Earth, Moon, and Planets (2019) 122:83–93
https://doi.org/10.1007/s11038-019-09523-6

A Catalog of Smaller Planets

Barton Paul Levenson[1]

Received: 3 February 2018 / Accepted: 10 May 2019 / Published online: 14 May 2019
© Springer Nature B.V. 2019

Abstract
A compilation was made of N = 89 planets or moons for which the mass and radius are known, between the limits of 0.01 and 10 times the mass of Earth. Although starting from a larger and higher-quality (because it excludes m sin i figures) sample than that of Weiss and Marcy (Astrophys J Lett 783:L6–L12, 2014), the chart of log density versus radius confirms the WM14 results: Density increases up to about 1.5 Earth radii and decreases for larger radii, probably as the planet retains hydrogen and helium on formation.

Keywords Catalogs · Exoplanets · Planet physical parameters · Planets

1 Introduction

The dimensions of planets began to become apparent in the early days of telescope astronomy, at least to the extent that Jupiter and Saturn appeared larger than Mars and Venus. Absolute dimensions—i.e., those in specific units, as opposed to by angular appearance or relative to some other standard–had to wait until the scale of the Solar system was deduced. The first roughly accurate estimate of the size of an AU was found by Christiaan Huygens in 1659, with Cassini and Richter obtaining a similar value in 1672. An estimate close to the modern value was found by Newcomb in 1895 (Goldstein 1985, *Conférence internationale des étoiles fondamentales* 1896).

In 1964, Dole (p. 29) attempted to relate density to radius for rocky terrestrial planets, using Earth, Mars, Luna, and Earth's surface rocks as data points. The relation he found was:

$$\rho = \rho_0 \exp(\mathrm{AR}) \tag{1}$$

where ρ is the planet's mean density in cgs units, ρ_0 is the surface-rock density, taken as 2.770 g cm^{-3}, A is a dimensionless constant equivalent to 0.6904, and R is the planet's radius in terms of the Earth (i.e. $R/R_\oplus$). It is apparent that Mercury falls far from this curve, and the fit is good, but not perfect, for the other terrestrial planets.

When exosolar planets began to be discovered in 1992, a much larger database became possible. Weiss and Marcy (2014, see also Marcy et al. 2014) found, based on a sample of

✉ Barton Paul Levenson
levenson1960@gmail.com

[1] Pittsburgh, USA

N = 65 bodies, that density tended to increase with radius up to about 1.5 Earth radii and thereafter declined, probably due to the planet, in formation, retaining volatiles from the preplanetary nebula. However, the MW14 sample mixed m sin i values in with absolute masses.

When estimates for the relations among planetary masses, radii, and/or densities become available, this may provide important clues to the internal makeup of such planets. It is already apparent that greater density in a terrestrial planet means few volatiles, and in the case of Mercury, a large metal core relative to the rest of the planet. Constraints on planet sizes in general, deduced from a large database of planet size estimates, could aid in modeling terrestrial planet interiors.

With this in mind, the author of this paper compiled a list of all worlds which met the following criteria:

- Mass known to be between 0.01 and 10 times that of Earth. Exoplanets with only m sin i figures available were excluded from the sample.
- Radius also known.

From these two data, many other figures can be derived from formulae based on Newton's law for gravity, and spherical geometry; including a planet's cross-sectional area, surface area, volume, density, surface gravity, circular velocity and escape velocity. The sample is listed in Table 1. It includes N = 89 bodies, nine of which are planets and satellites in the Solar system, and 80 of which are exoplanets. No dwarf planets such as Ceres or Pluto were included, as all fell under the minimum mass cut-off. The column Planet gives the planet's name or exosolar planet designation. $M/M_{\oplus}$, $R/R_{\oplus}$, and $F/F_{\oplus}$ columns give the planet's mass, radius, and solar or stellar insolation in terms of the Earth, while the columns +er and −er show positive and negative error bars—if only the positive figure is given, it is meant to apply in both directions. For flux, the error bars were always single-figure. All numerical columns are dimensionless.

2 Some Characteristics of the Data

It should be noted that much of this data is very preliminary, and no doubt subject to observational and even systematic error. The apparent density of Kepler-131c, for example, would be three times that of osmium if the given parameters are correct, which seems unlikely unless exotic physics are involved.

As many significant figures are listed as were given in the original sources.

For exoplanets, the radiative flux density received by the planet relative to Earth was derived by the following steps:

