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W. Ludwig, S. Eggl, D. Neubauer, J. Leitner, M. Firneis, et al.. Effective stellar flux calculations for limits of life-supporting zones of exoplanets. *Monthly Notices of the Royal Astronomical Society*, 2016, 458 (4), pp.3752-3759. <10.1093/mnras/stw509>. <hal-02320098>

HAL Id: hal-02320098

<https://hal.science/hal-02320098v1>

Submitted on 9 Sep 2021

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Effective stellar flux calculations for limits of life-supporting zones of exoplanets

W. Ludwig,^{1★} S. Ettl,^{2★} D. Neubauer,^{1,3} J. Leitner,^{1,4} M. G. Firneis^{1,4}
and R. Hitznerberger^{1,5}

¹University of Vienna, Research Platform ExoLife, Boltzmannngasse 5, A-1090 Vienna, Austria

²IMCCE, Observatoire de Paris, 77 Avenue Denfert-Rochereau, F-75014 Paris, France

³Institute for Atmospheric and Climate Science, ETH Zuerich, Universitaetstrasse 16, CH-8092 Zuerich, Switzerland

⁴Institute for Astrophysics, University of Vienna, Tuerkenschanzstrasse 17, A-1180 Vienna, Austria

⁵Faculty of Physics, University of Vienna, Boltzmannngasse 5, A-1090 Vienna, Austria

Accepted 2016 February 23. Received 2016 February 10; in original form 2015 August 6

ABSTRACT

Habitable zones (HZ) are key concepts in the quest for finding extrasolar planets that may host life as we know it. HZs encompass regions around a star that would allow for liquid water to be present on the surface of a rocky planet. However, water may not be the only solvent capable of producing and sustaining biospheres, so the concept of life-supporting zones (LSZs) was introduced as a generalization of the classical HZ for a broader range of solvents. The aim of this work is to offer a straightforward means of calculating LSZs similar to those presented by Kopparapu et al. for the HZ. We used a 1D radiative convective model to determine LSZ limits for water/ammonia mixtures and sulphuric acid. A simplified cloud model was used for offline sulphuric acid cloud simulation. Water clouds were accounted for by variations of surface albedo values. Compared to recently updated results by Kopparapu et al., our results lie well within the uncertainty range of the Toon algorithm for flux calculations. We found an inner limit of the LSZ closer and an outer limit further away from the star than the limits for the HZ would be. Recently discovered exoplanets (like Kepler 452-b) are shown to be positioned very well in the LSZ. The concept of LSZs adds additional perspectives to an exoplanet's ability to maintain life on its surface.

Key words: astrobiology – radiative transfer.

1 INTRODUCTION

The classical habitable zone (HZ) encompasses the region around a star that would allow for liquid water to be present on the surface of a terrestrial planet (e.g. Kasting, Whitmire & Reynolds 1993; Kopparapu et al. 2013) or Selsis et al. (2007). Wolf & Toon (2014) presented a summary of recent research data in connection with HZ calculations. The concept of water-based HZ was recently expanded by Neubauer et al. (2011) to include the presence of various other liquid solvents resulting in the concept of life-supporting zones (LSZs). The capacity for solvents other than water to support life has been investigated by Schulze-Makuch & Irwin (2004, 2006), Benner, Ricardo & Carrigan (2004) and Leitner et al. (2012). Life based on cryosolvents like methane is not considered impossible (McKay & Smith 2005), although habitats with very low temperatures would be needed, which are beyond the scope of our model at the moment. Laboratory experiments have been conducted on

the possible formation of amino acids in water/ammonia solutions (Turse et al. 2013) with promising results.

The extent of an LSZ depends on the physical and chemical properties of the basic solvent, as well as on planetary properties such as mass and atmospheric density and composition, which determine limits of surface temperatures that keep solvents in the liquid phase and prevent atmospheric gases from escaping into space. Effective insolation values ($S_{\text{eff}} = S/S_0$) are commonly used to characterize limits of HZs or LSZs. Here S and S_0 are the incident flux on the exoplanet and the flux incident on Earth, respectively. Since boiling and freezing points differ for various solvents, critical flux limits for the LSZ of these solvents have to be evaluated individually. Our goal is to further establish the concept of LSZs by presenting new estimates for critical stellar fluxes, which can easily be used to determine LSZ borders. The corresponding model is presented in Section 2 and its results are compared with results by Kopparapu et al. (2014), who used updated absorption spectra for H₂O and CO₂, which resulted in an inner limit of the water-based HZ further away from the star than in earlier studies of the HZ.

The goal of the present study is to calculate limits of the LSZ for solvents other than water, to provide fit parameters for the effective

* E-mail: wolfgang.ludwig@univie.ac.at (WL); siegfried.eggl@obspm.fr (SE)

insolation limits as a function of the stellar effective temperatures and to apply the model results to recently discovered possibly habitable planets. Section 3 provides discussion and summary of our data.

