From the Heliosphere to Astrospheres - Lessons for Exoplanets and their Habitability

779. WE-Heraeus-Seminar

16 – 20 January 2023

at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 779. WE-Heraeus-Seminar:

Whether or not we are alone in the universe has fascinated humanity for many centuries. New missions like the James Webb Space Telescope (JWST) and upcoming ones like the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) will deliver data addressing this crucial question within the next few decades. Of particular interest are exoplanets orbiting cool stars (in particular K- and M-stars) due to, e.g., favourable (planet/star) flux ratios. However, recent estimations showed that the exoplanetary radiation environment around such stars might be much harsher than what we know from the Sun. Thus, exoplanets could be exposed to an enhanced stellar radiation environment, which – in turn – could affect its habitability, e.g., due to a hazardous flux of energetic particles influencing atmospheric evolution, climate, photochemistry, and the atmospheric radiation dose.

This interdisciplinary seminar aims to bring together experts from astrophysics, particle physics, solar/stellar physics, planetary physics, and atmospheric chemistry/climate physics to understand the impacts of astrospheres, stellar winds, stellar radiation, and stellar space weather on the habitability of exoplanets/moons.

Scientific Organizers:

Priv. Doz. Dr. Konstantin Herbst University of Kiel, E-mail: herbst@physik.uni-kiel.de

Dr. Frederic Effenberger University of Bochum, E-mail: fe@tp4.rub.de

Dr. Klaus Scherer University of Bochum, E-mail: kls@tp4.rub.de

Administrative Organization:

Dr. Stefan Jorda
Mojca Peklaj

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-11
Fax +49 6181 92325-15
E-mail peklaj@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Introduction

Venue :

Physikzentrum
Hauptstraße 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone	+49 2224 9010-113 or -114 or -117
Fax	+49 2224 9010-130
E-mail	gomer@pbh.de
Internet:	www.pbh.de

Taxi Phone +49 2224 2222

Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (17:00 h - 21:00 hrs) and Monday morning

Program

Program *(CET)*

Sunday, 15 January 2023

17:00 – 21:00	ARRIVAL and REGISTRATION	
18:30	*BUFFET SUPPER*	

Monday, 16 January 2023

07:30	*BREAKFAST*	
09:00 – 09:15	Organizers	**Welcome**
09:15 – 09:45	Athanasios Papaioannou (ONLINE)	**The Case of Empirical Solar Energetic Particle Scaling Relations**
09:45 – 10:15	Svetlana Berdyugina	**Exoplanet Surface Structures**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:15	Adriana Valio	**Stellar Activity: Correlation Between Starspots and Superflares**
11:15 – 11:45	Brett Morris (ONLINE)	**Fading Memories of Magnetic Youths**
11:45 – 12:00	Judy Chebly	**Quantification of the Environment of Cool Stars Using Numerical Simulations**
12:00 – 12:30	**Discussion**	
12:30 – 14:00	*LUNCH BREAK*	

Program *(CET)*

14:00 – 14:45	Maximilian Günther	**Habitable (?) Worlds and Stellar Flares**
14:45 – 15:15	Meng Jin	**Global Magnetohydrodynamics Modeling of Solar Coronal Mass Ejections and Application to Solar Analogs**
15:15 – 15:45	Frederic Effenberger	**Modelling Stellar Energetic Particle Environments of Planets in Habitable Zones based on Stellar Activity**
15:45 – 16:15	Junxiang Hu	**Stellar CME-Driven Energetic Particles Events from Young Solar-like Stars**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:15	Julián David Alvarado-Gomez	**Coronal Mass Ejections in Magnetically Active Stars**
17:15 – 17:30	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
17:30 – 18:15	**Discussion**	
18:15 – 19:30	*DINNER*	
19:30	Tilman Spohn	**Evening Lecture: On the Geophysics of (Exo) Planets**

Program *(CET)*

Tuesday, 17 January 2023

07:30	*BREAKFAST*	
09:00 – 09:45	Klaus Scherer	**Habitable Astrospheres**
09:45 – 10:15	Theresa Lüftinger	**Living Around Young Suns: Magnetic Fields, Winds and Atmospheric Erosion around Young Stars and Implications for Habitability**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:15	Konstantinos Dialynas	**The Global Heliosphere: In-situ Ions from the Voyagers and Remotely Sensed ENAs from Cassini**
11:15 – 11:45	Jeffrey Linsky	**New Results Concerning the Local Interstellar Medium: Inhomogeneity, Interactions with Helio/astrospheres, and Pressure Balance**
11:45 – 12:00	Dominik Bomans	**Observations of Astrospheres from O to M Stars**
12:00 – 12:30	**Discussion**	
12:30 – 14:00	*LUNCH BREAK*	
14:00 – 14:45	Nicholas Eugene Engelbrecht (presented by Klaus Scherer)	**On the Three-Dimensional Transport of Galactic Cosmic Rays in Astrospheres**
14:45 – 15:15	Donna Rodgers-Lee	**The Energetic Particle Environment of Sun-like and M Dwarf Stars**
15:15 – 15:45	Veerle Sterken	**Synergies Between Dust and Heliospheric/Astrospheric Science**
15:45 – 16:15	Lennart Baalmann	**Synthetic Astrosphere Observations: The Intricate Role of Interstellar Dust**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:15	Kevin Heng	**The CHEOPS Mission: Selected Highlights of Scientific Results**

Program *(CET)*

17:15 – 18:15	**Discussion**
18:15	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*

Program *(CET)*

Wednesday, 18 January 2023

07:30	*BREAKFAST*	
09:00 – 09:45	Heike Rauer	**The PLATO Mission**
09:45 – 10:15	Francesco Pepe	**Observing Exoplanets with ESPRESSO**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:00	Dominique Meyer	**3D MHD Astrospheres: Applications to IRC-10414 and Betelgeuse**
11:00 – 11:15	Julien Dörner	**CRPropa 3.2 - An Advanced Framework for High-energy Particle Propagation in Extragalactic and Galactic Spaces**
11:15 – 11:30	Nikoleta Ilic	**Tidal Star-planet Interaction in Planet-hosting Wide Binaries**
11:30 – 11:45	Yu Xu	**Simulations of Stellar CMEs and their Responses in Synthetic Spectra**
11:45 – 12:00	**Poster Flash Presentations**	
12:00 – 12:30	**Discussion**	
12:30 – 12:45	**Conference Photo (outside at the main entrance)**	
12:45 – 14:00	*LUNCH BREAK*	
14:00	**Excursion**	
18:15	*DINNER / NETWORKING*	

Program *(CET)*

Thursday, 19 January 2023

07:30	*BREAKFAST*	
09:00 – 09:45	Lena Noack	**Interior Heating and Outgassing of Rocky Exoplanets**
09:45 – 10:15	Ekaterina Ilin	**Magnetic Star-planet Interactions**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:15	Jens Hoeijmakers	**High Resolution Spectroscopy of Ultra-hot Gas Giant Exoplanets**
11:15 – 12:00	Katja Poppenhäger	**The Young Planets in the V1298 Tau System and their Atmospheres**
12:00 – 12:30	**Discussion**	
12:30 – 14:00	*LUNCH BREAK*	
14:00 – 14:45	Vera Dobos	**Moons of Exoplanets: Formation, Orbital Stability and Habitability**
14:45 – 15:15	Harish Vedantham	**Radio Detection of Extrasolar Space Weather and Magnetic Fields**
15:15 – 15:45	Joachim Saur	**Brown Dwarfs as Ideal Candidates for Detecting UV Aurora Outside the Solar System: Hubble Space Telescope Observations of 2MASS J1237+6526**
15:45 – 16:15	Evangelia Samara (ONLINE)	**Which Terrestrial Exoplanets Deserve More Scrutiny for Atmospere Viability?**
16:15 – 16:45	*COFFEE BREAK*	
16:45 – 17:00	Florian Rünger	**Exomoon-induced Radial Velocity Signatures in Spectra of Exoplanetary Atmospheres**
17:00 – 17:15	Giulia Roccetti	**Long-term Presence of Liquid Water on the Surface of Exomoons Orbiting Ejected Free-floating Planets**
17:15 – 18:15	**Discussion**	

Program *(CET)*

18:15 – 19:30 *DINNER*

19:30 **Poster Session**

Program *(CET)*

Friday, 20 January 2023

07:30	*BREAKFAST*	
09:00 – 09:45	Konstantin Herbst	**Modeling the Impact of Cosmic Rays on (Exo)planetary Atmospheres**
09:45 – 10:15	Miriam Sinnhuber	**The Impact of Stellar Energetic Particles on the Composition of Planetary Atmospheres**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:15	John Lee Grenfell	**Effects of High Energy Particles on Atmospheric Chemistry in the Solar System and Beyond**
11:15 – 11:45	Paul Rimmer	**Timing is Everything: Kinetics of UV-Driven Prebiotic Chemistry**
11:45 – 12:30	**Discussion**	
12:30	*LUNCH*	

End of Seminar / Departure

Posters

Poster Session: Thursday, 19 January, 19:30 h (CET)

