# Water Planets in the Habitable Zone: Atmospheric Chemistry, Observable Features, and the case of Kepler-62*e* and -62*f*

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Abstract: Water planets in the habitable zone are expected to have distinct geophysics and geochemistry of their surfaces and atmospheres. We explore these properties motivated by two key questions: whether such planets could provide habitable conditions and whether they exhibit discernable spectral features that distinguish a water planet from a rocky Earth-like planet. We show that the recently discovered planets Kepler-62*e* and -62*f* are the first viable candidates for habitable zone water planet. We use these planets as test cases for discussing those differences in detail. We generate atmospheric spectral models and find that potentially habitable water planets show a distinctive spectral fingerprint in transit depending on their position in the habitable zone.

Subject headings: Astrobiology - atmospheric effects - methods: data analysis – Earth - planets and satellites: general – stars: individual (Kepler)

#### 1. Introduction

The possible existence of Earth and super-Earths<sup>1</sup>-size planets covered completely by a water envelope (water planets) has long fascinated scientists and the general public alike (Kuchner 2003, Leger et al.2004). No such planets are known in the Solar System. Sometimes referred to as "ocean planets", stemming from the implicit assumption of Habitable Zone (HZ) temperatures and a liquid water surface, water planets constitute a much broader class which is now known to exist in nature thanks to mean density measurements of а few transiting exoplanets (see e.g. Gautier et al.2012, Cochran et al.2011, Gilliland et al.2013).

Until recently all known candidates for water planets (Borucki et al.2013) were found orbiting very close to their stars.

Such planets, e.g., Kepler-18b, -20b, -68b, are very hot due to the high stellar flux, which ensures a smooth transition from an interior water envelope to a steam atmosphere with no liquid surface ocean (Rogers&Seager 2010; Valencia et al.2009). The discovery of many planetary systems with tightly packed inner planets by the Kepler mission has opened the prospect for getting mean densities of Earth-size planets in the habitable zone by transit-timing variations (TTVs) where radial velocity amplitudes are too small to measure (Lissauer et al.2011). Given the very low mean densities measured so far among the majority of such planets, e.g. those found in Kepler-11 (Lissauer et al.2013), Kepler-20 (Gautier et al.2012), Kepler-36 (Carter et al.2012), we anticipate that the first HZ super-Earths of radius below 2 Earth radii (R<sub>E</sub>) are more likely to be water planets than rocky ones. The recent discovery of the multiple transiting system Kepler-62, with two

 $<sup>^1</sup>$  Super-Earth size is used here for planets with radii between 1.25  $R_{\ast}$  and 2.0  $R_{\ast}.$ 

planets in its HZ (Borucki et al.2013), illustrates this point. We are motivated by the discovery of Kepler-62*e* and -62*f* to consider a more general approach to computing surface and atmospheric conditions on water planets in the HZ.

Water planets of Earth- to super-Earth sizes in the HZ fall into at least 2 types of interior geophysical properties, in terms of effect on their atmosphere: In a first Type, hereafter Type1, the core-mantle boundary connects silicates with high-pressure phases of water (e.g. Ice VI, VII), i.e. the liquid ocean has an icy bottom. In contrast in Type2 the liquid ocean has a rocky bottom, though no silicates emerge above the ocean at any time. The second type is essentially a rocky planet when viewed in terms of bulk composition. Both subtypes could possess a liquid ocean outer surface, a steam atmosphere, or a full cover of surface Ice I, depending on their orbit within the HZ and the magnitude of their greenhouse effect. Frozen water planets should show a subsequent increase in the surface albedo value due to high reflective ice covering a frozen surface and will be most easily detected by direct imaging missions operating in the visible, while IR imaging search will preferential detect warm water planets.

