The Astrophysical Journal Letters, 736:L25 (6pp), 2011 August 1 doi:10.1088/2041-8205/736/2/L25

EXPLORING THE HABITABLE ZONE FOR *KEPLER* PLANETARY CANDIDATES

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Received 2011 February 14; accepted 2011 May 23; published 2011 July 6

ABSTRACT

This Letter outlines a simple approach to evaluate habitability of terrestrial planets by assuming different types of planetary atmospheres and using corresponding model calculations. Our approach can be applied for current and future candidates provided by the *Kepler* mission and other searches. The resulting uncertainties and changes in the number of planetary candidates in the HZ for the *Kepler* 2011 February data release are discussed. To first order, the HZ depends on the effective stellar flux distribution in wavelength and time, the planet albedo, and greenhouse gas effects. We provide a simple set of parameters which can be used for evaluating future planet candidates from transit searches.

Key words: astrobiology – atmospheric effects – Earth – methods: data analysis – planets and satellites: general – stars: individual (Kepler)

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The *Kepler* mission recently announced 1235 planetary candidates (Borucki et al. 2011). We use atmospheric models to explore the potential for habitability of *Kepler* planetary candidates. Candidates with radii below 2 Earth radii are consistent with models of potentially rocky planets.

The habitable zone (HZ) concept was proposed for the first time by Huang (1959, 1960) and has been calculated by several authors after that (see, e.g., Rasool & DeBergh 1970; Hart 1979, 1978; Kasting et al. 1993; Selsis et al. 2007; Williams & Pollard 2002; Peña-Cabrera & Durand-Manterola 2004; Buccino et al. 2006; von Bloh et al. 2007; Spiegel et al. 2009). The main differences are in the climatic constraints imposed on the limits of the HZ by these studies. We focus on the circumstellar HZ that was defined by Kasting et al. (1993) as an annulus around a star where a planet with an atmosphere and a sufficiently large water content like Earth can host liquid water permanently on a solid surface. This definition of the HZ implies surface habitability because it is defined to allow remote detectability of life as we know it.

The two edges of the HZ are influenced by the relationship between the albedo of the planet and the effective temperature of the star (Figure 1). In this definition the inner edge of the HZ is defined as the location where the entire water reservoir can be vaporized by runaway greenhouse conditions, followed by the photo-dissociation of water vapor and subsequent escape of free hydrogen into space. The outer boundary is defined as the distance from the star where the maximum greenhouse effect fails to keep CO_2 from condensing permanently, leading to runaway glaciation.

Subsurface life that could exist on planets or moons with very different surface temperatures is not considered, because of the lack of atmospheric features that could be used to remotely assert habitability on such an object (Rosing 2005). We will not discuss the issue of life emerging in other solvents here.

Note that a planet found in the HZ is not necessarily habitable, since many factors may prevent habitability like the lack of water or ingredients necessary for the emergence of life (see, e.g., Zahnle et al. 2007; Selsis et al. 2007).

We outline how potential habitability can be evaluated for current and future candidates from the *Kepler* mission and other searches. We introduce the concept of the HZ in Section 2, discuss the influence of the main parameters in Section 3, and present our results—the difference in temperature of the recently announced *Kepler* planetary candidates and the location and extent of the HZ for these parameters—in Section 4. In Section 5 we discuss important additional uncertainties, and summarize our conclusions in Section 6.

2. THE DESCRIPTION OF THE HZ

Different aspects of what determines the boundaries of HZ have been discussed broadly in the literature. Our aim here is to focus on first-order effects and how they match the level of information and uncertainties for planets and planetary candidates from transiting searches, and in particular from the NASA *Kepler* mission. Therefore, we consider the smallest-size objects in the current *Kepler* sample with radii smaller than 2 Earth radii, because they could possess one of the types of atmospheres we will consider in our study. We assume that, if such planets are rocky, they could possess secondary atmospheres from outgassing that resemble Venus on the hot side and Mars on the cold side of the HZ, and ancient/current Earth near the middle. This range of atmosphere thicknesses and chemistries is sufficiently broad to illustrate the magnitude of the effects on the HZ boundaries

The planets we consider in the definition of the HZ have enough surface water—like Earth—to host liquid water for temperatures between 273 K and the critical temperature of water $T_c = 647$ K. Planets with less water will have a narrower HZ. In addition atmospheric CO_2 must accumulate in the planet's atmosphere when the mean surface temperature falls below 273 K. This is provided on a geologically active planet like Earth that continuously outgasses CO_2 and forms carbonates in the presence of surface water, by the carbonate–silicate cycle, which also stabilizes the long-term climate and atmospheric CO_2 content (Walker et al. 1981). The width and distance of HZ annulus—as well as the temperature—for an Earth-like planet depend to a first approximation on four main parameters:

