Waterworlds: Structures / Properties and Discoveries of Ocean Planets

Andria C. Schwortz

Department of Physics and Astronomy, University of Wyoming, 1000 E. University Ave., Laramie, WY, 82071

aschwort@uwyo.edu

ABSTRACT

In recent years a number of surveys, including the MEarth project (located in Arizona and run out of Cambridge, MA), and the COROT and Kepler space missions, have been dedicated to the discovery of extrasolar planets through transits. The properties (including structure and composition) and formation histories of many of the newly discovered exoplanets remains an open question. Driven by the search for an Earth-like planet, we have discovered a class of super-Earths or sub-Neptunes which may not fall into either of the traditional categories of terrestrial or gas giant planets, but instead form a new category of ocean planets. In this review paper, I outline the history of this field by looking at major theoretical breakthroughs and outlining recent discoveries of candidate ocean planets.

1. Definition

When the general public thinks of a water world or ocean planet, they typically think of the film *Waterworld* starring Kevin Costner (Reynolds 1995). The film's eponymous Waterworld planet is revealed in the opening sequence to be the planet Earth at some indeterminate time in the future when the polar ice caps have completely melted and the entire surface of the planet is covered with water. Approximately 2/3 of the surface of the Earth is currently covered with liquid water, with the fraction increasing if ice caps and glaciers are also included; (ignoring issues of conservation of mass) the fictional Waterworld is essentially 100% covered by water. However, either Earth or Waterworld are still fundamentally terrestrial planets: most of their mass is comprised of either metals (referred to as the core[1] henceforth) or of rocky material (mantle[1]), with essentially 0% of their mass in either liquid water or ice form.[2]

---

[1] In this paper, the terms "core" and "mantle" are used in the same way as for terrestrial planets, i.e., based upon their composition, with "core" meaning the metal-dominated region and "mantle" meaning the rocky region. Some other papers in the field of planetary science use the terms in the context of gas giants, where "core" refers to both metals and rocky materials, and "mantle" refers to the icy layer, i.e., based upon their role within the structure of the planet.

[2] The vast majority of water ice on Earth is in the phase known as ice I_h, also called ice-I or hexagonal ice. Some atmospheric ice takes the form of ice I_c or cubic crystalline ice, and further phases of ice exist through ice XV. While

The most commonly accepted definition of ocean planet or water world appears to be that proposed by Valencia et al. (2007): the planet must be composed of $> 10\%$ water by mass. According to their work, these objects typically have masses in the range of $1 - 10M_{\oplus}$, making them either super-Earths or sub-Neptunes. Under this definition Waterworld is not actually a water world.

2. Early theoretical works

The first reference to a planetary object possessing properties intermediary between terrestrial and gas giants appears to be Kuchner (2003). This paper focused on the timescale for retention of volatiles should a sub-Neptunian planet form past the snow line of a solar system and then migrate in to closer distances. In general, a planet can maintain a substantial amount of water indefinitely at a distance of $a \gtrsim 1.03\mathrm{AU}(L_*/L_{\odot})^{1/2}$ due to the formation of a thick protective water vapor atmosphere.

Léger et al. (2004) built upon this work by modeling a $6M_{\oplus}$ object composed of 50% ice (by mass). Such an object would have $3M_{\oplus}$ in metals and silicates (core and mantle respectively) and $3M_{\oplus}$ in ice. As can be seen in Fig. 1, the total radius of such an object would be $2R_{\oplus}$, with the outermost $60 - 140$km (depending upon surface temperature) consisting of liquid water. The planet's atmosphere would consist primarily of hydrogen early on, transitioning to N_2 and CO_2 as the hydrogen escaped. In addition, this atmosphere would act to protect the surface of the planet from some of the star's radiation, allowing liquid water to be retained on the surface of the planet at a closer distance than would be possible without the atmosphere, thus extending inwards the habitable zone (HZ) for an ocean planet. This work of Léger et al. did not directly address the radiation from the star, instead taking the surface temperature of the ocean planet as one of the input variables, and it is this variable which caused their resulting range of liquid water depths.