Surface and atmospheric conditions on water planets in the HZ have not been the subject of detailed studies. So far the work has focused on issues of evaporation (Kuchner 2003; Valencia et al.2009; Murray-Clay et al.2010) and boundary conditions to interior models (Valencia et al.2007, Grasset et al.2009, Fu et al.2010, Rogers&Seager 2010).

In this paper we develop an initial model for water planet atmospheres to allow assessment of their observables with future telescopes. This model will be based on many explicit and implicit assumptions using Earth as a template but taking into account anticipated differences in outgassing, geochemical cycling, global circulation, etc. to assess their observables with future telescopes. In this paper we describe a set of atmospheric models and their underlying assumptions in section 2, how they could be applied to interpret Kepler-62*e* and -62*f* as water planets in sections 3 and 4, and finish in section 5 with discussion and conclusions.

### 2. Atmospheric Models for Water Planets – Basic Assumptions

We assume here that the initial composition of icy planetesimals that assemble into water planets is similar to that of comets, mostly H<sub>2</sub>O, some NH<sub>3</sub> and CO<sub>2</sub>. An initial composition of ice similar to that of comets leads to an atmospheric model composition of 90%H<sub>2</sub>O, 5%NH<sub>3</sub> and 5%CO<sub>2</sub> (see also Leger et al.2004, simplified who the atmospheric photochemistry by assuming no CO nor is UV sensitive. CH<sub>4</sub>). NH<sub>3</sub> photodissociates and is converted into N<sub>2</sub> and  $H_2$  in a very short time frame, with  $H_2$ being lost to space (see e.g. Leger et al.2003, Lammer et al.2007). This shows that water planet atmospheres will have the same chemical constituents as oceanland planets.

The carbonate-silicate cycle that regulates CO<sub>2</sub> cycling on our own planet is effective due to weathering of exposed solid rock surface. Recent work (Abbot et al.2012) has shown that for an Earth-like planet, the carbonate-silicate cycle could continue to function largely unchanged for a continent surface fraction as low as 10%, with mid-ocean ridges taking over some of the recycling processes but argued that CO<sub>2</sub> cannot build up in the atmosphere of a Type2 water planet without continents. Therefore the HZ for water planets was inferred to be narrower than for planets with continents. Note that the arguments

presented in that work are generally only applicable to Type2 water planets, i.e. those with very low water-mass fraction. For Type1 water planets, i.e. Super-Earths with water-mass fractions like Earth or above, the deep oceans are separated from the rocky interior via a layer of highpressure ices. Therefore an alternative  $CO_2$ recycling mechanism will be required in water planets for cycling of abundant gases, like CO<sub>2</sub> and CH<sub>4</sub>. Such a cycle would depend on the properties of their clathration in water over a range of very high pressures. Methane clathrates are water molecule lattices that trap CH<sub>4</sub> molecules as guests by virtue of multiple hydrogen-bonding frameworks. Under very high pressures, common to super-Earth-size water planets, methane clathrates undergo a phase transition in their structure to a form known as filled ice. Levi et al (2013) studied this transition and concluded that CH<sub>4</sub> would be transported efficiently through the highdensity water-ice mantle of water planets in filled ice clathrates and eventually released in the atmosphere. It is well known that CO<sub>2</sub> substitutes CH<sub>4</sub> readily in normal-pressure clathrates (see e.g. Park et al.2006, Nago&Nieto 2011). We expect that this property can be extrapolated to filled ice, though this needs to be established. If so, this substitution will enable effective cycling of CO<sub>2</sub> through the atmosphere in water planets residing in the habitable zone (e.g., with water oceans at the surface) and thus provide an atmospheric feedback mechanism for CO<sub>2</sub> on water planets. As for Earth-like planets with continents, such a cycle would control the CO<sub>2</sub> levels, leading to waterdominated atmospheres for strong stellar irradiation and CO<sub>2</sub>-dominated atmosphere for low stellar irradiation.

