The Mass-Radius Relation Between 63 Exoplanets Smaller than 4 Earth Radii

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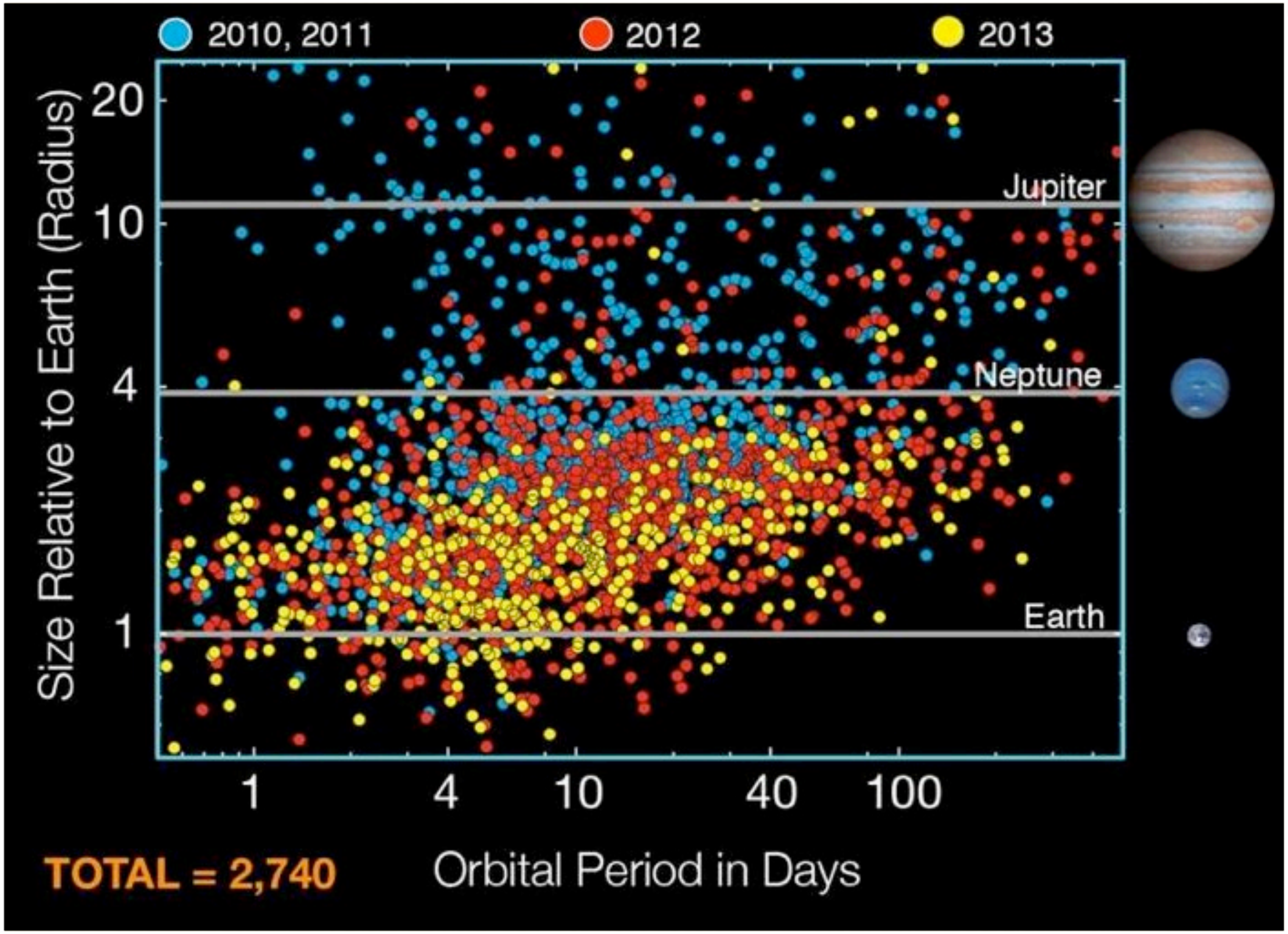
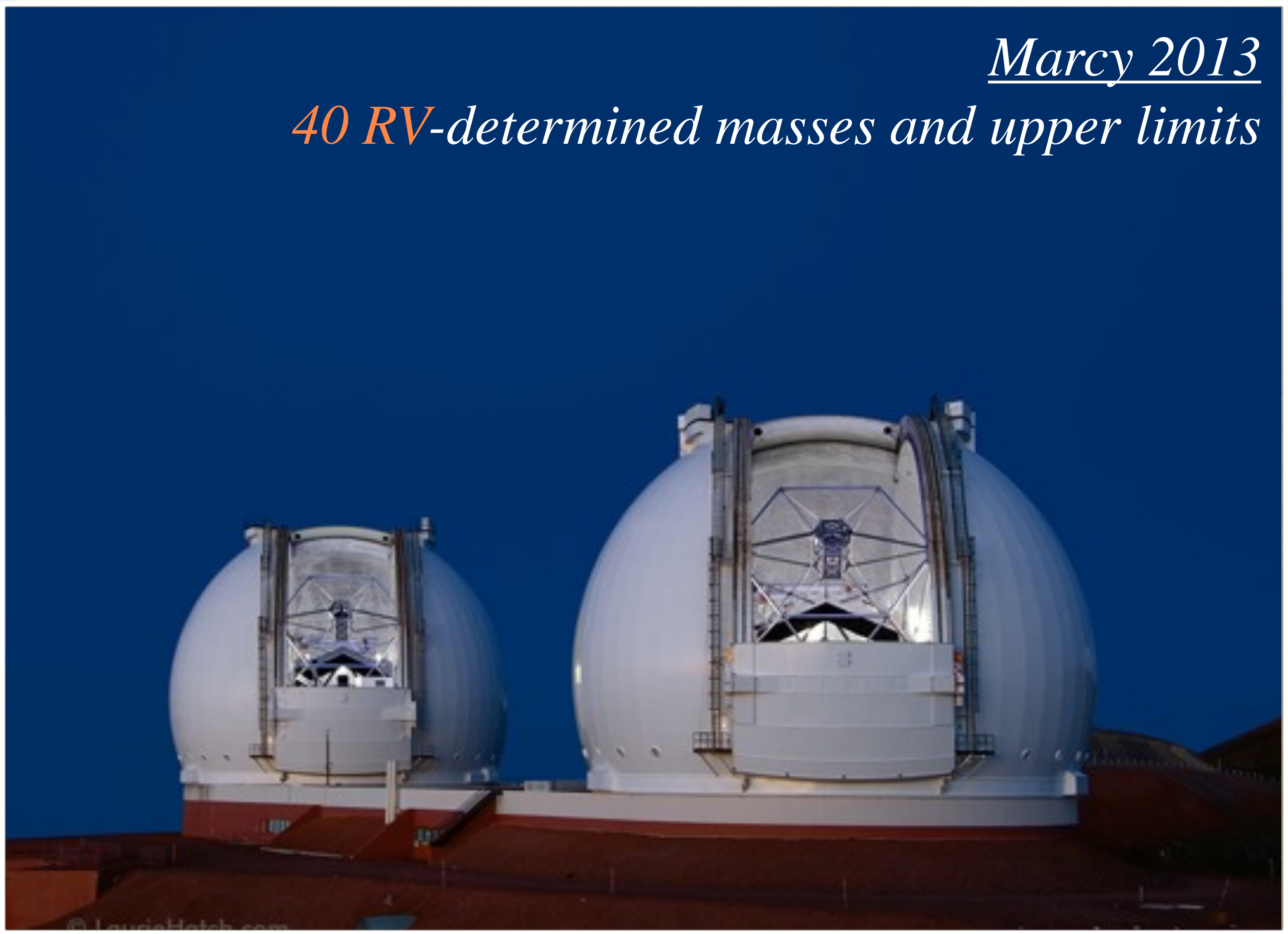
ABSTRACT

