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DISSERTATION

Titel der Dissertation

„Exotic Life and the Life Supporting Zone as a Basis for the Search for Extraterrestrial Life"

Verfasser

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In particular I want to say thanks to my parents. They have enabled me to study astronomy and physics and through their continuous support during this time they have never stopped to believe in me and my research.
Finally I want to thank all my friends for their patience during the time I spent working on this thesis.

Only something which has no history is capable of being defined.

Friedrich Nietzsche, in: *On the Genealogy of Morality*, II, 13, Leipzig, 1887

Abbreviations used in this thesis

CETI	communication with extraterrestrial intelligence
CCN	cloud condensation nuclei
IR	infrared
LINCOS	‘lingua cosmica’ (in Latin)
LSZ	life supporting zone
HZ	habitable zone
SETI	search for extraterrestrial intelligence

1. Introduction and Overview

Questions like “Are we alone?” or “Is there life, intelligent or not, on other planets?” accompany mankind since humans glance to the night sky. Even through the scientific discipline of astrobiology has experienced great progress within the last decades a final answer to these questions is far beyond our present knowledge. When we think of life on other planets, we are often limited to our present understanding of life, which is focused on the terrestrial sample.
The main aim of this present thesis is to discuss the topic of life beyond our terrestrial characteristics and to generalize presently used hand-tools in astrobiology and especially in astronomy in order not to open our mind only to life-as-we-do-not-know.

The present cumulative doctoral-thesis offers several scientific articles within the scope of exotic life, starting with a discussion on the nature of life-as-we-know-it, its principles and strategies followed by an attempt to generalize our terrestrial-oriented understanding of life to a universal one. Furthermore, evidence will be presented, that at least the origin of the (terrestrial) building blocks of life (the amino acids) are also possible in environments as well as with solvents different to the terrestrial ones. Therefore, an experiment was performed for an early Titan scenario after a large asteroid impact, where liquid water-ammonia composites can exist on the moon’s surface for thousands of years. This result is also of importance for icy-moon oceans as in these habitats water-ammonia composites will also be present and consequently the synthesis of amino acids seems at least to be possible. A technological feasibility study will accompany this idea, offering a space mission to Europa with a cryobot in order to look for signs of life within the outer icy crust layer of the moon. The present author also performed several studies on the impact of exotic life on the habitable zone. A new model – the so called ‘life supporting zone’ – has been developed to allow the determination of the potential existence of different liquids on planetary surfaces in more detail. Finally, a short review is given on LINCOS and NEW LINCOS, an artificial mathematical language for encoding signals and information with respect to the research of SETI and CETI. This study analyzes both – historical aspects and applications of CETI and LINCOS as well as its present deficiencies for potential interstellar communication in order to describe more than formal mathematical basics.

1.1 From Classical to Exotic Life

In the first section of the present thesis existing definitions and working hypotheses for life used nowadays are analyzed. They were found to list either detailed properties of terrestrial life (or individuals) or to include general strategies of life-as-we-know-it. Consequently, both approaches can be designated as geocentric descriptions of life. Thereby, a metabolism, evolution and reproduction often pose basic concepts utilized to describe our life. Especially the latter twos lead also to a problematic situation when used as strategies for the search for extraterrestrial life, because providing an experimental evidence for these system properties is far beyond our present technical possibilities.

Within the following article especially evolution and reproduction are studied with respect to their usability for definitions and descriptions of life and were found when strictly applied to the Homo sapiens sapiens, then even humanity cannot be designated as representative for life due to the symbiotic metabolism of all individuals and their consequent need of an ‘assisted reproduction’. The strategies will also fail when applied to sterile species as for example mules. It was found that the focus in descriptions of life should not be reproduction anymore, but the ability of a living system to conserve itself in general. Nevertheless, in order to look for life beyond Earth a general view on life is required, which also include solvents and chemical structures not necessarily utilized on Earth as well as considering environments, which are not of the terrestrial-like type.

1.1.1 Description of the work done by the present author

The following manuscript is reprinted in order to describe the work on the question how life can be defined in a universal context:

The need of a non-Earth centric concept of life
by **Johannes Leitner**, Maria Firneis

- Submitted to the journal “Life” on January 28, 2014
- Impact factor of the journal: not available (established in 2011)
- Quota of this study, done by the present author: 100 %
- **Work on the article done by the author of this thesis:**
  The whole study was done by the present author. This includes a literature study on existing definitions for life-as-we-know-it as well as on the few existing concepts on life-as-we-do-not-know. Weaknesses and common characteristics of various definition have been (re-)analyzed and evolution and reproduction as key characteristics of a life definition or hypothesis have been investigated in detail by the present author and have been shown not to be very strong features for the matter of defining life. The theory of exotic life has also been introduced in detail by the present author and based on the fundament of hypotheses for classic life, a new hypothesis for exotic life has been constructed. Thereby, the term exotic life was proposed for future discussions on life-as-we-do-not-know it and promoted and presented at various meetings, because the situation was still characterized by various different designations for the same concept in literature and the media (e.g. weird life). As it is difficult to search for exotic life with present strategies (“follow-the-water” and “follow-the-energy” theories), the present author proposed in this paper a “follow-the-nutrients”-strategy to search for exotic life in extraterrestrial habitats.

In addition to this paper, a selection of conference presentations and abstracts associated with this topic is given consecutively:

Leitner J. J., Firneis M. G., 2011a, *What can we learn from GFAJ-1 for defining life?* Abstracts of the Origins 2011 Meeting (ISSOL and IAU-Comm. 51 Joint International Meeting), held in Montpellier, France, July 3-8, 2011.

Leitner J. J., Firneis M. G., 2011b, *Defining life in a non-geocentric way*; Abstracts of the EPSC-DPS Joint Meeting 2011, held in Nantes, France, October 3-7, 2011.

Leitner J. J., Firneis M. G., 2011c, *Is it possible to define life as a universal concept? Reproduction, metabolism and evolution re-evaluated*; International Conference on the History and Philosophy of Astrobiology, held in Ven, Sweden, September 27-28, 2011.

Leitner J. J., Firneis M. G., 2012b, *How can we detect Life when we cannot define it in a general way?;* Paper presented at the International Workshop on Extraterrestrial Life – Beyond our Expectations, held in Vienna, Austria, May 21-22, 2012.

Leitner J. J., Firneis M. G., 2012c, *Is a definition of life only of academic or also of common interest?*; Paper presented at the Astrobiology Science Conference 2012, held in Atlanta, USA, April 16-20, 2012.

Additional material used to study definitions of life:

In the following selected definitions for life are given, which were not reprinted in details within the above mentioned manuscript, but were subject of studies for the development of the theory of exotic life.

- **Baross et al. (2007):** Characteristics of life on Earth: (1) It is chemical in essence; terran living systems contain molecular species that undergo chemical transformations (metabolism) under the direction of molecules (enzyme catalysts) whose structures are inherited, and heritable information is itself carried by molecules. (2) To have directed chemical transformations, terran living systems exploit a thermodynamic disequilibrium. (3) The biomolecules that terran life uses to support metabolism, build structures, manage energy, and transfer information tank advantage of the covalent bonding properties of carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur and the ability of heteroatoms, primarily oxygen and nitrogen, to modulate the reactivity of hydrocarbons. (4) Terran biomolecules interact with water to be soluble (or not) or to react (or not) in a way that confers the fitness on a host organism. The biomolecules found in terran life appear to have molecular structures that create properties specifically suited to the demands imposed by water. (5) Living systems that have emerged on Earth have done so by a process of radon variation in the structure of inherited biomolecules, on which was superimposed natural selection to achieve fitness. There are the central elements of the Darwinian paradigm.

- **Deamer (2010):** Properties of terrestrial life: (1) The machinery of life is composed of polymers, very long molecules composed of subunits called monomers. The primary polymers of life are nucleic acids and proteins, often called biopolymers. (2) The polymers interact with a membranous boundary that has three primary functions: containment, transport of nutrients, and energy transduction. (3) Biopolymers are synthetized in the container by linking together monomers – amino acids and nucleoids – using energy available in the environment. Polymer synthesis is the fundamental process leading to growth of a living system. (4) Nucleic acids have a unique ability to store and transmit genetic information. Proteins called enzymes have a unique ability to act as catalysts that increase the rates of metabolic reactions. (5) The genetic and catalytic polymers are incorporated into a cyclic feedback-controlled system in which information in the genetic polymers is used to direct the synthesis of the catalytic polymers, and the catalytic polymers take part in the synthesis of the genetic polymers. (6) During growth, the cyclic system of polymers reproduces itself, and the cellular compartment divides. (7) Reproduction is not perfect, so that variations arise, resulting in differences between cells in a population. (8) Because of different cells having varying capacities to grow and survive in a given environment, individual cells undergo selection according to their ability to complete for nutrients and energy. As a result, populations of cells have the capacity for evolution.

- **Dyson (1999):** Life is a material system that can acquire store, process, and use information to organize its activities.
- **Forterre (2010):** Life is the mode of existence of living organisms.
- **Forterre (2010):** Life is the mode of existence of ribosomal and capsid encoding organisms.
- **Forterre (2010):** A living organism is a collection of integrated organs (molecular machines/structures) producing individuals evolving through natural selection.
- **Joyce (1994):** Life is a self-sustaining chemical system capable of undergoing Darwinian evolution.
- **Kolb (2007):** A life definition in two different ways: (1) life as a phenomenon and (2) life as a set of characteristics of an individual organism: In the first way life is a continuous phenomenon, which is carried on by a series of individual organisms which themselves perish within a time period that is much shorter than that of the phenomenon of life. When we consider the life of an individual organism, we quickly realize that reproduction is not the key feature that makes it alive. Reproduction of some, but not of all individuals is essential. For the second way reproduction is not essential.
- **Kolb (2010):** The life of an organism is the sum of all its life forms over the period of time of the existence of the organisms.
- **Koshland (2002):** PICERAS – fundamental principles of life: P(rogram), I(mprovisation), C(ompartmentalization), E(nergy), R(egeneration), A(daptability), S(eclusion).
- **McKay (1991):** Life requires: (1) a source of energy, usually sunlight; (2) carbon; (3) liquid water; (4) some combination of other elements such as N, P, and S.
- **McKay (2004):** Life is a material system that undergoes reproduction, mutation, and natural selection.
- **Morange (2010):** The demarcation between life and non-life is the product of human history, not of evolutionary history.
- **Raulin (2010):** Life is a complex chemical system able to replicate and to evolve through natural selection.
- **Oparin (1924):** The bodies of all living things, beginning with the smallest bacteria and algae and ending with man, are constructed according to a definitive plan in which the greatest importance attaches, not to the external visible organization but to the fine structure of the protoplasma of the cells which make up the organism.

- **Oparin (1924):** The specific peculiarity of living organisms is only that in them there have been collected and integrated an extremely complicated combination of a large number of properties and characteristics which ware present in isolation in various dead, inorganic bodies. Life is not characterized by any special properties but by a definite, specific combination of these properties.

- **Schrödinger (1944):** Life feeds on negative entropy.

- **Schulze-Makuch and Irwin (2006):** Life is a complex system (1) composed of bounded compartments in a thermodynamic disequilibrium with the external environment, (2) capable of transforming energy and the surroundings to maintain a low-entropy state, and (3) persisting through the encoding and transmission of information for self-replication.

1.2 From the Habitable to the Life Supporting Zone

In *Kasting et al.* (1993) the modern concept of the habitable zone (HZ) was introduced, defining it as a region around a star, where an earth-like planet with a CO_2-H_2O-N_2-atmosphere can maintain liquid water on its surface and consequently fulfil one present known criterium for life-as-we-know-it (see *Figure 1* for the habitable zone after Kasting). Taking into account different atmospheric scenarios and Martian instead of Earth' mass, *Table 1* lists the computed habitable zone for our Solar System (*Kasting et al.,* 1993). Thereby, the inner and outer borders of the HZ are calculated in different ways, as a runaway greenhouse effect and water loss and CO_2 condensation, respectively.

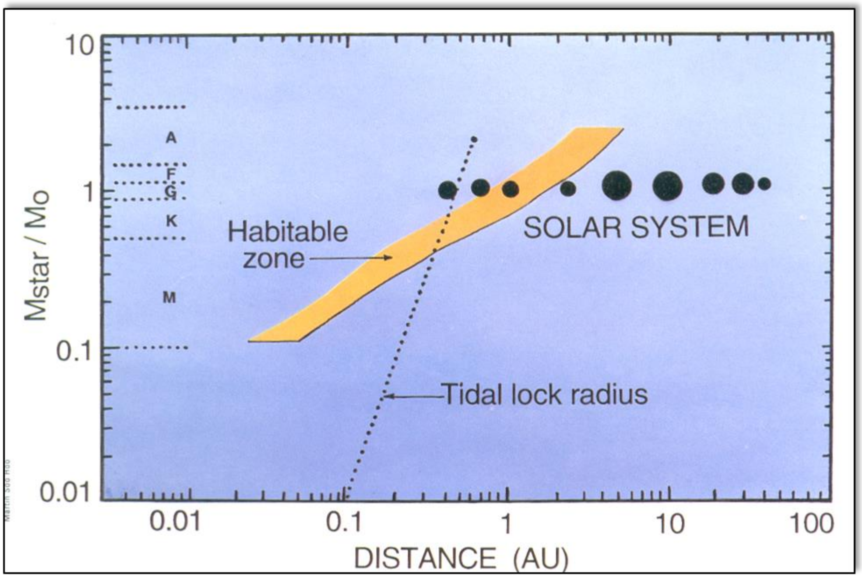

Figure 1: The habitable zone for main sequence stars. In particular the location of the habitable zone is shown for the Sun and the Solar System. Planet Earth is located inside the zone, but Venus and Mars are outside, implying that no liquid water is available on the surface of both planets (courtesy to James Kasting, image taken from his personal website at Penn State).

Model scenario	**Inner border [AU]**				**Outer border [AU]**	
	Runaway greenhouse		**Moist greenhouse**		**Maximum greenhouse**	
	Kasting *et al.* 1993	*Kopparapu et al.* 2013	*Kasting et al.* 1993	*Kopparapu et al.* 2013	*Kasting et al.* 1993	*Kopparapu et al.* 2013
Earth	0.84	0.97	**0.95**	**0.99**	**1.67**	**1.67**
Mars-sized planet	0.88	1.033	0.98	1.35	1.67	1.67
pN_2 = 0.1 bar	0.84		0.96		1.67	
pN_2 = 10 bar	0.84		0.88		1.69	
pCO_2 = 0,003 bar	0.84		0.97			
pCO_2 = 0,3 bar	0.84		1.00			
pCO_2 = 3 bar	0.84		0.95			
pCO_2 = 30 bar	0.84		0.90			

Table 1: The habitable zone in the Solar System computed for different mass scenarios and atmospheric composition scenarios of Earth (data taken from Kasting et al., 1993 and Kopparapu et al., 2013).Therein, the standard model denotes the present Earth parameters and pN_2 or pCO_2 denotes the atmospheric partial pressure of N_2 and CO_2, respectively.

In a follow-up study on the model of Kasting *Kopparapu et al.*, 2013 summarized several original weaknesses and developed an improved model. The original model was based on a one-dimensional, cloud-free climate model with absorption coefficients thought to be valid in the 1990s, but found to pose an underestimation of the thermal IR-absorption in warm, moist

greenhouse atmospheres. Another point of criticism was an overestimation of thermal IR-radiation by collision-induced absorption bands of CO_2. Finally, also the used effective temperatures from 7200 to 3700 K corresponding to F0 to M0 stellar classes did not correctly include frequently discovered M-stars with effective temperatures lower than 3700 K. In the new model of *Kopparapu et al.*, 2013 these effects are included (*Table 1* also offers a comparison of the new results with the old ones).
To summarize the extent of the habitable zone: in *Kasting et al., 2013* the habitable zone for an Earth-like planet within the Solar System was found to be from 0.95 to 1.67 AU, *Kopparapu et al.*, 2013 found the borders to be located from 0.99 to 1.67 AU. In *Figure 2* the schematic illustration of the new HZ is reprinted. Thereby it becomes apparent that for planets around stars with a higher effective temperature than 5000 K no clear distinction between moist and runaway greenhouse effect is observable.

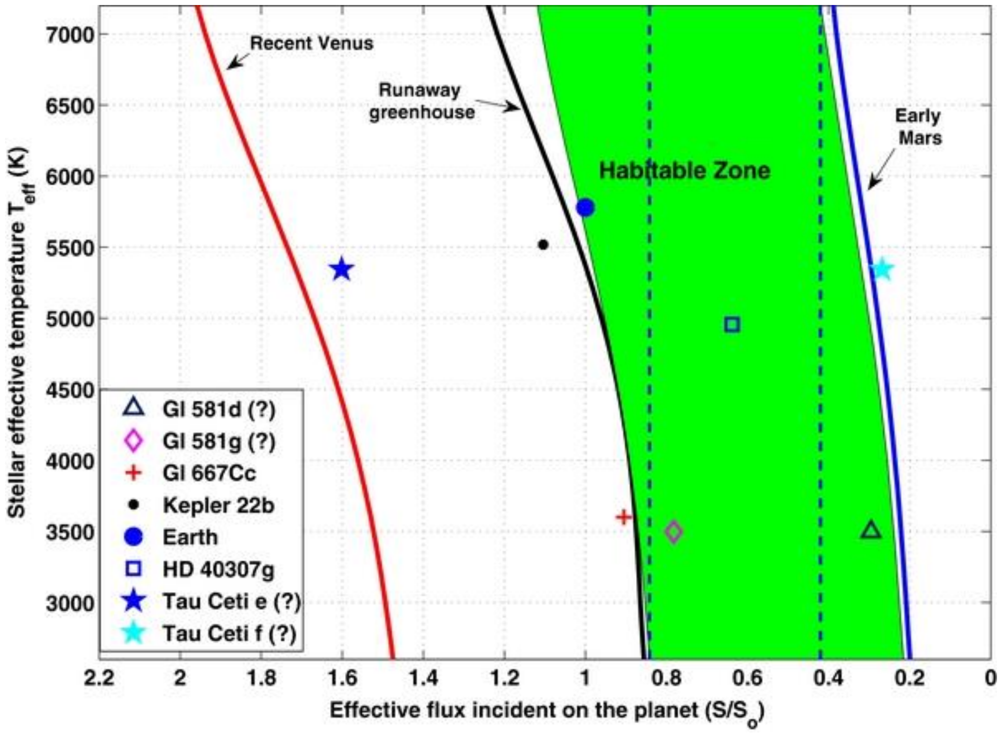

Figure 2: The extension of the newly developed model of the HZ for different effective temperatures. Several planets of interest are incorporated, whereby '?' denotes that the existence of these exoplanets is not finally clear (reprinted from Kopparapu et al. 2013).

The effect of clouds had also not been incorporated into the new model, even though, it is widely accepted that cloud-effects on the albedo can surpass greenhouse-effects. In a recent article *Kasting and Harman*, 2013 reported on the present problems on defining the inner edge of the HZ. In *Leconte et al.,* 2013 a three-dimensional global climate model was calculated for the Earth in order to show that the insolation threshold for a runaway greenhouse state is about 375 W m^{-2}. Clouds were identified to have a destabilizing effect on long-term warming, because high altitude cirrus clouds with a warming effect will increase the number and size of clouds corresponding to a higher surface temperature faster, than lower located, cooling stratus clouds. With these new results it was possible for the authors to shift the inner edge of the HZ to 0.95 AU, giving Earth more time (about 1 billion years) to enter a runaway greenhouse state.
Accepting these results and mechanisms, then the most probable location of the habitable zone in our Solar System is from 0.95. to 1.67 AU.

This formulation of the habitable zone is performed for water as solvent and consequently neglects the possibility of exotic life and so far, of life not necessarily based on water as solvent (*Leitner et al.,* 2008a,b; *Firneis et al.,* 2009; *Leitner,* 2009, 2010). It fits the conditions for terrestrial life, but continues a geocentric way of thinking on topics related to life in the Universe and astrobiology in general. The question arises if the terrestrial sample of life is the only possible one with respect to its ingredients, or if other solvents as well as other chemical structures than the carbon-based life on Earth are within the range of possibilities? This is what was outlined in the first section with the theory of exotic life.

In an outstanding summary *Baross et al.,* 2007 have discussed this possibility and opened one more time the discussion on alternative forms of life. Therein, several different solvents have been analysed with respect to their potential so serve as alternatives to water (see also *Firneis et al.,* 2009; *Leitner*, 2010*, Leitner et al.*, 2012a). Following the study of Baross and his colleagues study, hydrocarbons and apolar solvents also seem to be able to maintain different C-based structures, but polar solvents are especially suitable for providing an environment in which the origin and evolution of life, based on C=O (a chemical double-bond between carbon and oxygen) could take place. *Table* 2 provides an overview of some of these solvents discussed in the mentioned study.

Solvent	Freezing point [K]	Boiling point [K]	ΔT [K]
Polar solvents			
water	273	373	100
ammonia	195	240	45
sulfuric acid	283	563	280
formamide	273	495	222
Apolar solvents			
methane	91	112	21
ethane	101	184	83

Table 2: An overview on potential solvents for life is given (for a pressure of 1 bar, data from Baross et al., 2007).

Furthermore, in *Baross et al.,* 2007 also some characteristics of examples for alternative solvents are discussed:

- **Ammonia:** Due to the enhanced basicity of this solvent a C=O bond cannot be supported, but a C=N one. Furthermore, ammonia is common in space and its ability to act as a coolant (e.g. in in mixture with water) makes it an important alternative to pure water.
- **Sulphuric acid**: This is a strong acid and consequently not suited for C=O, but for C=C. It is characterized by a high reactivity, and its abundance in the Venusian cloud regions is sometimes discussed together with the question on potential Venusian life within these clouds (see *Schulze-Makuch et al.*, 2004).
- **Methane/ethane:** Both solvents in general are suited for C-based life forms, but they comprise only very small temperature ranges for their liquid phases. The organic reactivity of the solvents is comparable to water and their abundance in the Titan lakes (*Stofan et al.*, 2007) makes them to alternative solvents for potential life on Titan.
- **H_2/N_2:** To exist in the liquid phase very low temperatures are necessary, and it seems that mainly C=C bonds are potential candidates for life with this solvent. The very low reaction velocity of the solvents will not denote them as primary alternatives.
- **Formamide:** This solvent regarding its main characteristics is similar to ammonia, a synthesis of RNA, DNA and proteins seem to be possible. Its large range of the liquid phase underlines the attraction of this solvent and the similar dipole moment of formamide and water expresses that compounds, which are solvable in water, can also be solved in formamide.

A large range of the liquid phase is expected to support biogenesis by providing a stable region where the chemical reactions can take place and consequently, the larger the temperature range for the liquid phase of a solvent is, the more stable and long-time resistant habitats can result. The terrestrial planets in the Solar System are characterized by very circular orbits, but more eccentric orbits (for instance of exoplanets) will also have an important influence on the surface temperatures and consequently on the liquid phases, even though it was found that the long-term stability of the climate systems primarily depends on the average stellar flux received over an entire orbital period and not on the time span spent within the HZ (*Williams and Pollard,* 2002).

Baross et al., 2007 also investigated why the liquid phase is preferred over the gaseous and solid phases: A solvent can act as a catalyst for chemical reactions and it offers a stable reaction environment (within the liquid phase). Unsolved is the question for an absolute temperature range, which allows the synthesis of the building blocks of life. When considering C-based molecules the upper temperature limit is 600 K (at 1 bar), and above 800 K (independent of the pressure) no C-based bond remains stable. A further handicap is the fact that carbohydrates (which include C=O bonds) become unstable at temperatures below 373 K.

Ammonia and its ability to act as a coolant, and consequently its influence on the liquid phase of possible ammonia-water composites is of high importance for exotic life as well as for the discussion of the assumed ocean of the icy moon Europa. *Hussmann et al.*, 2006 studied the internal structure of several different icy moons and selected large trans-Neptunian objects and the implication of ammonia dissolved in the presumed oceans (calculations with concentrations up to 31.5 % ammonia have been performed). This study strengthens the hypothesis that solvents different to pure water, and especially water-ammonia composites could play an important role in icy celestial bodies. Additionally, the existence of lakes with liquid methane/ethane on Titan has to be taken into account (*Stofan et al.*, 2007).

With the background to get first experimental evidence for the theory of exotic life and especially for the hypothesis of alternative solvents, it was decided to perform a Miller-Urey-type experiment. Thereby, an early Titan scenario after an asteroid impact was decided to be simulated. Together with colleagues from the Washington State University an apparatus was built and in contrast to the original experiment from Miller and Urey (*Miller*, 1953) instead of water, a water-ammonia composite (mixing ration: 70:30) and an hypothetical early Titan atmosphere (0.05 bar hydrogen gas, methane gas 1 bar and ammonia gas 0.45 bar) was used. As observed in the original Miller-Urey as well as in various follow-up experiments by a large number of scientists the experiment resulted in the synthesis of amino acids (primarily: histidine His, aspartic acids Asp, tryptophan Trp, serine Ser, phenylalanine Phe, glutamic acid Glu, arginine Arg, leucine Leu, isoleucine Lle, valine Val and proline Pro). The experiment offers the worldwide first und clear evidence that also with alternative solvents the origin of the buildings blocks of life is possible. The results are reported in *Turse et al.*, 2013, which is reprinted within this thesis.

This result is not only of interest for Titan, but also for the icy moon oceans (e.g. on Europa). As a consequence of our results at least the possibility is given that also in these habitats life could exist. With HADES a feasibility study is further reprinted within this thesis (*Böttcher et al.*, 2009) which underlines that also with present available technology, it is possible to look at least in the upper parts of the ice crust of Europa for markers for life.

As this result strengthens once more the theory of exotic life, the question will arise how it could be possible to identify potential habitats for this life-as-we-do-not-know-it. In order to investigate in which regions around a star exotic life could be possible in general in *Leitner et al.,* 2008a the concept of the life supporting zone (LSZ) was introduced for the first time. Due to thermal and chemical conditions of the different solvents the LSZ consists of different solvent-subareas, which merge from one solvent to another and thus all together form a large region around a star (see *Figure 3*). Each solvent corresponds to a separate habitable zone, so as an example focussed on water, the classically described HZ results. Nevertheless, a lot of theoretical and laboratory work is necessary to investigate the ability of each potential solvent as origin of life in general as well as to define biomarkers for future search for life within this zones.

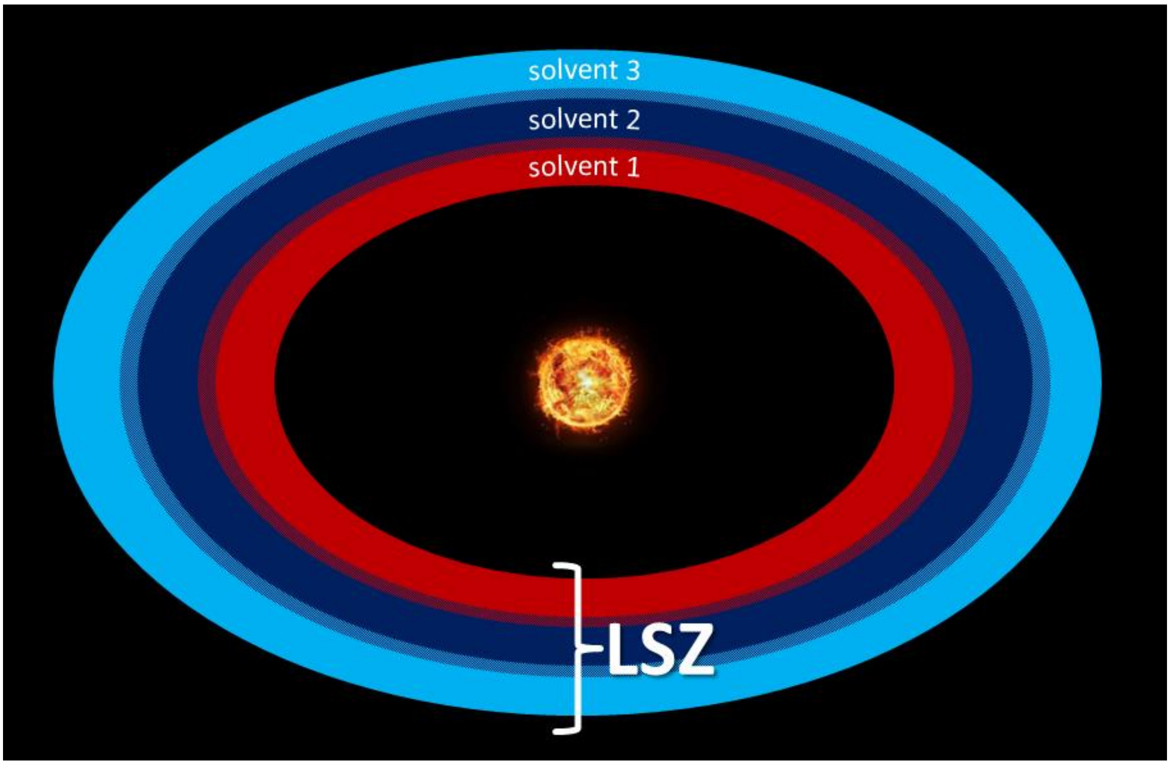

Figure 2: Schematic illustration of the principal idea of the Life Supporting Zone (LSZ). Different solvents merge and form all together a region around a star in which exotic life could be possible on the surface of a suitable planet. Thereby, each solvent represents its separate habitable zone.

The key parameter for the abundance of a solvent on a planetary surface is the specific surface temperature, which not only is the consequence of the central star parameters and celestial mechanical characteristics of the planets, but also of the planet's interior and atmosphere and their interaction. Furthermore, clouds will also play an important role controlling the planetary heat budget as their influence on the greenhouse effect also has been investigated in *Leconte et al.*, 2013. In *Leitner et al.*, 2010a-d and *Neubauer et al.*, 2010, 2011a-b a radiative-convective model was presented for the calculation of the planetary surface temperature and consequently of the extension of the LSZ. The model comprises of two parts: a cloud model in order to calculate cloud droplet distribution with optical properties of the droplets derived by using Mie theory (*Bohren and Huffman*, 2004) and a radiative-convection model. The cloud model originally was developed in *Neubauer*, 2009 and used to investigate cloud droplet formation and growth for water and have been generalized for this application to alternative solvents and clouds (e.g. H_2SO_4-clouds). As nothing is known on possible cloud condensation nuclei (CCN) in the atmosphere of exoplanets, it is assumed that aerosol formation processes follow the same physical principles of nucleation from the gas phase with pre-existing aerosols as well as that they are soluble or at least wettable. Microphysical processes of nucleation, condensation, coagulation, entrainment as well as radiative effects are included. For the case of the equilibrium temperature profile of the atmosphere we have further developed the model of *Manabe and Strickler*, 1964 and *Manabe and Wetherald*, 1967. The model allows the computation of the horizontal global surface temperature. For the calculation of radiative transfer through the planetary atmosphere the public domain software 'Streamer' (*Key and Schweiger*, 1998), which includes scattering and absorption of radiation by the gases and particles, was adapted. Rayleigh scattering, originally implemented in 'Streamer' for the air, was expanded to H_2O, CO_2, CO, CH_4, N_2O, NO, NH_3, and SO_2. Further absorbing gases: CH_4, NH_3, CO, SO_2, N_2O, NO, NO_2, and HNO_3 were implemented to the original H_2O, CO_2, O_2 and O_3. A detailed description of the model is given in *Neubauer et al.*, 2011, which is reprinted within this thesis. Validation runs for the developed model with respect to the surface temperature have

been simulated for Titan. For this scenario no clouds were implemented in the atmosphere and the known CH_4-profile (*Niemann et al.*, 2005) was simulated with a N_2-atmosphere and a mean surface pressure of 1496 mbar. With a mixture of N_2 and CH_2 as scattering gas, CH_4 as absorption gas and including collision induced absorption for N_2-N_2, N_2-CH_4,CH_4-CH_4, N_2-H_2 the model result in case of the moist adiabatic lapse rate in a surface temperature of 93.9 K. This temperature is in very good agreement with the reference surface temperature of 93.7 K so that it is apparent that the model is very well suited an accurate to determine the surface temperatures of planets and moons with a complex atmospheric layering.
This model has been used to calculate the life supporting zone and especially the habitable zones for different solvents especially water, sulfuric acid and a water-ammonia mixture (see *Neubauer et al.*, 2012, which is also reprinted in the second section. The planets selected are potential habitable planets as identified by the Kepler mission: Kepler-22b, KOI 268.01, KOI 701.03, KOI 854.01 and KOI 1026.01 (with planetary mass ranges between 1 and 10 masses of the Earth). The results are discussed in detail within the third section (Discussion and Summary).
One restriction applied to all these scenarios was the atmospheric surface pressure, which corresponds to the terrestrial one. In another study (*Neubauer et al.*, 2013) the outer limit of the life supporting zone for CO_2-rich atmospheres was modelled. Several studies have been performed on this matter for the case of low atmospheric pressures, but in the present case line and continuum absorption becomes more important. The calculations have been performed for sulfuric acid, water and water-ammonia solvent-scenarios as well as for a large spectrum of stellar and planetary parameters. The orbital distance of the model planet has been varied from 0.3 to 1.7 AU around a G-star, from 0.17 to 0.99 AU for K-stars and from 0.046 to 0.26 AU for M-stars. The stellar flux varied corresponding to the orbital distance from 118 to 3781 W m^{-2}. Planetary albedo was modeled from 01. to 0.8, planetary masses for 1 and 10 Earth-masses have been implemented as well as atmospheric pressure scenarios from 1 to 100 bar with pure CO_2. Additionally, this parameter study also has been applied to several different Kepler candidate planets in order to determine their habitability characteristics. The results of this study will be discussed with the previous one in the third section of this thesis.

1.2.1 Description of the work done by the present author

In following manuscripts are reprinted within this thesis in order to describe the studies on the potential origin of exotic life as well as the life supporting zone as a hand-tool to help with the identification of regions around stars, where classic and exotic life could exist:

Simulations of Prebiotic Chemistry under Post-Impact Conditions on Titan
by Carol Turse, **Johannes Leitner**, Maria Firneis and Dirk Schulze-Makuch

- Published online on December 17, 2013 in the journal "Life"
  Life, 3, p. 538-549, DOI: 10.3390/life3040538
- Impact factor of the journal: not available (established in 2011)
- Quota of this study, done by the present author:
  Idea/concept for the experiment: 100 %, theory: 100 %, experimental work: 0 %, analysis and discussion: 70 %
- **Work on the article done by the author of this thesis:**
  The idea and the concept for this study and the resulting paper was formulated by the present author. Therefore, the author looked for an international cooperation partner, because it was not possible to perform the laboratory study within the facilities of the research platform of ExoLife by the lack of a chemistry laboratory. Together with the allocated partners from Washington State University (WSU) the present author discussed and defined the experimental set-up and did the budget calculations for the experiment. The scenario for the experimental runs (e.g. the composition of the hypothetical atmosphere and the composition of the alternative solvent – a water-ammonia composite) was also performed by the present author. The present author also discussed with the partners further possibilities for the experiment as the experimental

temperature and pressure conditions, which finally – unfortunately – have not been able to cover a broader spectrum by financial restrictions for the experiment. The experiment in the laboratory itself was performed at a laboratory of the WSU in the USA and by the present author's colleague Carol Turse. The present author has also been strongly involved in the definition of the time sequence of the setting of the tesla coil sparks. The analysis of the samples have been performed by an external laboratory by the reason that the necessary analysis equipment was also not available at the laboratory at the Washington State University. Carol Turse sent back to the present author the final analysis report with the amino acids corresponding to the peaks in the spectrum. In the discussion part of the paper the experimental situation of the break-up of the amino acids after 7 days have been discussed by the present author. In addition to a probable contamination explanation for the identified diphosphate-like compound by a carry-over of the cleaning solution, which is identified by the present author, he also found another very probable explanation for the break-up of the amino acids: the continued sparkling, which posed the question on the maximum amount of ammonia in the solvent allowed to produce stable amino acids. This question will be matter of a follow-up study of the present author.

The HADES Mission Concept – Astrobiological Survey of Jupiter's Icy Moon Europa
by Thomas Böttcher#, Liliane Huber#, Lucille Le Corre#, **Johannes Leitner**#, David McCarthy#, Ricky Nilsson#, Carlos Teixeira#, Sergi Vaquer Araujo#, Rebecca Wilson#, Fatah Adjali, Martin Altenburg, Giacomo Briani, Peter Buchas, Aurélie Le Postollec, Teresa Meier
#these authors have contributed equally to the paper (see also original paper)
ANNOTATION: The sequence of authors marked with # is alphabetically (so that not Böttcher cannot be identified as the only first author), because these authors have contributed majorly to the article.

- Published online on August 26, 2009 in the "International Journal of Astrobiology"
- International Journal of Astrobiology, 8, p. 321-329, DOI: 10.1017/S147355040999022X
- Impact factor of the journal: 1.452 (2012)
- Quota of this study, done by the present author: Mission concept/objectives: 20 %, surface/interior science: 100 %, cryobot calculations: 100 %
- **Work on the article done by the author of this thesis:** The idea for this mission feasibility study was born during the Alpbach summer school on Astrobiology and has been completed by the authors during the following two years. The present author contributed to this study besides the general mission aspects and science objectives especially the whole part related to surface and interior science. This includes the proposed instrumental set-up as well as their technical limitations. Furthermore, the cryobot design was completely done by the present author. Several different scenarios have been studied by the present author, which includes drilling, melting and combinations of both techniques. Furthermore, also stability analyses on the crybot during the melting process, as well as heat budget and thermodynamic calculations on the velocity of melting through the crust of Europa have been performed by the present author.

Development of a Model to Compute the Extension of Life Supporting Zones for Earth-Like Exoplanets
by David Neubauer, Aron Vrtala, **Johannes Leitner**, Maria Firneis, Regina Hitzenberger

- Published online on December 3, 2011 in the journal "Origin of Life and Evolution of Biospheres"
- Origin of Life and Evolution of Biospheres, 41, p. 545-552, DOI: 10.1007/s11084-011-9259-9
- Impact factor of the journal: 1.831 (2012)

- Quota of this study, done by the present author:
  Concept/model description: 100 %, parameter definitions and calculations: 100 %, implementation of the new model in the existing code: 0 %, interpretation of data: 70 %
  ANNOTATION: Aron Vrtala has developed the first version of this model several years ago, but was not part of this and further studies related to the Life Supporting Zone.
- **Work on the article done by the author of this thesis:** The whole idea, concept and physical description of the model of the life supporting zone was done by the present author. Several first-author conference publications (see below) illustrate the step-by-step evolution of the model of the life supporting zone. Furthermore, the solvents used in the model have also been studied by the present author with respect to their physical parameters and their ability to serve in the process of the origin of life as well as with respect to mechanisms which could enable their presence on planets. The cloud and the radiative convective model was encoded prior to this study, and further developed by Neubauer and in accordance with the present author modified for the purpose of calculating the life supporting zone and the surface temperature of selected exoplanets. The calculations on the planetary (including atmospheric) parameters as well as the model parameter set-up of Earth, Venus and Titan have been done by the present author.

The Life Supporting Zone of Kepler-22b and the Kepler Planetary Candidates: KOI268.01, KOI701.03, KOI854.0 and KOI1026.01
by David Neubauer, Aron Vrtala, **Johannes Leitner**, Maria Firneis, Regina Hitzenberger

- Published online on August 7, 2012 in the journal "Planetary and Space Science"
- Planetary and Space Science, 73, p. 397-406, DOI: 10.1016/j.pss.2012.07.020
- Impact factor of the journal: 2.245 (2012)
- Quota of this study, done by the present author:
- Concept/model description: 100 %, parameter definitions and calculations of the physical properties of the planets of interest: 100 %, definition of the atmospheric scenarios: 50 %, implementation of the parameter in the existing model: 0 %, investigation of the spectral characteristics of M-stars: 100 %, interpretation of the data: 60 %
- **Work on the article done by the author of this thesis:** In this article the present author has investigated together with his colleagues the dimension of the life supporting zone around selected star systems and especially the surface temperature of selected exoplanets and exoplanet candidates, respectively. Based on the latest available observational data the present author has performed estimates on the potential of the Kepler (candidate) planets to host life. Further, the present author has done model calculations with the aim to get (better) estimations on the physical parameters of the most promising planets and with respect to their potential to host different solvents on their surfaces (which consequently is a function on the temperature of the planetary surfaces). The present author has defined the final model scenarios for the calculations in accordance to the present knowledge of stellar and planetary parameters – e.g. terrestrial-like or ocean planets. The parameters of the finally selected planets have been implemented in the model developed and described in the previous article. The present author together with Neubauer has defined different atmospheric scenarios for further implementation in the model of the life supporting zone. The life supporting zones have been calculated with the model described above and with respect to the planetary albedos, the potential of the planets to host the solvents of interest resulted. The interpretations of the data have been done by the present author in accordance with Neubauer.

The outer limit of the life supporting zone of exoplanets having CO_2-rich atmospheres: virtual exoplanets and Kepler Planetary Candidates
by David Neubauer, **Johannes Leitner**, Maria Firneis, Regina Hitzenberger

- Published online on May 2, 2013 in the journal “Planetary and Space Science”
- Planetary and Space Science, 84, p. 163-172, DOI: 10.1016/j.pss.2013.04.012
- Impact factor of the journal: 2.245 (2012)
- Quota of this study, done by the present author:
- Concept/model description: 100 %, parameter definitions and calculations of the physical properties of the planets of interest: 100 %, definition of the atmospheric/pressure scenarios: 50 %, implementation of the model: 0 %, data interpretation: 70 %
- **Work on the article done by the author of this thesis:** The main restriction in the previous two studies was posed by the limitation to the terrestrial surface pressure. The present author initiated further development of the previous described model up to pressures of 100 bar. The model code was further developed to simulate a large spectrum of exoplanet model scenarios defined and calculated by the present author in order to cover a broad range of potential exoplanet scenarios around defined M-, G- and K-stars. From the Kepler list of planetary candidates the present author selected various interesting objects for a verification of their potential habitability and did all the additional model calculations to provide the parameters for simulation runs. The model results have been interpreted by the present author in order to derive some general statements on the behavior of exoplanets and Super-Earths with respect to various planetary parameters.

In addition to these papers, a selection of conference presentations and abstracts associated with the outlined matter is given consecutively:

Firneis M. G., **Leitner J. J.**, Hitzenberger R., 2009, *The life supporting zone – looking for Life as we do not know at preset times*; Abstracts of the 4th European Planetary Science Congress, 2009, Abstract No. EPSC2009-554.

Leitner J. J., Schwarz R., Funk B., Pilat-Lohinger E., Firneis M .G., Dvorak R., Eybl V., Aittola M., 2008a, *Alternative solvents as a basis for life supporting zones in planetary systems*; Abstracts of the 3rd European Planetary Science Congress, 2008, Abstract No. EPSC2008-A-00485.

Leitner J. J., Schwarz R., Funk B., Pilat-Lohinger E., Firneis M. G., Aittola M., Lhotka C., Eybl V., 2008b, *Habitable zones around main sequence stars based on solvents others than water*; Abstracts of the International Extra-Solar Super-Earths Workshop, p. 38.

Leitner J. J., 2010, *The new concept of the life supporting zone as a topic of the research platform on ExoLife;* General Assembly of the Austrian Society for Astronomy and Astrophysics 2010, held in Graz, Austria, April 9-10, 2010.

Leitner J. J., Neubauer D., Schwarz D., Eggl S., Firneis M. G., Hitzenberger R., 2010a, *The life supporting zone I – from classic to exotic life*; Abstract of the European Planetary Science Congress, held in Rome, Italy, September 19-24, 2010.

Leitner J. J., Firneis M. G., Hitzenberger R., 2010b, *Potential habitats for exotic life within the life supporting zone*; Geophysical Research Abstracts, Vol. 12, Abstract No.: EGU2010-12544.

Leitner J. J., Schwarz R., Firneis M. G., Hitzenberger R., Neubauer D., 2010c, *Generalizing habitable zones in exoplanetary systems – the concept of the life supporting zone;* Abstracts of the Astrobiology Science Conference 2010, Abstract No. 5255, LPI Contribution No. 1538.

Leitner J. J., Schulze-Makuch D., Firneis M. G., Hitzenberger R., Neubauer D., 2010d, *Solvents of interest for exotic life on planetary bodies in life supporting zones around main sequence stars*; Abstracts of the 10th European Astrobiology Network Association Science Congress, p. 52-53.

Leitner J. J., Schulze-Makuch D., Firneis M. G., Hitzenberger R., Neubauer D., 2012a, *Solvents of Interest for Exotic Life on Planetary Bodies in Life Supporting Zones Around Main Sequence Stars*; Paleontological Journal, Vol. 46, Issue 9, p. 1091.

Neubauer D., Vrtala A., **Leitner J. J.**, Firneis M. G., Hitzenberger R., 2010, *The life supporting zone II – computation of its extension*; Abstracts of the European Planetary Science Congress, held in Rome, Italy, September 19-24, 2010.

Neubauer D., Vrtala A., **Leitner J. J.**, Firneis M. G., Hitzenberger R., 2011b, *Computation of the extension of life supporting zones*; Abstracts of the Origins 2011 Meeting (ISSOL and IAU-Comm. 51 Joint International Meeting), held in Montpellier, France, July 3-8, 2011.

Additional article:

Leitner J. J., 2009, *Exotisches Leben – Auf der Suche nach biologischer Komplexität abseits terrestrischer Normen*; Raumfahrt Concret, Nr. 59-60, p. 8-10.

1.3 CETI/LINCOS – Limits of Mathematical Languages

In our study on the evolution on the artificial mathematical language LINCOS and its further development NEW LINCOS, we have focused on its historical utilization and its usability for potential communication with extraterrestrial civilizations (CETI). With LINCOS and NEW LINCOS a language has been developed several years ago claiming to be able to encode not only mathematical relations self-explicant, but also to allow encoding of complex sociological matters. In a review we have analyzed this language which also has been used in the past to encode active SETI projects as COSMIC CALL (1999 and 2003). LINCOS/NEW LINCOS is meant to be auto-interpretative, which means elementary inductive definitions of terms and the use of elimination to deduce facts from premises is easily possible, when applied to formal science, but needs further improvement when it should be applied to encode complex sociological matters, as for example a description of the Human Being. This problem enhances, when assuming intelligent aliens, which comprise the same physical and chemical characteristics as well as environmental conditions as Mankind (no exotic forms of life), but nevertheless, they also need to have comparable sociological concepts.

1.3.1 Description of the work done by the present author

Following manuscript is reprinted in order to describe the work on the evolution of LINCOS and its limitations for CETI:

The evolution of LINCOS: A language for cosmic interpretation
by Maria Firneis, **Johannes Leitner**

- published in October 2013, in
- "The History and Philosophy of Astrobiology: Perspectives on the Human Mind and Extraterrestrial Life", Editors: D. Duner, J. Parthemore, E. Perrson, G. Holmberg; Cambridge University Press, p. 201-210.
- Quota of this study, done by the present author:
  Background research: 50 %, analysis and discussion: 50 %
- **Work on the article done by the author of this thesis:** Within this study the present author has performed some historical studies on the further development of LINCOS to NEW LINCOS and analyzed these artificial languages for present CETI purposes. Additionally also recent cosmic messages have been studied with respect to their information content and target and described firstly in a clear way. Thereby, the present author has performed especially the background research on NEW LINCOS and on the mathematical background of this code. Further, the present author analyzed the ability of LINCOS and NEW LINCOS with respect to its potential to encode non-mathematical (e.g. sociological and pictographic) information and concluded that within the present formulation of this language a non-human being would presumably not be able to decode a message.

In addition to this article, a conference presentation and abstract associated with this topic is given consecutively:

Firneis M. G., **Leitner J. J.**, 2011, *The evolution of LINCOS – a language for cosmic intercourse*; Abstracts of the International Conference on the History and Philosophy of Astrobiology, held in Ven, Sweden, September 27-28, 2011.