This new water planet model implies that atmospheric model profiles for water planets in the HZ should not differ substantially from atmospheric profiles for land-ocean planets, except for an increase in absorbed stellar flux due to the decreased surface reflectivity of water planets (see S5).

#### **3.** Habitable Zone for Water Planets

The "narrow" HZ is defined here classically as the annulus around a star where a rocky planet with a  $CO_2/H_2O/N_2$ atmosphere and sufficiently large water content (such as on Earth) can host liquid water on its solid surface (Kasting et al.1993). A conservative estimate of the range of the narrow HZ is derived from atmospheric models by assuming that the planets have a H<sub>2</sub>O- and CO<sub>2</sub>-dominated atmosphere with no cloud feedback (Kopparapu et al.2013). In this model, the locations of the two edges of the HZ are determined based on the stellar flux intercepted by the planet, at the inner edge by thermal run away due to saturation of the atmosphere by water vapor and at the outer edge by the freeze-out of CO<sub>2</sub> for a geologically active. planets that is Climatic stability is provided by a mechanism in which atmospheric CO<sub>2</sub> concentration varies inversely with planetary surface temperature. Cloud feedback will widen the limits of the HZ (see e.g. Selsis et al.2007, Zsoms et al.2012), we therefore use the empirical value for the HZ from our own Solar System as the "effective" HZ, defined by the initial solar fluxes received at the orbits of Venus and Mars during the early period of the solar system when the Sun was less luminous and Venus (1Gyr) and Mars (3.5Gyr) did not have liquid water on their surfaces. At that time Venus received an equivalent flux of  $1.78S_{\odot}$  and Mars of  $0.32S_{\odot}$  (Kopparapu et al.2013).

The HZ changes only slightly for water planets compared to the HZ of a land-ocean planet because at the limits of the HZ the albedo is solely dominated by the atmosphere and the surface albedo only has a small effect (see Fig.3 for insight on the effect of the surface albedo on the resulting atmospheric structure). But within the HZ for a given incident stellar flux a water planet has larger surface temperature due to the low surface reflection of water compared to land.

Cloud coverage influences the atmospheric temperature structure as well as the observability of spectral features (see e.g. Kaltenegger et al.2007, Selsis et al.2007, Kaltenegger&Traub 2009, Rauer et al.2010). On Earth cloud fractions is similar over water and land (see e.g. Zsom et al.2012). If sufficient cloud condensation nuclei are available, cloud coverage should be the same as for rocky planets for the same stellar insolation, but it will vary depending on the water planet's position in the HZ (Rugheimer et al.in prep). The position and pattern of individual cloud layers depend on planetary parameters like unknown rotation rate as well as surface topography. We mimic the effects of varying cloud coverage by varying the initial surface albedo in our atmospheric model from the standard 0.2 (see Kasting et al. 1993).

The atmospheric structure and the resulting HZ limits depend on the density of a planet's atmosphere, shifting the HZ outwards for lower mass and inwards for higher mass planets (see Kasting et al.1993, Kopparapu et al.2013). Without any further information on the relation of surface pressure to planetary mass, we make the first order assumption here, that if outgassing rates per  $m^2$  are held constant on a solid planet, and atmospheric loss rates decrease with planetary mass due to

increased gravity, assuming a similar stellar environment, then a more massive planet should have a higher surface pressure (for similar outgassing and atmospheric loss mechanisms). We scale the surface pressure of the planet to first order with its surface gravity (following e.g. Kaltenegger et al.2011) and explore the effect of different planetary mass in Fig.3. We use EXO-P (see e.g. Kaltenegger&Sasselov 2010 for details and reference) to model the atmosphere of water planets. EXO-P consists of a coupled one-dimensional radiativeconvective atmosphere code developed for rocky exoplanets based on a 1D-climate, 1D-photochemistry and 1D-radiative transfer model.

