Low Density Planets around Kepler-51 Revealed with Transit Timing Variations

Kento Masuda[1]
[1] Department of Physics, University of Tokyo
E-mail: masuda@utap.phys.s.u-tokyo.ac.jp

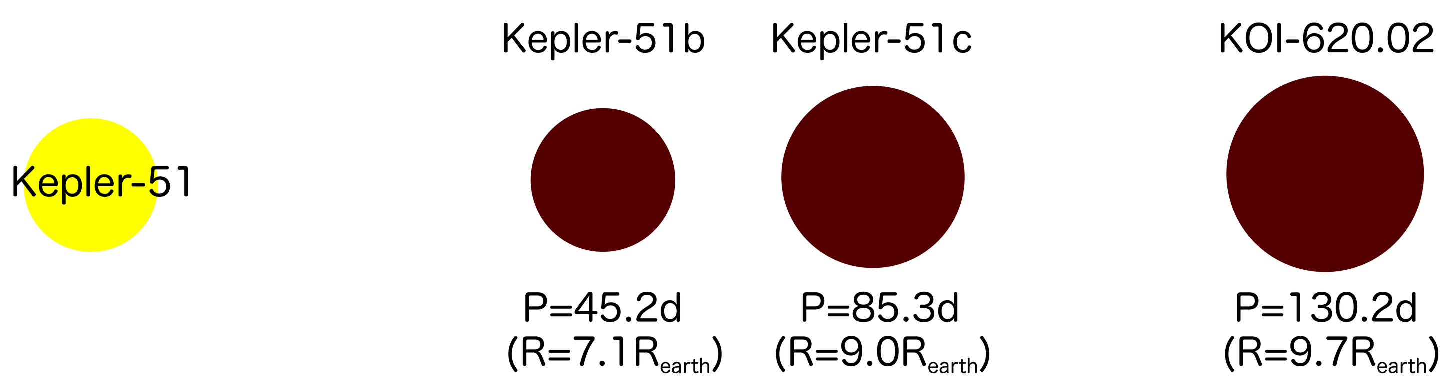
Masuda, K. 2014, ApJ, 783, 53
http://arxiv.org/abs/1401.2885