In addition to proposing a definition of ocean planet, Valencia et al. (2007) also determined the resulting radii for ocean planets of masses in the range of $1 - 10M_{\oplus}$ with all possible combinations of core/mantle/ice mass fractions. In the ternary plots of Fig. 2, Valencia et al. (2007) displays objects of masses $1 - 10M_{\oplus}$ for varying core/mantle/ice mass fractions along with a color scale to indicate the resulting radius of the object.

---

ice I_h is less dense than liquid water, most other forms of ice are more dense than liquid water and will form from liquid water at high pressures, as can be found at depths inside all types of planets. Throughout this paper the terms "ice," "water," and "ocean" are used interchangeably unless specified otherwise, and refer to all liquid and solid forms of H_2O (primarily) and smaller amounts of other volatiles (CH_4, NH_3, CO_2, etc.).

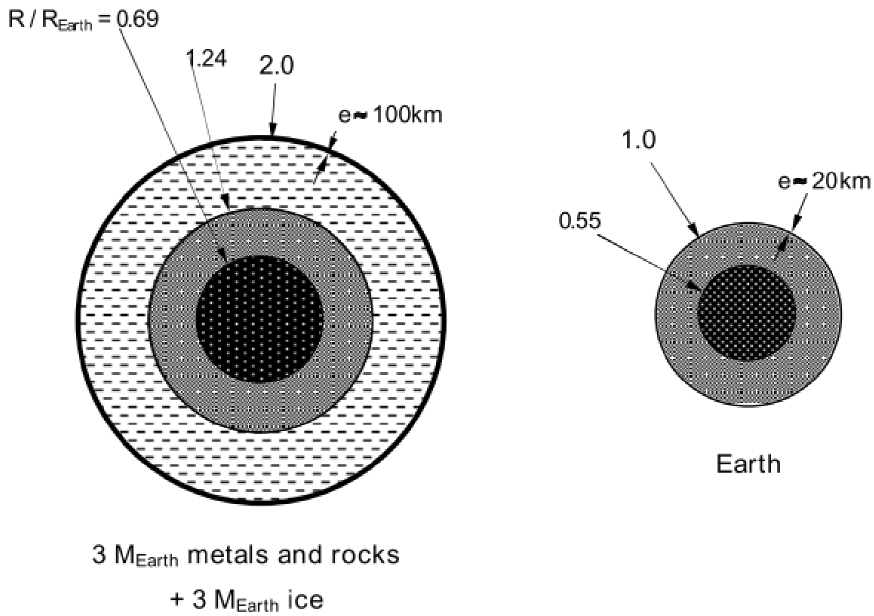

Fig. 1.— The model of Léger et al. (2004) was able to recover the properties of the Earth, shown on the right. On the left is their $6M_\oplus$ ocean planet, comprised of metallic core and rocky mantle ($3M_\oplus$ together), an icy layer ($3M_\oplus$), and a thin layer ($\sim$100km) of liquid water.

3. Formation

Objects the size of Neptune or slightly smaller are sometimes referred to as "ice giants" - unlike Jupiter and Saturn, a significant portion of their interiors is composed of solid ice. Both Neptune and Uranus are composed of approximately 65% ices, or at least $10M_\oplus$ (Hubbard & MacFarlane 1980). It is well-known that planets can and do migrate through disks (Jang-Condell 2013) so that a planet which forms out past a solar system's snow line[3] can migrate in to a distance at which its lighter gases (H, He) will escape from the atmosphere. When this happens, instead of possessing a thick hydrogen and helium atmosphere which protects the planet's ice layer, it will now be protected by a newly formed atmosphere composed of gas evaporated or sublimated from the ice layer. The result is that some of the ice layer may melt into liquid and/or escape (due to radiation from the star, impacts, and/or radioactivity), but some of it will remain in solid ice form. Such an object would retain all of the metallic core and rocky mantle present in its progenitor ice giant, the ice layer would either remain at the same mass or become smaller, and the predominantly hydrogen and helium gas layers would be lost to space.