1	Eliana Amazo-Gomez	**The Environment of Faculae- Versus Spot-dominated Stars**
2	Andreas Bartenschlager	**Investigation of the Influence of Stellar Particle Events and Galactic Cosmic Rays on the Atmosphere of TRAPPIST-1e**
3	Yurii Dumin	**The Faint Young Sun Paradox and the Anthropic Principle in the Context of Dark-Energy-Dominated Cosmology**
4	Filip Elekes	**Space Environment and Magnetospheric Poynting Fluxes of the Exoplanet Tau Boötis b**
5	Jubin Lirawi	**Climates of Short-period Tidally Locked Exoplanets**
6	Anna Julia Poser	**The Impact of Clouds on the Radius Evolution of Hot Jupiters**
7	Tanja Schumann	**SPP 1992 - Exploring the Diversity of Extrasolar Planets**
8	Kerstin Weis	**Structure Around LBV: Astrospheres or More?**
9	Jan Maik Wissing	**Determination of Rare SPE Spectra with Application to Earth and the Extrasolar Gas Giant HD209458b**
10	Joana Wokittel	**Exploration of Best-practice Telluric Correction Methods to Optimize Ground-based Exoplanet Spectroscopy for the Detection of Biosignatures**

Abstracts of Lectures

(in alphabetical order)

Coronal Mass Ejections in Magnetically Active Stars

J. D. Alvarado-Gómez[1], J. J. Drake[2], O. Cohen[3], C. Garraffo[2], F. Fraschetti[2] and K. Poppenhäger[1]

[1]*Leibniz Institute for Astrophysics Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*
[2]*Center for Astrophysics | Harvard & Smithsonian, 60 Garden St., Cambridge MA 02138, USA*
[3]*University of Massachusetts at Lowell, 600 Suffolk St., Lowell MA 01854, USA*

Coronal mass ejections (CMEs) are more energetic than any other class of solar phenomena. They arise from the rapid release of up to 10^{33} erg of magnetic energy mainly in the form of particle acceleration and bulk plasma motion. Their stellar counterparts, presumably involving much larger energies, are expected to play a fundamental role in shaping the environmental conditions around low-mass stars, in some cases perhaps with catastrophic consequences for planetary systems due to processes such as atmospheric erosion and depletion. Despite their importance, the direct observational evidence for stellar CMEs is almost non-existent. In this way, numerical simulations constitute extremely valuable tools to shed some light on eruptive behavior in the stellar regime. I will review recent results obtained from realistic modeling of CMEs in active stars, highlighting their key role in the interpretation of currently available observational constraints [1,2,3]. Emphasis will be given to M-dwarf stars, focusing on how the emerging EUV/X-ray/Radio signatures related to these events vary as a function of the magnetic properties of the star [4,5]. I will also present our latest simulations of extreme CMEs from the flare star AU Mic, and how these energetic events are expected to affect the two recently discovered exoplanets of this system [6,7,8]. Finally, I will discuss the implications and relevance of these numerical results in the context of future characterization of host star-exoplanet systems.

References

[1] J. D. Alvarado-Gómez et al., ApJ **862**, Issue 2, 93 (2018)
[2] S. P. Moschou et al., ApJ **877**, Issue 2, 105 (2019)
[3] J. D. Alvarado-Gómez et al., AN **343**, Issue 4, e210100 (2022)
[4] J. D. Alvarado-Gómez et al., ApJ Letters **884**, Issue 1, L13 (2019)
[5] J. D. Alvarado-Gómez et al., ApJ **895**, Issue 1, 47 (2020)
[6] J. D. Alvarado-Gómez et al., ApJ **928**, Issue 2, 147 (2022)
[7] O. Cohen et al., ApJ **934**, Issue 2, 189 (2022)
[8] F. Fraschetti et al., ApJ **937**, Issue 2, 126 (2022)

Synthetic astrosphere observations: the intricate role of interstellar dust

L. R. Baalmann[1], **S. Hunziker**[1], **K. Scherer**[2], **D. Malaspina**[3], **L. B. Wilson III**[4], **J. Kleimann**[2], **P. Strub**[5,6], **H. Krüger**[5], **H. Fichtner**[2], **D. J. Bomans**[7], **K. Weis**[7], **and V. J. Sterken**[1]

[1]*Institute for Particle Physics and Astrophysics, ETH Zürich, Zürich, Switzerland*
[2]*Institute for Theoretical Physics IV, Ruhr-Universität Bochum, Bochum, Germany*
[3]*Astrophysical & Planetary Sciences, University of Colorado, Boulder, USA*
[4]*NASA Goddard Space Flight Center, Greenbelt, USA*
[5]*Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany*
[6]*Universität Stuttgart, Institut für Raumfahrtsysteme, Stuttgart, Germany*
[7]*Astronomical Institute, Ruhr-Universität Bochum, Bochum, Germany*
E-Mail: lbaalmann@phys.ethz.ch

Comparisons of a simulated astrosphere to genuine observations require a projection of the three-dimensional model in appropriate observables like Hα or infrared dust emission. For astrospheres around OB stars, this is a comparably easy process: because interstellar dust (ISD) and gas are coupled, emissions in the infrared, much like Hα, can be directly computed for even a simple, single-fluid MHD astrosphere model. For astrospheres around cooler stars – which are far more likely to host habitable planets – only Hα emission can be calculated in-place. Here, gas and dust are no longer coupled, requiring elaborate simulations of ISD in addition to the MHD modelling. However, ISD dynamics within astrospheres are a complicated and not yet well-understood topic, warranting further in-situ investigation by the example of the heliosphere.

In this talk, we outline past and current efforts from two different fields to understand the interplay of interstellar dust with astrospheres, including an illustration of current in-situ measurements and predictions of interstellar dust in the heliosphere by the example of dust impacts on the Wind spacecraft.

Exoplanet Surface Structures

Svetlana V. Berdyugina[1,2]

[1]Leibniz-Institut für Sonnenphysik (KIS), Freiburg, Germany
[2] Istituto ricerche solari Aldo e Cele Daccò (IRSOL), Locarno, Switzerland

Surfaces of exoplanets can provide direct evidences for their habitability and possible life. In particular, such surface features as large-scale liquid water reservoirs (oceans), land masses, and life colonies, if present, are being encoded in stellar light reflected by exoplanets, when the planet rotates and orbits the star. Reflected light curves acquired in several spectral passbands can be inverted into albedo maps of exoplanets. Recently, a new technique ExoPlanet Surface Imaging (EPSI) demonstrated that albedo maps of Earth-like planets can be obtained with a subcontinental spatial resolution [1]. Moreover, multi-band (spectral) measurements allow for interpretation of surface features in terms of their mineral and biological composition using laboratory measurements of various samples [2]. Since signatures of photosynthetic organisms are especially prominent in polarized light, using polarimetric measurements increases the sensitivity for the extraterrestrial life detection. However, a proper interpretation of exoplanetary features requires understanding of both stellar and planetary variability during the light-curve acquisition. Stellar activity, e.g., due to starspots and flares, may contribute to the light-curve on time-scales and amplitudes larger than those due to intrinsic planetary structures. Also, atmospheric phenomena, such as clouds, large-scale weather patterns and seasons, add to the planetary variability. We develop models including these phenomena in order to be able to decipher reflected light spectra from exoplanets and search for life signatures on their surfaces.

References

[1] Berdyugina, S.V., Kuhn, J.R.: Surface Imaging of Proxima b and Other Exoplanets: Topography, Biosignatures, and Artificial Mega-Structures, Astronomical Journal, **158**, id. 246, 25 pp. (2019)

[2] Berdyugina, S.V., Harrington, D.M., Kuhn, J.R., Santl-Temkiv, T., Messersmith, E.J.: Remote Sensing of Life: Polarimetric Signatures of Photosynthetic Pigments as Sensitive Biomarkers, Int. J. Astrobiology, **15**, 45–56 (2016)

Observations of astrospheres from O to M stars

D.J. Bomans[1] **and K. Herbst**[2] **and K. Scherer**[3] **and K. Weis**[1]

[1]*Astronomical Institute, Ruhr University Bochum, Bochum, Germany*
[2] *Institute for Experimental and Applied Physics, Christian-Albrechts-University, Kiel, Germany*
[3]*Institute for Theoretical Physics IV, Ruhr University Bochum, Bochum, Germany*

Stellar astrospheres are product of the interaction of radiation and stellar wind and motion of the star through the interstellar medium (and the embedded magnetic field). They modulate the influence of the ambient interstellar medium, the interstellar radiation field, and cosmic rays, as well as the effects of the star on its planetary system.

I will present observations of astrospheres using UV, optical, and IR emission lines, thermal dust emission, and radio-continuum for stars across the Hertzsprung-Russell diagram, and discuss observational constraints for astrospheres of planet-hosting M stars.