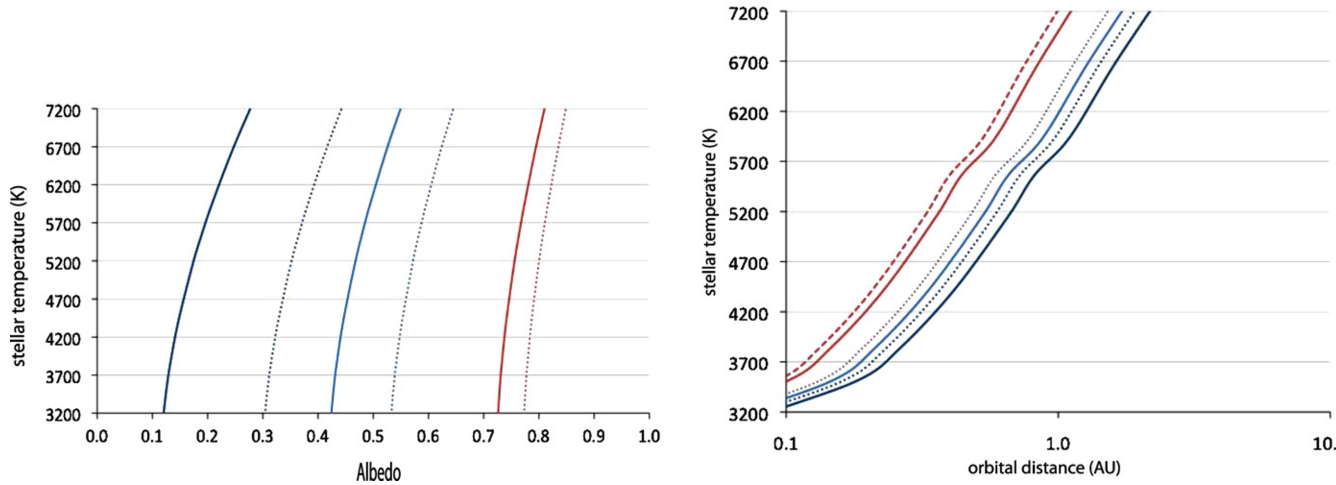

Figure 1. Left: maximum albedo at the inner edge of the HZ; right: the inner edge of the HZ for water loss (solid lines) and onset greenhouse (dashed lines) for 0%, 50%, and 100% cloud coverage.

(A color version of this figure is available in the online journal.)

(1) incident stellar flux which depends on stellar luminosity, spectral energy distribution, and eccentricity of the system; (2) planetary albedo; (3) greenhouse gas concentration; and (4) energy distribution in the planetary atmosphere.

3. INFLUENCE OF THE MAIN PARAMETERS ON THE HZ

The simpler calculation of the equilibrium temperature T_{eq} is often used to determine habitable candidates. It is based on the assumption that the planet radiates as a gray body, i.e., it does not have an atmosphere (see, e.g., Borucki et al. 2011). The stellar flux absorbed and radiated by the planet are given in Equations (1) and (2), respectively:

$$F = (1 - A)\pi r_{\mathrm{pl}}^2 \sigma T_{\mathrm{star}}^4 4\pi \mathrm{r}_{\mathrm{star}}^2 / (4\pi D^2) \tag{1}$$

$$f = \beta 4\pi r_{\mathrm{pl}}^2 \sigma T_{\mathrm{eq\_pl}}^4, \tag{2}$$

where σ is the Stefan–Boltzmann constant, r is the radius, T is the temperature, A is the Bond albedo of the planet, D is the planet's semimajor axis, and β represents the fraction of the planetary surface that reradiates the absorbed flux. The parameter β has extremes of 1–0.5, where for 1 the incident energy is uniformly reradiated by the entire surface of the planet (e.g., for a rapidly rotating planet with an atmosphere, like Earth), and 0.5, where only half of the planet surface is involved in the reradiation, as for a tidally locked, synchronous rotating planet without an atmosphere. One could use a generic emissivity factor in the divisor of Equation (1) to mimic atmospheric warming. We include the greenhouse effect in the atmosphere directly in our calculations (see, Equation (6) and Figure 1). By setting $f = F$, the equilibrium temperature $T_{\mathrm{eq\_pl}}$ of a planet is given by

$$T_{\mathrm{eq\_pl}} = T_{\mathrm{star}} \left((1 - A)\, r_{\mathrm{star}}^2 / 4\beta D^2\right)^{1/4}. \tag{3}$$