[3] Snow line refers to the distance from a star at which "the temperature of the nebular gas drops below the sublimation temperature for water" (Kuchner 2003).

In one particularly extreme case, Kuchner (2003) found that even though a sub-Neptunian object migrating inwards will lose mass due to escape of its volatiles, it is possible for a such a planet to be whittled down to as small as $0.1M_\oplus$ at distance of 0.3AU from a Sun-like star and still retain its volatiles in some form for the lifetime of the solar system.

4. Candidate ocean planets in or near habitable zones

Valencia et al. (2007) found that if a planet's radius is known with 5% accuracy and its mass is known with 10% accuracy, that this is sufficient information to determine whether the planet is terrestrial or oceanic. Transits are currently the most common method of determining a planet's radius, with instruments for this including MEarth and Kepler. Mass can be determined either through radial velocity (RV) measurements on instruments such as HARPS, Magellan's PFS, or Keck's HIRES for more massive and/or closer in planets, or through transit timing variations (TTV) in multiple planet systems. If only one of the mass and the radius is known, a lower limit for the other can be calculated as

$$R \propto M^{0.267-0.272} \tag{1}$$

(Valencia et al. 2006). This equation assumes a terrestrial super-Earth (rather than an oceanic sub-Neptune), hence the lower limit, with the range in the powers corresponding to different interior compositions (and thus densities). An upper limit can be calculated by assuming a gaseous (H/He) composition, but the majority of the candidate ocean planets found are at distances from their host star which make it unlikely for the planet to have retained these lighter volatiles for a significant amount of time.

What follows is a non-exhaustive list of some potential ocean planets, focusing primarily on those in or near their stars' HZ, including discussion of the objects' properties and how these were determined. The properties of all discussed planets, including the methods of determining these properties and the appropriate citations, are summarized in Table 1.

4.1. Candidates with known mass and radius

It appears that the first potential ocean planet to be discovered was GJ 1214b, as discussed by Charbonneau et al. (2009). Transits of the M dwarf star GJ 1214 were observed with MEarth leading to a determination of the planet's radius as $2.678R_\oplus$. They then followed up with HARPS RV measurements, allowing them to both confirm the existence of the transiting planet GJ 1214b, and to measure its mass as $6.55M_\oplus$. This mass and radius are consistent with either an ocean planet composed of 50-75% water (by mass), or with a small gas planet composed of a rocky core surrounded by a massive hydrogen and helium atmosphere, as is further confirmed by GJ 1214b's placement on a mass-radius plot as seen in Fig. 3. Charbonneau et al. points out that while this latter possibility of a small gaseous planet cannot be ruled out purely observationally, it is unlikely

Planet Name	Mass ($M_\oplus$)	Mass method (instrument)	Radius ($R_\oplus$)	Radius method (instrument)	Citation
GJ 1214b	6.55	RV (HARPS)	2.678	Transit (MEarth)	Charbonneau et al. (2009)
Kepler-11b	4.3	TTV (Kepler)	1.97	Transit (Kepler)	Lissauer et al. (2011), Lopez et al. (2012)
Kepler-22b	10.04 or 23.68	Modeled	2.38	Transit (Kepler)	Neubauer et al. (2012), Sotin et al. (2007)
Gliese 581g	3.7	*see caption*	$\gtrsim$1.42	Modeled	von Bloh et al. (2011), Valencia et al. (2006)
GJ 667C-b	5.68	RV (HARPS, Magellan/PFS, Keck/HIRES)	-	-	Anglada-Escude et al. (2012)
GJ 667C-c	4.54	RV (HARPS, Magellan/PFS, Keck/HIRES)	-	-	”
Kepler-62e	-	-	1.61	Transit (Kepler)	Borucki & et al. (2013)
Kepler-62f	-	-	1.41	Transit (Kepler)	”
Kepler-69c	-	-	1.71	Transit (Kepler)	Barclay et al. (2013)