The global heliosphere: *in-situ* ions from the Voyagers and remotely sensed ENAs from Cassini

K. Dialynas[1], S. M. Krimigis[1,2], R. B. Decker[2] and M. E. Hill[2]

[1]Office of Space Research and Technology, Academy of Athens,Greece.
[2] Applied Physics Laboratory, The Johns Hopkins University, Laurel, Maryland, USA

The path-breaking observations of the two Voyager spacecraft (V1 & V2) have revolutionized our understanding of the heliosphere's interaction with the Very Local Interstellar Medium[1] (VLISM). The V1 and V2 crossings from the termination shock (TS) (~94 and ~84 AU, respectively) led to the discovery of the reservoir of ions and electrons that constitute the heliosheath (HS), while their crossings of the heliopause (HP) (~122 AU and ~119 AU, respectively) pinpointed the extent of the upwind heliosphere's expansion into the VLISM and its rough symmetry[2]. Both crossings of the HP were associated with a depletion of particles of solar origin, an abrupt increase of GCRs, magnetic field and plasma density, whereas the temperature was found higher than expected. However, some puzzling differences were also identified. For example, the V1/Low Energy Charged Particle (LECP) measurements showed that the crossing of the HP was associated with the discovery of a flow stagnation region, possibly due to flux tube (FT) interchange instability at the boundary. Further use of the LECP measurements in V1 revealed the existence of a radial inflow of ~40-139 keV ions within the HS for ~9 AU before the HP, and a radial outflow over a spatial scale of ~28 AU past the HP, that corresponds to an ion population leaking from the HS into interstellar (IS) space. The Voyager *in-situ* LECP measurements were complemented by remote images of ~5.2-55 keV ENAs from Cassini/INCA, showing that the heliosphere forms a roughly symmetric time-dependent obstacle to the inward interstellar flow, following the outward propagating changes of the solar wind pressure through the solar cycle[3]. Further, the heliosphere responds promptly to those changes, within ~2-3 yrs, in both the nose and antinose directions. Since the Voyagers became interstellar (IS) missions, it was identified that the primary driver of the interaction of the heliosphere with the VLISM is the pressure of the IS magnetic field. The solar wind plasma is confined between the TS and the HP globally, forming a heliosheath that exhibits diamagnetic behavior and interacts directly with the strong interstellar magnetic field. The use of these observations drive the requirements for the particle and fields measurements from the future Interstellar Probe mission[4].

References

[1] Dialynas K. et al. Space Science Reviews, **218**:21 (2022)
[2] Krimigis, S. M. et al., Nature Astronomy, **3**:997-1006 (2019).
[3] Dialynas K. et al., Nature Astronomy, **1**:0115 (2017).
[4] McNutt, R. et al., Acta Astronautica, **196**, 13-28 (2022).

Moons of exoplanets: formation, orbital stability and habitability

V. Dobos[1], András Haris[2], Inga Kamp[1], Floris van der Tak[1,3], Dencs Z.[4], Regály Zs.[5]

[1]Kapteyn Astronomical Institute, University of Groningen, Groningen, Netherlands
[2]Department of Physics, University of Helsinki, Helsinki, Finland
[3]SRON Netherlands Institute for Space Research, Groningen, Netherlands
[4]Gothard Observatory, Eötvös Loránd University, Budapest, Hungary
[5]Konkoly Observatory, Budapest, Hungary

There are no confirmed exomoon discoveries to date. To find them, we need to know around which planets they can have a stable orbit for a long time scale. With this aim, we calculated the orbital evolution affected by tidal forces of large hypothetical moons around known exoplanets. We found that close-in planets, which are often easier to observe, cannot support stable orbits for moons. Consequently, the first exomoons discovered can be the ones that are also habitable. For this reason, we studied the habitability of hypothethical large moons around known exoplanets with the aim of identifying observation targets. Our target list can help to detect the first (habitable) exomoons. We also connect moon habitability to moon formation to have a better understanding on the expected moon sizes and orbital distances around specific planets.

CRPropa 3.2 – an advanced framework for high-energy particle propagation in extragalactic and galactic spaces

Julien Dörner[1,2] for the CRPropa collaboration

[1] Ruhr-Universtiy Bochum, Theoretical Physics IV, Bochum, Germany

[2] **R**uhr **A**stro **P**article and **P**lasmaphysics (RAPP) Center at Ruhr-Universtiy Bochum, Germany

With different environments the parameter of the transport of cosmic-rays can change dramatically. This can lead to major differences of the CR spectrum depending on the position in the Milky Way. Therefore, a detailed understanding and advanced modelling of the transport of CRs and the production of secondary radiation is necessary. The success of modelling the local cosmic-ray spectrum lays strongly on the input of multi-messenger and multi-wavelength observations.

CRPropa is an open source Monte-Carlo code for the propagation of high- and ultra-high-energy cosmic-rays and their secondaries in a consistent framework. In this talk, we will show the general approach of CR transport modelling with CRPropa and some of the newest features from version 3.2. This will include simulations of high-energy particles in diffusion dominated domains and self-consistent, fast modelling of electromagnetic cascades and interactions with customized photon fields. With the new CRPropa 3.2 version several technical updates and improvements were implemented which will be presented.

Modelling Stellar Energetic Particle Environments of Planets in Habitable Zones based on Stellar Activity

Frederic Effenberger[1], Du Toit Strauss[2], Konstantin Herbst[3] and Klaus Scherer[1]

[1]Ruhr-University, Bochum, Germany
[2] North-West University, Potchefstroom, South Africa
[3] Christian-Albrechts University, Kiel, Germany

Energetic particle environments in the inner zones around cool stars can play a crucial role in the habitability of exoplanets. Next to the galactic cosmic rays that are partially shielded by the stellar astrosphere, the particles accelerated directly by stellar activity can also play a significant role in the planetary radiation environment and the atmospheric chemistry. Here, we discuss steps to build an effective model of the energetic particle transport close to other stars based on their observed flaring activity. We consider the intermittent nature of particle injection correlated to the stellar activity light curve. State-of-the-art particle transport models based on experience with the heliospheric context are applied and evaluated. The potential implications for habitability and future prospects will be discussed.

On the Three-Dimensional Transport of Galactic Cosmic Rays in Astrospheres

N.E. Engelbrecht[1], K. Scherer[2], J. Light[1], K.D. Moloto[1], S.E.S. Ferreira[1], and K. Herbst[3]

[1]Centre for Space Research, North-West University, 2520, Potchefstroom, South Africa
[2] Institute for theoretical physics IV, Ruhr-Universitat¨ Bochum, D-44780 Bochum, Germany
[3] Institute for Experimental and Applied Physics, Christian Albrechts-Universitat¨ zu Kiel, D-24118 Kiel, Germany

Heliospheric studies of galactic cosmic ray (GCR) modulation have long shown that the transport of these particles, due to physical mechanisms of demonstrable significance such as for example drifts due to gradients in and curvatures of our stellar magnetic field, is inherently three-dimensional. As such, any study of the modulation of these particles in astrospheres requires a 3D approach to their transport. During this talk, preliminary results pertaining to GCR modulation in the astrosphere of Proxima Centauri will be presented, computed using a 3D stochastic solver for the Parker CR transport equation.

Effects of High Energy Particles on Atmospheric Chemistry in the Solar System and Beyond

J. L. Grenfell[1], M. Sinnhuber[2], K. Herbst[3],
A. Bartenschlager[2], B. Taysum[1], N. Iro[1], and H. Rauer[1,4,5]

[1]*Institute of Planetary Research (DLR-PF-EPA), Berlin, Germany*
[2]*Karlsruher Institute of Technology, Karlsruhe, Germany*
[3]*University of Kiel, Kiel, Germany*
[4]*Technical University of Berlin (TUB), Berlin, Germany*
[5]*Free University of Berlin (FUB), Berlin, Germany*

High Energy Particles (HEPs) interact with gaseous species in planetary atmospheres producing a cascade of secondary particles via so-called “air shower events”. These secondary particles can dissociate and ionize atmospheric species hence influencing atmospheric chemistry and climate. In an exoplanet context, the effect of HEPs could be particularly strong for the atmospheres of rocky exoplanets orbiting in the close-in habitable zone of cooler stars. In this talk we briefly review the effects of HEPs upon atmospheric chemistry in the Solar System for both rocky (Venus-Earth-Mars) and gas-giant (Jupiter) planets. Moving to an exoplanet context we then discuss the effect of HEPs upon hot Jupiter, mini-Neptune and terrestrial-type exoplanets[1]. Finally, we apply our unique diagnostic tool[2]. to analyze chemical pathways affecting potential atmospheric biosignatures on known terrestrial-type exoplanets.

References

[1] M. Scheucher, et al., ApJ, **863**, 1-11 (2018)
[2] R. Lehmann, JAC, **47**, 45-78 (2004)

Habitable(?) Worlds and Stellar Flares

M. Günther[1]

[1]*European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, Netherlands*

Our search for new exoplanets is bringing us closer to habitable worlds than ever before. Especially temperate super-Earths and sub-Neptunes orbiting the coolest stars open unique avenues as prime targets for transit discovery, dynamical mass measurements, and transmission spectroscopy of their atmospheres. However, with an eye on astrobiology, we also need to understand explosive stellar flaring and coronal mass ejections impacting exoplanets. These events can shape and even strip off exoplanet atmospheres, dissociate ozone, and extinguish biology - but they might also trigger prebiotic chemistry and initiate life on the surface. Fortunately, we can now study both exoplanets and flares in one go, leveraging modern surveys like TESS, SPECULOOS, and NGTS, and detailed characterisation with CHEOPS and ASTEP. Here, I will give an extensive overview of recent research highlights connecting exoplanet discovery and atmospheric studies with machine-learning-driven stellar flare detection. I will also include a deeper dive into a peculiar newly discovered class of strongly flaring young red dwarfs; these rapid rotators show complex light curve morphologies that are not yet understood - but may shed a dim light on the "toddler years" of some of the prime targets we investigate for habitability studies to date. Most importantly, I will link these astronomical findings to prebiotic chemistry and ozone sterilisation, identifying which new worlds might lie in a sweet spot for life - and will thus become the prime targets for future atmosphere and biosignature studies with JWST, Ariel, and LUVEX-class missions.