2. Peer-reviewed Manuscripts

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Conference article [1]

The Need of a Non-Earth Centric Concept of Life

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Abstract: Most definitions and working hypotheses for life used nowadays either list detailed properties of terrestrial life-forms or include general strategies of life-as-we-know-it. Consequently, both approaches can be designated as geocentric conceptions of life. Evolution and reproduction often pose basic concepts utilized to describe life, which accompany definitions of life as well as present strategies for the search for extraterrestrial life, although providing an experimental evidence for these system properties is far beyond our present technical possibilities. We demonstrate that both, evolution and reproduction are unsuitable strategies for definitions and descriptions of life, because when strictly applied to the Homo sapiens sapiens, then even the human population cannot be designated as representative for life due to the symbiotic metabolism of all individuals and their need of an 'assisted reproduction'. Consequently the focus regarding the description of life should not be reproduction anymore, but the ability of a living system to conserve itself. In order to look for life beyond Earth, a general view on life is required, which also includes solvents and chemical structures not necessarily implemented on Earth.

Keywords: definition of life; exotic life; reproduction; evolution

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[1] Leitner, J.J.; Firneis M. G. Defining life in a non-geocentric way. EPSC-DPS Joint Meeting, 6, Nantes, France, October 3-7, 2011.
Leitner, J.J.; Firneis M. G. Is a definition of life only of academic or also of common interest? AbSciCon 2012, Atlanta, USA, April 16-20, 2012.

1. Introduction

During the recent months and years a large number of proposals for definitions of life have been published (see for an overview e.g. [1-3]). Nevertheless, an international consensus on this question has not been achieved up to now due to different points of views on the nature of life in general, the difference between living and non-living individuals as well as systems and the representative characteristics of terrestrial life. There is also an ongoing discussion if it is possible to define life with only the terrestrial sample at hand and the fact that a general theory of life is necessary before defining life as a universal concept [4-5].

Nevertheless, as McKay [6] asked '*How can we find something, which we cannot define or describe?'*, we need at least some physical constraints of life for the search for life. Considering this background, a definition or hypothesis of life remains to be not only of philosophical interest, but seems to be a necessary step for the detection of extraterrestrial life. Therefore, even when we accept that an exact description of life is not within our present capabilities, it will be necessary to deepen our knowledge on the concepts of life, on its most important system parameters and strategies. Without such a model it is not possible to design proper experiments to detect life in extraterrestrial environments as it is not clear for which markers to look for.

Additionally, a description and theory of life should not only give an answer when asking for the parameters of life-as-we-know-it (now), but also on the scenarios for life-as-it-initially-was and life-as-it-could-be (not only artificial) [7], which makes looking for life-as-we-know-it just to the first justifiable step [8]. We should be open-minded to the possibility that life also exists in unexpected forms (see e.g. [9]). The aim of this study is not to summarize various definitions of life and to discuss them in detail, but to re-investigate the often used strategies of reproduction and evolution for definitions of life with focus to their usability for a life definition or description.

2. Life-As-We-Know-It – Terrestrial/Classical Life

Only in natural science more than 300 attempts for definitions of life can be found. 70 years ago Erwin Schrödinger centered the question on the nature of life on entropy [10]. He stated that life is the ability of an organism to channel a '*flow of order*' on itself in order to prevent a decay in chaos, thus to '*drink order*' from its environment. Based on this approach, following questions still remains unanswered: How much energy does life need to originate? Are there upper and lower boundaries that enable life to exist? Another well-known definition of life, the PICERAS definition [11], consists of seven pillars describing the principles of life: program, improvisation, compartmentalization, energy, regeneration, adaptability, and seclusion. These seven pillars describe the way life on Earth has selected for its existence, but it cannot excluded that extraterrestrial life potentially has found different ways [12].

In an outstanding study, Tsokolov [1] subdivided the existing definitions of life into three different categories: (1) life definitions that use terms that are themselves undefined or defined in different ways in different scientific disciplines, (2) lists of selected properties of terrestrial life are called a definition and (3) definitions based on the concept of minimal life. Minimal life designates the simplest life possible and does not deal with higher evolved life-forms. Nevertheless, taking minimal life into account, it is clear that the origin of life and its evolution is a continuous process, which complicates finding a definition [7]. Most approaches of definitions used nowadays refer to the second category of Tsokolov. A detailed example for such a definition is given in the study of Deamer [13] and takes both the nucleic acids and proteins of terrestrial life and their interactions into account. Unfortunately, a generalization of a detailed description of life holds the risk of neglecting the important points and attenuates itself (see also [13]).

The main aim of a definition of life is not to define life in elegant words, but to unveil its main parameters and strategies, which can help us to look for life on other worlds. Nevertheless, trying to define life in well-shaped phrases is not meaningless, because by doing so, we can obtain a better understanding of the problems of defining life and its possible strategies (see therefore also [14, 12]).

Furthermore, several listings of terrestrial properties of life focus on metabolism, thermodynamic disequilibrium, terrestrial elements of life: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur, water as solvent and reproduction and (Darwinian) evolution (see e.g. [15] and [1] and the references within). Especially these six chemical elements will often be designated as the key elements and water as the key solvent for terrestrial life. The original Miller-Urey experiment [16] and its follow-up experiments simulated the origin of the building blocks of life based on water as solvent and probing different atmospheric compositions as well as different energy sources as electric discharges, shock waves, thermal energy, UV-light, electron irradiation, and high-temperature plasma always resulted in the production of amino acids or associated predecessor molecules (see [17] for a review). According to these results for the presumable origin of terrestrial life and its need of water as solvent the “follow the water” strategy [18-19] seems to be plausible. Most of the present approaches in astronomy and astrobiology focus this concept, e.g. the theory of habitable zones [20] or more detailed: the usage of antibodies as a way to detect small peptides, proteins, and cells on Mars [21].

However, all these strategies focusing on the six terrestrial key elements of life and its building blocks as well as water have in common that they only allow a description of terrestrial life and so far, when used for the search for life only the detection of biomarkers or fragments for life-as-we-know-it is possible. Consequently, this approach can be designated as geocentric view of life.

Additionally several definitions, hypotheses or descriptions of life include, besides a metabolism, also Darwinian evolution and reproduction, although bringing an evidence for these mechanisms is far beyond our present technical capabilities. In the following two sections the usability of them is briefly re-investigated.

2.1. Evolution as a Convenient Criterion for Definitions of Life?

The NASA working hypothesis ‘*life is a self-sustaining chemical system capable of undergoing Darwinian evolution*’ [22] takes care of the evolutionary aspect of life and thereby also on its ability to adapt to changing environmental conditions. Luisi re-analyzed this hypothesis and proposed some additions because the original wording does not yield pragmatic aspects to search for [7]: The word ‘self-sustaining’ is considered not to be defined strictly enough as well as the phrase ‘capable to Darwinian evolution’. How should it be possible to observe such an evolution? When considering the timescale for evolutionary processes it seems in any case to be a non-useful strategy to search for when looking for life on other worlds. Based on this problem, Luisi proposed as an alternative ‘*a system* *which is self-sustaining by utilizing external energy/nutrients owing to its internal process of component production and coupled to the medium via adaptive changes which persist during the time of history of the system*'.

In a study of Benner [23] on the 'definition used by NASA' it is asked if it is necessary that a biological system is capable of Darwinian evolution during the whole lifetime of the species. As we discuss in the next section our answer to this question is no. Benner also discussed the word 'capable', which is additionally of high importance, because it does not rule out evolutionary processes beyond Darwinian evolution and includes all possible genetic engineering facets which could be possible within the next years and centuries in case of humans.

When not accepting evolution as a life criterion then 'a self-sustaining chemical system' will remain. As in the last years several times the phenomenon of fire has been discussed within the context of life, we would like to follow this path and add another critic on the 'NASA definition' within this context. As long as nutrients (flammable material in case of fire or nutrients for classical life-forms) will exist, fire will be alive. It shows a metabolism, a thermodynamic disequilibrium as well as it can reproduce itself for instance via flying sparks. So far, also 'self-sustaining chemical system' is not the way to hypothesize on life in an adequate way.

To summarize we have to ask: is evolution a necessary property for life or is it a consequence? In general, is a biological system without the ability for evolutionary processes within the range of possibilities, for instance by acquiring a very efficient repair mechanism? Is it alive anymore? Following Darwin and the modern evolutionary synthesis evolution with selection as the driving force, evolution seems to be the natural consequence of reproduction and it is inevitable. Consequently it is necessary to discuss the evolutionary potential of a biological system together with reproduction.

2.2. Reproduction as a Convenient Criterion for Definitions of Life?

As mentioned in the previous sections a large number of definitions and working hypotheses for life focus on the ability of reproduction. In case of generative reproduction it is apparent that this ability has to be complied more on a biological system, a population, rather than on one individual (see therefore also the popular anecdote given in [7, 11]). This fact cannot only be subjected to the gender of the individual. Furthermore, the age of the individuals also plays a dominant role as there have to be a specific percentage of the individuals in a system that must be able to reproduce itself.

Taking humanity as an example, not all individuals are fertile (excluding for the calculation separate individuals, who are unable or unwilling to reproduce themselves during their whole life-span). Differences, not only in genetics, ethnics, psycho-social background and as a consequence of different nutrition and medical care may form large distinctions between various countries. For the following estimation data only from Germany (total country), as an example for a country with a highly developed medical care system, are used. When considering German females, then their ability to reproduce begins close to acquiring the menarche and ends with the menopause. The mean age of menarche of females in Germany was found to be 12.2 years at present, the mean age of acquiring the menopause is 51 years [24]. When assuming a birth date in 2011 then the female life expectancy is 83.01 years [25]. Calculating the percentage of the time when a female individual in Germany will be in fecund state results in 46.7 % of their total lifespan. Further of interest is the question why human females acquire menopause in general. Besides humans only very few other species (e.g. great apes and thereby probably chimpanzees, orangutans, gorillas, baboons; macaques; subspecies of tamarins; as well as some whales) are known to acquire menopause [26]. Several different explanations exist (see [27] for an overview), but it seems to be more related to psycho-/social-reasons than to biological ones. This quota of individuals capable for reproduction will be irrelevant when considering the whole existing species of Homo sapiens sapiens, nevertheless, a specific percentage of a species should be able to reproduce to ensure an appropriate genetic diversity and the conservation of the species.

Another phenomenon of importance for the discussion of the utility of reproduction for definitions of life is the question on sterile species [28]. In this case reproduction once more cannot be applied for definitions and sterile species consequently do not take part in further Darwinian evolution [29]. In the study of Kolb [28] a solution to this problem is proposed by defining life in two different ways: (1) life as a phenomenon and (2) life as a set of characteristics of an individual organism: '*In the first way life is a continuous phenomenon, which is carried on by a series of individual organisms which themselves perish within a time period that is much shorter than that of the phenomenon of life. When we consider the life of an individual organism, we quickly realize that reproduction is not the key feature that makes it alive. Reproduction of some, but not of all individuals is essential. For the second way reproduction is not essential.*'

This concept backs our previous calculation, where it was shown that female humans are capable to reproduce less than 50 % of their life-time. But hybrids as mules or hinnies cannot reproduce themselves for 100 % of their life-time. It was earlier shown that reproduction as a key element for a definition of life in case of an individual is not suitable, and in the case of mules it is also not capable for the species as a biological system. Consequently, when not neglecting that mules are 'alive', then reproduction should be only interpreted as a probable, but not necessary consequence of life. For the sake of completeness it must be annotated that contrary to the public and scientific opinion that mules will be absolute sterile the old Roman phrase *cum mula peperit* describes the rare event, when still reproduction happens [30]. Kay reports in a study [31], that since 1527 60 events of mules giving births have been counted. An explanation for this rare but free of doubt existing phenomenon is still missing, but probably is related to a genetic defect in the different set of chromosomes of donkeys and horses. Nevertheless, such a small reproduction rate will not allow the species to sustain itself.

Additionally, we want to briefly discuss viruses. According to the concept of the three domains [32], viruses are not categorized as life-forms, but nevertheless, a debate on this topic is still ongoing (e.g. [28, 29, 33]) and very sensible to the applied definition of life. Following the NASA definition, viruses must be counted as life-forms. As it is known, a virus does not possess an own metabolism and consequently it needs a host cell for its reproduction. Kolb [28] defined the need of viruses to have host metabolisms/cells, to be parasitic on ribosomes as '*assisted reproduction*'. When we consider this situation within the context of humans an interesting problem will arise. A human being is only able to manage its metabolism with the help of microorganisms, which are needed for example for the supply of some vitamins, trace elements, essential amino acids or for the reduction of carbohydrates. A total amount of bacteria of about 10^{14} is associated with a human, in contrast to only 10^{10} cells of a human body [34]. Even when we neglect the high importance of microorganisms for the immune system, without bacteria we will not be able to survive. This kind of symbiosis between microorganisms and humans (not only humans, but also various other animals) could also be interpreted as 'assisted metabolism'. As we are parasitic on these compounds, the Homo sapiens sapiens can also be designated to need 'assisted reproduction'.

As a consequence the question remains unanswered, why when not including viruses in the tree of life, how can we include the humanity?

3. Life-As-We-Do-Not-Know-It – Exotic Life

With one sample of life at hand it would be a presumptuous and geocentric way of thinking to state that life elsewhere in the Universe has to show the same properties as life on Earth. This idea has been remarked by a large number of scientists all over the world. Nevertheless, presently we only know this one sample of life and our effort to acquire a second one has not been crowned with success up to now. Thereby, not only extraterrestrial habitats are of interest, even Earth could not be excluded to find different 'kinds of life' [35], but the question how to search for a second sample in the best way remains unsolved. As we are not able to define life-we-know, how can we reasonably search for life-we-do-not-know? Several definitions or working hypotheses for life in a universal manner will exist too, but most of these concepts do not allow deriving exact parameters and characteristics to look for.

Kolb [28, 36-37] gives a definition of life, which is proposed not to be geocentric: '*Life is a new quality brought upon an organic chemical system by a dialectic change resulting from an increase in the quantity of complexity of the system'*. In a similar way Pace [38] concluded that it is very likely that organic chemistry is the basis for life elsewhere in the Universe, which the given working hypothesis for life in this study also reflects: '*Life is a self-replicating, evolving system expected to be based on organic chemistry*'. Neglecting here 'self-replicating' as well as 'evolving system' as both phrases have been discussed earlier then the remaining core of the definition is the requirement of carbon as backbone for life. Nevertheless, even though life on Earth is based on organic chemistry, we do not know if this is the ultimate fundament for life.

Pace [38] mentioned the ability of silicon to serve as backbone for life. However, silicon as basis-element offers less possible interactions with other atoms than carbon. Some preliminary studies have been carried out on alternatives to water and carbon as the ultimate life ingredients [15, 39]. Rampelotto [40] has also re-investigated silicon as an alternative to carbon, which could especially suit as an alternative for environments with less water, without oxygen and with a higher surface pressure than on Earth. Several other authors [e.g. 41-42] have also illustrated alternatives to the terrestrial CHON biochemical system. Solvents different to water as ammonia, sulfuric acid or formamide, but also apolar solvents as methane, ethane, and cryosolvents were proposed by Baross et al. [15], but also composites of different solvents, e.g. water-ammonia mixtures, seems to pose an option. Such composites could be of great interest for icy moons, because model calculations show that large amounts of ammonia could be dissolved in potential water oceans of various satellites or TNOs [see e.g. 43]. Since lakes of (at least partly) liquid methane/ethane have been discovered on Titan [44], we definitely know an example for available alternative solvents in our Solar System. McKay and Smith [45] have studied the possibilities of methanogenic life on Titan based on the available energies and potential metabolisms. Plankensteiner et al. [46] performed laboratory experiments on a potential chemical evolution on Titan and besides nitriles produced also nitromethane, which can theoretically serve as a basis for a further synthesis of more complex organic compounds than amino acids. In another study, an early Titan scenario after an asteroid impact was simulated with respect to the synthesis of amino acids in a water-ammonia composite via a Miller-Urey apparatus [47]. Therein similar amino acids than in the classical Miller-Urey experiment originated and this underlines the fact that a dissolving ammonia in an extraterrestrial water reservoir still allows the origin of (terrestrial) building blocks of life.

Most definitions and working hypotheses for life used nowadays are not designed for life-as-we-do-not-know-it and consequently not able to deliver parameters to search for. In general, the idea that life elsewhere in the Universe necessarily has not to follow the same paths than life on Earth and it is not necessarily based on the same chemical characteristics than terrestrial life, is not revolutionary new (see for a historical overview [48]), but only a small number of studies on this topic have been carried out up to now. In a study of Schulze-Makuch [42] some properties for alien life in exotic forms are discussed: '*life is a complex system (1) composed of bounded compartments in thermodynamic disequilibrium with the external environment, (2) capable of transforming energy and the surroundings to maintain a low-entropy state, and (3) persisting through the encoding and transmission of information for self-replication*'. This concept with respect to the arguments (1) and (2) is similar to the list of properties of life of Baross et al. [15], but without focusing on specific chemical elements and consequently more universal than Baross' listing, but in a geocentric way of thinking argument (3) remains. A more advanced definition is given in a follow-up study of Schulze-Makuch and Irwin [49] where a '*living entity is defined as (1) a self-organizing bounded local environment in disequilibrium with its surroundings that (2) converts free energy and materials from its environment through metabolic processes that maintain a low entropy state and perform work, and that (3) reproduces its form from raw materials and its functional capabilities on the basis of an instructional code transmitted to successive reiterations of the entity*'. A similar universal definition is given in Irwin and Schulze-Makuch [50], again using reproduction as a criterion for the definition. Self-replication in the first definition-attempt is a terrestrial concept and we wish to repeat, that we cannot exclude life-forms without self-replication, but with a very efficient molecular repair mechanism for example. When we try to formulate this argument more generally, then we should only focus on the ability of a species to be able to conserve itself.

4. Conclusions

Nietszche once wrote '*there are concepts that can be defined, whereas others only have a history*' (cf. [52-53]). On the one hand we should learn more about the concepts of life and its history and evolution, and after acquiring a (universal) theory of life and a second sample, we can continue to define life in an adequate and elegant way. But on the other hand, for acquiring a second sample of life, we should not neglect the possibility of life beyond the terrestrial properties and resulting from the arguments discussed previously against evolution and reproduction as key terms for a working hypothesis of life (see also [6]), we will propose here a more general hypothesis of life. The following list of properties is related in some arguments to the list definition in [15], but generalizes the terrestrial components: (1) life is based on a metabolism, which is working symbiotically or asymbiotically, (2) life exploits a thermodynamic disequilibrium, (3) the macromolecules that enable the metabolisms, the building of structures, energy management and transfer of information, are a consequence of specific elements to form polymers with the ability to chemically bind functional groups, (4) the molecules of life interact with a solvent to be soluble (or not) or to react (or not) in a way that confers fitness of the life-form, (5) life has the ability to conserve its species.

The third argument also mentions the building of structures, which is realized via cells in case of terrestrial life, and seems to be an essential ingredient for life. Within this context the lack of structural properties in the popular definition of life used by NASA is criticized in [12].

Life does not necessarily have to be based on the six key-elements of terrestrial life and on the interaction of biomolecules with water to be soluble (or not) or to show a reaction (or not). A hypothetical life-form, which is not based on the six key-elements of terrestrial life and water, should be designated as exotic life. We propose the phrase 'exotic life' for this possible phenomenon [51], because in the present literature a lot of different names are used to describe alternative forms of life (alternative life, exo-life, weird life, etc.). While using (classic) life for life-as-we-know-it on Earth, exotic life describes life which we-do-not-know (but we cannot rule out that it even exists on Earth). Nevertheless, the question remains how to look for life, classical or exotic, in a general manner. The follow-the-water strategy [18-19] lays the focus on the solvent, the follow-the-energy [54-55] can be derived from the thermodynamic disequilibrium condition, but both have failed in our previous attempts to find life. In contrast the search for biomarker seems to be a promising alternative when we can determine accurate compounds, which only within a living system can be synthetized. Great afford are done on this concept at the moment, but also limiting factors as the spectroscopic resolution have to be improved in order to identify compounds in extrasolar planet atmospheres, which also can be associated with life. This follow-the-nutrients strategy seems to be the most promising way to look for (exotic) life, but a lot of laboratory work is still necessary to validate the idea of life beyond water and carbon and to derive adequate markers.

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Conflicts of Interest

The authors declare no conflict of interest.

References and Notes

1. Tsokolov, S.A. Why is the definition of life so elusive? Epistemological considerations. *Astrobiology* **2009**, 9, 401-412.
2. Bedau, M. An Aristotelian account of minimal life. *Astrobiology* 2010, 10, 1011-1020.
3. Bains, W. What do we think life is? A simple illustration and its consequences. *Int. J. Astrobiol.* **2013**, DOI: http://dx.doi.org/10.1017/S1473550413000281.
4. Cleland, C.E.; Chyba, C.F. Defing 'life'. *Origins Life Evol. Biospheres* **2002**, 32, 387-393.
5. The meaning of life. http://seedmagazine.com/content/article/the_meaning_of_life (accessed on 30 December 2013).

6. McKay, C.P. What is life – and how do we search for it in other worlds. *PLoS Biol.* **2004**, 2, 1260-1263.
7. Luisi, P.L. About various definitions of life. *Origins Life Evol. Biospheres* **1998**, 28, 613-622.
8. Raulin, F. Searching for an exo-life in the Solar System. *Origins Life Evol. Biospheres* **2010**, 40, 191-193.
9. Leitner, J.J.; Firneis M. G. Defining life in a non-geocentric way. In *Abstracts of the EPSC Meeting* 2011. EPSC-DPS Joint Meeting 2011, Nantes, France, October 3-7, 2011.
10. Schrödinger, E. *What is life?* Cambridge University Press, Cambridge, UK, 1944.
11. Koshland, D.E. The seven pillars of life. *Science* **2002**, 295, 2215-2216.
12. Zhuravlev, Y.N.; Avetisov, V.A. The definition of life in the context of its origin. *Biogeosciences* **2006**, 3, 281-291.
13. Deamer, D. Special collection of essays: what is life? *Astrobiology* **2010**, 10, 1001-1002.
14. Morange, M. The resurrection of life. *Origins Life Evol. Biospheres* **2010**, 40, 179-182.
15. Baross, J.A. et al. *The limits of organic life in planetary systems*. Committee on the Limits of Organic Life in Planetary Systems, Committee on the Origins and Evolution of Life, National Research Council, National Academies Press, Washington DC, USA, 2007.
16. Miller, S.L. A production of amino acids under possible primitive Earth conditions. *Science* **1953**, 117, 528-529.
17. Rode, B.M.; Fitz, D.; Jakschitz, T. The first steps of chemical evolution towards the origin of life. *Chem. Biodiversity* **2007**, 4, 2674-2702.
18. Hubbard, G.S.; Naderi, F.M.; Garvin, J.B. Following the water, the new program for Mars exploration. *Acta Astronaut.* **2002**, 51, 337-350.
19. Jones, E.G.; Lineweaver, C.H. To what extent does terrestrial life “follow the water”? *Astrobiology* **2010**, 10, 349-361.
20. Kasting, J.F.; Whitmore, D.P.; Reynolds, R.T. Habitable zones around main sequence stars. *Icarus* **1993**, 101, 108-128.
21. Fernández-Calvo, P.; Näke, C.; Rivas, L.A.; García-Villadangos, M.; Gómez-Elvira, J.; Parro, V. A multi-array competitive immunoassay for the detection of broad-range molecular size organic compounds relevant for astrobiology. *Planet. Space Sci.* **2006**, 54, 1612-1621.
22. Joyce, G. Preface. In *Origins of Life: The Central Concepts*, D.W. Deamer, G.R. Fleischaker, Publisher: Jones and Barlett, Boston, 1994.
23. Benner, S.A. Defining life. *Astrobiology* **2010**, 10, 1021-1030.
24. Kahl, H.; Schaffrath-Rosario, A.; Schlaud M. Sexuelle Reifung von Kindern und Jugendlichen in Deutschland – Ergebnisse des Kinder- und Jugendgesundheitssurveys (KiGGS). *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz* **2007**, 50, 677-685.
25. Lebenserwartung in Deutschland. http://www.lebenserwartung.info/index-Dateien/ledeu.htm (accessed on 30 December 2013).
26. Walker, M.L.; Herndon, J.G. Menopause in nonhuman primates? *Biol. Reprod.* **2008**, 79, 398-406.
27. Morton, R.A.; Stone, J.R.; Singh, R.S. Mate Choice and the Origin of Menopause. *PLoS Comput. Biol.* **2013**, 9, 1-8.

28. Kolb, V.M. On the applicability of the Aristotelian principles to the definition of life. *Int. J. Astrobiol.* **2007**, 6, 51-57.
29. Raoult, D.; Forterre, P. Redefining viruses: lessons from Mimivirus. *Nat. Rev. Microbiol.* **2008**, 6, 315-319.
30. Chandley, A.C.; Clarke, C.A. Cum mula peperit. *J. R. Soc. Med.* **1985**, 78, 800-801.
31. Morocco's mule miracle. http://news.bbc.co.uk/2/hi/sci/tech/2290491.stm (accessed on 04 January 2014).
32. Woese, C.R.; Kandler, O.; Wheelis M.L. Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. *Proc. Natl. Acad. Sci.* U. S. A. **1990**, 87, p. 4576-4579.
33. Forterre, P. Defining life: the virus viewpoint. *Origins Life Evol. Biospheres* **2010**, 40, 151-160.
34. Vieira, L.Q.; Oliveira, M.R.; Neumann, E.; Nicoli, J.R.; Vieira, E.C. Parasitic infections in germfree animals. *Braz. J. Med. Biol. Res.* **1998**, 31, 105-110.
35. Davies, P.C.W.; Lineweaver, C.H. Finding a second sample of life on Earth. *Astrobiology* **2005**, 5, 154-163.
36. Kolb, V.M. Short definitions of life. In *Fundamentals of Life*, G. Pályi, C. Zucchi, L. Caglioti; Publisher: Elsevier, New York, USA, 2002.
37. Kolb, V.M. On the applicability of the principle of the quantity-to-quality transition to chemical evolution that led to life. *Int. J. Astrobiol.* **2005**, 4, 227-232.
38. Pace, N.R. The universal nature of biochemistry. *Proc. Natl. Acad. Sci.* U. S. A. **2001**, 98, 805-808.
39. Baross, J.A. The definition of life and the origin of life on Earth. *Bull. Am .Astron. Soc.* **2002**, 34, 1213.
40. Rampelotto, P.H. The search for life on other planets: sulfur-based, silicon-based, ammonia-based life. *J. Cosmol.* **2010**, 5, 818-827.
41. Bains, W. Many chemistries could be used to build living systems. *Astrobiology* **2004**, 4, 137-167.
42. Schulze-Makuch, D.; Irwin, L.N. The prospect of alien life in exotic forms on other worlds. *Naturwiss.* **2006**, 93, 155-172.
43. Hussmann, H.; Sohl, F.; Spohn, T. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. *Icarus* **2006**, 185, 258-273.
44. Stofan, E.R.; Elachi, C.; Lunine, J.I.; Lorenz, R.D.; Stiles, B.; Mitchell, K.L.; Ostro, S.; Soderblom, L.; Wood, C.; Zebker, H.; Wall, S.; Janssen, M.; Kirk, R.; Lopes, R.; Paganelli, F.; Radebaugh, J.; Wyne, L.; Anderson, Y.; Allison, M.; Boehmer, R.; Callahan, P.; Encrenaz, P.; Flamini, E.; Francescetti, G.; Gim, Y.; Hamilton, G.; Hensley, S.; Johnson, W.T.K.; Kelleher, K.; Muhleman, D.; Paillou, P.; Picardi, G.; Posa, F.; Roth, L.; Seu, R.; Shaffer, S.; Vetrella, S.; West, R. The lakes of Titan. *Nature* **2007**, 445, 61-64.
45. McKay, C.P.; Smith, H.D. Possibilities for methanogenic life in liquid methane on the surface of Titan. *Icarus* **2005**, 178, 274-276.
46. Plankensteiner, K.; Reiner, H.; Rode, B.M.; Mikoviny, T.; Wisthaler, A.; Hansel, A.; Märk, T.D.; Fischer, G.; Lammer, H.; Rucker, H.O. Discharge experiments simulating chemical evolution on the surface of Titan. *Icarus* **2007**, 187, 616-619.

47. Turse, C.; Leitner, J.J.; Firneis, M.G.; Schulze-Makuch, D. Simulations of Prebiotic Chemistry under Post-Impact Conditions on Titan. *Life* **2013**, 3, 538-549.
48. Raulin-Cerceau, F. What possible life forms could exist on other planets: a historical overview. *Origins Life Evol. Biospheres* **2010**, 40, 195-202.
49. Schulze-Makuch, D.; Irwin, L.N. *Life in the Universe - Expectations and Constraints*. Publisher: Springer, Berlin, Germany, 2008.
50. Irwin, L.N.; Schulze-Makuch, D. *Cosmic Biology - How Life Could Evolve on Other Worlds*. Publisher: Springer, New York, USA, 2011.
51. Leitner, J.J.; Neubauer, D.; Schwarz, R.; Eggl, S.; Firneis, M.G.; Hitzenberger, R. The life supporting zone I – from classic to exotic Life. In *Abstracts of the European Planetary Science Congress* 5, Rome, Italy, September 19-24, 2010.
52. Tirard, S.; Morange, M.; Lazcano, A. The definition of life: a brief history of an elusive scientific endeavor. *Astrobiology* **2010**, 10, 1003-1009.
53. Lazcano, A. What is life? A brief historical overview. *Chem. Biodiversity* **2008**, 5, 1-15.
54. Hoehler, T.M. Biological energy requirements as quantitative boundary conditions for life in the subsurface. *Geobiology* **2004**, 2, 205-215.
55. Hoehler, T.M.; Amend, J.P.; Shock E.L. A “follow the energy” approach for astrobiology. *Astrobiology* **2007**, 7, 819-823.

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Article

Simulations of Prebiotic Chemistry under Post-Impact Conditions on Titan

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Abstract: The problem of how life began can be considered as a matter of basic chemistry. How did the molecules of life arise from non-biological chemistry? Stanley Miller's famous experiment in 1953, in which he produced amino acids under simulated early Earth conditions, was a huge leap forward in our understanding of this problem. Our research first simulated early Earth conditions based on Miller's experiment and we then repeated the experiment using Titan post-impact conditions. We simulated conditions that could have existed on Titan after an asteroid strike. Specifically, we simulated conditions after a potential strike in the subpolar regions of Titan that exhibit vast methane-ethane lakes. If the asteroid or comet was of sufficient size, it would also puncture the icy crust and bring up some of the subsurface liquid ammonia-water mixture. Since, O'Brian, Lorenz and Lunine showed that a liquid water-ammonia body could exist between about 10^2–10^4 years on Titan after an asteroid impact we modified our experimental conditions to include an ammonia-water mixture in the reaction medium. Here we report on the resulting amino acids found using the Titan post-impact conditions in a classical Miller experimental reaction set-up and how they differ from the simulated early Earth conditions.

Keywords: prebiotic chemistry; Miller-Urey; Titan; amino acids

1. Introduction

In his famous experiment, Stanley Miller added supposed components of the early Earth's atmosphere to a closed system containing a sample "early ocean" as well as electrodes to simulate lightening [1]. His experimental reducing atmosphere contained methane, hydrogen, ammonia and water vapor. After seven days, Miller detected amino acids in the ocean flask in this closed system. Specifically, the amino acids found were alanine, glycine and aspartic acid [1]. Although several different groups had attempted simple organic synthesis under primitive conditions beginning in the early 20th century [2–4], Miller was the first to put the synthesis in the perspective of Darwin's "prebiotic soup". Essentially, he initiated the whole field of the origin of life as a topic of serious scientific investigation. Even though further research has shown that the early atmosphere on the Earth may not have been as rich in methane (and thus reducing) as Miller thought [5,6], with carbon dioxide playing a larger role, localized reducing environments could have existed near volcanic activity [7]. Replicates of the Miller-Urey experiment with carbon dioxide instead of methane have shown that amino acids are much harder to make in the carbon dioxide rich atmosphere [8] However, Miller's experiments remain relevant as a starting point and inspiration in the investigations of the origin of life. Variations of Miller's experiments, some completed by Miller himself, have been completed that include aspects of hydrothermal vents, neutral atmospheres, reducing H_2S atmospheres, as well as volcanic conditions [9]. In each of these variations amino acids or organic precursors of amino acids are produced at some level.

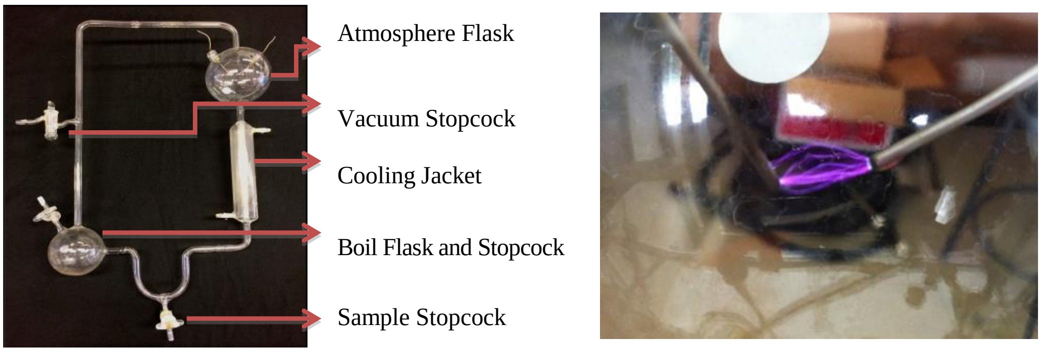
Our research first simulated early Earth conditions based on Miller's experiment and then reproduced it using conditions that may occur on Saturn's largest moon Titan. Specifically we modeled conditions that could occur after a large impact on Titan. We simulated conditions that could have existed on Titan after an asteroid strike [10]. Specifically, we simulated conditions after a potential strike in the subpolar regions of Titan that exhibit vast methane-ethane lakes. If the asteroid or comet was of sufficient size, it would also puncture the icy crust and bring up some of the subsurface liquid ammonia-water mixture. Since O'Brien, Lorenz and Lunine [11] showed that a liquid water-ammonia body could exist for up to thousands of years on Titan after an asteroid impact we modified our experimental conditions to include the ammonia-water liquid in the reaction medium. Static discharge or lightening are expected on Titan due to atmospheric processes such as convective storms [12,13] and as side effect of the asteroid impact. Other discharge experiments simulating the chemical evolution on Titan have shown that it is possible to make carbon, hydrogen and nitrogen compounds that are important precursors to amino acids [14]. Here, we report on the resulting amino acids found using Titan post-impact conditions in a classical Miller experimental reaction set-up and how they differ from the simulated early Earth conditions.

2. Experimental Section

2.1. Experimental Apparatus and Cleaning

An apparatus was built replicating the original apparatus used by Stanley Miller in 1953 [1]. This apparatus contains a 250 mL round bottom flask attached to a 1000 mL atmospheric flask that is in turn attached to a u-bend sample port via a water-jacketed condensation tube (Figure 1a). A heating jacket attached to a Staco variable transformer surrounds the 250 mL round bottom flask and there are several sample ports and stopcocks along the perimeter of the apparatus. Most samples are taken using the stopcock attached to the bottom u-bend. An electrical spark is applied to the leads on the atmospheric flask using a high voltage (20,000–45,000 volts) Tesla coil attached to an analog timer to provide a random on/off cycles. This Tesla coil then initiates a spark in the atmospheric flask (Figure 1b). Before each experimental run (and between each subsequent run) the apparatus was cleaned with approximately 150 mL of a hot 10% sodium hydroxide solution followed by 5 rinses each with about 70 mL of Nanopure water. 150 mL of a dilute sulfuric acid was then added followed by 5 rinses each with Nanopure water. The apparatus was then filled with 190 mL of ddH_2O and boiled for 24 h to thoroughly flush the system. The water was then removed and another rinse with 200 mL of ddH_2O was completed.

Figure 1. (**a**) Custom built reaction apparatus used to simulate early Earth and Titan post-impact conditions; (**b**) Spark gap inside the atmospheric flask.



(**a**) (**b**)

2.2. Experimental Conditions: Early Earth

After the cleaning procedures were completed approximately 200 mL of ddH_2O was added back to the round bottom flask. Vacuum was applied for 10 min to purge the solution of gases. Hydrogen gas was then added to a pressure of 1 bar followed by application of vacuum for another 10 min. The vacuum purge and hydrogen flush procedure was repeated 3 times. After the final vacuum purge, gases were added in the following order to the following pressures: (1) hydrogen gas, 0.2–0.3 bar, (2) methane gas, 0.2–0.3 bar and (3) ammonia gas 0.2–0.3 bar. The total pressure inside the apparatus approached 1 bar. All stopcocks were then closed and a cooling water bath was applied to the condensation tube. Heat was applied using a Staco variable transformer and the solution was brought to a constant boil. After a constant boil was achieved the Tesla coil attached to a manual timer was used to apply a spark (up to 45,000 volts) to the electrode in the upper chamber (Figure 1b). The spark was applied in a random manner using an analog timer attached to the electrical outlet. The experiment was run for 7 days. Samples were taken at the end of 7 days using the sample stopcock (Figure 1a). These experimental conditions were repeated three times for a total of three early Earth samples. Samples were stored in screw top GC/MS sample vials at +4 °C until analysis was completed.

2.3. Experimental Conditions: Titan Post-Impact, Time Course Experiment

The round bottom flask was filled with 200 mL of 30% aqueous ammonia and the apparatus was placed under vacuum for 10 min to purge the solution of gases. The system was then flushed with hydrogen gas and placed under vacuum three times (10 min each time) to completely purge the system and solution. Gases were then added in the following order to the following pressures: hydrogen gas to 0.05 bar, methane gas to 1.0 bar and ammonia to 0.45 bar (~1.5 bar total). The water was then brought to a boil and the spark was applied using the Tesla coil up to a maximum of 45,000 volts (Figure 1b). The spark was applied in a random manner using an analog timer attached to the electrical outlet. The apparatus was run for 7 days and samples were taken over a time course (Table 1). Samples were taken at the beginning of the experiment (sample 1), 2 days post-application of spark (sample 2), 4 days post-application of spark (sample 3) and 7 days post-application of spark (sample 4). The samples taken at the beginning of the experiment (sample 1), 4 days post-spark application (sample 3) and 7 days post-spark application (sample 4) were taken using the sample stopcock (Figure 1a). The samples taken at 2 days (sample 2) were taken using the vacuum stopcock because a light pink color was noted in the reaction mixture in that area at 2 days post-spark application. This pink color was apparent at the sample stopcock from day four onward. These conditions were repeated three times resulting in three sets of time-course Titan post-impact samples. Samples were stored in screw top GC/MS sample vials at +4 °C until analysis was completed.

Table 1. Sample number, identification and location of sample in the apparatus.

Sample	Identification	Sample Location
Sample 1	Starting mixture of 30% aqueous ammonia	Sample Stopcock
Sample 2	2 days post-spark application	Vacuum Stopcock
Sample 3	4 days post-spark application	Sample Stopcock
Sample 4	7 days post-spark application	Sample Stopcock

2.4. Sample Analysis

All samples were run on a Waters MALDI Q-TOF Premier Micromass instrument in ESI+ Q-TOF W mode using direct injection. The injection method was direct using a 1 mL GC syringe coupled to a small motor so that the sample was injected continuously over a period of 10 min. All samples were diluted 1:10 in water before injection. A solution of 10% formic acid/0.1M sodium hydroxide/acetonitrile at a ratio of 1/1/8 was used to calibrate the instrument. The peaks from each sample with an intensity value above 15% were again run in MS-MS mode to help with identification and analysis. Post-run processing of samples was done on the MassLynx software from Waters Laboratories Informatics and included peak smoothing using the Savitzky Golay method and peak centering. Both processes reduced the background and limited peak widths to a value of 6 at half height.

The peak lists were then annotated based on the relative intensity of the peak. For example, in Titan time course sample 1 only peaks with relative intensities above 3 were considered. In other samples the background was such that only peaks with relative intensities above the background noise were considered. For example, in Titan time course sample 2, the background was such that only peaks with relative intensities over 40 were considered in the analysis.

After each file was annotated, the metabolite MS and MS-MS database from the Scripps Center for Metabolomics was used to search for peak matches [15]. The cut-off point for peak matches was 10 ppm. Peaks in the MS spectra were also identified by hand using the distances between peaks and known starting solutions as a guide.

3. Results and Discussion

3.1. Early Earth Conditions

The amino acids observed from the early Earth conditions are very similar to the amino acids seen in the original Miller experiment and in several follow-up experiments [1,9]. In Stanley Miller's original experiment he found alanine (α and β), glycine and aspartic acid. As it is given in Table 2, we also found these three amino acids as well as several others. However, the main components of the reaction mixture, based on peak abundance, were alanine, glycine and aspartic acid.

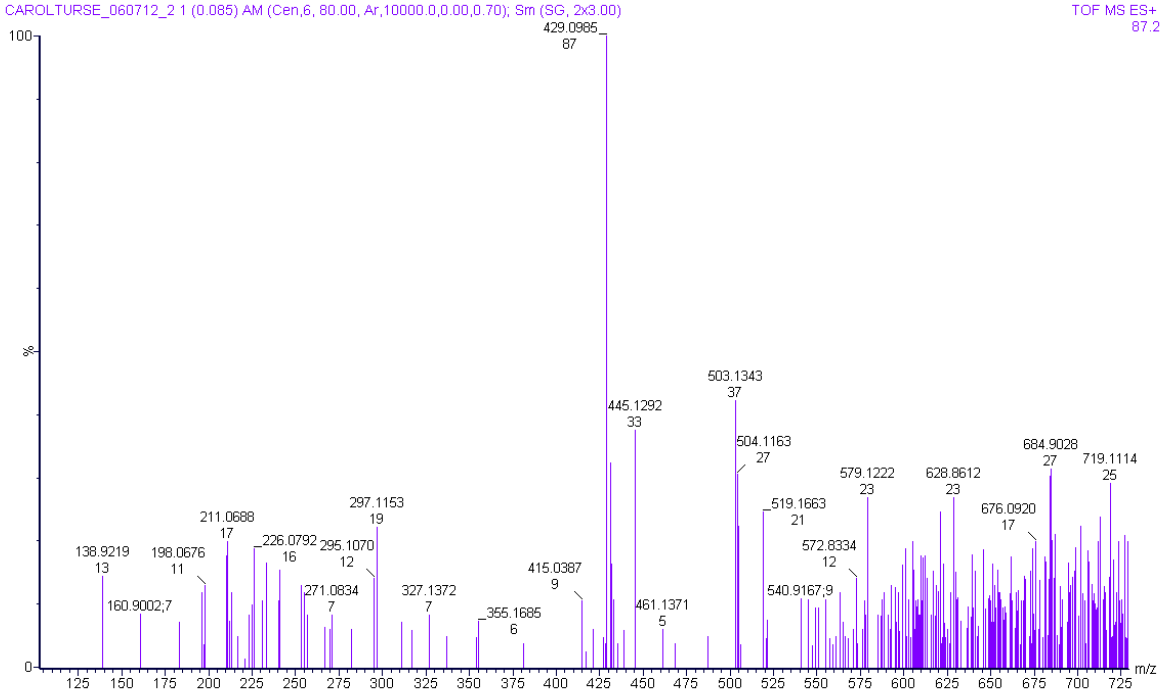
Table 2. Amino acids found under early Earth experimental conditions.

Residue Mass (*m/z*) (monoisotopic, MH^{+1})	Peak Identification	Chemical Formula
72.03712	Alanine	C_3H_5NO
58.02147	Glycine	C_2H_3NO
116.02695	Aspartic Acid	$C_4H_5NO_3$
114.08407	Isoleucine	$C_6H_{11}NO$
88.03203	Serine	$C_3H_5NO_2$
102.04768	Threonine	$C_4H_7NO_2$
113.08407	Leucine	$C_6H_{11}NO$
115.04293	Asparagine	$C_4H_6N_2O_2$
129.09497	Lysine	$C_6H_{12}N_2O$
100.06842	Valine	C_5H_9NO
130.0426	Glutamic Acid	$C_5H_7NO_3$
148.06842	Phenylalanine	C_9H_9NO
98.05277	Proline	C_5H_7NO

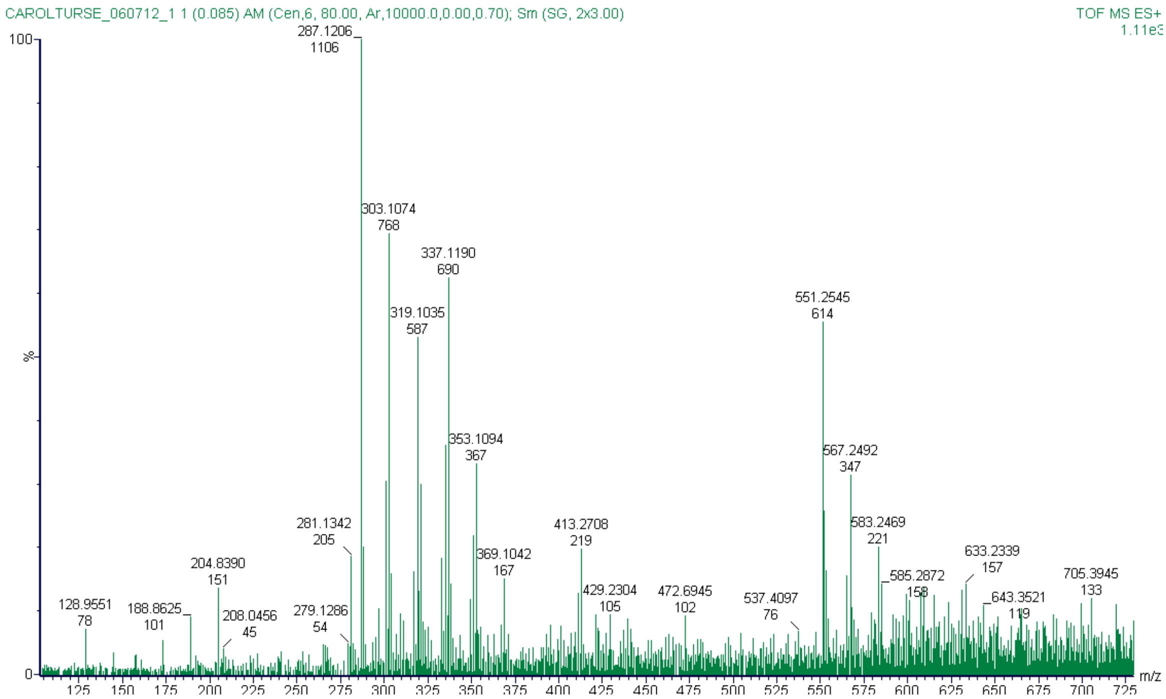
3.2. Titan Post-Impact Conditions, Time Course Experiment

The Titan time course experiments produced a range of amino acids as seen in Table 3 below. All of the reaction mixtures, except for the starting solution, were light pink in color, as opposed to the red-brown mixtures seen for the early Earth conditions. Miller attributed the red-brown color in the reaction mixture to organic compounds adsorbing to the colloidal silica from the reaction vessel [1]. It is important to note that he also observed a light pink color prior to the final red-brown of the reaction mixture. Representative spectra of all four time points are shown in Figure 2. Recall that a total of four samples were taken over the course of the 7 day Titan time course experiment. Sample 1 consisted of the starting solution of 30% aqueous ammonia, sample 2 was taken from the joint prior to the atmospheric chamber at 2 days post spark application, sample 3 was taken from the U-bend joint 4 days post spark application and sample 4 was taken from the boil flask 7 days post spark application.

Figure 2. Representative MS Spectra from the Titan Time Course Experiments. All time points are the result of three independent replicates. (**a**) Sample 1, starting solution of 30% aqueous ammonia; (**b**) Sample 2, joint, 2 days post spark application; (**c**) Sample 3, U-bend, 4 days post spark application; (**d**) Sample 4, boil flask, 7 days post spark application.