1. The bolometric luminosity L of the central star was derived from its radius R and effective temperature Te via the relation

$$L = 4\pi R^2 \sigma T^4 \tag{2}$$

   where σ is the Stefan-Boltzmann constant.
2. The radiative flux density was calculated from the inverse square law:

$$F/F\oplus = \frac{L/L\odot}{a^2} \tag{3}$$

Table 1 The catalog

Planet	$M/M_{\oplus}$	+er	−er	$R/R_{\oplus}$	+er	−er	$F/F_{\oplus}$	Error	References
55 ρ^1 Cnc Ab	8.63	0.35		2.00	0.14		2589	30	Dawson and Fabrycky (2010)
CoRoT-7b	8	1.2		1.58	0.1		1600	1000	Ferraz-Mello et al. (2011)
Earth	1.0000			1.0000			1.0000		Williams (2016a)
Gliese 1132b	1.62	0.55		1.16	0.11		16	1.1	Berta-Thompson et al. (2015)
Gliese 1214b	6.55	0.98		2.64	0.13		15.7	14.8	Berta-Thompson et al. (2011)
HD 97658b	7.55	0.83	0.79	2.247	0.098	0.095	47.7	27.5	Van Grootel et al. (2014)
HR 8832b	4.74	0.19		1.602	0.055		176	112	Gillon et al. (2015)
HR 8832c	4.36	0.22		1.511	0.047		62.1	26.9	Gillon et al. (2015)
I Io	0.01496			0.28590			0.0369		Williams (2016d)
I Luna	0.01230			0.27270			1.0000		Williams (2017)
III Ganymede	0.024812			0.41300			0.0369		Williams (2016d)
IV Callisto	0.018015			0.37832			0.0369		Williams (2016d)
K2-111b	8.6	3.9		1.9	0.2				Fridlund et al. (2017)
K2-141b	5.08	0.41		1.510	0.05				Malavolta et al. (2018)
Kepler-100b	7	3		1.35	0.04		434	261	Masuda (2014)
Kepler-102e	8.9	2.0		2.22	0.07		21.1	15.8	Masuda (2014)
Kepler-105c	4.6	0.9		1.60	0.3				Masuda (2014)
Kepler-114c	2.8			1.6					Brennan (2013)
Kepler-114d	4.80	5.09		2.48	0.08		18		Xie (2014)
Kepler-11b	1.9	1.4	1.0	1.8	0.03	0.05	130	70	Lissauer et al. (2013)
Kepler-11c	2.9	2.9	1.6	2.87	0.05	0.06	91.5	50.3	Lissauer et al. (2013)
Kepler-11d	7.3	0.8	1.5	3.12	0.06	0.07	43.6	23.8	Lissauer et al. (2013)
Kepler-11e	8.0	1.5	2.1	4.19	0.07	0.09	27.5	15.19834285	Lissauer et al. (2013)
Kepler-11f	2.0	0.8	0.9	2.49	0.04	0.07	16.8	9.2	Lissauer et al. (2013)
Kepler-131c	8	6		0.86	0.07				Masuda (2014)
Kepler-138b	0.066			0.52	0.03		9.94	7.39	Rowe et al. (2014)
Kepler-138c	1.97			1.20	0.07		6.8	5.1	Rowe et al. (2014)

Table 1 (continued)

Planet	$M/M_{\oplus}$	+er	−er	$R/R_{\oplus}$	+er	−er	$F/F_{\oplus}$	Error	References
Kepler-138d	0.64			1.21	0.08		3.37	3.49	Rowe et al. (2014)
Kepler-177b	7.24	1.26	1.16	4.04	0.29		47.2	8.0	Jontof-Hutter et al. (2015)
Kepler-20b	9.7	1.41	1.44	1.91			347	247	Fressin et al. (2012)
Kepler-20e	0.81	0.86	0.42	0.868			180	130	Fressin et al. (2012)
Kepler-20f	1.42	1.62	0.75	1.034			38.05	26.44574738	Fressin et al. (2012)
Kepler-289b	7.3	6.8		2.15	0.10		26.2	15.5	Schmitt et al. (2015)
Kepler-289c	4.0	0.9		2.68	0.17		11	7	Schmitt et al. (2015)
Kepler-305c	6.10	9.47		3.24	1.10		67		Xie (2014)
Kepler-307b	7.44	0.81	0.87	2.43	0.09		59.7	5.0	Jontof-Hutter et al. (2015)
Kepler-307c	3.64	0.65	0.58	2.20	0.07		44.0	3.7	Jontof-Hutter et al. (2015)
Kepler-338e	9	7	6	1.56	0.07		410	270	Rowe et al. (2014)
Kepler-36b	4.45			1.486			218		Carter et al. (2012)
Kepler-36c	8.08			3.679			176		Carter et al. (2012)
Kepler-37b	0.01			0.299			45.56		Barclay et al. 2013
Kepler-406b	6.3	1.4		1.46	0.03				Masuda (2014)
Kepler-406c	2.7	1.8		0.87	0.03				Masuda (2014)
Kepler-454	6.8	1.4		2.37	0.13		117	60	Gettel et al. (2015)
Kepler-48b	3.94	2.1		1.88	0.10				Masuda (2014)
Kepler-48d	7.93	4.6		2.04	0.11				Masuda (2014)
Kepler-51b	2.1	1.5	0.8	7.1	0.3		16.46	17.60	Masuda (2014)
Kepler-51c	4	0.4		9.0	2.8	1.7	7.057	7.545777577	Masuda (2014)
Kepler-51d	7.6	1.1		9.7	0.5		4.016	4.295545355	Masuda (2014)
Kepler-60b	4.20			1.68					Stettler (2016)
Kepler-60c	3.85			1.87					Stettler (2016)
Kepler-60d	4.16			1.95					Stettler (2016)

Table 1 (continued)