The uncertainties in deriving $dT_{\mathrm{eq\_pl}}$ (called dT_{pl} hereafter) are discussed in Section 5. Note that for a planet with a dense atmosphere, like Earth, T_{eq} does not indicate any physical temperature at the surface or in the atmosphere. T_{eq} has to be below 270 K for the planet to be habitable. As discussed in detail in Selsis et al. (2007), if the surface temperature of a habitable planet stays below the T_{c} of water, the thermal emission of the planet cannot exceed the greenhouse threshold of about 300 W m^{-2} which corresponds to a blackbody radiating at 270 K. A planet radiating above 270 K either has a $T_{\mathrm{surf}} < T_{\mathrm{crit}}$, but no liquid water on its surface, or a considerable amount of water and a $T_{\mathrm{surf}} > 1400$ K, which allows the planet to balance the absorbed stellar radiation by radiating in the visible and radio wavelength where water opacity is negligible. Both cases are not habitable for life as we know it. We set the outer limit of the HZ to $T_{\mathrm{eq}} < 175$ K here, which corresponds to a planet at 2.4 AU in the present solar system. Note that these values could be even lower due to selective cloud coverage.

We consider three models of Earth-like planets to calculate the edges of the HZ: high CO_2, current-Earth, or high H_2O atmospheres, for stars with effective temperatures between 3700 K and 7200 K. These models, representing a planet on the outer, middle, and inner edges of the HZ, derive the limits for the HZ, l_{in} and l_{out}, given in Equations (4) and (5) (Kasting et al. 1993; Selsis et al. 2007):

$$l_{\mathrm{in}} = \left(l_{\mathrm{in\_sun}} - a_{\mathrm{in}} T_{\mathrm{star}} - b_{\mathrm{in}} T_{\mathrm{star}}^2\right) (L/L_{\mathrm{sun}})^{1/2} \tag{4}$$

$$l_{\mathrm{out}} = \left(l_{\mathrm{out\_sun}} - a_{\mathrm{out}} T_{\mathrm{star}} - b_{\mathrm{out}} T_{\mathrm{star}}^2\right) (L/L_{\mathrm{sun}})^{1/2}, \tag{5}$$

with $a_{\mathrm{in}} = 2.7619 \times 10^{-5}$, $b_{\mathrm{in}} = 3.8095 \times 10^{-9}$, $a_{\mathrm{out}} = 1.3786 \times 10^{-4}$, $b_{\mathrm{out}} = 1.4286 \times 10^{-9}$, and $T_{\mathrm{Star}} = T_{\mathrm{eff}} - 5700$, l_{in} and l_{out} in AU, and T_{eff} in K.

Depending on the fractional cloud cover, the theoretical outer edge of the HZ for our Sun occurs between 1.67 AU in the cloud-free limit, 1.95 AU and 2.4 AU for 50% and 100% cloud cover, respectively (for more details on cloud effects on the HZ see, e.g., Forget & Pierrehumbert 1997; Mischna et al. 2000; von Paris et al. 2008; Wordsworth et al. 2010; Kitzmann et al. 2010). Note that the water-loss limit for $T_{\mathrm{surf}} = 373$ K for the 50% cloud case corresponds to the "Venus water loss limit," empirically derived from the position of Venus in our solar system (0.72 AU).

Here, we use the limits of the current HZ of our solar system assuming 0%, 50%, and 100% cloud coverage that gives l_{in} as 0.84–0.95, 0.68–0.76, and 0.46–0.51 and l_{out} as 1.67, 1.95, and