### 4. Models for transiting Type1 Water-Planets in the HZ - the Kepler-62 and -69 systems

Kepler-62 (Borucki et al.2013) and Kepler-69 (Barclay et al.2013) are multitransiting planet systems with individual planets in or close to the HZ (Fig.1 and 2). Kepler-62b, c, d, e, and f have radii of 1.31, 0.54, 1.95, 1.61 and 1.41R<sub>E</sub> with less than 5% errors, orbiting a K2V star of 4925±70°K (0.21±0.02L<sub>0</sub>) at periods of 5.7, 12.4, 18.2, 122.4 and 267.3 days, respectively (Borucki et al.2013). The outermost planets Kepler-62e and -62f are super-Earth-size planets in the HZ of their host star, receiving 1.2±0.2 and 0.41±0.05 times the solar flux at Earth's orbit  $(S_0)$ . Kepler-69b, and -69c have radii of about 2.2 and 1.7  $(+0.34-0.29)R_E$  orbiting a 5638 ±168°K Sun-like star. Kepler-69c has semi-major axis to stellar radius ratio a/R<sub>Star</sub>=148 (+20-14) at periods of 13.7 and 242.5days respectively (Barclay et al.2013). Due to the large uncertainty in luminosity of the star, the outermost planet Kepler-69c receives  $1.91 (+0.43 - 0.56)S_0$ 

The small radii of Kepler-62e and -62f indicate that the planets should not have retained primordial hydrogen atmospheres at their insolation and estimated ages of about 7Gyr (Rogers et al.2011, Lopez et al.2013, Lammer al.2009, et Gaidos&Pierrehumbert 2010), making them strong candidates for solid planets, and not Mini-Neptunes. Given the large amount of solid objects already present in the Kepler-62 system on orbits inward of -62e, and following the recent results on the Kepler-11 cohort of 6 low-density planets with tightly packed close-in orbits (Lissauer et al.2013) it strongly suggests that -62e and -62f formed outside the ice line and are therefore our first HZ water planets. While other possibilities remain open until their actual masses are measured, for the purposes of this paper we'll assume that they are indeed water planets on low-eccentricity orbits and model both biotic and abiotic atmospheres.

For Kepler-62*e* we set the  $O_2$  mixing ratio to 0.21 (biotic),  $0.21 \times 10^{-6}$  (abiotic). We set  $CO_2$  to 10ppm for both simulations for Kepler-62e at the inner part of the HZ, which corresponds to the conservative lower limit for C4 photosynthesis (Heath 1969. Pearcy&Ehleringer 1984) and calculate what levels of CO<sub>2</sub> are needed for Kepler-62f to maintain liquid water on its surface, which results in 5bar of CO<sub>2</sub> for the considered Albedo range. For Kepler-62f we set  $O_2$  to 0.21atm for the biotic model. Maintaining a constant mixing ratio for the biotic case like for Kepler-62e would yield unrealistically high O<sub>2</sub> pressures. For the biotic case we use only trace amounts of O<sub>2</sub>. The CH<sub>4</sub>  $1.31 \times 10^{11}$ flux is set to (biotic)  $4x10^{-9}$ (Rugheimer et al.2013), molecules/cm<sup>2</sup>/s (abiotic) (see e.g. Kasting&Caitling 2003, Segura et al.2007) for both planets.

#### 5. Discussion and Conclusions

For Kepler-62*e*'s radius a water planet's mass would be in the range 2- $4M_E$ . Kepler-62*f* has a smaller radius of 1.41R<sub>E</sub>, so its mass would be 1.1-2.6M<sub>E</sub>. The transition from liquid water to the first solid phase of Ice VI occurs at 0.63 to 2.2GPa, depending on the temperature. Beyond 2.2GPa, the solid phase water is Ice VII. The depth of the liquid ocean is thus in the range of 80 to 150km for these two planets. The radius of Kepler-69c R<sub>p</sub>=1.7 (+0.34 -0.23)R<sub>E</sub> has very large error bars, therefore the mass range is illdefined.