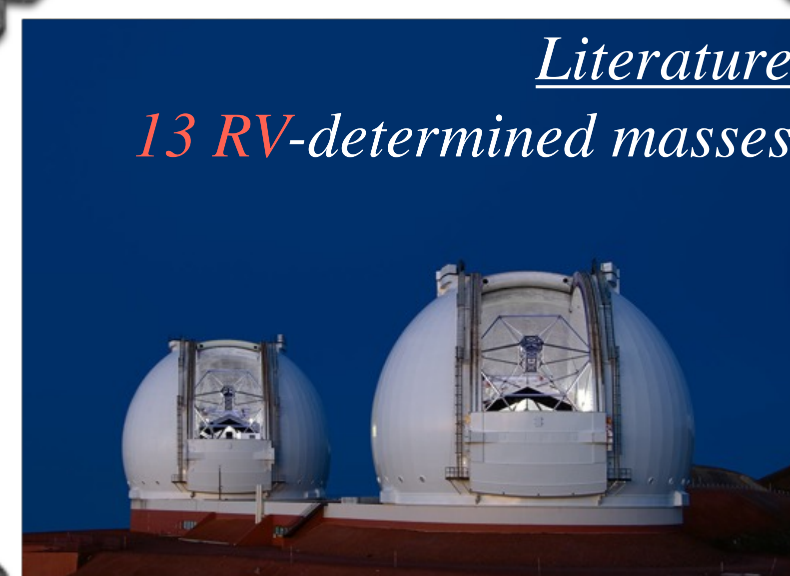
We study the masses and radii of 60 exoplanets smaller than $4R_\oplus$ with orbital periods shorter than 100 days. We find a nearly linear mass-radius relation: $M_P/M_\oplus = 3.17\,(R_P/R_\oplus)^{0.87}$, which is a shallower power-law index than in many previous mass-radius relations. The RMS of planet masses to this fit is 3.9 $M_\oplus$, and our best fit has reduced $\chi^2 = 3.1$, indicating a diversity in planet compositions below $4R_\oplus$. Fitting density vs. radius with a polynomial, we find $\rho = 11.50 - 5.97(R_P/R_\oplus) + 0.84(R_P/R_\oplus)^2$. The mass-radius and mass-density relations reflect that planet density decreases as radius increases, indicating that larger exoplanets have a significant fraction of volatiles by volume (such as H/He envelopes). Exoplanets have densities comparable to that of Earth at $R_P \sim 1.5R_\oplus$, indicating likely rocky compositions among planets smaller than 1.5 $R_\oplus$. The scaling of the mass-radius relationship for exoplanets with $R_P < 1.5R_\oplus$ is not well-constrained but if we include the solar system terrestrial planets, we find that a relationship of $M_P/M_\oplus = 1.08\,(R_P/R_\oplus)^{3.45}$ is a significant improvement over the nearly linear relationship.