Table 1: A non-exhaustive list of candidate ocean planets in or near their stars' habitable zones. See citations for uncertainties. For Gliese 581g, the values used in this table are the means of the extreme values explored in von Bloh et al. (2011). von Bloh et al. does not directly cite their source/method for the mass of Gliese 581g, though it appears to be based upon Vogt et al. (2010). The radius is determined by von Bloh et al. using a theoretical scaling law derivied by Valencia et al. (2006) for terrestrial super-Earths (see Eq. 1), and thus is a lower limit.

based on current theories of planet formation, so it is most probable that GJ 1214b is an ocean planet.

Kepler-11 is a G dwarf star, and via transits Lissauer et al. (2011) discovered a total of 6 planets orbiting it. TTV was then used to determine the masses of each planet. With these two methods together, Lissauer et al. determined that Kepler-11b has a radius of $1.97R_\oplus$ and a mass of

$4.3M_{\oplus}$. Taking these properties of Kepler-11b (and the other planets in the system) as given, Lopez et al. (2012) then went on to model the formation and structure of each of these objects. They considered three possibilities for the composition of low-mass low-density planets: terrestrial, ocean planets, and hydrogen/helium. To determine the best model, they not only examined the current mass and radius of the planet, but also determined the likely mass loss rate due to XUV radiation from the star. Based upon the mass and radius of Kepler-11b and the radiation received at the planet from the star Kepler-11, Lopez et al. decided that Kepler-11b must be an ocean planet. Further reference to modeling also indicates that many of the planets in the system likely did not form *in situ*, but instead that all the planets in the system formed as "water rich sub-Neptunes" (Lopez et al. 2012) beyond the system's snow line and then migrated in.

4.2. Unconfirmed candidates

In order to confirm an object as an ocean planet, even based solely upon models, we need both a mass and a radius measurement. With only one of the two values, we can at best put limits on the other value - a lower limit can be found by assuming terrestrial composition (metal and rock), and an upper limit by assuming the object is primarily gaseous. Assuming a terrestrial composition by default for super-Earths/sub-Neptunes appears to be the preference of most authors.

Kepler-22b has a radius of $2.38R_{\oplus}$ (Neubauer et al. 2012) according to Kepler observations. Neubauer et al. modeled the mass of the planet via the method of Sotin et al. (2007) and using two different scenarios for its composition: if the planet is terrestrial, then its mass is approximately $10M_{\oplus}$, while if it is an ocean planet then its mass is approximately $24M_{\oplus}$. For either scenario, additional modeling shows that Kepler-22b falls within the HZ of the star. While some subsequent papers have referred to Kepler-22b as a confirmed ocean planet, Neubauer et al. themselves were more modest in their claim, saying only that it is a possible scenario and more information is required to determine its composition conclusively.

For Gliese 581g, von Bloh et al. (2011) have calculated a radius assuming a terrestrial composition. The mass given in Table 1 is quoted by von Bloh et al. (2011) without a source given, though it appears to be based upon Vogt et al. (2010)'s HARPS and HIRES (Keck) measurements. Vogt et al. gives a lower limit to its mass of $3.1M_{\oplus}$ due to the $m \sin i$ degeneracy; presumably von Bloh et al.'s range of $3.1 - 4.3M_{\oplus}$ is determined by examining the distribution of $\sin i$ values. von Bloh et al. then goes on to determine Gliese 581g's radius using Valencia et al.'s theoretical scaling law dervied for terrestrial super-Earths (see Eq. 1). This radius therefore is a lower limit - if the object were less dense than a terrestrial planet, (for example, if it were an ocean planet), then the radius would be greater. von Bloh et al. concludes based upon this lower limit for radius and through modeling the effective temperature of the planet, that Gliese 581g is consistent with a terrestrial planet whose surface is nearly entirely covered with water, akin to the fictional terrestrial Waterworld discussed in Sec. 1, however Gliese 581g's mass is also consistent with it being an ocean planet.