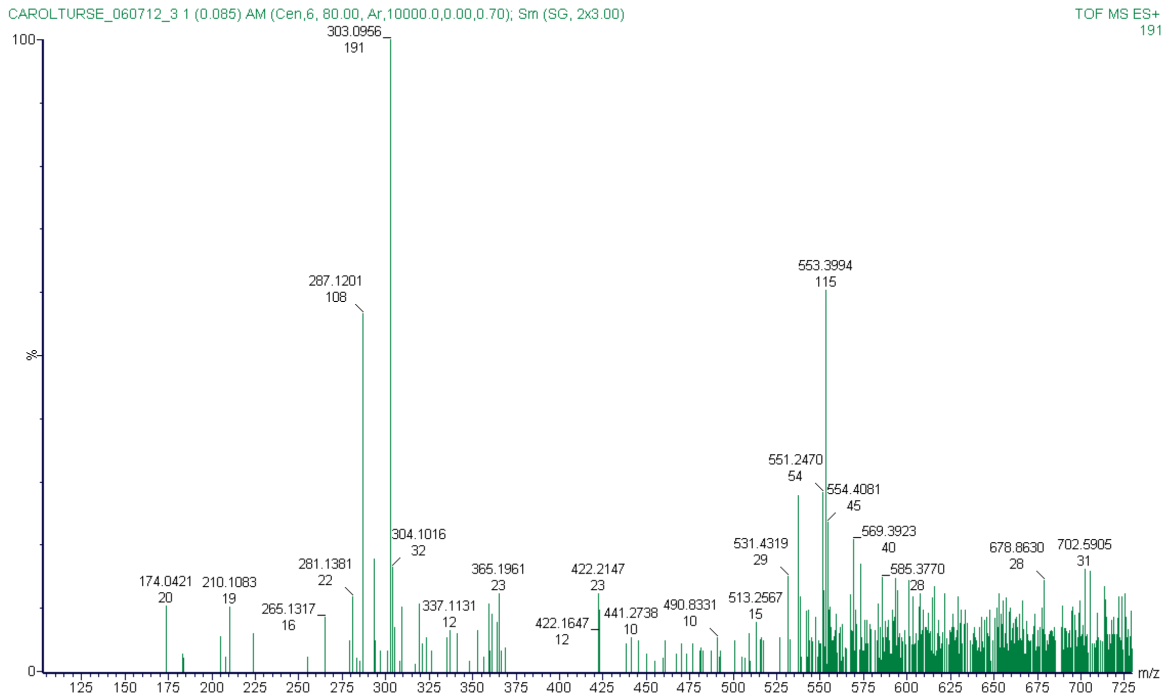


(**a**)

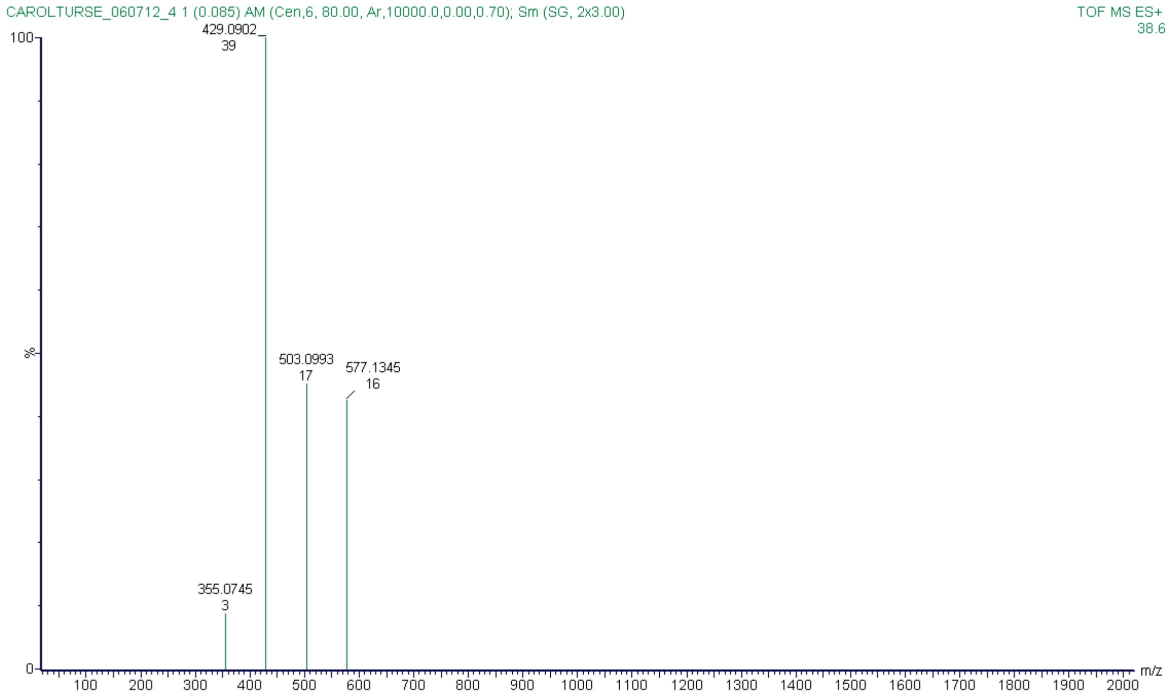


(**b**)

Figure 2. *Cont*.



(c)



(d)

Table 3. Amino Acids found in the Titan Time Course Experiments. All time points listed represent three independent replicates. Shaded green boxes in samples 2, 3 and 4 represent amino acids found in common between all three time points. The results from the early Earth condition experiments are included for reference.

	Time Course Sample Number	**1**	**2**	**3**	**4**	**Early Earth Conditions**
Compound Identification, relative abundance (%)		Ammonia (30% aqueous)	Glutamine, <10%	Histidine, 50%	Larger ring structures only, no single amino acids	Glycine
			Alanine, 25%	Aspartic Acid, <10%		Alanine
			Tyrosine, <10%	Tryptophan, <10%		Aspartic Acid
			Serine, <10%	Serine, <10%		Serine
			Phenylalanine, 50%	Phenylalanine, 25%		Phenylalanine
			Glutamic acid, <10%	Glutamic acid, <10%		Glutamic acid
			Arganine, <10%	Arganine, <10%		Asparagine
			Leucine, <10%	Leucine, <10%		Leucine
			Isoleucine, <10%	Isoleucine, <10%		Isoleucine
			Valine, <10%	Valine, <10%		Valine
				Proline, <10%		Proline
						Lysine
						Threonine

3.2.1. Titan Sample 1, Starting Solution of 30% Aqueous Ammonia

The starting solution of 30% aqueous ammonia is shown in the representative spectrum in Figure 2. The peak gaps between adjacent peaks correspond to the molecular weight of nitrogen, hydrogen and oxygen in the positive ion mode. For example, if you consider peaks 303.1074 and 287.1206 you see a difference of 15.9868, which corresponds to nitrogen plus hydrogen. Since the solution is aqueous, hydroxide ion peaks are also common.

3.2.2. Titan Sample Solution 2

These samples were taken 2 days after the experiment was started when we noticed a pink-red clear liquid pooling near the vacuum stopcock joint area prior to the atmospheric chamber. The joint area is located at the stopcock that leads to the inlet port for the gases used in the experiment. The amino acids in this sample are found in complexes of two to three amino acids (mostly groups of two). Specifically, glutamine, alanine, tyrosine, serine and phenylalanine were found in groups of two to three while glutamic acid, arginine, leucine, isoleucine and valine were found in separate groups of two to three amino acids each. The higher *m/z* peaks on the spectra represented multiple ring-type structures and are mostly occluded by the higher background.

3.2.3. Titan Sample Solution 3

These samples were taken 4 days after the experiment started and had a slight pink color but had not reached the bright pink color seen at the end of 7 days. Samples were collected from the sample stopcock at the bottom of the apparatus. The amino acids were found in complexes of two to three amino acids. In this sample, arginine, proline, serine, aspartic acid, leucine, valine, isoleucine, glutamic acid, tryptophan, phenylalanine and histidine were seen in groups of two to three amino acids each. The most amino acids were identified from sample 3 as well as the most number of two to three amino acids groupings. The higher *m/z* peaks contained multiple ring-type structures and were mostly occluded by the higher background.

3.2.4. Titan Sample Solution 4: Sample Taken from the Boil Flask

These samples were taken at the end of the 7 day experiments from the 250 mL round bottom flask using the sample stopcock. The samples were all a light pink in color. In sample 4 no amino acids were identified but several large ring structures were present. These structures included proanthocyanidin, alpha-L-rhamnopyranosyl-(1->2)-beta-D-galactopyranosyl-(1->2)-betva-D-glucuronopyranoside and a diethylstilbestrol diphosphate-like compound. All of these compounds have two or more benzene-like ring structures. The identification of a diphosphate-like compound was of some concern since no phosphorus was added to the reaction mixture. However, this could be explained by some carry-over from the cleaning solutions used on the Miller-Urey apparatus or as a lack in the database of spectra. Since the diphosphate compound didn’t appear on the spectra for samples 2 and 3, and since it did not appear in the starting solution, the problem is most likely one with the database.

3.3. Discussion

We were successful in replicating the original Miller-Urey early Earth conditions and produced many of the same amino acids seen by Stanley Miller. In particular we identified alanine, glycine and aspartic acid just as Miller did. Our experiments also identified several more amino acids than Miller (Table 2), which can be attributed to advanced analysis techniques.

In contrast, in the Titan time course samples we see an intriguing pattern emerge. Amino acids start to be produced 2 days after the application of spark and continue to increase in structural complexity (groups of two amino acids and then groups of three amino acids) up to 4 days after the spark is applied. Samples taken 2 days after the start of the experiment were taken from the vacuum stopcock because this is where we noticed a distinct pink-red clear solution. This pink color could be due to organonitrogen, like the pink-orange haze on Titan that is due to organic photochemistry in the atmosphere [16]. This pink color could also be similar to the pink color observed by Miller in his apparatus after a few days of running the experiment [1]. He attributed the pink-red color to organic compounds adsorbing to the colloidal silica from the reaction vessel and noticed that the pink color eventually turned into a dark red-brown color. Based on the spectra from day 2 forward, the pink color observed in the reaction vessel is most likely due to organonitrogen compounds. Day 2 samples included molecules such as pterins and pteridines and the day 4 samples included nitrotoluene molecules. These molecules are most likely the cause of the pink-orange color observed in our reaction vessel. Also, in contrast to Miller's experiment, our reaction solution stayed a pink-orange color and did not change into a dark red-brown color even after 7 days of running the experiment.

Both the 2 day and 4 day time points included the amino acids serine, phenylalanine, glutamic acid, arginine, leucine, isoleucine and valine. While glutamine, alanine and tyrosine were observed in the 2 day sample, they were not present in the day 4 sample. However, at 4 days post-spark application we did observe histidine, aspartic acid, proline and tryptophan. The emergence of aspartic ac id and the absence of alanine in the 4 days sample could be attributed to the pH of the sample mixture. In previous spark discharge experiments it has been noted that acidification of the reaction mixture reduced the yield of amino acids observed at the end of the experiment [8]. In our samples, the pH of the starting solution was near a pH of 12 (average of 11.6), dropped to pH 9 by day 2 and reduced further to pH 8 by day 4. The pH then held at 8 until the end of the experiment. Further analysis of the da ta showed that after 7 days of running the experiment, the amino acid groupings seen earlier start to break down and the chemical components in the mixture form large multiple ring structures. This in in contrast to the early Earth condition experiments where we still see a fairly complex mixture of amino acids 7 days after the start of the experiment (Tables 1 and 2). This breakdown of amino acid groupings could be due to the further acidification of the reaction mixture after the 4 days time point.

While our experiments are the first to simulate Titan post-impact conditions, other researchers have completed simulations of Titan atmospheric conditions. Due to the presence of large, complex organic molecules in Titan's upper atmosphere, Horst *et al.* [17] simulated upper atmospheric conditions on Titan and produced a range of amino acids and nucleotide bases. In particular, they produced cytosine, uracil, thymine, guanine, glycine, alanine and adenine [17]. The only amino acid produced in common between the atmospheric experiments and our experiments was the amino acid alanine. However, these results are exciting in that they provide another source of prebiotic material on Titan.

Overall, our experiments show that it is possible to produce a wide range of amino acids on Titan in post-impact conditions. This finding could have important implications for the chemical evolution and possibly for an origin of life on Titan, either in the past or even persisting to the present day. It is especially interesting that we observed a wider range of amino acids in the Titan condition experiments than in the early Earth condition experiments. These amino acids were also always found in groups of two three and not individually. Even the eventual break down of amino acids observed at the 7 day time point could have implications for life on Titan since the larger carbon ring structures could also be important in the chemical "soup" of life by acting as scaffolds for the building of chains of amino acids. On the other hand they could, however, be just a tar-like substance presenting a dead-end scenario for the development toward further complexity. If the latter scenario is correct, it would mean that the availability of amino acids for further organic synthesis reactions may be severely time-constrained and reactions toward higher prebiological complexity have to set in within a few days after the impact event in order to proceed. The observation that these amino acids are grouped together may provide a hint that such reactions are indeed occurring. Further experiments and analysis of the created organic compounds are needed to resolve this important question.

4. Conclusions

The Titan post-impact reaction conditions produced amino acids beginning at least 2 days post application of spark and continued to increase in quantity and complexity (groupings of two to three amino acids were observed) up to 4 days after the spark was applied. The most common amino acids observed were serine, phenylalanine, glutamic acid, arganine, leucine, isoleucine and valine. However, after 7 days of experimental activity the groupings of amino acids seen at day 4 started to break down and form large carbon ring structures. Our results show that not only is it possible to produce amino acids under Titan post-impact conditions, we see different amino acids from those identified in the original Miller conditions. Further experiments using our Miller apparatus will include the addition of sulfur to the reaction mixture as well as trace gases (tholins) found in the atmosphere of Titan.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Miller, S.L. A production of amino acids under possible primitive earth conditions. *Science* **1953**, *117*, 528–529.
2. Oparin, A.I.; Lorenz, R.D.; Lunine, J.I. *The Origin of Life*; U.S. Government Printing Office: Washington, DC, USA, 1968.
3. Lob, W. Uber des Verhalten des Formamids Unter der Wirkung der stillen Entladung, Ein Beitrag zur Stickstoff-Assimilation. *Berichte der Deutschen Chemischen Gesellschaft* **1913**, *46*, 684−697, (in German).
4. Garrison, W.M.; Morrison, J.G.; Hamilton, A.A.; Benson, M.; Calvin, M. The reduction of carbon dioxide by ionizing radiation. *Science* **1951**, *114*, 416–418.
5. Kasting, J.F.; Pollack, J.B.; Crisp, D. Effects of high CO_2 levels on surface temperature and atmospheric oxidation state of the early Earth. *J. Atmos. Chem.* **1984**, *1*, 403–428.
6. Kasting, J.F. Early Earth's atmosphere. *Science* **1993**, *259*, 920–926.
7. Anderson, R.; Gathman, S.; Hughes, J.; Björnsson, S.; Jónasson, S.; Blanchard, D.C.; Moore, C.B.; Survilas, H.J.; Vonnegut, B. Electricity in volcanic clouds. *Science* **1965**, *148*, 1179–1189.
8. Cleaves, H.J.; Chalmers, J.H.; Lazcano, A.; Miller, S.L.; Bada, J.L. A reassessment of prebiotic organic synthesis in neutral planetary atmospheres. *Orig. Life Evol. Biosph.* **2008**, *38*, 105–115.
9. Bada, J.L. New insights into prebiotic chemistry from Stanley Miller's spark discharge experiments. *Chem. Soc. Rev.* **2013**, *42*, 2186–2196.

10. Schulze-Makuch, D.; Grinspoon, D.H. Biologically enhanced energy and carbon cycling on Titan? *Astrobiology* **2005**, *5*, 560–567.
11. O'Brien, D.P.; Lorenz, R.D.; Lunine, J.I. Numerical calculations of the longevity of impact oases on Titan. *Icarus* **2005**, *173*, 243–253.
12. Fischer, G.; Gurnett, D.A. The search for Titan lightning radio emissions. *Geophys. Res. Lett.* **2011**, *38*, doi:10.1029/2011GL047316.
13. Horvath, G.; Skalny, J.D.; Mason, N.J.; Klas, M.; Zahoran, M.; Vladoiu, R.; Manole, M. Corona discharge experiments in admixtures of N_2 and CH_4: A laboratory simulation of Titan's atmosphere. *Plasma Sources Sci. Technol.* **2009**, *18*, doi:10.1088/0963-0252/18/3/034016.
14. Plankensteiner, K.; Reiner, H.; Rode, B.M.; Mikoviny, T.; Wisthaler, A.; Hansel, A.; Märk, T.D.; Fischer, G.; Lammer, H.; Rucker, H.O. Discharge experiments simulating chemical evolution on the surface of Titan. *Icarus* **2007**, *187*, 616–619.
15. Scripps Center for Metabolomics. Available online: http://metlin.scripps.edu/ (accessed on 4 November 2013).
16. Lavvas, P.; Yelle, R.V.; Vuitton, V. The detached haze layer in Titan's mesophere. *Icarus* **2009**, *201*, 626–633.
17. Horst, S.M.; Yelle, R.V.; Buch, A.; Carrasco, N.; Cernogora, G.; Dutuit, O.; Quirico, E.; Sciamma-O'Brien, E.; Smith, M.A.; Somogyi, A.; *et al.* Formation of amino acids and nucleotide bases in a Titan atmosphere simulation experiment. *Astrobiology* **2012**, *12*, 809–817.

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The HADES mission concept – astrobiological survey of Jupiter's icy moon Europa

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Abstract: The HADES Europa mission concept aims to provide a framework for an astrobiological in-depth investigation of the Jupiter moon Europa, relying on existing technologies and feasibility. This mission study proposes a system consisting of an orbiter, lander and cryobot as a platform for detailed exploration of Europa. While the orbiter will investigate the presence of a liquid ocean and characterize Europa's internal structure, the lander will survey local dynamics of the ice layer and the surface environment. The lander releases a cryobot, that melts into the ice, will sample the pristine subsurface and is expected to provide data on organic and gaseous content and putative bio-signatures. In summary, we present the scientific objectives for an astrobiological investigation of Europa, resulting in a mission concept with a detailed evaluation of scientific instrumentation, mission sequences, basic design of the spacecraft, technology needs and cost estimations.

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Introduction

Jupiter's icy moon Europa is one of the most promising target objects for astrobiological exploration in the Solar System. Europa is suspected to host an ocean between its geodynamically active icy crust and its silicate mantle, where the main conditions for habitability may be fulfilled (Carr *et al.* 1998; Pappalardo *et al.* 1999; Kargel *et al.* 2000). Faults and cracks in the ice of Europa indicate a history of material upwelling from below by the influence of tidal forces (Sotin *et al.* 2002) and cryovolcanism (Fagents 2003), perhaps carrying liquid water to the near surface. Chaotic terrain resembling Arctic pack ice suggests regular reworking and recycling of the icy crust (Carr *et al.* 1998). It is likely that the suspected liquid

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ocean extends down to the silicate mantle where minerals and heat from hydrothermal vents may create ambient conditions suitable for biochemical reactions. The low number of impact craters indicates a geologically young surface, continuously remodelled by geological activity (Ruiz & Tejero 2003). Protected from the vacuum and radiation from the space, conditions that favoured the origin and evolution of life on Earth may also exist on Europa and the production of prebiotic key compounds has already been demonstrated in laboratory experiments for a simulated Europa-like environment (Kempe & Kazmierczak 2002).

Pioneer, Ulysses, Voyager, Galileo, Cassini and the recent New Horizons flyby have provided valuable insights into the Jupiter system and Europa. Taking into consideration the present knowledge available, future missions are required to reveal how the Jupiter system works and whether Europa is really habitable or not (Blanc *et al.* 2009). Thus Europa has been defined as a high priority target in the NASA Space Science Enterprise Strategic Plan and the European Space Agency's (ESA's) 'Cosmic Vision 2015–2025' strategic document (NRC 1999; ESA 2005).

In order to assess the habitability of Europa, several different mission proposals currently exist and are under development. Both the Europa Geophysical Explorer and Europa Astrobiology Lander NASA mission concepts are proposals focusing on elemental geological and astrobiological questions. The Laplace mission is part of ESA's Cosmic Vision programme between 2015 and 2025. It will deploy a triad of orbiting platforms in order to perform coordinated measurements of Europa and the Jovian satellites with regards to the magnetosphere, the atmosphere, the interior of Jupiter and the surface and internal structure of Europa (Blanc *et al.* 2009). Previously published Europa mission concepts adhere to a single exploration strategy focusing either on exploration from an orbiter or on a well-equipped lander. In the present paper, a new mission to Europa is proposed that combines several strategies to create a multifunctional platform for an efficient surface and sub-surface investigation of Europa with an emphasis on habitability and the potential for life. The HADES Europa (High Altitude and Direct Environmental Sampling of Europa) mission concept comprises three main mission elements: an orbiter for precise mapping of surface and subsurface geological features, a lander for a more detailed geophysical characterization and a cryobot to penetrate the crust and analyse the subsurface ice.

Science objectives

The HADES mission will focus on an astrobiological investigation of the Jovian moon Europa. Its primary scientific goal is to assess the habitability of Europa and to search directly for signs of complex organic chemistry that could be indicators of past or present life. The estimation of Europa's habitability will mainly be based on the presence of a putative subsurface ocean. Characterizing and understanding its structure, its formation and the dynamic processes that sustain it, such as the strong geological activity triggered by Jupiter tidal forces, is of prime importance. These geological and gravitational characteristics of the Jovian moon have been considered to be crucial factors in the possible development of life on Europa. Thus the primary science objectives are to:

I. search for the presence of a liquid subsurface ocean;
II. characterize the depth and laminar structure of Europa's icy crust and putative subsurface ocean;
III. search for geological activity; and
IV. detect and profile organic molecules present in upwelled ice at different depths.

Several strategies are combined to meet these goals. These include global mapping strategies as well as *in-situ* analysis:

1. precise gravity field measurement (Objective I and II);
2. ice layer and ice/liquid water interface detection (Objective I and II);
3. accurate topographic data (Objective III);
4. high resolution identification of geological features (Objective III);
5. characterization of the surface mineral composition (particular emphasis at sites with evidence of upwelling) (Objective III);
6. direct analysis of organic molecules, gaseous inclusions and biomarkers in the ice at varying depths (Objective IV).

Although an orbital study can provide valuable insights into many aspects concerning habitability, a lander would provide *in-situ* geophysical data and is indispensable for accurate chemical ice sample analysis. These *in-situ* measurements are necessary to gain insights into the organic inventory of Europa's icy crust and its putative subsurface ocean. Only these experiments can finally address the question of whether a biosphere actually is or has been present on Europa. If there are no indications of an existing or extinct biosphere, it would be of great value for the debate on the origin of life to estimate Europa's stage of prebiotic evolution. However, the harsh radiation environment on the surface of Europa reaching over 100 kGy/year (NRC 2000) will extensively modify and destroy potential biomarkers and complex organic molecules. The main source of this radiation is high-energy electrons and ions from Jupiter's magnetosphere. As the radiation dose strongly declines with increasing depth in the ice mantle, pristine material is expected to be accessible at sites that indicate recent upwelling of material from below the surface. With latest upwelling events 10^7 years ago, the accumulated radiation dose may decrease several meters below the surface to less than 500 kGy. At this dose potential biomarkers or prebiotic organic molecules should be preserved (McKay 2002). At depths of 10–25 m the dose could be low enough even to preserve some intact cells of a potential subsurface biosphere. Thus, for an astrobiological survey of Europa, a subsurface tool will be necessary to access pristine material.

Science instruments

HADES science instruments have been carefully selected to meet the science objectives as detailed above. All proposed instrumentation is based on spaceflight heritage or on existing technology, thus providing high operational reliability and involving minor development effort.

Orbiter instruments

Radio science

Radio science experiments utilize the built-in spacecraft radio communication system and a network of antennas on Earth to measure signal deviations, such as refractions and Doppler shifts, resulting from bodies crossing the signal emitted from the High Gain Antenna (HGA). This will provide detailed data on the masses and ephemerides of Europa and additionally can be used to study Jupiter. An ultra-stable oscillator must be added to the orbiter payload to stabilize power and frequency of the radio signal and increase the resolution for a Europa study (Iess & Boscagli 2001). By utilizing the accurate position of the spacecraft, determined by radio tracking, along with accelerometer data (orbiter engineering payload), information about the variation of the gravitational field of Europa will be retrieved. This should lead to improved estimations of the internal structure of Europa and the putative subsurface ocean.

Laser altimeter

Based on the Mercury Laser Altimeter, on board the Messenger Mission to Mercury (Gold 2001), the HADES altimeter will provide topographic information and permit 3D modelling of the surface morphology, including the consequences of tidal deformation. Tidal effects are due mainly to the gravitational attraction of Jupiter and can provide evidence for the presence of a subsurface ocean (Pappalardo *et al.* 1999). If Europa has an ocean, a tidal bulge of about 30 meters is expected and will easily be detected with a resolution of 0.3 m; in the absence of an ocean the deformation would be less than 3 m (Edwards *et al.* 1997).

To gain accurate topographic information, the exact location of the spacecraft and its orientation have to be determined by the complementary use of the radio science system. The performance of the altimeter can be evaluated during Venus flybys while studying the clouds. Altimeter-derived surface morphology (rapid analysis after Europa orbit insertion) will constrain the location of the landing site.

Surface Spectral Imaging System

Europa's surface will be comprehensively imaged and surveyed for general tectonic features and cratering, with spatially resolved spectroscopy allowing investigation of ice crystallinity and mixture, mineral composition, and potential organic materials in areas of recent cryovolcanism. The orbiter will carry a compact Surface Spectral Imaging System (SSIS), akin to the SIMBIO-SYS package developed for the ESA/Jaxa BepiColombo mission to Mercury (Schulz 2004). This package comprises a High Spatial Resolution Imaging Channel (HRIC) (Colangeli *et al.* 2006), a Stereo Channel (STC) (Sgavetti *et al.* 2007), and a Visible and Infrared Hyperspectral Imager (VIHI) (Sgavetti *et al.* 2007). Required adaptations involve larger apertures compensating for lower photon flux levels (roughly a factor of two with consideration to orbit altitude and surface albedo differences) and increased shielding to protect from higher radiation doses. The STC will include an extended spectral range to 0.4–1.0 μm and the global stereo mapping will be improved by using 5 instead of 3 bands.

The hyperspectral imager will enable mapping and identification of mineralogical species, ice composition, grain size distribution and crystallinity. With its spectral range extended to at least 3.5 μm, the detection of characteristic organic molecule absorption bands can be achieved. Correlated with surface features from high spatial resolution imaging, the stereo mapping, and radar sounding data, the imager can yield information on the most suitable investigation site for the lander and cryobot. Furthermore, mapping the distribution of organic molecules at the surface may yield sites of special astrobiological interest, enabling the very detailed but locally restricted *in-situ* analysis of the cryobot to be set within a more global context. The mineral composition of the surface may point towards geological activity below the surface and imply ecological niches and potential energy sources for a putative biosphere.

Europa Ice-Penetrating Radar

The Europa Ice-Penetrating Radar (EIPR) will enable the study of the thickness and potential layering of the icy crust. Models including flexure analysis of Europa's icy crust have shown that the ice thickness can range between <1 km and >30 km (Billings & Kattenhorn 2005). Considerations of different ice composition and formation models, respectively, have resulted in a 50 MHz optimal frequency for ice-penetrating radar on Europa. Depths of 20 km can be reached (Blankenship *et al.* 1999) and within the expected orbiter lifetime of 60 days a total radar surface coverage of up to 75% can be achieved (ESA 2004). Estimations of layering and thickness of the icy crust will be of prime importance for the assessment of the habitability of Europa and the definition of further astrobiological exploration strategies.

Magnetometer

A three-axial fluxgate magnetometer will allow accurate mapping of Europa's magnetic field. The instrument is appended to a deployed boom to separate it as far as possible from the spacecraft's internal electromagnetic fields. Two sensors with different sensitivities will be applied: one for the high-energetic field of Jupiter (0.5–20 mT) and a second one for the weaker induced field of Europa (20–500 nT) (Kivelson *et al.* 1992). Data regarding structure and intensity of the induced magnetic field can provide more detailed information on a putative subsurface ocean.

Lander instruments

Geophone

Seismic analysis of Europa is to be provided by a geophone-based technology device, an equally reliable but safer approach than current seismographic systems that are unable to withstand strong decelerations.

Four sensors, attached to the landing quadropod, will provide a square-shaped contact frame to the ice, enabling three-dimensional location of sound sources. Direct contact of all four sensors with the surface is necessary to permit detection of original sound wave amplitudes. This will be enabled by the insertion into the surface of the sensors, either by melting into the ice or by a pointed sensor design that will penetrate the ice. Spontaneous noisy features are expected to occur often on Europa's surface due to reforming processes in cracks in the icy crust and by impacting asteroids (Lee *et al.* 2003). Fine resolution cartographic assessment of the nearby ice is achievable by using high sampling rates up to 50 kHz. Notwithstanding the difficulties in spatial resolution due to small-scale sensor frame aberrations, a high sampling rate approach can be a means of increasing the reliability and resolution of measurements. The geophone will reveal the thickness of Europa's icy crust and the depth of its potential subsurface ocean, making it an optimal tool for a detailed survey of the habitability of Europa.

Descent Imaging and Tracking System

The Descent Imaging and Tracking System (DITS) includes a descent camera, an inertial measurement unit and a laser altimeter. The laser altimeter and the inertial measurement unit will monitor the descent trajectory and control thrusting. The descent imager will provide high-resolution images (1000×1000 pixels) of the landing site at high frequency. Combined, this data will accurately characterize the geomorphology in the vicinity of the landing site, which is essential for an accurate interpretation of the results from the geophysical and chemical analysis of lander and cryobot.

HADES Environmental Package

The HADES Environmental Package (HEP) comprises sensors to determine physical properties during lander descent and later on the surface, such as temperature and pressure, and a radiometer for direct environmental sensing. The radiometer will use heritage of the MARIE instrument (Martian Radiation Environment Experiment) of the Mars Odyssey spacecraft and provide data on the overall radiation flux of energetic particles in Jupiter's vicinity and on Europa's surface (Zeitlin *et al.* 2003). HEP will help to investigate characteristics of Europa's thin atmosphere and to establish a profile of its diurnal changes. The results will put constraints on the stability of organic compounds (including putative biomarkers) near the surface, the radiolytic surface chemistry and the loss rates of surface material.

Cryobot instruments

The cryobot instruments will analyse pristine ice core samples recovered by a deployable drill. Sampling is scheduled every 5 m during the cryobot melting its way into the subsurface.

Gas Chromatograph Mass Spectrometer

The Gas Chromatograph Mass Spectrometer (GC-MS) is proposed as the main analytical instrument of the cryobot for investigating the organic inventory of Europa's icy crust, assessing chirality and isotopic ratios and determining gaseous compounds within the ice. The instrument can be adapted from COSAC, the GC-MS of ROSETTA Mission's Philae Lander, that has been developed for the purpose of ice sample analysis of the comet 67P/Churyumov-Gerasimenko (Goesmann *et al.* 2007).

Samples taken from a retrieved ice core can be either heated gradually from $-100\ ^{\circ}C$ to $+600\ ^{\circ}C$ in a pyrolyser device or reacted with N,N-Dimethylfomamide dimethylacetal at $100\ ^{\circ}C$ to derivatize less volatile compounds like amino acids and preserve their stereochemical information (Goesmann *et al.* 2005). Vaporized compounds are separated via a set of gas chromatography (GC) columns differing in selectivity and analysed by a time of flight (TOF) mass analyser. The columns for the GC will be chosen respecting the astrobiological goal of the mission and differ from those of the COSAC experiment. The MS will generate 10,000 spectra (each 16 bit) per minute during a 17-minute run per column. For each ice sample, eight columns will be run in two replicates.

Apart from the chemical structure, potential biosignatures can be detected by isotopic discrimination and an enantiomeric excess of one stereoisomer of chiral compounds. While deviations in isotopic ratios can be derived directly from mass spectra of appropriate resolution, the use of chiral GC columns (Skelley & Mathies 2003) allows the separation of even enantiomers, and the analysis of their abundances from peak integration.

Antibody array

Antibody arrays have been proven to provide a powerful and highly sensitive tool for biomarker detection on Earth and have been proposed in many studies for astrobiological exploration in the Solar System. Complementary to the GC-MS analysis, the antibodies can cover a broad range of complex organic structures and extend the sensitivity of detection down to part-per-billion (ppb) levels (Fernandez-Calvo *et al.* 2006; Parro *et al.* 2007). The proposed HADES system is based on the SOLID 2 system, a multi-array competitive immunoassay currently under final development by the Centro de Astrobiologia INTA-CSIC (Parro *et al.* 2007), with target molecules comprising widespread biomarkers of extant life, prebiotic compounds and paleomolecular remnants of ancient life forms. Antibody species will be carefully selected to be focused on molecules that are considered to be of exobiological relevance (e.g. hopanes, sugars, amino acids, nucleobases, lipids and polycyclic aromatic hydrocarbons).

Sample sterility and clean distribution into the antibody array system is of prime importance for the quality of the experiments. Thus, three equal arrays are suggested to be used at each sample acquisition, providing duplicates for every sample and a reference array, which is loaded with a well-defined standard for internal performance control.

Mission overview

HADES will have an expected flight duration of 6 years to reach the Jupiter system. During the first 3 years, inner Solar System flybys will allow instrument calibration and the completion of additional scientific goals. For instance, communications procedures, imaging and spectral analysis will be acquired from the Venus cloud system. During the cruise to Jupiter, distant imaging of the Galilean satellites and a survey of atmospheric variations of Jupiter will be carried out by the orbiter (imaging, radio science) until the Jupiter Orbit Insertion (JOI) and finally, the Europa Polar Orbit Insertion (EPOI) sequences.

The HADES mission timeline follows two different phases for the study of Europa, the first being the remote sensing of the surface from orbit. Orbiter instruments will be active during the entire mission, to obtain a maximum spatial coverage. Due to the harsh radiation environment around Jupiter, the survival time of the spacecraft around Europa is estimated to be between 60 and 90 days (Blanc *et al.* 2009). The second phase is the direct measurements of the ice surface and subsurface. The intended payload, lander and cryobot will consist of proven technologies adapted for the environmental conditions of this Jovian moon.

Upon EPOI at Europa, the orbiter will begin to map the surface, prioritizing the pre-selected landing site. The site pre-selection, using datasets from previous missions, is based on the assumption that recent geological activity has resulted in areas where liquid water and/or warm ice has upwelled and solidified on the surface (Fagents 2003). Areas characterized as 'strike-slip' faults, chaotic terrain, lineae and lenticulae are preferred for site selection because they involve upwelled material. The final selection will be based on the results of the geomorphology analysis from the HADES imaging and altimetry.

Environmental measurements and imaging are recorded during the probe descent. In order to characterize surface conditions and to study the molecular composition of samples of ice, access to the Europan surface and subsurface is necessary. A geophone network will monitor ice and meteoric sonic activity during lander lifetime to infer physical properties of the icy crust and determine the interface ice/liquid. This would be best achieved by a soft landing and then boring/melting to at least several meters below the surface using the cryobot. During descent into the ice, fresh samples protected from high-energy particles within Jupiter's environment are made available for chemical analysis. Pristine samples will be acquired by drilling parallel to the surface and delivered to the GC-MS and the antibody array.

During the cruise, the dataset collected by all the instruments will be transferred to Earth-based antennas using the HGA of the orbiter. Once in orbit around Europa, a polar orbit with its plane always facing Earth is chosen to maximize the transmission time. Connection with Earth will be within 50 of the $\sim$60 days of the mission; there will be no connection for at least 10 days because Europa appears behind Jupiter during its rotation seen from Earth.

Trajectory analysis

The HADES baseline mission is proposed for a launch in February 2020. Two launcher rockets, Proton or AtlasV, can be considered for direct escape from Earth's gravity field without applying a transfer orbit. The transfer from Earth to Jupiter will be achieved by a series of gravity assisted manoeuvres during a 6-year cruise. Mission analysis revealed that for a liquid bipropellant propulsion system the best performance is obtained with a Venus-Earth-Earth Gravity Assist (VEEGA) sequence. The 2020 launch window will involve a relatively low deep-space manoeuvre budget with a ΔV of 86 m s^{-1} for the launch plus VEEGA transfer and a ΔV of 1273 m s^{-1} for the JOI. The cruise is achieved by accelerating in deep space and reducing speed upon arrival at Jupiter (in 2026). This approach requires more propellant than a gravity assist manoeuvre in the Jovian System, but reduces the transit time (Atzei 2007).

The final trajectory will be a polar orbit around Europa with an inclination of 93° at a height of 200 km above the surface and an orbital period of 136.7 min, resulting in a ground track repeat every 3.55 days. This enables a line-of-sight (LOS) connection to Earth for data transmission for 83% of the mission time. The EPOI sequence requires a ΔV of 700 m s^{-1} and the landing a ΔV of 1300 m s^{-1}. The final sequence employs hazard avoidance technology in order to safely deliver the payload to the surface. A laser altimeter and imaging camera (see above) will help to detect hazards in the landing zone during descent. An autonomous on-board evaluation and control system will in this case be able to select a safer place and subsequently manoeuvre the lander to the new site.

The HADES spacecraft, lander, and cryobot design

Design drivers

For the preferred launch window in 2020 an optimal performance can be achieved using AtlasV as carrier rocket. This allows a maximum payload mass of 1962 kg. The spacecraft, lander and cryobot are designed respecting the corresponding mass and size constraints of AtlasV, which was chosen as launcher for the mission baseline option. Table 1 shows the mass, power and data requirements for the scientific instrumentation. An overview on the overall mass budget and a detailed breakdown for orbiter, lander and cryobot is given in Table 2. The use of hardened components resulting from ongoing ESA research and development activities is anticipated. The procurement, handling and launch of radioisotope thermoelectric generators (RTGs) will require the participation or collaboration of NASA or ROSCOSMOS.

In order to survive the harsh radiation environment around Europa, the spacecraft will carry 8 mm aluminium shielding and individual hardware hardened to tolerate an accumulation of 10 kGy over 60 days.

Planetary protection

Although ionizing radiation on Europa may reduce the probability of contamination, any astrobiological investigation

Table 1. *Science instruments for the orbiter, the lander and the cryobot*

Instruments	Mass (kg)	Power (W)	Data (Mb)
Orbiter instruments			
Ultra-stable oscillator	3	10	none
Laser altimeter	5	23	262
SSIS	28	26	10 000
EIPR	10	68	2000
Magnetometer	5.7	4	90
Lander instruments			
DITS	14.5	96	100
Geophone	2	4	200
HEP	3.7	8	5
Cryobot instruments			
GC-MS	4.85	8	27
Antibody array	2.1	30	120

of Europa and its subsurface should achieve the highest reasonable level of safeguard on forward contamination (NRC 2000). Although the COSPAR planetary protection guidelines do not yet address an astrobiological survey of Europa in detail, the guidelines recommend missions to Europa with an orbiter as category III and a lander as category IV. We suggest handling the HADES lander for Europa with astrobiological purpose as a category IVb mission according to the COSPAR classification system for Mars, while the orbiter may be considered to be category III. Sterilization to a total bio-burden analogous to that of the Viking landers' pre-sterilization levels for the HADES orbiter, as well as post-sterilization levels for the HADES lander and cryobot, will be required, in addition to a comprehensive contamination risk analysis.

For *in-situ* ice sampling and analysis, the bio-burden reduction will have to be greater than for a category IV mission. Any additional organic load has to be minimized for the sample drawing device (i.e. the drill) and all parts that may be in contact with the analytical instruments of the cryobot. Furthermore, the overall organic inventory has to be characterized and documented. The implementation of the planetary protection plan can be adapted from the ESA/EXOMARS strategy.

Orbiter

Structure

The spacecraft – consisting of an orbiter, a lander, and a cryobot – has a height of 3 m, a diameter of 2.5 m, and a mass of 4.2 t (including margins). The outer structure is aligned to fit into the fairing of an AtlasV rocket. The magnetometer boom and the RTGs are deployed after launch.

Attitude and orbital control

Attitude and orbital control are achieved using sensors and actuators on the spacecraft. An inertial guidance system tracks the current position and angle, based on earlier position and acceleration. The perpendicular to the plane of the orbit will be determined by a gyrocompass, while a sun sensor and three star trackers will provide information about the spacecraft orientation. A monopropellant thruster system allows orbital correction. Control of the spacecraft

Table 2. *Power and mass budget table for the orbiter and the lander*

	Mass (kg)	Power, max. (W)
Orbiter		
Bus		
Structure, mechanism and cabling	230	
Tank	20	0
Orbital control	150	0
Communication	100	35
RTG	33	–
Command and Data Handling	30	20
Radiator	20	0
Attitude control	20	18
Payload		
Instruments	52	131
Margin	35	
Total	690	
Lander		
Bus		
Structure, mechanism and cabling	270	
Tank	290	0
Communication	3	75
Command and Data Handling	5	10
Payload		
Instruments	21	100[a]/38[b]
Margin	41	
Total	630	
Cryobot		
Bus		
Structure, mechanism and cabling	64	
RTG	57	–
Heating	–	310/430[c]
Payload		
Instruments	7	38
Drill	7	15
Margin	15	
Total	150	
Spacecraft total (dry)	1470	
Propellant	2242	
Margin (+10% ΔV)	458	
Spacecraft total (wet)	4170	

[a] During descent.
[b] After landing.
[c] Day/night operations.

Table 3. *RTG beginning-of-life (BOL) and end-of-life (EOL) power budget table for the orbiter and the lander*

	RTG (Orbiter)	RTG (Lander)
Electrical power (BOL)	279 W	656 W
Electrical power (EOL)	255 W	600 W
Thermal power (BOL)	4367 W	10 932 W
Thermal power (EOL)	3995 W	9400 W
Mass of Fuel ($^{238}PuO_2$)	9271 g	21 810 g

Table 4. *Overall mission cost analysis*

		Items	Cost (M€ (M$))	% of total
Ground segment facilities		Launcher	150 (220)	10.6
		Mission Operations Centre (MOC)[a] Spacecraft Operations Centre (SOC)[b] PI teams[c]	98 (144)	7.0
Space segment	Orbiter	Electrical (RTG procurement)	150 (220)	10.6
		Mechanical	50 (73)	3.5
		Payload	50 (73)	3.5
	Lander	Electrical (from cryobot)	60 (88)	4.3
		Mechanical	50 (73)	3.5
		Payload	25 (37)	1.8
	Cryobot	Electrical (RTG procurement)	300 (440)	21.3
		Mechanical	50 (73)	3.5
		Payload	20 (29)	1.4
		Propulsion	65 (95)	4.6
Planetary protection			50 (73)	3.5
Pre-implementation phase			6 (9)	0.4
Contingency			280 (410)	19.9
Outreach (0.5 M€/year)			6 (9)	0.4
Total			1410 (2066)	100

[a] Mission planning, orbiter monitoring and control, orbit and attitude determination and control, communications with spacecraft, data downlink.
[b] Coordination of the long- and short-term scientific planning of the mission, preparing with PI teams the detailed operational timelines and delivering them to the MOC.
[c] Interacting with the SOC, to prepare operational timelines for their instrument and to provide high-level scientific data for long-term archiving.

orientation is achieved using a set of reaction/momentum wheels and a cold gas thruster system. For the final orbit around Europa, altitude control is provided by an additional nadir-pointing thruster. An innovative horizon sensor for accurate positioning around Europa will be required.

Thermal control

Optimal operations of instruments require a well-regulated thermal household which will be established by outsourcing of the RTGs radiators (RTGs deployed via booms); using the HGA as thermal protection; applying 5 m^2 of additional radiator area; the implementation of heater, heatpipes and heatswitches; and multilayer insulation.

Communications

The HGA ($D=4$ m, $G=47.5$ dB, $P=35$ W, $\Theta=0.656°$, $\eta=0.6$) is the main communication link from the orbiter to Earth. In order to maximize the transmission time to Earth, a polar orbit with its orbital plane facing the Earth was chosen, resulting in a LOS connection within 50 of 60 days. A data volume of about 15 GB is transmitted in the X-band at 8 GHz, with a data rate of 30 kbps during 60 days in orbit around Europa. Five Low Gain Antennas (LGAs) are used for redundancy of the signal and for communication with the ground stations when the HGA is depointed from the LOS – this problem will not arise while orbiting Europa. A helix antenna pointing towards Europa's surface is provided for communication with the lander in the UHF-band. Finally, three ground stations on Earth are required for optimum coverage of HADES data transfer and communication capacities.

Power supply

Several constraints, such as mission objectives or environmental conditions, influenced the choice of the electrical power system (EPS) device for HADES. The EPS is required to supply a high-power current during the whole duration of the mission (5 years) for the purpose of maintaining ambient temperatures for the spacecraft systems and the scientific payload, and at the same time, enabling the Cryobot to melt through the Europan icy crust (to a depth of about 25 m). Considering these requirements, together with the EPS lifetime limitation, the application of RTGs appears to be the most favourable option for the HADES mission concept (Table 3).

During the launch, the heat transfer from the RTG will be controlled using a Xe insulation system. In addition, the alpha radiation emitted by the RTGs can easily be shielded and will not adversely affect the general spacecraft and science operations.

Charge control

A device controlling the charge of the spacecraft is of special importance regarding the high radiation environment in the Jupiter system. Photoemission-based sensors will control the internal and external electrical charge distribution throughout the spacecraft (Oh 2001), in order to avoid interfering effects of charge accumulations within the payload.

Lander

Thermal control

Due to the cold conditions on the surface of Europa (approximately 100 K), the lander module has to be heated during the entire duration of the mission.

Communications

The patch antenna (size $40 \times 40\ \mathrm{cm}^2$, $P = 75$ W, $\Theta = 120°$; second antenna as redundancy) onboard the lander transmits data at a rate of 120 kbps in the UHF-band. This high data rate is required due to a limited LOS time for the orbiter of only 5 min every 1.8 days. Therefore, this results in a total transmission time of 170 min within the 60 days of the expected lifetime for the lander.

Cryobot

The cryobot is a large structure including at its front end an RTG providing heat to melt the ice, and energy for both the instruments and the lander. Attached to the far end, there is a cable spool containing more than 50 m of cable used as a connection to the lander for power and data transfer. The main scientific goal of the cryobot is the *in-situ* analysis and profiling of the ice layer up to a potential depth of 25 m. To estimate the rate of melting into the ice for the given cryobot geometry, we used a simple, thermally conductive ice layer model to retrieve the temperature profile (Biele *et al.* 2002), and an energy balance approximation. In addition, estimations of sublimation effects have to be taken into account (Kömle *et al.* 2002) resulting in the reduction of the initial probe velocity by a factor of 7.7. Calculations using the model of Biele *et al.* (2002) reveal that the HADES cryobot will reach a depth of 10.5 m after only 2 days. The final target depth is expected to be 25 m, stopping every 5 m for sampling.

Technology needs

Although current technology already allows an exploration mission to Europa, the development and experimental validation of a variety of new technological advances may reduce the risk of several of the mission's stages as well as increase the quality and amount of scientific data. These include, for example, advances in communication technology and data storage and transfer, which will most likely occur in forthcoming years and are expected to occur at the latest during the preparation phase of the mission. Alternative power sources may reduce problems associated with the use of RTGs. Advancement of onboard analysis systems, such as antibody array systems, may also provide a wider range of possible operations to be held *in-situ*, in the near future.

Cost estimations

The overall mission costs are within the range of typical Class L planetary missions. The values presented in Table 4 were estimated according to general recommendations and extrapolations of previous mission proposals, considering that internal costs are included. For the EPS, a reference value of about one million US dollars (approximately 0.7 M€) per 50 W of power supply was considered.