2 THE RADIATIVE CONVECTIVE MODEL

Similar to Kopparapu et al. (2014), we use a 1D radiative convective computational model (RCM), see Neubauer et al. (2011), to calculate effective flux limits. LSZ calculations have been done before with the present model for virtual exoplanets and some Kepler candidates assuming CO₂ atmospheres with a range of fixed stellar distances and variations in stellar and planetary properties (Neubauer et al. 2013). Our code is based on a modified version of the public domain software *STREAMER* (Key & Schweiger 1998). Radiative equations are solved using the two-stream algorithm by Toon et al. (1989). The correlated-k method is applied to calculate absorption coefficients (Fu & Liou 1992). The corresponding molecular data were obtained from the HITRAN 2008 data base and integrated using the programs *KSPECTRUM* and *KDISTRIBUTION*.¹

2.1 Model input

Luminosities, radii and effective temperatures for typical stars on the main sequence were obtained from Boyajian et al. (2012a,b). The stellar properties were used to calculate Planck spectra and derive intensities for the relevant *STREAMER* wavelength bands. Additional spectra were obtained from the Virtual Planetary Laboratory² (Segura et al. 2003, 2005). Atmospheric gas absorption coefficients in the Earth-like and CO₂-dominated atmospheres were calculated using the correlated-k method (Fu & Liou 1992). The effect of clouds in Earth-like atmospheres was simulated by increasing the planet's surface albedo (to about 0.22). The same method was used by Haqq-Misra et al. (2008), Ramirez et al. (2014) or Kopparapu et al. (2014).

Convective adjustment was done according to Manabe & Strickler (1964) and Manabe & Wetherald (1967) for CO₂-dominated atmospheres and according to Kasting (1988) for Earth-like atmospheres. Leconte et al. (2013) were able to show that the flux limit for Earth-like atmospheres can be much higher than previously assumed in 1D calculations, they calculated mean surface temperatures using a 3D model of the planet and showed that the best agreement with 1D results was achieved by setting relative humidity to constant values of 45 per cent in the 1D case for the inner HZ limit. We followed this suggestion in our calculations.

In our model, we assumed Earth-like rotation rates, which means that the incoming solar energy is distributed evenly over the planet's surface (i.e. the mean incident flux can be taken as a fourth of the total incoming flux). The inner flux limit for tidally locked planets (Yang, Cowan & Abbot 2013) and for planets with slower rotation rates than Earth (Yang et al. 2014) could be even higher due to an increased albedo effect. There are no suggestions on how to correct for these feedback albedo effects in 1D models. For comparison to effective flux limits calculated with our 1D model for planets with Earth-like atmospheres, the increased inner limit due to these 3D effects (Yang et al. 2014) is added in Fig. 3.

¹ Documentation and program codes available at <https://www.openhub.net/p/kspectrum>.

² <http://depts.washington.edu/naivpl/content/welcome-virtual-planetary-laboratory>

Table 1. Solvents selected for our model scenarios.

| Solvent | Water | Water/Ammonia 15 per cent wt | Sulphuric acid |
|------------------------|-------|---------------------------------|-------------------|
| Freezing point (1 atm) | 273 K | 250 K | 283 K |
| Boiling point (1 atm) | 373 K | 373 K | 563 K |

On the other hand, absorption and scattering by water vapour gets less significant in the atmosphere as the planet's outer zone distance from its parent star reaches the critical value for maintaining surface water in the liquid phase, because water vapour pressure decreases with decreasing temperatures and is relatively low at 273 K. For the Venus-like atmospheric scenario with H₂SO₄ clouds (VL), absorption coefficients of atmospheric gases were computed with the exponential-sum fitting of transmissions method (ESFT), by Wiscombe & Evans (1977) and transmission functions computed with *LOWTRAN 7* (Kneizys et al. 1988). Because of the restricted validity of the absorption coefficients in terms of temperature and pressure, an atmospheric surface pressure of 1013.25 mbar was assumed for this scenario. Apart from the lower surface pressure, the atmospheric composition is similar to Venus: 96.5 per cent CO₂, 3.5 per cent N₂, 0.015 per cent SO₂, 0.002 per cent water vapour and 0.0017 per cent CO; see Basilevsky & Head (2003) and Titov et al. (2007). The clouds in the VL scenario are simplified but retain the optical properties of the main clouds in Venus' atmosphere. A single layer cloud that consists of H₂SO₄-droplets (with a liquid H₂SO₄ mixing ratio of 5 mg m⁻³) is inserted between 180 and 430 mbar with a cloud optical thickness of 6.0. The optical properties of these H₂SO₄-droplets are computed offline with a cloud parcel model and a Mie theory code (Bohren & Huffman 1983). The cloud parcel model was initialized with conditions typical for the base of the main cloud deck on Venus and the gaseous H₂SO₄ mixing ratio was assumed to increase with altitude as in the atmosphere of Venus (for details, see Neubauer et al. 2012).