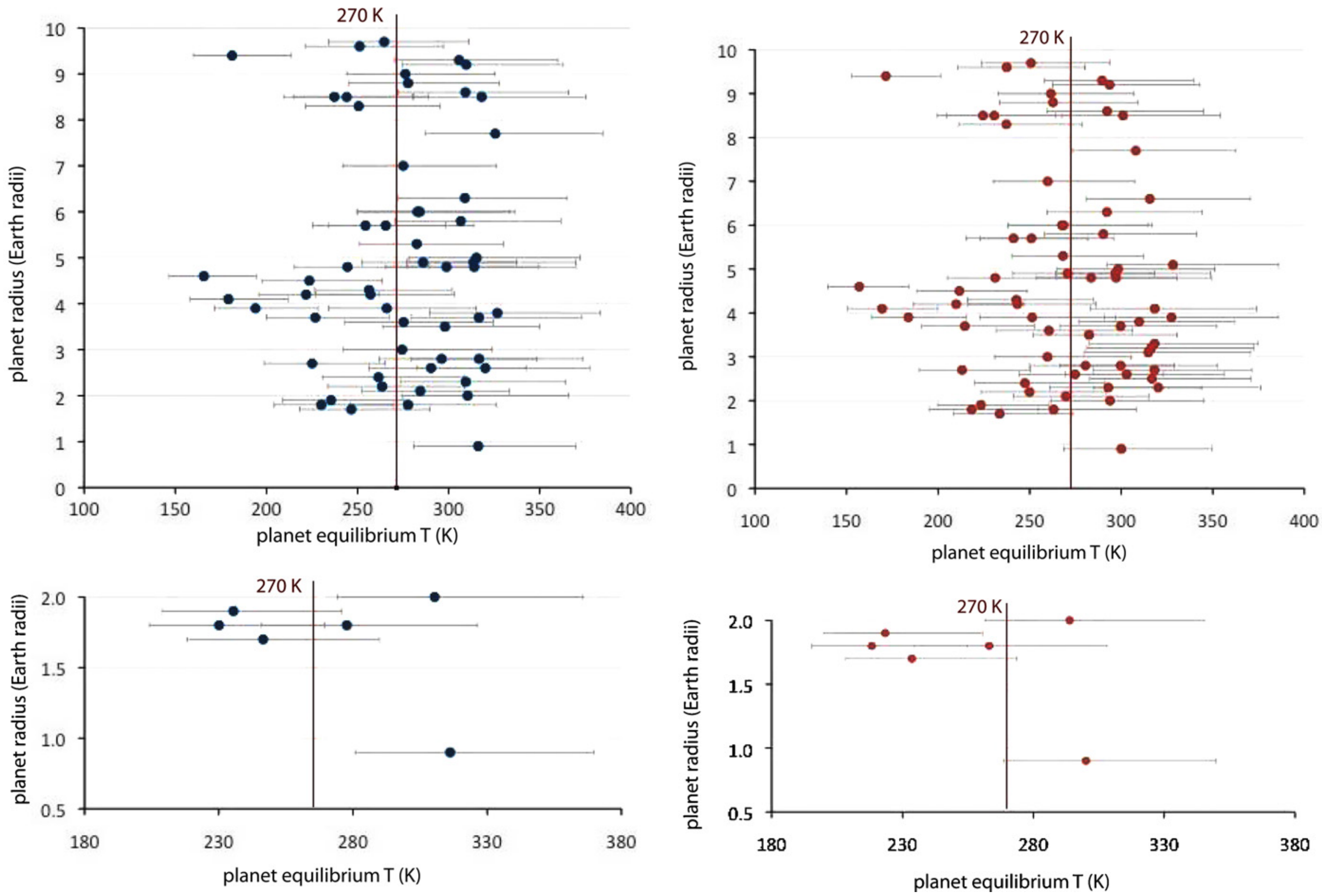

Figure 2. Minimum equilibrium temperature of the *Kepler* planet candidates' (left) water loss limit and onset greenhouse (right) for 50% cloud coverage. Error bars indicate 0% and 100% cloud cover, the line indicates 270 K. Details for the six potentially rocky planets (lower panel).

(A color version of this figure is available in the online journal.)

2.4, respectively (see Kasting et al. 1993; Selsis et al. 2007). The two values quoted for l_{in} represent the runaway greenhouse and the water loss limit ($T_{surf} = 373$ K), for the inner limit of the HZ. Note that the effect of the spectral type on the albedo (see Figure 1) was estimated for a cloud-free atmosphere, therefore the 100% cloud value is used here to explore the effect of clouds on the HZ (dashed lines).

The T_{surf} sets the surface vapor pressure, especially on the inner edge of the HZ, where most of the *Kepler* candidates are found (see Figures 2 and 3). The water vapor in turn affects T_{surf} because it blocks the outgoing IR radiation and reduces the atmospheric laps rate. It initially decreases the planet's albedo by absorbing stellar NIR radiation. For $T_{surf} > 373$ K and surface vapor pressure above 1 bar, the bond albedo increases, due to the strong Rayleigh backscattering in the visible and the saturation of the NIR water absorption bands. The bond albedo decreases with decrease in stellar temperature because of the redshift of the stellar spectrum that deposits most of the stellar flux onto the planet's atmosphere at wavelength longward of the highly reflective Rayleigh scattering regime (see Figure 1).