Planet	$M/M_{\oplus}$	+er	−er	$R/R_{\oplus}$	+er	−er	$F/F_{\oplus}$	Error	References
Kepler-62b	2.1	6.9	2.1	1.31	0.04		70.7	42.7	Borucki et al. (2013)
Kepler-62c	0.1	3.9	0.1	0.54	0.03		25	15	Borucki et al. (2013)
Kepler-62d	5.5	8.5	5.5	1.95	0.07		15.0	9.0	Borucki et al. (2013)
Kepler-62e	4.5	14.2	2.6	1.61	0.05		1.19	0.72	Borucki et al. (2013)
Kepler-62f	2.8	7.4	1.6	1.41	0.07		0.420	0.254	Borucki et al. (2013)
Kepler-68b	8.3	2.2	2.4	2.31	0.06	0.09	410.4	226.2	Gilliland et al. (2013)
Kepler-68c	4.8	2.5	3.6	0.953	0.037	0.042	190.4	104.9	Gilliland et al. (2013)
Kepler-70b	0.440			0.759			610000	350000	Charpinet et al. (2011)
Kepler-70c	0.655			0.867			380000	220000	Charpinet et al. (2011)
Kepler-78b	1.86	0.38	0.25	1.173	0.0159	0.089	4200		Pepe et al. (2013)
Kepler-79c	5.9	1.9	2.3	3.72	0.08		63.2	37.8	Jontof-Hutter et al. (2014)
Kepler-79d	6.0	2.1	1.6	7.16	0.13	0.16	26.8	16.0	Jontof-Hutter et al. (2014)
Kepler-79e	4.1	1.2	1.1	3.49	0.14		14.8	8.8	Jontof-Hutter et al. (2014)
Kepler-80b	6.93			2.67			40.5		MacDonald et al. (2016)
Kepler-80c	6.74			2.74			28.0		MacDonald et al. (2016)
Kepler-80d	6.75			1.53			127		MacDonald et al. (2016)
Kepler-80e	4.13			1.60			72.7		MacDonald et al. (2016)
Kepler-87c	6.4	0.8		6.3	0.3		6.63	3.76	Ofir et al. (2013)
Kepler-88b	8.70			3.780			80		Xie (2014)
Kepler-92c	5.69	6.36		2.40	0.05				Xie (2014)
Kepler-93b	4.02	0.68		1.478	0.019		280	170	Dressing et al. (2015)
Kepler-97b	3.5	1.9		1.51	0.13				Masuda (2014)
Kepler-98b	3.5	1.6		2.0	0.2				Masuda (2014)
Kepler-99b	6.1	1.3		1.51	0.08				Masuda (2014)
LHS 1140b	6.65	1.82		1.430	0.10		0.390	0.305	Dittmann et al. (2017)

Table 1 (continued)

Planet	$M/M_{\oplus}$	+ er	− er	$R/R_{\oplus}$	+ er	− er	$F/F_{\oplus}$	Error	References
Mars	0.10745			0.53202			0.43075		Williams (2016c)
Mercury	0.055273			0.38294			6.6735		Williams (2016a)
TRAPPIST-1b	0.79	0.27		1.127	0.028		4.268		Wang et al. (2017)
TRAPPIST-1c	1.63	0.63		1.100	0.028		2.274		Wang et al. (2017)
TRAPPIST-1d	0.33	0.15		0.788	0.020		1.145		Wang et al. (2017)
TRAPPIST-1e	0.24	0.56	0.24	0.915	0.025		0.6633		Wang et al. (2017)
TRAPPIST-1f	0.36	0.12		1.052	0.026		0.383		Wang et al. (2017)
TRAPPIST-1g	0.566	0.038		1.154	0.029		0.259		Wang et al. (2017)
TRAPPIST-1h	0.086	0.084		0.777	0.025		0.148		Wang et al. (2017)
Venus	0.81500			0.94990			1.9113		Williams (2016b)
VI Titan	0.022529			0.4042			0.0110		Williams (2015)
Wasp-47e	9.10	5.5	3.6	1.82	0.4		3900	4200	California Inst. of Technol. (2018)

where a is the semimajor axis in AU. Semimajor axes, and thus flux densities, were not available for all worlds listed.

3. Error propagation methods were used to find the error figures on the relative flux densities.

3 Methods

The data as graphed (Fig. 1) are sloped down at both ends, implying, if density is taken as a function of radius, an inflection point between the two ends. The planets in the sample were ordered by radius. Chow tests (see, e.g., Doran 1989, p. 146) were then performed with a ten percent trim to find the maximum Fisher's F value, and thus the most likely location of the actual break (Fig. 2). This occurred ($F_{2,85}=22.74$, $p<10^{-8}$) at a radius of 1.53 times Earth, corresponding to a density 1.88 times Earth and a mass 6.75 times Earth; the values for the exoplanet Kepler-80d.