For CO₂-dominated atmospheres or for atmospheres with sulphuric acid clouds like on Venus, no calculations similar to those of Yang et al. (2013) or Yang et al. (2014) for slowly rotating or tidally locked planets with Earth-like atmospheres were performed in this study. We used the same planetary mass–radius relation as Kopparapu et al. (2014) to scale background gas pressure of planets more massive than Earth. Kopparapu et al. (2014) assumed that planets with masses greater than 5 M_⊕ would not be rocky anymore (M_⊕ designates the mass of Earth). Below that mass limit, they used the following equation to estimate background pressure values for super Earths:

$$P_s = P_s^0 0.937 \left(\frac{R_p}{R_0} \right)^{2.40}, \quad (1)$$

where P_s and P_s^0 are the pressure values of planets more massive than Earth and of planets with an Earth-like mass, respectively. R_p and R_0 are the corresponding radii. The solvents used in our scenarios are listed in Table 1. Sulphuric acid and ammonia have been proposed as a possible solvent by Giles et al. (2003) or Bains (2004) since they are present, for instance, in Venusian clouds or possibly in subsurface oceans (Hussmann, Sohl & Spohn 2006). Schulze-Makuch & Irwin (2006), for example, discussed the life-supporting abilities of these solvents.

Effective fluxes were calculated via quadratic fitting using equation (2).

$$S_{\text{eff},0} = S_0 + at + bt^2, \quad (2)$$

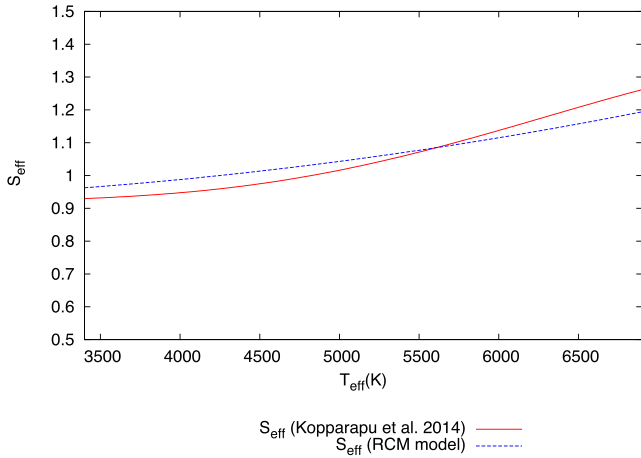


Figure 1. Comparison of effective fluxes calculated with the Kopparapu (Kopparapu et al. 2014) and our RCM models over a range of effective stellar temperatures.

with $t = T_{\text{eff}} - 5778 \text{ K}$, T_{eff} being the star temperature the effective flux is calculated for, with fit parameters S_0 , a and b . LSZ limits in astronomical units can be obtained via equation (3) (see also Kopparapu et al. 2014),

$$d = \sqrt{\left(\frac{L}{L_{\text{Sun}} \times S_{\text{eff}}}\right)} \text{ au}, \quad (3)$$

L and L_{sun} designating star's and Sun's luminosity.

2.2 Model comparison

We compared our data for water as a solvent with the results obtained by Kopparapu et al. (2014). Fig. 1 contains a comparison of effective fluxes calculated with both models. Additionally, Table 2 shows values calculated with both models for different star types, covering stellar effective temperatures from 3400 to 6900 K. The maximum difference is about 5.6 per cent in calculations of effective flux limits, which is well within the 0 per cent to 10 per cent range of uncertainty generally assumed for the two-stream algorithm (Toon et al. 1989). Differences in HZ limit distances from the star are below 2 per cent for most of the effective temperature range, exceeding to 2.7 per cent for over 6500 K stars. Those differences are small, and because of the good agreement of our calculations and the Kopparapu et al. model for the water-based HZ, we apply our model to generate limits of LSZs.

Table 2. Comparison between the model by Kopparapu et al. (2014) and our model. The first column shows the effective star temperature of some sample stars data taken from Boyajian et al. (2012a,b) and Segura et al. (2003, 2005). The next two columns give the calculated effective fluxes for the inner limit of the water habitable zone for the Kopparapu model and our radiative convective model (RCM) respectively, followed by the relative distance in per cent, the inner zone limits of the water habitable zone in units of au for the Kopparapu model and our RCM model are given in the next two columns, followed by the per cent difference. Our data were obtained by calculating fluxes with a constant atmospheric relative humidity of 45 per cent for the inner water habitable zone. Astronomical units were calculated via equation (3). A graphical comparison of effective fluxes can be seen in Fig. 1.

| $T_{\text{eff}} \text{ (K)}$ | $S_{\text{eff}} \text{ Kopp.}$ | $S_{\text{eff}} \text{ REM}$ | per cent diff | Kopp. (au) | Rcm (au) | per cent diff |
|------------------------------|--------------------------------|------------------------------|-----------------|------------|----------|-----------------|
| 3400 | 0.929 | 0.963 | 3.43 per cent | 0.157 | 0.154 | − 1.76 per cent |
| 4780 | 0.996 | 1.029 | 3.24 per cent | 0.520 | 0.512 | − 1.66 per cent |
| 5261 | 1.043 | 1.060 | 1.59 per cent | 0.625 | 0.620 | − 0.81 per cent |
| 5778 | 1.107 | 1.098 | − 0.85 per cent | 0.950 | 0.954 | 0.42 per cent |
| 6265 | 1.175 | 1.137 | − 3.30 per cent | 1.875 | 1.906 | 1.61 per cent |
| 6900 | 1.261 | 1.194 | − 5.64 per cent | 2.096 | 2.154 | 2.70 per cent |