Conclusion

The exploration of the Jovian System, and particularly of the satellite Europa, is of considerable astrobiological relevance. Previous results suggesting the presence of a subsurface ocean make Europa one of the most interesting planetary bodies for the search for life in our Solar System. High priority has therefore been assigned to Europa exploration missions in ESA's 'Cosmic Vision' strategy (ESA 2005) and NASA's strategic plans (NRC 1999). Recently proposed missions have a variety of solutions, including orbiter and lander options. Constraints related to power and budget require cost-effective strategies to be considered. A scientifically and economically comprehensive coupling of the necessary instrumentation to answer a sequence of relevant questions, in one single mission instead of several separate missions, raises the cost-effectiveness of such a mission to Europa in a significant manner. The HADES mission, coupling an orbiter, a lander and a cryobot, is specifically designed to safely overcome the technical difficulties known to exist. The HADES mission concept ensures an answer to the primary question of whether there actually exists a liquid ocean beneath the icy crust, but also allows for immediate *in-situ* analysis of possible organic molecules or biomarkers present in the ice. Combined, this makes HADES an unprecedented compact experimental platform for a comprehensive astrobiological investigation of Europa. Although this mission relies on existing technology, near-future technological advances and optimizations may provide the possibility of alternative power sources, as well as considerable reductions in power demand, total mass and budget, further increasing the cost-effectiveness of this mission.

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References

Atzei, A. (2007). *ESA's Jovian Technology Reference Studies: The Challenge of Studying Europa and the Jovian System.* European Space Agency, ESA-ESTEC, Europa Focus Group.

Biele, J., Ulamec, S., Garry, J., Sheridan, S., Morse, A.D., Barber, S., Wright, I., Tüg, H. & Mock, T. (2002). Melting probes at Lake Vostok and Europa. In *Proc. 2nd Eur. Workshop on Exo/Astrobiology*, Graz., ESA SP-518, pp. 253–260.

Billings, S.E. & Kattenhorn, S.A. (2005). *Icarus* **177**, 397–412.

Blanc, M. *et al.* (2009). *Exp. Astron.* **23**, 849–892.

Blankenship, D.D. *et al.* (1999). Feasibility study and design concept for an orbiting ice-penetrating radar sounder to characterize in three-dimensions the European ice mantle down to (and including) any ice/ocean interface, prepared by the JIMO Europa Radar Sounder Instrument Definition Team.

Carr, M.H. *et al.* (1998). *Nature* **391**, 363–365.

Colangeli, L., Marra, G., Mazzotta Epifani, E., Palumbo, P., Flamini, E., Debei, S. & the SIMBIO-SYS International Team (2006). *Mem. S.A. It. Suppl.* **9**, 170–172.

Edwards, B.C. *et al.* (1997). *Proc. SPIE Int. Soc. Opt. Eng.* **3111**, 249–261.

ESA – European Space Agency (2005). *Cosmic Vision, Space Science for Europe 2015–2025*, ESA BR-247. ESA Publications Division, The Netherlands.

ESA – European Space Agency (2004). *ELRR – Europa Low Resource Radar*, CDF Study Report CDF-27(A), p. 149. ESA Publications Division, The Netherlands.

Fagents, S.A. (2003). *J. Geophys. Res.* **108**, 13–19.

Fernandez-Calvo, P., Nake, C., Rivas, L.A., García-Villadangos, M., Gomez-Elvira, J. & Parro, V. (2006). *Planet. Space Sci.* **54**, 1612–1621.

Goesmann, F., Rosenbauer, H., Roll, R., Szopa, C., Raulin, F., Sternberg, R., Israel, G., Meierhenrich, U., Thiemann, W. & Munoz-Caro, G. (2007). *Space Sci. Rev.* **128**, 257–280.

Goesmann, F., Rosenbauer, H., Roll, R. & Böhnhardt, H. (2005). *Astrobiology* **5**, 622–631.

Gold, R.E. (2001). *Planet. Space Sci.* **49**, 1467–1479.

Iess, L. & Boscagli, G. (2001). *Planet. Space Sci.* **49**, 1597–1608.

Kargel, J.S., Kaye, J.Z., Head, J.W., Marion, G.M., Sassen, R., Crowley, J.K., Ballesteros, O.P., Grant, S.A. & Hogenboom, D.L. (2000). *Icarus* **148**, 226–265.

Kempe, S. & Kazmierczak, J. (2002). *Astrobiology* **2**, 123–130.

Kivelson, M.G., Khurana, K.K., Means, J.D., Russell, C.T. & Snare, R.C. (1992). *Space Sci. Rev.* **60**, 357–383.

Kömle, N.I., Kargl, G. & Steller, M. (2002). Melting probes as a means to explore planetary glaciers and ice caps. In *Proc. 2nd Eur. Workshop on Exo/Astrobiology*, Graz., ESA SP-518, pp. 305–308.

Lee, S., Zanolin, M., Thode, A.M., Pappalardo, R.T. & Makris, N.C. (2003). *Icarus* **165**, 144–167.

McKay, C.P. (2002). *Adv. Space Res.* **30(6)**, 1601–1605.

National Research Council, NRC (2000). *Space Studies Board, Preventing the Forward Contamination of Europa*. National Academy Press, Washington DC.

National Research Council, NRC (1999). *Space Studies Board, A Science Strategy for the Exploration of Europa*. National Academy Press, Washington DC.

Oh, D. (2001). Photoemission based spacecraft charging sensor, US Patent 6332590.

Pappalardo, R.T. *et al.* (1999). *Geophys. Res.* **104**, 24015–24055.

Parro, V., Rivas, L.A. & Gómez-Elvira, J. (2007). *Sci. Rev.* **135**, 293–311.

Ruiz, J. & Tejero, R. (2003). *Icarus* **162**, 362–373.

Schulz, R. (2004). *J. Physique IV* **121**, 249–257.

Sgavetti, M., Pompilio, L., Carli, C., de Sanctis, M.C., Capaccioni, F., Cremonese, G. & Flamini, E. (2007). *Planet. Space Sci.* **55**, 1596–1613.

Skelley, A.M. & Mathies, R.A. (2003). *J. Chromatogr. A* **1021**, 191–199.

Sotin, C., Head III, J.W. & Tobie, G. (2002). *Geophys. Res. Lett.* **29(8)**, 1233.

Zeitlin, C., Cleghorn, T., Cuccinotta, F., Saganti, P., Andersen, V., Lee, K., Pinsky, L., Atwell, W. & Turner, R. (2003). Results from the Martian Radiation Environment Experiment MARIE. *Lunar and Planetary Science XXXIV*, Abstract # 1878.

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Development of a Model to Compute the Extension of Life Supporting Zones for Earth-Like Exoplanets

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Abstract A radiative convective model to calculate the width and the location of the life supporting zone (LSZ) for different, alternative solvents (i.e. other than water) is presented. This model can be applied to the atmospheres of the terrestrial planets in the solar system as well as (hypothetical, Earth-like) terrestrial exoplanets. Cloud droplet formation and growth are investigated using a cloud parcel model. Clouds can be incorporated into the radiative transfer calculations. Test runs for Earth, Mars and Titan show a good agreement of model results with observations.

Keywords Life supporting zone · Habitable zone · Radiative convective model · Cloud parcel model

Introduction

Life as we know it uses water as a solvent, which has been common on Earth since the early history of the planet. Its liquid temperature range, its physical buffering capacity and other characteristics make it ideal for the complex chemical interactions of terrestrial biomolecules. But exotic life, based on a different biochemistry (Baross et al. 2007) may be possible. For exotic life the properties of possible solvents like sulfuric acid, ammonia, methane, ethane or mixtures of them (see Table 1) could be as well suited as or even advantageous to those of water (Schulze-Makuch and Irwin 2004). On Titan, as an example

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Table 1 Physical properties of water and possible alternative solvents (adapted from Schulze-Makuch and Irwin 2004)

Property	H_2O	NH_3	H_2SO_4	CH_4	C_2H_6
Molar mass (g/mol)	18.02	17.03	98.08	16.04	30.07
Density (g/ml)	0.997 (25°C)	0.696 (−33.3°C)	1.831 (25°C)	0.426 (−164°C)	0.572 (−112°C)
Melting Point (°C at 1 bar)	0.0	−77.7	10	−182.5	−183
Boiling Point (°C at 1 bar)	100.0	−33.3	337	−161.5	−89
Range of Liquid (°C at 1 bar)	100	44.4	327	21	94
Critical Temperature (°C)	374	132	NA	−82.6	32.3
Critical Pressure (bar)	215	111	NA	45.5	47.8
Enthalpy of Fusion (kJ/mol)	6.0	5.7	10.7	0.94	2.7
Enthalpy of Vaporization (kJ/mol)	40.7	23.3	61.9	8.2	14.7
Dielectric Constant (ε_r)	80.1 (20°C)	22.5 (−34°C)	101 (25°C)	1.7 (−182°C)	1.9 (−178°C)
Viscosity (10^{-4} Pa·s)	8.9 (25°C)	2.7 (−34°C)	260 (25°C)	1.2 (−164°C)	2.3 (−112°C)
Dipole Moment (10^{-30} C·m)	6.2	4.9	9.0	0.0	0.0

for different environmental conditions, water is not liquid on the surface but methane or ethane could be possible solvents for exotic life.

The classical habitable zone for water is defined (Huang 1959, 1960; Hart 1978; Kasting et al. 1993) as the region around a star where liquid water may exist on the surface of a planet. Energy balance calculations show that the widths and the locations of habitable zones for alternative solvents (Leitner et al. 2010b) can be quite different from those for the classical habitable zone (Leitner et al. 2010a) because of the different temperature ranges for liquid alternative solvents (see Table 1). The life supporting zone (LSZ) is defined (Leitner et al. 2010b) as the zone consisting of all the habitable zones belonging to the considered solvents. To calculate the LSZ a radiative convective model for planetary atmospheres was further developed. For radiative transfer calculations the public domain software ‘Streamer’ was modified to provide an interface with the cloud model, to increase the spectral range for radiative transfer calculations and to include additional scattering and absorbing gases as well as collision induced absorption. As clouds dominate the radiative transfer when they are present, clouds are incorporated in this model.

Model Description

Two models are used: a cloud model and a radiative convective model. The cloud model is used to calculate cloud droplet distributions. The optical properties of these droplet distributions are computed offline using Mie theory (Bohren and Huffman 1983) and used as an input for the radiative convective model. These optical properties depend on the refractive indices of the solvents, which are taken from literature. The radiative convective model then yields the surface temperature of exoplanets.

Cloud Model

A cloud model developed for terrestrial water clouds by Neubauer (2009) is used to investigate cloud droplet formation and growth consisting of water or alternative solvents (e.g. H_2SO_4-clouds). Physico-chemical constants for the solvents available in the literature are used for the computations. As nothing is known about possible cloud condensation nuclei (CCN) in the atmosphere of exoplanets, we assume cloud formation processes follow the same physical principles of solvent condensation from the gas phase on pre-existing aerosol particles formed by the same physical processes as on Earth which are soluble in or at least wettable by the solvent. The model is a cloud parcel model which describes an ascending air parcel containing the droplets (following Kornfeld 1970; Houze 1993; Pruppacher and Klett 1997). The model includes the microphysical processes of nucleation, condensation and coagulation and radiative effects (Chen and Lamb 1994). Entrainment is also considered.

The CCN and the cloud droplets are each categorized into 100 size bins in the model. The scheme of Ochs and Yao (1978) for the method of moments is used to reduce numerical dispersion. A typical background aerosol distribution was employed for Earth. A constant updraft velocity of 0.75 m/s was used for the calculations for Earth and entrainment was implemented by considering the motion of the cloud droplets as a random walk between the upper and the lower cloud boundary (Mason 1952, 1960). The CCN start either with their equilibrium radius on the Köhler curve or if they are larger than a critical radius their initial radius is calculated with a parameterization given by Kogan (1991). The condensational growth uses the algorithm suggested by Chen and Lamb (1994) and accounts for radiative effects (Roach 1975; Brown 1980; Welch et al. 1986; Bott et al. 1990; Harrington et al. 2000; Conant et al. 2002). The continuous and stochastic coagulation equations are solved for a sedimentation and a Brownian diffusion kernel following Ochs and Yao (1978).

The cloud model provides cloud droplet size distributions for different cloud liquid solvent content (e.g. cloud liquid water content) which are stored in a database for use by the radiative convective model.

Radiative Convective Model

The equilibrium temperature profile of the atmosphere and the surface temperature of exoplanets are obtained with a model based on Manabe and Strickler (1964) and Manabe and Wetherald (1967) which we further developed for our purposes.

The atmospheric lapse rate calculated for radiative equilibrium is adjusted (i.e. convective adjustment) not to exceed a given lapse rate (e.g. the applicable dry or moist adiabatic lapse rate). For water vapor a constant absolute humidity, a constant relative humidity (Manabe and Wetherald 1967) or a troposphere fully saturated with water vapor (Kasting 1988; deviations from ideal gas law at high water vapor amounts are implemented) may be chosen. The model computes the horizontally and annually averaged global surface and atmospheric temperatures. The model uses an explicit Euler method with a variable time step for convergence of atmospheric and surface temperatures against thermal equilibrium and hard convective adjustment (Rennó et al. 1994). Several cloud layers with vertically constant optical properties can be inserted in the model atmosphere. Vertical levels in the atmosphere were chosen in constant steps on a logarithmic pressure scale.

Besides the spectral class of the star and the distance between the star and the exoplanets, the surface temperature strongly depends on the amount of atmospheric gases (in particular greenhouse gases), aerosol particles, clouds and surface albedo. Different scenarios (e.g. varying cloud amount, surface albedo, amount of atmospheric gases, etc.) can be investigated for each solvent to calculate the width and the location of the habitable zone belonging to the solvent.

For radiative transfer calculations we modified a version of the public domain program 'Streamer' (Key and Schweiger 1998). 'Streamer' accounts for scattering and absorption of radiation by gases and particles. The long wave spectrum consists of 105 wavelength bands between 4 μm and 500 μm and the shortwave spectrum of 24 wavelength bands between 0.2 μm and 5 μm (0.28 μm and 4 μm in the original 'Streamer' program). Built-in types of surface albedo as well as other values can be chosen. The radiative transfer equation can be solved in 'Streamer' by two different numerical methods to increase the precision of the calculation (Stamnes et al. 1988; Toon et al. 1989). The spectrum of the Sun is built-in in 'Streamer'. The cloud optical properties calculated offline by the cloud model and Mie theory (Bohren and Huffman 1983) are used as an input for 'Streamer' when desired. Rayleigh-scattering is calculated for air in original 'Streamer', and was expanded by us to include also the scattering by H_2O, CO_2, CO, CH_4, N_2O, NO, NH_3 and SO_2. Besides H_2O, CO_2, O_2 and O_3 (original 'Streamer' absorbing gases) we included other atmospheric absorbing gases in our model: CH_4, NH_3, CO, SO_2, N_2O, NO, NO_2 and HNO_3. The exponential-sum fitting of transmissions-method (ESFT, Wiscombe and Evans 1977) was applied for this purpose and the necessary transmission functions were computed using LOWTRAN 7 (Kneizys et al. 1988) and LBLRTM (Clough et al. 2005). These transmission functions are accurate only for pressures and temperatures typical for Earth's atmosphere: LOWTRAN 7: temperature range: approx. 215–300 K, pressure range: approx. 1–0.1(0.01 for CO_2, NO, N_2O) atm; LBLRTM: temperatures and pressures inside the normal range of Earth's atmosphere between 0 and 120 km in altitude. For CH_4 and wavelengths ≤5 μm the transmission functions were computed with absorption coefficients from Karkoschka and Tomasko (2010) and from Irwin (2010) (temperature range: 50–300 K, pressure range: $10–10^{-8}$ atm), for wavelengths >5 μm LBLRTM was used. Continuum absorption by water vapor is included in the original 'Streamer'. We extended the model to calculate collision induced absorption by N_2-N_2, N_2-H_2, N_2-CH_4, CH_4-CH_4 and CO_2-CO_2 collisions (Borysow and Frommhold 1986a, 1986b, 1987a, 1987b; Borysow and Tang 1993; Gruszka and Borysow 1997; Baranov et al. 2004). The 'Streamer' code imposes some limitations: radiative transfer can be computed for only one scattering gas and four absorbing gases. Due to these limits we choose one scattering gas (or a mixture with fixed mixing ratios, e.g. N_2, air) and up to four main atmospheric absorbing gases out of the list (each added gas absorbing in a significant spectral range slows down the model) plus continuum absorption and/or collision induced absorption for each scenario.

First Results

Table 2 shows parameters and atmospheric compositions used in the test runs. A test run for Earth with a surface albedo of 0.1 (Manabe and Strickler 1964) and an average cloud cover (high and low level clouds; Kitzmann et al. 2010) and a critical lapse rate of −6.5 K/km showed a good agreement of the atmospheric temperature profile and surface temperature with observed values. For this test run, atmospheric mixing ratios for N_2, O_2 and CO_2 of 78%, 21% and 0.038% respectively (Bauer et al. 1997; IPCC 2007) and a surface pressure of 1013 mbar were used. The O_3 and H_2O profiles were taken from Manabe and Wetherald (1967) and Manabe and Strickler (1964) respectively. A constant absolute humidity was used for water vapor in this run. H_2O, CO_2, O_3 and O_2 were selected to include the most important greenhouse gases and be able to compute the stratospheric temperature structure. CH_4 and N_2O, though they provide of the order of 3–4 K of greenhouse effect, were

Table 2 Parameters and atmospheric compositions used in the test runs

Parameter	Earth	Mars	Titan
Number of vertical levels	37	28	28
Surface pressure (mbar)	1013	6.5	1496
Top of the atmosphere-pressure (mbar)	0.2	0.001	0.78
Scattering gas	air	CO_2	N_2-CH_4 mixture
Absorbing gases	H_2O, CO_2, O_2, O_3	CO_2	CH_4
Collision induced absorption	–	CO_2-CO_2	N_2-N_2, N_2-CH_4, CH_4-CH_4, N_2-H_2
High level cloud cover	15%	–	–
Low level cloud cover	39.5%	–	–
Cloud overlap	0%	–	–

omitted as only four absorbing gases can be chosen (see subsection Radiative convective model).

The computations for Mars and Titan were done without clouds in their atmospheres. For Mars atmospheric mixing ratios for CO_2 and N_2 have been taken as 95% and 5% respectively (Taylor 2010; the mixing ratio for N_2 is 2.7% but N_2 represents the rest of the Martian atmospheric gases in this test run). Further absorbing gases have been omitted as their presence does not significantly change the surface temperature. The surface pressure is 6.5 mbar (Taylor 2010). A test run for Mars with a 'dusty' adiabatic lapse rate of −2 K/km (Taylor 2010) showed a good agreement of the atmospheric and surface temperatures with observed temperatures.

For Titan the CH_4 profile given by Niemann et al. (2005) was used with a N_2 atmosphere and a surface pressure of 1496 mbar. C_2H_2 and C_2H_6 could not be included as absorbing gases as we could not obtain the necessary transmission functions. H_2 is included

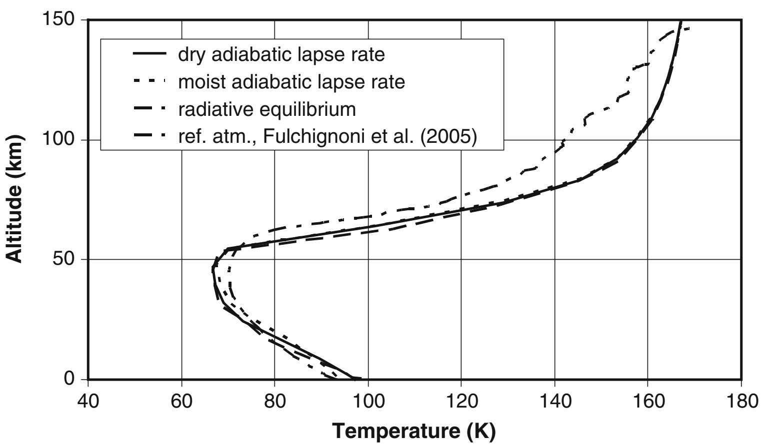

Fig. 1 Temperature profile of Titan for model runs without clouds and for a reference atmosphere (dashed-dotted line; Fulchignoni et al. 2005). Three different approaches for convective adjustment are shown, radiative equilibrium (i.e., no adjustment, dashed line), adjustment with a dry adiabatic lapse rate (solid line) and adjustment with a most adiabatic lapse rate (dotted line). The surface temperature of the run with the moist adiabatic lapse rate adjustment of 93.9 K agrees well with the reference surface temperature of 93.7 K

with a mixing ratio of 0.1% via collision induced absorption by N_2-H_2 collisions. Condensation clouds of CH_4 were omitted in this test run as they only have a small effect on the temperature structure of Titan (McKay et al. 1989). Due to limitations of the radiative transfer program haze was also omitted, but this has no significant impact on surface and tropospheric temperatures (McKay et al. 1989; Lavvas et al. 2008). The model results for the surface temperature are in good agreement with observed values and the atmospheric temperature profile agrees qualitatively with observed temperatures (see Fig. 1). The deviations of the temperatures in the stratosphere might be a result of the absence of haze, C_2H_2 and C_2H_6.

Summary

A radiative convective model was further developed to compute the width and the location of the life supporting zone (LSZ) for different, alternative solvents around the Sun and other main sequence stars. The formation and growth of cloud droplets are investigated for the different solvents with a cloud model. Clouds can be included in the calculation of the width and the location of the LSZ.

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References

Baranov YI, Lafferty WJ, Fraser GT (2004) Infrared spectrum of the continuum and dimmer absorption in the vicinity of the O2 vibrational fundamental in O2/CO2 mixtures. J Mol Spectrosc 228:432–440. doi:10.1016/j.jms.2004.04.010

Baross JA et al (2007) The limits of organic life in planetary systems. National research council. National Academies Press, Washington

Bauer et al (1997) Erde und Planeten. In: Bergmann L, Schaefer C (eds) Lehrbuch der Experimentalphysik 7. Walter de Gruyter, Berlin

Bohren CF, Huffman DR (1983) Absorption and scattering of light by small particles. Wiley, New York

Borysow A, Frommhold L (1986a) Theoretical collision induced rototranslational absorption spectra for modeling Titan's atmosphere: H2-N2 pairs. Astrophys J 303:495–510. doi:10.1086/164096

Borysow A, Frommhold L (1986b) Collision induced rototranslational absorption spectra of N2-N2 pairs for temperatures from 50 to 300 K. Astrophys J 311:1043–1057. doi:10.1086/164841

Borysow A, Frommhold L (1987a) Collision induced rototranslational absorption spectra of CH4-CH4 pairs at temperatures from 50 to 300K. Astrophys J 318-940-943. doi:10.1086/165426

Borysow A, Frommhold L (1987b) Collision induced rototranslational absorption spectra of N2-N2 pairs for temperatures from 50 to 300K: Erratum. Astrophys J 320:437. doi:10.1086/165558

Borysow A, Tang C (1993) Far infrared CIA spectra of N2-CH4 pairs for modeling of Titan's atmosphere. Icarus 105:175–183. doi:10.1006/icar.1993.1117

Bott A, Sievers U, Zdunkowski W (1990) A radiation fog model with a detailed treatment of the interaction between radiative transfer and fog microphysics. J Atmos Sci 47:2153–2166. doi:10.1175/1520-0469(1990)047<2153:ARFMWA>2.0.CO;2

Brown R (1980) A numerical study of radiation fog with an explicit formulation of the microphysics. Q J R Meteorol Soc 106:781–802. doi:10.1002/qj.49710645010

Chen JP, Lamb D (1994) Simulation of cloud microphysical and chemical processes using a multicomponent framework. Part I: Description of the microphysical model. J Atmos Sci 51:2613–2630. doi:10.1175/1520-0469(1994)051<2613:SOCMAC>2.0.CO;2

Clough SA, Shephard MW, Mlawer EJ, Delamere JS, Iacono MJ, Cady-Pereira K, Boukabara S, Brown PD (2005) Atmospheric radiative transfer modeling: A summary of the AER codes. J Quant Spectrosc Radiat Transf 91:233–244. doi:10.1016/j.jqsrt.2004.05.058

Conant WC, Nenes A, Seinfeld JH (2002) Black carbon radiative heating effects on cloud microphysics and implications for the aerosol indirect effect 1. Extended Köhler theory. J Geophys Res 107(D21):4604–4612. doi:10.1029/2002JD002094

Fulchignoni M et al (2005) In situ measurements of the physical characteristics of Titan's environment. Nature 438:785–791. doi:10.1038/nature04314

Gruszka M, Borysow A (1997) Roto-translational collision-induced absorption of CO2 for the atmosphere of Venus at frequencies from 0 to 250 cm^-1 and at temperature from 200K to 800K. Icarus 129:172–177. doi:10.1006/icar.1997.5773

Harrington JY, Feingold G, Cotton WR (2000) Radiative impacts on the growth of a population of drops within simulated summertime Arctic stratus. J Atmos Sci 57:766–785. doi:10.1175/1520-0469(2000)057<0766:RIOTGO>2.0.CO;2

Hart MH (1978) The evolution of the atmosphere of the Earth. Icarus 33:23–39. doi:10.1016/0019-1035(78)90021-0

Houze RA (1993) Cloud dynamics. Academic Press, San Diego

Huang SS (1959) Occurrence of life in the universe. Am Sci 47:397–402. http://www.jstor.org/stable/27827376

Huang SS (1960) Life outside the solar system. Sci Am 202:55–63. doi:10.1038/scientificamerican0460-55

IPCC (2007) Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Irwin P (2010) http://www.atm.ox.ac.uk/user/irwin/. Accessed December 2010

Karkoschka E, Tomasko MG (2010) Methane absorption coefficients for the jovian planets from laboratory, Huygens, and HST data. Icarus 205:674–694. doi:10.1016/j.icarus.2009.07.044

Kasting JF (1988) Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. Icarus 74:472–494. doi:10.1016/0019-1035(88)90116-9

Kasting JF, Whitmore DP, Reynolds RT (1993) Habitable Zones around main sequence stars. Icarus 101:108–128. doi:10.1006/icar.1993.1010

Key JR, Schweiger AJ (1998) Tools for atmospheric radiative transfer: Streamer and FluxNet. Comput Geosci 24:443–451. doi:10.1016/S0098-3004(97)00130-1

Kneizys FX, Shettle EP, Abreu LW, Chetwynd JH, Anderson GP, Gallery WO, Selby JEA, and Clough SA (1988) Report AFGL-TR-88-0177, Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts

Kitzmann D, Patzer ABC, von Paris P, Godolt M, Stracke B, Gebauer S, Grenfell JL, Rauer H (2010) Clouds in the atmospheres of extrasolar planets I. Climatic effects of multi-layered clouds for Earth-like planets and implications for habitable zones. Astron Astrophys 511:A66. doi:10.1051/0004-6361/200913491

Kogan YL (1991) The simulation of a convective cloud in a 3-D model with explicit microphysics. Part I: Model description and sensitivity experiments. J Atmos Sci 48:1160–1189. doi:10.1175/1520-0469(1991)048<1160:TSOACC>2.0.CO;2

Kornfeld P (1970) Numerical solution for condensation of atmospheric vapor on soluble and insoluble nuclei. J Atmos Sci 27:256–264. doi:10.1175/1520-0469(1970)027<0256:NSFCOA>2.0.CO;2

Lavvas PP, Coustenis A, Vardavas IM (2008) Coupling photochemistry with haze formation in Titan's atmosphere, Part II: Results and validation with Cassini/Huygens data. Planet Space Sci 56:67–99. doi:10.1016/j.pss.2007.05.027

Leitner JJ, Neubauer D, Schwarz R, Eggl S, Firneis MG, Hitzenberger R (2010a) The life supporting zone I - From classic to exotic life. In: European Planetary Science Congress Abstracts 5:EPSC2010-677

Leitner JJ, Schwarz R, Firneis MG, Hitzenberger R, Neubauer D (2010b) Generalizing habitable zones in exoplanetary systems - The concept of the life supporting zone. Astrobiology Science Conference 2010 Abstract #5255

Manabe S, Strickler RF (1964) Thermal equilibrium of the atmosphere with a convective adjustment. J Atmos Sci 21:361–385. doi:10.1175/1520-0469(1964)021<0361:TEOTAW>2.0.CO;2

Manabe S, Wetherald RT (1967) Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J Atmos Sci 24:241–259. doi:10.1175/1520-0469(1967)024<0241:TEOTAW>2.0.CO;2

Mason BJ (1952) Production of rain and drizzle by coalescence in stratiform clouds. Q J R Meteorol Soc 78:377–386. doi:10.1002/qj.49707833708

Mason BJ (1960) The evolution of droplet spectra in stratus cloud. J Atmos Sci 17:459–462. doi:10.1175/1520-0469(1960)017<0459:TEODSI>2.0.CO;2

McKay CP, Pollack JB, Courtin R (1989) The thermal structure of Titan's atmosphere. Icarus 80:23–53. doi:10.1016/0019-1035(89)90160-7

Neubauer D (2009) Modellierung des indirekten Strahlungseffekts des Hintergrundaerosols in Österreich. Dissertation, University of Vienna

Niemann HB et al (2005) Titan's atmosphere from the GCMS instrument on the Huygens probe. Nature 438:779–784. doi:10.1038/nature04122

Ochs HT, Yao CS (1978) Moment-conserving techniques for warm cloud microphysical computations. Part I: Numerical techniques. J Atmos Sci 35:1947–1958. doi:10.1175/1520-0469(1978)035<1947:MCTFWC>2.0.CO;2

Pruppacher HR, Klett JD (1997) Microphysics of clouds and precipitation. Kluwer Academic Publishers, Dordrecht

Rennó NO, Emanuel KA, Stone PH (1994) Radiative-convective model with an explicit hydrological cycle 1. Formulation and sensivity to model parameters. J Geophys Res 99(D7):14429–14441. doi:10.1029/94JD00020

Roach WT (1975) On the effect of radiative exchange on the growth by condensation of a cloud or fog droplet. Q J R Meteorol Soc 102:361–372. doi:10.1002/qj.49710243207

Schulze-Makuch D, Irwin LN (2004) Life in the universe. Springer, New York

Stamnes K, Tsay SC, Wiscombe W, Jayaweera K (1988) Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. Appl Opt 27:2502–2509. doi:10.1364/AO.27.002502

Taylor FW (2010) Planetary atmospheres. Oxford University Press, Oxford

Toon OB, McKay CP, Ackerman TP, Santhanam K (1989) Rapid calculation of radiative heating rates and photodissociation rates in inhomogeneous multiple scattering atmospheres. J Geophys Res 94 (D13):16,287–16,301. doi:10.1029/JD094iD13p16287

Welch RM, Ravichandran MG, Cox SK (1986) Prediction of quasi-periodic oscillations in radiation fogs. Part I: Comparison of simple similarity approaches. J Atmos Sci 43:633–651. doi:10.1175/1520-0469(1986)043<0633:POQPOI>2.0.CO;2

Wiscombe WJ, Evans JW (1977) Exponential-sum fitting of radiative transmission functions. J Comput Phys 24:416–444. doi:10.1016/0021-9991(77)90031-6

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The life supporting zone of Kepler-22b and the Kepler planetary candidates: KOI268.01, KOI701.03, KOI854.01 and KOI1026.01

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The concept of the life supporting zone is a generalization of the concept of the habitable zone (and therefore for water based life, i.e. life-as-we-know-it) to other solvents (and to life-as-we-do-not-know-it). We present an estimate of life supporting zones of Kepler-22b and the Kepler planetary candidates KOI268.01, KOI701.03, KOI854.01 and KOI1026.01. The life supporting zone envelopes in this study the water, sulfuric acid and water/ammonia mixture habitable zones. Planetary surface temperatures were computed with a radiative convective model for "Venus-like" and "Earth-like" atmospheric scenarios including clouds. For Kepler-22b an Earth-like planet and an ocean planet (50 wt% H_2O) scenario are investigated. Restrictions on stellar and planetary input parameters are derived from the model simulations. The input parameters with the largest influence on planetary surface temperature are the stellar flux, the planets' surface albedo, the considered atmospheric scenario and cloud properties. Water and thick H_2SO_4-clouds lead to lower surface temperatures for small values of surface albedos and higher temperatures for higher albedos. For thin H_2SO_4-clouds the cooling effect dominates. All planet(ary candidate)s investigated are likely to lie in the life supporting zone. Kepler-22b and KOI701.03 are likely to lie in the water habitable zone.

1. Introduction

Exotic life may be based on solvents other than water. Polar, non-polar and supercritical cryosolvents have been discussed in the literature (see e.g. Raulin et al., 1995; Bains, 2004; Benner et al., 2004; Schulze-Makuch and Irwin, 2004; 2006; Baross et al., 2007; Leitner et al., 2010a). Polar solvents other than water are for example sulfuric acid and ammonia, which exist or may exist in the solar system in the liquid phase. The sulfuric acid clouds on Venus may be a possible habitat for life (see Schulze-Makuch and Irwin, 2006 and references therein). Subsurface oceans consisting of a water/ammonia mixture may exist on satellites in the outer solar system (Hussmann et al., 2006). A water/ammonia ocean could also form on Titan's surface in the future when the Sun evolves into a red giant (Lorenz et al., 1997). Titan already is next to Earth the only terrestrial object in the solar system with a stable presence of a liquid on the surface as hydrocarbon lakes were detected on Titan (Stofan et al., 2007). Several studies discussed the possibilities of prebiotic molecules or life in these lakes (McKay and Smith, 2005; Schulze-Makuch and Grinspoon, 2005; Baross et al., 2007; Plankensteiner et al., 2007; Norman and Fortes, 2011).

The classic habitable zone for life-as-we-know-it is the region around a star where liquid water may exist on the surface of a planet. The life supporting zone (Leitner et al., 2010b), is defined as a wider region around a host star compared to the classical habitable zone. It envelopes the separate habitable zones for the considered different solvents possibly suited for life which may also overlap. The concept of the life supporting zone was introduced to take the habitable zones for possible life based also on solvents other than water (Leitner et al., 2010c) into account.

The Kepler mission detected 1235 planetary candidates from 2 May through 16 September 2009 (Borucki et al., 2011) with 54 candidates in the temperature range of the water habitable zone. Kepler-22b (KOI87.01) is the first confirmed exoplanet of these planetary candidates which lies in the habitable zone for water based life (Borucki et al., 2012). Kaltenegger and Sasselov (2011) further studied the habitability of the Kepler planetary candidates and identified six candidates (at 100% cloud coverage) within the water habitable zone with radii less than 2 Earth-radii.

The goal of our study is an investigation of the water, sulfuric acid and water/ammonia mixture habitable zones for Kepler-22b and four Kepler planetary candidates: KOI268.01, KOI701.03, KOI854.01 and KOI1026.01 (see Table 1). We investigate an Earth-like planet

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Table 1
Stellar and planetary input parameters.

Host star	$T_{effective}$ (K)	Radius (R_{Sun})	Mass (M_{Sun})	Spectral type			
268	4808	0.79	0.73	K			
701	4869	0.68	0.83	G/K			
Kepler-22	5518	0.98	0.97	G			
854	3743	0.49	0.43	K			
1026	3802	0.68	0.52	K			
Planetary Candidate	**$T_{equilibrium}$ (K)**	**Radius (R_{Earth})**	**Mass[a] (M_{Earth})**	**a (AU)**	**Period (days)**	**ESI[b]**	**$T_{Anti-GH}$[c] (K)**
268.01	295	1.75	7.71	0.406	110.37	0.71	248
701.03	262	1.73	7.39	0.454	122.39	0.82	220
Kepler-22b (terrestrial)	262	2.38	23.68	0.849	289.86	0.74	220
Kepler-22b (50 wt% H_2O)	262	2.38	10.04	0.849	289.86	0.80	220
854.01	248	1.91	10.61	0.217	56.1	0.79	209
1026.01	242	1.77	8.04	0.325	94.1	0.80	203

[a] Calculated according to Sotin et al. (2007).
[b] Earth Similarity Index (Schulze-Makuch et al., 2011); values above 0.8 may be considered Earth-like (see also Fig. S8); for the calculation of ESI values the surface temperature of the ELRHCL scenario for a surface albedo of 0.1 was used.
[c] Surface temperature for a complete anti-greenhouse effect $T_{Anti-GH}=T_{equilibrium}\sqrt[4]{0.5}$.

and an ocean planet (50 wt% H_2O) scenario for Kepler-22b. Kepler-22b and the four candidates have masses (calculated according to Sotin et al., 2007; see Table 1) between 1 and approx. 10 Earth masses (M_{Earth}). As they are relatively distant to their host stars (Table 1) we assume that they have not been exposed to extreme particle and stellar wind conditions impacting their atmospheres during early stages of their planetary systems. The XUV flux of late type stars (i.e., spectral types G, K, M) decreases with the age of the stars (see Lammer et al., 2009 and references therein). As the age of the host stars is unknown we assume that the stellar XUV irradiation is no danger to the assumed atmospheres. Kepler-22b and the four planetary candidates have a relatively large Earth Similarity Index (ESI; Schulze-Makuch et al., 2011; see Table 1 and Fig. S8; for the calculation of ESI values the surface temperature of the ELRHCL scenario for a surface albedo of 0.1 was used). KOI701.03 may be considered Earth-like.

2. Materials and methods

2.1. Water and other solvents as basis for life

Why water is a good solvent for life-as-we-know-it and also its disadvantages are well discussed in the literature (e.g. Schulze-Makuch and Irwin, 2004; Baross et al., 2007). Water acts as a thermal moderator on Earth because of its high heat capacity, the wide temperature range for the liquid phase (at a pressure of 1013.25 mbar water is liquid between 273 K and 373 K) and because water is a good heat insulator. Because of its high dipole-moment water is a good solvent for ionic and polar covalent bonds but not a good solvent for molecules with non-polar covalent bonds such as those of hydrophobic organic molecules like lipids. Dehydration is inhibited in water and requires energetically expensive and elaborately catalyzed reactions.

A water/ammonia mixture stays liquid at lower temperatures compared to water. The freezing point of a water/ammonia mixture with 15 wt% ammonia is 250 K (for a pressure of 1013.25 mbar; Kargel, 1992; Leliwa-Kopystynski et al., 2002). Below this temperature part of the mixture stays liquid ammonia enriched until even a mixture of peritectic composition, 33 wt% ammonia, freezes at 176 K (Croft et al., 1988). Biochemistry in ammonia is conceivable by replacing C=O carbonyl units by C=N units (Benner et al., 2004). "Ammono" analogs of terrestrial biomolecules were proposed by Raulin et al. (1995) where O atoms are replaced by NH. Bains (2004), Schulze-Makuch and Irwin (2006), Baross et al. (2007) discuss ammonia or water–ammonia mixtures as possible solvents.

Sulfuric acid might be a solvent alternative to water. Hypotheses exist for metabolism in acidic aerosols as found in the cloud layers on Venus. The C=C bond can support a metabolism as an analog of the C=O unit (Benner et al., 2004). Sulfuric acid as a possible solvent is discussed by Benner et al. (2004), Baross et al. (2007). Sulfuric acid is liquid between 283 K and 563 K at a pressure of 1013.25 mbar.

2.2. General considerations for modeling of atmospheres

We use a radiative convective model to compute the surface temperatures of the candidates assuming atmospheric scenarios with Venus-like and Earth-like compositions. The effects of clouds on the temperatures of Earth-like (exo)planets have been studied before by others using radiative convective models and Earth's atmosphere but varying cloud coverage (Kasting, 1988; Kitzmann et al., 2010). Following the method of Kitzmann et al. (2010), we use measured cloud properties of Earth and estimates for cloud properties of Venus to study the effect of clouds for the selected planetary candidates for various atmospheric scenarios.

2.3. Radiative convective model

The model (Neubauer et al., 2011) is based on the model by Manabe and Strickler (1964), Manabe and Wetherald (1967) and was further developed to compute the equilibrium temperature profile of the atmosphere and the surface temperature of exoplanets. The atmospheric lapse rate calculated for radiative equilibrium is adjusted (i.e. hard convective adjustment; Rennó et al., 1994) not to exceed a given lapse rate, i.e. the dry adiabatic lapse rate in the Venus-like scenario and the moist adiabatic lapse rate (see e.g. Satoh, 2004) in the Earth-like scenarios, see Section 2.5. Vertical levels in the atmosphere were chosen in constant steps on a logarithmic pressure scale.

For radiative transfer calculations we modified the public domain program 'Streamer' (Key and Schweiger, 1998; other parts are described by Toon et al., 1989; Stamnes et al., 1988, 1994, 2000) to provide an interface to the cloud model, to increase the spectral range for radiative transfer calculations and to include additional scattering and absorbing gases. The 2-stream algorithm by Toon et al. (1989) is used to solve the radiative transfer equation. The long wave spectrum consists of 105 wavelength bands between 3 μm and 500 μm and the short wave spectrum of 24 wavelength bands between 0.2 μm and 5 μm. The cloud optical properties calculated by the cloud model and Mie theory (code BHMIE, Bohren and Huffman, 1983) are used as an input for 'Streamer'. Original 'Streamer' can calculate Rayleigh-scattering only for air. We expanded the calculation to include Rayleigh scattering by H_2O, CO_2, CO, CH_4, N_2O, NO, NH_3 and SO_2. Besides the absorption by H_2O, CO_2, O_2 and O_3 (original 'Streamer'), absorption by other atmospheric gases (CH_4, NH_3, CO, SO_2, N_2O, NO, NO_2 and HNO_3) was included for the current model. The exponential-sum fitting of transmissions-method (ESFT, Wiscombe and Evans, 1977) was applied for this purpose and we computed the necessary transmission functions using LOWTRAN 7 (Kneizys et al., 1988). These transmission functions are accurate only for pressures and temperatures typical for Earth's atmosphere (temperature range: approx. 215–300 K, pressure range: approx. 1–0.1(0.01 for CO_2, NO, N_2O) atm). We tested the validity of the temperature dependence of the transmission functions between 200 K and 400 K by line-by-line calculations and found it to be accurate to within a few percent. As collision-induced absorption (Crawford et al., 1949; Frommhold, 1993) is not included in the radiative transfer program the surface temperatures in the Venus-like atmospheric scenario are probably somewhat too low for large values of surface albedo. At the low surface temperatures obtained for a high surface albedo in this scenario the absorption in the far infrared would be mostly due to collision-induced absorption which would enhance the greenhouse effect. For low surface temperatures also the emission of the planet's surface is shifted to longer wavelengths further enhancing the greenhouse effect due to collision-induced absorption.

For a complete anti-greenhouse effect the surface temperature of an (exo)planet is calculated as: $T_{\text{Anti-GH}} = T_{\text{equilibrium}}\sqrt[4]{0.5}$ (McKay et al., 1991; see Table 1). The anti-greenhouse effect was not computed in this study but can be estimated, depending on its magnitude, as the difference in surface temperatures of Kepler-22b and the four planetary candidates between the predicted temperatures given in Fig. 1 and Figs. S1–S6 and the surface temperature calculated for a complete anti-greenhouse effect.

2.4. Cloud model

Cloud droplet formation and growth are investigated with a cloud model developed for terrestrial water clouds (Neubauer, 2009) which was later modified (Neubauer et al., 2011) for clouds consisting of alternative solvents (e.g. H_2SO_4-clouds). We assume that aerosol formation processes follow the same physical principles of nucleation from the vapor phase and erosion of bulk material as on Earth (for basic information on aerosol formation mechanisms see e.g. Seinfeld and Pandis, 2006) and assume the presence of cloud condensation nuclei (CCN) soluble in or at least wettable by the considered solvents. As no data is available for the aerosol of the Kepler candidates or other exoplanets, an aerosol size distribution typical for Earth's background aerosol is used as an input for the cloud model and typical aerosol concentrations found on Earth are assumed in the Earth-like scenarios (compiled from data given by Hitzenberger et al., 2001; Bauer et al., 2002; Iorga et al., 2007) and for Venus in the Venus-like scenarios (Knollenberg and Hunten, 1980). The activation of aerosol particles as CCN and the subsequent cloud droplet growth calculated by the cloud model depend on physico-chemical properties of the solvents such as saturation vapor pressure, surface tension, diffusion coefficient, density or mass accommodation coefficient. Values for the solvents were taken from Murray, 1967; Beard and Pruppacher, 1971; Palmer and Williams, 1975; Pruppacher and Rasmussen, 1979; Myers, 1983; Kulmala and Laaksonen, 1990; Pruppacher and Klett, 1997 (and references therein); Hess et al., 1998; Pöschl et al., 1998; Hanson and Eisele, 2000, Vehkamaki et al., 2002; Haynes, 2012; Linstrom and Mallard, 2012.

The cloud model is a cloud parcel model which describes an ascending air parcel containing the droplets (following Kornfeld, 1970; Houze, 1993; Pruppacher and Klett, 1997). As cloud droplets can form only from supersaturated vapors water surface reservoirs (e.g. water oceans) in the Earth-like atmospheric scenarios and photochemical production of sulfuric acid in the Venus-like atmospheric scenarios were assumed. For water clouds initial values of temperature, pressure and saturation state typical for low level clouds in Earth's atmosphere were used. For H_2SO_4-clouds initial values of temperature, pressure and H_2SO_4-mixing ratio typical for the base of the main cloud deck on Venus were chosen. The H_2SO_4-mixing ratio was set to increase with increasing altitude as in Venus' atmosphere. A constant updraft velocity of 0.75 m/s was used for the calculations and entrainment was implemented by considering the motion of the cloud droplets as a random walk between the upper and the lower cloud boundary (Mason, 1952, 1960). The CCN and the cloud droplets are each categorized into 100 and 150 size bins in the model. The scheme of Ochs and Yao (1978) for the method of moments is used to reduce numerical dispersion. The CCN are assumed to start either with their equilibrium radius on the Köhler curve or a parameterized radius (Kogan, 1991) if they are larger than a certain, updraft dependent radius. The growth by condensation is simulated using the algorithm by Chen and Lamb (1994). Radiative effects (Roach, 1975; Brown, 1980; Welch et al., 1986; Bott et al., 1990; Harrington et al., 2000; Conant et al., 2002) are taken into account. The continuous and stochastic coagulation equations together with a sedimentation and a Brownian diffusion kernel are solved following Ochs and Yao (1978).

The cloud model provides cloud droplet size distributions for different cloud liquid solvent content (in analogy to cloud liquid water content) which are stored as a dataset. Cloud droplet size distributions with liquid solvent content typical for Earth or Venus clouds are selected for computations of the life supporting zone. The optical properties of these droplet distributions are computed offline using the refractive indices of the solvents and Mie theory (BHMIE, Bohren and Huffman, 1983) and are used as an input for the radiative convective model.

In a fully coupled cloud and radiative convective model cloud properties like altitude, optical depth, droplet concentration or droplet size distribution would change with atmospheric temperatures. This feedback could considerably change the radiative effect of the clouds. In all scenarios assumed in the present study we assume or compute and select (one or more) fixed value(s) for these cloud properties that are typical for water clouds on Earth or H_2SO_4-clouds on Venus. By comparing simulations with and without clouds these assumptions allow a rough estimate of the influence of clouds on the location of the solvents habitable zones.

2.5. Atmospheric composition

We assume three different sets of atmospheric compositions (see Table 2) for Kepler-22b and the super-Earth sized (Borucki et al., 2011) planetary candidates. Due to the restrictions imposed by the current radiative transfer program, we assume an atmospheric surface pressure of 1013.25 mbar in all scenarios. Each scenario consists of a cloud free and a cloudy case.