Super-Earths and Mini-Neptunes are Common (Kepler)



Mass determinations and upper limits of 63 exoplanets smaller than 4 $R_\oplus$ from RVs, TTVs





63 Masses of Exoplanets Smaller than 4 R⊕ (40 from Marcy+ 2013, submitted)

Table 1
Exoplanets with Masses or Mass Upper Limits and $R_P < 4R_\oplus$

Name	Per (d)	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Flux[a] ($F_\oplus$)	First Ref.	Mass, Radius Ref.
[b]55 Cnc e	0.737	8.38±0.39	1.990±0.084	2439.690	McArthur et al. (2004)	Endl et al. (2012), Dragomir et al. (2013a)
CoRoT-7 b	0.854	7.42±1.21	1.58±0.1	1779.433	Queloz et al. (2009), Léger et al. (2009)	Hatzes et al. (2011)
GJ 1214 b	1.580	6.45±0.91	2.65±0.09	16.631	Charbonneau et al. (2009)	Carter et al. (2011)
HD 97658 b	9.491	7.87±0.73	2.34±0.16	48.106	Howard et al. (2011)	Dragomir et al. (2013b)
Kepler-10 b	0.837	4.60±1.26	1.46±0.02	3675	Batalha et al. (2011)	Batalha et al. (2011)
[c]Kepler-11 b	10.304	1.90±1.20	1.80±0.04	126.512	Lissauer et al. (2011)	Lissauer et al. (2013)
[c]Kepler-11 c	13.024	2.90±2.20	2.87±0.06	91.443	Lissauer et al. (2011)	Lissauer et al. (2013)
[c]Kepler-11 d	22.684	7.30±1.10	3.12±0.07	43.563	Lissauer et al. (2011)	Lissauer et al. (2013)
[c]Kepler-11 f	46.689	2.00±0.80	2.49±0.06	16.747	Lissauer et al. (2011)	Lissauer et al. (2013)
Kepler-18 b	3.505	6.90±3.48	2.00±0.10	462.244	Borucki et al. (2011)	Cochran et al. (2011)
Kepler-20 b	3.696	8.47±2.12	1.91±0.16	346.711	Borucki et al. (2011)	Gautier et al. (2012)
Kepler-20 c	10.854	15.73±3.31	3.07±0.25	82.445	Borucki et al. (2011)	Gautier et al. (2012)
Kepler-20 d	77.612	7.53±7.22	2.75±0.23	5.985	Borucki et al. (2011)	Gautier et al. (2012)
[c]Kepler-30 b	29.334	11.3±1.4	3.90 ±0.20	21.496	Borucki et al. (2011)	Sanchis-Ojeda et al. (2012)
[c]Kepler-36 b	13.840	4.46±0.30	1.48±0.03	217.365	Borucki et al. (2011)	Carter et al. (2012)
[c]Kepler-36 c	16.239	8.10±0.53	3.68±0.05	175.646	Carter et al. (2012)	Carter et al. (2012)
Kepler-68 b	5.399	8.30±2.30	2.31±0.03	409.092	Borucki et al. (2011)	Gilliland et al. (2013)
Kepler-68 c	9.605	4.38±2.80	0.95±0.04	189.764	Batalha et al. (2013)	Gilliland et al. (2013)
Kepler-78 b	0.354	1.69±0.41	1.20±0.09	3093.388	Sanchis-Ojeda et al. (2013)	Howard et al. (2013)
KOI-41.01	12.816	0.85±4.00	2.20±0.05	213.371	Borucki et al. (2011)	Marcy et al. (2013)
KOI-41.02	6.887	7.34±3.20	1.32±0.04	472.831	Borucki et al. (2011)	Marcy et al. (2013)
KOI-41.03	35.333	-4.36±4.10	1.61±0.05	55.812	Borucki et al. (2011)	Marcy et al. (2013)
KOI-69.01	4.727	2.59±2.00	1.50±0.03	220.120	Borucki et al. (2011)	Marcy et al. (2013)
KOI-82.01	16.146	8.93±2.00	2.22±0.07	17.278	Borucki et al. (2011)	Marcy et al. (2013)
KOI-82.02	10.312	3.80±1.80	1.18±0.04	31.184	Borucki et al. (2011)	Marcy et al. (2013)
KOI-82.03	27.454	0.62±3.30	0.88±0.03	8.250	Borucki et al. (2011)	Marcy et al. (2013)
KOI-82.04	7.071	-1.58±2.00	0.58±0.02	51.315	Borucki et al. (2011)	Marcy et al. (2013)
KOI-82.05	5.287	0.41±1.60	0.47±0.02	78.407	Borucki et al. (2011)	Marcy et al. (2013)
KOI-94 b	3.743	10.50±4.60	1.71±0.16	1155.374	Batalha et al. (2013)	Weiss et al. (2013)
KOI-104.01	2.508	10.84±1.40	3.51±0.15	214.674	Borucki et al. (2011)	Marcy et al. (2013)