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The CHEOPS Mission: Selected Highlights of Scientific Results

Kevin Heng

Ludwig Maximilian University of Munich, Bavaria, Germany

The Characterising Exoplanet Satellite (CHEOPS) mission of the European Space Agency (ESA) is its first S-class mission. Launched in December 2019, it is a photometer designed to monitor transiting exoplanets with a precision of ~10 parts per million (ppm) or better. Its Guaranteed Telescope Observation (GTO) program was designed, over several years, and implemented by a science team comprising members from multiple European nations. As the former spokesperson of the Atmospheric Characterisation scientific theme, which later evolved into Working Group 4 of the CHEOPS mission, I will describe its scientific goals and motivation, which are mainly focused on measuring the geometric albedos and phase curves of hot Jupiters, as well as performing long-term monitoring of the enigmatic 55 Cancri e. I will focus on three highlights: the phase curve of the ultra-hot Jupiter KELT-9b and the measured geometric albedos of the benchmark hot Jupiters HD 189733b and HD 209458b. I will end with describing some future work: comparative exoplanetology of the TOI-178 system (where a CHEOPS-led proposal has procured Cycle 1 James Webb Space Telescope Guest Observer time) and why understanding geochemical outgassing is key to understanding the atmospheres of super Earths and sub-Neptunes.

Modelling the impact of cosmic rays on (exo)planetary atmospheres

K. Herbst[1], A. Bartenschlager[2], J. L. Grenfell[3], N. Iro[3], M. Sinnhuber[2], B. Taysum[3], and F. Wunderlich[3]

[1] *IEAP, Christian-Albrechts-Universität zu Kiel, Kiel, Germany*
[2] *Institut für Meteorologie und Klimaforschung, KIT, Eggenstein-Leopoldshafen, Germany*
[3] *Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt, Berlin, Germany*

Exoplanets are as diverse as they are fascinating. They vary from ultrahot Jupiter-like low-density planets to presumed gas-ice-rock mixture worlds that feature twice the Earth's bulk density. But much remains to be explored regarding the great diversity of exoplanetary atmospheres. With the James Webb Space Telescope (JWST) observing the first potential Earth-like exoplanetary atmospheres, we are now on the verge of entering a new era of exoplanetary science in which potential atmospheric biosignatures (such as ozone, nitrous oxide, and methane) are interpreted with increasing sophistication in terms of the evolution of the planet-star system, to assess and discount so-called false positives. However, to interpret the upcoming observations, model studies of planetary atmospheres that account for various processes — like an atmospheric escape, outgassing, climate, photochemistry, the physics of air showers, and the transport of cosmic rays through astrosphers, planetary magnetic fields, and planetary atmospheres — are necessary.

Here, as an introduction to the field, the impact of cosmic rays (CRs) on the atmospheric ionization and radiation exposure of the solar system planets Earth, Mars, and Venus will be discussed. Further, utilizing our unique model suite INCREASE [1, 2], we will present our most recent results of the CR impact on the habitability of the Earth-like exoplanet TRAPPIST-1e. Thereby, we will discuss the CR-induced radiation hazard on water-based life forms at the planetary surface of TRAPPIST-1e and give an outlook on the impact of CRs on atmospheric biosignatures due to potential stellar super flare events.

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High resolution spectroscopy of ultra-hot gas giant exoplanets

H.J. Hoeijmakers[1]
[1]Lund Observatory, Lund, Sweden

Ultra-hot Jupiters tend to orbit hot early type stars in short periods and are heated to extreme temperatures far over 2,000 K on their day-sides. All but the most strongly bound molecules are dissociated and many atoms may be significantly thermally ionised. The dominant sources of line opacity are due to metals and some molecules including metal oxides. Much of these absorb efficiently at short wavelengths, causing strong thermal inversions. These inversions affect the atmospheric structure, chemistry, as well as global circulation of gas and heat. Excitingly, these thermal inversions can be observed very effectively using high-resolution spectroscopy of the day-side, where a multitude of metals exhibit line emission. Together with transmission spectroscopy that senses the day-to-night terminator, we can use these observations to constrain the chemical and thermal structure of the atmosphere in three dimensions. We have analysed observations of a collection of ultra-hot Jupiters, and find tantalising commonalities and differences between them.

Stellar CME-Driven Energetic Particles Events from Young Solar-like Stars

J. Hu[1,2], V. Airapetian[3,4], G. Li[1,2], G. Zank[1,2], and M. Jin[5]

[1]*University of Alabama in Huntsville, Huntsville, AL, USA*
[2]*The Center for Space Plasma and Aeronomic Research, Huntsville, AL, USA*
[3]*American University, D.C., USA*
[4]*NASA/GSFC, Greenbelt, MD, USA*
[5] *Lockheed Martin Solar & Astrophysics Lab, Palo Alto, CA, USA*

Detection of superflares on active G to M dwarf stars opened a new avenue in understanding the properties of eruptive events and their impact on exoplanetary environments. Energetic solar flares are usually associated with fast Coronal Mass Ejections (CMEs) that produce extended shocks, the sites of efficient particle acceleration. Here, we present the results of a coupled improved Particles Acceleration and Transport in Heliopshere (iPATH) model with the 3D MHD model, Alfven Wave Solar Model (AWSoM), to study initiation, evolution and transport of Stellar Energetic Particle (StEP) events associated with superflares from young (400-600 Myr) and infant (1-10 Myr) solar-like stars. We derive the scaling of StEP's fluence and hardness of energy spectra with CME speed and associated flare energy. This study focuses on the acceleration of protons to very high energy (from hundreds of MeVs up to tens of GeVs) particles and their impact on erosion and chemistry of exoplanetary atmospheres. We also carry out a StEP case study using the data-constrained simulation of the ultra-fast stellar CME at Kappa[1] Ceti. The StEP associated with the CME-driven shock will be simulated with the inclusion of the shock information in the coronal region, which will greatly improve the accuracy for the StEP fluences at higher energies shortly after the CME eruption. These results have crucial implications for the prebiotic chemistry and expected biosignatures from atmospheres of early Earth and young rocky exoplanets as well as the chemistry and isotopic composition of circumstellar disks around infant suns.

Tidal star-planet interaction in planet-hosting wide binaries

N. Ilic[1,2], K. Poppenhaeger[1,2], and M.S. Hosseini[1,2]

[1]Leibniz-Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany
[2] University of Potsdam, Am Neuen Palais 10, 14469 Potsdam, Germany
E-mail: nilic@aip.de

The evolutionary path of single stars is mostly governed by angular momentum loss in the process of magnetic braking. However, if a star has a close-in stellar or planetary companion, tidal interaction may alter the stellar rotation and activity evolution. We explored if exoplanetary systems display observational evidence for star-planet tidal interaction in terms of such altered stellar rotation and activity level. Determining ages and therefore the expected rotational states of single field stars is very challenging. We, therefore, used a sample of planet-hosting stars that are accompanied by wide stellar companions. Without needing knowledge about the absolute ages of the stars, we test for relative differences in activity and rotation of the planet hosts and their co-eval stellar companions, using X-ray observations to measure the stellar activity levels. Employing three different tidal interaction models, we find that host stars with strongly tidally interacting planets display elevated activity levels compared to their companion stars. We also find that those activity levels and stellar rotation periods follow the usual rotation-activity relationships, implying that the effect is indeed caused by a long-term tidal interaction and not a purely magnetic interaction. Therefore, tidal star-planet interaction should be considered as an important process that is able to alter the stellar rotation rate and activity level, and therefore alter habitability conditions on planets that reside in the stellar habitable zone.

Magnetic star-planet interactions

E. Ilin[1]

[1]Leibniz-Institut für Astrophysik Potsdam (AIP), Potsdam, Germany

If we want to find out what makes for a habitable (exo)planet, we must understand the magnetic fields that surround them. We picture star-planet systems as embedded in a mixture of dynamo-generated and fossil fields, in analogy to the Solar System. Additionally, magnetized plasma flows out from the star and across the interplanetary space at a variety of speeds, densities, and temporal behaviors. While there is no doubt that magnetic fields play a major role in these systems, their architectures give us reason to expect that it differs considerably from our own. Yet, as of today, we are in dire need of techniques that can measure this dynamic magnetic environment at the required resolution.

Lately, magnetic star-planet interactions have been emerging as a key part of the solution. The processes involved can be traced back to the otherwise undetectable fields that bridge the distance between a planet and its host. More specifically, flaring star-planet interactions can be used as highly localized probes into star-planet system fields.

In this talk, I will map out our current understanding of magnetic, and in particular flaring, star-planet interactions from a theory-informed and observation-focused point of view. We will gain an overview over the insights about stars, planets and their shared environment that we have obtained from these interactions so far. We will conclude by looking ahead to what we can expect from observations of magnetic star-planet interactions in the near future.