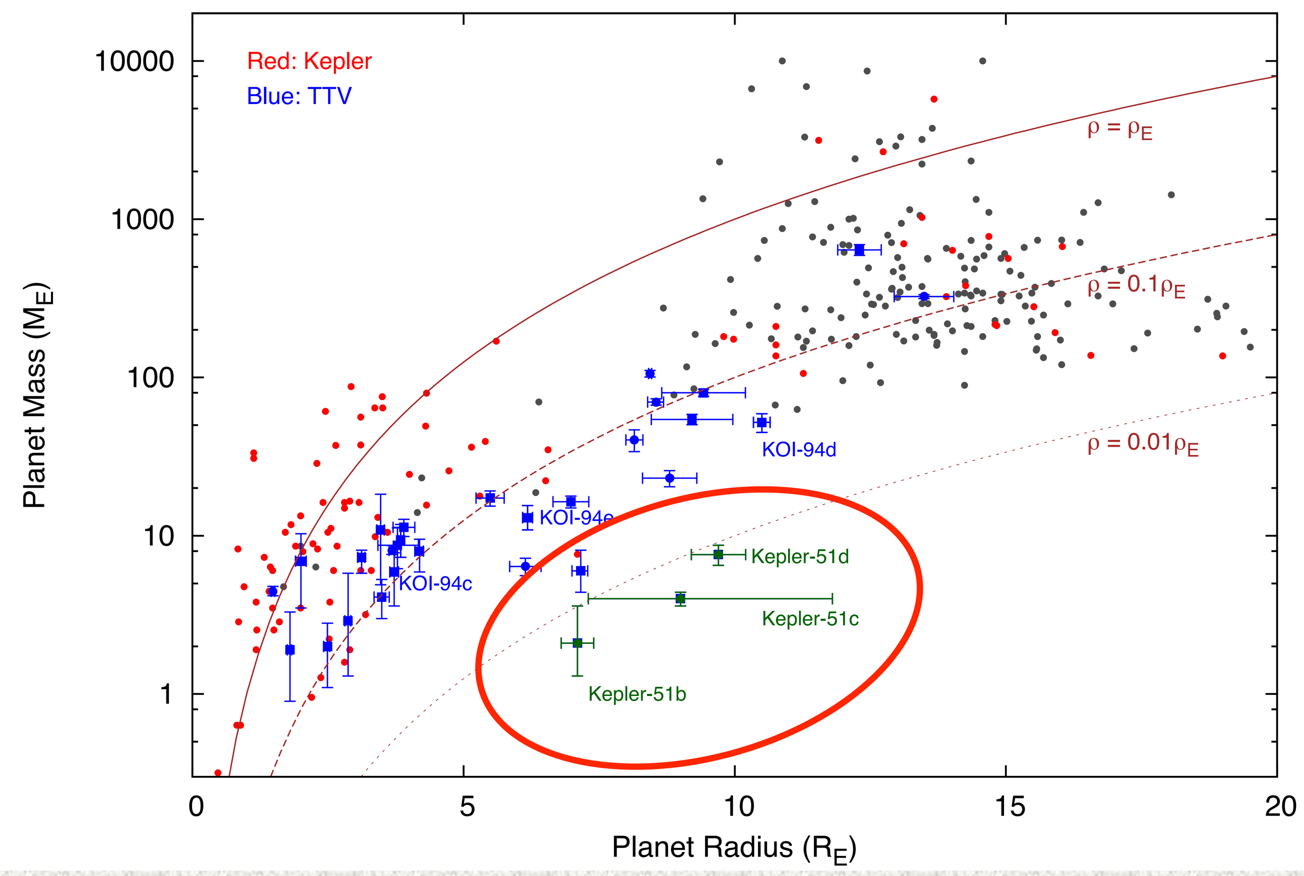
Abstract

We present an analysis of the transit timing variations (TTVs) in the multi-transiting planetary system around Kepler-51 (KOI-620). This system consists of two confirmed transiting planets, Kepler-51b (P_b = 45.2 days) and Kepler-51c (P_c = 85.3 days), and one transiting planet candidate KOI-620.02 (P_{02} = 130.2 days), which lie close to a 1:2:3 resonance chain. Our analysis shows that their TTVs are consistently explained by the three-planet model, and constrains their masses as M_b = 2.1 (-0.8, +1.5) M_{Earth} (Kepler-51b), M_c = 4.0 ± 0.4 M_{Earth} (Kepler-51c), and M_{02} = 7.6 ± 1.1 M_{Earth} (KOI-620.02), thus confirming KOI-620.02 as a planet in this system (Kepler-51d). The masses inferred from the TTVs are rather small compared to the planetary radii based on the stellar density and planet-to-star radius ratios determined from the transit light curves. Combining these estimates, we find that all three planets in this system have densities among the lowest determined, $\rho_p < 0.05$ g cm^{-3}. With this feature, the Kepler-51 system serves as another example of low-density compact multi-transiting planetary systems.