2.5.1. Venus-like (VL) scenario

The first scenario simulates a Venus-like (VL) atmosphere i.e. an atmosphere with 96.5% CO_2, 3.5% N_2, 0.015% SO_2, 0.002% water vapor and 0.0017% CO (Basilevsky and Head, 2003;

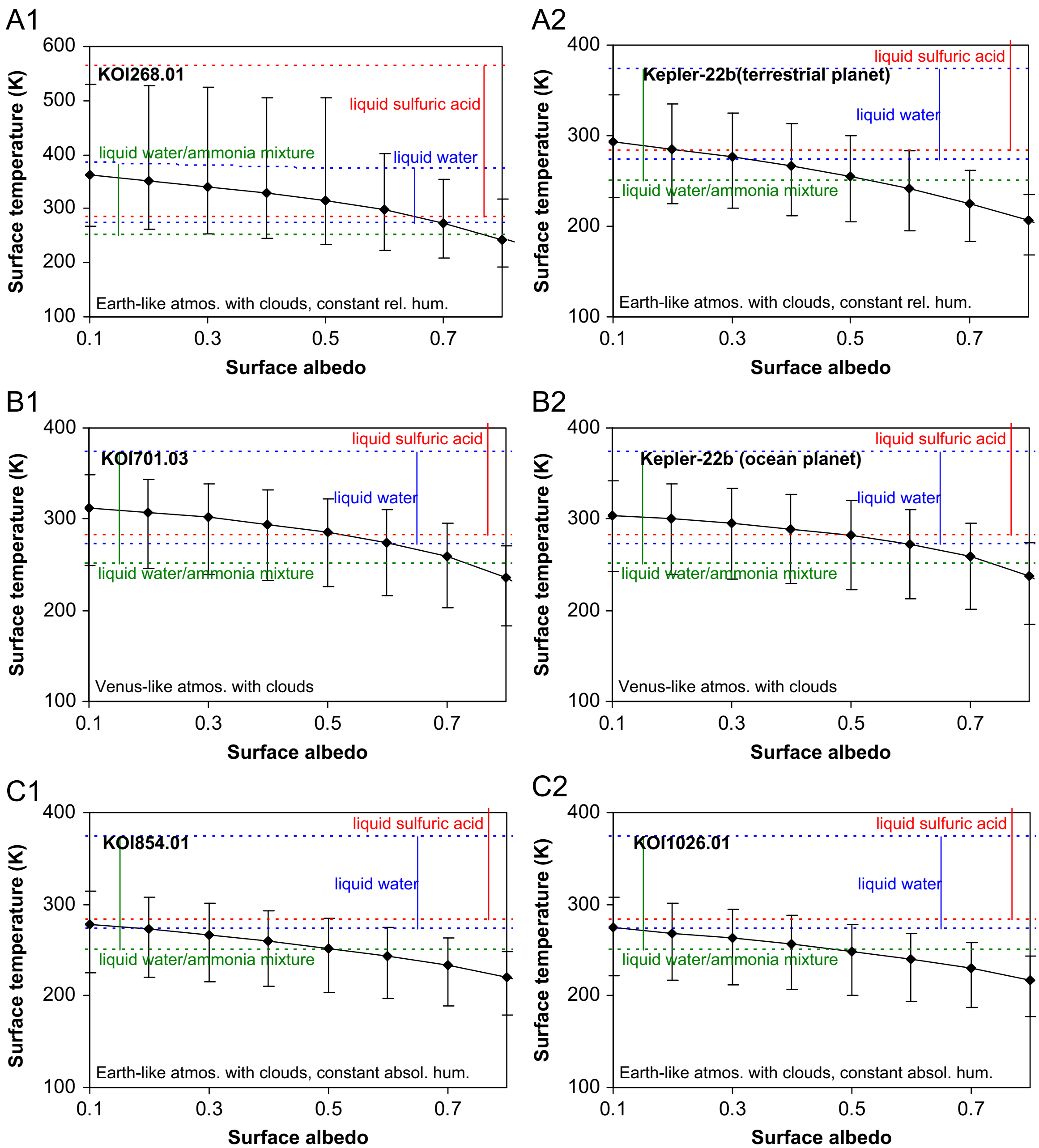

Fig. 1. Predicted surface temperature of the planet(ary candidate)s is shown as a function of surface albedo. Also shown is the change in predicted surface temperature due to the variation range of the stellar flux and the inner and outer border of the solvents habitable zones. For clarity, only in panel A1 the inner border of the sulfuric acid habitable zone is shown (note also the change in ordinate scale). (A1, A2) ELRHCL scenario for Kepler-22b (terrestrial planet) and KOI268.01 (note that the surface pressure and therefore the boiling temperature of water changes in this atmospheric scenario). (B1, B2) VLCL (thick) scenario for Kepler-22b (ocean planet) and KOI701.03. (C1, C2) ELAHCL scenario for KOI854.01 and KOI1026.01.

Table 2
Scenarios, variation range of parameters and solvents used in the simulations.

Atmospheric composition	Venus-like (VL)		Earth-like (ELAH, ELRH)
Aerosol size distribution		Earth background	
Cloud droplet concentration (1/cm^3)	570		160
Cloud optical depth τ (at 0.6 μm)	0.7 (VLCL-thin), 6.0 (VLCL-thick), H_2SO_4 gas reduced		2.2, 4.7 (ELAHCL, ELRHCL)
Variation range		Stellar flux, stellar spectrum, surface albedo, planetary gravity	
Planetary density	terrestrial: Kepler-22b, all planetary candidates		50 wt% H_2O: Kepler-22b
Solvents		water, water/ammonia mixture (15 wt% ammonia), sulfuric acid	

Titov et al., 2007) but scaled to the surface pressure of 1013.25 mbar. In the cloudy Venus-like case (VLCL) the clouds are simplified and assumed to be less extensive compared to Venus: a single liquid H_2SO_4-cloud layer is inserted (instead of three cloud layers consisting of H_2SO_4/H_2O droplets; James et al., 1997; Mills et al., 2007). The cloud liquid H_2SO_4 content is set to

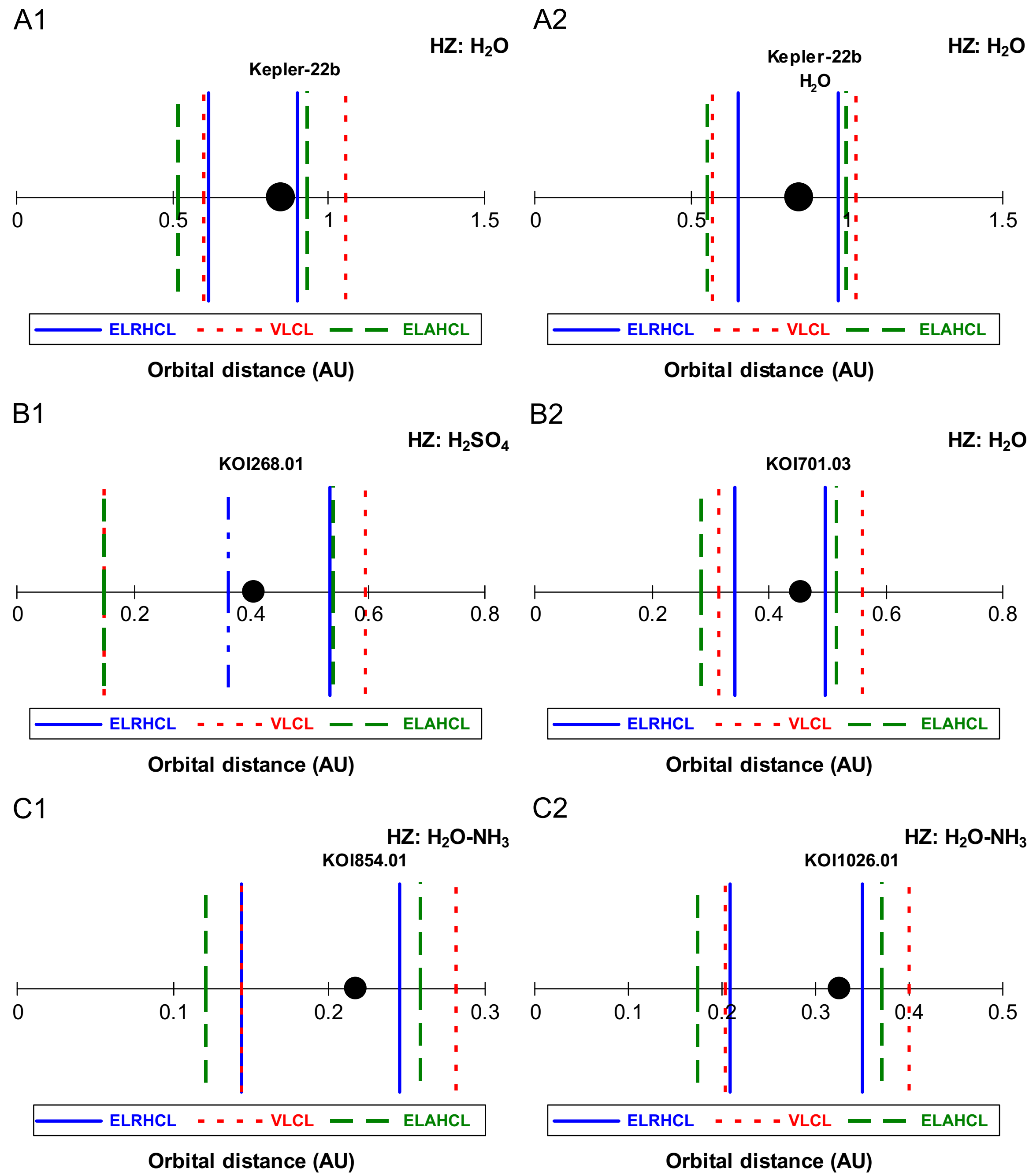

Fig. 2. Inner and outer borders of the solvents habitable zones are shown for an assumed surface albedo of 0.2 for all atmospheric scenarios (0.1 for the ocean planet scenario of Kepler-22b). In each panel the inner and outer borders are displayed for the ELRHCL (solid line), VLCL (thick clouds; short dashes), ELAHCL (long dashes) atmospheric scenarios. (A1, A2) Water habitable zone for Kepler-22b (terrestrial planet) and Kepler-22b (ocean planet) respectively. (B1, B2) Sulfuric acid habitable zone for KOI268.01 and KOI701.03 respectively. The onset of the runaway greenhouse effect was chosen as the inner border of the sulfuric acid habitable zone for KOI268.01 and the ELRHCL scenario. (C1, C2) Water/ammonia mixture habitable zone for KOI854.01 and KOI1026.01 respectively.

5 mg/m^3, the corresponding cloud droplet size distribution is chosen from the cloud model dataset and the cloud is assumed to cover the whole planet. For this cloud liquid H_2SO_4 content the liquid droplets of this cloud droplet size distribution have an effective radius of 1.6 μm and a concentration of 160/cm^3 which are in good agreement with corresponding values for Venus' clouds (based on Krasnopolsky and Pollack, 1994; James et al., 1997, Mills et al., 2007). The production region of H_2SO_4 gas is assumed to be in a region around 160 mbar as on Venus (Bullock and Grinspoon, 2001). Three cloud scenarios are investigated: a scenario with a thin cloud layer between 180 and 200 mbar with an optical depth τ of 0.7 (at 0.6 μm), a scenario with a thick cloud layer between 180 and 430 mbar with an optical depth τ of 6.0 (at 0.6 μm) and a scenario with the H_2SO_4 gas mixing ratio reduced by a factor 100 compared to Venus. These Venus-like scenarios may not be realistic for the ocean planet scenario of Kepler-22b but are included in this study for comparison reasons.

2.5.2. Earth-like (EL) scenarios

2.5.2.1. Earth-like constant absolute humidity (ELAH) scenario. This scenario models an Earth-like (ELAH) atmosphere consisting of

78.1% N_2, 20.9% O_2, and 380 ppm CO_2 (Bauer et al., 1997; IPCC, 2007) and a typical water vapor profile (assuming constant absolute humidity; Manabe and Strickler, 1964). In the cloudy case (ELAHCL) two liquid water cloud layers are assumed. The low level cloud is assumed to have a cloud top pressure of 826 mbar (the geometrical thickness of the clouds in the Earth-like scenarios is determined by their optical depth) and an optical depth τ of 4.7 (at 0.6 μm) and to cover 39.5% of the planet, while the high level cloud is assumed to have a cloud top pressure of 267 mbar and τ of 2.2 (at 0.6 μm) and to cover 15.0% of the planet and no overlap between low and high level cloud is assumed (Kitzmann et al., 2010, based on results by Rossow and Schiffer, 1999; Warren et al., 2007). For both cloud layers the computed effective radius of the liquid droplets is 6 μm and their concentration is 570/cm^3 for the chosen cloud liquid water content of 0.5 g/m^3, which agrees roughly with typical terrestrial stratus clouds (Pruppacher and Klett, 1997).

2.5.2.2. Earth-like constant relative humidity (ELRH) scenario. This scenario (ELRH; ELRHCL) resembles the ELAH scenario except that a constant relative humidity typical for Earth is assumed in the atmosphere. The relative humidity at the surface is set to 77% and is decreased with increasing altitude (see Manabe and Wetherald, 1967).

For all cloudy scenarios the cloud top pressure, the cloud optical depth and the cloud cover are from measurements for typical clouds of Earth and Venus (with adaptations in the cloudy Venus-like scenario). The cloud droplet size distributions are computed with the cloud model. Cloud droplet size distributions with liquid solvent content typical for Earth or Venus clouds are selected for computations of the life supporting zone.

3. Results

Model runs were performed for all the atmospheric scenarios and different values of planetary surface albedos for planets and planetary candidates. Stellar fluxes of the central stars of these (possible) planetary systems are considered. The largest changes in predicted planetary surface temperature are caused by changes in the stellar flux, the planets' surface albedo, the considered atmospheric scenario and by clouds (Table S2). The stellar spectrum used and variations in the planetary gravity lead to smaller variations in predicted surface temperature (Table S2).

The results of our simulations are presented in the following way:

- Figs. 1 and 2 show an overview of predicted surface temperatures of the planet(ary candidate)s and the location of the solvents habitable zones. The dependence on surface albedo and atmospheric scenarios is also presented there.
- The dependence of predicted surface temperature on other model parameters is shown in Table S2.
- Details of the influence of model parameters on modeled surface temperature are discussed below.

3.1. Influence of stellar spectrum on modeled surface temperature

Two different stellar spectra were used for each host star: the spectrum of the Sun with fluxes scaled to the effective temperature of the host star and a blackbody spectrum according to the effective temperature of the host star. As the host stars have low effective temperatures compared to the Sun, the blackbody spectrum leads to a decrease in Bond albedo (see below) for all planetary candidates and scenarios as Rayleigh scattering is reduced. The predicted surface temperature also increases due to increased absorption at the surface in the near infrared except for the VLCL (thick cloud) scenarios (Kepler-22b and all planetary candidates), the VLCL (thin cloud) scenario for Kepler-22b, KOI854.01 and KOI1026.01 and the VL scenario for Kepler-22b. The additional absorption of near infrared stellar radiation in the atmosphere which reduces the amount of radiation reaching the surface is large enough in these cases to decrease the predicted surface temperature.

3.2. Influence of planetary mass on modeled surface temperature

An uncertainty in the planetary radius of 25% (Borucki et al., 2011; Kaltenegger and Sasselov, 2011) and the assumption of a radius-mass relation for terrestrial planets according to Sotin et al. (2007) for all planet(ary candidate)s leads to a range of their gravitational acceleration of 41%. We assume three values for gravitational acceleration in all our simulations: nominal (calculated from planetary input parameters), increased (nominal gravitational acceleration increased by 41%) and decreased (nominal gravitational acceleration decreased by 41%). In all considered cases, an increase of the assumed gravitational acceleration of a planet leads to a decrease of the predicted surface temperature and a decrease of the gravitational acceleration to an increase of the predicted surface temperature (see also Kasting et al., 1993). The only exception is the VLCL (thick cloud) scenario for low values of surface albedo for Kepler-22b and all planetary candidates. In these cases the altered albedo effect dominates over the altered greenhouse effect so an increase of gravitational acceleration leads to an increase of the predicted surface temperature and vice versa for a decrease of gravitational acceleration. This dependence on gravitational acceleration and therefore planetary mass is also reflected in the two scenarios for Kepler-22b, which differ in their assumed planetary masses. The predicted surface temperatures for Kepler-22b (50 wt% H_2O) are larger than for Kepler-22b (terrestrial) in all atmospheric scenarios except for the VLCL (thick cloud) scenario for low values of surface albedo.

3.3. Influence of Bond albedo and surface albedo

The objects of the solar system show a large variability of surface albedo. We therefore varied the surface albedo between 0.1 and 0.8 (approx. between the albedo of the Moon and that of fresh snow). We computed the lower and upper boundaries for the surface albedos (Table S1) of KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 that have to be satisfied for the planetary candidates to lie in the water habitable zone. For a water/ammonia mixture the upper boundary of the surface albedos is higher while for sulfuric acid it is smaller if the planet(ary candidate)s are to lie in the respective habitable zones (see Sections 4.2 and 4.3). For scenario ELRH for KOI268.01 and the increased stellar flux a runaway greenhouse effect was found to occur for an albedo < 0.7. The values of predicted surface temperatures in these cases should rather be taken as an indication of the runaway greenhouse effect and not directly as computed surface temperatures, as the radiative transfer program and the moist adiabatic convective adjustment are working outside their valid ranges under these conditions. The runaway greenhouse effect also occurs for the cloudy scenario ELRHCL and the increased stellar flux (Fig. 1, Panel A2) for albedos less than 0.6.

For the cloudy Earth-like atmospheric scenarios ELAHCL and ELRHCL the surface albedo of KOI1026.01 would have to be very low: 0.1 and < 0.1 respectively for liquid water on its surface. A water/ammonia mixture (15 wt% ammonia) would remain liquid for surface albedos < 0.5 and < 0.35 respectively.

Table 3
Habitability of the planet(ary candidate)s. Most conservative boundaries on surface albedo are shown.

Planetary Candidate	Water habitable zone	Water/ammonia mixture habitable zone	Sulfuric acid habitable zone
268.01	0.1–0.7	0.1–0.75	<0.65*
701.03	<0.40*	<0.60*	<0.35*
Kepler-22b (terrestrial)	<0.35*	<0.55*	<0.30*
Kepler-22b (50 wt% H_2O)	<0.40*	<0.55*	<0.35*
854.01	<0.15	<0.40*	≤ 0.10
1026.01	<0.10	<0.35*	–

* Planet(ary candidate) likely in habitable zone.

We computed changes in surface temperature and Bond albedo (Table S2) for variations of stellar and planetary input parameters within their variation ranges given by Borucki et al. (2011), Brown et al. (2011), Kaltenegger and Sasselov (2011). The Bond albedo is a result of the surface albedo of the planetary candidates and the scattering and absorption by atmospheric gases and clouds.

3.4. Influence of atmospheric scenarios

The Venus-like atmospheric scenario results in the highest predicted surface temperatures followed by the Earth-like scenario with constant absolute humidity and the Earth-like scenario with constant relative humidity. An exception is KOI268.01 where for low values of surface albedo the third scenario leads to the highest predicted surface temperatures. This is due to the large amounts of water vapor at these temperatures which even lead to a runaway greenhouse effect for an increased stellar flux.

3.5. Influence of clouds

The clouds in the VLCL/ELAHCL/ELRHCL scenarios lead to a cooling for small values of surface albedo and a warming for large values of surface albedo. The warming is caused by the greenhouse effect of the water or sulfuric acid clouds. In the ELAHCL scenario the Bond albedo increases by 0.08 for Kepler-22b and all four planetary candidates. For Kepler-22b and the planetary candidates the increase in Bond albedo is the same or a little lower in the ELRHCL scenario compared to the ELAHCL scenario. This is due to increased Rayleigh scattering at low atmospheric temperatures in the model (occurring for large values of surface albedo in the ELRH(CL) scenario) which reduces the impact of clouds on Bond albedo. In the VLCL scenario with reduced H_2SO_4 gas mixing ratio no clouds form so it is similar to the VL scenario. The clouds in the VLCL (thin cloud layer) and VLCL (thick cloud layer) scenarios increase the Bond albedo by 0.05–0.07 and 0.16–0.24 respectively for Kepler-22b and the planetary candidates. The greenhouse effect of the thin H_2SO_4-cloud layer is very small.

3.6. Influence of stellar flux, predicted surface temperature and habitability

In Fig. 1(Panel A1, A2) the predicted surface temperatures of Kepler-22b (terrestrial) and KOI268.01 are shown for the ELRHCL scenario. Fig. 1(Panel B1, B2) gives surface temperatures obtained for the VLCL (thick cloud) scenario for Kepler-22b (50 wt% H_2O) and KOI701.03. Fig. 1(Panel C1, C2) was obtained with the ELAHCL scenario for KOI854.01 and KOI1026.01 (all as a function of the planets' surface albedo). There the change in predicted surface temperature due to the variation range of the stellar flux and the inner and outer border of the solvents habitable zones is also displayed. Uncertainties of the stellar temperature of 200 K, the stellar radius of 25% and the semi-major axis of 8% (Borucki et al., 2011; Brown et al., 2011; Kaltenegger and Sasselov, 2011) lead to a variation range for the stellar flux of 54% for Kepler-22b, 55% for KOI268.1 and KOI701.03 and 57% for KOI854.01 and KOI1026.01 respectively. The planet(ary candidate)s are assumed to reradiate the absorbed flux completely and their IR emissivity is assumed to be 1.0. We assume three flux values: nominal flux (calculated form stellar and planetary input parameters), increased flux (nominal flux increased by variation range) and decreased flux (nominal flux decreased by variation range) in all simulations. The predicted surface temperatures are shown as a function of surface albedo for all atmospheric scenarios in Figs. S1–S6 in Supplementary Material for KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 respectively. The predicted surface temperatures in the Venus-like scenario are usually higher than in the Earth-like scenarios (see Fig. 1, Panel A2, B2). KOI268.01 has the highest predicted surface temperatures, especially for the ELRH(CL) scenarios (Fig. 1, Panel A1). Following in order of decreasing predicted surface temperature for most scenarios are KOI701.03, Kepler-22b (50 wt% H_2O) and Kepler-22b (terrestrial). KOI854.01 and KOI1026.01 have quite similar, relatively low predicted surface temperatures for all scenarios with KOI854.01's surface being slightly warmer (see Fig. 1, Panel C1, C2).

From the restrictions on surface albedo for all atmospheric scenarios (see Table S1 for water habitable zone) the most stringent are chosen to assess habitability. We assume that these most conservative boundaries determine how likely a planet (ary candidate) is in a solvents habitable zone (Table 3):

- Kepler-22b and KOI701.03 likely lie in the water (Fig. 2, Panel A1, A2, B2), water/ammonia mixture (not shown) and sulfuric acid (not shown) habitable zones.
- KOI268.01 likely lies in the sulfuric acid habitable zone (Fig. 2, Panel B1). KOI268.01 is close to the inner limit of the water, and water/ammonia mixture habitable zones (not shown). Its surface albedo must therefore not be too low (≥ 0.1) for KOI268.01 to lie in these solvents habitable zones.
- KOI854.01 and KOI1026.01 are at or outside the outer limit of the water and the sulfuric acid habitable zones in the Earth-like scenarios (ELAHCL, ELRHCL; not shown) and therefore more likely in the water/ammonia mixture habitable zone (Fig. 2, Panel C1, C2).

In Fig. 2 the inner and outer limits of the solvents habitable zones are shown for Kepler-22b and the four planetary candidates for all cloudy atmospheric scenarios (for thick clouds in the VLCL scenario) and a surface albedo of 0.2 (0.1 in the Kepler-22b (50 wt% H_2O) scenario where water and a small amount of ammonia/ice were assumed at the surface). Fig. S7 in Supplementary Material gives the same limits for all cloud-free atmospheric scenarios. A detailed discussion of the solvents habitable zones and therefore the life supporting zone is given in Sections 4.1–4.3.

4. Life supporting zones

4.1. Water habitable zone

Kepler-22b (scenario: terrestrial/50 wt% H_2O) and KOI701.03 need the least restrictions on stellar and planetary input parameters to lie within the water habitable zone.

For KOI268.1 and the cloud free atmospheric scenarios the surface albedo must not be too low (≥ 0.1) if liquid water is to exist on the surface. If the atmospheric water vapor amount in the simulations depends on atmospheric temperatures and the stellar flux is increased there may even be a runaway greenhouse effect for this planetary candidate. This restriction on the surface albedo is eliminated when clouds are considered in the atmosphere.

KOI854.01 and KOI1026.01 lie within the habitable zone in Venus atmospheric composition like atmospheric scenarios for a surface albedo less than 0.5 and 0.45 respectively. In the Earth-like scenarios (ELAH, ELRH) the albedo has to be rather low (0.3, 0.2 for KOI854.01 and 0.2, 0.15 for KOI1026.01) so for these scenarios a surface covered with ice or snow has to be ruled out. With clouds in the atmosphere (ELAHCL, ELRHCL) the model predicts that the planetary candidates lie within the habitable zone for the Earth-like scenarios only for very low surface albedos (0.2, 0.15 for KOI854.01 and 0.1, <0.1 for KOI1026.01).

Kaltenegger and Sasselov (2011) calculated with a simple approach the inner and outer limits of the water habitable zone for 0%, 50% and 100% clouds for all Kepler planetary candidates assuming Earth-like planets with high CO_2, current Earth or high H_2O atmospheres. From their results a lower boundary of the Bond albedo of roughly 0.55, 0.25, <0.1 and <0.1 for KOI268.01, KOI701.03, KOI854.01 and KOI1026.01, respectively, can be estimated. Their calculations indicate that the Bond albedo has no upper restriction for all planetary candidates.

For our atmospheric scenarios the lower boundary of the Bond albedo was found to be about 0.15 for KOI268.01, whereas for KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 no restriction was found. The upper boundary of the Bond albedo must not be larger than about 0.63, 0.37, 0.33, 0.37, 0.20 and 0.16 for KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 respectively for liquid water to exist on their surfaces in our atmospheric scenarios. These upper boundaries are higher for the Venus atmospheric composition like scenarios and when clouds are in the atmosphere (see Table S1). The boundaries for Bond albedo differ from the boundaries estimated from Kaltenegger and Sasselov (2011) because of differences in the atmospheric compositions, cloud conditions, planetary gravity and used models.

4.2. Water/ammonia mixture habitable zone

Kepler-22b (scenario: terrestrial/50 wt% H_2O) and KOI701.03 need the least restrictions on stellar and planetary input parameters for the model to predict that they are within the water/ammonia mixture habitable zone.

The surface albedo of KOI268.1 must not be too low for this planetary candidate to lie in the water/ammonia mixture habitable zone (see discussion in Section 4.1).

KOI854.01 and KOI1026.01 more likely lie in the water/ammonia mixture habitable zone than in the water habitable zone because for low surface albedos all the atmospheric scenarios predict surface temperatures where a water/ammonia mixture remains liquid, whereas pure water would freeze at temperatures predicted by the Earth-like scenarios (Figs. S5 and S6).

The surface albedos of Kepler-22b and all four planetary candidates could be higher for the planets to be in a water/ammonia mixture habitable zone compared to the water habitable zone. The restrictions on the upper values of surface albedo for KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 would for our atmospheric scenarios on average be higher (for the 250 K limit) by a value of 0.12, 0.17, 0.2, 0.18, 0.23 and 0.25 respectively than the corresponding restrictions for the water habitable zone.

For all atmospheric scenarios the lower boundary of the Bond albedo is the same as for the water habitable zone, whereas the Bond albedo must not be larger than about 0.70, 0.57, 0.52, 0.52, 0.39 and 0.34 for KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 respectively for a water/ammonia mixture to stay liquid on the surface of the planet/planetary candidates.

4.3. Sulfuric acid habitable zone

Because of the high surface temperatures of KOI268.01 predicted in some scenarios, KOI268.01 is more likely in the sulfuric acid habitable zone than in the water or the water/ammonia mixture habitable zone (see discussion in Section 4.1).

Kepler-22b (terrestrial/50 wt% H_2O) and KOI701.03 would also lie in the sulfuric acid habitable zone but the restrictions on stellar and planetary input parameters have to be more stringent than for the water or the water/ammonia mixture habitable zone.

KOI854.01 is unlikely and KOI1026.01 is very unlikely to lie in the sulfuric acid habitable zone for the atmospheric scenarios investigated here because of their low predicted surface temperatures except for the Venus atmospheric composition like scenarios with low surface albedos.

A sulfuric acid habitable zone requires lower surface albedos for Kepler-22b and all four planetary candidates compared to the water habitable zone. The restrictions on the upper values of surface albedo for KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O), KOI854.01 and KOI1026.01 would for our atmospheric scenarios on average be lower by a value of 0.04, 0.09, 0.09, 0.08, 0.10 and 0.13 respectively than the corresponding restrictions for the water habitable zone.

No restrictions for the lower boundary of the Bond albedo were found for the sulfuric acid habitable zone, whereas the Bond albedo must not be larger than about 0.56, 0.32, 0.27, 0.32 and 0.11 for KOI268.01, KOI701.03, Kepler-22b (terrestrial), Kepler-22b (50 wt% H_2O) and KOI854.01 respectively. For KOI1026.01 all Earth-like scenarios predict that sulfuric acid would freeze on the surface of the planetary candidate. In the Venus atmospheric composition like scenarios the Bond albedo must not be larger than 0.36 for KOI1026.01 to lie in the sulfuric acid habitable zone.

5. Conclusions

We derived restrictions on stellar and planetary input parameters for an estimate of life supporting zones of Kepler-22b (terrestrial/ocean planet scenario) and KOI268.01, KOI701.03, KOI854.01 and KOI1026.01 for Venus-like and Earth-like atmospheric scenarios including clouds. For the cloudy atmospheric scenarios we used cloud properties that are typical for water clouds on Earth or H_2SO_4-clouds on Venus. In the considered scenarios the cloud albedo (cooling) effect dominates for water and thick H_2SO_4-clouds and small values of surface albedos and the greenhouse effect (warming) for higher albedos. For thin H_2SO_4-clouds the cooling effect dominates for all assumed surface albedos.

Next to changes in the stellar flux, the considered atmospheric scenario and clouds, the largest changes in predicted planetary surface temperature are caused by the assumed planets' surface albedo. Kepler-22b (terrestrial planet scenario), Kepler-22b (ocean planet scenario), KOI268.01, KOI701.03, KOI854.01 and KOI1026.01 lie in the water habitable zone in all scenarios if their respective surface albedos are <0.35, <0.4, 0.1–0.7, <0.4, <0.15 and <0.1. Kepler-22b (terrestrial/ocean planet scenario) and the four candidates would lie in the water/ammonia mixture habitable zone for surface albedos <0.55, <0.55, 0.1–0.75, <0.6, <0.4 and <0.35 respectively. Kepler-22b (terrestrial/ocean planet scenario), KOI268.01, KOI701.03 and KOI854.01 would also lie in the liquid sulfuric acid zone for surface albedos <0.3, <0.35, <0.65, <0.35 and ≤ 0.1 respectively. These most stringent restrictions on surface albedo are applicable for all atmospheric scenarios and are assumed to determine habitability.

Kepler-22b and the planetary candidate KOI701.03 are likely to lie in the water, sulfuric acid and water/ammonia mixture habitable zones. KOI268.01 likely lies in the sulfuric acid habitable zone and KOI854.01 and KOI1026.01 are likely in the water/ammonia mixture habitable zone. But all planet(ary candidate)s investigated are likely to lie in the life supporting zone enveloping in this study the water, sulfuric acid and water/ammonia mixture habitable zones.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.pss.2012.07.020

References

Bains, W., 2004. Many chemistries could be used to build living systems. Astrobiology 4, 137–167.

Baross, J.A., et al., 2007. The Limits of Organic Life in Planetary Systems. National Research Council. National Academies Press, Washington DC.

Basilevsky, A.T., Head, J.W., 2003. The surface of Venus. Reports on Progress in Physics 66 (10), 1699–1734.

Bauer, et al., 1997. Erde und Planeten. In: Bergmann, L., Schaefer, C. (Eds.), Lehrbuch der Experimentalphysik 7. Walter de Gruyter, Berlin.

Bauer, H., Kasper-Giebl, A., Löflund, M., Giebl, H., Hitzenberger, R., Zibuschka, F., Puxbaum, H., 2002. The contribution of bacteria and fungal spores to the organic carbon content of cloud water, precipitation and aerosols. Atmospheric Research 64, 109–119.

Benner, S.A., Ricardo, A., Carrigan, M.A., 2004. Is there a common chemical model for life in the universe? Current Opinion in Chemical Biology 8, 672–689.

Beard, K.V., Pruppacher, H.R., 1971. A wind tunnel investigation of the rate of evaporation of small water drops falling at terminal velocity in air. Journal of the Atmospheric Sciences 28, 1455–1464.

Bohren, C.F., Huffman, D.R., 1983. Absorption and Scattering of Light by Small Particles. Wiley, New York.

Borucki, W.J., Koch, D.G., Basri, G., Batalha, N., Brown, T.M., Bryson, S.T., Caldwell, D., Christensen-Dalsgaard, J., Cochran, W.D., DeVore, E., Dunham, E.W., Gautier III, T.N., Geary, J.C., Gilliland, R., Gould, A., Howell, S.B., Jenkins, J.M., Latham, D.W., Lissauer, J.J., Marcy, G.W., Rowe, J., Sasselov, D., Boss, A., Charbonneau, D., Ciardi, D., Doyle, L., Dupree, A.K., Ford, E.B., Fortney, J., Holman, M.J., Seager, S., Steffen, J.H., Tarter, J., Welsh, W.F., Allen, C., Buchhave, L.A., Christiansen, J.L., Clarke, B.D., Desert, J.-M., Desert, M., Fabrycky, D., Fressin, F., Haas, M., Horch, E., Howard, A., Isaacson, H., Kjeldsen, H., Kolodziejczak, J., Kulesa, C., Li, J., Machalek, P., McCarthy, D., MacQueen, P., Meibom, S., Miquel, T., Prsa, A., Quinn, S.N., Quintana, E.V., Ragozzine, D., Sherry, W., Shporer, A., Tenenbaum, P., Torres, G., Twicken, J.D., Van Cleve, J., Walkowicz, L., 2011. Characteristics of planetary candidates observed by Kepler, II: analysis of the first four months of data. Astrophysical Journal Letters 736, 19 (22pp).

Borucki, W.J., Koch, D.G., Batalha, N., Bryson, S.T., Rowe, J., Fressin, F., Torres, G., Caldwell, D.A., Christensen-Dalsgaard, J., Cochran, W.D., DeVore, E., Gautier III, T.N., Geary, J.C., Gilliland, R., Gould, A., Howell, S.B., Jenkins, J.M., Latham, D.W., Lissauer, J.J., Marcy, G.W., Sasselov, D., Boss, A., Charbonneau, D., Ciardi, D., Kaltenegger, L., Doyle, L., Dupree, A.K., Ford, E.B., Fortney, J., Holman, M.J., Steffen, J.H., Mullally, F., Still, M., Tarter, J., Ballard, S., Buchhave, L.A., Carter, J., Christiansen, J.L., Demory, B.O., Désert, J.M., Dressing, C., Endl, M., Fabrycky, D., Fischer, H., Haas, M.R., Henze, C., Horch, E., Howard, A.W., Isaacson, H., Kjeldsen, H., Johnson, J.A., Klaus, T., Kolodziejczak, J., Barclay, T., Li, J., Meibom, S., Prsa, A., Quinn, S.N., Quintana, E.V., Robertson, P., Sherry, W., Shporer, A., Tenenbaum, P., Thompson, S.E., Twicken, J.D., Van Cleve, J., Welsh, W.F., Basu, S., Chaplin, W., Miglio, A., Kawaler, S.D., Arentoft, T., Stello, D., Metcalfe, T.S., Verner, G.A., Karoff, C., Lundkvist, M., Lund, M.N., Handberg, R., Elsworth, Y., Hekker, S., Huber, D., Bedding, T.R., Rapin, 2012. Kepler-22b: A 2.4 Earth-radius planet in the habitable zone of a Sun-like star. Astrophysical Journal 745, 120 (16pp).

Bott, A., Sievers, U., Zdunkowski, W., 1990. A radiation fog model with a detailed treatment of the interaction between radiative transfer and fog microphysics. Journal of the Atmospheric Sciences 47, 2153–2166.

Brown, R., 1980. A numerical study of radiation fog with an explicit formulation of the microphysics. Quarterly Journal of the Royal Meteorological Society 106, 781–802.

Brown, T.M., Latham, D.W., Everett, M.E., Esquerdo, G.A., 2011. Kepler input catalog: Photometric calibration and Stellar classification. Astronomical Journal 142, 112 (18pp).

Bullock, M.A., Grinspoon, D.H., 2001. The recent evolution of climate on Venus. Icarus 150, 19–37.

Chen, J.P., Lamb, D., 1994. Simulation of cloud microphysical and chemical processes using a multicomponent framework. Part I: description of the microphysical model. Journal of the Atmospheric Sciences 51, 2613–2630.

Conant, W.C., Nenes, A., Seinfeld, J.H., 2002. Black carbon radiative heating effects on cloud microphysics and implications for the aerosol indirect effect 1. Extended Köhler theory. Journal of Geophysical Research 107 (D21), 4604–4612.

Crawford, M.F., Welsh, H.L., Locke, J.L., 1949. Infrared absorption of oxygen and nitrogen induced by intermolecular forces. Physical Review 41, 1607.

Croft, S.K., Lunine, J.I., Kargel, J.S., 1988. Equation of State of ammonia-water liquid: derivation and planetological applications. Icarus 73, 279–293.

Frommhold, L., 1993. Collision-induced absorption in gases. Cambridge University Press, Cambridge.

Hanson, D.R., Eisele, F., 2000. Diffusion of H_2SO_4 in humidified nitrogen: hydrated H_2SO_4. Journal of Physical Chemistry A 104, 1715–1719.

Harrington, J.Y., Feingold, G., Cotton, W.R., 2000. Radiative impacts on the growth of a population of drops within simulated summertime Arctic stratus. Journal of the Atmospheric Sciences 57, 766–785.

Haynes, W.M. (Ed.), 92nd ed. CRC Press/Taylor and Francis, Boca Raton, FL.

Hess, M., Koepke, P., Schult, 1998. Optical properties of aerosols and clouds: the software package OPAC. Bulletin of the American Meteorological Society 79, 831–844.

Hitzenberger, R., Berner, A., Giebl, H., Drobesch, K., Kasper-Giebl, A., Löflund, M., Urban, H., Puxbaum, H., 2001. Black carbon (BC) in alpine aerosols and cloud water—concentrations and scavenging efficiencies. Atmospheric Environment 35, 5135–5141.

Houze, R.A., 1993. Cloud Dynamics. Academic Press, San Diego.

Hussmann, H., Sohl, F., Spohn, T., 2006. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. Icarus 185, 258–273.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Iorga, G., Hitzenberger, R., Kasper-Giebl, A., Puxbaum, H., 2007. Direct radiative effect modeled for regional aerosols in central Europe including the effect of relative humidity. Journal of Geophysical Research 112, D01204.

James, E.P., Toon, O.B., Schubert, G., 1997. A numerical microphysical model of the condensational Venus cloud. Icarus 129, 147–171.

Kaltenegger, L., Sasselov, D., 2011. Exploring the habitable zone for Kepler planetary candidates. Astrophysical Journal Letters 736, L25 (6pp).

Kargel, J.S., 1992. Ammonia-water volcanism on icy satellites: phase relations at 1 atm. Icarus 100, 556–574.

Kasting, J.F., 1988. Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. Icarus 74, 472–494.

Kasting, J.F., Whitmore, D.P., Reynolds, R.T., 1993. Habitable zones around main sequence stars. Icarus 101, 108–128.

Key, J.R., Schweiger, A.J., 1998. Tools for atmospheric radiative transfer: Streamer and FluxNet. Computers and Geosciences 24, 443–451.

Kitzmann, D., Patzer, A.B.C., von Paris, P., Godolt, M., Stracke, B., Gebauer, S., Grenfell, J.L., Rauer, H., 2010. Clouds in the atmospheres of extrasolar planets I. Climatic effects of multi-layered clouds for Earth-like planets and implications for habitable zones. Astronomy and Astrophysics 511, A66.

Kneizys, F.X., Shettle, E.P., Abreu, L.W., Chetwynd, J.H., Anderson, G.P., Gallery, W.O., Selby, J.E.A., Clough, S.A., 1988. Report AFGL-TR-88-0177, Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts.

Knollenberg, R.G., Hunten, D.M., 1980. The microphysics of the clouds of Venus: results of the Pioneer Venus particle size spectrometer experiment. Journal of Geophysical Research 85, 8039–8058.

Kogan, Y.L., 1991. The simulation of a convective cloud in a 3-D model with explicit microphysics. Part I: model description and sensitivity experiments. Journal of the Atmospheric Sciences 48, 1160–1189.

Kornfeld, P., 1970. Numerical solution for condensation of atmospheric vapor on soluble and insoluble nuclei. Journal of the Atmospheric Sciences 27, 256–264.

Krasnopolsky, V.A., Pollack, J.B., 1994. H_2O–H_2SO_4 system in Venus' clouds and OCS, CO, and H_2SO_4 profiles in Venus' troposphere. Icarus 109, 58–78.

Kulmala, M., Laaksonen, A., 1990. Binary nucleation of water-sulfuric acid system: comparison of classical theories with different H_2SO_4 saturation vapor pressures. Journal of Chemical Physics 93, 696–701.
Lammer, H., Bredehöft, J.H., Coustenis, A., Khodachenko, M.L., Kaltenegger, L., Grasset, O., Prieur, D., Raulin, F., Ehrenfreund, P., Yamauchi, M., Wahlund, J.-E., Grießmeier, J.-M., Stangl, G., Cockell, C.S., Kulikov, Yu.N., Grenfell, J.L., Rauer, H., 2009. What makes a planet habitable? Astronomy and Astrophysics Review 17, 181–249.
Leitner, J.J., Schulze-Makuch, D., Firneis, M.G., Hitzenberger, R., Neubauer, D., 2010a. Solvents of interest for exotic life on planetary bodies in life supporting zones around main sequence stars. Abstracts of the 10th European Astrobiology Network Association Science Congress, pp. 52–53.
Leitner, J.J., Schwarz, R., Firneis, M.G., Hitzenberger, R., Neubauer, D., 2010b. Generalizing habitable zones in exoplanetary systems—the concept of the life supporting zone [abstract 5255]. Astrobiology Science Conference (2010) Abstracts, League City.
Leitner, J.J., Neubauer, D., Schwarz, R., Eggl, S., Firneis, M.G., Hitzenberger, R., 2010c. The Life Supporting Zone I—from Classic to Exotic Life [abstract EPSC2010-677]. In: Proceedings of the 5th European Planetary Science Congress Abstracts, Rome.
Leliwa-Kopystynski, J., Maruyama, M., Nakajima, T., 2002. The water-ammonia phase diagram up to 300 MPa: application to icy satellites. Icarus 159, 518–528.
Linstrom, P.J., Mallard, W.G. (Eds.), 2012. National Institute of Standards and Technology, Gaithersburg MD 20899.
Lorenz, R.D., Lunine, J.I., McKay, C.P., 1997. Titan under a red giant sun: A new kind of habitable moon. Geophysical Research Letters 24, 2905–2908.
Manabe, S., Strickler, R.F., 1964. Thermal equilibrium of the atmosphere with a convective adjustment. Journal of the Atmospheric Sciences 21, 361–385.
Manabe, S., Wetherald, R.T., 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. Journal of the Atmospheric Sciences 24, 241–259.
Mason, B.J., 1952. Production of rain and drizzle by coalescence in stratiform clouds. Quarterly Journal of the Royal Meteorological Society 78, 377–386.
Mason, B.J., 1960. The evolution of droplet spectra in stratus cloud. Journal of the Atmospheric Sciences 17, 459–462.
McKay, C.P., Pollack, J.B., Courtin, R., 1991. The Greenhouse and Anti-greenhouse effects on Titan. Science 253, 1118–1121.
McKay, C.P., Smith, H.D., 2005. Possibilities for methanogenic life in liquid methane on the surface of Titan. Icarus 178, 274–276.
Mills, F.P., Esposito, L.W., Yung, Y.L., 2007. Atmospheric Composition, Chemistry, and Clouds. In: Esposito, L.W., Stofan, E.R., Cravens, T.E. (Eds.), Exploring Venus as a Terrestrial Planet. American Geophysical Union, Washington DC.
Murray, F.W., 1967. On the computation of saturation vapor pressure. Journal of Applied Meteorology 6, 203–204.
Myers, R.T., 1983. What is the boiling point and heat of vaporization of sulfuric acid? Journal of Chemical Education 60, 1017–1018.
Neubauer, D., 2009. Modellierung des indirekten Strahlungseffekts des Hintergrundaerosols in Österreich. Dissertation. University of Vienna, Vienna.
Neubauer, D., Vrtala, A., Leitner, J.J., Firneis, M.G., Hitzenberger, R., 2011. Development of a model to compute the extension of life supporting zones for Earth-like exoplanets. Origins of Life and Evolution of the Biosphere 41, 545–552.
Norman, L.H., Fortes, A.D., 2011. Is there life on … Titan? Astronomy and Geophysics 52, 39–42.
Ochs, H.T., Yao, C.S., 1978. Moment-conserving techniques for warm cloud microphysical computations. Part I: numerical techniques. Journal of the Atmospheric Sciences 35, 1947–1958.
Palmer, K.F., Williams, D., 1975. Optical Constants of Sulfuric Acid; application to the clouds of Venus? Applied Optics 14, 208–219.
Plankensteiner, K., Reiner, H., Rode, B.M., Mikoviny, T., Wisthaler, A., Hansel, A., Mark, T.D., Fischer, G., Lammer, H., Rucker, H.O., 2007. Discharge experiments simulating chemical evolution on the surface of Titan. Icarus 187, 616–619.
Pöschl, U., Canagaratna, M., Jayne, J.T., Molina, L.T., Worsnop, D.R., Kolb, C.E., Molina, M.J., 1998. Mass accommodation coefficient of H_2SO_4 vapor on aqueous sulfuric acid surfaces and gaseous diffusion coefficient of H_2SO_4 in N_2/H_2O. Journal of Physical Chemistry A 102, 10082–10089.
Pruppacher, H.R., Rasmussen, R., 1979. A wind tunnel investigation of the rate of evaporation of large water drops falling at terminal velocity in air. Journal of the Atmospheric Sciences 36, 1255–1260.
Pruppacher, H.R., Klett, J.D., 1997. Microphysics of Clouds and Precipitation. Kluwer Academic Publishers, Dordrecht.
Raulin, F., Bruston, P., Paillous, P., Sternberg, R., 1995. The low temperature organic chemistry of Titan's geofluid. Advances in Space Research 15, 321–333.
Rennó, N.O., Emanuel, K.A., Stone, P.H., 1994. Radiative-convective model with an explicit hydrological cycle 1. Formulation and sensivity to model parameters. Journal of Geophysical Research 99 (D7), 14429–14441.
Roach, W.T., 1975. On the effect of radiative exchange on the growth by condensation of a cloud or fog droplet. Quarterly Journal of the Royal Meteorological Society 102, 361–372.
Rossow, W.B., Schiffer, R.A., 1999. Advances in understanding clouds from ISCCP. Bulletin of the American Meteorological Society 80, 2261–2287.
Satoh, M., 2004. Atmospheric Circulation Dynamics and General Circulation Models. Springer, Berlin.
Schulze-Makuch, D., Irwin, L.N., 2004. Life in the Universe. Springer, New York.
Schulze-Makuch, D., Grinspoon, D.H., 2005. Biologically enhanced energy and carbon cycling on Titan? Astrobiology 5, 560–567.
Schulze-Makuch, D., Irwin, L.N., 2006. The prospect of alien life in exotic forms on other worlds. Naturwissenschaften 93, 155–172.
Schulze-Makuch, D., Méndez, A., Fairén, A.G., von Paris, P., Turse, C., Boyer, G., Davila, A.F., António, M.R.D., Catling, D., Irwin, L.N., 2011. A two-tiered approach to assessing the habitability of exoplanets. Astrobiology 11, 1041–1052.
Seinfeld, J.H., Pandis, S.N., 2006. Atmospheric Chemistry and Physics. Wiley, Hoboken.
Sotin, C., Grasset, O., Mocquet, A., 2007. Mass–radius curve for extrasolar Earth-like planets and ocean planets. Icarus 191, 337–351.
Stamnes, K., Tsay, S.C., Wiscombe, W., Jayaweera, K., 1988. Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. Applied Optics 27, 2502–2509.
Stamnes, K., Tsay, S.C., Wiscombe, W., 1994. A general-purpose, numerically stable computer code for discrete-ordinate-method radiative transfer in scattering and emitting layered media, Part I: Documentation of Methodology.
Stamnes, K., Tsay, S.C., Wiscombe, W., Jayaweera, K., Laszlo, I., 2000. A General-Purpose Numerically Stable Computer Code for Discrete-Ordinate-Method Radiative Transfer in Scattering and Emitting Layered Media, in: DISORT Report v1.1.
Stofan, E.R., Elachi, C., Lunine, J.I., Lorenz, R.D., Stiles, B., Mitchell, K.L., Ostro, S., Soderblom, L., Wood, C., Zebker, H., Wall, S., Janssen, M., Kirk, R., Lopes, R., Paganelli, F., Radebaugh, J., Wye, L., Anderson, Y., Allison, M., Boehmer, R., Callahan, P., Encrenaz, P., Flamini, E., Francescetti, G., Gim, Y., Hamilton, G., Hensley, S., Johnson, W.T.K., Kelleher, K., Muhleman, D., Paillou, P., Picardi, G., Posa, F., Roth, L., Seu, R., Shaffer, S., Vetrella, S., West, R., 2007. The lakes of Titan. Nature 445, 61–64.
Titov, D.V., Bullock, M.A., Crisp, D., Renno, N.O., Taylor, F.W., Zasova, L.V., 2007. Radiation in the atmosphere of Venus. In: Esposito, L.W., Stofan, E.R., Cravens, T.E. (Eds.), Exploring Venus as a Terrestrial Planet. American Geophysical Union, Washington DC.
Toon, O.B., McKay, C.P., Ackerman, T.P., Santhanam, K., 1989. Rapid calculation of radiative heating rates and photodissociation rates in inhomogeneous multiple scattering atmospheres. Journal of Geophysical Research 94 (D13), 16287–16301.
Vehkamaki, H., Kulmala, M., Napari, I., Lehtinen, K.E.J., Timmreck, C., Noppel, M., Laaksonen, A., 2002. An improved parameterization for sulfuric acid-water nucleation rates for tropospheric and stratospheric conditions. Journal of Geophysical Research 107 (D22), 4622.
Warren, S.G., Eastman, R.M., Hahn, C.J., 2007. A survey of changes in cloud cover and cloud types over land from surface observations, 1971-96. Journal of Climate 20, 717–738.
Welch, R.M., Ravichandran, M.G., Cox, S.K., 1986. Prediction of quasi-periodic oscillations in radiation fogs. Part I: comparison of simple similarity approaches. Journal of the Atmospheric Sciences 43, 633–651.
Wiscombe, W.J., Evans, J.W., 1977. Exponential-sum fitting of radiative transmission functions. Journal of Computational Physics 24, 416–444.

