Day 4, Friday, 2.9.2022

Table of Content: Session 7
Talks

KEYNOTE

Planetary Atmospheres and the Search for Signs of Life beyond Earth

Sara Seager[1]

[1]MIT

37 Eta Earth Revisited: How many Earth-like Habitats might there be in the Milky Way?

Scherf M[1,2], Lammer H[1], Sproß L[2]

[1]Space Research Institute, Austrian Academy of Sciences, [2]Institute of Physics, University of Graz

53 Detecting super-Earths in the habitable zone

Hara N[1], Dumusque X[1], Crétignier M[1], Unger N[1], Delisle J[1]

[1]Université de Genève

45 Exploring habitability evolution in rocky planets with climate and atmospheric models

Silva L[1,2], Biasiotti L[3,1], Bisesi E[1], Ivanovski S[1], Maris M[1,2], Murante G[1,2], Simonetti P[1,3], Vladilo G[1]

[1]INAF/OATs, [2]IFPU, [3]UniTs

12 CO2 ocean bistability on terrestrial exoplanets

Graham R[1], **Lichtenberg T[1]**, Pierrehumbert R[1]

[1]Atmospheric, Oceanic and Planetary Physics, University of Oxford

8 Biosignatures through rocky planet evolution around other stars

Rugheimer S[1], Kaltenegger L, Rimmer P

[1]York University

57 Is ozone a reliable proxy for molecular oxygen?

Kozakis T[1], Mendonça J[1], Buchhave L[1]

[1]Technical University Of Denmark

43 Looking for biosignatures in exoplanets atmospheres with RISTRETTO and ANDES: a topic at the heart of the newly created Life in Universe Center in Geneva

Bolmont E[1,2], Lovis C[2,1], Ehrenreich D[1,2], Kasparian J[1,2], Ibelings B[1,2], McGinnis D[1,2], Winssinger N[1,2], Caricchi L[1,2], Castelltort S[1,2], Mueller A[1,2]
[1]Center Life in the Universe, [2]University of Geneva

23 Could the mid-infrared space interferometer LIFE find biosignatures in the spectrum of the Earth in time?

Alei E[1,2], Konrad B[1], Rugheimer S[3], Mollière P[4], Angerhausen D[1], Quanz S[1,2], the LIFE collaboration[5]
[1]ETH Zurich, Institute for Particle Physics & Astrophysics, [2]National Center of Competence in Research PlanetS (www.nccr-planets.ch), [3]Oxford University, [4]Max-Planck-Institut für Astronomie, [5]The LIFE collaboration (www.life-space-mission.com)

Posters Session 7

19 Reconsidering the habitability of planets in the light of climate multistability

Bhatnagar S[1], Bolmont E[1], Brunetti M[1], Kasparian J[1]
[1]University of Geneva

26 Towards Detecting Signatures of Life with the Future LIFE Telescope

Konrad B[1,2], Alei E[1,2], Angerhausen D[1,2], Quanz S[1,2], the LIFE team[3]
[1]ETH Zürich, [2]National Center of Competence in Research PlanetS (www.nccr-planets.ch), [3]www.life-space-mission.com

904 Investigation of the Faint Young Sun Paradox Through the Lens of Stellar Astrophysical Modeling and Interferometric Observations

KhaDeem D Coumarbatch (1),Petrus Martens (2); William Danchi (3); Vladimir Airapetian (4)

(1) Georgia State University; (2) NASA Goddard Space Flight Center

911 The LIFE space mission: characterizing atmospheres of terrestrial exoplanets and searching for habitable worlds and biosignatures

Daniel Angerhausen (1), Sascha Quanz (1), and the LIFE collaboration (2)

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Talks Session 7

13:00 -13:40

KEYNOTE

Planetary Atmospheres and the Search for Signs of Life beyond Earth

Sara Seager[1]
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For thousands of years, inspired by the star-filled dark night sky, people have wondered what lies beyond Earth. Today, the search for signs of life is a key motivator in modern-day planetary exploration. The newly launched James Webb Space telescope will enable us to study gases in rocky exoplanet atmospheres, possibly including “biosignature” gases that might be attributed to life. Closer to home, a now controversial detection of phosphine gas in the Venus atmosphere has reignited studies of Venus, from re-investigation of decades’ old atmosphere anomalies to new laboratory investigations of organic molecules’ stability and chemistry in sulfuric acid (the composition of Venus’ cloud particles). New exoplanet atmosphere discoveries as well as growing evidence for Venus as a potentially habitable planet give us hope towards make progress on answering the ancient questions about the possibility of life beyond Earth.