The "winning" regressions were:

$$\log\left(\frac{\rho}{\rho\oplus}\right) = -0.4083 + 0.3969\left(\frac{R}{R\oplus}\right)$$
$$\mathrm{N} = 44,\ \mathrm{R}^2 = 0.203,\ p < 0.00214 \tag{4}$$

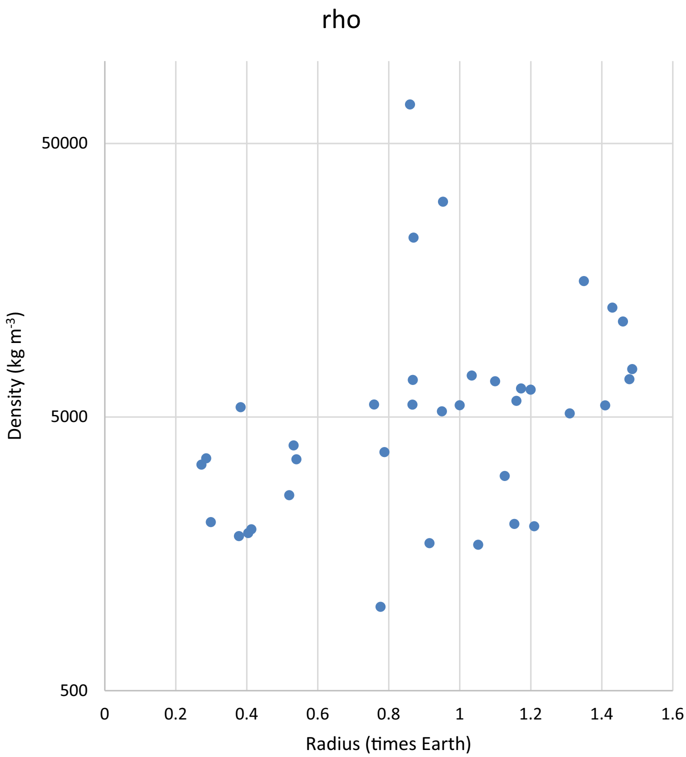

Fig. 1 Log density versus radius

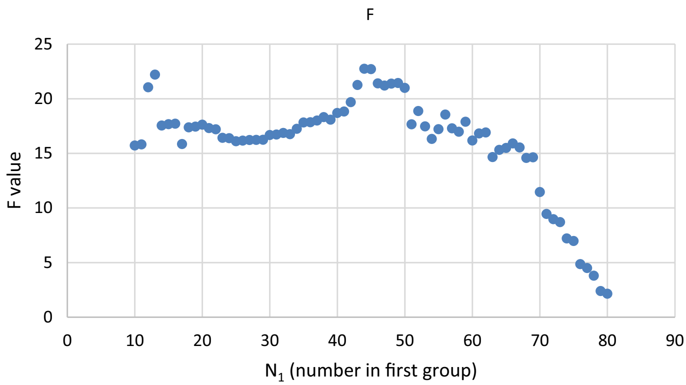

Fig. 2 Chow test F values. The horizontal axis is N_1, the size of group 1. By definition, $N_1 + N_2 = N$ where N is the total sample size

for smaller, presumably rocky planets, and

$$\log\left(\frac{\rho}{\rho\oplus}\right) = 0.3862 - 0.3071\left(\frac{R}{R\oplus}\right) \tag{5}$$
$$N = 45,\ R^2 = 0.883,\ p < 9.29 \times 10^{-22}$$

for larger, presumably volatile-rich planets. Note the oppositely signed slopes and intercepts.

At $R/R_\oplus = 1.53$, Eq. 4 gives $\rho/\rho_\oplus = 1.58$ (corresponding to $M/M_\oplus = 5.66$), while Eq. 5 gives $\rho/\rho_\oplus = 0.825$ (and $M/M_\oplus = 2.95$). Partly this is due to the sparseness of the sample, but at the same time, it would seem that composition matters.

Flux was not considered in this analysis, although the figures are available for most (not all) of the planets in the sample. Low flux undoubtedly accounts for the low densities of the Galilean satellites and Titan (i.e., they formed beyond the ice line), while very high flux may explain either the devolatilization of rocky planets or the extended gas envelopes of sub-Neptune planets. Speculation on this point is deferred until further analysis can be done.

4 Conclusions

The chart of data from this paper's sample (Fig. 1) shows the same effect as that in the study of Marcy and Weiss (2014), although not subject to the same methodological problem (MW14 included m sin i values along with masses). The upper limit to the linear size of a rocky planet appears to be near 1.5 Earth radii, and the upper limit to its mass is in the vicinity of six Earth masses under normal circumstances. The few known larger "rocky" bodies, invariably subject to much higher stellar radiative flux than Earth, may perhaps be the cores of evaporated gas or ice giants.

References

T. Barclay, J.F. Rowe, J.J. Lissauer, D. Huber, F. Fressin, S.B. Howell, S.T. Bryson, W.J. Chaplin, J.-M. Désert, E.D. Lopez, G.W. Marcy, F. Mullally, D. Ragozzine, G. Torres, E.R. Adams, E. Agol, D. Barrado, S. Basu, T.R. Bedding, L.A. Buchhave, D. Charbonneau, J.L. Christiansen, J. Christensen-Dalsgaard, D. Ciardi, W.D. Cochran, A.K. Dupree, Y. Elsworth, M. Everett, D.A. Fischer et al., A sub-mercury-sized exoplanet. Nature **494**, 452–454 (2013)