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Short Communication

The outer limit of the life supporting zone of exoplanets having CO_2-rich atmospheres: Virtual exoplanets and Kepler planetary candidates

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ABSTRACT

CO_2 rich atmospheres have been considered for the outer limit of the classic water habitable zone. Here we provide a database for the outer limit of the life supporting zone consisting of a sulfuric acid, a water and a water/ammonia mixture (15 wt% ammonia) habitable zone for virtual exoplanets having CO_2-rich atmospheres and orbiting G-, K-, or M-dwarf stars. We used recent CO_2 line and continuum absorption data for CO_2 pressures up to 100 bar for our simulations. Scenarios for different stellar spectra, stellar fluxes, planetary surface albedos, atmospheric pressures and planetary masses are explored. One notable result is that the surface temperature does not strongly increase if CO_2 pressure is larger than approximately 25 bar, due to increased Rayleigh scattering or CO_2 condensation at the surface and a thereby reduced greenhouse effect in these cases. The database is created for virtual exoplanets and applied to Kepler planetary candidates. All of the considered planetary candidates likely lie within the outer limit of the life supporting zone.

1. Introduction

The life supporting zone (Leitner et al., 2010a, 2010b) is a generalization of the classic habitable zone (Kasting et al., 1993) defined for life-as-we-know-it to possible life based on solvents other than water (Leitner et al., 2010c). Life-as-we-do-not-know-it is not necessarily based on water and a potential metabolism need not dependent on the chemical characteristics of C, O, H, N, S and P (Baross et al., 2007). This leads to the new concept of the life supporting zone. The life supporting zone extends the classic habitable zone by enveloping all the habitable zones of the considered solvents which may overlap. Life supporting zones were computed by Neubauer et al. (2012) for Super-Earth planetary candidates and Kepler-22b for sulfuric acid, water and a water/ammonia mixture as solvents. Sulfuric acid and ammonia have been discussed by Raulin et al. (1995), Bains (2004), Benner et al. (2004), Schulze-Makuch and Irwin (2004, 2006), Baross et al. (2007), Leitner et al. (2012) as possible solvents. Sulfuric acid clouds in Venus atmosphere and possible subsurface oceans of satellites of outer planets in the solar system have been hypothesized for example by Giles et al. (2003), Bains (2004), Schulze-Makuch and Irwin (2006) and many others as possible habitats for life.

The computations by Neubauer et al. (2012) were done for Earth atmospheric pressures. Here we investigate the outer limit of the life supporting zone for CO_2 atmospheres with surface pressures up to 100 bar. For the outer limit of the classic water habitable zone, studies were performed using CO_2 atmospheres for virtual exoplanets (Kasting et al., 1993) or observed exoplanets like Gliese 581c and Gliese 581d (Selsis et al., 2007; Von Paris et al., 2010). For Gliese 581d and a pure CO_2 atmosphere scenario, CO_2 partial pressures greater than 10 bar are necessary for surface temperatures above the melting point of water (Wordsworth et al., 2010a, 2011).

The Kepler mission announced the detection of 1091 new planetary candidates in February 2012 (Batalha et al., 2013). This gives a total of 2321 planetary candidates detected by the Kepler mission. Kaltenegger and Sasselov (2011) developed a fast method to estimate whether these planetary candidates are located in their respective host stars' water habitable zones. This method is based upon radiative convective model simulations for virtual exoplanets orbiting main sequence stars (Kasting et al., 1993; Selsis et al., 2007). For exotic life Schulze-Makuch et al. (2011) introduced the Planetary Habitabiliy Index (PHI) to rate the

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probability of exotic life on exoplanets and exomoons. PHI is based on the presence of a stable substrate, available energy, appropriate chemistry and the potential for holding a liquid solvent. In the present study we focus on the last aspect.

While different radiation codes produce similar results for CO_2-atmospheres at low atmospheric pressures, the choice of line and continuum absorption becomes important at high atmospheric CO_2 abundance (Halevy et al., 2009). In our simulations we use the correlated-k approach based upon line-by-line calculations for CO_2 absorption and we included CO_2 continuum absorption data by Baranov et al. (2004) and collision induced absorption (Gruszka and Borysow, 1997).

We perform computations for the outer limit of sulfuric acid, water and water/ammonia mixture (15 wt% ammonia) habitable zones. The goal of this study is to obtain a database of surface temperatures for virtual planets for a large parameter space of planetary and stellar input parameters for each habitable zone and therefore the life supporting zone. The influence of each parameter on the computed surface temperature is discussed in Section 3. This database may be used to estimate the habitability of exoplanets. An application of the database to planetary candidates detected by the Kepler mission is presented in Section 4.

2. Materials and methods

Surface temperature computations were performed with a radiative convective model (details are given by Neubauer et al., 2011). The planetary and stellar input parameters are given in Table 1. Each parameter was varied for each combination of the other parameters, i.e. we explored a parameter space the size of 3(spectrum) × 15 (distance) × 8(albedo) × 5(pressure) × 2(mass) resulting in 3600 simulations. We use three different stellar spectra, representative of a G-dwarf (the Sun), a K-dwarf (HD22049, a K2V star) and an M-dwarf (AD Leo, an M4.5V star). The stellar spectra data are taken from the Virtual Planetary Laboratory (http://vpl.astro.washington.edu) and Gueymard (2003). The stellar flux was varied in 15 steps corresponding to an orbital distance of 0.3–1.7 AU in 0.1 AU steps for the solar spectrum and corresponding orbital distances for the K-dwarf and M-dwarf stellar spectra (the fluxes shown are for fast rotating planets). The surface albedo was varied in 0.1 steps between 0.1 and 0.8 (roughly the albedos of the Moon and Triton/fresh snow). Computations were performed for an Earth-sized planet (1 M_{Earth}) and a Super-Earth-sized planet (10 M_{Earth}). The atmosphere was assumed to consist entirely of CO_2 at five different surface pressures between 1 and 100 bar (roughly the surface pressure of Earth and of Venus respectively). Other greenhouse gases would increase the surface temperature of the exoplanets so the neglect of further greenhouse gases leads to a lower range for the surface temperatures. CO_2 condensation in the atmosphere and at the surface was taken into account following the method described by Forget et al. (1998) as the neglect of CO_2 condensation would considerably change the computed surface temperature of the exoplanets (see Wordsworth et al., 2010a).

The radiative transfer code we used ('Streamer'; Key and Schweiger, 1998) was adapted by us to use the correlated-k (Lacis and Oinas, 1991) approach. The programs kspectrum and kdistribution (http://code.google.com/p/kspectrum/) were used to compute correlated-k coefficients from the HITRAN 2008 database (Rothman et al., 2009). SubLorentzian profiles by Perrin and Hartmann (1989) were used for the CO_2 far line absorption. We implemented collision induced absorption (Gruszka and Borysow, 1997) by using the code of Gruszka and Borysow (1998) and added CO_2 continuum absorption data by Baranov et al. (2004). Our CO_2 absorption parameterization is therefore similar to the one recommended by Wordsworth et al. (2010b) for dense CO_2 atmospheres.

For the Kepler planetary candidates we use a multilinear interpolation to determine the surface temperature of the planetary candidates, i.e. we perform a linear interpolation for the actual value of each parameter.

Liquid sulfuric acid solidifies at a temperature of 283 K, water freezes at 273.15 K; a water ammonia mixture (15 wt% ammonia) freezes at 250.4 K (a water ammonia mixture of peritectic composition (33 wt% ammonia) would freeze at 176 K, Croft et al., 1988). We assume a water ammonia mixture with 15 wt% ammonia which is assumed for the maximum ammonia abundance for possible subsurface oceans on the outer planets' satellites in the solar system (Hussmann et al., 2006). For the computations for sulfuric acid we assume that no water exists on the surface of the planet. At an atmospheric pressure of 100 bar a water ammonia mixture (15 wt% ammonia) freezes at 249.5 K. This decrease by 0.9 K compared to the freezing temperature at 1 bar atmospheric pressure is smaller than uncertainties in other model parameters. Uncertainties in e.g. the planetary gravity or the stellar flux lead the variations of the computed planetary surface temperature of a few Kelvin to a few dozens of Kelvin (see Neubauer et al., 2012).We therefore neglect here the pressure dependence of the freezing temperature of the considered solvents.

3. Results for virtual exoplanets

The surface temperature of an exoplanet with a CO_2 rich atmosphere depends on various stellar and planetary parameters. We present here results for the parameters and their variation

Table 1
Planetary and stellar parameter space.

	Stellar flux (W/m²)	Orbital distance (G-dwarf; AU)	Orbital distance (K-dwarf; AU)	Orbital distance (M-dwarf; AU)	Surface albedo	Stellar spectrum	Atmospheric pressure (bar)	Planetary mass (M_{Earth})
Variation range	3781	0.3	0.17	0.046	0.1	G (Sun)	1	1
	2127	0.4	0.23	0.06	0.2	K (HD22049)	5	10
	1361	0.5	0.29	0.08	0.3	M (AD Leo)	25	
	945	0.6	0.35	0.09	0.4		50	
	694	0.7	0.41	0.11	0.5		100	
	532	0.8	0.47	0.12	0.6			
	420	0.9	0.52	0.14	0.7			
	340	1	0.58	0.15	0.8			
	281	1.1	0.64	0.17				
	236	1.2	0.7	0.18				
	201	1.3	0.76	0.2				
	174	1.4	0.82	0.21				
	151	1.5	0.87	0.23				
	133	1.6	0.93	0.24				
	118	1.7	0.99	0.26				

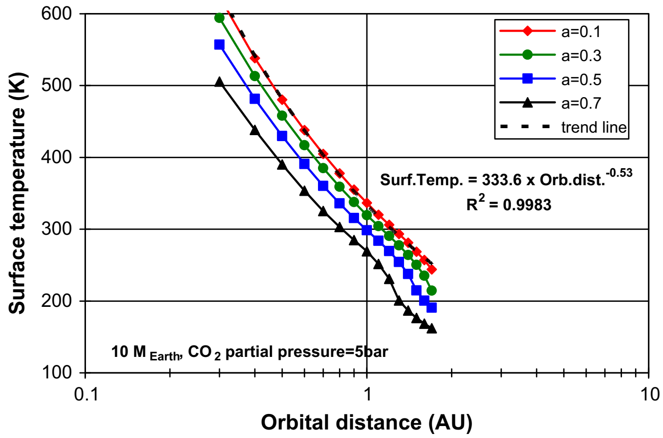

Fig. 1. Surface temperature of a virtual exoplanet with a mass of 10 M_{Earth}, a CO_2 partial pressure of 5 bar, for a G-dwarf star. Surface temperatures are given for four values of surface albedo (dimensionless). For a surface albedo of 0.1 a trend line is shown.

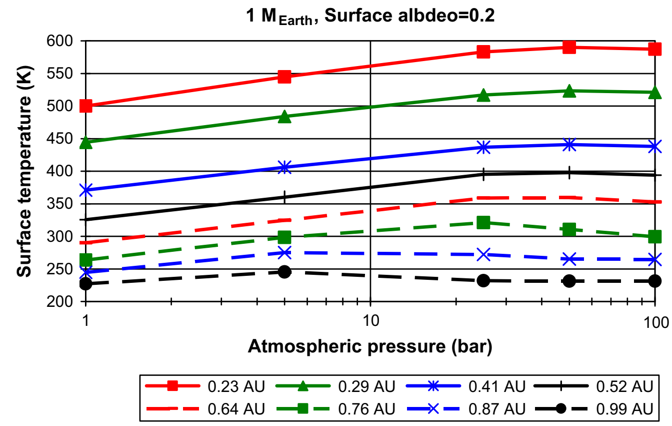

Fig. 2. Surface temperature of a virtual exoplanet with a mass of 1 M_{Earth}, a surface albedo of 0.2, for a K-dwarf star. Surface temperatures are shown for different orbital distances in AU.

range given in Table 1. CO_2 condensation is included in the simulation. There is a subsection for each parameter i.e. orbital distance, atmospheric pressure, CO_2-condensation, albedo, planetary mass, stellar spectrum and other parameters for clarity.

3.1. Orbital distance

From energy balance calculations an inverse square root relation between orbital distance and surface temperature of an exoplanet can be expected. This relation is reproduced in our computations for all three stellar spectra as long as CO_2 does not condense on the surface. Fig. 1 shows surface temperatures for a 10 M_{Earth} virtual exoplanet with a 5 bar CO_2 atmosphere for four different surface albedos. For a surface albedo of 0.1 a trend line is shown which reflects an almost inverse square root relation. For larger values of surface albedo there is a drop in surface temperature at large orbital distances due to condensation of CO_2 at the surface of the exoplanet and a thereby reduced greenhouse effect.

3.2. Atmospheric pressure

We computed surface temperatures for atmospheric surface pressures of 1, 5, 25, 50 and 100 bar at the beginning of the simulation. The surface pressure in radiative-convective equilibrium may be lower due to condensation of atmospheric CO_2 at the surface. In Fig. 2 the surface temperature of a 1 M_{Earth} virtual exoplanet around a K-dwarf star for a surface albedo of 0.2 and varying orbital distance is shown. There is an almost linear increase (on a logarithmic scale) of the surface temperature up to an initial surface pressure of 25 bar due to the increased greenhouse effect. For larger values of surface pressure at the beginning of the computation the surface temperature reaches a plateau or even decreases slightly (see also Fig. 4). This is less pronounced for the M-dwarf star than for the G-dwarf and K-dwarf stars. The main reason for the plateau or decrease is increased Rayleigh scattering at higher surface pressures and CO_2 condensation at the surface. Another cause is that at higher atmospheric pressure the atmosphere has a larger vertical extent. CO_2 condensation occurs in this case at higher altitudes (see Fig. 3). The latent heat flux due to CO_2 condensation in the upper atmosphere and CO_2 evaporation/sublimation in the lower atmosphere is increased for large initial surface pressures resulting in a cooling of the lower atmosphere and the surface (Kasting, 1991). CO_2 condensation at the surface occurs for the configuration in Fig. 2 only at orbital distances equal to or larger than 0.76 AU.

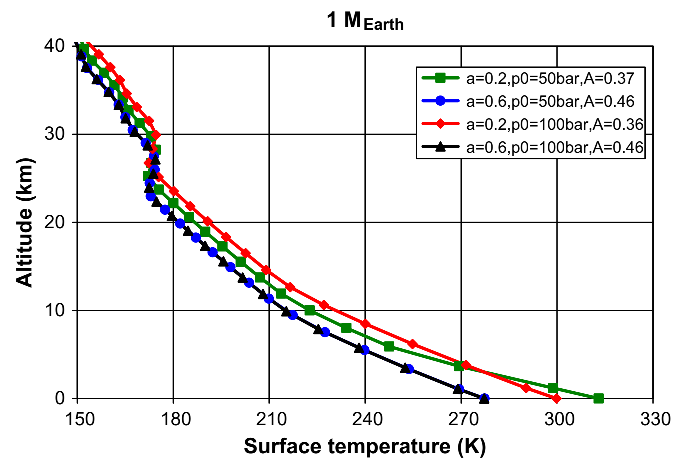

Fig. 3. Atmospheric temperature profiles for a virtual exoplanet of 1 M_{Earth} of a G-dwarf star at 1.2 AU orbital distance. The temperature profiles are shown for surface albedos a of 0.2 and 0.6 and initial surface pressures p_0 of 50 and 100 bar. Regions of different temperature gradient are apparent which are determined by convective adjustment, CO_2 condensation and absorption of stellar flux in the near infrared by CO_2.

3.3. CO_2-condensation

CO_2 condensation can occur in the atmosphere and at the surface of an exoplanet. This happens typically for large orbital distances and/or large values of surface albedo (i.e. for low incoming/absorbed flux).

In the case of large values of surface albedo, CO_2 condensation in the atmosphere occurs at lower altitudes which reduces the latent heat flux (see Fig. 3). In case of large values of surface albedo, the atmosphere also has a smaller vertical extent compared to the case of low surface albedo (cf. Section 3.2). In Fig. 3 the surface temperature of a 1 M_{Earth} virtual exoplanet around a G-dwarf star for surface albedos a of 0.2 and 0.6 and initial surface pressures p_0 of 50 and 100 bar is shown. For the case of the largest absorption of stellar flux at the surface (a=0.2, p_0=50 bar) the temperatures in the lowest atmospheric layers are determined by radiative convective equilibrium. At higher altitudes and for the other cases in Fig. 3 CO_2 condensation leads to an increase of the temperature gradient. The surface temperature in the case of p_0=100 bar (and a=0.2) is lower than in the case of p_0=50 bar (and a=0.2). There are two reasons for this: the first is that in the p_0=100 bar case less stellar flux is absorbed at the surface

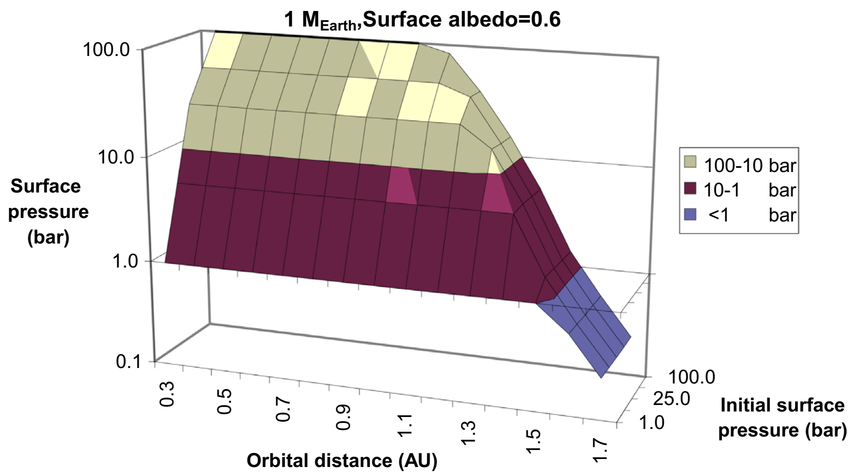

Fig. 4. Surface pressure of a virtual exoplanet with a mass of 1 M_{Earth}, a surface albedo of 0.6, for a G-dwarf star. Surface temperatures are shown for different orbital distances and different surface pressures at the beginning of the simulations.

(36.1 W/m² compared to 43.5 W/m² in the $p_0=50$ bar case) and more is scattered back into space (151.6 W/m² compared to 146.1 W/m² in the $p_0=50$ bar case). The second reason is that proportionally more of the energy provided by the stellar flux is used to heat the atmosphere via CO_2 condensation and subsequent evaporation/sublimation in the $p_0=100$ bar case due to lower temperatures near the surface.

The altitude of the inversion due to absorption of stellar flux in the near infrared by CO_2 varies for different atmospheric pressures and surface albedos. For high atmospheric pressures and small values of surface albedo the inversion height is larger and vice versa for lower atmospheric pressures and large values of surface albedo.

CO_2 condensation at the surface of an exoplanet results in a decrease of atmospheric pressure and surface temperature. In Fig. 4 the surface pressure of a virtual exoplanet with a mass of 1 M_{Earth} and a surface albedo of 0.6 orbiting around a G-dwarf star is presented. The dependency of the surface pressure on orbital distance and initial surface pressure in the equilibrium state is shown. If the stellar flux is sufficiently low, CO_2 condensation at the surface reduces the atmospheric pressure and eventually leads to similar atmospheric pressures and similar surface temperatures for different starting pressures or even a total collapse of the atmosphere on the surface.

For planets orbiting the M-dwarf star surface condensation is strongly reduced for the same stellar flux compared to K- and G-dwarf stars (cf. Section 3.6). As a result the planetary surface temperatures are strongly increased for the M-dwarf stellar spectrum compared to the K- and G-dwarf stellar spectrum for the same stellar flux.

3.4. Albedo

The Bond albedo increases with atmospheric pressure as can be seen in Fig. 5a for small values of surface albedo due to increased Rayleigh scattering. For large values of surface albedo the Bond albedo increases only slightly with increasing atmospheric pressure. The only exception is for the M-dwarf stellar spectrum und large values of surface albedo. There is a decrease in Bond albedo with increasing atmospheric pressure in this case (see Fig. 5b) due to increased near-infrared absorption of stellar flux in the atmosphere.

Simulations were performed for surface albedos between 0.1 and 0.8. Large values of surface albedo lead to lower surface temperatures. The surface albedo has a strong influence on the surface temperature of exoplanets having atmospheres with low atmospheric pressure but at high atmospheric pressure surface albedo becomes less important (see Fig. 6).

CO_2 absorption of stellar flux in the atmosphere depends on the surface albedo. It is increased for large values of surface albedo because more of the stellar flux is then reflected at surface. The increased reflected flux as well as the incoming flux are absorbed by CO_2 in the atmosphere. To illustrate this, the absorptance *A* of stellar flux *F* in the atmosphere may be defined (Halthore et al., 2005) using fluxes at the top of the atmosphere (TOA) and at the surface (SFC):

$$A=\frac{(F^{\downarrow}-F^{\uparrow})_{TOA}-(F^{\downarrow}-F^{\uparrow})_{SFC}}{F^{\downarrow}{}_{TOA}},$$

where $^{\uparrow}$, $_{\downarrow}$ indicate upwelling and downwelling fluxes, respectively. Values for *A* for a 1 M_{Earth} around a G-dwarf star for different atmospheric pressures and surface albedos are given in Figs. 7 and 3. *A* is higher for large values of surface albedo but the atmospheric temperatures are dominated by thermal infrared and heat fluxes (cf. Fig. 3).

3.5. Planetary mass

A 10 M_{Earth} exoplanet has a stronger gravitational acceleration than a 1 M_{Earth} exoplanet, so for the same atmospheric pressure the smaller exoplanet's atmosphere has a larger column depth. In most cases the 1 M_{Earth} exoplanet has higher surface temperatures, i.e. the increased greenhouse effect dominates over the increased albedo effect. This increase is most pronounced for high surface albedos but is even then only in the order of a few Kelvin. At high atmospheric pressure and low surface albedo, higher surface temperatures for the 10 M_{Earth} exoplanet are possible (see Fig. 8).

The Bond albedo is larger for the smaller mass planet due to increased Rayleigh scattering and the difference is more pronounced at higher atmospheric pressures.

3.6. Stellar spectrum

Surface temperatures are higher for M-dwarf stars than for K-dwarf stars and higher for K-dwarf stars than for G-dwarf stars. This is due to the shift of the stellar flux to longer wavelengths at lower effective temperature. This shift leads to decreased Rayleigh scattering and increased near-infrared absorption by CO_2 for the K-dwarf star and especially the M-dwarf star. Fig. 9 shows the surface temperature difference between a K-dwarf and a G-dwarf stellar spectrum at the same stellar flux for a 1 M_{Earth} exoplanet with a surface albedo of 0.2.

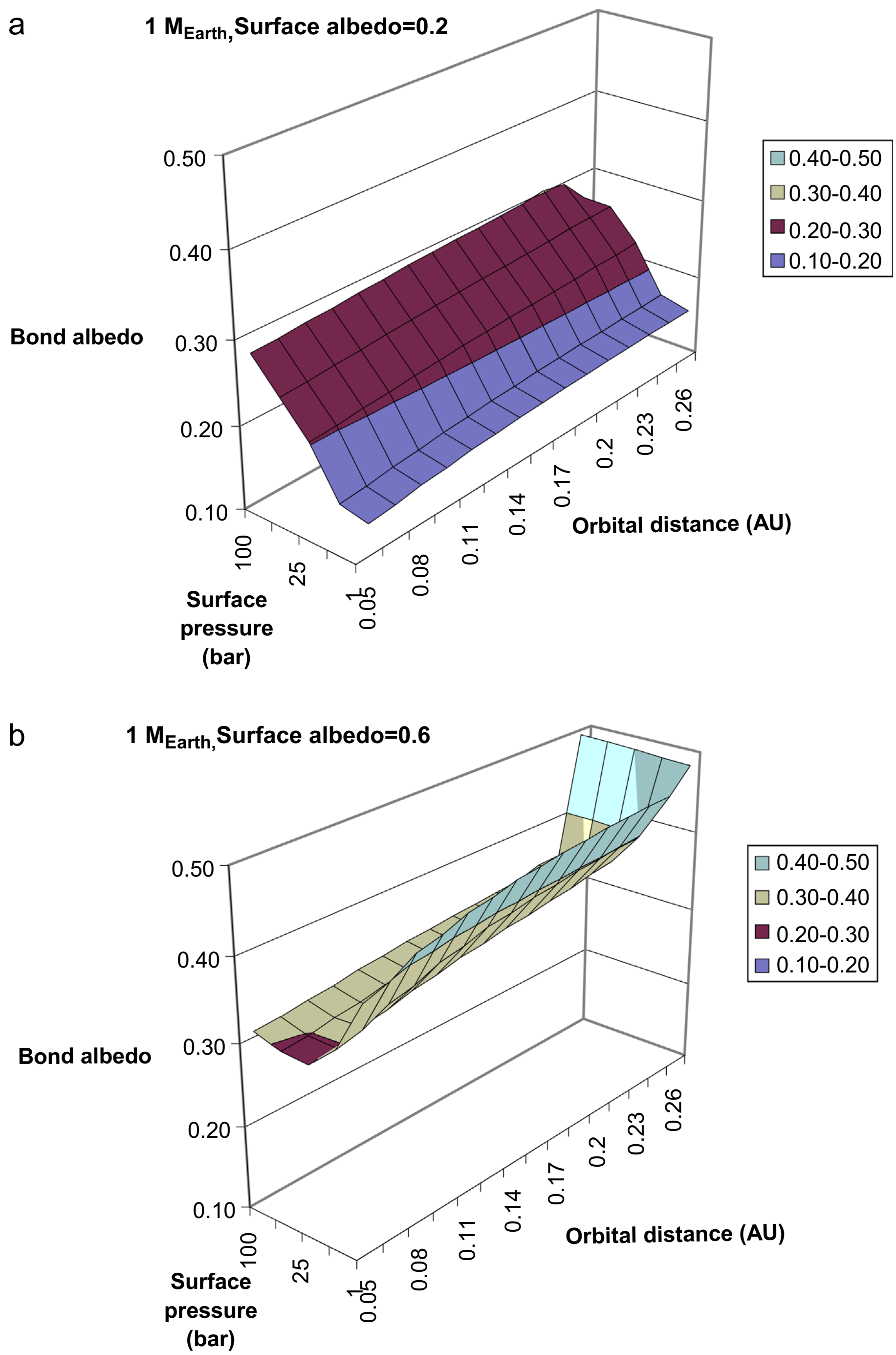

Fig. 5. The Bond albedo (dimensionless) of a virtual exoplanet with a mass of 1 M_{Earth}, for a M-dwarf star, for different surface temperatures and orbital distances. The surface albedo is (a) 0.2 and (b) 0.6.

The difference in surface temperature is larger at higher atmospheric pressures. CO_2 condensation at the surface appears for G-dwarf stars at higher values of stellar flux than for K-dwarf stars. This is discernible by the peaks in the temperature difference in Fig. 9 for low values of stellar flux.

As a consequence, for a stellar flux where a solvent may already freeze on the surface of a planet orbiting a G-dwarf star, on planets orbiting a K-dwarf or M-dwarf star the solvent may still be liquid. The habitability of planets orbiting late-type stars may on the other hand be limited by tidal locking (see Section 3.7) or stronger particle, stellar wind and XUV fluxes (Lammer et al., 2009).

3.7. Other parameters

Nitrogen exists in significant amounts in the atmospheres of Venus, Earth, Mars and Titan. N_2 affects the radiative transfer in Earth's atmosphere most prominently by Rayleigh scattering but also by pressure broadening of H_2O and CO_2 spectral lines (Goldblatt et al., 2009) and collision induced absorption (especially at dry atmospheric conditions; Höpfner et al., 2012). For exoplanets orbiting K-dwarf and especially M-dwarf stars the increase in Rayleigh scattering due to additional N_2 in the atmosphere would be much less pronounced than for exoplanets orbiting G-dwarf

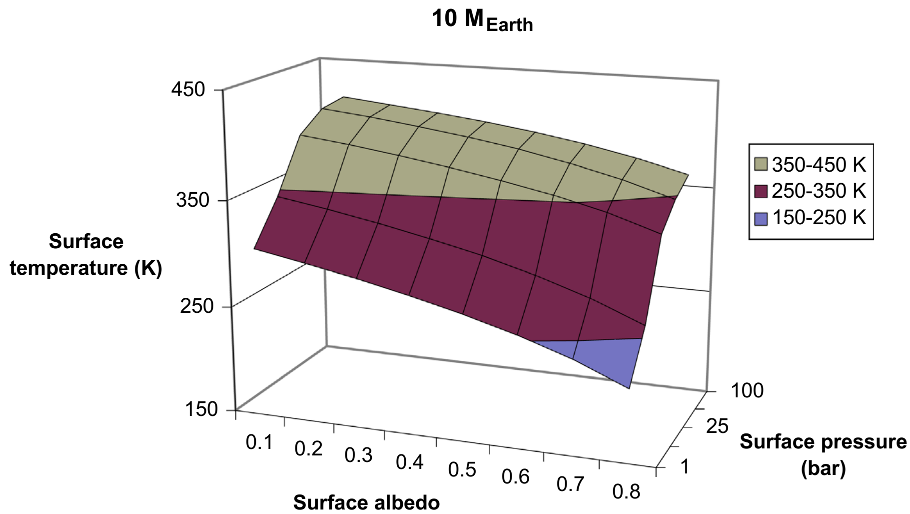

Fig. 6. Surface temperature of a virtual exoplanet with a mass of 10 M_{Earth}, for a M-dwarf star, for different surface albedos and surface pressures.

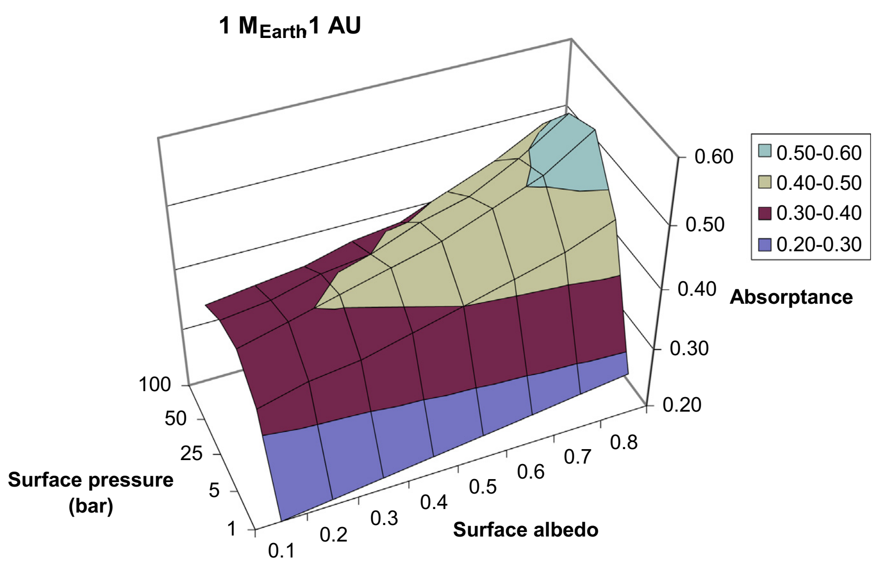

Fig. 7. Absorptance *A* (dimensionless) of stellar flux in the atmosphere of a 1 M_{Earth} virtual exoplanet orbiting a G-dwarf star for different values of surface albedo and surface pressure. The decrease in *A* at higher atmospheric pressures is caused by increased Rayleigh scattering.

stars. The cooling due to increased scattering will also be partly compensated by warming induced by pressure broadening and collision induced absorption. Wordsworth et al. (2010a) pointed out that the effect of additional N_2 is small for dense CO_2 atmospheres for a planet orbiting a M-dwarf star and that a partial pressure of at least 20 bar N_2 is necessary for a significant increase in planetary albedo. We therefore did not include N_2 in our computations.

Additional greenhouse gases such as water vapor or methane would lead to an increased greenhouse effect (Pavlov et al., 2000; von Paris et al., 2010) and therefore higher surface temperatures. The neglect of further greenhouse gases leads to a lower range for the surface temperatures at the outer limit of the life supporting zone in our simulations.

We consider condensation of CO_2 in the atmosphere but neglect the effect of CO_2-clouds which are likely to form under such conditions. CO_2-ice clouds can warm the atmosphere by scattering infrared radiation as in the atmosphere of Mars (Forget and Pierrehumbert, 1997). Depending on the height and thickness, CO_2-ice clouds may also cool the surface (Mischna et al., 2000). The radiative forcing by CO_2 clouds is also influenced by the microphysical properties of the ice particles which in turn depend on atmospheric dynamics (Colaprete et al., 2003).

The overall effect of clouds in Earth's atmosphere results in a cooling of the surface but a reduction in low level clouds and an increase in high level clouds may also lead to a warming of the surface (Goldblatt and Zahnle, 2011; Rondanelli and Lindzen, 2012). Because of the complexity involved in including clouds in the simulations we neglected clouds in this study.

Some planets close to their host stars could be tidally locked in orbit-rotation resonances. Wordsworth et al. (2011) showed with a 3D general circulation model that horizontal heat transport and greenhouse warming are sufficiently strong for dense CO_2-atmospheres to prevent a collapse of the atmosphere. Also Spiegel et al. (2008) showed that in atmospheres of slowly rotating planets the energy is efficiently redistributed because of the weaker Coriolis force. Our 1D simulations should therefore provide reasonably accurate estimates of the outer limit of the life supporting zone.

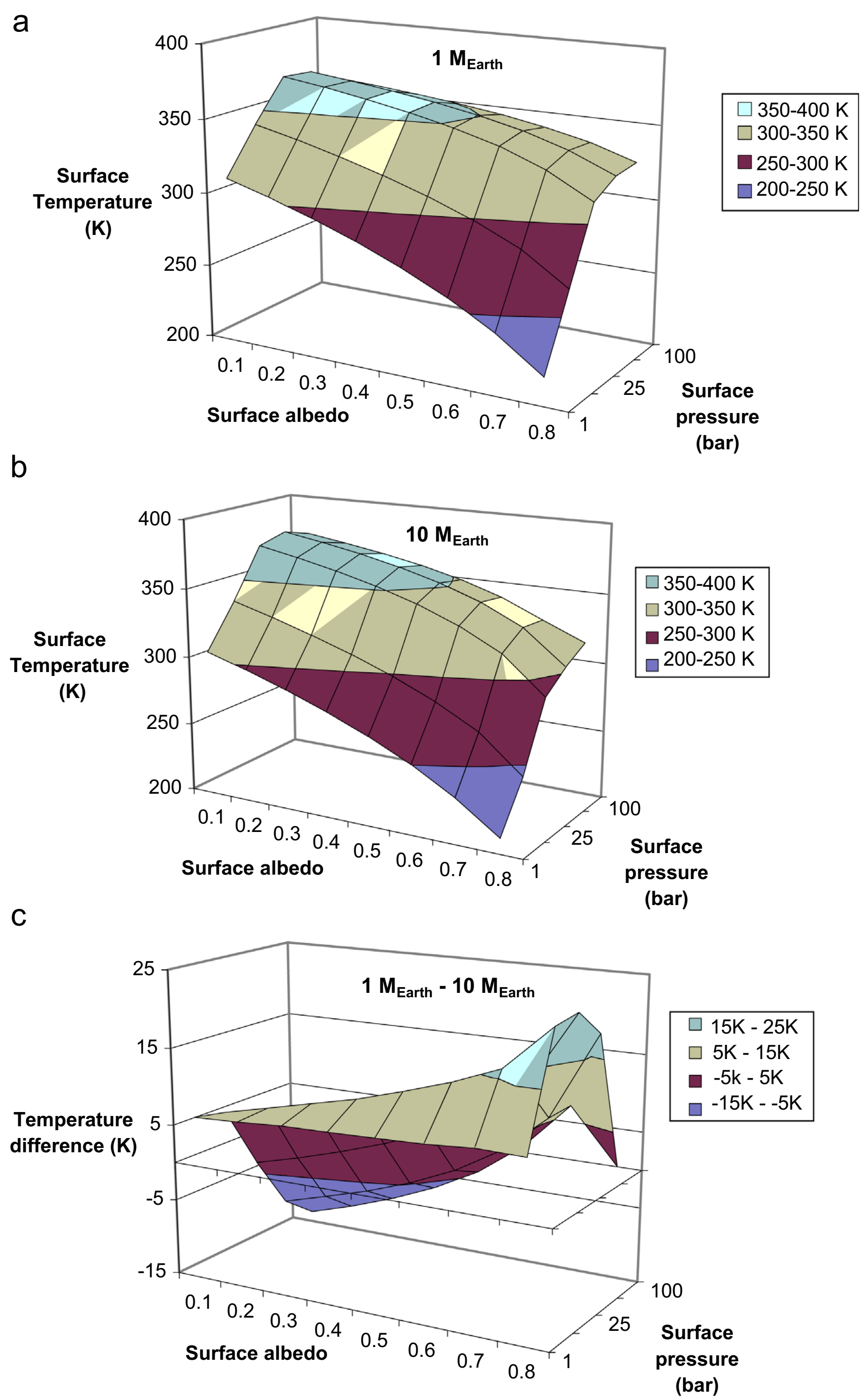

Fig. 8. Surface temperature of (a) an Earth-sized planet (1 M_{Earth}), (b) a Super-Earth-sized planet (10 M_{Earth}) and (c) surface temperature difference between the planets all as functions of surface pressure and surface albedo.

4. Results for Kepler planetary candidates

The database of surface temperatures for virtual planets is applied in this section to selected planetary candidates detected by the Kepler mission (Borucki et al., 2011; Batalha et al., 2013). Stellar and planetary input parameters for the planetary candidates are given in Tables 2 and 3. We selected planetary candidates with radii of approx. 2 R_{Earth} or less and low equilibrium temperatures. We calculated the mass of the planetary candidates following Sotin et al. (2007) assuming either a terrestrial planet or an ocean planet scenario. For the computations of the limits of the habitable zones we assumed an upper limit of the planetary mass of 10 M_{Earth} for terrestrial or ocean planets. If in the terrestrial planet mass scenario the mass would be larger than 10 M_{Earth}, we used the ocean planet mass scenario instead. We selected planetary candidates with a mass more similar to Earth because these are more likely to have a magnetic field (Gold et al., 2012). The low equilibrium temperature criterion is used because we are primarily interested in the outer limit of the life supporting zone (further planetary candidates could

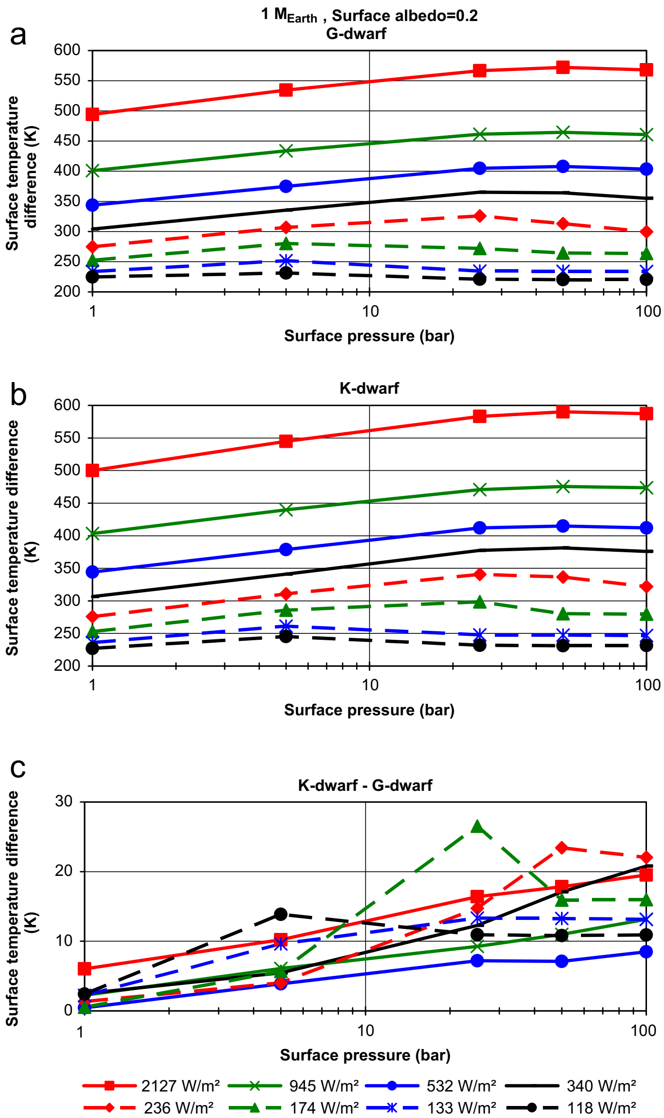

Fig. 9. Surface temperature of a 1 M_{Earth} virtual exoplanet with a surface albedo of 0.2 for (a) a K-dwarf, (b) a G-dwarf stellar spectrum and (c) surface temperature difference between the two stellar spectra all at the same stellar flux as functions of surface pressure and stellar flux (W/m²).

possibly lie within the inner limit of the sulfuric acid habitable zone displayed in Fig. 10).

In Fig. 10 the outer limits of the sulfuric acid, water and water/ammonia mixture (15 wt% ammonia) habitable zones are shown for selected Kepler planetary candidates. As CO_2-ice clouds or additional greenhouse gases would move the limits further outwards (see Section 3.7), the computations shown here are conservative estimates. Also indicated in Fig. 10 are the inner limits of the water and sulfuric acid habitable zones. The actual inner limit of the water habitable zone may be quite different from the computations with the atmospheric scenarios used here as additional greenhouse gases (such as water vapor) and clouds may move the inner limit in either direction. The computations for the inner limit of the sulfuric acid habitable zone presented in Fig. 10 are a conservative estimate of the actual inner limit as long as no additional greenhouse gases are in the atmosphere.

A surface albedo of 0.2 and a CO_2 surface pressure of 1 bar were used in all computations. If the initial atmospheric pressure is changed the limits shown are still valid. Higher surface pressure would increase in most cases surface temperatures and shift the limits outwards (see Section 3.2 and Fig. 7). Larger values of surface albedo instead shift the limits inwards (see Section 3.4 and Fig. 7). For CO_2 surface pressures of 25 bar or more all planetary candidates have computed surface temperature above the freezing temperature of the considered solvents regardless of the assumed surface albedo. This holds also for CO_2 surface pressures of 5 bar or more for the last eight planetary candidates in Table 3. Table 4 gives the maximum value of surface albedo a planetary candidate could have so the considered solvents may be liquid on its surface.

Table 2
Stellar input parameters of selected Kepler planetary candidates.

Host star	$T_{effective}$ (K)	Radius (R_{Sun})
1686	3665	0.52
854	3743	0.52
87	5510	0.85
701	4807	0.60
1361	4050	0.51
1871	4449	0.61
2469	4727	0.72
2474	5284	0.70
1739	5677	0.83
2626	3735	0.53
268	4808	0.75
812	4097	0.56
2290	4969	0.66
438	4351	0.56
1938	5071	0.66
2650	3900	0.51
2124	4103	0.54

5. Summary

We computed a comprehensive database of surface temperatures for exoplanets that may be used to assess habitability. We applied the database to selected planetary candidates detected by the Kepler mission. Our 1-dimensional simulations show that CO_2-rich atmospheres can effectively heat the surface of an exoplanet but the increase in surface temperature by increased CO_2 surface pressure is limited by increased Rayleigh scattering, CO_2-condensation in the atmosphere and at the surface. CO_2-condensation at the surface lowers the greenhouse effect whereas CO_2-condensation in the atmosphere leads to a warmer and more extended atmosphere but a colder surface. The almost linear increase (on a logarithmic scale) of the surface temperature up to an initial CO_2 surface pressure of 25 bar reaches a plateau or even decreases slightly at higher pressures. For late type stars with lower effective temperature which are emitting at longer wavelengths this limit by CO_2-condensation is at greater relative orbital distances (i.e. lower stellar fluxes), as the near-infrared absorption is increased and Rayleigh scattering decreased for exoplanets orbiting these stars. The assumed surface albedo strongly influences the planetary surface temperature as long as the atmospheric pressure is below about 25 bar. At higher atmospheric pressure the surface albedo becomes less important. The change in surface temperature due to different assumed planetary mass is small compared to changes in other parameters.

All 17 selected Kepler planetary candidates are very likely inwards of the outer limit of the life supporting zone consisting of a sulfuric acid, a water and a water/ammonia mixture (15 wt% ammonia) habitable zone even at low CO_2 surface pressures. For high CO_2 surface pressures the assumed surface albedo becomes

Table 3
Planetary input parameters of selected Kepler planetary candidates.

KOI number	Radius (R_{Earth})	Orb. dist. (AU)	$T_{equilibrium}$ (K)	Period (days)	Mass[a] (M_{Earth})			ESI[b]
					Terrestrial	Ocean	Computation	
1686.01	1.41	0.236	240	56.9	3.5	1.5	3.5	0.86
854.01	2.26	0.235	247	56.1	19.6	8.3	8.3	0.74
87.01	2.10	0.805	250	289.9	15.0	6.4	6.4	0.77
701.03	1.57	0.417	255	122.4	5.2	2.2	5.2	0.86
1361.01	2.17	0.242	258	59.9	16.9	7.2	7.2	0.78
1871.01	2.18	0.347	260	92.7	17.2	7.3	7.3	0.77
2469.01	2.13	0.457	262	131.2	15.8	6.7	6.7	0.77
2474.01	1.45	0.550	263	176.8	3.9	1.7	3.9	0.88
1739.01	1.85	0.695	273	220.7	9.4	4.0	9.4	0.79
2626.01	1.46	0.182	281	38.1	4.0	1.7	4.0	0.85
268.01	1.64	0.411	286	110.4	6.1	2.6	6.1	0.80
812.03	2.02	0.212	293	46.2	13.0	5.5	5.5	0.73
2290.01	1.75	0.362	296	91.5	7.7	3.3	7.7	0.77
438.02	2.10	0.230	298	52.7	15.0	6.4	6.4	0.72
1938.01	2.10	0.374	298	96.9	15.0	6.4	6.4	0.72
2650.01	1.26	0.170	299	35.0	2.3	1.0	2.3	0.85
2124.01	1.02	0.197	300	42.3	1.1	0.5	1.1	0.90

[a] Calculated according to Sotin et al. (2007).
[b] Earth Similarity Index (Schulze-Makuch et al., 2011); values above 0.8 may be considered Earth-like.