13:40 – 14:00

37

Eta Earth Revisited: How many Earth-like Habitats might there be in the Milky Way?

Scherf M[1,2], Lammer H[1], Sproß L[2]
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Without aerobic life, the simultaneous presence of N2 and O2 in the Earth's atmosphere would be chemically incompatible over geologic timescales. The existence of an N2-O2-dominated atmosphere on an exoplanet would, hence, not only constitute a potential biosignature of aerobic life. It would also have to meet certain astro- and geophysical criteria to originate, evolve and to sustain.

Our definition of Eta-Earth, therefore, builds on the concept of a so-called Earth-like Habitat (EH), i.e., a planet within the complex habitable zone for life, at which N2 and O2 are simultaneously present as the dominant species while CO2 only comprises a minor constituent in its atmosphere. By our present scientific knowledge, certain criteria must be fulfilled to allow the existence of such an Earth-like atmosphere. These can be subsumed within a new probabilistic formula for estimating a maximum number of EHs. Some of these criteria, such as the bolometric luminosity and XUV flux evolution of a star, or the distribution of rocky exoplanets within the habitable zones of different stellar spectral types, are already rather well studied and can be tested through further observations. Other important criteria, like the prevalence of working carbon-silicate and nitrogen cycles, or the origin of life are by now poorly, or entirely un-constrained. Further factors, like the presence of a large moon or the importance of an intrinsic magnetic field, are not only poorly constrained but its significance for the evolution and stability of an Earth-like Habitat are even debated. While our new formula for estimating the maximum number of EHs can in principle incorporate all these factors as well as unknowns, we by now must restrict ourselves to the ones that are either well understood or can at least be tested soon. Based on our current knowledge, this approach only allows us to probabilistically estimate a maximum number of exoplanets on which an Earth-like Habitat can in principle evolve. The real number of EHs might, therefore, be significantly lower than our current best estimate but additional criteria should be verifiable in near future by upcoming ground- and space-based instrumentation such as PLATO, the E-ELT, or by the kinds of the proposed space-based observatory LUVOIR.

By considering all the factors that are presently scientifically quantifiable to at least some extent, we will present our current best estimate for the maximum number of EHs that might exist within the galaxy and will particularly focus on the role a star might play in the evolution and stability of such a habitat. If we substitute Eat-Earth, the mean number of rocky planets per star within the habitable zone, to only account for the mean number of EHs per star, Eta-EH, we end up with a number much smaller than the current best estimates for Eta-Earth. It is, therefore, scientifically not justified to presume that all potential habitats inside a habitable zone for complex life will evolve similar to Earth.

14:00 – 14:20

53

Detecting super-Earths in the habitable zone

Hara N[1], Dumusque X[1], Crétignier M[1], Unger N[1], Delisle J[1]
[1]*Université de Genève*

Direct imaging is one of the most promising ways to characterize the atmosphere of Earth-like planets and find biosignatures. The yield of the upcoming spectro-imagers such as PCS@ELT, LUVOIR/HaBex is greatly improved if targets are detected in advance. Our goal is to detect terrestrial planets in the habitable zone of their star within 15 pc of the Earth. Radial velocities are capable, in principle, to detect such targets, but are severely limited by the presence of stellar activity. In this talk, I present the recent advances we made in the data analysis of radial velocities, their application to HARPS data, and the detection of new candidates in the habitable zone. This progress opens perspectives on a new census of nearby stars.