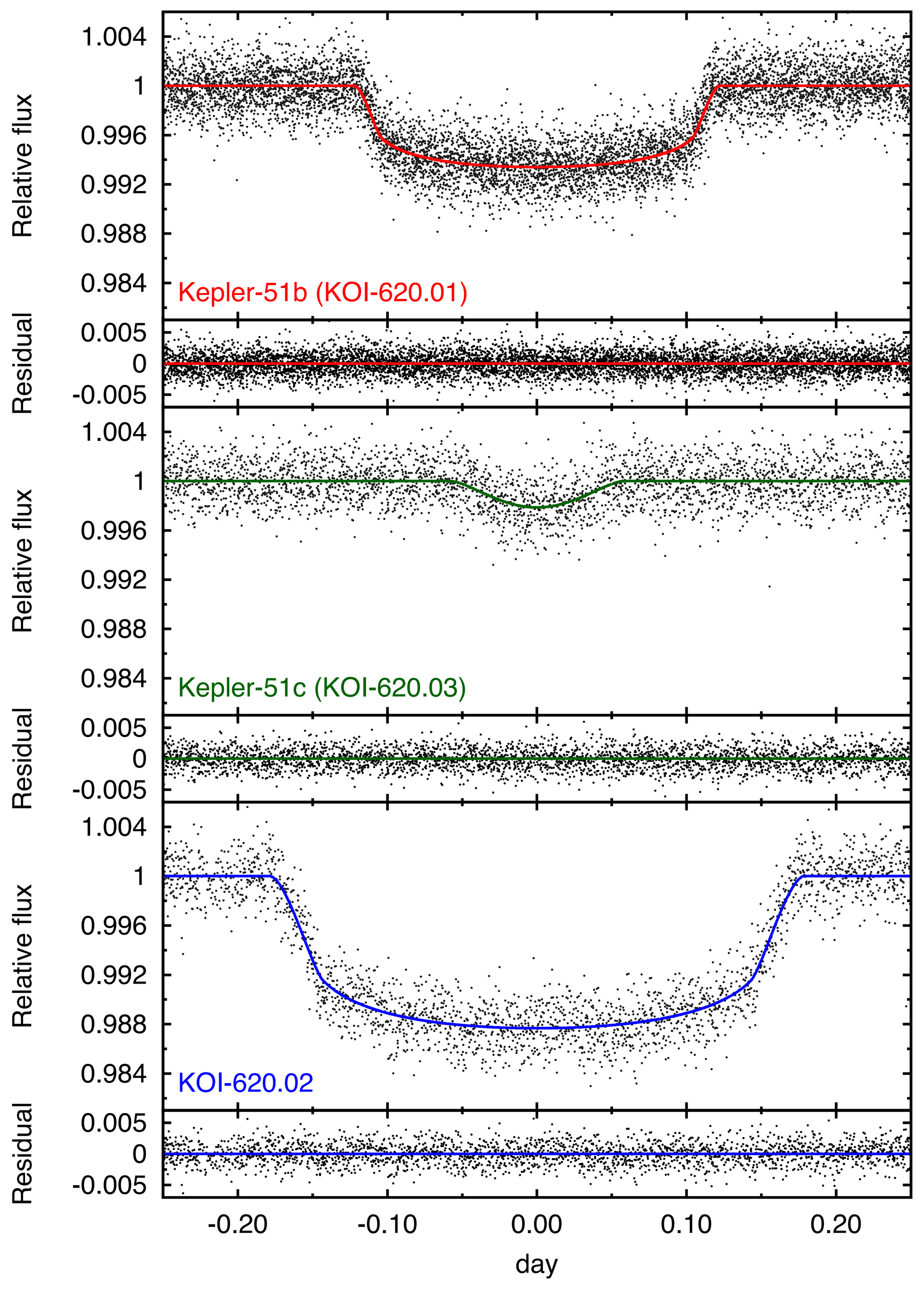
The Kepler-51 System

- ❖ Two confirmed transiting planets (Kepler-51b, Kepler-51c) & one transiting planet candidate (KOI-620.02)
- ❖ Faint host star (K_p = 14.7) → difficult to confirm with RVs
- ❖ Close to a 1:2:3 mean motion resonance → prominent TTVs expected
- ❖ Small TTVs considering their long orbital periods and sizes