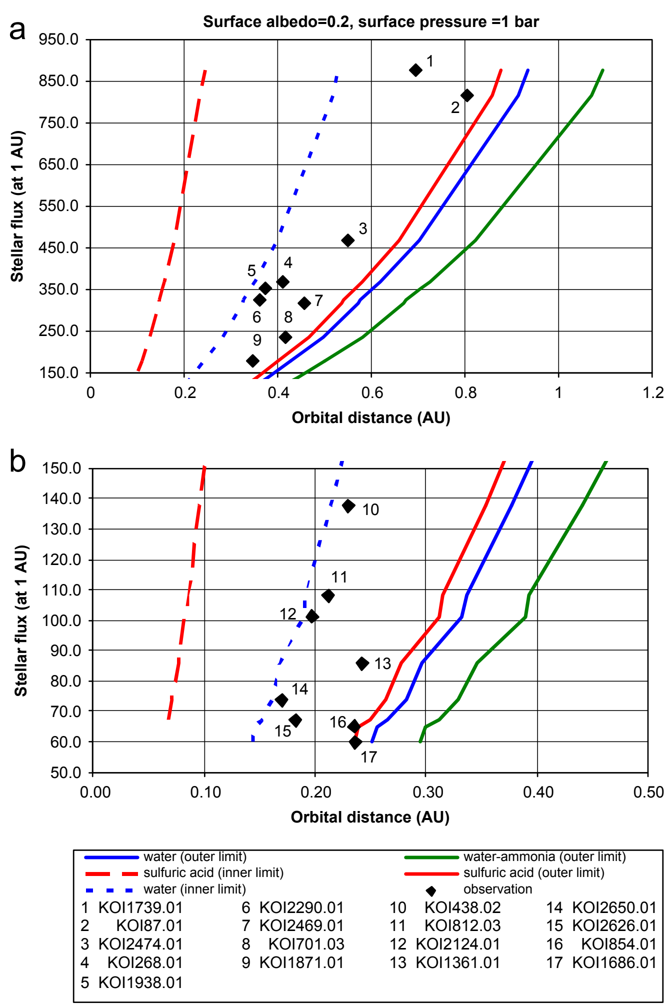

Fig. 10. Outer (and inner) limits of sulfuric acid, water and a water/ammonia mixture (15 wt% ammonia) habitable zones for selected Kepler planetary candidates. (a) For planets orbiting stars with stellar fluxes at 1 AU larger than 150 W/m², (b) for stellar fluxes at 1 AU below 150 W/m². A surface albedo of 0.2 and a CO_2 surface pressure of 1 bar were used in all these computations, fluxes shown are for fast rotating planets.

Table 4
Maximum surface albedo allowed for a planetary candidate to lie in a solvent's habitable zone for CO_2 surface pressures of 1 and 5 bar. If no value is given the surface albedo may have any value between 0.1 and 0.8.

KOI number	Sulfuric acid HZ		Water HZ		Water/ammonia (15 wt% ammonia) HZ	
	p_0=1 bar	p_0=5 bar	p_0=1 bar	p_0=5 bar	p_0=1 bar	p_0=5 bar
1686.01	0.2	0.6	0.3	0.7	0.5	–
854.01	0.2	0.6	0.3	0.6	0.5	0.7
87.01	0.3	0.6	0.4	0.6	0.5	0.7
701.03	0.3	0.6	0.4	0.7	0.6	–
1361.01	0.4	0.7	0.4	0.7	0.6	–
1871.01	0.4	0.7	0.5	0.7	0.6	–
2469.01	0.4	0.7	0.5	0.7	0.6	–
2474.01	0.4	0.7	0.5	0.7	0.6	–
1739.01	0.5	0.7	0.5	0.7	0.7	–
2626.01	0.6	–	0.6	–	0.7	–
268.01	0.6	–	0.6	–	0.7	–
812.03	0.6	–	0.7	–	–	–
2290.01	0.6	–	0.7	–	–	–
438.02	0.7	–	0.7	–	–	–
1938.01	0.6	–	0.7	–	–	–
2650.01	0.7	–	0.7	–	–	–
2124.01	0.7	–	0.7	–	–	–

less important and for 25 bar or more all planetary candidates have computed surface temperature above the freezing temperature of the considered solvents. The selected planetary candidates are also likely to lie inwards of the inner limit of the sulfuric acid habitable zone as long as there is no strong greenhouse effect due to greenhouse gases other than CO_2.

Acknowledgments

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References

Bains, W., 2004. Many chemistries could be used to build living systems. Astrobiology 4, 137–167.

Baranov, Y.I., Lafferty, W.J., Fraser, G.T., 2004. Infrared spectrum of the continuum and dimmer absorption in the vicinity of the O_2 vibrational fundamental in O_2/CO_2 mixtures. Journal of Molecular Spectroscopy 228, 432–440.

Baross, J.A., et al., 2007. The Limits of Organic Life in Planetary Systems. National Research Council. National Academies Press, Washington D.C..

Batalha, N.M., Rowe, J.F., Bryson, S.T., et al., 2013. Planetary candidates observed by Kepler, III: analysis of the first 16 months of data. Astrophysical Journal Supplement Series 204, 24.

Benner, S.A., Ricardo, A., Carrigan, M.A., 2004. Is there a common chemical model for life in the universe? Current Opinion in Chemical Biology 8, 672–689.

Borucki, W.J., Koch, D.G., Basri, G., Batalha, N., Brown, T.M., Bryson, S.T., Caldwell, D., Christensen-Dalsgaard, J., Cochran, W.D., DeVore, E., Dunham, E.W., Gautier III, T.N., Geary, J.C., Gilliland, R., Gould, A., Howell, S.B., Jenkins, J.M., Latham, D.W., Lissauer, J.J., Marcy, G.W., Rowe, J., Sasselov, D., Boss, A., Charbonneau, D., Ciardi, D., Doyle, L., Dupree, A.K., Ford, E.B., Fortney, J., Holman, M.J., Seager, S., Steffen, J.H., Tarter, J., Welsh, W.F., Allen, C., Buchhave, L.A., Christiansen, J.L., Clarke, B. D., Desert, J.-M., Endl, M., Fabrycky, D., Fressin, F., Haas, M., Horch, E., Howard, A., Isaacson, H., Kjeldsen, H., Kolodziejczak, J., Kulesa, C., Li, J., Machalek, P., McCarthy, D., MacQueen, P., Meibom, S., Miquel, T., Prsa, A., Quinn, S.N., Quintana, E.V., Ragozzine, D., Sherry, W., Shporer, A., Tenenbaum, P., Torres, G., Twicken, J.D., Van Cleve, J., Walkowicz, L., 2011. Characteristics of planetary candidates observed by Kepler, II: analysis of the first four months of data. Astrophysical Journal Letters 736, 19 (22 pp.).

Colaprete, A., Haberle, R.M., Toon, O.B., 2003. Formation of convective carbon dioxide clouds near the south pole of Mars. Journal of Geophysical Research 108 (E7), 5081.

Croft, S.K., Lunine, J.I., Kargel, J.S., 1988. Equation of State of ammonia–water liquid: derivation and planetological applications. Icarus 73, 279–293.

Forget, F., Pierrehumbert, R.T., 1997. Warming early Mars with carbon dioxide clouds that scatter infrared radiation. Science 278, 1273–1276.

Forget, F., Hourdin, F., Talagrand, O., 1998. CO_2 snowfall on Mars: simulation with a general circulation model. Icarus 131, 302–316.

Goldblatt, C., Zahnle, K.J., 2011. Clouds and the faint young sun paradox. Climate of the Past 7, 203–220.

Giles, M.M., Fritsen, C.H., Eicken, H., Payne, M.C., 2003. The search for life on Europa: limiting environmental factors, potential habitats, and Earth analogues. Astrobiology 3, 785–811.

Gold, M.W., Leitner, J.J., Firneis, M.G., 2012. Do Super-Earths have convective cores? [abstract EGU2012-3662]. Geophysical Research Abstracts, vol. 14, Vienna.

Goldblatt, C., Claire, M.W., Lenton, T.M., Matthews, A.J., Watson, A.J., Zahnle, K.J., 2009. Nitrogen-enhanced greenhouse warming on early Earth. Nature Geoscience 2, 891–896.

Gruszka, M., Borysow, A., 1997. Roto-translational collision-induced absorption of CO_2 for the atmosphere of Venus at frequencies from 0 to 250 cm^{-1} and at temperature from 200 K to 800 K. Icarus 129, 172–177.

Gruszka, M., Borysow, A., 1998. Computer simulation of the far infrared collision induced absorption spectra of gaseous CO_2. Molecular Physics 93, 1007–1016.

Gueymard, C.A., 2003. The sun's total and spectral irradiance for solar energy applications and solar radiation models. Solar Energy 76, 423–453.

Halthore, R.N., et al., 2005. Intercomparison of shortwave radiative transfer codes and measurements. Journal of Geophysical Research 110, D11206.

Halevy, I., Pierrehumbert, R.T., Schrag, D.P., 2009. Radiative transfer in CO_2-rich paleoatmospheres. Journal of Geophysical Research 114, D18112.

Höpfner, M., Milz, M., Buehler, S., Orphal, J., Stiller, G., 2012. The natural greenhouse effect of atmospheric oxygen (O_2) and nitrogen (N_2). Geophysical Research Letters 39, L10706.

Hussmann, H., Sohl, F., Spohn, T., 2006. Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-neptunian objects. Icarus 185, 258–273.

Kaltenegger, L., Sasselov, D., 2011. Exploring the habitable zone for Kepler planetary candidates. Astrophysical Journal Letters 736, L25–L30.

Kaltenegger, L., Sasselov, D., 2011. Exploring the habitable zone for Kepler planetary candidates. Astrophysical Journal Letters 736, L25 (6 pp.).

Kasting, J.F., Whitmore, D.P., Reynolds, R.T., 1993. Habitable zones around main sequence stars. Icarus 101, 108–128.

Key, J.R., Schweiger, A.J., 1998. Tools for atmospheric radiative transfer: Streamer and FluxNet. Computers & Geosciences 24, 443–451.

Lacis, A., Oinas, V., 1991. A description of the correlated-k distribution method for modeling non-gray gaseous absorption, thermal emission and multiple scattering in vertically inhomogeneous atmospheres. Journal of Geophysical Research 96, 9027–9063.

Lammer, H., Bredehöft, J.H., Coustenis, A., Khodachenko, M.L., Kaltenegger, L., Grasset, O., Prieur, D., Raulin, F., Ehrenfreund, P., Yamauchi, M., Wahlund, J.-E., Grießmeier, J.-M., Stangl, G., Cockell, C.S., Kulikov, Yu.N., Grenfell, J.L., Rauer, H., 2009. What makes a planet habitable? Astronomy and Astrophysics Review 17, 181–249.

Leitner, J.J., Schwarz, R., Firneis, M.G., Hitzenberger, R., Neubauer, D., 2010a. Generalizing habitable zones in exoplanetary systems—the concept of the life supporting zone [abstract 5255], LPI Contribution No. 1538. In: Proceedings of Astrobiology Science Conference Abstracts, League City.

Leitner, J.J., Firneis, M.G., Hitzenberger, R., 2010b. Potential habitats for exotic life within the life supporting zone [abstract EGU2010-12544]. Geophysical Research Abstracts, vol. 12, Vienna.

Leitner, J.J., Neubauer, D., Schwarz, R., Eggl, S., Firneis, M.G., Hitzenberger, R., 2010c. The life supporting zone I—From classic to exotic life [abstract EPSC2010-677]. In: Proceedings of 5th European Planetary Science Congress Abstracts, Rome.

Leitner, J.J., Schulze-Makuch, D., Firneis, M.G., Hitzenberger, R., Neubauer, D., 2012. Solvents of interest for exotic life on planetary bodies in life supporting zones around main sequence stars. Paleontology Journal 46 (9), 1091.

Mischna, M.A., Kasting, J.F., Pavlov, A., Freedman, R., 2000. Influence of carbon dioxide clouds on early Martian climate. Icarus 145, 546–554.

Neubauer, D., Vrtala, A., Leitner, J.J., Firneis, M.G., Hitzenberger, R., 2011. Development of a model to compute the extension of life supporting zones for Earth-like exoplanets. Origins of Life and Evolution of Biospheres 41, 545–552.

Neubauer, D.,Vrtala, A., Leitner, J.J., Firneis, M.G., Hitzenberger, R., 2012. The life supporting zone of Kepler-22b and the Kepler planetary candidates: KOI268.01, KOI701.03, KOI854.01 and KOI1026.01. Planetary and Space Science 73 (1), 397–406.

Pavlov, A.A., Kasting, J.F., Brown, L.L., Rages, K.A., Freedman, R., 2000. Greenhouse warming by CH_4 in the atmosphere of early Earth. Journal of Geophysical Research 105 (E5), 11981–11990.

Perrin, M.Y., Hartmann, J.M., 1989. Temperature-dependent measurements and modeling of absorption by CO_2–N_2 mixtures in the far line-wings of the 4.3-μm CO_2 band. Journal of Quantitative Spectroscopy and Radiative Transfer 42, 311–317.

Raulin, F., Bruston, P., Paillous, P., Sternberg, R., 1995. The low temperature organic chemistry of Titan's geofluid. Advances in Space Research 15, 321–333.

Rondanelli, R., Lindzen, R.S., 2012. Comment on “clouds and the faint young sun paradox” by Goldblatt and Zahnle (2011). Climate of the Past 8, 701–703.

Rothman, L.S., Gordon, I.E., Barbe, A., et al., 2009. The HITRAN 2008 molecular spectroscopic database. Journal of Quantitative Spectroscopy and Radiative Transfer 110, 533–572.

Schulze-Makuch, D., Irwin, L.N., 2004. Life in the Universe. Springer, New York.

Schulze-Makuch, D., Irwin, L.N., 2006. The prospect of alien life in exotic forms on other worlds. Naturwissenschaften 93, 155–172.

Schulze-Makuch, D., Méndez, A., Fairén, A.G., von Paris, P., Turse, C., Boyer, G., Davila, A.F., António, M.R.S., Catling, D., Irwin, L.N., 2011. A two-tiered approach to assessing the habitability of exoplanets. Astrobiology 11 (10), 1041–1052.

Selsis, F., Kasting, J.F., Levrard, B., Paillet, J., Ribas, I., Delfosse, X., 2007. Habitable planets around the star Gliese 581? Astronomy & Astrophysics 476, 1373–1387.

Sotin, C., Grasset, O., Mocquet, A., 2007. Mass–radius curve for extrasolar Earth-like planets and ocean planets. Icarus 191, 337–351.

Spiegel, D.S., Menou, K., Scharf, C.A., 2008. Habitable climates. Astrophysical Journal 681, 1609–1623.

Von Paris, P., Gebauer, S., Godolt, M., Grenfell, J.L., Hedelt, P., Kitzmann, D., Patzer, A. B.C., Rauer, H., Stracke, B., 2010. The extrasolar planet Gliese 581d: a potentially habitable planet? Astronomy & Astrophysics 522, A23.

Wordsworth, R.D., Forget, F., Selsis, F., Madeleine, J.B., Millour, E., Eymet, V., 2010a. Is Gliese 581d habitable? Some constraints from radiative-convective climate modeling. Astronomy & Astrophysics 522, A22.

Wordsworth, R.D., Forget, F., Eymet, V., 2010b. Infrared collision-induced and far-line absorption in dense CO_2 atmospheres. Icarus 210, 992–997.

Wordsworth, R.D., Forget, F., Selsis, F., Millour, E., Charnay, B., Madeleine, J.B., 2011. Gliese 581D is the first discovered terrestrial-mass exoplanet in the habitable zone. Astrophysical Journal Letters 733, L48.

CHAPTER NINE

THE EVOLUTION OF LINCOS: A LANGUAGE FOR COSMIC INTERPRETATION

MARIA G. FIRNEIS AND JOHANNES J. LEITNER

Introduction

In the 1820s, Carl Gauss in Germany and Joseph Johann Littrow in Austria proposed ideas on how to communicate with non-terrestrial species. Unfortunately, they never published their proposals; they only discussed them in public talks. Gauss is said to have proposed a huge Pythagorean rectangular triangle of sides three and four units in length (the units were undefined; one unit length could be about 100 miles) and a hypotenuse of five units, with proportional squares arising from the three sides, to be constructed in the plains of Siberia. The intention was that it should be visible to potential observers on the Moon (Raulin-Cerceau, 2010, see Figure 1).

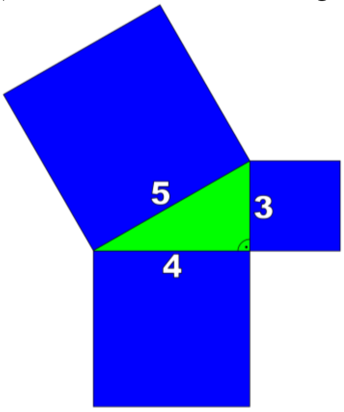

Figure 1. The huge Pythagorean rectilinear triangle proposed by Gauss to be constructed in the plains of Siberia.

Littrow proposed a similar triangle, to be sited in the Sahara, constructed as gigantic channels filled with water and topped with kerosene. The kerosene would be lit at night as a fiery signal for observers on the Moon. Sometimes his idea is presented differently: the channels as set of huge, 30 km-diameter concentric rings. Again, his intention was something discernible as an artificial structure hinting of our existence to any would-be observers. Raulin-Cerceau (2010) gives an outstanding summary of other early ideas, centering on French proposals; Dick (1996) offers a likewise outstanding overview of Twentieth Century suggestions.

We have the English biologist Lancelot Hogben to thank for offering a starting point for a language to ease communications. In 1954, he created Astraglossa as a means of communication via short and long radio pulses. These pulses have to be applied when simpler means such as direct transmissions of pictures are not available. In case a "Rosetta stone" offering identical texts in languages such as English and Russian also is not available, pulses are a reasonable tool. He based his proposal on earlier radioglyphic schemes. A radioglyph is a picture intended for interstellar communication sent via radio waves. Morrison (1962) elaborated on Astraglossa. Short pulses represented numbers, long pulses represented such operations as addition or subtraction (Hogben, 1963). The following example from Hogben's book (p. 127) illustrates the basic concept:

1 + 2 + 3 = 6
(i) 1 . . F_a . .1 . 1 . .F_a . . 1 . 1 . 1 . . F_b . . 1 . 1 . 1 . 1 . 1 . 1
(ii) 1 . . F_a . .1 . 1 . .F_a . . 1 . 1 . 1 . . F_b . . F_s . . F_b . . 1 . 1 . 1 . 1 . 1 . 1

F_a signifies addition and F_b identity. F_s introduces the symbol for six.

LINCOS: Background and concept

LINCOS was created as a playground for these nascent ideas. As an abbreviation of "*lingua cosmica"*, it is a so-called constructed or artificial language. *Contra* naturally evolved languages, such languages are devised efficiently for grammar, vocabulary, and individual phonology. Sometimes they are created to facilitate human communication (e.g. Esperanto), sometimes to bring fiction to life (Klingon in Star Trek). Artifical languages has given us the science of *astrolinguistics* (Ollongren, 2008).

Hans Freudenthal conceived LINCOS as a means of communication with intelligent aliens. Born 17 September 1905 in Luckenwalde, Germany, died 13 October 1990 in Utrecht, the Netherlands, Freudenthal was for many years an outstanding mathematician at the University of Utrecht. A specialist in topology and Lie groups, he intended to create a self-explanatory language that could be taught using a large number of examples formulated mathematically. It assumed a common knowledge between human and alien, which for him meant mathematics – if only because the aliens would need to think in ways somehow similar to our own if they were to understand our communicative intentions. He further assumed they would have access to powerful means of communication at long wavelengths, which are as free from cosmic disturbance as is technically possible. One strategy could focus around decimetric radio frequencies, the other around optical frequencies observable by large optical telescopes as used by "Optical SETI" (Ross and Kingsley, 2011).

Freudenthal constructed LINCOS as a sort of a *Gedankenexperiment*, with a 200-or-so-page manual (*LINCOS: Design of a Language for Cosmic Intercourse*, 1960) offering a step-by-step description of the language.

Description of Classic LINCOS

The original text is divided into such topics as mathematics, time, behaviour and space, and motion and mass. Freudenthal planned a second volume addressing social aspects of humanity but never got it written. Evidently, Freudenthal lost interest in the subject due to mounting conceptual difficulties when applying LINCOS for other than mathematical contents due to the potential different sociological aspects of alien receivers (see also Dick, 1996).

Table 1 displays a sample of the mathematical code. The signals are coded *X* and *O* for easy legibility; *ver* (Latin *verum*) means "true" and *fal* (Latin *falsum*) means "false".

Integers, rational numbers, real numbers, complex numbers, and prime numbers (Int, Rat, Rea, Com, and Pri) are introduced one after another. Certain essential constants (e, i, π) are also defined. Combination of terms allows for remarkable complexity: LINCOS is even able to express Einstein's theory of special relativity (see Figure 2).

Bassi (1992) offers a concise review of Freudenthal's book. Bassi suggests that LINCOS be broadcast via radio signals of varying duration and wavelength, a possibility not mentioned anywhere by Freudenthal. Freudenthal's focus lay with claiming that it should be optimally systematic in the sense that syntactic and semantic categories should be marked phonetically (see Bassi, 1992).

Fuchs (1973) used Morse code with signals of short (piep) and long (pieep) duration; an interrupt indicated the "equals sign". Binary notation can be used instead of decimal notation. For the decimal code an example is :

3 = 3 results in
piep - piep - piep -- pieep -- piep - piep – piep

In similar fashion, binary notation can be used to show the same example:

0101010000111000010101
with 000 as "break" and 0111 as "=".

For chatting with extraterrestrials, Freudenthal (1960) suggests the following dialogue (Table 2), where "ben" and "mal" indicating approval and disapproval respectively, and "tan" (Latin *tan=tamen*, "nevertheless") for "but", are added to the earlier "ver" and "fal".

Mathematical Code	**LINCOS Code**
1 = 1 true	X O X ϵ ver
1 < 2 true	X OO XX ϵ ver
2 = 3 false	XX O XXX ϵ fal
2 > 1 true	XX OOO X ϵ ver
(1 < 2) and (3 > 1) true	X OO XX A XXX OOO X ϵ ver
(1 = 2) and (1 = 1) false	X O XX A X O X ϵ fal
(1 = 2) or (1 < 2) true	X O XX AA X OO XX ϵ ver
(1 + 1 = 2) true	X P X O XX ϵ ver
(1 + 2 = 4) or (1 > 2) false	X P XX O XXXX AA X OOO XX ϵ fal

Table 1. Mathematical code versus LINCOS code.

CH. IV] SPACE, MOTION, MASS 205

Erg ⁚ Cea t_1 . X Vul · $A \in$ Sea Cmt 1 .
→ · Nes : Cea t_1 . X Ced ·
Nne Y Vul . $A \in$ Sea Cmt $\sqrt{1 - v^{10}/c^{10}}$ ⁏ :
Qia ⁏ · Pon ⁏ $w \in$ Und Ath .
∧ ⁚ ∨ ⌜t . t'⌝ · t ⌢ t' . = Cea . t_1 · ∧ : t Usq t' ·
Apu Y . Usd . Apu z_N · w Mov ⁚
∧ ⁝ ∧n ⁝ $n+1$. ∈ Num · ∧ . $n \leq N$. → ⁚ $w_n \in$ Und Ath .
∧ ⁚ ∨ ⌜t . t'⌝ · t ⌢ t' = Cea t_1 · ∧ : t Usq t' ·
Apu z_n . Usd . Apu Y · w_n Mov ⁝
∧ : ∧t · tw Apu z_n . ↔ . tw_n Apu z_n :
∧ ⁚ ∧n · z_n Par A . → ⁝ u_n = . w_n Apu z_0 · ∧ · u'_n = . w_n Apu Y ⁚
∧ : U Uni . u_1 . u_2 . Etc : ∧ : U' Uni · u_1' . u_2' . Etc ⁏ .
Erg ⁝ Nes · Cea t_1 . X Ced . $U \in$ Sea Cmt $10\,c^{-1}$:
Erg : Nes · Cea t_1 . Y Ced . $U' \in$ Sea Cmt $10\,c^{-1}\sqrt{(c+v)/(c-v)}$ ·
∧ ⁝ Cea t_1 . Y Inq Y : $\beta \in$ Pos . ∧ . $A \in$ Sea Cmt β .
∧ · w Apu z_n . t_n Pst . w Apu Y · ∧ · [1]
w_n Apu Y . t'_n Pst . w Apu Y ·
→ ⁚ Nes · Cea t_1 . Y Ced : $t'_n = 10\,t_n$.
∧ . Cmt $\beta = (t_{n+1} - t_n)(c-v)$. ∧ . Cmt $10\,\beta = (t'_{n+1} - t'_n)(c-v)$ ·
Erg . Cmt $10\,\beta = 10\,c^{-1}\sqrt{(c+v)/(c-v)}\,(c-v)$ · Erg . β
$= \sqrt{1 - v^{10}/c^{10}}$ ∗

A short proof of Lorentz contraction.

4 28 6. ∗ Hb Inq Ha ⁞
Pon ⁏ . X ⌢ Y ⌢ $Z \in$ Hom . ∧ · δ . Mul > . Sec 1 ·
∧ ⁏ ∨ ⌜a . b . c⌝ ⁝ ∧t ⁝ $t_1 - \delta \leq t \leq t_1 + \delta$. → ⁚ Cel X . t · = a :
∧ : Cel Y . t · = b : ∧ : Cel Z . t · = c : ∧ : Cel Rel $X\,Y$. t · = x :
∧ : Cel Rel $Y\,Z$. t · = y : ∧ : Cel $X\,Z$. t · = z .
∧ · t Loc Y . ⊂ : Cvx · t Loc X . ∪ . t Loc Z ⁏ ·
Erg . $z = (x+y)/(1 + xy/c^{10})$ ⁏ :
Qia ⁏ · Pon ⁏ $W \subset$ Und Ath . ∧ . α ⌢ β ⌢ $\gamma \in$ Pos .
∧ . $U \in$ Sea Sec α . ∧ . $U' \in$ Sea Sec β . ∧ . $U'' \in$ Sea Sec γ .
∧ ⁝ ∧ ⌜u . u' . u''⌝ ⁝ u Par U . ∧ . u' Par U' . ∧ . u'' Par U'' ·
↔ ⁚ ∨ ⌜w . t . t''⌝ · $w \in W$. ∧ : t Usq t'' · Apu X . Usd .
Apu Z · w Mov :
∧ · u = . w Apu X · ∧ · u' = . w Apu Y · ∧ · u'' = w Apu Z ⁏ .
Erg ⁝ Cea t_1 . X Vul · $U \in$ Sea Sec 1 :
→ ⁚ Nes · Cea t_1 . X Ced : Nne Y Vul . $U' \in$ Sea Sec $\sqrt{(c+x)/(c-x)}$ ·
∧ · Nne Z Vul . $U'' \in$ Sea Sec $\sqrt{(c+z)/(c-z)}$ ⁝
∧ ⁚ Cea t_1 . Y Vul · $U' \in$ Sea Sec 1 :

[1] Inadvertently I introduced a t_n, which for $n = 1$ does not mean the explicit t_1.

Figure 2. An extract from Freudenthal's book illustrating the formulation of Einstein's special relativity in LINCOS code.

Dialogue	**LINCOS**
H_a asks H_b: what X satisfies 2x = 5?	H_a Inq H_b · ?x 2x = 5
H_b asks H_a: 5/2	H_b Inq H_a · 5/2
H_a says to H_b: good	H_a Inq H_b · ben
H_a says to H_b: what x satisfies 4x = 10?	H_a Inq H_b · ?x 4x = 10
H_b says to H_a: 10/4	H_b Inq H_a · 10/4
H_a says to H_b: bad	H_a Inq H_b · mal
H_b says to H_a: 4 × 10/4 = 10 true	H_b Inq H_a · 4 × 10/4 ϵ ver
H_a says to H_b: true, but bad: x = 5/2	H_a Inq H_b · ver tan mal x = 5/2

Table 2. Examples for an intergalactic dialogue based on Freudenthal.

Bassi (1992) readily admits that LINCOS is not a perfect creation: e.g., no syntactic and semantic classification has been developed, while questions starting with "why" or "whether" are "indistinguishable from affirmative statements" (Bassi, 1992, p. 7). Two different words are used for "but". In (1974), Freudenthal acknowledged that the optimal level of formalization in the language had not been achieved.

Cosmic Call

In 1999 and again in 2003, LINCOS was used as the basis for an enterprise called *Cosmic Call*. Dumas (2007; Dutil and Dumas, 2001) describes how a message consisting of a scientific part plus a part created by the interested public was conceived. The public message contained music as well as fifty personal messages.

Using mathematics, a frame of pixels was set around images to overcome the difficulties confronted in the Arecibo/Drake message of 1974 (NAIC staff, 1975) – where, due to interstellar noise, a one-bit error was sufficient to collapse the whole information structure. The 70-meter dish of the Evapatoria, Ukraine, deep-space radar telescope was used for the 6 July 2003 transmission, with a 150 kW transmitter on 6 cm wavelength. Financing was provided by the US (Texas)-based company Team Encounter. Unlike the 1999 transmission, which was divided into 23 frames, the 2003 transmission consisted of one single frame transmitted over and over again (Braastad and Zaitsev, 2003).

Symbols for the numbers 1 through 9 were created using a 5×7 bitmap. Then, as in the original LINCOS, symbols were created for mathematical operations, along with pi and delta and various physical units: kilogram, meter, Kelvin, year, etc. Names were given to important chemical elements. Physical concepts such as proton, Planck constant, cosmological constant, etc.; biological concepts such as adenosine, cell, male, people, etc.; astronomical names for the planets, Sun, and universe; and other concepts like ocean, sky, target, age, etc. followed.

The stage set, a message was assembled including the contents of the earlier Arecibo message, information on the Solar System, a description of DNA, and a Fuller-map representation of Earth's continents. Five stars were targeted (see Table 3), chosen for their position near the galactic plane (Braastad and Zaitsev, 2003) in a region where interstellar scintillation is minimal: between 60° and 90° longitude of galactic centre.

Star (Constellation)	VMag	SpType	RA J2000	DE J2000
HIP 26335 (in Orion)	8.78	K7	05 36 30. 99	+ 11 19 40.3
HIP 43587 (55 Cnc) (in Cancer)	5.96	G8V	08 52 35.81	+ 28 19 51.0
HIP 4872 (in Cassiopeia)	9.56	K5V	01 02 38.87	+62 20 42.20
HIP 53721 (47 UMa) (in Ursa Major)	5.03	G0V	10 59 27.974	+ 40 25 49.92
HIP 7918 (in Andromeda)	4.96	G2V	01 41 47.143	+ 42 36 48.13

Table 3. Target stars from the 2003 Cosmic Call transmission (Braastad and Zaitsev, 2003). Data extracted from http://vizier.u-strasbg.fr.

A New Lingua Cosmica

Beginning in 2000, Alexander Ollongren (2005) started developing a new proposal based on formal lambda calculus and the calculus of constructions, including inductive definitions. The lambda calculus was originally developed by Whitehead and Russell (1910; 1912; 1913) and popularized by Kleene (1935) and Church (1936). It is a formal language for investigating functions or maps. It describes the definitions of functions and formal parameters as well as the input of actual parameters. It provides a successful characterization of computability (Barendregt, 1984). The theory behind it is analogous to that of number theory.

Kleene (1936) proved that lambda computability is equivalent to Gödel-Herbrand recursiveness; while Turing (1937) showed that Turing-machine computability is equivalent to lambda definability. In the 1970s it was shown that logical proofs could be formulated as lambda representations (Barendregt, 1984). The lambda calculus laid the foundations for programming languages like LISP by providing their operational semantics.

In 2010, Ollongren expanded the LINCOS system to include logic terms he called entities, which, by their concrete declaration, may be variables, hypotheses, or definitions, including inductive definitions. Global variables and constants are introduced via the definition of maps expressed by typed λ abstraction (Barendregt, 1992). Logical properties are expressed via the binary connectives ∧ (“and”) and ∨ (“or”) and the unary operator ¬ (“negation”).

Through constructive logic, the members of sets with special properties are expressed as unparameterized maps, allowing a general λ abstraction to verify a test hypothesis: i..e., λ abstractions in any given LINCOS text are representations of reality modes. Nesting of λ abstractions may occur. The scope of local variables is restricted, so that they may occur elsewhere in the text. Global variables form a superior body of λ abstractions and therefore cannot be redefined. One further token, the semicolon, serves as a mapping operator.

The Aristotelian syllogism – called Barbara by medieval scholars – will serve as illustration. It may be read: *all astronomers are human, and all stargazers are astronomers; therefore, all stargazers are human* (Ollongren, 2005). In LINCOS it looks like this:

FACT Barbara
(All x : D)
((astronomers : x) → (human : x)) ∧ ((star gazers : x) → (astronomers : x))
→ (star gazers : x) → (human : x)

Base *D* represents the general aspect of the problem whose properties are “astronomers”, “human”, and “stargazers”.

As Ollongren (2010) allows, questions remain whether an alien culture will be able to interpret all the symbols contained in an interstellar message, “where the tokens serve as links between abstract and concrete signatures” (Ollongren, 2010, p. 1442). In a later paper, Ollongren (2011) elaborates a logical arbiter function that, via parallel processes, interprets a dynamic process in a linguistic system. As illustration, he translates the opening scene of Hamlet, where the ghost appears, into *Lingua Cosmica*. No reference to time sequences is necessary; proper state vectors model the necessary interruptions using eight parallel threads.

Turning things around, Elliot (2010) offers a scenario of what might happen if an interstellar message would be received on Earth, based on recognizable mathematical/logical structures. Using Zipf’s Law, phrase-like chunks hinting at words or word sequences – where the frequency of a word is inversely proportional to its rank in a frequency table – would allow cryptoanalysis to reveal the underlying language-like structure in the same way that the linguistic signals of human languages reveal lexical and grammatical patterns: so e.g. correlation profiles between pairs of words have been investigated for various human languages. Such an analysis allows the possibility clearly to distinguish language from interstellar noise: e.g., a pulsar or the random noise generated by interstellar hydrogen.

Maccone’s (2010) statistical approach to the Drake equation suggests that the probability of finding intelligent extraterrestrials within a one-sigma distance should be within 1361 to 3979 ly. If so, this large distance would prohibit any communication.

Conclusion

We have provided an overview of the various attempts to convey at least the symbolic fundamentals of communication to an unknown alien intelligence. The updated version of LINCOS – NEW LINCOS – is meant to support auto-interpretation. Auto-interpretation in this sense considers "the case of elementary inductive definitions of terms, and the use of elimination to deduce facts from premises" (Ollongren, 2005, p. 1). NEW LINCOS has room for further improvement. Human beings are on the verge of showing off their existence to a probable interstellar community.

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References

Barendregt, H. 1984. *The Lambda Calculus: Its Syntax and Semantics*. Amsterdam: North Holland Publ.
—. 1992. "Lambda Calculi with Types." In *Handbook of Logic in Computer Science* 2, edited by S. Abramsky, D. M. Gabbay, T. S. E. Maibaum, 117–309. Oxford: Oxford University Press.
Bassi, B. 1992. "Were it Perfect, Would it Work Better? Survey of a Language for Cosmic Intercourse." http://www.brunobassi.it/scritti/lincos.html.
Braastad, R., and A. Zaitsev. 2003. "Synthesis and Transmission of Cosmic Call 2003 Interstellar Radio Message." http://www.cplire.ru/html/ra&sr/irm/CosmicCall-2003/index.html.
Church, A. 1936. "An unsolvable problem of elementary number theory." *Am J Math* 58:345–363.
Dick, S. J. 1996. *The Biological Universe: The Twentieth-Century Extraterrestrial Life Debate and the Limits of Science*. Cambridge: Cambridge University Press.
Dumas, S. 2007. "The 1999 and 2003 messages explained." http://www3.sympatico.ca/stephane_dumas/CETI/messages.pdf.
Dutil, Y., and S. Dumas. 2001. "Error Correction Scheme in Active SETI." http://www3.sympatico.ca/stephane_dumas/CETI/dutil_dumas.pdf.
Elliot, J. R. 2010. "Detecting the Signature of Intelligent Life." *Acta Astronaut* 67:1419–1426.
Freudenthal, H. 1960. *LINCOS: Design of a Language for Cosmic Intercourse*. Amsterdam: North-Holland Publ.
—. 1974. "Cosmic Language." *Current Trends in Linguistics* 12:1019–1042.
Fuchs, W. 1973. *Leben unter fernen Sonnen*. München: Droemer Knaur.
Hogben, L. 1963. *Science in Authority*. New York: Norton.
Kleene, S. 1935. "A theory of positive integers in formal logic." *Am J Math* 57:153–173, 219–244.
—. 1936. "λ-definability and recursiveness." *Duke Math J* 2:340–353.
Morrison, P. 1962. "Interstellar Communication." *Bull Philo Soc Wash* 16:78.
Maccone, S. 2010. "The Statistical Drake Equation." *Acta Astronaut* 67:1366–1383.
NAIC staff. 1975. "The Arecibo Message of November, 1974." *Icarus* 26:462–466.
Ollongren, A. 2005. "On Auto-Interpretation in LINCOS." http://www.liacs.nl/~ollongre/auto-Interpretation%20LINCOS.html.
—. 2008. "Astrolinguistics: A Guide for Calling E.T." http://www.alexanderollongren.nl/ASTROLINGUISTICS,%20A%20GUIDE%20FOR%20CALLING%20E%20T.htm.
—. 2010. "On the signature of LINCOS." *Acta Astronaut* 67:1440–1442.
—. 2011. "Processes in Lingua Cosmica." *Acta Astronaut*, doi:10.1016/j.actaastro.2011.09.017.
Raulin-Cerceau, F. 2010. "The Pioneers of Interplanetary Communication: From Gauss to Tesla." *Acta Astronaut* 67:1391–1398.
Ross, M., and S. Stuart. 2011. *Optical SETI: Moving Toward the Light*. Berlin Heidelberg: Springer.
Turing, A. M. 1937. "Computability of λ-definability." *J Symbolic Logic* 2:153–163.
Whitehead, A., and B. Russell. 1910. *Principia Mathematica*, Vol. 1, Cambridge: Cambridge University Press.
Whitehead, A., and B. Russell. 1912. *Principia Mathematica*, Vol. 2, Cambridge: Cambridge University Press.
Whitehead, A., and B. Russell. 1913. *Principia Mathematica*, Vol. 3, Cambridge: Cambridge University Press.

3. Discussion and Summary

Within this thesis several different topics concerning extraterrestrial life, and thereby especially concerning life, which is not necessarily based on the same chemical characteristics than life on Earth have been addressed. The aim of this chapter is to summarize the results of these studies and to bring them together in order to provide a new tool – the life supporting zone – for the search for life-as-we-know-it as well as for life-as-we-do-not-know-it.

In the first section the question how life can be defined or at least described is discussed. An analysis of the existing definitions of life made apparent that most of the existing definitions continue a geocentric way of thinking when describing life by assuming that the characteristics of terrestrial life are of universal nature. With only one sample of life at hand it would be presumptuously to state that life elsewhere in the Universe must be of the terrestrial kind. When considering the different definitions in detail, it becomes apparent that a large number of them is focused on terrestrial strategies as metabolism, reproduction or evolution. Even the NASA definition of life, which is '*life is a self-sustaining chemical system capable of undergoing Darwinian evolution*' (*Joyce*, 1994), does not help in deriving parameters useful for designing experiments for the search for life on other planets. Several other authors (e.g. *Luisi*, 1998) also have criticized this definition. In order to underline this problem, mules and hinnies have been addressed once more (see also *Kolb*, 2007) within this thesis, as they are sterile hybrids, which cannot take part in evolutionary processes. It is common that life definitions cannot be applied to individuals, but on species or biological systems. Nevertheless, the whole species of mules/hinnies is sterile and consequently, when applying a definition, which includes reproduction or evolution the species cannot be accounted for life. Within this context also viruses have been discussed, which classically are not considered as life due to their need of a host cell. In the present study the Homo sapiens sapiens also has been discussed within this context and was found to be on the one hand a symbiotic form of life due to its need of microorganisms for maintaining the essential metabolism, and on the other hand in case of female humans to be only 46.7 % of the total life-time to be able to reproduce. Analog to viruses also Homo sapiens sapiens needs an 'assisted metabolism' and consequently also have an 'assisted reproduction'. This leads to the conclusion that humans are not 'self-sustaining'. With this result and further the problem of evolution not to be observable within the time-frame of a space mission, the NASA definition for life becomes useless. Additionally within the studies concerning the first part of this thesis the focus in definitions of life on water as solvent as well as on the six terrestrial key elements for life (carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphor) was criticized with respect to the possible unknown nature of life elsewhere in the Universe. Consequently the term 'exotic life' was introduced to denote any potential life not necessarily based on the terrestrial properties and strategies of life and to open our mind for the possibility of life-we-do-not-know-it.

A first definition or hypothesis on the nature of this exotic life was developed in the following way: (1) life is based on a metabolism, which is working symbiotically or asymbiotically, (2) life exploits a thermodynamic disequilibrium, (3) the macromolecules that enable the metabolisms, the building of structures, energy management and transfer of information, are a consequence of specific elements to form polymers with the ability to chemically bind functional groups, (4) the molecules of life interact with a solvent to be soluble (or not) or to react (or not) in a way that confers fitness of the life-form, (5) life has the ability to conserve its species.

In the first part of the second section of the present thesis a Miller-Urey-type experiment on the synthesis of amino acids under early Titan conditions after an asteroid impact was presented. With an atmosphere, which was assumed to represent early Titan as well as a water-ammonia mixture as solvent, which is expected to stay liquid on the surface after an asteroid strike for a time period up to 10 000 years, the origin of amino acids was shown. Thereby, it is of great importance that as solvent not pure water, but a water-ammonia composite was used. Precisely, a 30 % aqueous ammonia solution was used together with an atmosphere with a total pressure of 1.5 bar and containing of 0.05 bar hydrogen gas, 1.0 bar methane gas, and 0.45 bar ammonia gas. This experiment-configuration poses the worldwide-first experiment of this type (see *Miller*, 1953 for a description of the original experiment and *Rode et al.*, 2007 for a review on different scenarios). In the original set-up, but also in various follow-up scenarios, amino acids as the building blocks of life have originated. In *Table 3* the resulting amino acids under Titan conditions are compared to our previous experiment for an early Earth scenario with water as solvent and a primitive atmosphere consisting of 0.2-0.3 bar hydrogen gas, 0.2-0.3 bar methane gas and 0.2-0.3 bar ammonia gas (see also *Turse et al.*, 2013) as well as with the results described in the original paper by *Miller*, 1953. Sparkling was used as energy source for both experiments.

Scenario	**Early Earth (*Miller*, 1953; Miller and Urey, 1959)**	**Early Earth scenario[1]**	**Early Titan scenario[2]**
Solvent	water	water	30 % aqueous ammonia
Atmosphere	CH_4, NH_3, H_2O, H_2	H_2, CH_4, NH_3	CH_4, NH_3, H_2
Compound identification, relative abundance (%)	Glycine	Glycine	Histidine, 50 %
	α-alanine	Alanine	Aspartic acid, < 10 %
	β-alanine	Aspartic acid	Tryptophan, < 10 %
	Aspartic acid (uncertain)	Serine	Serine, < 10 %
	α-amino-n-butyric acid (uncertain)	Phenylalanine	Phenylalanine, 25 %
	Glycine	Glutamic acid	Glutamic acid, < 10 %
	Glycolic acid	Asparagine	Arganine, < 10 %
	Sarcosine	Leucine	Leucine, < 10 %
	Alanine	Isoleucine	Isoleucine, < 10 %
	Lactic acid	Valine	Valine, < 10 %
	N-methylalanine	Proline	Proline, < 10 %
	α-amino-n-butyric acid	Lysine	
	α-aminoisobutyric acid	Threonine	
	α-hydroxybutric acid		
	β-alanine		
	Succinic acid		
	Aspartic acid		
	Glutamic acid		
	Iminodiacetic acid		
	Iminodiacetic-propionic acid		
	Formic acid		
	Acetic acid		
	Propionic acid		
	Urea		
	N-methyl urea		

Table 3: A comparison of the identified compounds in the original experiment by Miller and by our simulation-runs for early Earth and early Titan. Compounds as described in the original work of Miller, 1953 are listed (Miller, 1953). After a reanalysis a more detailed determination of the compounds was possible (see Miller and Urey, 1959). In our runs the samples were taken: [1]7 days, [2]4days after the experiment started.

Especially when considering the previously mentioned theory on exotic life, these results become interesting as in an early Titan scenario with a 30 % aqueous ammonia solution the synthesis of amino acids is possible. Nevertheless, it was also observed that 7 days after applying sparking in the experiment the amino acid groupings break down and the chemical components in the mixture formed large multiple ring structures, a situation which did not happen in the early Earth scenario, but could be a result of further acidification of the reaction mixture in the course of time, which corresponds to the observed decrease of the pH value from about 12 of the starting solution, to 9 after 2 days and further to 8 after 4 days. This pH value of 8 remains stable up to the end of the experiment after 7 days. Overall, the experiment proves

the possibility of the origin of amino acids in a post-impact early Titan scenario and it should be annotated, that 30 % ammonia is a very high concentration, which implies that lower concentrations are likely to support more stable amino acids. For the future further studies on the subject of alternative solvents in general, but especially on different water-ammonia mixtures as well as on sulfuric acid are scheduled. One very promising environment, in which an ocean with a distinct concentration of ammonia is presumed, is presented by the icy moon Europa.
Europa is also addressed within this thesis with a feasibility study for a three-element space mission consisting of an orbiter, a lander and a cryobot. Within or below the icy crust of Europa an up to 100 km deep ocean is assumed and often designated as one of the most promising regions in the Solar System for extraterrestrial life. Even though the best way to handle such a search for life would be a probe descending into the ocean, but at present many unsolved technical problems will exist that prevent such a mission in the near future. In the present feasibility study (*Böttcher et al.*, 2009) a melting probe is presented in order to melt down into the icy crust up to 25 m and to perform further measurements on potential markers for life. The whole mission is completely feasible with available technology and consequently, will have the potential to pose a new milestone in science on Europa.