Global Magnetohydrodynamics Modeling of Solar Coronal Mass Ejections and Application to Solar Analogs

Meng Jin

Lockheed Martin Solar & Astrophysics Lab, Palo Alto, CA, USA

The broad topic of space weather represents the constantly changing physical conditions in the near-Earth environment, which is significantly influenced by the solar wind, coronal mass ejections (CMEs), and Solar Energetic Particles (SEPs). Due to their critical importance to space weather prediction, significant efforts have been made in developing physics-based solar wind and CME/SEP models. In the first part of this talk, I will present some of our recent efforts of high-fidelity solar eruption modeling from the Sun to Earth, which emphasizes how the unique information provided by the advanced modeling, when combined with observations, could facilitate our understanding of fundamental processes in space and astrophysics. In the second part of this talk, I will discuss how the knowledge about our own star could help for exploration of exo-solar systems and habitable worlds in the universe, as well as developing new techniques to detect stellar CMEs.

New results concerning the Local Interstellar Medium: Inhomogeneity, Interactions with Helio/Astropheres, and Pressure Balance

Jeffrey Linsky[1]
[1] University of Colorado, Boulder Colorado, USA

I will describe the emerging new picture of the very local ISM (VLISM) and its interactions with the heliosphere and astrospheres in which exoplanets are embedded. One source of data comes from high-resolution ultraviolet spectra of nearby stars that contain one or more narrow interstellar absorption lines produced by neutral and ionized gas in the sight line to the star. These spectra obtained primarily with the STIS instrument on HST show that within about 10 pc there are many clouds with different velocity vectors and physical properties. Recent results show that these clouds are inhomogeneous with scales smaller than 5,000 AU. The clouds appear to fill the available space within 4 pc with overlap regions that have mixed properties. The very local environment in contact with the heliosphere is a mixed cloud region.

The second source of data is from satellites like Voyager, New Horizons, IBEX, and Ulysses inside of the heliosphere that measure the properties of plasma and neutral atoms inside the heliosphere and the inflowing neutral helium from the pristine VLISM. These data support quantitative models of the heliosphere regions (heliosheath, heliopause, disturbed VLISM). We find pressure balance between the different regions of the heliosphere, the surrounding pristine VLISM, the Local Cavity, and the gravitational force of the Galaxy. The identification of astrospheres and the stellar wind mass flux are measured from additional absorption blue-shifted from the interstellar absorption. Mass loss and photochemistry in exoplanet atmospheres are driven by stellar EUV radiation and stellar winds.

Living Around Young Suns: Magnetic Fields, Winds and Atmospheric Erosion around Young Stars and Implications for Habitability

T. Lueftinger[1] and S. Boro Saikia[2]

[1]European Space Agency, ESTEC, Noordwijk, The Netherlands
[2]Department of Astrophysics, University of Vienna, Austria

Planets orbiting young, active stars are embedded in an environment that is far from being as calm as the present solar neighbourhood. They experience the extreme environments of their host stars, which cannot have been without consequences for young stellar systems and the evolution of Earth-like planets to habitable worlds. Stellar Space Weather, triggered by magnetism and the related stellar activity is THE crucial driver of ionization, photodissociation, and chemistry in planetary atmospheres. Winds can compress planetary magnetospheres and even strip away the outer layers of their atmospheres, thus having an enormous impact on the atmospheres and the magnetospheres of surrounding exoplanets.

Stellar magnetic fields and winds also control the spin-down and therefore the activity evolution of a star. Modelling of magnetic fields and their winds is extremely challenging, both from the observational and the theoretical points of view, and only ground breaking advances in observational instrumentation and a deeper theoretical understanding of magnetohydrodynamic processes in stars enable us to model stellar magnetic fields and their winds – and the resulting influence on the atmospheres of surrounding exoplanets – in more and more detail. We address questions on the formation and habitability of environments in young, active stellar/planetary systems. We will discuss how stellar evolutionary aspects in relation to spin-down, activity, magnetic fields and winds influence the erosion of planetary atmospheres in the habitable zone.

3D MHD astrospheres: applications to IRC-10414 and Betelgeuse

D. M.-A Meyer[1], A. Mignone[2], M. Petrov[3], K. Scherer[4,5], P.F.Velazquez[6], P. Boumis[7]

1.Institut für Physik und Astronomie, Universität Potsdam,, Karl-Liebknecht-Strasse 24/25, D-14476 Potsdam, Germany
2. Dipartimento di Fisica Generale Facoltà di Scienze M.F.N., Università degli Studi di Torino, Via Pietro Giuria 1, I-10125 Torino, Italy
3. Max Planck Computing and Data Facility (MPCDF), Gießenbachstrasse 2, D-85748 Garching, Germany
4. Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universitäat Bochum, D-44780 Bochum, Germany
5. Research Department, Plasmas with Complex Interactions, Ruhr-Universitäat Bochum, D-44780 Bochum, Germany
6. Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, CP 04510, Mexico City, Mexico
7. Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, 15236, Penteli, Greece

A significative fraction of all massive stars in the Milky Way move supersonically through their local interstellar medium (ISM), producing bow shock nebulae by wind-ISM interaction. The stability of these observed astrospheres around cool massive stars challenges precedent 2D (magneto-)hydrodynamical (MHD) simulations of their surroundings. We present 3D MHD simulations of the circumstellar medium of runaway M-type red supergiant stars moving with velocity $v^* = 50$ km s−1 (Meyer et al. 2021). We treat the stellar wind with a Parker spiral and assume a 7 μG magnetization of the ISM. Our free parameter is the angle θ mag between ISM flow and magnetization, taken to 0◦ , 45◦ , and 90◦ . It is found that simulation dimension, coordinate systems, and grid effects can greatly affect the development of the modelled astrospheres. Nevertheless, as soon as the ISM flow and magnetization directions differs by more than a few degrees (θ mag ≥ 5◦), the bow shock is stabilized, most clumpiness and ragged structures vanishing. The complex shape of the bow shocks induce important projection effects, e.g. at optical H α line, producing complex of astrospheric morphologies. We speculate that those effects are also at work around earlier-type massive stars, which would explain their diversity of their observed arc-like nebula around runaway OB stars. Our 3D MHD models are fitting well observations of the astrospheres of several runaway red supergiant stars. The results interpret the smoothed astrosphere of IRC-10414 and Betelgeuse (αOri) are stabilized by an organized non-parallel ambient magnetic field. Our findings suggest that IRC-10414 is currently in a steady state of its evolution, and that Betelgeuse's bar is of interstellar origin.

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Fading memories of magnetic youths

Brett M. Morris[1]

[1]*Space Telescope Science Institute, Baltimore, MD, USA*

Telescopic observations of sunspots have been collected since Galileo, tracking their motions on the rotating solar surface and evolution in time. Despite the ever-improving precision of space-based photometry, starspot distributions on distant stars are notoriously hard to infer from rotational modulation of disk-integrated stellar photometry [1]. While we expect that young F, G, and K stars have larger spot coverage than older stars based on spectroscopic activity indicators [2], the relationship between age and spot coverage is challenging to constrain because the inversion problem suffers from many degeneracies. We take an approximate Bayesian approach to the photometric inversion problem [3]. We extract a simple observational light curve statistic for cluster stars observed with Kepler, K2, and TESS photometry, and infer which spot coverages are consistent with the observations via a simple starspot forward model [4]. The clusters range in age from 10 Myr to 4 Gyr, and decrease in typical spot coverage with age, from about 10% to 1%, respectively. Such constraints are in demand as exoplanet characterization pushes to smaller and younger planets, and spectroscopic contamination by stellar magnetic activity interferes with transmission spectroscopy, for example [5].

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Interior heating and outgassing of rocky exoplanets

L. Noack[1]

[1]*Freie Universität Berlin, Institute of Geological Sciences, Berlin, Germany*

The possible evolution paths of rocky planets – and therefore of their atmospheres – can be very diverse, and depend on several different processes related to for example the planet's mass and composition. Here I will give an overview of the different geophysical aspects that have been identified in the community in recent years and that are highly relevant for the long term thermal and chemical evolution of a planet - from the interior to the surface and atmosphere. These aspects include amongst others the specific composition of the planet (for example in terms of iron and volatile content, mantle rock composition, melt redox state), the planet differentiation into metal core and silicate mantle, the role of plate tectonics, and volcanic outgassing efficiency.

The latter critically depends on the interior energy budget and production of partial melt that can raise to the surface. Inside Earth, this heat is mostly produced by radiogenic heat sources, and left-over energy from the planetary accretion phase (called secular cooling). Close-in rocky exoplanets, depending on their exact orbital configuration and the magnetic field strength and alignment of their host star, may melt more easily due to additional energy sources such as tidal heating or magnetic induction heating, and should experience stronger volcanic outgassing than more Earth-like rocky planets.

