94d: 3-4 σ smaller
  ★ Also supported by the analysis using the analytic TTV formula by Lithwick et al. (2012)
- Further follow-up required

Best-fit parameters obtained from TTV analysis

Parameter	Value ($m_d = 106 M_\oplus$)	Value ($m_d = 73 M_\oplus$)	Value (TTV only)
KOI-94c			
m_c	$11.8^{+1.6}_{-1.5}$	$13.9^{+2.7}_{-2.7}$	$9.4^{+2.4}_{-2.1}$
$e_c \cos \varpi_c$	$0.0329^{+0.0047}_{-0.0055}$	$0.0092^{+0.0264}_{-0.0050}$	$0.0143^{+0.0080}_{-0.0059}$
$e_c \sin \varpi_c$	$-0.0104^{+0.0038}_{-0.0042}$	$-0.0031^{+0.0067}_{-0.0061}$	$0.0045^{+0.0091}_{-0.0079}$
χ^2_c	84	62	56
KOI-94d			
m_d	106 (fixed)	73 (fixed)	$52.1^{+6.9}_{-7.1}$
$e_d \cos \varpi_d$	$0.055^{+0.011}_{-0.014}$	$-0.016^{+0.064}_{-0.011}$	$-0.022^{+0.014}_{-0.011}$
$e_d \sin \varpi_d$	$0.012^{+0.011}_{-0.012}$	$0.0093^{+0.018}_{-0.018}$	$0.0075^{+0.021}_{-0.018}$
χ^2_d	66	48	43
KOI-94e			
m_e	$15.9^{+2.4}_{-2.2}$	$12.9^{+3.0}_{-2.3}$	$13.0^{+2.5}_{-2.1}$
$e_e \cos \varpi_e$	$0.067^{+0.014}_{-0.019}$	$-0.069^{+0.120}_{-0.018}$	$-0.078^{+0.021}_{-0.014}$
$e_e \sin \varpi_e$	$0.042^{+0.012}_{-0.017}$	$-0.022^{+0.032}_{-0.016}$	$-0.025^{+0.017}_{-0.014}$
$(\chi^2_c + \chi^2_d)$/d.o.f	150/57	110/57	99/56

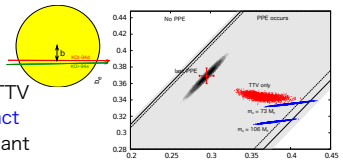
Implication for the PPE: when will it occur next ?

❖ Two-body prediction

- Occurrence of the PPE in a certain double transit
  → minimum separation between planets vs. sum of planetary radii
- Analytic model neglecting the interaction among the planets
  → next PPE by KOI-94d and KOI-94e occurs in the double transit around UT 2026 April 1/2
- What if we include the multi-body interaction ?

❖ Multi-body prediction

- Orbit integration using the parameters obtained from TTV
- Variation of the transit impact parameter b is most significant
- PPE still occurs in the same double transit (at least in 1 σ)



Summary & Outlook

✓ TTV analysis of KOI-94c, KOI-94d and KOI-94e
- Mass, eccentricity, longitude of periastron
- Solution with small eccentricities & small m_d

✓ Multi-body effect is not significant for the time of the next PPE

➢ Discrepancy between TTV and RV results

➢ Four-planet model may not fully describe the system
- TTV of KOI-94e cannot be explained (another perturber ?)
- Direct fit to the transit times (not TTVs) are not successful (?)

➢ Interesting target of further study

References

- Hirano, T., et al. 2012, ApJ, 759, L36
- Weiss, L. M., et al. 2013, ApJ, 768, 14
- Lithwick, Y., Xie, J., & Wu, Y. 2012, ApJ, 761, 122