Anglada-Escude et al. (2012) reanalyzed HARPS RV data on the M1.5 dwarf GJ 667C (the third star in the system, with AB being a close binary) and supplemented this with additional observations using PFS (Magellan) and HIRES. GJ 667C-b had been previously detected, but new data analysis methods of Anglada-Escude et al. pulled out two additional planets in the system as well as an overall trend to the RV of the star which is consistent with a longer-period gas giant. Planets GJ 667C-b and GJ 667C-c both have masses consistent with super-Earths or sub-Neptunes at $5.68M_{\oplus}$ and $4.54M_{\oplus}$ respectively, however radius measurements are required to confirm this with any certainty. Anglada-Escude et al. determined that the chances of these planets transiting their star is in the range of $1-3\%$, and should they do so they would result in a significant dimming at 0.3%. GJ 667C-c is located within the star's HZ, so if it does turn out to be an ocean planet it may have a significant fraction of liquid water rather than ice.

The Kepler team recently announced (Borucki & et al. 2013) the discovery of five planets orbiting Kepler-62. Unfortunately with radii all less than $2R_{\oplus}$, even at terrestrial densities all the planets in this system are too low mass to cause a measurable RV of the star itself with any equipment currently existing, and also too low mass to cause measurable TTV with other planets in the system. Kepler-62e and f are both located in or near the star's HZ, and with radii of $1.61R_{\oplus}$ and $1.41R_{\oplus}$ they are both super-Earths. Based on the age of the star and the effective temperatures of the planets, these planets are not likely to be gaseous, leaving the possibilities of either terrestrial or ocean planets.

Also announced in recent weeks was the discovery of Kepler-69c around a sun-like star (Barclay et al. 2013). Both Kepler-69b and c are super-Earths with radii of $2.24R_{\oplus}$ and $1.7R_{\oplus}$, respectively, with Kepler-69c in or near the star's HZ with an effective temperature of 299K. The range of possible radii for Kepler-69c, $1.48-2.05R_{\oplus}$ indicates that the planet is on the boundary between a terrestrial planet and a "volatile rich" (i.e., oceanic) planet. Based upon the effective temperature and the liklihood of a highly eccentric oribt ($e \leq 0.79$), it is possible for Kepler-69c to have a liquid surface ocean for at least part of its orbit.

5. Future work

Additional work is required to confirm the composition of candidate (extrasolar) ocean planets. There are many objects for which we know only the mass or the radius, and both are needed to be able to accurately model the planet's composition. In cases where we know the radius of the object but do not yet know the mass, spectrometers of the future may be sufficiently accurate to allow the detection of lower mass planets and planets farther from their host start via the RV method.

Astronomers are in the early stages of taking spectra of transiting exoplanets' atmospheres. When this is advanced further, the detection of water and other volatiles in the atmosphere will help confirm the evaporation and sublimation of the ice layer of an ocean planet.

In the meantime, future missions to solar system ice bodies, such as NASA's ongoing New

Horizons mission to Pluto and other Kuiper Belt Objects, and ESA's upcoming JUpiter ICy Moon Explorer (JUICE) to Jupiter's moons Europa, Ganymede, and Callisto, will help us to better characterize the properties of smaller icy bodies. While these are clearly not identical to ocean planets due to their smaller masses (and resulting lower interior pressures), the information learned about smaller icy bodies will help us to set limits on our modeling of larger icy super-Earths and sub-Neptunes.

6. Summary

As shown by Valencia et al. (2007), mass and radius together sufficiently constrain the composition of a planet for us to determine whether an object is an ocean planet or terrestrial. The currently accepted theory for the formation of an ocean planet is that they form as sub-Neptunes or super-Earths of $1 - 10M_{\oplus}$ past the snow line of a solar system, and then subsequently migrate inwards, where they lose their H/He envelopes due to higher effective temperatures.