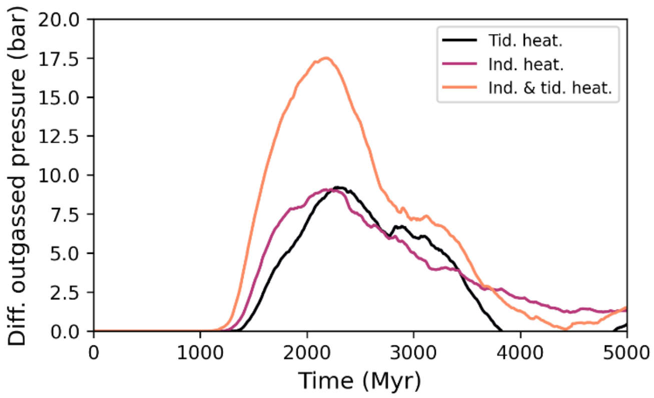

Fig 1: Results of an example simulation for Proxima Cen b to demonstrate the potential impact of tidal and/or induction heating in addition to radiogenic heating and secular cooling. The outgassing efficiency is expressed here via the difference in outgassed atmospheric pressure w.r.t. the reference case (only radiogenic heating and secular cooling) and increases in a similar way for both additional heat sources.

Fig. 1 shows a comparison of outgassing efficiency for different types of internal heat production based on [1] for a model configuration for Proxima Cen b that seems probable in terms of composition, actual planet mass and planet eccentricity.

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The case of Empirical Solar Energetic Particle Scaling Relations

Athanasios Papaioannou[1] and **Konstantin Herbst[2]**

[1] *National Observatory of Athens/IAASARS, Athens, Greece*
[2] *IEAP Christian-Albrechts-Universitat zu Kiel, Kiel, Germany*

Within a stellar context there are no recordings of Stellar Energetic Particles. Therefore, in order to discuss the potential impact of stellar (super)flares and coronal mass ejections (CMEs) to the space radiation environment conditions, a Sun-as-a-Star analogue is attempted. In this regard, scaling relations between Solar Energetic Particles (SEPs) peak proton flux (or fluence), flare signatures and CME characteristics at the Sun are being used. On the one hand, observations of solar and stellar flares show commonalities, suggesting a similar origin. On the other hand, solar eruptive events show scaling between flares, CMEs and SEPs. Thus, if applied to stellar flares and CMEs, a powerful and relatively straightforward way to probe the radiation environment at other stellar enviroments is within our reach. In this talk, a summary of the physical assumptions concerning global energetics of flares, CMEs and SEPs combined with their scaling relations is put forth. In particular, scaling relations expressing the CME speed (V_{CME}), and SEP peak flux (I_P) and fluence (F_P) in terms of flare SXR flux (F_{SXR}) are being presented. These are then combined with observations, estimating the upper limits of V_{CME} and F_P to be associated with known solar (super)flares, providing context for the stellar case.

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Observing Exoplanets with ESPRESSO

F. A. Pepe[1]

[1]*Département d'astronomie, Université de Genève, 1290 Versoix, Switzerland*

The ESPRESSO spectrograph at the VLT started operations on the October 1st, 2018. Within the frame of the Guaranteed-Time Observations we have executed three main programs concerning exoplanets: 1) A 'blind search for rocky exoplanets in the habitable zone of solar-like stars; 2) Transit spectroscopy of exoplanetary atmospheres; 3) Radial-velocity follow-up and precise mass determination of transiting exoplanets. During my talk I shall present the main results of these programs highlighting ESPRESSO's capabilities and performances. I won't omit a discussion on lessons learnt regarding instrumentation and observations. Also, I shall try to provide hints on how ESPRESSO(-like) instruments will contribute in the understanding of exoplanets and their habitability also in future.

The young planets in the V1298 Tau system and their atmospheres

K. Poppenhaeger[1,2]

[1]Leibniz Institute for Astrophysics Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[2] Potsdam University, Institute for Physics and Astronomy, Karl-Liebknecht-Str. 24/25,
14476 Potsdam, Germany

The atmospheres of planets can undergo significant erosion through evaporation. Different evaporation processes are investigated by the community, with atmospheric escape being driven by the stellar high-energy irradiation and escape driven by the core heat of the planets themselves being the main processes under study. For the stellar-driven evaporation it is important to take the high-energy evolution of the host star into account. We have recently characterized the high-energy environment of the four young planets in the ca. 25 Myr-old system V1298 Tau [1], where we found the host star to be highly magnetically active. The atmospheric mass loss can be quite significant over the next gigayears, and depends not only on the stellar activity, but also on the masses of the young exoplanets which have recently been refined [2]. The continued erosion of the planetary atmospheres can push some of the planets in the system from being mini-Neptunes, i.e. planets with substantial gas envelopes being located above the so-called exoplanet radius gap, to becoming super-Earths, i.e. mainly rocky planets below the radius gap [3], depending on the activity evolution of the host star. Multi-planet systems, both young and old, contain valuable "fossil" information about the evaporation history of exoplanets.

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The PLATO Mission

Heike Rauer, DLR, Institute of Planetary Research and FU Berlin, Germany

PLATO (PLAnetary Transits and Oscillations of stars) is ESA's M3 mission and designed to detect and characterize extrasolar planets by high-precision, long-term photometric and asteroseismic monitoring of a large number of stars. PLATO will detect small planets around bright stars, including terrestrial planets in the habitable zone of solar-like stars. With the complement of radial velocity observation from ground, planets will be characterized for their radius, mass, and age with high accuracy. PLATO will provide us the first large-scale catalogue of well-characterized small planets up to intermediate orbital periods, relevant for a meaningful comparison to planet formation theories and to better understand planet evolution. It will make possible comparative exoplanetology to place our solar system planets in a broader context. PLATO will study host stars using asteroseismology, allowing us to determine the stellar properties with high accuracy, substantially enhancing our knowledge of stellar structure and evolution.

PLATO is scheduled for a launch date end 2026. Following the successful Critical Milestone Review, ESA has given green light for the implementation of the spacecraft and the payload, which includes the serial production of its 26 cameras. This presentation will focus on PLATO science goals and provide an overview on mission development status.

Timing is Everything: Kinetics of UV-Driven Prebiotic Chemistry

P.B. Rimmer[1]

[1]*Cavendish Laboratory, University of Cambridge,*
JJ Thomson Ave, Cambridge CB3 0HE, United Kingdom

I will provide an overview of UV-driven prebiotic chemistry, concentrating on the cyanosulfidic and carboxysulfitic scenarios [1,2,3]. I will then discuss several ongoing projects to measure rate constants for reactions [4,5] and the application of these measurements to prebiotic chemistry on the surface of rocky planets [6,7]. These efforts are only part of the story. A larger amount of the chemical parameter space needs to be mapped out in order to analyze these scenarios and others using chemical networks. This will allow us to determine the interference from the geochemical environment, both positive and negative, following the approach of Walton et al. [8]. The goal is to discover productive organic chemistry that can take place without the chemist being present, and to identify where this chemistry is most likely to take place, both in the context of a microphysical environment, and in a planetary context. I will conclude by discussing this planetary context, focusing specifically on the interference chemistry caused by stellar activity [9].

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Long-term presence of liquid water on the surface of exomoons orbiting ejected free-floating planets

G. Roccetti[1,2], T. Grassi[3], B. Ercolano[2,4], K. Molaverdikhani[2,4], A. Crida[5], D. Braun[6] and A. Chiavassa[5]

[1]European Southern Observatory, Garching bei München, Germany
[2] Universitäts-Sternwarte, Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[3]Max-Planck-Instityt für extraterrestrische Physik, Garching bei München, Germany
[4]Exzellenzcluster „Origins“, Garching bei München, Germany
[5]Université Côte d’Azur, Observatoire de la Côte d’Azur, Nice, France
[6]Department of Physics, Center for Nanoscience Ludwig-Maximilians-Universität München, München, Germany

Free-floating planets (FFPs) can result from dynamical scattering processes happening in the first few million years of a planetary system's life. Several models predict the possibility, for these isolated planetary-mass objects, to retain exomoons after their ejection. FFPs are good candidates for the detection of exomoons [1]. Without the glare produced by a nearby star, high-contrast imaging is not necessary to detect the photometric transit signal of a potential satellite and the detection of massive moons should be already possible with existing instrumentation. The tidal heating mechanism and the presence of an atmosphere with a relatively high optical thickness may support the formation and maintenance of oceans of liquid water on the surface of these satellites [2]. In order to study the timescales over which liquid water could be maintained, we perform dynamical simulations of the ejection process and infer the resulting statistics of the population of surviving exomoons around FFPs. The subsequent tidal evolution of the moons' orbital parameters is a pivotal step to determine when the orbits will circularize, with a consequential decay of the tidal heating. We find that, considering CO2-dominated atmospheres, close-in ($a < 15$ Jupiter radii (R_J)), and massive moons (above the mass of Pluto) could retain liquid water on their surfaces for very long timescales, depending on the mass of the atmospheric envelope and the surface pressure assumed. For Earth-like pressure conditions ($p_0 = 1$ bar), satellites with a semi-major axis as close as 15 R_J and with an initial eccentricity of 0.30 could sustain liquid water on their surfaces up to 400 Myr. For higher surface pressures (10 and 100 bar), moons with semi-major axes of 18 and 24 R_J and smaller initial eccentricities (0.12 and 0.05) could lie in the Habitable Zone up to 3 and 10 Gyr, respectively

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The energetic particle environment of Sun-like and M dwarf stars

D. Rodgers-Lee[1]

[1]*Dublin Institute for Advanced Studies, Dublin, Ireland*
Email: dlee@cp.dias.ie

Energetic particles, in the form of stellar energetic particles and Galactic cosmic rays, can drive the formation of prebiotic molecules that are important for the origin of life [1]. The flux of stellar energetic particles and Galactic cosmic rays reaching exoplanets depends on the stellar wind environment of the host star. Much progress has been made in translating our knowledge of the observed suppression of Galactic cosmic rays by the solar wind to the level of suppression we might expect in other stellar systems.