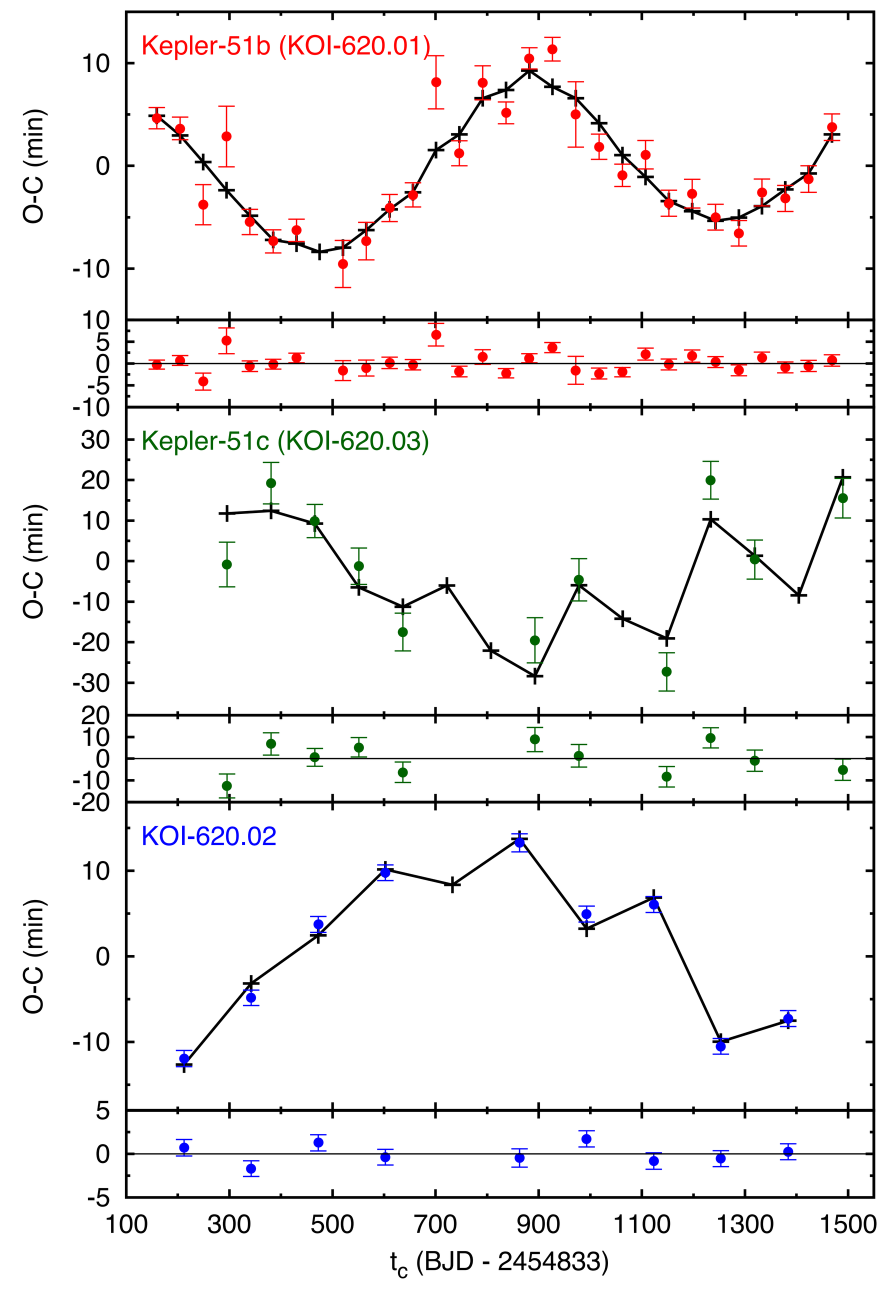




Light Curve & TTV Analysis



Phase-folded transit light curves. Solid lines show the best-fit transit models.



Numerical fit (black solid lines) to the observed transit times (colored points).

- ❖ Phase-folded Transit
  → R_p/R_s (planet-to-star radius ratio), ρ_s (mean stellar density)
- ❖ TTV (Transit Timing Variation)
  → M_p/M_s (planet-to-star mass ratio), e cosω, e sinω
- ❖ Absolute dimensions of the planets
  - Density: $\rho_p = \rho_s (M_p/M_s)(R_p/R_s)^{-3}$ (purely from transit & TTV)
  - Mass & Radius: $M_s = 1.04 \pm 0.12\, M_{sun}$ (KIC)
    → $M_p = M_s (M_p/M_s)$, $R_p = (3M_s/4\pi\rho_s)^{1/3} (R_p/R_s)$

❖ Extremely Low Density Planets!

Kepler-51d

Parameter	Kepler-51b	Kepler-51c	KOI-620.02
M_p ($M_\oplus$)	$2.1^{+1.5}_{-0.8}$	4.0 ± 0.4	7.6 ± 1.1
R_p ($R_\oplus$)	7.1 ± 0.3	$9.0^{+2.8}_{-1.7}$	9.7 ± 0.5
ρ_p (g cm^{-3})	$0.03^{+0.02}_{-0.01}$	$0.03^{+0.02}_{-0.03}$	0.046 ± 0.009
a (AU)	0.2514 ± 0.0097	0.384 ± 0.015	0.509 ± 0.020
e	0.04 ± 0.01	$0.014^{+0.013}_{-0.009}$	$0.008^{+0.011}_{-0.008}$
T_{eq} (K)	543 ± 11	439 ± 9	381 ± 8

Details of the TTV Analysis

❖ Data

- Long cadence PDCSAP fluxes from Q1-Q11 (t_c <~ 1100)
- Short cadence PDCSAP fluxes from Q12-Q16 (t_c >~ 1100)