4. RESULTS

To simply estimate if a planet is potentially habitable (175 K $< T_{eq} <$ 270 K), one can use Equation (6) to approximate T_{eq} for Earth-like planets around different stars using albedo from Figure 1. Equation (6) also includes the effect of eccentricity (Williams & Pollard 2002), note that for a rapid rotating planet β should be set to 1 (see the discussion):

$$T_{eq} = T_{star}\left((1-A)r_{star}^2 \big/ (4\beta D^2(1-e^2)^{1/2})\right)^{1/4}. \qquad (6)$$

Assuming circular orbits and 50% cloud coverage in accordance to the "Venus water loss limit" leads to 27 *Kepler* planetary candidates with 175 K $< T_{eq} <$ 270 K. Among those are three planetary candidates that have radii smaller than 2 Earth radii (Table 1). The biggest change in T_{pl} results from the change of albedo of the planets depending on the cloud coverage (see Figure 1) which maintains 12 and 2 potentially rocky planets for a clear atmosphere and 67 and 4 potentially rocky planetary candidates for 100% cloud coverage, respectively. Eccentricity only has a very small effect on the temperature of the planet, an eccentricity of 0.2 and 0.6 results in an average incident stellar flux increase of 2% and 25%, respectively, but only a difference of 2–10 deg on T_{pl}.

Figure 1 shows the maximum albedo at the inner edge of the HZ (left) and the inner edge of the HZ for water loss (solid lines) and onset greenhouse (dashed lines) for 0%, 50%, and 100% cloud coverage for main-sequence stars from 3700 K to 7200 K derived from Equation (4). 1223 of the 1235 stars that host planetary candidates in the *Kepler* data release have temperatures above 3700 K. Using the maximum and minimum albedo values at the inner and outer edges of the HZ, respectively, and (Equation (6)), one can calculate a minimum T_{eq} for a planetary candidate to assess habitability. Table 1 and Figure 2 show the minimum T_{eq} derived for 0%,

