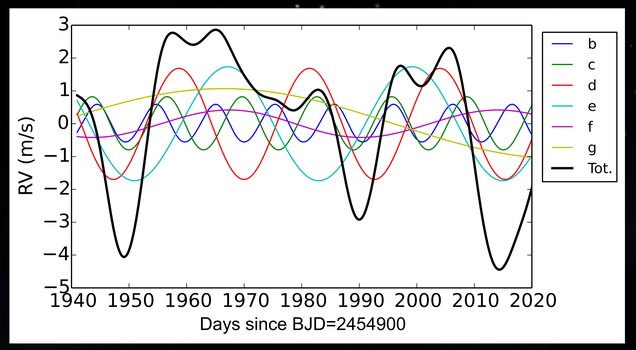
Constraining The Masses of the Kepler-11 Planets with Radial Velocities

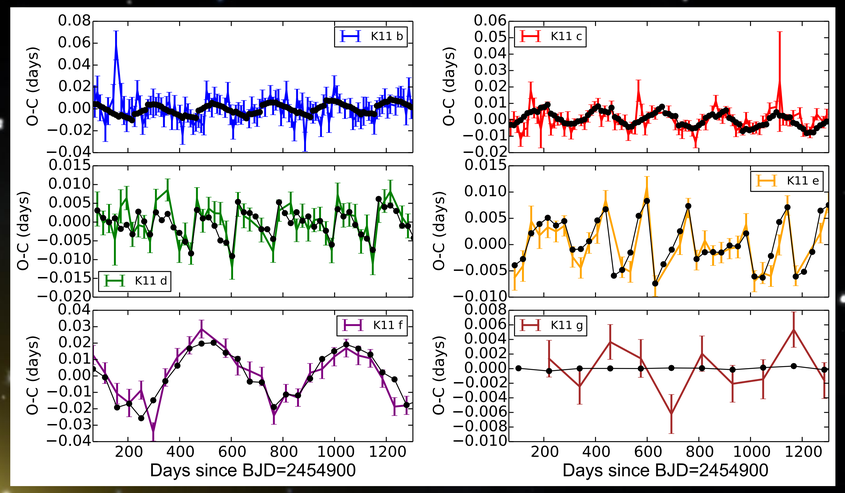
Lauren M. Weiss[1,2], Geoffrey W. Marcy[1], Howard T. Isaacson[1], Katherine M. Deck[3], Jack J. Lissauer[4], Daniel Jontof-Hutter[5]
[1]U.C. Berkeley, [2]Ken & Gloria Levy Fellow, [3]California Institute of Technology, [4]NASA Ames, [5]Pennsylvania State University

Abstract

Kepler-11 is a sun-like (G0) star with 6 transiting planets discovered by the *Kepler* Mission. Five of the six planets have been found to have ultra-low densities through N-body dynamical analysis of their transit timing variations (TTVs). Numerically reproducing TTVs has become a new method for solving the masses of planets, but this method is susceptible to certain dynamic degeneracies: the planet eccentricity is degenerate with the planet mass, and perturbations caused by non-transiting planets could be misattributed to the transiting planets. Furthermore, the masses of planets characterized by TTV analysis are systematically 2x lower than the masses (including non-detections) reported by radial velocity (RV) analysis for planets of the same radius. We address the discrepancy between the TTV- and RV- determined planet masses by measuring the RVs of Kepler-11 at opportunistic times, as determined by the ephemerides of the transiting planets. We obtained 17 RVs of Kepler-11 system with Keck/HIRES over the summer of 2014. From our RVs only, we place a 3σ upper limit on the masses of the Kepler-11 planets of 2x their nominal masses. Thus, we demonstrate that the RVs are consistent with the ultra-low masses determined by the TTVs. We use the simplectic N-body integrator TTVFAST to jointly model the RVs and Q1-Q16 TTVs of Kepler-11, deriving new and improved planet masses and densities for the five inner planets and constraining the mass of the outermost planet better than TTVs can do alone. The consistency of the TTVs and RVs in the Kepler-11 system bodes well for N-body simulations of TTVs for other Kepler systems that are too faint for RV follow-up.