14:20 – 14:40

45

Exploring habitability evolution in rocky planets with climate and atmospheric models

Silva L[1,2], Biasiotti L[3,1], Bisesi E[1], Ivanovski S[1], Maris M[1,2], Murante G[1,2], Simonetti P[1,3], Vladilo G[1]
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The potential of hosting surface liquid water on rocky planets is generally quantified according to the current stellar and planetary parameters of the detected planets. On the other hand, the potential of currently hosting life rests on environmental conditions favorable for the onset of life at early evolutionary phases. These phases are characterized by lower instellations, and, as for Earth, also a range of different planetary parameters are to be expected (e.g. land-ocean coverage, rotation rate). The ensuing potential evolution of the surface/atmospheric conditions implies different observable transit/emission spectra.
We have developed a flexible climate model (ESTM, Earth-like planet Surface Temperature Model, Vladilo et al. 2015; Biasiotti et al. 2022) coupled with a radiative transfer atmospheric model (EOS, Simonetti et al. 2022) for terrestrial-type exoplanets suited for multi-parameter explorations (atmospheric pressure and composition; stellar type; orbital and planetary parameters). Among other applications, we can track the conditions of habitability as a function of the luminosity evolution of the central star, and of other evolving planetary factors.
We have applied our models to investigate the epoch of the onset of life-sustaining conditions in Kepler-452b (Silva et al. 2017), and are exploring the range of atmospheric compositions allowing a habitable Archean Earth. The EOS RT model allows us to compute the expected spectrum for each simulated climate.

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15:15 -15:35

12

CO2 ocean bistability on terrestrial exoplanets

Graham R[1], **Lichtenberg T[1]**, Pierrehumbert R[1]
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Cycling of carbon dioxide between the atmosphere and interior of rocky planets can stabilise global climate and enable planetary surface temperatures above freezing over geologic time. However, variations in global carbon budget, tectonics, and unstable feedback cycles between planetary sub-systems have the potential to destabilise the climate and surface geochemistry of rocky exoplanets toward regimes unknown in the modern Solar System.

We performed atmospheric radiative transfer and surface weathering simulations to probe the stability of climate equilibria for rocky, ocean-bearing exoplanets at instellations relevant for planetary systems in the outer regions of the circumstellar habitable zone across different tectonic settings and stellar masses. Characterising these planets with future astronomical surveys will inform our understanding of the diversity of climate states of rocky planets, particularly under low irradiation and with increasing atmospheric carbon budget, similar to the early Earth.

Our simulations suggest bistability between an Earth-like climate state with efficient carbon sequestration and an alternative stable climate equilibrium where CO_2 condenses at the surface and forms a blanket of either clathrate hydrate or liquid CO_2. At increasing instellation and with ineffective weathering, the latter state oscillates between cool, surface CO_2-condensing and hot, non-condensing climates. CO_2 bistable climates can emerge immediately upon magma ocean crystallisation and remain stable for billions of years.

The carbon dioxide-condensing climates follow an opposite trend in CO_2 partial pressure versus instellation compared to the weathering-stabilised planet population, with divergent spectroscopic features in the near- to mid-infrared. This suggests the possibility of observational discrimination between these distinct climate categories across the rocky exoplanet census.

15:35 – 15:55

8

Biosignatures through rocky planet evolution around other stars

Rugheimer S[1], Kaltenegger L, Rimmer P
[1]*York University*

When we observe the first terrestrial exoplanet atmospheres, we expect to find planets around a wide range of stellar types, UV environments, and geological conditions. Since the first exoplanets available for characterization will be likely for M dwarf host stars, understanding the UV environment of these cool stars is a vital step in understanding the atmospheres of these planets. Additionally, the atmospheres of these planets will not been fixed in time. Earth itself offers many possible atmospheric states of a planet. We set out to examine how an Earth-like planet at different geological epochs might look around FGKM star types from a prebiotic world to modern Earth.

15:55 – 16:15

57

Is ozone a reliable proxy for molecular oxygen?