❖ Method

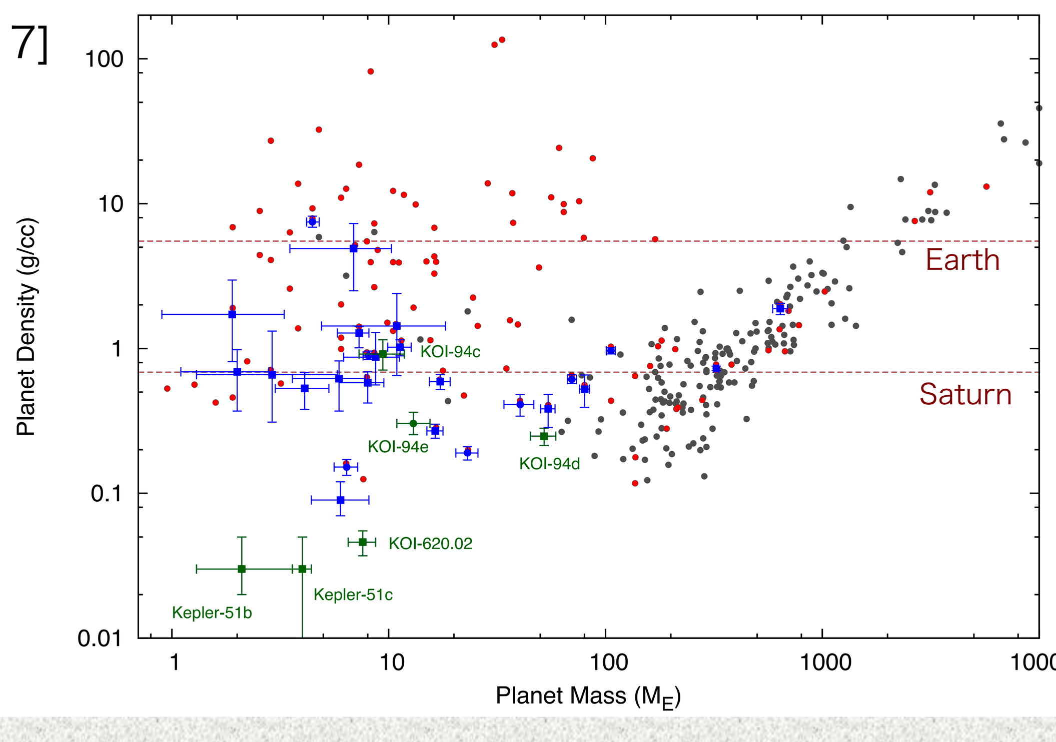
- Orbit integration: fourth-order Hermite scheme[1]
- Transit times were determined by finding minima of the star-planet distance → compared to the observation
- Fit for m (mass), e (eccentricity), ω (argument of periastron), P (orbital period), T_c (transit time nearest to the calculation epoch) of each planet
  * coplanarity assumed, transit duration variation not modeled
- χ^2 minimization with the downhill simplex method & MCMC search

Summary & Implications

✓ All the three planets in the Kepler-51 system have fantastically low densities (less than 1/10 of Saturn)

➢ Structure models[2][3] suggest that these planets have rich gas envelopes (mass comparable to their cores)
→ Envelope accretion begins at relatively low masses?
...but, accretion must stop before/during the runaway phase[4]

➢ Low-density planets are rather common in compact multi-transiting systems confirmed with TTVs
- masses from TTVs are lower than those from RVs[5]
- systematics in TTV?[6, 7]
- intrinsic feature?



References

[1] Kokubo, E., & Makino, J. 2004, PASJ, 56, 861
[2] Lopez, E. D., & Fortney, J. J. 2013, arXiv:1311.0329
[3] Howe, A. R., Burrows, A., & Verne, W. 2014, arXiv:1402.4818
[4] Ikoma, M., & Hori, Y. 2012, ApJ, 753, 66
[5] Weiss, L. M., & Marcy, G. W. 2014, ApJ, 783, L6
[6] Dreizler, S., & Ofir, A. 2014, arXiv:1403.1372
[7] Masuda, K., Hirano, T., Taruya, A., et al. 2013, ApJ, 778, 185