Predicted Radial Velocity (RV, black) of Kepler-11 over summer 2014, using the orbital ephemerides for the planets derived from transit measurements (1, 2) and the planet masses calculated from transit timing variations (TTVs, 2). The colored curves are the RV contribution from each planet.



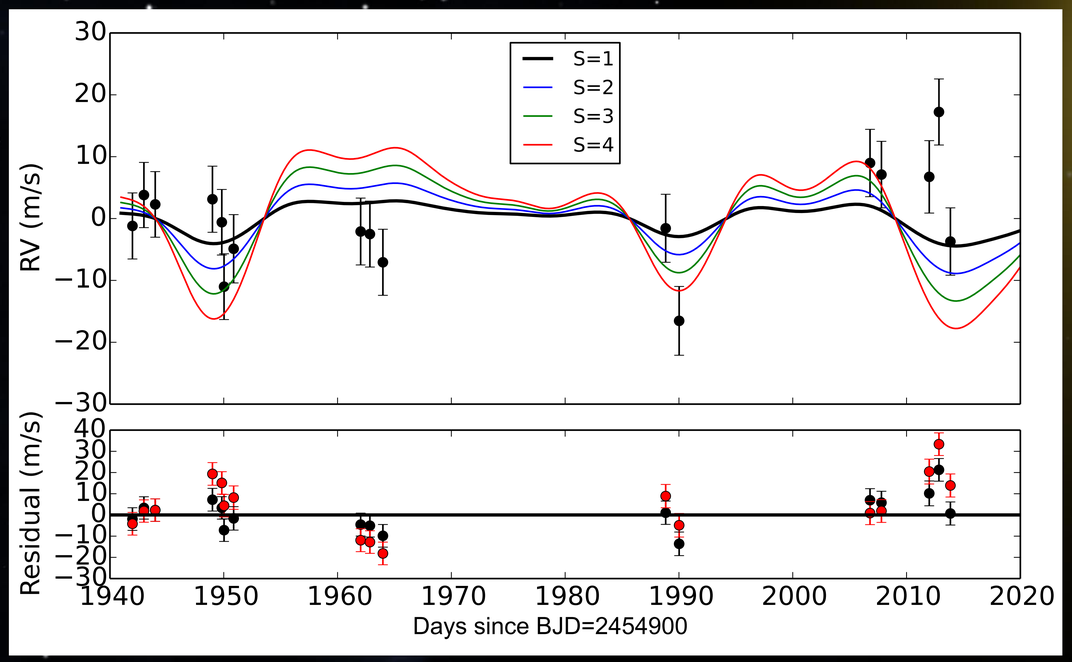
Observed transit timing variations (TTVs) of the Kepler-11 planets (colored lines and error bars) and the best dynamical model using TTVFAST (3) to reproduce the observed TTVs and RVs. There are 313 TTV data + 17 RV data (330 data), and χ^2=380.

Table 2
Kepler-11 Best Fit Dynamical Properties

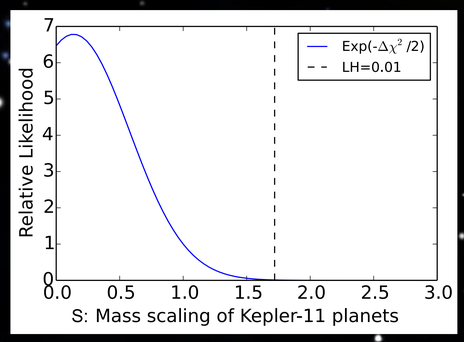
Planet	Period (d)	Ecc.	Inc. (°, fixed)	Ω (°, fixed)	ω (°)	M.A. (°)	Mass ($M_\oplus$)	Radius[a] ($R_\oplus$)	Density (g/cc)
Kepler-11b	10.30483	0.045	89.64	0	45.54	127.15	$1.87^{+0.43}_{-0.53}$	1.80 ± 0.04	1.76 ± 0.46
Kepler-11c	13.02386	0.025	89.59	0	51.32	189.72	$2.63^{+0.80}_{-0.63}$	2.87 ± 0.05	0.61 ± 0.17
Kepler-11d	22.69197	0.003	89.67	0	146.29	21.97	$7.36^{+0.63}_{-1.16}$	3.12 ± 0.06	1.34 ± 0.12
Kepler-11e	31.99412	0.013	89.89	0	228.40	318.26	$8.19^{+0.77}_{-0.66}$	4.19 ± 0.08	0.61 ± 0.06
Kepler-11f	46.69292	0.013	89.47	0	335.55	105.43	$1.94^{+0.32}_{-0.88}$	2.49 ± 0.05	0.69 ± 0.21
Kepler-11g	118.3973	0.039	89.87	0	34.51	295.63	$< 27.6^b$	3.33 ± 0.07	$< 4.11^b$