Kozakis T[1], Mendonça J[1], Buchhave L[1]
[1]*Technical University Of Denmark*

Molecular oxygen (O2) paired with a reducing gas is regarded as a promising biosignature pair for atmospheric characterization of terrestrial exoplanets. In circumstances when O2 may not be detectable in a planetary atmosphere (for instance, at mid-IR wavelengths) it has been suggested that O3, the photochemical product of O2, could be used as a proxy to infer the presence of O2. While O3 is not directly produced by life, it plays an important role in habitability as the ozone layer is the primary source of UV shielding for surface life on modern Earth. However, O3 production is known to have a nonlinear dependence on O2, as well as being strongly influenced by the UV spectrum of the host star. To evaluate the reliability of O3 as a proxy for O2 we used Atmos, a 1D coupled climate/photochemistry code, to study the O2-O3 relationship for "Earth-like'' habitable zone planets around a variety of stellar hosts (G0V-M5V) for O2 abundances from 0.01%-150% of the Present Atmospheric Level (PAL) on modern Earth. We studied how O3 emission features for these planetary atmospheres varied for different O2 and O3 abundances using the radiative transfer code PICASO. Overall we found that the O2-O3 relationship differed significantly around different stellar hosts, with different trends for hotter stars (G0V-K2V) than cooler stars (K5V-M5V). Planets orbiting hotter host stars experience an increase in O3 when O2 levels are initially decreased from the present atmospheric level, with maximum O3 abundance occurring at 25-55% PAL O2. Although this effect may seem counterintuitive, it is due to the pressure dependency on O3 production, as with less atmospheric O2 incoming UV photons capable of O2 photolysis are able to reach lower (denser) regions of the atmosphere to spark O3 formation. This effect is not present for planets orbiting our cooler host stars (K5V-M5V), as the weaker incident UV flux (especially FUV flux) does not allow O3 formation to occur at dense enough regions of the atmosphere such that the faster O3 production outweighs a smaller source of O2 from which to create O3. As a result, for cooler host stars the O3 abundance decreases as O2 decreases, albeit nonlinearly. Interpretation of O3 emission spectral features was found to require knowledge of the atmosphere's temperature profiles -particularly the temperature differences between the planetary surface and stratospheric temperature- which are highly influenced by the amount of stratospheric O3. Planets experiencing higher amounts of incident UV have more efficient O3 production and UV absorption leading to larger stratospheric temperature inversions, and therefore shallower emission features. Overall it will be extremely difficult (or impossible) to infer precise O2 levels from an O3 measurement, however, with information about the UV spectrum of the host star and context clues, O3 will provide valuable information about potential surface habitability of an exoplanet.

16:15 – 16:35

43

Looking for biosignatures in exoplanets atmospheres with RISTRETTO and ANDES: a topic at the heart of the newly created Life in Universe Center in Geneva

Bolmont E[1,2], Lovis C[2,1], Ehrenreich D[1,2], Kasparian J[1,2], Ibelings B[1,2], McGinnis D[1,2], Winssinger N[1,2], Caricchi L[1,2], Castelltort S[1,2], Mueller A[1,2]

[1]Center Life in the Universe, [2]University of Geneva

Since the detection of the first exoplanet orbiting a star like the Sun, the University of Geneva has been at the forefront of exoplanet research. Starting from an extensive expertise in planet detection (with radial velocity), the observatory is also now an important actor in the atmosphere characterization of exoplanets (e.g. Ehrenreich et al. 2020). Today the focus is shifting towards the atmospheric characterization of small temperate planets, such as Proxima-b and the TRAPPIST-1 planets. The university is therefore actively participating to the ground-based instruments RISTRETTO@VLT and ANDES@E-ELT. These instruments will use a technique based on high-contrast imaging and high-resolution spectroscopy to characterize the reflected light from temperate planets and to eventually detect biosignatures in their atmospheres. In particular, it has been shown that such a method could lead to a detection of oxygen in the atmosphere of Proxima-b (Lovis et al. 2017).

However, to be able to correctly identify a biosignature, one needs to be able to identify false positives. So, one needs to know how the atmosphere interacts with the planetary interior, with the incoming stellar radiation, and with many different other processes. A multi-disciplinary approach is therefore necessary.