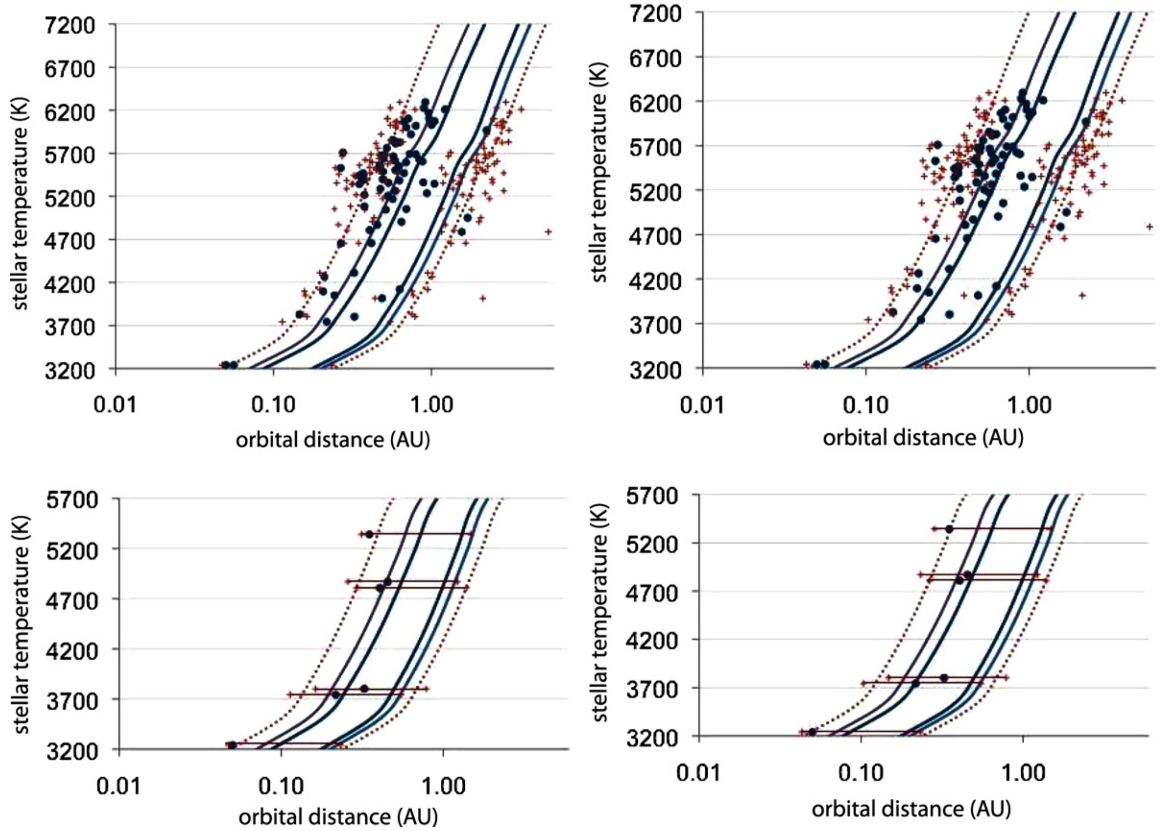

Figure 3. Extent of the HZ for (left) water loss limit for 0% and 50% cloud coverage (inner limits) and 100% cloud coverage (outer limit dashed line), (right) runaway greenhouse onset and position of potentially habitable *Kepler* planetary candidates in the HZ, individual HZ limits are indicated with crosses. Details for the six potentially rocky planets (lower panel).

(A color version of this figure is available in the online journal.)

Table 1

Characteristics of the Potentially Rocky Habitable *Kepler* Planetary Candidates (KOI, $R_{\rm pl}$, Period, $T_{\rm eff}$, $R_{\rm star}$, $T_{\rm eq}$) for 0%, 50%, and 100% Clouds

KOI	$R_{\rm pl}$	D	$T_{\rm eff}$	$R_{\rm star}$	$T_{\rm eq}$	$T_{\rm eq}$ (K) Water Loss			$T_{\rm eq}$ (K) Runaway GH		
		(AU)	(K)		Kepler	0%	50%	100%	0%	50%	100%
1026.01	1.8	0.325	3802	0.68	243	256	230	191	241	218	182
854.01	1.9	0.217	3743	0.49	248	262	235	195	247	223	186
701.03	1.7	0.454	4869	0.68	263	275	247	203	259	234	194
268.01	1.8	0.406	4808	0.79	296	310	278	229	292	263	218
326.01	0.9	0.05	3240	0.27	332	352	316	263	332	300	250
70.03	2	0.35	5342	0.7	333	347	310	255	326	294	243
314.02	1.6	0.128	3900	0.61	375	396	356	295	373	338	281
518.02	1.9	0.23	4822	0.76	387	405	363	299	381	344	285
494.01	1.8	0.157	4854	0.52	390	408	366	302	384	346	287
1263.01	2	0.182	4007	0.9	393	414	372	308	390	353	294
899.03	1.7	0.091	3653	0.55	396	418	376	312	395	357	298
504.01	1.7	0.228	5403	0.68	412	428	383	315	402	363	299
446.02	1.7	0.164	4492	0.7	409	430	386	319	405	366	304
1281.01	2	0.265	5546	0.82	430	446	400	328	420	378	312
1591.01	1.5	0.134	5130	0.49	433	451	404	333	425	383	317
148.03	2	0.235	5063	0.89	435	454	407	335	427	385	319
663.02	1.7	0.124	4156	0.7	435	459	412	341	432	391	325
718.03	1.5	0.261	5801	0.78	442	457	409	335	430	387	318
560.01	1.8	0.154	5142	0.59	444	463	415	342	436	393	325
486.01	1.4	0.152	5625	0.51	454	471	421	346	443	399	328
1435.01	1.7	0.234	5744	0.75	454	469	420	344	441	397	327

50%, and 100% cloud coverage using the maximum albedo for Earth-like planets and indicates which rocky planets or satellites could have $T_{\rm eq} < 270$ K.

Table 2 and Figure 3 show the limits of the HZ for 0%, 50%, and 100% cloud coverage for all *Kepler* candidates that could be rocky and potentially be habitable. Note that the HZ is only

Table 2
Two Inner Limits and Outer Limit of the HZ for *Kepler* Planetary Candidates in the HZ of Their Stars for 0%, 50%, and 100% Clouds, Sorted by T_{eq}