Z.K. Berta-Thompson, D. Charbonneau, J. Bean, J. Irwin, C.J. Burke, J.-M. Désert, P. Nutzman, E.E. Falco, The GJ1214 super-earth system: stellar variability, new transits, and a search for additional planets. Astrophys. J. **736**, 12–27 (2011)

Z.K. Berta-Thompson, J. Irwin, D. Charbonneau, E.R. Newton, J.A. Dittmann, N. Astudillo-Defru, X. Bonfils, M. Gillon, E. Jehin, A rocky planet transiting a nearby low-mass star. Nature **527**, 204–207 (2015)

W.J. Borucki, E. Agol, F. Fressin, L. Kaltenegger, J. Rowe, H. Isaacson, D. Fischer, N. Batalha, J.J. Lissauer, G.W. Marcy, D. Fabrycky, J.-M. Désert, S.T. Bryson, T. Barclay, F. Bastien, A. Boss, E. Brugamyer, L.A. Buchhave, C. Burke, D.A. Caldwell, J. Carter, D. Charbonneau, J.R. Crepp, J. Christensen-Dalsgaard, J.L. Christiansen, D. Ciardi, W.D. Cochran, E. DeVore, L. Doyle, A.K. Dupree, M. Endl, M.E. Everett, E.B. Ford, J. Fortney, T.N. Gautier III, J.C. Geary, A. Gould, M. Haas, C. Henze, A.W. Howard, S.B. Howell, D. Huber, J.M. Jenkins, H. Kjeldsen, R. Kolbl, J. Kolodziejczak, D.W. Latham, B.L. Lee, E. Lopez, F. Mullally, J.A. Orosz, A. Prsa, E.V. Quintana, R. Sanchez-Ojeda, D. Sasselov, S. Seader, A. Shporer, J.H. Steffen, M. Still, P. Tenenbaum, S.E. Thompson, G. Torres, J.D. Twicken, W.F. Welsh, J.N. Winn, Kepler-62: a five-planet system with planets of 1.4 and 1.6 Earth radii in the habitable zone. Sci. Express **340**, 587–590 (2013)

P. Brennan, *Kepler-114 c* (2013), https://exoplanets.nasa.gov/newworldsatlas/5931/. Accessed 22 Jan 2018

California Inst. of Technol. *Wasp-47* (2018). https://exoplanetarchive.ipac.caltech.edu/cgi-bin/DisplayOverview/nph-DisplayOverview?objname=WASP-47&type=PLANET_HOST. Accessed 24 Jan 2018

J.A. Carter, E. Agol, W.J. Chaplin, S. Basu, T.R. Bedding, L.A. Buchhave, J. Christensen-Dalsgaard, K.M. Deck, Y. Elsworth, D.C. Fabrycky, E.B. Ford, J.J. Fortney, S.J. Hale, R. Handberg, S. Hekker, M.J. Holman, D. Huber, C. Karoff, S.D. Kawaler, H. Kjeldsen, J.J. Lissauer, E.D. Lopez, M.N. Lund, M. Lundkvist, T.S. Metcalfe, A. Miglio, L.A. Rogers, D. Stello, W.J. Borucki, S. Bryson, J.L. Christiansen, W.D. Cochran, J.C. Geary, R.L. Gilliland, M.R. Haas, J. Hall, A.W. Howard, J.M. Jenkins, T. Klaus, D.G. Koch, D.W. Latham, P.J. MacQueen, D. Sasselov, J.H. Steffen, J.D. Twicken, J.N. Winn, Kepler-36: a pair of planets with neighboring orbits and dissimilar densities. Science **337**, 556–559 (2012)

S. Charpinet, G. Fontaine, P. Brassard, E.M. Green, V. van Grootel, S.K. Randall, R. Silvotti, A.S. Baran, R.H. Østensen, S.D. Kawaler, J.H. Telting, A compact system of small planets around a former red-giant star. *Nature* **480**, 496–499 (2011). *Conférence internationale des étoiles fondamentales*, Paris, 18–21 May 1896

R.I. Dawson, D.C. Fabrycky, Radial velocity planets de-aliased. A new, short period for Super-Earth 55 Cnc e. Astrophys. J. **722**, 937–953 (2010)

J.A. Dittmann, J.M. Irwin, D. Charbonneau, X. Bonfils, N. Astudillo-Defru, R.D. Haywood, Z.K. Berta-Thompson, E.R. Newton, J.E. Rodriguez, J.G. Winters, T.-G. Tan, J.-M. Almenara, F. Bouchy, X. Delfosse, T. Forveille, C. Lovis, F. Murgas, F. Pepe, N.C. Santos, S. Udry, A. Wünsche, G.A. Esquerdo, D.W. Latham, C.D. Dressing, A temperate rocky super-Earth transiting a nearby cool star. Nature **544**, 333–357 (2017)

H.E. Doran, *Applied Regression Analysis in Econometrics* (Marcel Dekker Inc., New York, 1989), p. 146