3 CALCULATIONS OF LSZS

Calculations were done for Earth-like planets with Earth-like atmospheres and for Earth-like planets with CO_2 -dominated atmospheres, both with rotation rates similar to current Earth rates. For HZs, the inner edge is defined so that the atmosphere does not transition into a runaway greenhouse state. The outer edge of the HZ is often defined via the maximum greenhouse limit. According to Kopparapu et al. (2013), maximum warming is achieved at about 8 bar of CO_2 . Neubauer et al. (2013) found a maximum warming for 25 bar of CO_2 due to increased Rayleigh scattering and CO_2 condensation at the surface. Further increase of CO_2 caused no more warming. It is not evident that a similar high amount of CO_2 , as it is assumed for the outer HZ limit, is present in scenarios with water/ammonia. Therefore, no calculations were made with this solvent and high CO_2 Earth-like atmospheric scenarios. Outer LSZ limits for water/ammonia in those scenarios were calculated assuming CO_2 concentrations of 400 ppm. We calculated LSZ for different solvents in pure CO_2 or Venus-like scenarios. Atmospheres of several bars of CO_2 pressure would be necessary to achieve a maximum greenhouse effect used to determine outer HZ limits. Atmospheric composition in our model is assumed to remain constant, with the exception of the amount of water vapour in the Earth-like scenario, which is adapted according to the temperature of the respective atmospheric layer and atmospheric CO_2 condensing on the surface. LSZ inner and outer limits were then determined by calculating effective flux limits. The inner edge of the LSZ is defined so that the surface temperature value of the exoplanet does not exceed the value for the respective solvent to exist in its liquid phase. Outer limits of the LSZ incident flux are determined by the largest distance from the host star at which the respective solvent remains liquid on the planet's surface.

For the inner water and water/ammonia zone limits, the distance between the planet and its parent star was varied in steps of 0.001 au until a runaway greenhouse state was reached. As stated in Section 2, recent results presented by Leconte et al. (2013) for the inner limit of water based atmospheres were accounted for by keeping the relative humidity at 45 per cent.

3.1 Results for selected zones

We provide inner and outer limits for LSZs of water, water/ammonia and outer zone limits of sulphuric acid for planets with 1 bar atmospheres. The inner zone limit for sulphuric acid would be the same as it is for water assuming an Earth-like atmosphere, because the boiling point temperature of sulphuric acid is 583 K and an

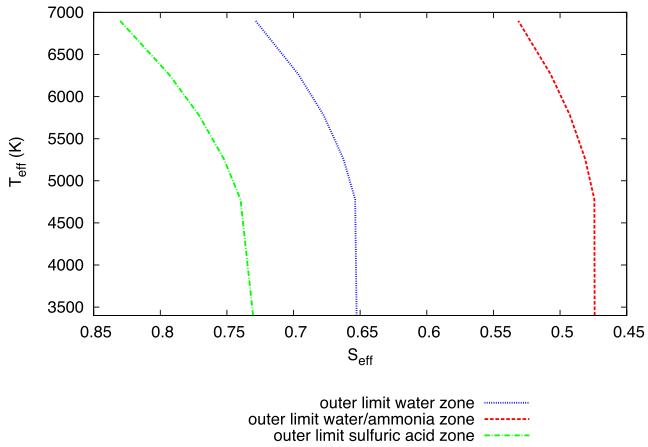


Figure 2. Effective flux limits for LSZ of planets with CO₂ atmospheres. Stellar temperatures range from 3400 to 6800 K. Results are shown for the outer limits of the water, water/ammonia and sulphuric acid zones.

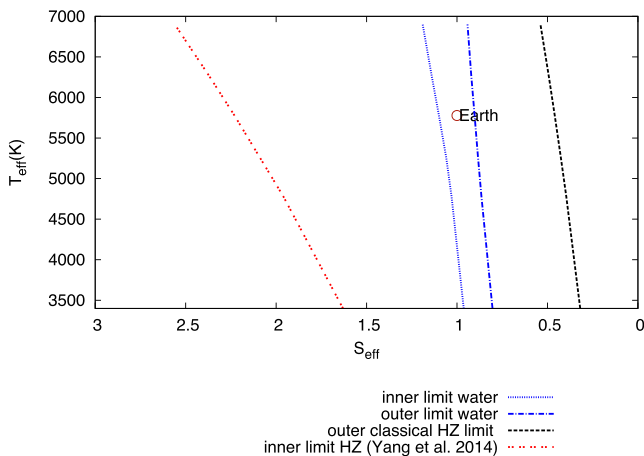


Figure 3. Effective flux limits for LSZ of planets with Earth-like atmospheres. Stellar temperatures range from 3400 to 6800 K. Results are shown for the water LSZ. Also included are the classical HZ outer limit and the limit for slowly rotating and tidally locked planets according to Yang et al. (2014).