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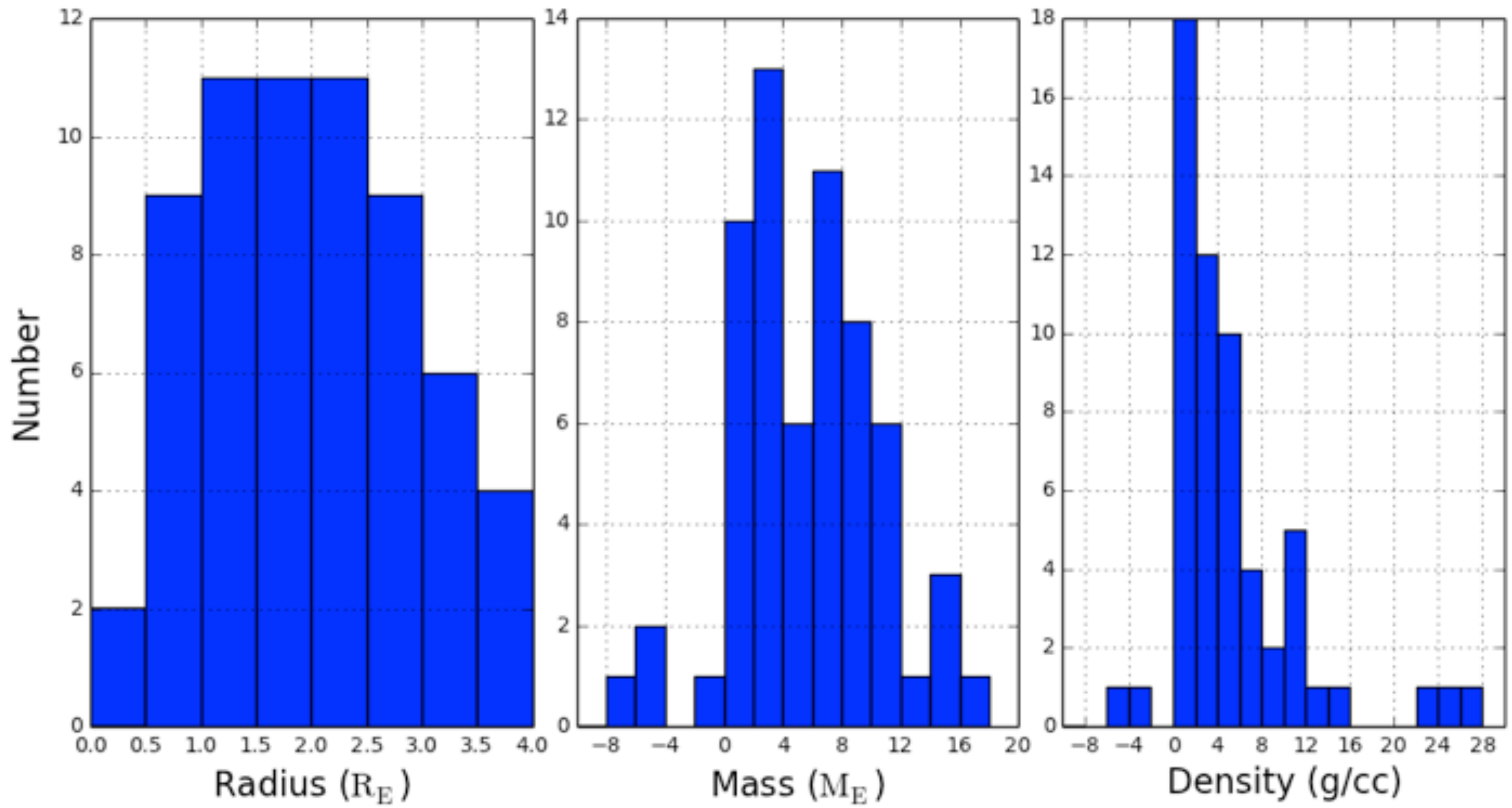
KOI-108.01	15.965	14.11±4.70	3.37±0.09	124.197	Borucki et al. (2011)	Marcy et al. (2013)
KOI-116.01	13.571	10.44±3.20	2.50±0.32	84.462	Borucki et al. (2011)	Marcy et al. (2013)
KOI-116.02	43.844	11.17±5.80	2.56±0.33	15.645	Borucki et al. (2011)	Marcy et al. (2013)
KOI-116.03	6.165	0.15±2.80	0.82±0.11	239.077	Borucki et al. (2011)	Marcy et al. (2013)
KOI-116.04	23.980	-6.39±7.00	0.95±0.13	43.146	Borucki et al. (2011)	Marcy et al. (2013)
KOI-122.01	11.523	13.00±2.90	3.42±0.09	182.708	Borucki et al. (2011)	Marcy et al. (2013)
KOI-123.01	6.482	1.30±5.40	2.37±0.07	444.879	Borucki et al. (2011)	Marcy et al. (2013)
KOI-123.02	21.223	2.22±7.80	2.52±0.07	94.934	Borucki et al. (2011)	Marcy et al. (2013)
KOI-148.01	4.778	3.94±2.10	1.88±0.10	168.932	Borucki et al. (2011)	Marcy et al. (2013)
KOI-148.02	9.674	14.61±2.30	2.71±0.14	225.109	Borucki et al. (2011)	Marcy et al. (2013)
KOI-148.03	42.896	7.93±4.60	2.04±0.11	13.545	Borucki et al. (2011)	Marcy et al. (2013)
KOI-152 b	13.4845	10.9±6.70	3.47±0.07	161.456472	Borucki et al. (2011)	Jontof-Hutter et al. (2013)
KOI-152 c	27.4029	5.9±2.10	3.72±0.08	63.225260	Borucki et al. (2011)	Jontof-Hutter et al. (2013)
KOI-152 e	81.0659	4.1±1.15	3.49±0.14	14.833204	Borucki et al. (2011)	Jontof-Hutter et al. (2013)
KOI-153.01	8.925	-4.60±6.20	2.19±0.06	50.981	Borucki et al. (2011)	Marcy et al. (2013)
KOI-153.02	4.754	7.10±3.30	1.82±0.05	63.986	Borucki et al. (2011)	Marcy et al. (2013)