C.D. Dressing, D. Charbonneau, X. Dumusque, S. Gettel, F. Pepe, A.C. Cameron, D.W. Latham, E. Molinari, S. Udry, L. Affer, A.S. Bonomo, L.A. Buchhave, R. Cosentino, P. Figueira, A.F.M. Fiorenzano, A. Harutyunyan, R.D. Haywood, J.A. Johnson, M. Lopez-Morales, C. Lovis, L. Malavolta, M. Mayor, G. Micela, F. Motalebi, V. Nascimbeni, D.F. Phillips, G. Piotto, D. Pollacco, D. Queloz, K. Rice, D. Sasselov, D. Segransan, A. Sozzetti, A. Szentgyorgyi, C. Watson, The mass of Kepler-93b and the composition of terrestrial planets. Astrophys. J. (2015). https://arxiv.org/pdf/1412.8687.pdf. Accessed 23 Jan 2018

S. Ferraz-Mello, M. Tadeu dos Santos, C. Beaugé, T.A. Michtchenko, A. Rodríguez, On planetary mass determination in the case of super-Earths orbiting active stars. The case of the CoRoT-7 system. Astron. Astrophys. **531**, A161 (2011)

F. Fressin, G. Torres, J.F. Rowe, D. Charbonneau, L.A. Rogers, S. Ballard, N.M. Batalha, W.J. Borucky, S.T. Bryson, L.A. Buchhave, D.R. Ciardi, J.-M. Desert, C.D. Dressing, D.C. Fabrycky, E.B. Ford, T.N. Gautier III, C.E. Henze, M.J. Holman, A.W. Howard, S.B. Howell, J.M. Jenkins, D.G. Koch, D.W. Latham, J.J. Lissauer, G.W. Marcy, S.N. Quinn, D. Ragozzine, D.D. Sasselov, S. Seager, T. Barclay,

F. Mullally, S.E. Seader, M. Still, J.D. Twicken, S.E. Thompson, K. Uddin, Two Earth-sized planets orbiting Kepler-20. Nature **482**, 195–198 (2012)

M. Fridlund, E. Gaidos, O. Barragán, C.M. Persson, D. Gandolfi, J. Cabrera, T. Hirano, M. Kuzuhara, S. Csizmadia, G. Nowak, M. Endl, S. Grziwa, J. Korth, J. Pfaff, B. Bitsch, A. Johansen, A.J. Mustill, M.B. Davies, H.J. Deeg, E. Palle, W.D. Cochran, P. Eigmüller, A. Erikson, E. Guenther, A.P. Hatzes, A. Kiilerich, T. Kudo, P. MacQueen, N. Narita, D. Nespral, M. Pätzold, J. Prieto-Arranz, H. Rauer, V. van Eylen, K2-111 b–a short period super-Earth transiting a metal poor, evolved old star. Astron. Astrophys. **604**, A16 (2017)

S. Gettel, D. Charbonneau, C.D. Dressing, L.A. Buchhave, X. Dumusque, A. Vanderburg, A.S. Bonomo, L. Malavolta, F. Pepe, A.C. Cameron, D.W. Latham, S. Udry, G.W. Marcy, H. Isaacson, A.W. Howard, G.R. Davies, V. Silva Aguirre, H. Kjeldsen, T.R. Bedding, E. Lopez, L. Affer, R. Cosentino, P. Figueira, A.F.M. Fiorenzano, A. Harutyunyan, J.A. Johnson, M. Lopez-Morales, C. Lovis, M. Mayor, G. Micela, E. Molinari, F. Motalebi, D.F. Phillips, G. Piotto, D. Queloz, K. Rice, D. Sasselov, D. Segransan, A. Sozzetti, C. Watson, S. Basu, T.L. Campante, J. Christensen-Dalsgaard, S.D. Kawaler, T.S. Metcalfe, R. Handberg, M.N. Lund, M.S. Lundkvist, D. Huber, W.J. Chaplin, The Kepler-454 system: a small, not-rocky inner planet, a Jovian World, and a distant companion. Astrophys. J. (2015). https://arxiv.org/pdf/1511.09097.pdf. Accessed 24 Jan 2018

R.L. Gilliland, G.W. Marcy, J.F. Rowe, L. Rogers, G. Torres, F. Fressin, E.D. Lopez, L.A. Buchhave, J. Christensen-Dalsgaard, J.-M. Desert, H. Isaacson, J.M. Jenkins, J.L. Lissauer, W.J. Chaplin, S. Basu, T.S. Metcalfe, Y. Elsworth, R. Handberg, S. Hekker, D. Huber, C. Karoff, H. Kjeldsen, M.N. Lund, M. Lundkvist, A. Miglio, D. Charbonneau, E.B. Ford, J.J. Fortney, M.R. Haas, A.W. Howard, S.B. Howell, D. Ragozzine, S.E. Thompson, Kepler-68: three planets, one with a density between that of Earth and Ice Giants. Astrophys. J. (2013). https://arxiv.org/pdf/1302.2596.pdf. Accessed 21 Jan 2018

M. Gillon, B.-O. Demory, V. van Grootel, F. Motalebi, C. Lovis, A.C. Cameron, D. Charbonneau, D. Latham, E. Molinari, F.A. Pepe, D. Ségransan, D. Sasselov, S. Udry, M. Mayor, G. Micela, G. Piotto, A. Sozzetti, Two massive rocky planets transiting a K-dwarf 6.5 parsecs away. (2015). https://arxiv.org/ftp/arxiv/papers/1703/1703.01430.pdf. Accessed 24 Jan 2018