Fig.2 shows that the stellar flux values at the limit are 1.66 to  $0.27S_{\odot}$  for the effective HZ and 0.95 to  $0.29S_{\odot}$  for the narrow HZ, respectively, for Kepler-62 and 1.78 to  $0.29S_{\odot}$  for the effective HZ and 1.01 to  $0.35S_{\odot}$  for the narrow HZ for Kepler-69 (based on models by Kopparapu et al.2013). The intercepted flux at the orbit of Kepler-62e and -62f, make both planets candidates for liquid water on their surface. If the atmosphere of Kepler-62f is accumulates several bar of atmospheric  $CO_2$  (1.6 to 5bar, depending on the model planetary mass and surface albedo) it would be covered by liquid water on its surface, otherwise it would be ice covered. This first possibility allows an interesting comparison of a warm Type1 water planet in the inner and outer part of the HZ, the second possibility allows us to compare warm and frozen Type1 water planets in this system (Fig. 4). These differences are similar to the variations with temperatures of rocky planet spectra, but water planets are hotter at a given distance from their star.

Fig.2 shows that Kepler-69c lies outside the effective HZ corresponding to the nominal stellar flux, but the error bar

on the star's flux allows the possibility that the planet is within the inner edge of the effective empirical HZ. To explore the atmospheric features of transiting water planet, we concentrate on the Kepler-62 system here, where both planets are within the star's HZ. We run Exo-P models tuned to the Kepler-62 parameters and explore the effect of changing cloud parameters by varying the surface albedo from 0.2 to 0.3 mimicing increased cloud coverage for Kepler-62e, and from 0.2 to 0.1 for Kepler-62f mimicing decreased cloud coverage. Fig.3 shows the atmospheric structure of both planets as Type1 water planets for the maximum and minimum mass and explore their changes with surface albedo (nominally 0.2). Interior models (see Zeng&Sasselov 2013) of Kepler-62e models give a scaled surface pressure of 0.78 to 1.56 times Earth's and surface temperatures for the low mass case of 303.7K and 306.8K(A=0.2) and 292.5K and 296.9K(A=0.3) for the abiotic and biotic cases, respectively. Models for the high planetary mass case result in surface temperatures of 308.1K and 310.5K(A=0.2) 293.1K and and 297.5K(A=0.3) for the abiotic and biotic cases, respectively.

Atmospheric models for Kepler-62f show that 1.6bar of  $CO_2$  is needed to warm the surface temperature above freezing for an albedo of 0.1 and 5bar of CO<sub>2</sub> is needed to obtain Earth's global temperature average of 288K for an albedo of 0.3. Models of Kepler-62f lead to a scaled surface pressure of 0.56 to 1.32 times Earth's. We add 5bar of  $CO_2$  to this surface what results in pressure, temperatures of 288.3K and 289.2K(A=0.1) 280.5K and and 281.6K(A=0.2) for the abiotic and biotic cases, respectively. For the high mass case of Kepler-62f, we obtain surface temperatures of 298.4K and

279.7K(A=0.1) and 287.8K and 280.6K(A=0.2) for the abiotic and biotic cases, respectively.

We use two model calculations (the lowest surface pressure and gravity consistent with Kepler-62e and -62f, for biotic conditions) as example to explore if transmission spectra show differences between different planetary conditions as future well as inform instrument sensitivity requirements. Using the highest planetary mass in the interior models would decrease the observable spectral features by a factor of about two. Fig.4 synthetic the corresponding shows transmission spectra of (top) a waterdominated atmosphere warm water planet (using model parameters for a light Kepler-62*e*) and (middle) a CO<sub>2</sub>dominated atmosphere frozen water planet (using model parameters for a light Kepler-62f with only 100 times Present Atmospheric Level CO<sub>2</sub>), and of a current Earth analog (bottom). The comparison clearly shows stronger  $CO_2$  in the transmission spectra of a water planet on outer edge of the HZ compared to a water planet the inner edge of the HZ, but lower O<sub>3</sub> and H<sub>2</sub>O features. Therefore relatively low resolution spectra allow such planets to be characterized for telescopes like JWST (see e.g. Kaltenegger&Traub 2009, Deming et al.2009, Rauer et al.2010, Belu et al.2011, van Paris et al.2013) as well as high resolution ground based telescopes like E-ELT (Snellen et al.2013).