We have discovered a number of possible ocean planets. In the cases of GJ 1214b and Kepler-11b, both their masses and radii are known so their composition can be directly determined from models, and both planets are consistent with Valencia et al. (2007)'s definition of ocean planet. For Kepler-22b and Gliese 581g, we have only their radius or their mass (respectively), and modeling gives us a limit or range of values for the other quantity. These derived values are consistent with either terrestrial or ocean planets, however since the modeling assumes one or the other this circular reasoning is not conclusive. And lastly for GJ 667C-b, GJ 667C-c, Kepler-62e, Kepler-62f, and Kepler-69c we have only the mass (first two) or the radius (last three) of the planet, which are consistent with the $1 - 10M_{\oplus}$ range of super-Earth/sub-Neptune objects which could be either terrestrial or ocean planets. There do not appear to be any works yet modeling the other quantity of mass and radius for these five objects.

With future work using better spectrometers and by determining the spectra of transiting planetary atmospheres, we should be able to confirm whether these objects are actually ocean planets by either determining their mass from RV measurements, or by directly determining the composition of their atmospheres and comparing it to models for ocean planets.

REFERENCES

Anglada-Escude, G., Arriagada, P., Vogt, S. S., Rivera, E. J., Butler, P., Crane, J. D., Shectman, S. A., Thompson, I. B., Haghighipour, N., Carter, B. D., & et al. 2012, ApJ Letters, 116

Barclay, T., Burke, C. J., Howell, S. B., Rowe, J. F., Huber, D., Jenkins, J. M., Kolbl, R., Marcy, G. W., Quintana, E. V., Still, M., & et al. 2013, ApJ

Borucki, W. J. & et al. 2013, Science

Charbonneau, D., Berta, Z. K., Irwin, J., Burke, C. J., Nutzman, P., Buchhave, L. A., Lovis, C., Bonfils, X., Latham, D. W., Udry, S., & et al. 2009, Nature, 462, 8914

Hubbard, W. B. & MacFarlane, J. J. 1980, Journal of Geophysical Research, 85, 225

Jang-Condell, H. 2013, Personal communication

Kuchner, M. J. 2003, ApJ, 596, 105108

Léger, A., Selsis, F., Sotin, C., Guillot, T., Despois, D., Lammer, H., Ollivier, M., Brachet, F., & Valette, C. 2004, Icarus, 115

Lissauer, J. J., Fabrycky, D. C., Ford, E. B., Borucki, W. J., Fressin, F., Marcy, G. W., Orosz, J. A., Rowe, J. F., Torres, G., Welsh, W. F., & et al. 2011, Nature, 470, 538

Lopez, E. D., Fortney, J. J., & Miller, N. K. 2012, ApJ, 17

Neubauer, D., Vrtala, A., Leitner, J. J., Gertrude Firneis, M., & Hitzenberger, R. 2012, Planetary and Space Science, 73, 397406

Reynolds, K. 1995, Waterworld (Universal Pictures)

Sotin, C., Grasset, O., & Mocquest, A. 2007, Icarus, 337351

Valencia, D., OConnell, R. J., & Sasselov, D. 2006, Icarus, 181, 545554

Valencia, D., Sasselov, D. D., & OConnell, R. J. 2007, The Astrophysical Journal, 665, 14131420

Vogt, S. S., Butler, R. P., Rivera, E. J., Haghighipour, N., Henry, G. W., & Williamson, M. H. 2010, The Astrophysical Journal, 723, 954965

von Bloh, W., Cuntz, M., Franck, S., & Bounama, C. 2011, Astronomy & Astrophysics, 528, A133

This preprint was prepared with the AAS LATEX macros v5.2.