Earth-like atmosphere would have reached a runaway greenhouse state long before the surface could reach this temperature. Inner and outer limits of zones for water and sulphuric acid were also calculated for a 1 bar CO₂-dominated atmosphere scenario and outer limits of zones for these solvents for a 8 bar CO₂-dominated atmosphere scenario. Total atmospheric pressure for planets more massive than Earth with Earth-like atmospheres was scaled according to the concepts outlined in Section 2. There are no additional calculations for more massive planets with CO₂-dominated atmospheres because the higher background pressure does not influence the absorption behaviour of the CO₂-dominated atmosphere as was shown by Kopparapu et al. (2014).

The inner limit of the HZ coincides with the inner limit of the water/ammonia zone because the saturation vapour pressure of ammonia is higher than the saturation vapour pressure of water. Therefore, ammonia evaporates at lower temperatures and the inner zone limit remains unchanged.

Fig. 3 shows the classical HZ for Earth-like atmospheres and for different stellar effective temperatures. For comparison, we also

included the inner limit of the water zone referring to the results by Yang et al. (2013) and Yang et al. (2014).

LSZ for water/ammonia and sulphuric acid for Earth-like atmospheres can be found in Fig. A1, with regards to effective fluxes as well as distances from their parent star. In general, the water/ammonia zone extends further from its parent star than the water zone. This is due to the different freezing point temperature of water/ammonia mixtures. In fact, this result highlights the possibility of life to exist on planets further away from the host star without the need of additional CO₂ in the atmosphere. Calculations for outer limits of water/ammonia and sulphuric acid LSZ for CO₂-dominated atmospheres are shown in Fig. 2. As expected, zone limits for this scenario are at fluxes less than those calculated for Earth-like atmospheres due to the warming effect of CO₂. Sulphuric acid LSZ for CO₂-dominated atmospheres are shown in Fig. A2, calculated for effective fluxes and distances from their parent star.

3.2 LSZ for Super Earths

We calculated limits for LSZ of planets more massive than Earth with Earth-like atmospheres. According to Kopparapu et al. (2014), limiting flux values for the inner edge of Super Earth HZs should be greater than limiting flux values for Earth twins, because their greenhouse gas column depth is lower due to the increased gravity and, therefore, leads to less energy absorption. Our calculations for more massive planets are in agreement with this theory. We applied our concepts of the LSZ to Super Earths and provide additional results for zone limiting fluxes for those planets. Fig. 3, for instance, shows the results for the inner edge of the HZ of a 5 M_⊕ planet, which is closer to the host star than for a 1 M_⊕ planet (a background gas pressure according to equation 1 was used).

Results for LSZ effective flux limits for different solvents, Earth-like planets with CO₂-dominated atmospheres, and for Earth-like planets more massive than Earth are provided in Table 3.

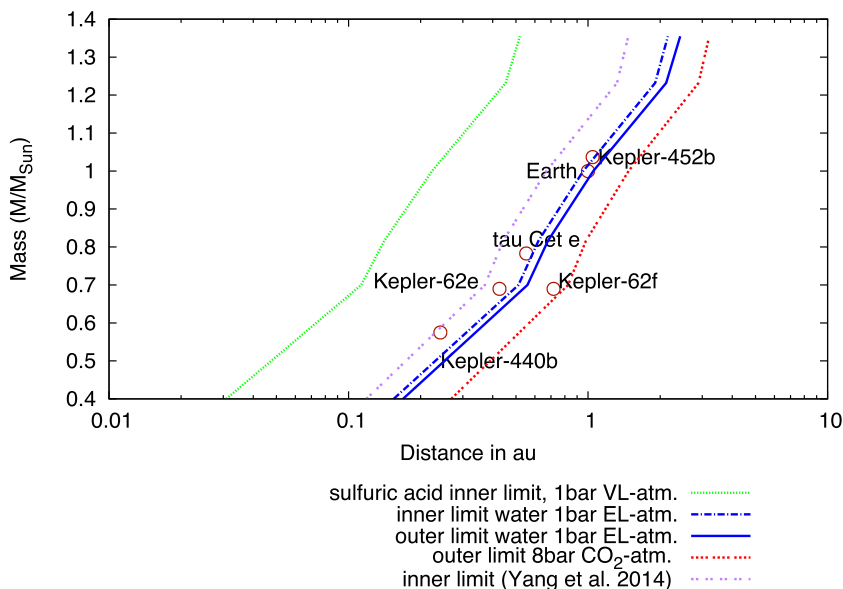
3.3 LSZ and recently discovered possibly habitable planets

Fig. 4 shows LSZ limits in units of star mass (M/M_⊙) versus au. The inner limit in this figure is represented by the inner zone limit for sulphuric acid for VL-atmospheres. The outer limit is represented by the 8 bar CO₂-dominated atmosphere for water/ammonia mixtures. Inner and outer water zones are added as well as the results from Yang et al. (2014) for tidally locked and slowly rotating planets in order to enable an easier comparison for recently discovered exoplanets. Planet data are taken from the Planetary Habitability Laboratory (<http://phl.upr.edu/projects/habitable-exoplanets-catalog>). These planets are examples of planets believed to be possibly habitable for life as we know it. Tau Ceti e, Kepler-62e, Kepler-440b are a little bit outside of the 1D HZ, recently discovered Kepler-452b (Jenkins et al. 2015) at the inner edge of the HZ; however, they are all located within the sulphuric acid LSZ and within the HZ limit according to Yang et al. (2014). Kepler-62f would be within the 8 bar of CO₂ LSZ. This shows that the restriction to HZs only could be misleading, because atmospheres of these planets do not need large amounts of CO₂ and H₂O in order to maintain other solvents than water in their liquid phases.