KOI-244.02	6.239	9.60±4.20	2.71±0.05	667.269	Borucki et al. (2011)	Marcy et al. (2013)
KOI-245.01	39.792	1.87±9.08	1.94±0.06	7.710	Borucki et al. (2011)	Marcy et al. (2013)
KOI-245.02	21.302	3.35±4.00	0.75±0.03	16.291	Borucki et al. (2011)	Marcy et al. (2013)
KOI-245.03	13.367	2.78±3.70	0.32±0.02	37.373	Borucki et al. (2011)	Marcy et al. (2013)
KOI-246.01	5.399	5.97±1.70	2.33±0.02	375.530	Borucki et al. (2011)	Marcy et al. (2013)
KOI-246.02	9.605	2.18±3.50	1.00±0.02	220.199	Borucki et al. (2011)	Marcy et al. (2013)
KOI-261.01	16.238	8.46±3.40	2.67±0.22	73.950	Borucki et al. (2011)	Marcy et al. (2013)
KOI-283.01	16.092	16.13±3.50	2.41±0.20	71.656	Borucki et al. (2011)	Marcy et al. (2013)
KOI-283.02	25.517	8.25±5.90	0.84±0.07	28.891	Borucki et al. (2011)	Marcy et al. (2013)
KOI-292.01	2.587	3.51±1.90	1.48±0.13	851.551	Borucki et al. (2011)	Marcy et al. (2013)
KOI-299.01	1.542	3.55±1.60	1.99±0.22	1581.816	Borucki et al. (2011)	Marcy et al. (2013)
KOI-305.01	4.604	6.15±1.30	1.48±0.08	90.372	Borucki et al. (2011)	Marcy et al. (2013)
KOI-321.01	2.426	6.35±1.40	1.43±0.03	713.204	Borucki et al. (2011)	Marcy et al. (2013)
KOI-321.02	4.623	2.71±1.80	0.85±0.03	291.503	Borucki et al. (2011)	Marcy et al. (2013)
KOI-1442.01	0.669	0.06±1.20	1.07±0.02	3645.770	Borucki et al. (2011)	Marcy et al. (2013)
KOI-1612.01	2.465	0.48±3.20	0.82±0.03	1691.964	Borucki et al. (2011)	Marcy et al. (2013)
KOI-1925.01	68.958	2.69±6.20	1.19±0.03	6.165	Borucki et al. (2011)	Marcy et al. (2013)