S.J. Goldstein Jr., Christian Huygens' measurement of the distance to the sun. Observatory **105**, 32–33 (1985)

D. Jontof-Hutter, E.B. Ford, J.F. Rowe, J.J. Lissauer, D.C. Fabrycky, C. van Laerhoven, E. Agol, K.M. Deck, T. Holczer, T. Mazeh, Secure TTV mass measurements: ten Kepler exoplanets between 3 and 8 $M_{\oplus}$ with diverse densities and incident fluxes. Astrophys. J. (2015). https://arxiv.org/pdf/1512.02003.pdf. Accessed 22 Jan 2018

D. Jontof-Hutter, J.J. Lissauer, J.F. Rowe, D.C. Fabrycky, Kepler-79's low density planets. Astrophys. J. **785**, 15–28 (2014)

J.J. Lissauer, D. Jontof-Hutter, J.F. Rowe, D.C. Fabrycky, E.D. Lopez, E. Agol, G.W. Marcy, K.M. Deck, D.A. Fischer, J.J. Fortney, S.B. Howell, H. Isaacson, J.M. Jenkins, R. Kolbl, D. Sasselov, D.R. Short, W.F. Welsh, All six planets known to orbit Kepler-11 have low densities. Astrophys. J. **770**, 131–170 (2013)

M.G. MacDonald, D. Ragozzine, D.C. Fabrycky, E.B. Ford, M.J. Holman, H.T. Isaacson, J.J. Lissauer, E.D. Lopez, T. Mazeh, L. Rogers, J.F. Rowe, J.H. Steffen, G. Torres, A dynamical analysis of the Kepler-80 system of five transiting planets. Astron. J. **152**, 105–123 (2016)

L. Malavolta, A.W. Mayo, T. Louden, V.M. Rajpaul, A.S. Bonomo, L.A. Buchhave, L. Kreidberg, M.H. Kristiansen, M. Lopez-Morales, A. Mortier, A. Vanderburg, A. Coffinet, D. Ehrenreich, C. Lovis, F. Bouchy, D. Charbonneau, D.R. Ciardi, A.C. Cameron, R. Cosentino, I.J.M. Crossfield, M. Damasso, C.D. Dressing, X. Dumusque, M.E. Everett, P. Figueira, A.F.M. Fiorenzano, E.J. Gonzales, R.D. Haywood, A. Harutyunyan, L. Hirsch, S.B. Howell, J.A. Johnson, D.W. Latham, E. Lopez, M. Mayor, G. Micela, E. Molinari, V. Nascimbeni, F. Pepe, D.F. Phillips, G. Piotto, K. Rice, D. Sasselov, D. Ségransan, A. Sozzetti, S. Udry, C. Watson, An ultra-short period rocky super-Earth with a secondary eclipse and a Neptune-like companion around K2-141. Astron. J. (2018). https://arxiv.org/pdf/1801.03502.pdf. Accessed 24 Jan 2018

G.W. Marcy, H. Isaacson, A.W. Howard, J.F. Rowe, J.M. Jenkins, S.T. Bryson, D.W. Latham, S.B. Howell, T.N. Gautier III, N.M. Batalha, L. Rogers, D. Ciardi, D.A. Fischer, R.L. Gilliland, H. Kjeldsen, J. Christensen-Dalsgaard, D. Huber, W.J. Chaplin, S. Basu, L.A. Buchhave, S.N. Quinn, W.J. Borucki, D.G. Koch, R. Hunter, D.A. Caldwell, J. van Cleve, R. Kolb, L.M. Weiss, E. Petigura, S. Seager, T. Morton, J.A. Johnson, S. Ballard, C. Burke, W.D. Cochran, M. Endl, P. MacQueen, M.E. Everett, J.J. Lissauer, E.B. Ford, G. Torres, F. Fressin, T.M. Brown, J.H. Steffen, D. Charbonneau, G.S. Basri, D.D. Sasselov, J. Winn, R. Sanchis-Ojeda, J. Christiansen, E. Adams, C. Henze, A. Dupree, D.C. Fabrycky, J.J. Fortney, J. Tarter, M.J. Holman, P. Tenenbaum, A. Shporer, P.W. Lucas, W.F. Welsh, J.A. Orosz, T.R. Bedding, T.L. Campante, G.R. Davies, Y. Elsworth, R. Handberg, S. Hekker, C. Karoff, S.D. Kawaler, M.N. Lund, M. Lundkvist, T.S. Metcalfe, A. Miglio, V. Silva Aguirre, D. Stello, T.R. White, A. Boss, E. Devore, A. Gould, A. Prsa, E. Agol, T. Barclay, J. Coughlin, E. Brugamyer, F. Mullally, E.V. Quintana, M. Still, S.E. Thompson, D. Morrison, J.D. Twicken, J.-M. Desert, J. Carter, J.R. Crepp, G. Hebrard, A. Santerne, C. Moutou, C. Sobeck, D. Hudgins, M.R. Haas, P. Robertson, J. Lillo-Box, D. Barrado, Masses, radii, and orbits of small Kepler planets: The transition from gaseous to rocky planets. Astrophys. J. Supp. Ser. (2014). http://w.astro.berkeley.edu/~gmarcy/22kois.pdf. Accessed 22 Jan 2018