It has to be kept in mind that the uncertainties of planetary and star data, e.g. in planet mass, star temperature or in star–planet distance, generally are large enough, that it is difficult to determine whether a planet is located inside or outside of a specific zone, especially near to the edge of an LSZ.

Table 3. Fit parameters for calculations of stellar flux limits of the LSZ. Atmospheres are given in bold type letters. Fluxes which were calculated with respect to these atmospheres for different solvents are provided in the rows below in normal type.

| Parameters | $S_{\text{eff}\odot}$ | a | b |
|--|-----------------------|-------------------|-------------------|
| 1bar CO₂ atmospheres | | | |
| Outer water limit | 6.774 372 70e-01 | 3.399 841 77e-05 | 1.027 237 06e-08 |
| Inner sulphuric acid limit | 1.034 724 06e+01 | 5.174 123 84e-04 | 2.388 734 47e-07 |
| Outer sulphuric acid limit | 7.709 598 90e-01 | 4.137 026 50e-05 | 1.022 326 75e-08 |
| 8bar CO₂ atmospheres | | | |
| Outer sulphuric acid limit | 4.924 566 74e-01 | 7.372 686 57e-05 | 4.716 227 23e-09 |
| Outer water limit | 4.596 571 28e-01 | 6.725 445 88e-05 | 3.324 580 06e-09 |
| 1bar EL – atmospheres | | | |
| Inner water limit | 1.097 638 90e+00 | 7.664 045 06e-05 | 8.347 440 10e-09 |
| Outer water limit | 9.032 329 38e-01 | 3.664 880 70e-05 | -2.062 630 61e-09 |
| Outer sulphuric acid limit | 1.001 404 04e+00 | 4.161 816 50e-05 | -3.128 731 96e-09 |
| Outer water/ammonia limit | 6.713 541 86e-01 | 3.395 702 69e-05 | 1.316 092 35e-08 |
| 1bar VL – atmospheres | | | |
| Inner sulphuric acid limit | 1.953 34938e+01 | -4.959 287 17e-04 | 5.859 013 79e-07 |
| Outer sulphuric acid limit | 1.089 99222e+00 | -9.251 370 08e-06 | 2.758 889 40e-08 |
| 5 M_⊕ planets | | | |
| EL – atmospheres | | | |
| Inner water limit | 1.258 91846e+00 | 9.966 469 37e-05 | 6.213 883 16e-09 |
| Outer water limit | 1.039 81839e+00 | 8.596 812 12e-05 | 1.669 908 10e-08 |
| Outer water/ammonia limit | 8.306 52838e-01 | 6.267 340 68e-05 | 1.202 595 56e-08 |
| Outer sulphuric acid limit | 1.039 81839e+00 | 8.596 81212e-05 | 1.669 908 10e-08 |

**Figure 4.** LSZs calculated with our model for 1 M_⊕ planets and stellar effective temperatures from 3400 to 6900 K. Recently discovered planet data, taken from the Planetary Habitability Laboratory (<http://phl.upr.edu/projects/habitable-exoplanets-catalog>), for planets believed to possibly be habitable are included to show their positions compared to LSZ zone limits. Also included are recently discovered Kepler 452-b (Jenkins et al. 2015) as well as Earth.

3.4 Summary and outlook

The concept of LSZ has been introduced as a generalization of the classical HZ by Leitner et al. (2010). LSZs are based on solvents other than water. In this work, we present the corresponding effective flux limits that can be used to calculate LSZ limit distances analogous to the classical HZs by Kopparapu et al. (2013). We used a 1D radiative convective model based on the open source software STREAMER. Gas absorption coefficients were calculated with the programs KSPECTRUM and KDISTRIBUTION using data from the HITRAN 2008 data base and LOWTRAN7-ESFT for the VL-atmosphere.

A comparison between our results and those of Kopparapu et al. (2014) showed a good agreement for the inner edge of the HZ. The maximum differences in fluxes were within 7 per cent, which results in a maximum deviation of about 4 per cent regarding HZ borders. These deviations are well within the uncertainties given by Toon et al. (1989) for flux calculations using a two-stream algorithm.

LSZ limits were calculated for different solvents, such as water, water/ammonia and sulphuric acid. Inner and outer limits for these zones are provided for reasonable atmospheric scenarios and the positions of recently discovered exoplanets within these calculated zones are presented. Zones with limits extending towards a greater

or smaller distance from the star than the water zone are an additional element in the way of thinking about possible life on other planets.

Our results are provided in an easily accessible manner, namely as fit parameters for the effective insolation limits as a function of the stellar effective temperatures.