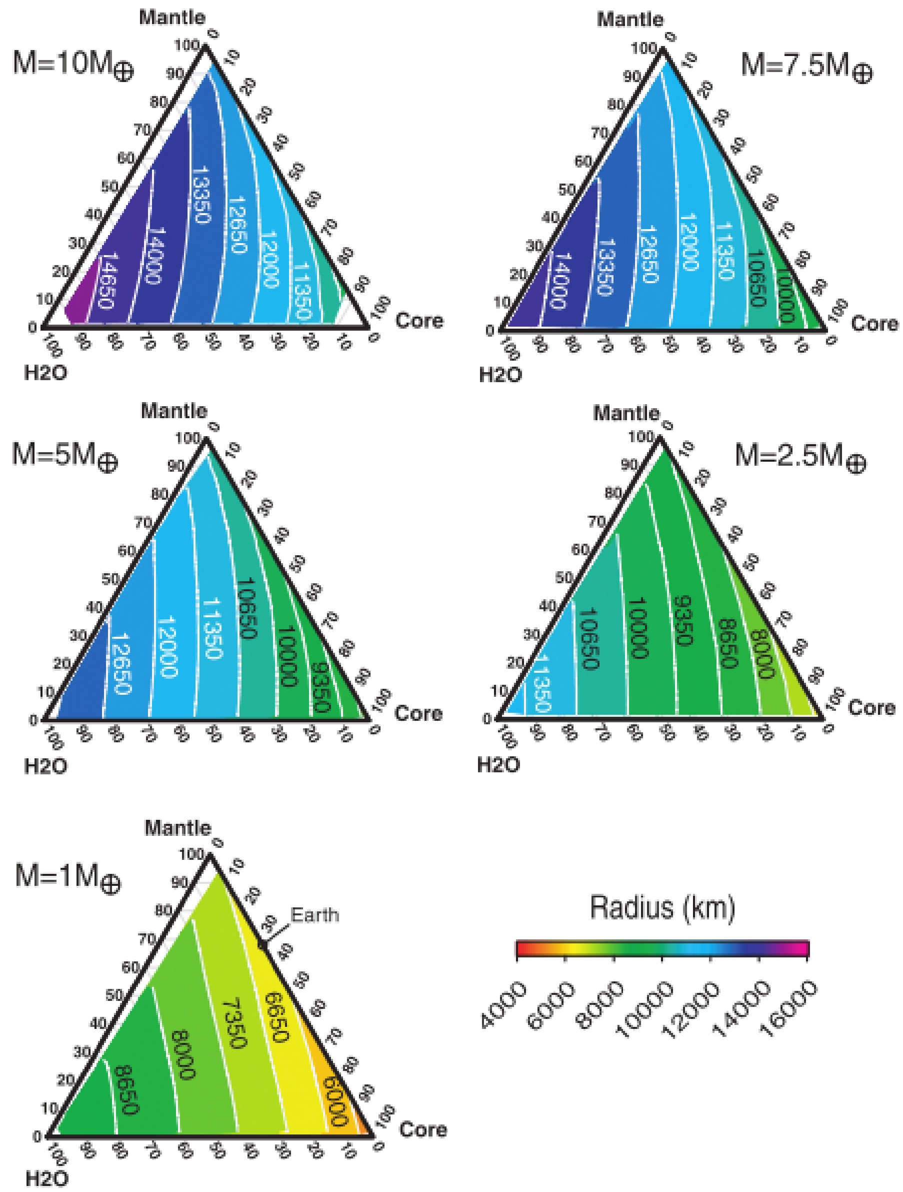

Fig. 2.— A series of ternary diagrams (Valencia et al. 2007) showing core/mantle/ice mass fractions for objects ranging in mass from $10M_\oplus$ down to $1M_\oplus$. The color contours indicate the radius of a planet with the indicated mass and core/mantle/ice mass fractions.