I will present our results on the Galactic cosmic ray fluxes for a number of nearby M dwarf and solar-type stars [2,3,4]. I will discuss how studying the energetic particle environment of warm Neptunes, gas giant planets that are not typically thought to be habitable, can help inform us in the future about the conditions present on rocky planets orbiting in the habitable zone of their stars. I will also present our recent results studying the energetic particle environment of the M dwarf system, GJ 436. Finally, I will outline open questions in the field and how observations with JWST, and upcoming mission such as Ariel, may probe the energetic particle environment of gas giants.

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Exomoon-induced radial velocity signatures in spectra of exoplanetary atmospheres

M.Sc. F. Ruenger[1] **and Prof. K. Poppenhaeger**[1,2]

[1]University of Potsdam, Germany
[2]Leibniz Institute for Astrophysics (AIP), Potsdam, Germany

E-mail: fruenger@astro.physik.uni-potsdam.de

Exomoons, i.e. moons orbiting exoplanets, are interesting ingredients in our understanding of exoplanet habitability. Here we present a possible alternative for exomoon detections through high-resolution spectroscopy. We make use of the planetary atmosphere as a tool to precisely determine the exoplanet's overall radial velocity. Based on analytical sandbox models employing simple Keplerian mechanics for different scenarios, we make order-of-magnitude estimations on the expected planetary radial velocity oscillations and give an overview of the challenges we still need to overcome.

Which terrestrial exoplanets deserve more scrutiny for atmosphere viability?

E. Samara[1], S. Patsourakos[2], M. K. Georgoulis[3]

[1]*Centre for mathematical Plasma-Astrophysics, KU Leuven, Leuven, Belgium*
[2]*Department of Physics, University of Ioannina, Ioannina, Greece*
[3]*Research Center of Astronomy and Applied Mathematics (RCAAM) of the Academy of Athens, Athens, Greece*

We introduce a practical and physically intuitive method to assess whether a given exoplanet is a viable candidate for the existence of an atmosphere thanks to an efficient magnetospheric shielding from intense space weather activity originating from its host star. Our proposed mASC (magnetic Atmosphere Sustainability Constraint) relies on a best-case scenario for the dynamo-generated planetary magnetic field and subsequent magnetic pressure, and a worst-case scenario for the magnetic pressure of stellar CMEs. It provides a dimensionless ratio R whose excursion from unity implies accordingly an "atmosphere likely" ($R < 1$) or an "atmosphere unlikely" ($R > 1$) scenario. In this work, we implement our mASC on six "famous" exoplanets whose discovery was greeted with praise and hopes of habitability. These are Kepler-438b, Proxima-Centauri b, and Trappist-1d, -1e, -1f, -1g. We conclude that for none of them the existence of an atmosphere is likely while our findings are robust for five out of six cases. We conclude that the mASC ratio could help set observing priorities and suggest which exoplanets deserve further scrutiny, possibly toward the ultimate search of potential biosignatures, among other objectives.

Brown dwarfs as ideal candidates for detecting UV aurora outside the Solar System: Hubble Space Telescope observations of 2MASS J1237+6526

J. Saur[1], C. Willmes[1], C. Fischer[1], A. Wennmacher[1], L. Roth[2], A. Youngblood[3], D.F. Strobel[4], A. Reiners[5]

[1]University of Cologne, Cologne, Germany; [2]KTH Royal Institute of Technology, Stockholm, Sweden; [3]LASP University of Colorado, Boulder, USA; [4]Johns Hopkins University, Baltimore, USA; [5]University of Göttingen, Göttingen, Germany

Observations of auroral emission are powerful means to remotely sense the space plasma environment around planetary bodies and ultracool dwarfs. Therefore, successful searches and characterization of aurorae outside the Solar System will open new avenues in the area of extrasolar space physics. Introducing a parameter referred to as auroral power potential, we show that brown dwarfs, due to their typically strong surface magnetic fields and fast rotation, can produce auroral UV powers on the order of 10^{19} watt or more. Considering their negligible thermal UV emission, their potentially powerful auroral emissions make brown dwarfs ideal candidates for detecting extrasolar UV aurorae. We specifically search for UV aurora on the late-type T6.5 brown dwarf 2MASS J1237+6526. Based on Hubble Space Telescope observations obtained at near-UV, far-UV, and Ly-alpha wavelengths of 2MASS J1237+6526 we find possible emission from 2MASS J1237+6526, but cannot conclusively attribute it to the brown dwarf due to low signal-to-noise values in combination with non-systematic trends in the background fluxes. The observations provide upper limits for UV emission of about 1×10^{19} watt, which lies in the range of the theoretically expected values.

Habitable atsrospheres

K. Scherer[1], K. Herbst[2,] D. J. Bomans[3], N. E. Engelbrecht[4], S.E.S. Ferreira[4], L. Baalmann[5], F. Effenberger[1], J. Kleimann[1]

[1]*Institute for Theoretical Physics IV, RUB, Bochum, Germany*
[2]*Institut für Experimentelle and Angewandte Physik,CAU, Kiel, Germany*
[3] *Astronomisches Institut, RUB, Bochum, Germany*
[4]*Centre for Space Research, NWU, South Africa*
[5]*Institute for Particle and Astroparticle Physics, ETH, Switzerland*

The habitable planets around a host star are not only influenced by the stellar wind or flare activity, but are also embedded in the interstellar environment, which can also influence these planets and their atmospheres. We will show that, for certain classes of astrospheres, the inflow of the neutrals on the top of an exoplanetary atmosphere can be large.

This is done by modelling the interaction between the stellar wind and the interstellar medium using a two fluid MHD model. Moreover, such an 3D MHD simulation will also allow us to study the modulation of galactic cosmic rays in 3D, incorporating a turbulence transport model, so that the diffusion coefficients and the drift velocities can be modelled as far as possible from first principles.

We will also discuss the latter point.

The impact of stellar energetic particles on the composition of planetary atmospheres

M. Sinnhuber[1], **A. Bartenschlager[1], L. Grenfell[2], and K. Herbst[3]**

[1]Karlsruher Institute of Technology, Karlsruhe, Germany
[2] DLR Institute for Planetary Research, Berlin, Germany
[3]University of Kiel, Kiel, Germany

Energetic particles from the sun can have a great impact on the Earth's atmosphere: In the upper atmosphere above ~90 km, particle precipitation impacts the energy budget by Joule and particle heating, and collisions with abundant air atoms and molecules leads to the well-known auroral airglow. However, particle precipitation also affects the chemical composition of the atmosphere to much lower altitudes, down to about 30 km due to collision reactions which excite, ionize, or dissociate abundant species, initiating chains of fast chemical reactions leading, e.g., to the formation of nitric oxides, and to catalytic destruction of ozone at the top of the stratospheric ozone layer. These chains of processes are well understood for Earth[1]; however, as they depend on the main constituents of the Earth's middle atmosphere with a fixed mixing ratio of N_2 and O_2 and abundant water vapor, as well as on the strength and spectral shape of the solar radiation, they will likely be different in other planetary atmospheres, and with different stellar radiation.

We will summarize the state of the art for the terrestrial atmosphere, and present results of new model experiments of large solar or stellar particle events with our INCREASE modelling chain[2] for a thin CO_2-dominated atmosphere and weak solar illumination (Mars), and for a series of Earth-like atmospheres with varying amounts of CO_2, H_2O, N_2 and O_2, with a red-shifted stellar radiation (Trappist-1e).

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On the Geophysics of (Exo)Planets

Tilman Spohn

ISSI, Bern, CH and DLR Institute of Planetary Research, Berlin, D

More than 5000 exoplanets have been detected, with another >5000 candidates awaiting confirmation. Of the confirmed planets, about 1500 have radii < R_{Earth} and about 270 masses smaller than 10 Earth masses. A significant number of planets orbit their host star in the habitable zone and potentially harbor extraterrestrial life. While the concept of the habitable zone is useful is useful for a first assessment of the chance of detecting extraterrestrial life, it is likely too unspecific for targeting sophisticated follow-up observation.

These considerations show that a discussion of the “workings” of exoplanets should go far beyond simple models of their interior and their environment based on their radius and mass and on their orbital distance from the host star. Rather, the discussion should include aspects of geophysics and geology such as the tectonic modes, atmosphere and magnetic field evolution and star – planet interactions, from the process of formation to later in the evolution of the planet’s envelopes. The rocky planets in the solar system matter in this context as type-examples for lifeless and mostly waterless rocky planets that may have earlier had more clement environmental conditions.