Recently, and following the 2019 Nobel prize in physics attributed to Michel Mayor and Didier Queloz for the discovery of 51 Peg b, the University of Geneva decided to create a faculty center, the "Life in the Universe Center". The members of the center include experts in astrophysics, geophysics, chemistry, climatology and biology. The center aims at leading interdisciplinary projects on the origin of life on Earth and the search for life in our solar system and in exoplanetary systems to contribute to the world research on fundamental questions: How did life emerge and how did it diversify on Earth? What is the nature of life? Is the Universe full of life? How can we detect life elsewhere than on Earth?

Several projects have started and will start in the near future in the center on the following topics:
- The rise of molecular complexity on primitive Earth
- Multi-stability of climates and habitability
- Evolution under extraterrestrial conditions
- The atmosphere as a mirror for geological processes

I will present some of these new interdisciplinary scientific projects and how they relate to the search of biosignatures in exoplanets atmospheres that we will be able to carry out with instruments like RISTRETTO and ANDES.

16:35 – 16:55

23

Could the mid-infrared space interferometer LIFE find biosignatures in the spectrum of the Earth in time?

Alei E[1,2], Konrad B[1], Rugheimer S[3], Mollière P[4], Angerhausen D[1], Quanz S[1,2], the LIFE collaboration[5]
[1]ETH Zurich, Institute for Particle Physics & Astrophysics, [2]National Center of Competence in Research PlanetS (www.nccr-planets.ch), [3]Oxford University, [4]Max-Planck-Institut für Astronomie, [5]The LIFE collaboration (www.life-space-mission.com)

At the dawn of the search for life in the universe, we are focusing our efforts on designing new instruments that are able to characterize the atmospheres of terrestrial exoplanets. One of our main goals is to find "biosignatures", the spectral signatures of gases linked to potential biological activity (e.g. O2 and its photochemical product O3, as well as CH4). Using nulling interferometry in the mid-infrared wavelength range, the Large Interferometer for Exoplanets (LIFE, Quanz et al. 2018, 2021) will allow us to further constrain the bulk parameters and the surface conditions of a few dozens of terrestrial planets, as well as to gather information about their atmospheric structure and composition. At this stage of the mission development, atmospheric retrieval studies are essential to determine the technical requirements for LIFE. Because of the lack of observational data, we rely on theoretical spectra of terrestrial exoplanets to develop analysis pipelines that could be most effective for the characterisation of such targets. We feed these spectra to Bayesian retrieval routines to produce a statistically robust analysis of an atmospheric spectrum given a set of parameters (pressure-temperature structure, chemical abundance, planetary dimensions).
In this contribution, we analysed simulated spectra of the Earth at various stages of its evolution calculated by Rugheimer & Kaltenegger (2018): a prebiotic Earth at 3.9 billion years ago (Ga), the Earth after the Great Oxygenation Event (GOE) at 2.0 Ga, and after the Neoproterozoic Oxygenation Event (NOE) at 0.8 Ga, and the modern Earth. We considered an Earth-sized planet on a 1 AU orbit around a Sun-like star at 10 pc from the observer, at the minimum LIFE requirements (spectral resolution R=50, signal-to-noise ratio S/N=10, wavelength range $\Delta\lambda = 4 - 18.5\ \mu m$) as determined in Konrad et al. (2022). We created mock observations with LIFE by running the simulated spectra through the LIFEsim simulator (Dannert et al., 2022) considering all major astrophysical noise sources.
We find that, with the minimum requirements, LIFE could detect O3 in the atmosphere if the O2 abundance is at least 2% (10% Present Atmospheric Level). This corresponds to the NOE and the modern Earth scenarios. CH4 could be constrained in terrestrial atmospheres if its abundance is of the order of 0.1% (GOE and NOE Earth scenarios). We find that the NOE Earth is a particularly convenient scenario to simultaneously constrain O3 and CH4. To retrieve more precise and accurate results of the O3 and CH4 abundance in atmospheres of potentially inhabited exoplanets, we suggest increasing the S/N to 20 for the most promising candidates (Alei et al., 2022).