We have defined two types of water planets, Type1, which are true water planets in their bulk composition and Type2 which are rocky planets with water covering all surface and postulated a new cycling mechanism for  $CO_2$  using clathrates. A detailed atmospheric model of the specific planets of Kepler-62*e* and -62*f* as Type1 water planets permits for liquid water on each, if -62*f* accumulates several bar of  $CO_2$  in its atmosphere. The Kepler-62e models show a warm water planet, between the limits of the narrow HZ and the effective HZ with increased cloud coverage. These planets allow comparison of water planets with warm water- and CO<sub>2</sub>-dominated atmosphere in HZ, with discernable differences in their transmission spectra. Fig. 4 shows that the transmission spectrum allows an interesting comparison of warm waterversus CO<sub>2</sub>-dominated as well as warm and cold water planets in this system. These differences are similar to the variations with temperatures of rocky planet spectra, but water planets are hotter at a given distance from their star.

Kepler-62*e* and -62*f* are the first viable candidates for HZ water planets which would be composed of mostly solids, consisting of mostly ice (due to the high internal pressure) surrounding a silicateiron core. The nominal flux intercepted at Kepler-69*c* is too high for it to be in the effective HZ, but the large error bars on its star's flux allow for this planet close to the inner edge of the empirical HZ.

Water planets in the HZ are completely novel objects, which do not exist in our own Solar System. The atmospheric models presented here predict detectable features in the spectra of water planets in the HZ in transit. Therefore we expect that future remote characterization will allow us to distinguish water planets at different parts of their HZ.

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### References

Abbot, D., Cowan, N.B., Ciesla, F.J. 2012, ApJ, 756, 13

Abe, Y, Abe-Ouchi, A., Sleep, N.H.,

Zahnle, K.J. 2011, Astrobiology 11, 443

Barclay et al. 2013, ApJ, in press

Belu, A. R., Selsis, F., Morales, J., et al. 2011, A&A, 525, A83

Borucki, W et al. 2013, Science

Borucki, W. J. et al. 2011, ApJ, 736, 19

Carter, J.A. et al. 2012, Science, 337, 556

Cochran, W.D. et al. 2011, ApJS, 197, 19

Deming, D., Seager, S., Winn, J., et al.

2009, Pub. Astron. Soc. Pac., 121, 952

Fu, R., O'Connell, R.J., Sasselov D.D. 2010, ApJ, 708, 1326

Gautier, T.N. et al. 2012, ApJ, 749, 19

Heath, O. V. S. The Physiological Aspects of Photosynthesis, Stanford Univ. Press, 1969.

Kaltenegger, L., Sasselov D.D. 2010, ApJ. 708, 1162

Kaltenegger, L., Segura, A., Mohanty, S. 2011, ApJ, 733, 1

Kaltenegger, L., Traub, W.A. 2009, ApJ, 698, 519

Kaltenegger, L., Traub, W.A., Jucks, K.W. 2007, ApJ, 658, 598

Kasting, J. E., Whitmire, D.P., Reynolds, R. T. 1993, Icarus, 101, 108

Kasting, J. F. & Catling, D. 2003, Ann.

Rev. Astron. Astrophys. 41:429–63.