We believe that the concept of LSZ is a promising new avenue to explore in astrobiology. Different atmospheres and different solvents as a basis for life could be incorporated not only into other 1D models, but also into 3D models. 3D calculations similar to those done by Lecote et al. (2013) and Yang et al. (2014) could provide helpful input for future calculations with 1D models and would probably extend the range of credible scenarios for planets capable of supporting life. It would be of special interest to extend feedback albedo effect calculations for slowly rotating or tidally locked planets, like those by Yang et al. (2013) and Yang et al. (2014), to clouds based on other solvents, like sulphuric acid clouds on Venus. The application of our results for LSZ limits to newly discovered possibly habitable planets indicates that the restriction to HZs only could be misleading, because atmospheres of these planets do not need large amounts of CO₂ and H₂O in order to maintain other solvents than water in their liquid phases.

ACKNOWLEDGEMENTS

This work was performed within the research platform ExoLife of the University of Vienna (<http://www.univie.ac.at/EPH/exolife>). We thank Vincent Eymet (University of Toulouse) for codes of KSPECTRUM and KDISTRIBUTION. Data were mostly obtained via calculations on the Vienna Scientific Cluster.

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APPENDIX A: LSZ CALCULATED FOR PLANETS WITH 1 BAR EARTH-LIKE, VENUS-LIKE AND CO₂ ATMOSPHERES

Figures for LSZ referenced in the text.