KOI	R_{pl}	D	T_{eff}	R_{star}	HZ_{in} Cloud: 0%		HZ_{out}	HZ_{in} Cloud: 50%		HZ_{out}	HZ_{in} Cloud: 100%		HZ_{out}
99.01	4.6	1.693	4951	1.11	0.70	0.79	1.46	0.57	0.64	1.69	0.39	0.43	2.05
1439.01	4.1	2.235	5967	1.22	1.09	1.23	2.14	0.88	0.98	2.51	0.59	0.66	3.10
1477.01	9.4	1.044	5346	0.71	0.52	0.59	1.05	0.42	0.47	1.22	0.29	0.32	1.50
868.01	12.5	0.629	4118	0.71	0.32	0.36	0.68	0.26	0.29	0.79	0.18	0.20	0.95
881.02	3.9	0.693	5053	0.6	0.39	0.45	0.81	0.32	0.36	0.94	0.22	0.24	1.15
683.01	4.2	0.839	5624	0.78	0.63	0.71	1.25	0.51	0.57	1.46	0.34	0.38	1.79
1582.01	4.5	0.626	5384	0.64	0.47	0.53	0.96	0.38	0.43	1.12	0.26	0.29	1.37
1503.01	2.7	0.535	5356	0.56	0.41	0.46	0.83	0.33	0.37	0.97	0.23	0.25	1.19
1099.01	3.7	0.573	5665	0.55	0.45	0.51	0.89	0.36	0.40	1.04	0.25	0.27	1.28
433.02	13.4	0.935	5237	1.08	0.76	0.86	1.55	0.62	0.69	1.80	0.42	0.47	2.20

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

defined for rocky planets, the focus of our search for habitable conditions.

Applying our analysis to the whole *Kepler* planetary sample of 1235 transiting planetary candidates, assuming the maximum Earth-like Bond albedo at the inner edge of the HZ, results in 12, 27, 67 planetary candidates with T_{eq} smaller than the water evaporation limit for 0%, 50%, and 100% clouds, as well as 18, 43, 76 with T_{eq} lower than the runaway greenhouse limit, respectively. Among those 2, 3, 6 as well as 3, 4, 6 planets, respectively, have radii below 2 Earth radii, consistent with rocky planets (KOI1026.01, 854.01, 701.03, 268.01, 326.01, 70.03). Note that two planets KOI771.01 and KOI99.01 lie outside the outer edge of the HZ for 0% and KOI771.01 outside even for 100% cloud coverage. Many of the 54 planetary candidates announced in the *Kepler* sample as in the HZ based on simple calculations are with more detailed study (Table 2) outside the HZ of their host stars because T_{eq} is above 270 K.

Figure 3 shows that the individual stellar parameters need to be taken into account to determine the limits of the HZ. For several *Kepler* planetary candidates the nominal (line) and individual (crosses) stellar limits of the HZ differ (solid lines for 0%, 50% and dashed line for 100% cloud coverage) (see Equations (4) and (5)). In the nominal calculations the radius of the host star is generally derived from stellar models for a stellar temperature. Using real stellar parameters changes the stellar luminosity and therefore T_{pl} and the limits of the HZ (crosses) as seen in Figure 3, e.g., for KOI 701.03 and KOI 268.01.

The location of the *Kepler* planets is consistent with our expectations to find hot small planets first and cooler ones when further *Kepler* data and thus planets in larger orbits are available.

5. DISCUSSION

The biggest uncertainty in dT_{pl} is due to uncertainties in the stellar parameters (Brown et al. 2011; Borucki et al. 2011). For the *Kepler* sample these values are on average $dT_{star}/T_{star} = 3.6\%$, $dr_{star}/r_{star} = 25\%$, distance D (assuming negligible uncertainty in the orbital periods) is given by $dD \approx dM_{star}/3M_{star}$ where dM_{star} is about 25%. Using $dT_{pl}/T_{pl} = dT_{star}/T_{star}$, $dT_{pl}/T_{pl} = dr_{star}/2r_{star}$, and $dT_{pl}/T_{pl} = dD/2D$ results in 3.6%, 12.5%, and 4%, respectively. These errors influence the limits of the HZ substantially as seen in Figure 3 and could explain the difference between some of the nominal and individual stellar limits of the derived HZ. The uncertainty of dT_{pl}/T_{pl} based on planetary parameters is 12.5% due to uncertainties in β (here assumed to be 0.75 ± 0.25) and a maximum of 12% due to the range of Bond albedos for the water loss limit and 18% for the greenhouse onset limit (see Figure 1) using $dT_{pl}/T_{pl} = d\beta/4\beta$ and $dT_{pl}/T_{pl} = dA/4(1-A)$. This leads to an accumulated error of 20%–24% in the estimate of the T_{pl} for the water loss limit and greenhouse onset, respectively (consistent with the 22% Borucki et al. 2011).