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Posters Session 7

19

Reconsidering the habitability of planets in the light of climate multistability

Bhatnagar S[1], Bolmont E[1], Brunetti M[1], Kasparian J[1]
[1]*University of Geneva*

The search for life in the universe is one of the major drivers of astrophysics research. Both, external factors (e.g., stellar type) and internal ones (e.g., climate + geophysics) affect the habitability of planets, and consequently, the habitable zone (HZ; Kasting et al. 1993). The climate of a planet is a complex system where different components (the atmosphere, ocean, ice, biomes and so on) interact non-linearly. The core idea of climate multistability is that under the same external forcing, a planet can exist in multiple alternative steady states due to several feedbacks (for e.g., the ice-albedo feedback, Boltzmann radiation, clouds; Strogatz 2018; Brunetti et al. 2019). Multistability can have implications for habitability as planets can shift from an uninhabitable to a habitable state (or vice-versa), at the same external forcing. If these transitions occur very quickly, life might not be able to cope with the change, and could potentially cease to exist. Abrupt climatic transitions have also occurred several times even on Earth, with the climate cycling between temperate and glacial/snowball conditions (Evans et al. 1997; Hoffman et al. 1998). These have been the cause of some mass extinction events and subsequent recoveries of life.
In this study, we investigate climate multistability and its implications on habitability and the HZ. We construct a 1-dimensional energy balance model and implement typical climate feedbacks, including a runaway greenhouse effect parameterisation for high temperatures (>322.5 K; Turbet et al. 2021; Chaverot et al. in prep). With this model, we obtain three steady states for an Earth-like aquaplanet at 1.00 AU from a Sun-like star: (a) Snowball (204 K), (b) Warm State (290 K), and (c) Very Hot State (888 K). We further find that the HZ extends between 0.94 AU to 1.01 AU for this model planet. Moreover, we also show that for a slower-rotating version of this Earth-like aquaplanet, the HZ extends between 0.90 AU to 1.08 AU. Multistability facilitates uninhabitable states (e.g., snowball) to tip into a habitable one (e.g., warm state), potentially extending the range of planets that may have access to a habitable regime. In the near future, these simulations will be refined using a more extensive and robust climate model, the 3-D LMD-Generic Global Climate Model (LMDG GCM).

26

Towards Detecting Signatures of Life with the Future LIFE Telescope

Konrad B[1,2], Alei E[1,2], Angerhausen D[1,2], Quanz S[1,2], the LIFE team[3]
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Temperate terrestrial exoplanets commonly occur in our galaxy (Bryson et al., 2021). A long-term goal of exoplanet research is to characterize the atmospheres of a sizable sample of temperate planets, and identify habitable or even inhabited worlds. Since the sensitivity of planned telescopes is likely insufficient, we focus our efforts on designing next generation telescopes such as the space-based 'Large Interferometer For Exoplanets' (LIFE, Quanz et al. 2018, 2021). LIFE will measure the mid-infrared (MIR) thermal emission spectrum of exoplanets, which encodes valuable information on the exoplanet's size, atmospheric pressure-temperature structure, and atmospheric composition. One aim is to search for 'biosignature pairs' in these atmospheres. These are pairs of gases that rapidly react with each other and therefore should not be present simultaneously in an exoplanet atmosphere, unless replenished at a high rate by life. An example of such a pair is O2 and its photochemical byproduct O3 together with CH4 or N2O, (Lovelock 1965, Lippincott et al. 1967).

A crucial step in the development of LIFE is to determine how accurately an exoplanet's MIR spectrum needs to be determined in order to be able to robustly infer the presence of biosignature pairs in its atmosphere. To answer this question, we study a simulated Earth-twin exoplanet orbiting a Sun-like star at a distance of 10 pc (Konrad et al. 2021). We use LIFEsim (Dannert & Ottiger et al. 2022) to calculate the wavelength-dependent signal-to-noise ratio (S/N) of the exoplanet spectrum expected for observations with LIFE, and consider all major astrophysical noise sources. We generate a grid of observations covering different wavelength ranges, spectral resolutions (R) and S/Ns. We then use an inverse modeling approach to analyze how well the atmospheric structure and composition of the Earth-twin exoplanet can be constrained from different quality MIR spectra and if the biosignature pairs of interest are detectable. These results provide first constraints for LIFE's instrument requirements.