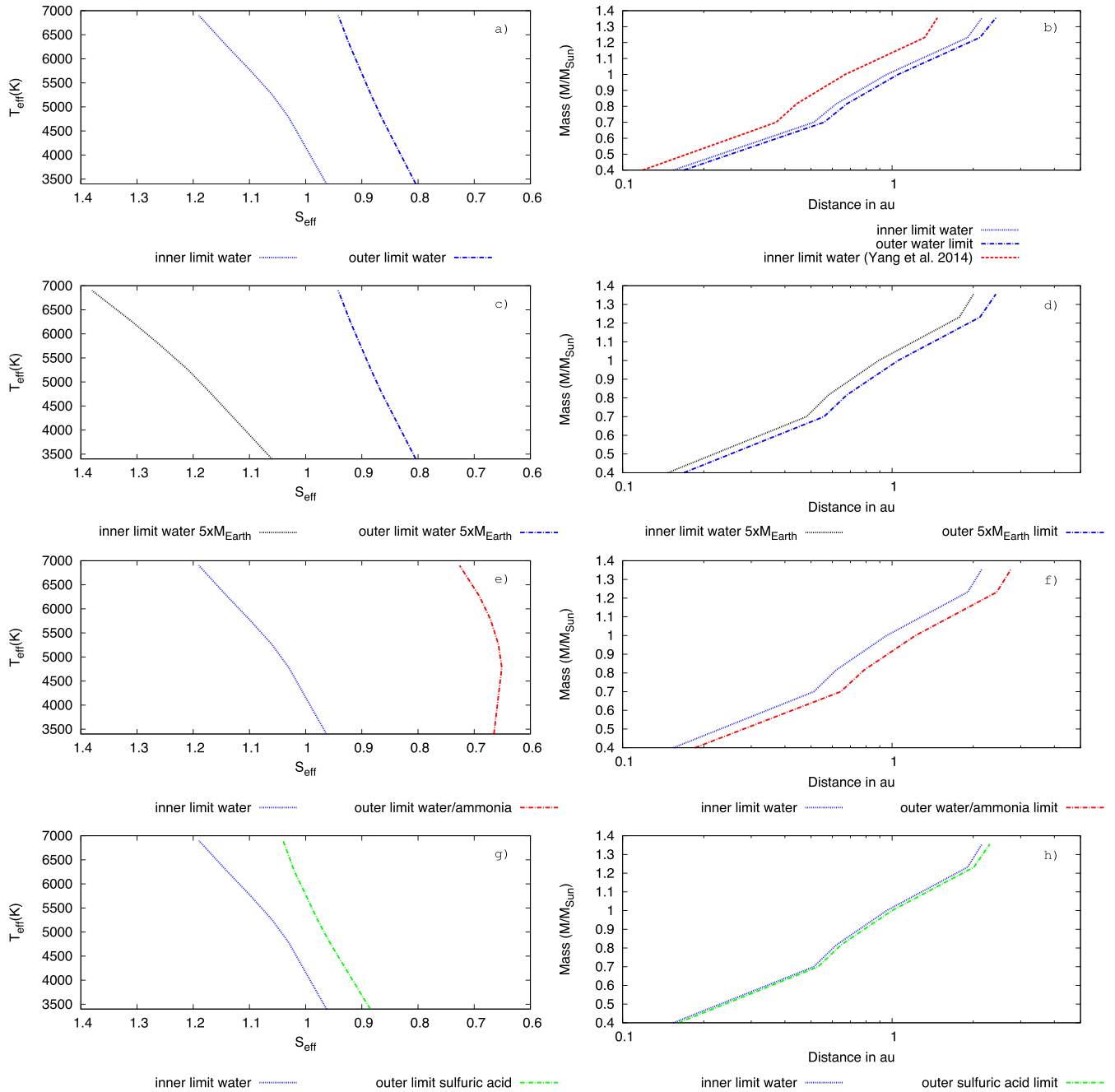


Figure A1. Effective flux limits for LSZ of planets with EL-atmospheres. Figures on the left-hand side (figures a, c, e and g) show LSZ limits in terms of effective fluxes for different solvents. It can be seen in figure c that the inner LSZ limit is shifted more towards the parent star for planets with masses up to $5 M_{\oplus}$. The water/ammonia LSZ outer limit is the limit most distant from its parent star. Inner limits for water/ammonia and sulphuric acid LSZ are the same as the inner limit for the water LSZ, since the atmosphere enters a runaway greenhouse state at the distance from its parent star corresponding to the inner water limit. Figures on the right-hand side (figures b, d, f and h) show the corresponding limits in terms of au and star masses.

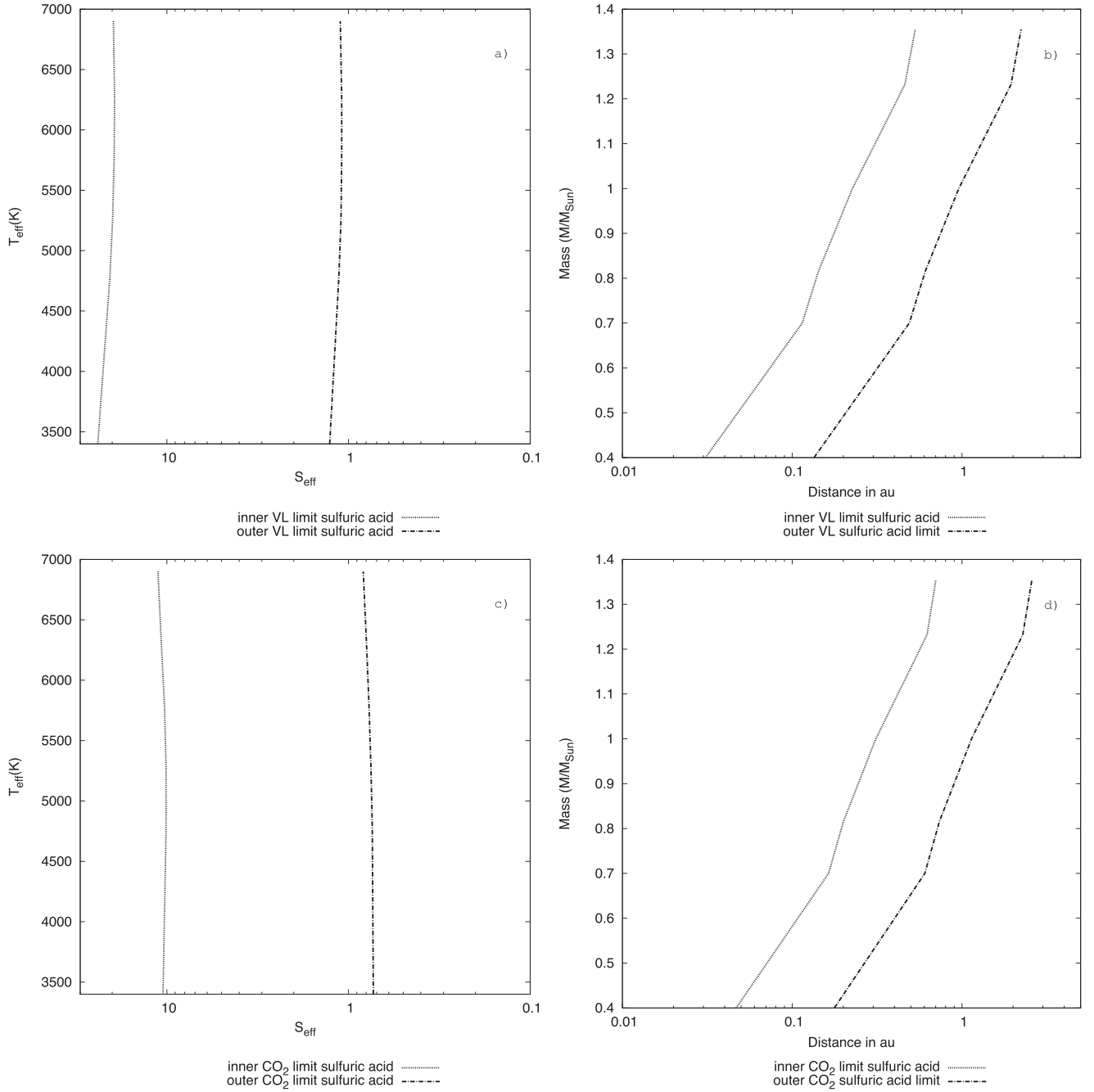


Figure A2. LSZ for Venus-like and CO₂-like atmospheres for sulphuric acid. The sulphuric acid cloud effect can be seen in shift of the inner LSZ limit towards the parent star for the VL atmosphere. CO₂ atmosphere was calculated without clouds. Figures a and b show the limits for VL atmospheres in terms of effective flux and in terms of distance in au, respectively. Figures c and d show the limits and distances for CO₂ atmospheres.

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