[a] Incident stellar flux is calculated as $F/F_\oplus = (R_\star/R_\odot)^2(T_{\rm eff}/5778{\rm K})^4 a^{-2}\sqrt{1/(1-e)^2}$, where a is the semi-major axis in A.U. and e is the eccentricity.

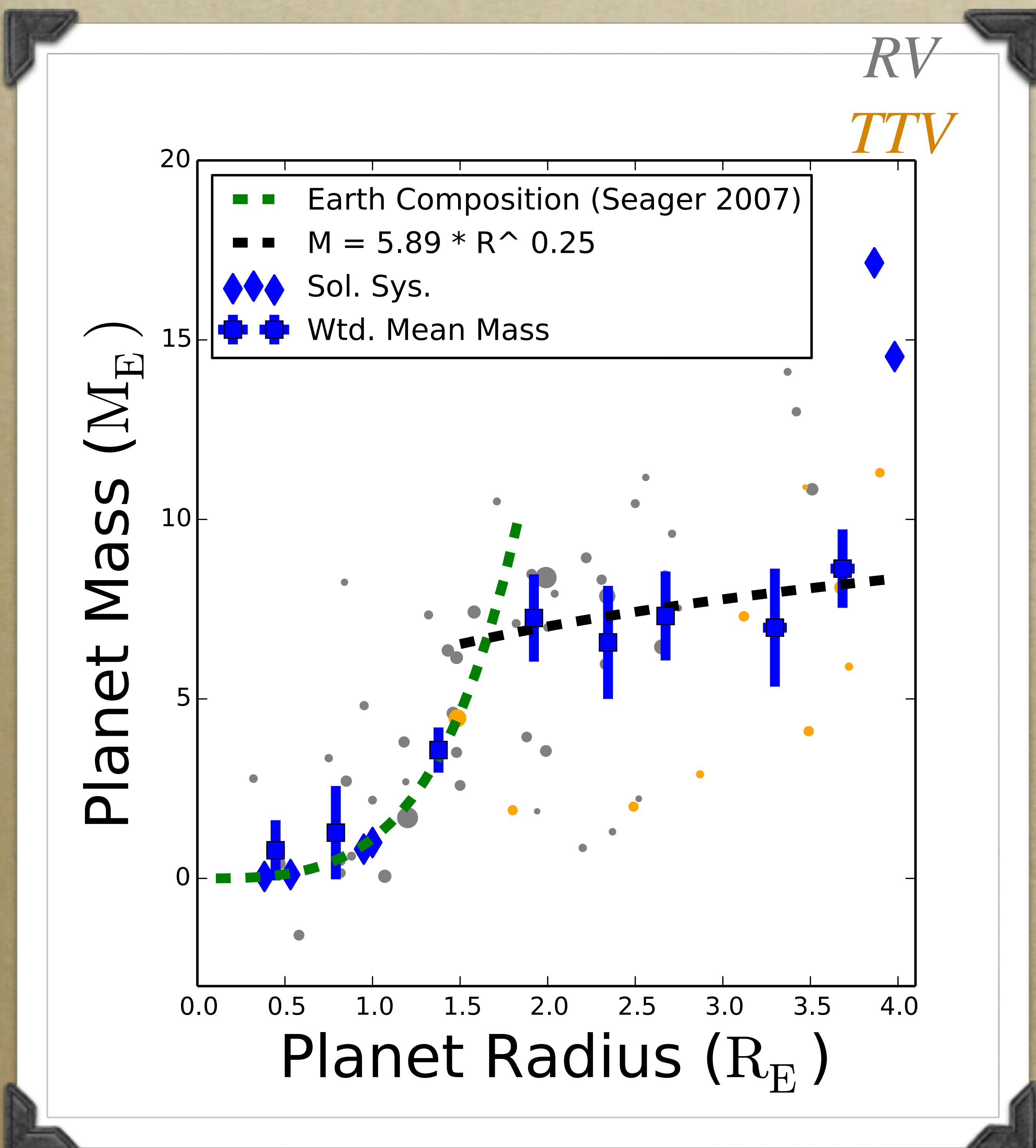
[b] Mass is from Endl et al. (2012), radius is from Dragomir et al. (2013a). The density is calculated from these values.