In the second section of the present thesis the classical habitable zone introduced by *Kasting et al.*, 1993 is discussed. It defines a region around a star, where liquid water is possible on a planetary surface and was originally devised to be located from 0.84 to 1.67 AU for the Solar System. Due to some progress in climate modeling as well as our understanding of radiative modelling *Kopparapu et al*. 2013 together with *Kasting and Harman*, 2013 and *Leconte et al.*, 2013 the most probable location of the present habitable zone is from 0.95-1.67 AU. But nevertheless, with combing the habitable zone with liquid water on a planetary surface, the focus is still life-as-we-know-it. In order to follow the concept of exotic life and its alternative solvents the model of the life supporting zone was developed by the author. Different habitable zones for specific solvents, which are suitable for life in principle, are superimposed to form a region around a star, where also these solvents could exist in their liquid phase on planetary surfaces. The model of the life supporting zone is a radiation-convective model (*Neubauer et al.*, 2011), which includes clouds and their condensation nuclei and is described in detail within the second section and the associated papers. A validation run of the model has shown its high accuracy be resulting in a surface temperature based on a moist adiabatic lapse rate of 93.9 K, which is in a very good agreement with the reference surface temperature of 93.7 K for Titan, with only a difference of 0.2 K.
In order to expand the model to calculate the life supporting zone of selected extrasolar planets, several assumption have been performed. The habitable zones for three different solvents have been chosen to be calculated: water-, sulfuric acid- and a water-ammonia mixture-HZ. Five planets with masses from approximately 1-10 Earth masses have been selected: Kepler-22b and for the Kepler planetary objects of interest KOI268.01, KOI701.03, KOI854.012 und KOI1026.01. In case of Kepler 22-b an Earth-like and an ocean-planet scenario (with 50 wt.% water) have been defined. Three different atmospheric composition scenarios have been defined: a Venus-like with a single H_2SO_4 cloud-layer in three different thicknesses, an Earth-like with different cloud top altitudes for the two cloud-layers and absolute and relative humidity scenarios. Two different stellar spectra have been implemented: the spectrum of the Sun, a blackbody spectrum with fluxes according to the effective temperature of the host stars. Uncertainties of the planetary masses have been taken into account as well as the surface albedo has been varied from 0.1 to 0.8.
For all planetary objects the surface temperatures have been calculated as well as the location of the solvent-specific habitable zones for the five host stars for the described scenarios, whereby it was found that the largest impacts on the surface temperature are given by the stellar fluxes, the planetary surface albedos, the atmospheric composition and by the clouds. Impacts have been derived from the stellar spectrum as well as from the planetary gravity, but are quite smaller than those caused by the other parameters. In *Table 4* the most conservative boundaries on the surface albedos are shown that enable a localization of planets within a habitable zone (reprinted from *Neubauer et al.*, 2012).

Planetary object	Water- HZ [AU]	Water-ammonia- mixture HZ (15 wt.%) [AU]	Sulfuric acid- HZ [AU]
268.01	0.1-0.7	0.1 - 0.75	< 0.65
701.03	< 0.40	< 0.60	< 0.35
854.01	< 0.15	< 0.40	≤ 0.10
1026.01	< 0.10	< 0.35	-
Kepler-22b (terr.)	< 0.35	< 0.55	< 0.30
Kepler-22b (ocean)	< 0.40	< 0.55	< 0.35

Table 4: Conservative boundaries of the surface albedos for five selected host stars (reprinted from Neubauer et al., 2012).

All five planets are discussed in detail in Neubauer et al., 2012, here only Kepler-22b should be considered. This planet needed the least restrictions to be located within the water habitable zone for all atmospheric scenarios (please note that even in the Venus atmospheric composition scenario the surface pressure was fixed in the model to 1 bar), when the upper boundary of the Bond albedo is 0.33 is case of terrestrial planet and 0.37 for the scenario of an ocean planet. The upper boundaries are higher when assuming a Venusian atmospheric composition and when clouds are included. Similarly Kepler-22b will also allow a water-ammonia mixture on its surface (in both scenarios), whereby the surface albedos could be somewhat higher for this solvent than in the pure water-HZ. Furthermore, Kepler-22b can also host liquid sulfuric acid on its surface, but the restrictions on stellar and planetary input parameters have to be more stringent than for water or water-ammonia. *Figure 4* illustrates the separate habitable zone and the resulting life supporting zone for three selected planets: Kepler-22b (terrestrial scenario), KOI 268.01 and KOI 854.01. For this map the inner and outer borders are calculated for an assumed surface albedo of 0.2 for all possible scenarios regarding the atmospheric composition with one exception of a surface albedo of 0.1 for the ocean planet scenario of Kepler-22b. Thereby, ELRHCL denotes an Earth-like relative humidity scenario including clouds, ELAHCL an absolute humidity scenario including clouds and VLCL corresponds to a Venusian atmospheric composition including clouds. The result of our study concerning Kepler-22b is also confirmed by other authors to be located within the water-HZ (e.g. *Borucki et al.*, 2012, *Kaltenegger and Sasselov*, 2011). The latter authors have also confirmed the location of the four others modeled planetary candidates to be located within the habitable zone also with respect to different assumptions on their cloud cover from 0 to 100 % and assuming the maximum Earth-like Bond albedo at the inner edge of the habitable zone.
To summarize the results it can be stated that all five planets are potentially habitable and further investigations are strongly recommended in order to learn more on the planetary parameters as well as in future to look to possible atmospheres.

Besides these scenarios the model was also applied to hypothetical extrasolar planets with dense CO_2-atmospheres (up to 100 bar) around G-, K- and M-stars in order to determine the outer boundaries of the life supporting zone (*Neubauer et al.*, 2013). One important discovery was that a higher partial pressure than 25 bar of CO_2 will not result in a further distinct increase of the surface temperature. Based on the model description outlined in the first and second sections, the model was applied to 17 selected Kepler planetary candidates, which are likely to be located inward of the outer boundary of the life supporting zone for sulfuric acid, water and water-ammonia mixtures (15 wt. %) even at low pressures. For high pressures of CO_2 the surface albedo becomes less important and for 25 bar all candidates were found to have a surface temperature above the freezing point of the corresponding solvents. Furthermore, all candidates have been identified to be located inward of the inner boundary as long as no other greenhouse gases contribute to the greenhouse effect. *Table 5* will list the selected candidates with their maximum surface albedo that allows a position with the corresponding habitable zone for two different scenarios of CO_2 pressure at the planetary surface: 1 and 5 bar (table reprinted from *Neubauer et al.*, 2013). Finally it can be stated that still nowadays several very interesting planets are known which have the potential to host liquids and consequently life on their surfaces. Further observations are necessary to learn more on these planets (or planet candidates) to derive accurate conclusions, but the scenarios investigated offer a broad spectrum of possibilities for planetary albedos to still host life-we-know-it or even life-as-we-do-not-know-it.

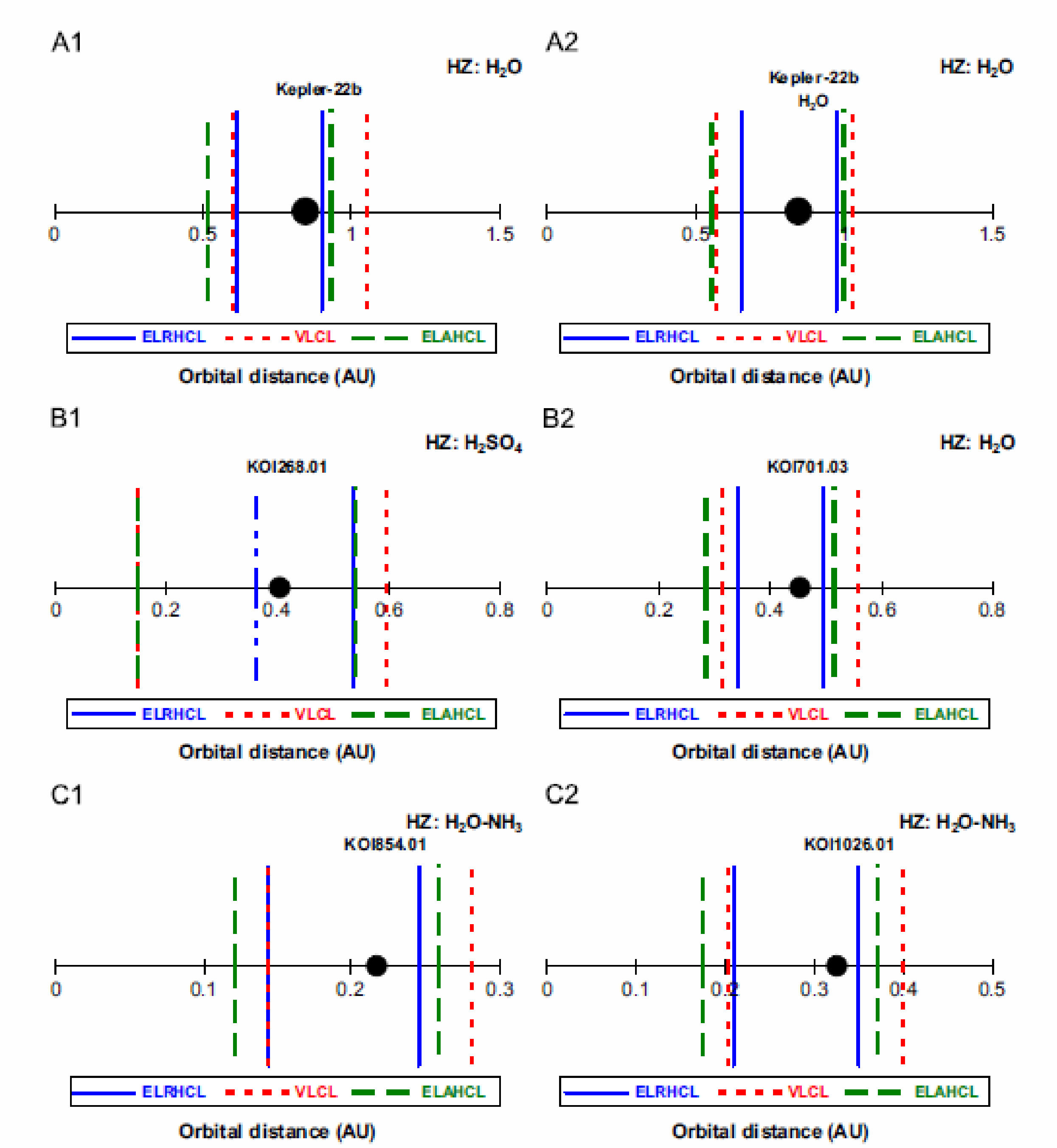

Figure 4: Illustration of the separate habitable zone and the resulting life supporting zone for three selected planets (reprinted from Neubauer et al., 2012).

KOI	Sulfuric acid-HZ		Water-HZ		Water-ammonia-mixture HZ (15 wt. %)	
	1 bar	5 bar	1 bar	5 bar	1 bar	5 bar
1686.01	0.2	0.6	0.3	0.7	0.5	
854.01	0.2	0.6	0.3	0.6	0.5	0.7
87.01	0.3	0.6	0.4	0.6	0.5	0.7
701.03	0.3	0.6	0.4	0.7	0.6	
1361.01	0.4	0.7	0.4	0.7	0.6	
1871.01	0.4	0.7	0.5	0.7	0.6	
2469.01	0.4	0.7	0.5	0.7	0.6	
2474.01	0.4	0.7	0.5	0.7	0.6	
1739.01	0.5	0.7	0.5	0.7	0.7	
2626.01	0.6		0.6		0.7	
268.01	0.6		0.6		0.7	
812.03	0.6		0.7			
2290.01	0.6		0.7			
438.02	0.7		0.7			
1938.01	0.6		0.7			
2650.01	0.7		0.7			
2124.01	0.7		0.7			

Table 5: Maximum surface albedo allowed for the planets or planetary candidates to host liquids on their surfaces (reprinted from Neubauer et al., 2013). If no value is given in the table the albedo is allowed to range from 0.1 to 0.8.

The last part of this thesis makes a small step aside from the question on the nature of life and regions around stars, which could host life. In *Firneis et al.*, 2013 an overview is given on the history of ideas to communicate with an extraterrestrial intelligence. Therein especially the artificial mathematical language LINCOS is analyzed for its potential of encoding messages as well as its historical usability (COSMIC CALL) and further, its development to NEW LINCOS. NEW LINCOS is a symbolic language based on lambda calculus, which claims for itself to be auto-interpretative. Auto-interpretative means elementary inductive definitions of terms and the use of elimination to deduce facts from premises, which allows easy handling, when applied to formal science, but needs further improvement, when should be applied to encode complex sociological matters, as for example a description of the Human Being.

Abstract (in English)

Within the present thesis the question on life, which does not conform with the terrestrial characteristics of life (primarily: water as solvent and carbon, hydrogen, oxygen, nitrogen, sulphur and phosphor) is discussed.
Starting with an investigation of presently used definitions and descriptions of life in general, a critical reflection on the main characteristics of the NASA definition of life follows. Classical used strategies as reproduction as well as evolution seem not to be suited to describe life in general as well as not-adequate strategies to search for life within a timely limited mission on a planetary surface. As only one sample for life is known it would be presumptuous and a continuation of a geocentric way of thinking to declare life-as-we-know-it on Earth to be a universal concept. Within this context the present author has developed a more generalized hypothesis of life, which also allows exotic representations – life not necessarily based on water as solvent as well as on the six terrestrial key elements for life.
In order to consolidate the theory of exotic life and to investigate the question if the origin of amino acids as the building blocks of life can also be functioning with alternative solvents an experimental set-up as realized by Miller and Urey (1953) for the early Earth environment was chosen. Based on the original idea of the synthesis of amino acids an experiment was designed together with colleagues from the Washington State University (USA). Thereby a water-ammonia solvent (mixing ration: 70:30) and an atmosphere comparable to early Titan (0.05 bar hydrogen gas, methane gas 1 bar and ammonia gas 0.45 bar) was used. As observed in the original Miller-Urey as well as in various follow-up experiments by a large number of scientists the experiment resulted in the synthesis of amino acids (primarily: histidine His, aspartic acids Asp, tryptophan Trp, serine Ser, phenylalanine Phe, glutamic acid Glu, arginine Arg, leucine Leu, isoleucine Lle, valine Val and proline Pro). The experiment offers the worldwide first und clear evidence that also with alternative solvents the origin of the buildings blocks of life is possible. This results is not only for Titan of interest, but also for the oceans hosted by several icy moons (e.g. on Europa) as it is assumed that large amounts of ammonia are dissolved in these oceans. As a consequence of our results at least the possibility is given that also in these habitats life could exist. With HADES a feasibility study is reprinted, which underlines that also with present available technology it is possible to look for markers for life at least in the upper parts of the ice crust of Europa,
The classical habitable zone introduced by Kasting defines the region around a star, where liquid water is possible on a planetary surface. In order to follow the concept of exotic life and its alternative solvents the model of the life supporting zone was developed by the author. Different habitable zones for specific solvents, which are suitable for life in principle, are superimposed to form a region around a star, where these solvents also could exist in their liquid phase on planetary surfaces. The model of the life supporting zone is a radiation-convective model, which includes clouds and their condensation nuclei. Different atmospheric scenarios and solvents have been modeled in order to calculate planetary surface temperature scenarios with a larger accuracy than provided in the model of Kasting. Assuming different planetary albedos in a similar way than the albedos of the terrestrial planets within in Solar System, the life supporting zone was modeled for the Solar System as well as for Kepler-22b and for the Kepler planetary objects of interest KOI268.01, KOI701.03, KOI854.012 und KOI1026.01. The position of these planets was found be located within the life supporting zone for water or in a water-ammonia zone. Kepler-22b and KOI701.03 additionally will also allow sulfuric acids on their surfaces. Besides these scenarios the model was also applied for extrasolar planets with dense CO_2-atmospheres (up to 100 bar) around G-, K- and M-stars in order to determine the outer boundaries of the life supporting zone. Another result of interest was that a higher partial pressure than 25 bar of CO_2 results not in a further distinct increase of the surface temperature.

The last part of the present thesis was concentrated on the question of active SETI and especially on the mathematic artificial language LINCOS developed by Hand Freudenthal. LINCOS was still implemented for several interstellar communication attempts (COSMIC CALL) 1999 and 2003). Freudenthal claims for his language that besides the encoding of formal

scientific contexts also sociological models can be explained, which based on our analysis on LINCOS as well as NEW LINCOS at present is not fully achieved.

Abstract (in German)

In der vorliegenden Arbeit wurde die Leitfrage der möglichen Existenz von extraterrestrischem Leben, welches nicht den biochemischen Prinzipien des irdischen Lebens gleicht (primär: Wasser als Lösungsmittel und Kohlenstoff, Wasserstoff, Sauerstoff, Stickstoff, Schwefel und Phosphor als Basis) behandelt.
Ausgehend von einer Untersuchung der aktuellen Lebensdefinitionen und insbesondere der Definition, welche auch die NASA für ihre Studien verwendet, folgt eine kritische Betrachtung der tragenden Prinzipien der NASA Definition. Klassische Strategien des irdischen Lebens wie Reproduktion und Evolution sind weder geeignet Leben zu definieren, noch um die Existenz von Lebewesen in Rahmen einer zeitlich begrenzen Mission auf der Oberfläche eines anderen Planeten experimentell nachzuweisen. Obwohl es aktuell nur eine einzige Stichprobe für das Leben gibt, wäre es vermessen und sogar eine Fortsetzung eines geozentrischen Denkansatzes die irdischen Charakteristika für universell gültig zu erklären. In diesem Zusammenhang wurde vom Autor der vorliegenden Arbeit eine verallgemeinerte Hypothese für Leben entwickelt, die auch exotische Formen, solche die nicht zwangsläufig auf dem Lösungsmittel Wasser und den sechs irdischen Basiselementen des Lebens beruhen, berücksichtigt.
Um die Theorie des exotischen Lebens zu untermauern und insbesondere der Frage nachzugehen, ob die Entstehung der Bausteine des Lebens (Aminosäuren) auch mit alternativen Lösungsmitteln funktioniert, wurde ein experimenteller Zugang gewählt. Basierend auf dem Originalaufbau von Miller und Urey (1953) für die Urerde wurde gemeinsam mit Kollegen von der Washington State University (USA) ein Experiment mit einem Wasser-Ammoniak-Gemisch (Mischungsverhältnis: 70:30) und einer Atmosphäre von der angenommen wird, dass sie auf dem Ur-Titan zu finden war (0.05 bar Wasserstoffgas, 1 bar Methan, 0.45 bar Ammoniakgas) durchgeführt. Wie im Originalexperiment resultierte auch das neue Experiment in der Synthese von Aminosäuren (primär: Histidin His, Asparaginsäure Asp, Trypthopan Trp, Serin Ser, Phenylalanine Phe, Glutaminsäure Glu, Arginin Arg, Leucin Leu, Icoleucin Lle, Valin Val und Prolin Pro). Dadurch konnte erstmalig der eindeutige Beweis erbracht werden, dass auch in alternativen Lösungsmitteln die Synthese der Lebensbausteine möglich ist. Dieses Ergebnis ist darüber hinaus auch für die inneren Ozeane von Eismonden (beispielsweise vom Jupitermond Europa) von Bedeutung, da hierfür aktuell angenommen wird, dass große Mengen von Ammoniak im Wasser gelöst sein könnten und obiges experimentelle Ergebnis die mögliche Entstehung von Leben in diesen extraterrestrischen Habitaten zumindest zulässt. Mit HADES wurde eine Machbarkeitsstudie durchgeführt, die zeigte, dass auch mit der heute verfügbaren Technologie mit einer Schmelzsonde in die obere Eiskruste des Jupitermondes Europa eingedrungen werden kann um dort nach Spuren von Leben zu suchen.
Die klassische habitable Zone nach Kasting definiert die Region um einen Stern, in der es auf der Oberfläche eines Planeten flüssiges Wasser geben kann. Um der Theorie des exotisches Lebens gerecht zu werden und alternative Lösungsmittel, beziehungsweise Gemische von Wasser mit anderen Lösungsmitteln zu berücksichtigen, wurde das Modell der life supporting zone entwickelt. Verschiedene habitable Zonen für spezifische Lösungsmittel, die für Leben prinzipiell geeignet sein könnten, überlagern sich und bilden so eine Zone um einen Stern, in der diese Lösungsmittel ebenfalls in ihrer flüssigen Phase auf der Oberfläche eines Planeten vorliegen können.
Das Modell der life supporting zone ist ein Strahlungs-Konvektionsmodell, welches Kondensationskeime und die Entstehung von Wolken mitberücksichtigt. Es wurde für verschiedene Atmosphärenszenarien und Lösungsmittel umgesetzt und erlaubt eine über das Modell von Kasting hinausgehende Modellierung der planetaren Oberflächentemperatur. Unter Annahme von planetaren Albedos, ähnlich zu denen der terrestrischen Planeten, wurde die life supporting zone zusätzlich zum Sonnensystem, auch für Kepler-22b und für die planetaren Kandidatenobjekte der NASA Keplermission KOI268.01, KOI701.03, KOI854.012 und KOI1026.01 umgesetzt. Die Position dieser Planeten wurde als in der life supporting zone liegend gefunden und dabei entweder in der klassischen Wasserzone oder in einer Wasser-Ammoniakzone. Kepler-22b und KOI701.03 könnten darüber hinaus auch noch flüssige

Schwefelsäure auf ihren Oberflächen beherbergen. Neben diesen Szenarien wurde das Modell auch noch auf die Untersuchung von extrasolaren Planeten mit dichten CO_2-Atmosphären (bis 100 bar) um G-, K- und M-Sterne angewandt. Solche Atmosphären dienen für die Bestimmung der äußeren Grenze der life supporting zone und zeigen darüber hinaus auch noch, dass ein höherer Partialdruck als 25 bar CO_2 keine deutlichen Temperaturzunahmen mehr bedingt.
Der letzte Teil der Arbeit widmete sich der Frage des aktiven SETI und dabei insbesondere der von Hans Freudenthal entwickelten mathematischen Kunstsprache LINCOS und ihrer aktuellen Grenzen. LINCOS wurde bereits für mehrere interstellare Kommunikationsversuche zur Anwendung gebracht (COSMIC 1999 und 2003). Ein Anspruch, der von Freudenthal an LINCOS gestellt wurde, dass neben der Kodierung von formalwissenschaftlichen Zusammenhängen auch beispielsweise soziologische Modelle kodiert werden können, ist nach unserer Studie bisher noch nicht erfolgreich umgesetzt.

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References

Baross J. A. et al., 2007, *The limits of organic life in planetary systems*; National Academies Press, Washington D.C.

Böttcher T., Huber L., Le Corre L., Leitner J. J., McCarthy D., Nilsson R., Teixeira C., Vaquer Araujo S., Wilson R., Adjali F., Altenburg M., Briani G., Buchas P., Le Postollec A., Meier T., 2009, *The HADES mission concept – astrobiological survey of Jupiter's icy moon Europa*; International Journal of Astrobiology, 8, p. 321-329.

Bohren C. F., Huffman D. R., 2004, *Absorption and scattering of light by small particles*; Wiley-VCH, New York 2004.

Borucki W. J. et al., 2012, Kepler-22b: *A 2.4 Earth-radius planet in the habitable zone of a Sun-like star*; The Astrophysical Journal, 745, 120, pp. 16.

Deamer D., 2010, *Special collection of essays: what is life?* Astrobiology 10, p. 1001-1002.

Dyson, F., 1999, *Life in the Universe: is life digital or analog?* Scientific Colloquia 1999-2000 Fall-Winter Series, Goddard Space Flight Center.

Firneis M. G., Leitner J. J. and Hitzenberger R., 2009, *The life supporting zone – looking for Life as we do not know at preset times*; Abstracts of the 4th European Planetary Science Congress, 2009, Abstract No. EPSC2009-554.

Firneis M. G., Leitner J. J., 2011, *The evolution of LINCOS – a language for cosmic intercourse*; Abstracts of the International Conference on the History and Philosophy of Astrobiology, held in Ven, Sweden, September 27-28, 2011.

Firneis M. G., Leitner J. J., 2013, *The evolution of LINCOS: a language for cosmic interpretation*; In: The History and Philosophy of Astrobiology: Perspectives on the Human Mind and Extraterrestrial Life (eds. D. Duner, J. Parthemore, E. Perrson), Cambridge University Press, p. 201-210.

Forterre, P., 2010, *Defining life: the virus viewpoint*; Origins of Life and Evolution of the Biospheres 40, p. 151-160.

Hussmann H., Sohl F., Spohn T., 2006, *Subsurface oceans and deep interiors of medium-sized outer planet satellites and large trans-Neptunian objects*; Icarus, 185, p. 258-273.

Joyce G., 1994, *Foreword*. In: Deamer, D. W., Fleischaker, G. R. (Eds.), Origins of Life: The Central Concepts, Jones and Barlett, Boston, p. xi-xii.

Kaltenegger L., Sasselov D., 2011, *Exploring the habitable zone for Kepler planetary candidates*; Astrophysical Journal Letter, 736, L25, pp. 6.

Kasting J., Whitmire D. P., Reynolds R. T., 1993, *Habitable zones around main sequence stars*; Icarus, 101, p. 108-128.

Kasting J., Harman C.E., 2013, *Inner edge of the habitable zone*; Nature, 504, p. 221-223.

Key J., Schweiger A. J., 1998, *Tools for atmospheric radiative transfer: Streamer and FluxNet;* Computers & Geosciences, 24, p. 443-451.

Kolb V. M., 2007, *On the applicability of the Aristotelian principles to the definition of life*; International Journal of Astrobiology 6, p. 51-57.

Kolb V. M., 2010, *On the applicability of dialetheism and philosophy of identity to the definition of life*; International Journal of Astrobiology 9, p. 131-136.

Kopparapu R. K., Ramirez R., Kasting J. F., Eymet V., Robinson T. D., Mahadevan S., Terrien R. C., Domagal-Goldman S., Meadows V., Deshpande R., 2013, *Habitable zones around main sequence stars: new estimates*; The Astrophysical Journal, 765, p. 131-147.

Koshland D. E., 2002, *The seven pillars of life*; Science, 295, p. 2215-2216.

Leconte J., Forget F., Charnay B., Wordsworth R., Pottier A., 2013, *Increased insolation threshold for runaway greenhouse processes on Earth-like planets*; Nature, 504, p. 268-271.

Leitner J. J., 2009, *Exotisches Leben – Auf der Suche nach biologischer Komplexität abseits terrestrischer Normen*; Raumfahrt Concret, Nr. 59-60, p. 8-10.

Leitner J. J., 2010, *The new concept of the life supporting zone as a topic of the research platform on Exolife;* General Assembly of the Austrian Society for Astronomy and Astrophysics 2010, held in Graz, Austria, April 9-10, 2010.

Leitner J. J. Schwarz R., Funk B., Pilat-Lohinger E., Firneis M .G., Dvorak R., Eybl V., Aittola M., 2008a, *Alternative solvents as a basis for life supporting zones in planetary systems*; Abstracts of the 3rd European Planetary Science Congress, 2008, Abstract No. EPSC2008-A-00485.

Leitner J. J., Schwarz R., Funk B., Pilat-Lohinger E., Firneis M. G., Aittola M., Lhotka C., Eybl V., 2008b, *Habitable zones around main sequence stars based on solvents others than water*; Abstracts of the International Extra-Solar Super-Earths Workshop, p. 38.

Leitner J. J., Neubauer D., Schwarz D., Eggl S., Firneis M. G., Hitzenberger R., 2010a, *The life supporting zone I – from classic to exotic life*; Abstract of the European Planetary Science Congress, held in Rome, Italy, September 19-24, 2010.

Leitner J. J., Firneis M. G., Hitzenberger R., 2010b, *Potential habitats for exotic life within the life supporting zone*; Geophysical Research Abstracts, Vol. 12, Abstract No.: EGU2010-12544.

Leitner J. J., Schwarz R., Firneis M. G., Hitzenberger R., Neubauer D., 2010c, *Generalizing habitable zones in exoplanetary systems – the concept of the life supporting zone;* Abstracts of the Astrobiology Science Conference 2010, Abstract No. 5255, LPI Contribution No. 1538.

Leitner J. J., Schulze-Makuch D., Firneis M. G., Hitzenberger R., Neubauer D., 2010d, *Solvents of interest for exotic life on planetary bodies in life supporting zones around main sequence stars*; Abstracts of the 10th European Astrobiology Network Association Science Congress, p. 52-53.

Leitner J. J., Firneis M. G., 2011a, *What can we learn from GFAJ-1 for defining life?* Abstracts of the Origins 2011 Meeting (ISSOL and IAU-Comm. 51 Joint International Meeting), held in Montpellier, France, July 3-8, 2011.

Leitner J. J., Firneis M. G., 2011b, *Defining life in a non-geocentric way*; Abstracts of the EPSC-DPS Joint Meeting 2011, held in Nantes, France, October 3-7, 2011.

Leitner J. J., Firneis M. G., 2011c, *Is it possible to define life as a universal concept? Reproduction, metabolism and evolution re-evalated*; International Conference on the History and Philosophy of Astrobiology, held in Ven, Sweden, September 27-28, 2011.

Leitner J. J., Schulze-Makuch D., Firneis M. G., Hitzenberger R., Neubauer D., 2012a, *Solvents of interest for exotic life on planetary bodies in life supporting zones around main sequence stars*; Paleontological Journal, 46, p. 1091.

Leitner J. J., Firneis M. G., 2012b, *How can we detect Life when we cannot define it in a general way?;* Paper presented at the International Workshop on Extraterrestrial Life – Beyond our Expectations, held in Vienna, Austria, May 21-22, 2012.

Leitner J. J., Firneis M. G., 2012c, *Is a definition of life only of academic or also of common interest?*; Paper presented at the Astrobiology Science Conference 2012, held in Atlanta, USA, April 16-20, 2012.

Luisi P. L., 1998, Searching for an exo-life in the Solar System; Origins of Life and Evolution of the Biospheres, 28, p. 613-622.

Manabe S., Strickler R. F., 1964, *Thermal equilibrium of the atmosphere with a convective adjustment*; Journal of Atmospheric Science, 21, p. 361-385.

Manabe S., Wetherald R. T., 1967, *Thermal equilibrium of the atmosphere with a given distribution of relative humidity*; Journal of Atmospheric Science, 24, p. 241-259.

Miller, S. L., 1953, *A production of amino acids under possible primitive Earth conditions*; Science, 117, p. 528-529.

McKay C. P., 1991, *Urey prize lecture: planetary evolution and the origin of life*, Icarus, 91, p. 93-100.

McKay C. P., 2004, *What is life – and how do we search for it in other worlds*? PLoS Biology, 2, p. 1260-1263.

Morange M., 2010, *The resurrection of life*; Origins of Life and Evolution of the Biospheres, 40, p. 179-182.

Neubauer, D., 2009, *Modellierung des indirekten Strahlungseffekts des Hintergrundaerosols in Österreich*, Phd thesis, University of Vienna, Austria.

Neubauer D., Vrtala A., Leitner J. J., Firneis M. G., Hitzenberger R., 2010, *The life supporting zone II – computation of its extension*; Abstracts of the European Planetary Science Congress, held in Rome, Italy, September 19-24, 2010.

Neubauer D., Vrtala A., Leitner J. J., Firneis M. G., Hitzenberger R., 2011a, *Development of a model to compute the extension of life supporting zones for Earth-like exoplanets*; Origin of Life and Evolution of Biospheres, Vol. 41, p. 545-552.

Neubauer D., Vrtala A., Leitner J. J., Firneis M. G., Hitzenberger R., 2011b, *Computation of the extension of life supporting zones*; Abstracts of the Origins 2011 Meeting (ISSOL and IAU-Comm. 51 Joint International Meeting), held in Montpellier, France, July 3-8, 2011.

Neubauer D., Vrtala A., Leitner J. J., Firneis M. G., Hitzenberger R., 2012, *The life supporting zone of Kepler-22b and the Kepler Planetary Candidates: KOI268.01, KOI701.03, KOI854.0 and KOI1026.01*; Planetary and Space Science, 73, p. 397-406.

Neubauer D., Leitner J. J., Firneis M. G., Hitzenberger R., 2013, *The outer limit of the life supporting zone of exoplanets having CO2-rich atmospheres: virtual exoplanets and Kepler Planetary Candidates*; Planetary and Space Science, 84, p. 163-172.

Niemann H. B. et al., 2005, *Titan's atmosphere from the GCMS instrument on the Huygens probe*; Nature, 438, p. 779-784.

Raulin F., 2010, *Searching for an exo-life in the Solar System*; Origins of Life and Evolution of the Biospheres, 40, p. 191-193.

Rode B. M., Fitz D., Jakschitz T., 2007*, The first steps of chemical evolution towards the origin of life*; Chemistry & Biodiversity, 4, p. 2674-2702.

Oparin A. I., 1924, *The origin of life* [Proiskhozhdenie zhizny. Moscow: Izd.Moskovsguu Rabochii]. English translation in: Bernal, J. D. (Ed.), *The origin of life* (1967), Weidenfeld and Nicolson, London, p. 199-234.

Schrödinger E., 1944, *What is life?* Cambridge University Press, Cambridge 1944.

Schulze-Makuch D., Grinspoon D. H., Abbas O., Irwin L. N., Bullock M. A., 2004, *A sulfur-Based survival strategy for putative phototrophic life in the Venusian atmosphere*; Astrobiology, 4, p. 11-18.

Schulze-Makuch D., Irwin L. N., 2006, *The prospect of alien life in exotic forms on other worlds*. Naturwissenschaften, 93, p. 155-172.

Stofan E. R. et al., 2007, *The lakes of Titan*; Nature, 445, p. 61-64.

Turse C., Leitner J. J., Firneis M. G., Schulze-Makuch D., 2013, *Simulations of prebiotic chemistry under post-impact conditions on Titan*; Life, 3, p. 538-549.

Williams D.M., Pollard D., 2002, *Earth-like worlds on eccentric orbits: excursions beyond the habitable zone*; International Journal of Astrobiology, 1, p. 61-69.

Curriculum Vitae

General:

Name:	Johannes Leitner
Academic degree:	Mag. rer. nat.
Title:	CMC
Date of birth:	05.09.1977
Place of birth:	Baden/NÖ
Nationality:	Austria

Academic/professional career:

1984 – 1988:	Elementary school in Grillenberg, Austria
1988 – 1992:	Gymnasium in Berndorf, Austria
1992 – 1993:	Technical engineering school for Communications Engineering in Mödling, Austria
1993 – 1997:	Technical engineering school for EDP and management in Wr. Neustadt, Austria
1998 – 1999:	Training/education in outdoor-pedagogics (Government of Vienna, Austria)
10/1999:	Start of the studies in Physics and Astronomy (Univ. of Vienna)
10/2005 – 02/2006:	Tutor for „UE Planetology 1" (Univ. of Vienna, Inst. for Astronomy)
01/2006:	Training/education: „Brittle Deformation and Microtectonics" (Univ. Oulu, Finnland)
04/2006 – 06/2006:	ERASMUS Scholarship: Department for Physical Sciences, Division for Astronomy, University of Oulu, Finnland
10/2006:	Graduation in Astronomy (Magister rerum naturalium, graduated with honours)
10/2006:	Start of the PhD studies in Astronomy at the Inst. for Astronomy, Univ. of Vienna
10/2006 – 02/2007:	Tutor for „UE Planetology 2" (Univ. of Vienna, Inst. for Astronomy)
01/2007 – 12/2007:	Research scholarship, Univ. of Vienna, on "Heat flow and planetary structure models for Venus"
04 – 05/2007:	Research visit at the Dept. for Physical Sciences, Astronomy, Univ. of Oulu, Finland
07/2007:	ESA Alpbach Summer School on Astrobiology
09/2007 – 02/2008:	External University lector for „UE Planetology 1" (Univ. of Vienna, Inst. for Astronomy)
01/2008 – 12/2008:	Scientific staff member of the Austrian Academy of Sciences, Institute for Space Research, Graz, Austria
02/2008:	Research visit at the Austrian Academy of Sciences, Institute for Space Research, Graz, Austria
03/2008 – 08/2008:	External University lector for „UE Planetology 2" (Univ. of Vienna, Inst. for Astronomy)
08/2008:	Training/education: European Forum Alpbach, Austria: certificates for: "Climate change and what we need to do about it" and "Who is in control? How the brain controls our thoughts and actions"
09/2008 – 02/2009:	External University lector for „VU Methodical tools for planetary sciences " (Univ. of Vienna, Inst. for Astronomy)
03/2009 – 08/2009:	External University lector for „UE Planetology 1" (Univ. of Vienna, Inst. for Astronomy)
05/2009 – 05/2012:	Univ. Assistant, Research Platform ExoLife (Alternative Solvents as a Basis for Life Supporting Zones in (Exo-)Planetary Systems), Univ. of Vienna, founding member
09/2009 – 02/2010:	Lecturer for „VO Planetology 2", „SE Seminary on the Research platform on ExoLife: Astrobiology" (Univ. of Vienna, Inst. for Astronomy)
03/2010 – 08/2010:	Lecturer for „VO Stars and Planets", „VU Methodical tools for planetary sciences", "Special aspects of Astrobiology " (Univ. of Vienna, Inst. for Astronomy)
09/2010 – 02/2011:	Lecturer for „VU Planetology of the inner solar system", „Astrobiology: Astronomical aspects of the origin of life" (Univ. of Vienna, Inst. for Astronomy)
03/2011 – 08/2011:	Lecturer for „VU Planetology of the outer solar system", „Astrobiology: Criteria for the habitability of exoplanets" (Univ. of Vienna, Inst. for Astronomy)
09/2011 – 02/2012:	Lecturer for „VU Methodical tools for planetary sciences ", „SE Special aspects of Astrobiology" (Univ. of Vienna, Inst. for Astronomy)

03/2012 – 08/2012:	Lecturer for „SE Actual research on the solar system“, „SE Astrobiology: Astronomical aspects of the existence of life“ (Univ. of Vienna, Inst. for Astronomy)
05/2012:	Certification: Certified Management Consultant (CMC), WKO/Incite
08/2012 – 10/2013:	Consultant for internationalization (AUBC)
09/2012 – 02/2013:	Lecturer for „SE Astrobiology: Astronomical aspects of the origin of life“ (Univ. of Vienna, Inst. for Astronomy)
03/2013 – 08/2013:	Lecturer for „SE Astrobiology: Habitability of (icy)moons“ (Univ. of Vienna, Inst. for Astronomy)
08/2013:	Certification: „Certified Trainer“, WBA, Austria
09/2013 – 02/2014:	Lecturer for „SE Astrobiology: Panspermia and terraforming of (exo)planets“ (Univ. of Vienna, Inst. for Astrophysics)
03/2014 – 09/2014:	Lecturer for “SE Astrobiology: Astronomical aspects of classic and exotic life on (exo-)planets (Univ. of Vienna, Inst. for Astrophysics)
since 11/2012:	Project scientist, Research Platform: ExoLife, Univ. of Vienna
since 09/2013:	Managing director at SCI.E.S.COM e.U.

National/international scientific memberships:

AG (Astronomische Gesellschaft)	since 2005
AGU (American Geophysical Union)	since 2006
COSPAR (Committee on Space Research), Assoc. Member	since 2006
DGG (Deutsche Geophysikalische Gesellschaft)	since 2003
EANA (European Exo/Astrobiology Network Association)	since 2009
EGU (European Geosciences Union)	since 2004
ÖGAA (Österreichische Gesellschaft für Astronomie und Astrophysik)	since 2002
ÖPG (Österreichische Physikalische Gesellschaft)	since 2005

Review activities:

05/2008 – 04/2012:	ESF (European Science Foundation)
since 09/2008:	“Advances in Space Research” Journal
since 03/2010:	“Planetary and Space Science” Journal
since 10/2010:	“Journal of Cosmology” Journal
since 06/2011:	“Astrobiology” Journal
since 10/2011:	“Origin of Life and Evolution of Biospheres” Journal
since 08/2012:	„Cellular Origin, Life in Extreme Habitats and Astrobiology“ Journal
since 10/2012:	“Life” Journal
since 11/2012:	“International Journal of Astrobiology” Journal

Awards:

Award for the best Diploma thesis of the ÖGAA, 2006
Best poster award (as first author), 10th EANA Conference, Pushchino, Russia, 2010
Recognition letter of the University of Vienna, 2010
Recognition letter of the City of Vienna: “Successful Congress-Organizer”, 2012
Best poster award (as co-author), 13rd EANA Conference, Szezecin, Poland, 2010

(Co-)Organization of conferences/workshops:

COSPAR Meeting 2006, Beijing, China: Venus Express Poster Season: *Chair*
2nd General VEP Meeting 2006, Paris, France: Organization Committee: *Member* and Descent probes science payload round table: *Chair*
3rd General VEP Meeting 2006, Berlin, Germany: Organization Committee: *Member*
1st VEP Landing-Sites Workshop, 2006, Vienna Austria: Organization Committee: *Chair*
4th General VEP Meeting 2007, Oxford, UK: Organization Committee: *Member*
5th VEP Executive Meeting 2007, Vienna, Austria: Organization Committee: *Chair*
2nd European Planetary Science Congress, 2007, Potsdam, Germany: Venus Geology and Geophysics: *Co-Convenor*
International Workshop on Astrobiology: Extraterrestrial Life – Beyond our Expectations, 2012, Vienna, Austria: Scientific Organizing Committee: *Member,* Local Organizing Committee: *Chair*

Scientific expeditions:

performed by the EOG (Eclipse Observing Group) of the Institute of Astrophysics, University of Vienna
Scientific observation of the Venus Transit 2004 near Cairo, Egypt
Scientific observation of the total solar eclipse 2006 near Jalu, Libya

Scientific observation of the total solar eclipse 2008 near Jiayuguan, China
Scientific observation of the total solar eclipse 2009 in Wuzhen, China
Determination of the astronomical orientation of the Cham towers in Nha Trang, Vietnam, July 2009
Scientific observation of the total solar eclipse 2010 near El Calafate, Argentina
Scientific observation of the total solar eclipse 2012 near Cairns, Australia

Additional qualifications:
Programming: C, C++, Pascal, HTML, Assembler, Maple
PADI Open Water Diver
PADI DAN Oxygen Provider
Member of the scout group Berndorf for more than 15 years and more than 5 years group leader of different groups
Public Outreach for astronomy, physics, astrobiology and natural sciences in general (VHS, University Meets Public, Vienna Science Festival, Lange Nacht der Forschung, Science Slam, Science Salon, Kepler Salon, etc.)
Special education seminaries in training and teaching

Scientific and public outreach activities summary:
Chapters in scientific book: 4
Conference abstracts: 86
Conference posters: 63
Conference talks: 32
Popular articles: 3
Popular science books: 1
Popular talks: 117
Public discussions: 2
Printed interviews: 19
Radio interviews: 9
TV interviews: 2
Scientific guest talks: 2
Scientific papers: 10
Scientific commentaries: 1
School projects: 1
Total: 352

List of selected publications:

Turse C., **Leitner J. J.**, Firneis M. G., Schulze-Makuch D., 2013, Simulations of Prebiotic Chemistry under Post-Impact Conditions on Titan; Life, Vol., 3, p. 538-549.

Firneis M. G., **Leitner J. J.**, 2013, *The evolution of LINCOS: A language for cosmic interpretation*; In: The History and Philosophy of Astrobiology: Perspectives on the Human Mind and Extraterrestrial Life (eds. D. Duner, J. Parthemore, E. Perrson), Cambridge University Press, p. 201-210.

Neubauer D., **Leitner J. J.**, Firneis M. G., Hitzenberger R., 2013, *The outer limit of the life supporting zone of exoplanets having CO2-rich atmospheres: virtual exoplanets and Kepler Planetary Candidates*; Planetary and Space Science, Vol. 84, p. 163-172.

Leitner J. J., Firneis M. G., Hitzenberger R., 2013, *Astrobiology as an interdisciplinary starting point to natural sciences for high-potential children*; Abstracts of the EPSC (European Planetary Science Congress) Meeting 2013, held in London, UK, September 8-13, 2013.

Leitner J. J., Turse C., Firneis M., Schulze-Makuch D., 2013, *Simulations of prebiotic chemistry under post-impact conditions on Titan*; Bulletin SPG/SSP, Vol. 30, p. 130.

Neubauer D., Vrtala A., **Leitner J. J.**, Firneis M. G., Hitzenberger R., 2012, *The Life Supporting Zone of Kepler-22b and the Kepler Planetary Candidates: KOI268.01, KOI701.03, KOI854.0 and KOI1026.01*; Planetary and Space Science, Vol. 73, p. 397-406.

Wilson, C. F., Chassefiére E., Hinglais E., Baines K., Balint T., Berthelier J. J., Blamont, Durry G., Ferencz Cs., Grimm R. E., Imamura T., Josset J. J., Leblanc F., Lebonnois S., **Leitner J. J.**, Limaye S. S., Marty B., Palomba E., Pogrebenko S., Rafkin S. C. R., Tabboys D. L., Wieler R., Zasova L. V., Szopa C., and the EVE Team, 2011, *The 2010 European Venus Explorer (EVE) Mission Proposal;* Experimental Astronomy, Vol. 33, p. 305-335; DOI 10.1007/s10686-011-9259-9.

Leitner J. J., Firneis M. G., 2011, *A Brief Consideration of Early Panspermia Based on Astronomical and Celestial Mechanical Arguments*; Journal of Cosmology, Vol., 16, ttp://journalofcosmology.com/JoC16pdfs/indexVol16CONTENTS.htm.

Neubauer D., Vrtala A., **Leitner J. J.**, Firneis M. G., Hitzenberger R., 2011, *Development of a Model to Compute the Extension of Life Supporting Zones for Earth-Like Exoplanets*; Origin of Life and Evolution of Biospheres, Vol. 41, Nr. 6, p. 545-52.

Leitner J. J., Firneis M. G., 2011, *Metallicites of planet-hosting G-stars and their implications for terrestrial-like planets – a statistical analysis*; EPSC-DPS Joint Meeting 2011, held in Nantes, France, October 3-7, 2011.

Leitner J. J., Firneis M. G., 2011, *Lehrmeister Weltall – Astrobiologie als interdisziplinärer Zugang zur Naturwissenschaft*; in University Meets Public –Nachlese, Ausgewählte Beiträge zum Thema „Lernende Gesellschaft", Eds. (E. Brugger, E. Gornik, B. Neichl, N. Tomaschek), Verlag Edition Volkshochschule, 2011, p. 70-81.

Leitner J. J., Firneis M. G., 2011, Why we must go to Mars; in: A One Way Mission To Mars – Colonizing the Red Planet (eds. Davies P., Schulze-Makuch D., Cosmology Science Publishers, Cambridge, USA, ISBN: 098-295-524-3.

Aittola M., Öhman T., **Leitner J. J.**, Kostama V.-P., Raitala J., 2010, *The Structural Control of Venusian Impact Craters*; Icarus, Vol. 205, p. 356-363.

Böttcher T., Huber L., LeCorre L., **Leitner J. J.**, McCarthy D., Nilsson R., Teixeira C., Vaquer Araujo S., Wilson R., Adjali F., Altenberg M., Briani G., Buchas P., Le Postollec A. and Meier T., 2009, *The HADES Mission Concept – Astrobiological Survey of Jupiter's Icy Moon Europa*; International Journal of Astrobiology, Vol. 8, No. 4, p. 321-329.

Chassefiére E., Korablev O., Imamura T., Baines K., Wilson C. F., Titov D., Aplin K., Balint T., Blamont J., Cochrane C., Ferencz Cs., Ferri F., Gerasimov M., **Leitner J. J.**, Lopez-Moreno J., Marty B., Martynov M., Pogrebenko S., Rodin A., Whiteway J., Zasova L., and the EVE Team, 2009, *European Venus Explorer: An in-situ Mission to Venus Using a Balloon Platform*; Advances in Space Research, Vol. 44, p. 106-115.

Chassefiére E., Korablev O., Imamura T., Baines K., Wilson C. F., Titov D., Aplin K., Balint T., Blamont J., Cochrane C., Ferencz Cs., Ferri F., Gerasimov M., **Leitner J. J.**, Lopez-Moreno J., Marty B., Martynov M., Pogrebenko S., Rodin A., Whiteway J., Zasova L., and the EVE Team, 2009, *European Venus Explorer (EVE) – An in-situ Mission to Venus*, Experimental Astronomy, Vol. 23, Issue 3, p. 741-760.

Smrekar S., Elkins-Tanton L., **Leitner J. J.**, Lenardic A., Mackwell S., Moresi L., Parmentier M., Stofan E., 2007, *Tectonic and Thermal Evolution of Venus and the Role of Volatiles: Implications for Understanding the Terrestrial Planets*; in: Venus as a Terrestrial Planet (eds. Esposito, Stofan, Cravens), AGU Monograph Series, Vol. 176, p. 45-71, ISBN 13: 978-0-87590-441-2.

Aittola M., Öhman T., **Leitner J. J.**, Raitala J., 2007, *The Characteristics of Polygonal Impact Craters on Venus*; Earth, Moon, and Planets, Vol. 101, Nr. 1-2, p. 41-53.