K. Masuda, Very low-density planets around Kepler-51 revealed with transit timing variations and an anomaly similar to a planet-planet eclipse event. (2014). https://arxiv.org/pdf/1401.2885.pdf. Accessed Jan 21 2018

A. Ofir, S. Dreizler, M. Zechmeister, T.-O. Husser, An independent planet search in the Kepler dataset. II. An extremely low-density super-Earth mass planet around Kepler-87. Astron. Astrophys. (2013). https://arxiv.org/pdf/1310.2064.pdf. Accessed 22 Jan 2018

F. Pepe, A.C. Cameron, D.W. Latham, E. Molinari, S. Udry, A.S. Bonomo, L.A. Buchhave, D. Charbonneau, R. Cosentino, C.D. Dressing, X. Dumusque, P. Figueira, A.F.M. Fiorenzano, S. Gettel, A. Harutyunyan, R.D. Haywood, K. Horne, M. Lopez-Morales, C. Lovis, L. Malavolta, M. Mayor, G. Micela, F. Motalebi, V. Nascimbeni, D. Phillips, G. Piotto, D. Pollacco, D. Queloz, K. Rice, D. Sasselov, D. Ségransan, A. Sozzetti, A. Szentgyorgi, C.A. Watson, An Earth-sized planet with an Earth-like density. Nature **503**, 377–386 (2013)

J.F. Rowe, S.T. Bryson, G.W. Marcy, J.J. Lissauer, D. Jontof-Hutter, F. Mullally, R.L. Gilliland, H. Issacson, E. Ford, S.B. Howell, W.J. Borucki, M. Haas, D. Huber, J.H. Steffen, S.E. Thompson, E. Quintana, T. Barclay, M. Still, J. Fortney, T.N.I.I.I. Gautier, R. Hunter, D.A. Caldwell, D.R. Ciardi, E. Devore, W. Cochran, J. Jenkins, E. Agol, J.A. Carter, J. Geary, Validation of Kepler's multiple planet candidates. III: light curve analysis and announcement of hundreds of new multi-planet systems. Astrophys. J. **784**, 45–182 (2014)

J.R. Schmitt, E. Agol, K.M. Deck, L.A. Rogers, J.Z. Gazak, D.A. Fischer, J. Wang, M.J. Holman, K.J. Jek, C. Margossian, M.R. Omohundro, T. Winarski, J.M. Brewer, M.J. Giguere, C. Lintott, S. Lynn, M. Parrish, K. Schawinski, M.E. Schwamb, R. Simpson, A.M. Smith, Planet hunters VII. Discovery of a new low-mass, low-density planet (PH3 c) Orbiting Kepler-289 with mass measurements of two additional planets (PH3 b and d). Astrophys. J. (2015). https://arxiv.org/pdf/1410.8114.pdf. Accessed 24 Jan 2018

U. Stettler, Kepler-60. (2016). http://nccr-planets.ch/blog/2016/11/01/kepler-60/. Accessed 21 Jan 2018

V. Van Grootel, M. Gillon, D. Valencia, N. Madhusudhan, D. Dragomir, A.R. Howe, A.S. Burrows, B.-O. Demory, D. Deming, D. Ehrenreich, C. Lovis, M. Mayor, F. Pepe, D. Queloz, R. Scuflaire, S. Seager, D. Segransan, S. Udry, Transit confirmation and improved stellar and planet parameters for the super-earth HD 97658 b and its host star. Astrophys. J. **786**, 2–31 (2014)

S. Wang, D.-H. Wu, T. Barclay, G.P. Laughlin, Updated masses for the TRAPPIST-1 planets. Astrophys. J. (2017) https://arxiv.org/abs/1704.04290. Accessed 24 Jan 2018

L.M. Weiss, G.W. Marcy, The mass-radius relation for 65 exoplanets smaller than 4 Earth radii. Astrophys. J. Lett. **783**, L6–L12 (2014)

D.R. Williams, Saturnian Satellite Fact Sheet (2015). https://nssdc.gsfc.nasa.gov/planetary/factsheet/saturniansatfact.html. Accessed 18 Jan 2018

D.R. Williams, Mercury Fact Sheet. (2016). https://nssdc.gsfcnasa.gov/planetary/factsheet/mercuryfact.html. Accessed 18 Jan 2018

D.R. Williams, Venus Fact Sheet. (2016). https://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html. Accessed 18 Jan 2018

D.R. Williams, Moon Fact Sheet. (2017). https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html. Accessed 18 Jan 2018

D.R. Williams, Mars Fact Sheet. (2016). https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html. Accessed 18 Jan 2018

D.R. Williams, Jovian Satellite Fact Sheet. (2016). https://nssdc.gsfc.nasa.gov/planetary/factsheet/joviansatfact.html. Accessed 18 Jan 2018

J.-W. Xie, Transit timing variation of near-resonance planetary pairs. II. Confirmation of 30 planets in 15 multiple-planet systems. Astrophys. J. Supp. Ser. **210**, 25–34 (2014)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.