We find that Earth-like O3 abundances are detected in all simulated LIFE observations, due to the strong O3 MIR absorption feature. Since O3 is a photochemical byproduct of O2, its detection indicates that significant amounts of O2 are present in the atmosphere too. Earth-like N2O abundances are not detectable in any of the considered cases. In contrast, the detection of CH4 shows a strong dependence on the quality of the measured spectrum. For high quality spectra (R of at least 50, S/N of at least 10), we can detect Earth-like CH4 abundances and infer the presence of the O2/O3-CH4 biosignature pair, which could be interpreted as a first indicator of biological activity.

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904

Investigation of the Faint Young Sun Paradox Through the Lens of Stellar Astrophysical Modeling and Interferometric Observations

KhaDeem D Coumarbatch (1),Petrus Martens (2); William Danchi (3); Vladimir Airapetian (4)

(1) Georgia State University; (2) NASA Goddard Space Flight Center

The Faint Young Sun Paradox (FYSP) describes a gap in our understanding of the evolution of life as we know it as it implies that liquid water on both Earth and Mars should have been frozen during the early evolution of the Sun. By utilizing the one-dimensional MESA (Modules for Experiments in Stellar Astrophysics) code, we investigate the parameters of an initially more massive Sun at different ages along its main sequence lifetime. A second approach to the same paradox is the observational study of Sun-like stars at an earlier stage in their evolution. This is achieved with interferometric angular diameter measurements of intermediate mass stars within 60 parsecs using the CHARA Array in conjunction with Gaia EDR3 parallaxes to determine their physical diameters for the use in three-dimensional Magnetohydrodynamic simulations. The overall objective is to address the Faint Young Sun Paradox through stellar astrophysics while applying observational measurements to understand the early Solar System and nearby exoplanet habitability.

911

The LIFE space mission: characterizing atmospheres of terrestrial exoplanets and searching for habitable worlds and biosignatures

Daniel Angerhausen (1), Sascha Quanz (1), and the LIFE collaboration (2)

(1) ETH Zurich; (2) www.life-space-mission.com

The atmospheric characterization of a significant number of terrestrial planets, including the search for habitable and potentially inhabited planets, is probably the major goal of exoplanetary science and one of the most challenging endeavours in 21st century astrophysics. The Large Interferometer For Exoplanets (LIFE) addresses this challenge by investigating the scientific potential and technological challenges of an ambitious mission employing a formation-flying nulling interferometer in space working at mid-infrared wavelengths. LIFE's observing wavelength range is 4-17.5 µm (requirement) / 3-20 µm (goal) and the required spectral resolution is 35 (req.) / 50 (goal). The total mission lifetime is anticipated to be 5-6 years (requirement), consisting of a 2.5 year search phase for the detection of hundreds of planets and an up to 3.5 years characterization phase for the detailed investigation of atmospheric diversity and the search for biosignatures. Breakthroughs in our understanding of the exoplanet population as well as significant progress in relevant technologies justify the need, but also the feasibility, for a future mission like LIFE to investigate one of the most fundamental questions of humankind: Are we alone in the Universe?

999

How long can cold planets be warm enough for liquid water?

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Potential habitable worlds outside the solar system might be planets that are very different from Earth. Cold super-Earths which retain their primordial, H-He dominated atmosphere could have surfaces that are warm enough to host liquid water. This would be due to the collision induced absorption (CIA) of infra-red light by hydrogen, which increases with pressure. We investigate the existence and duration of this exotic habitat by simulating planets of different core masses, envelope masses and semi-major axes. Evolution models for the host-stars luminosity and the planet's intrinsic heat and radius are incorporated, as well as an atmosphere evaporation model. We find that terrestrial and super-Earth planets with masses of 1 to 10 Earth masses can maintain temperate surface conditions for more than 9 Gyr at radial distances larger than 2 AU. This suggests that a large number of planets in the galaxy could be candidates for habitability and that the concept of planetary habitability should not only be focussed on Earth-analogues.