Table 2 shows the complete sample of planetary candidates that could be in the HZ assuming the error reduces or increases T_{pl} by 22%. Assuming the error decreases T_{eq}, the number of planetary candidates in the water loss HZ increases the number of planetary candidates from 12, 27, 67 to 45, 67, 124, while it decreases to 4, 5, 19 assuming the error increases T_{pl} by 22% for 0%, 50%, and 100% clouds, respectively. The number of small, potentially rocky planets in that sample (Table 1) changes from 2, 3, and 6 to 3, 4, and 14 planetary candidates assuming the error reduces T_{pl} (KOI 1026.01, 854.01, 701.03, 268.01, 326.01, 70.03, 314.02, 518.02, 494.01, 1263.01, 899.03, 504.01, 446.02, 1281.01) and to 0, 0, 3 for an increase in T_{pl} by 22%, respectively (see Tables 1 and 2) for 0%, 50%, and 100% clouds, respectively.

The HZ does not apply to gas planets, but would apply to rocky satellites that could potentially be detected in the *Kepler* data (see, e.g., Kaltenegger 2010; Kipping et al. 2009). A detailed discussion of limits of habitability of exomoons is presented in Williams et al. (1997). Using the most extreme limits for the inner edge of the HZ—empirically determined by the current flux at Venus' orbit, which is about 30% higher than the initial flux at Venus' orbit—would result in 41 planets in the HZ with T_{eq} between 175 K and 307 K, four of those have radii consistent with a rocky planet (KOI701.03, 1026.01, 268.01, and 854.01).

Due to the close orbit of the planetary candidates to their star, tidal locking can be explored using the reradiation parameter β. However detailed models for Earth have shown that even for planets in synchronous rotation, direct illumination of only one hemisphere does not prevent habitability for planets with even modestly dense atmospheres (Haberle et al. 1996; Joshi et al. 1997; Joshi 2003; Edson et al. 2011; Wordsworth et al. 2010; Heng et al. 2011), provided atmospheric cycles transport heat from the day side to the night side. Therefore the limits of the HZ are unlikely to change significantly due to synchronous rotation for Earth-like planets.

6. CONCLUSIONS

The NASA *Kepler* mission recently announced 1235 planetary candidates. We use atmospheric models to explore the potential for habitability of *Kepler* planetary candidates. Tables 1 and 2 and Figures 2 and 3 show the temperature as well as the extent of the HZ for the *Kepler* planetary candidates that could potentially be habitable.

The three main points of this Letter are (1) to provide a simple approximation (Equation (6)) for habitability of Earth-like planets from the data provided by transit surveys like *Kepler* (using maximum albedo values from atmospheric models Figure 1) to assess their potential as a habitat, (2) to demonstrate that one needs to consider the individual stellar parameters to determine the limits of the HZ, and (3) to explore the change in the sample located in the HZ due to individual factors in Equation (6) and associated errors. Many of the 54 planetary candidates announced in the *Kepler* sample in the HZ, based on simple calculations, are—with a more detailed study, outside the HZ of their host stars, because T_{eq} is above 270 K (see Table 1 for all potentially rocky planets).

Applying our analysis to the whole *Kepler* planetary sample of 1235 transiting planetary candidates, assuming the maximum Earth-like Bond albedo for rocky planet atmospheres (see Figure 1, Table 2), results in 12, 27, and 67 planetary candidates with T_{eq} smaller than the water loss limit ($T_{\mathrm{surf}} = 373$ K) for 0%, 50%, and 100% clouds, respectively, and 18, 43, and 76 planetary candidates with temperatures lower than the runaway greenhouse limit, respectively. Among those are 2, 3, 6 as well as 3, 4, 6 planets, respectively, that have radii below 2 Earth radii consistent with rocky planets (KOI1026.01, 854.01, 701.03, 268.01, 326.01, 70.03).

The potentially rocky planet candidates in multiple systems in the *Kepler* 2011 February data release, KOI701.3 and KOI70.3, are extremely interesting objects because their mass could be determined using transit time variations to calculate a mean density and potentially confirm high density and rocky characteristics (Table 1). Assuming errors will reduce T_{eq} (see the discussion) KOI314.02, 899.03, 446.02, 518.02, and 70.03 are also part of that sample.

Note that even if these small planetary candidates can be confirmed to have a mean density consistent with a rocky composition, many aspects can prevent a planet in the HZ from being habitable, e.g., limited amount of water or other ingredients essential for life. Therefore the atmosphere of planets has to be characterized to explore if the planet is a potential habitat or shows signs of life.

Due to the large average distance of 500–1000 pc to its target stars, *Kepler*'s results can only provide statistics of the amount of planets per star. That, as well as the increasing number of small potentially rocky planets shown by the new *Kepler* results, strengthens the scientific case for a mission to find and characterize such small planets orbiting stars close to our Sun.

We are grateful to Jim Kasting and Franck Selsis for comments and discussion. L.K. acknowledges support from NAI and DFG funding ENP Ka 3142/1-1.

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