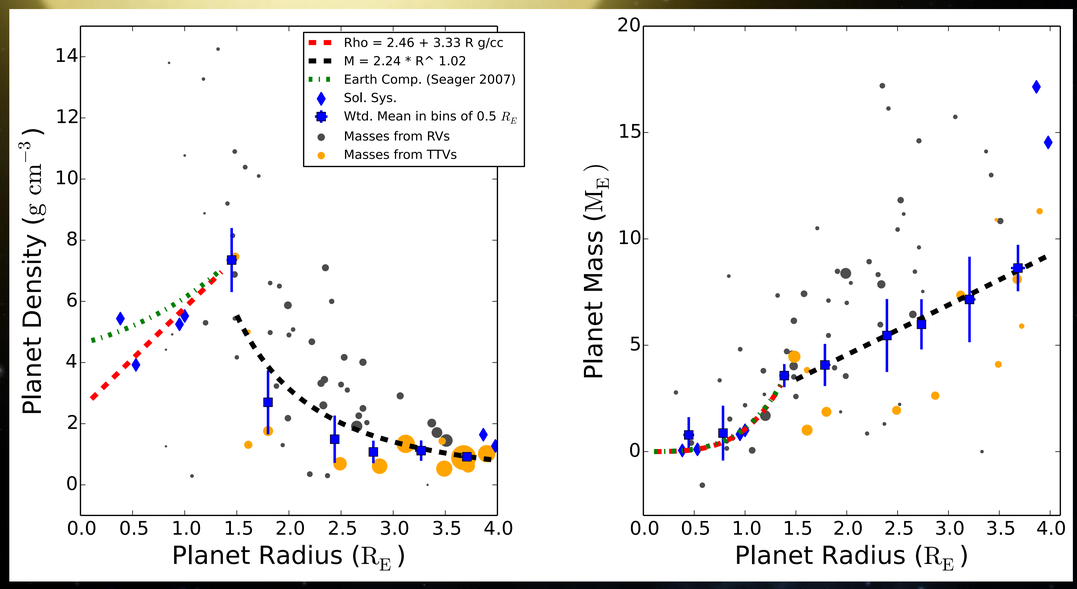
Note. — Osculating Elements determined at epoch BJD - 2454900 = 64.67
[a] From Lissauer et al. (2013)
[b] 2σ upper limit.

Kepler-11 planet orbital properties and masses, based on the best dynamical fit to the TTVs and RVs. The masses obtained are within 10% of those found previously (2).



Above: Radial velocity of Kepler-11 measured in 17 nights during the summer of 2014. The black curve shows the original predicted RV of the star. Scaling the planet masses by S, where S=2 (blue), 3 (green), and 4 (red) allows us to explore whether the TTV masses were systematically too low. One can see by eye that S=1 is superior to S=4. The residuals of S=1 (black) and S=4 (red) are shown in the bottom panel. Right: The relative likelihood of different values of S, based on their goodness of fit to the RVs. The RVs prefer low values of S, finding S < 2 with 3σ confidence.





Density versus radius (left) and mass versus radius (right) for exoplanets smaller than 4 Earth radii (R_E) with measured masses or mass upper limits. The masses are determined by RVs (gray) or TTVs (gold). The point size corresponds to $1/\sigma^2$. Blue squares show the weighted mean density (left) and mass (right) in bins of 0.5 Earth radii from 1-4 Earth radii. The blue diamonds are solar system planets. The blue points illustrate the transition from primarily rocky planets below 1.5 R_E to planets with a gaseous layer above 1.5 R_E. The red line is an empirical linear fit to density versus radius for R < 1.5 R_E, the black line is an empirical fit to mass vs. radius for R > 1.5 R_E.

References: (1) Lissauer et al. 2011; (2) Lissauer et al. 2013; (3) Deck et al. 2014