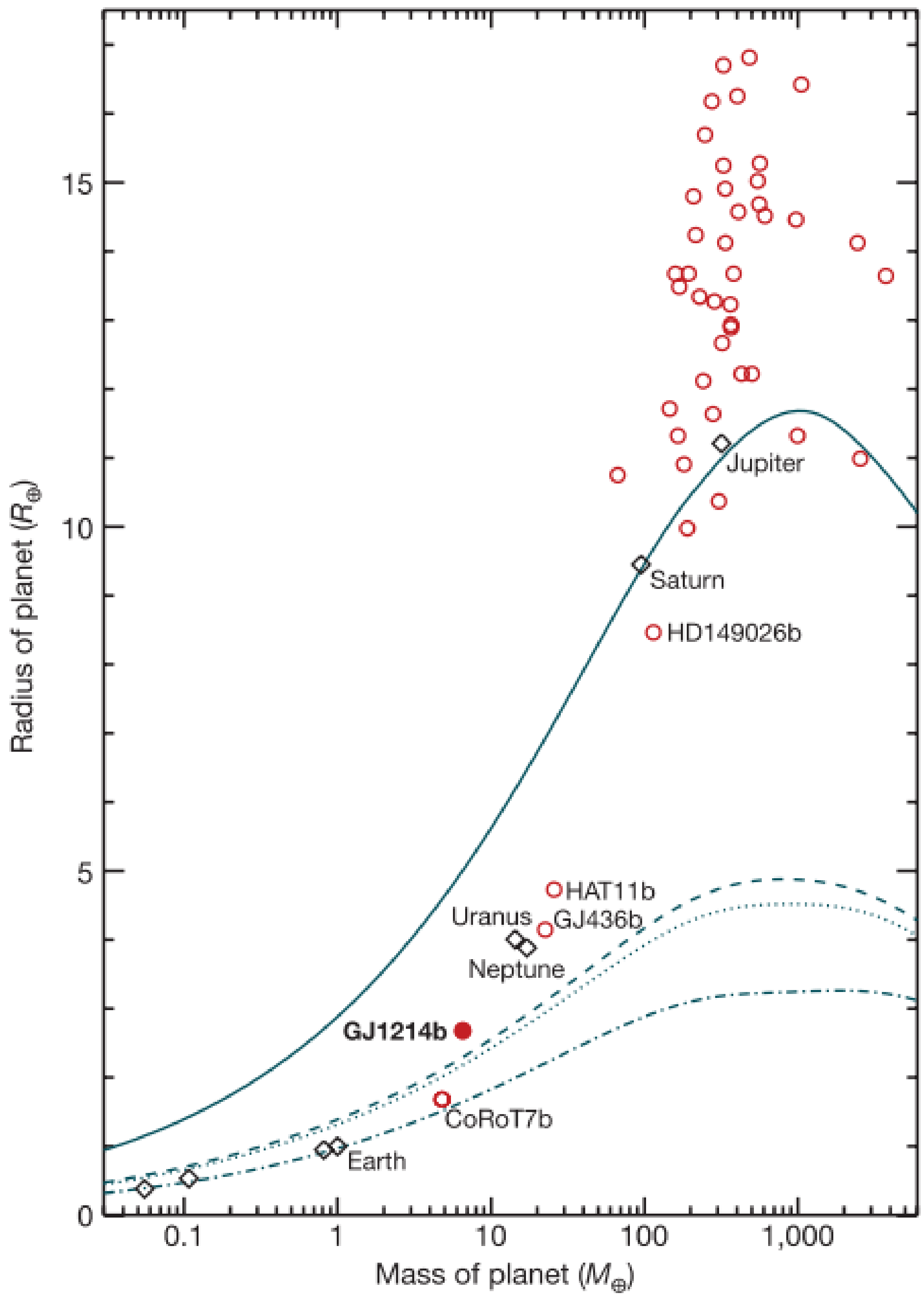

Fig. 3.— Mass-radius plot of a number of known planets (Charbonneau et al. 2009). Note how GJ 1214b falls far above the lower dashed line for terrestrial planets, slightly above the middle dashed line for ocean planets, and below the upper solid line for gas giants.