[c] Planet mass determined by TTVs of a neighboring planet

63 Exoplanets Smaller than 4 $R_\oplus$

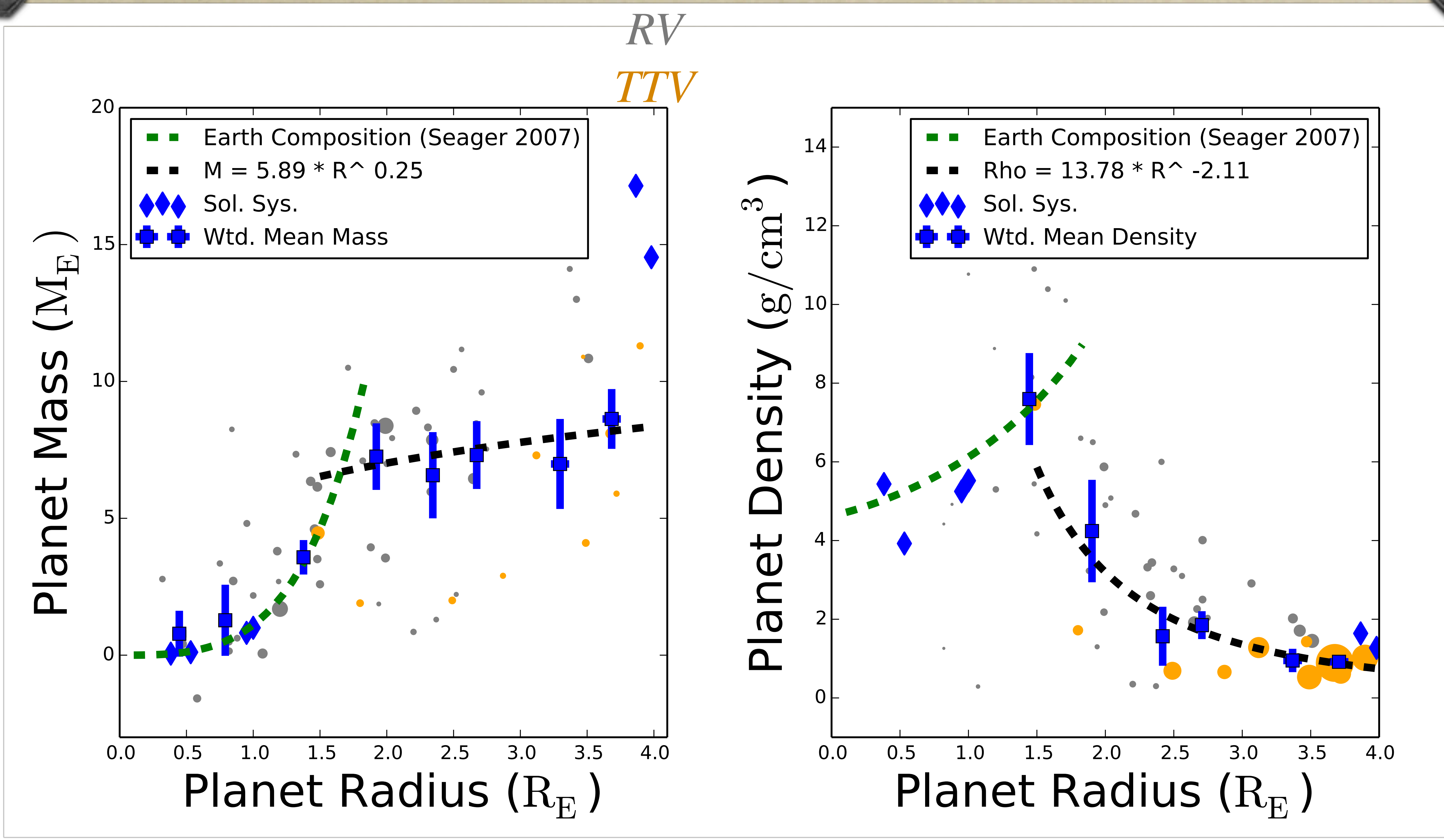


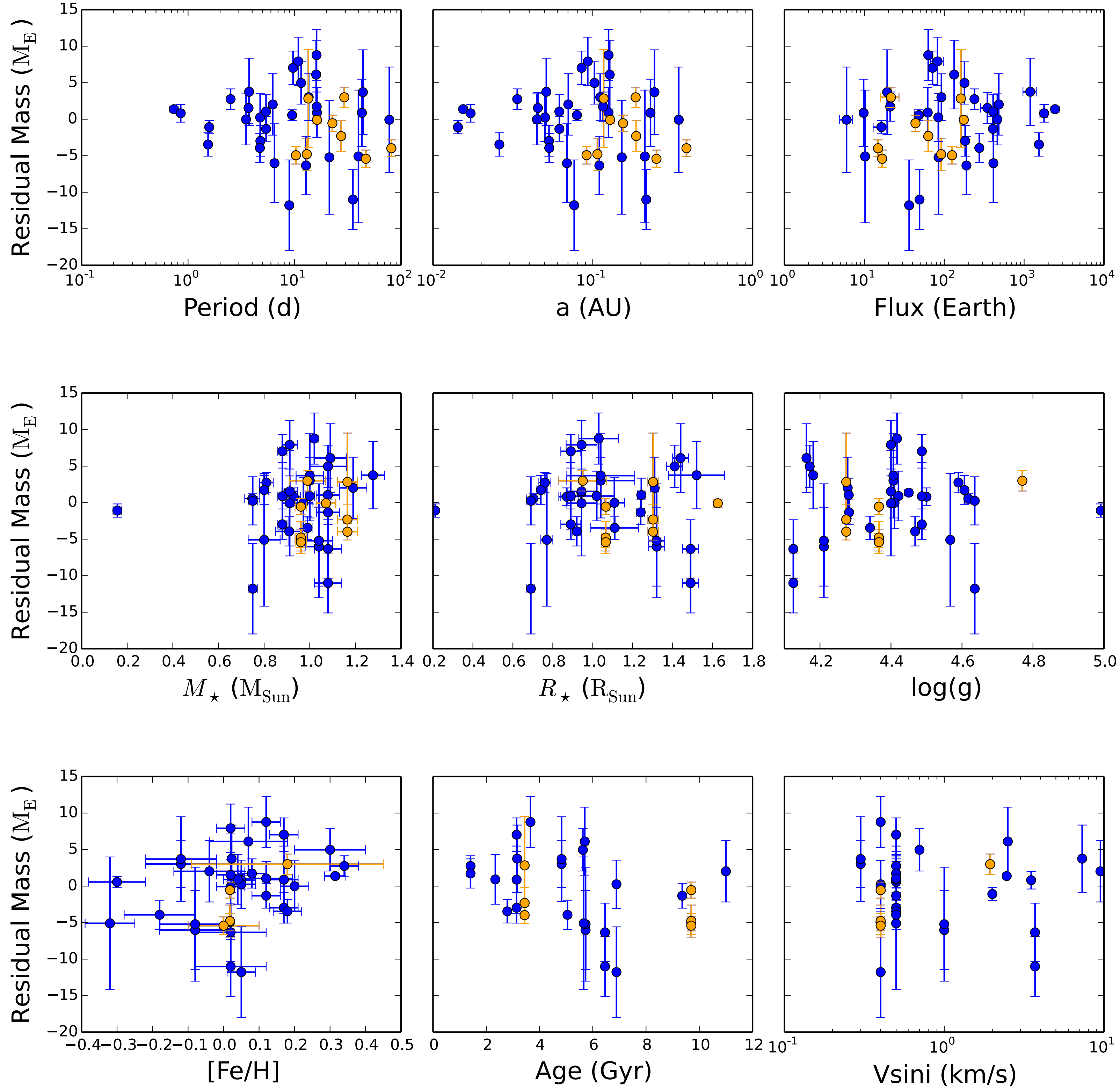
The mass-radius relations for small exoplanets.



- *$1.5 < R < 4\ R_\oplus$: Near-flat M-R relation indicates H/He envelope*
- *$R < 1.5\ R_\oplus$: consistent with Seager 2007*
- *TTVs systematically detect lower masses than RVs*

Mass-Radius Relation for 63 Exoplanets Smaller than 4 R⊕





RV

TTV

No significant correlation with residuals.

Mass-Radius Relation for 63 Exoplanets Smaller than 4 R⊕