Kasting, J.F., Pollack, J.B., Crisp, D. 1984, J. Atmos. Chem., 403

Kopparapu, R.K. et al. 2013, ApJ, 2013arXiv1301.6674K

Kuchner, M. 2003, ApJ, 596, L105

Lammer, H. et al. 2009, Space Science Reviews, 139, 399

Lee, J. et al. 2010, ApJ, 716, 1208

Leger, A. et al. 2004, Icarus, 169, 499

Levi, A., Sasselov D.D., & Podolak, M., 2013, ApJ, accepted

Li, Z. & Sasselov, D.D. 2013, PASP, 2013arXiv1301.0818Z

Lissauer, J., et al. 2013, arXiv:1303.0227

Lissauer, J.J. et al. 2011, Nature, 470, 53. Lopez, E.D., Fortney, J.J., Miller, N. K. 2013, ApJ, in press arXiv:1205.0010v2 Marcus, R., Sasselov D.D., Hernquist, L., Stewart, S. 2010, ApJ, 712, L73 Murray-Clay, R.A., Chiang, E.I., Murray, N. 2009, ApJ, 693, 23 Nago, A., & Nieto, A. 2011, JGR, vol. 2011, Article ID 239397, doi:10.1155/2011/239397 O. Grasset, J. Schneider, C. Sotin 2009, ApJ, 693, 722 Pearcy, R. W. & Ehleringer, J. 1984, Plant Cell Envir. 7, 1–13 Rauer, H. et al. 2011, A&A, 529, A8 Rogers, L. & Seager, S. 2010, ApJ, 716, 1208 Rugheimer et al. 2013, Astrobiology 133: 251-269 Rugheimer et al. 2013b, in prep Segura, A. et al. 2005, Astrobiology, 5, 706 Selsis, F. et al. 2007, A&A, 476, 1373

Snellen, I., et al. 2013, A&A, http://arxiv.org/abs/1208.4116 2013

Toon, O.B., McKay, C.P., Ackerman, T.P., Santhanam K. 1989, J. Geophys. Res. 94, 16287

Traub, W.A. & Stier, M.T. 1976, Applied Optics, 15, 364

Valencia, D., O'Connell, R.J., Sasselov D.D. 2007, ApJ, 665, 1413

Valencia, D., O'Connell, R.J., Sasselov, D.D. 2006, Icarus, 181, 545

vonParis, P., et al. 2013, A&A, arXiv:1301.0217v1

Youngjune Park, Do-Youn Kim , Jong-

Won Lee, Dae-Gee Huh, Keun-Pil Park,

Jaehyoung Lee , and Huen Lee , 2006, PNAS, 103, 12690

Zeng, L. & Sasselov, D.D. 2013, PASP, 2013arXiv1301.0818Z.

Zsom, A., Kaltenegger, L., Goldblatt, C. 2012, Icarus, 221, 603



**Fig.1.** Mass-radius plot showing Kepler-62*e* and -62*f* as presumed water planets (blue lozenges), compared to Venus, Earth, and transiting exoplanets. Kepler-69c ( $R_p$ =1.7 +0.34-0.23 $R_E$ ) is not shown due to its very large error bars. The curves are theoretical models (Li&Sasselov 2013); the dashed line the maximum mantle stripping limit (Marcus et al.2010).



**Fig.2.** Comparison of known transiting exoplanets with measured radii less than 2.5  $R_{\circ}$  in the HZ to the Solar System planets. The sizes of the circles indicate the relative sizes of the planets to each other. The dashed and the solid lines indicate the edges of the narrow and effective HZ, respectively (Kopparapu et al.2013).



**Fig.3.** Temperature and mixing ratios for  $H_2O$ ,  $O_3$  and  $CH_4$  for biotic and abiotic atmospheric models for water planets in the inner(top) and outer(bottom) part of the HZ (using planetary parameters for Kepler-62*e* and -62*f*).



**Fig.4.** Synthetic transmission spectra of atmospheric models for a hot(top) and cold(middle) water planet, using Kepler-62*e* and -62*f* parameters (see text), and the Earth in transit(bottom) for comparison.