To the geoscientist, planets play an important role as objects of comparison, if only to assess how unusual or common Earth is and motivate considerations of its properties in ways that would likely never have been raised otherwise. For instance, recent data and models [e.g.,1] suggest that the Earth is unusually dry allowing for land surfaces with high net primary (bio)productivity, NPP, that would else have been flooded. Moreover, its balanced share of land and ocean surfaces maximizes the NPP [e.g., 2] but is arguably an unexpected consequence of plate tectonics [3] maximizing the total length of subduction zones. More likely outcomes based on the tectonic mode alone would be either a land planet or an ocean planet. Are we simply very fortunate to live on a planet with these properties?

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Synergies between dust and heliospheric/astrospheric science

V.J. Sterken[1] and M. Landgraf[2] and S. Hunziker[1] and L. Baalmann[1] and K. Dialynas[3] and K. Herbst[4] and A. Li[5] and P. Frisch[6] and J. Miller[7] and B. Fields[8] and J. Baggaley[9]

[1] *Institute for Particle Physics and Astrophysics, Physics Dept., ETH Zürich, Wolfgang-Pauli Strasse 27, Zürich, Switzerland*
[2] *ESA-ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, the Netherlands*
[3] Office of Space Research and Technology, Academy of Athens, 4, Soranou Efesiou str., 11527, Papagos, Athens, Greece
[4] *Inst. of Exp. and Applied Physics (IEAP), Fac. of Math. and Natural Sciences, Christian-Albrechts-University of Kiel, Leibnizstrasse 11-19, 24118, Kiel, Germany*
[5] *Department of Physics and Astronomy, University of Missouri, 223 Physics Building, Columbia, MO 65211, Missouri, USA*
[6] *University of Chicago, Astronomy & Astrophysics Center, 5640 South Ellis Ave, Chicago, 60637, Illinois (IL), USA*
[7] *Astronomy Department, Boston University, Cambridge, Massachusetts, USA*
[8] *Center for Theoretical Astrophysics, Departments of Astronomy and Physics, University of Illinois, Urbana, IL 61801, Illinois, USA*
[9] *Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand*

In this talk we focus on the synergies between heliospheric/astrospheric and cosmic dust science, on the space missions that can propel these two fields (and their interrelations) forward, and how the dust environment may influence the conditions for life on Earth.

We present the state of knowledge of interstellar dust in the Local Interstellar Cloud and dust in the heliosphere, how they influence each other, the relevant measurements made in the solar system, observations using astronomical methods, current modelling efforts, and the dust dynamics in the heliosphere. We highlight the open and compelling science questions related to the dust-heliosphere interaction, give examples of missions / mission concepts that examine both, and finish the talk with some remarks about the possible influences of the dust environment on habitability of planets.

Stellar activity: correlation between starspots and superflares

Alexandre Araújo[1] and Adriana Valio[1]

[1]Center for Radio Astronomy and Astrophysics Mackenzie (CRAAM), Mackenzie Presbyterian University, São Paulo, Brazil

Stellar magnetic activity, just like that of the Sun, manifests itself in the form of flares and spots on the surface of the star. In the solar case, flares originate in active regions. In this work, we present a study of the activity of the a few stars observed by Kepler, including flare detection and spot modeling from planetary transits. Our goal is to search for a correlation between the properties of starspots with the energy of superflares. We focus on Kepler-411 [1] is a K2V type star with an average rotation period of 10.52 days, radius of 0.79 R_{sun}, and a mass of 0.83 M_{sun}. Transit mapping allowed for the characterization of 198 starspots with estimates of their radius and temperature. Visual inspection of the light curves of Kepler-411 yields the identification of 65 superflares. The detected superflares lasted from 8 to 260 minutes, with energies varying from 10^{33}–10^{35} ergs. A positive correlation between the area of starspots and the energy of superflares was found when considering the averages taken every 16–35 days, with the highest correlation occurring for averages every 21 days, probably related to the lifetime of the Kepler-411 spots. We also investigate why other stars with many spots detected do not produce any flare.

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Radio detection of extrasolar space weather and magnetic fields

Harish K. Vedantham[1,2]

[1] *ASTRON- Netherlands Institute for Radio Astronomy*
[2] *Kapteyn Astronomical Institute, University of Groningen*

Low frequency (< few hundred MHz) radio observations uniquely probe several processes that determine the habitability of exoplanets such as coronal mass ejections and exoplanet magnetospheres. Radio observations of such phenomena in the solar system are commonplace. I will argue that the extrasolar frontier is now also within reach thanks to powerful new low-frequency telescopes such as LOFAR. I will describe an observational program using LOFAR to systematically survey the low-frequency radio sky for stellar, brown dwarf and exoplanetary emissions with unprecedented sensitivities. I will present some early successes of this campaign including (a) the discovery of evidence for magnetic interaction between a star and its planet (b) the discovery of a cold brown dwarf directly in the radio band using its magnetospheric emissions and (c) solar-type radio bursts on nearby stars possibly associated with coronal mass ejections. I will end with an outlook for harnessing radio astronomy's unique diagnostic capabilities to advance exoplanet science.

Simulations of Stellar CMEs and their responses in synthetic spectra

Yu Xu[1,2], Julián David Alvarado-Goméz[2], Hui Tian[1] and Katja Poppenhaeger[2]

[1]School of Earth and Space Sciences, Peking University, 100871 Beijing, People's Republic of China
[2] Leibniz Institute for Astrophysics Potsdam, 14482 Potsdam, Germany

Coronal mass ejections (CMEs) on the hosting stars are considered to be one of the decisive factors that affect the habitability of its orbiting planets. We conducted MHD simulations of stellar CMEs on late-type stars using the Space Weather Modeling Framework (SWMF). We traced the propagation and evolution of CMEs in the three-dimensional (3D) outputs. Coronal dimming/brightening are shown on the synthetic EUV images in different passbands. Line profiles of several EUV and soft X-ray lines are calculated. Doppler shifts or the red-blue wing asymmetry, and their developments are expected to be seen during the launch and early propagation of CMEs. Our investigations set constrains on the detectability of stellar CMEs through line asymmetries and provide guidelines for the future search of stellar CMEs.

Abstracts of Posters

(in alphabetical order)

The environment of faculae- versus spot-dominated stars

E. M. Amazo-Gómez[1] and K. Poppenhäger[1, 2]

[1] Leibniz Institute for Astrophysics Potsdam, Germany

[2] University of Potsdam, Germany

Photospheres of sunlike stars have been found to display a smooth transition between being dominated by spots or by faculae features. We found that the Sun lies in the transition between the spot and faculae domination regime. Some hypotheses have been explored suggesting that such surface manifestations may correlate with different magnetic dynamo modes. By using a recently developed method based on the Gradient of the Power Spectra (GPS), we quantified the ratio between faculae to spot signatures based on solar and stellar light curves. We characterized a sample of 30 sunlike stars, with and without detected exoplanets, which we have identified to have different levels of spot- or faculae-dominance on their surface. We analyzed the longitudinal magnetic field and additional activity indicators such as the S-Index from the calcium H&K core line, H-alpha, and the Ca triplet in the near infrared. We interpret the differences between having spot- versus faculae-dominated stellar surfaces in the context of possible different effects over their stellar environment and planetary habitability.

Investigation of the Influence of Stellar Particle Events and Galactic Cosmic Rays on the Atmosphere of TRAPPIST-1e

Andreas Bartenschlager, Miriam Sinnhuber
Karlsruher Institute of Technology, Germany

John Lee Grenfell, Ben Taysum, Fabian Wunderlich
German Aerospace Center, Berlin, Germany

Konstantin Herbst
University of Kiel, Germany

andreas.bartenschlager@kit.edu

Abstract

The launch of the James Webb Space Telescope (JWST) in December 2021 opens up the possibility of studying the composition of exoplanetary atmospheres in habitable zones, such as TRAPPIST-1e, in the near future. With the help of numerical models of the exoplanetary atmospheres, the observations and the processes behind them can be better understood and interpreted (Herbst et al., 2022). We investigate the influence of stellar energetic particles (SEPs) and galactic cosmic rays (GCR) on the atmospheric chemistry of exoplanets around a very active M-star using the ion chemistry model ExoTIC. In collaboration with the University of Kiel and DLR Berlin, we perform model experiments with different N_2 or CO_2 dominated atmospheres, depending on the initial CO_2 partial pressure, as well as humid and dry conditions (Wunderlich et al., 2020), taking into account the ionization rates for such events. A further specification regarding the scenarios results from the distinction between dead and alive atmospheres, which are characterized by a lower or higher oxygen fraction in the initial conditions. Preliminary results show a significant impact of SEP events on the chemical composition of the atmosphere, including biosignatures such as O_3. The strength and structure of these impacts depend on the composition of the starting atmosphere, in particular on the availability of oxygen as well as N_2 and water vapour.

Keywords
ExoTIC, Exoplanetary Atmospheres, SEP and GCR events

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The Faint Young Sun Paradox and the Anthropic Principle in the Context of Dark-Energy-Dominated Cosmology

Yurii V. Dumin[1,2] **and Michal Křížek**[3]

[1] *Max Planck Institute for the Physics of Complex Systems, Dresden, Germany*
[2] *Sternberg Astronomical Institute, Lomonosov Moscow State University, Russia*
[3] *Institute of Mathematics, Czech Academy of Sciences, Prague, Czech Republic*
E-mail: dumin@pks.mpg.de, krizek@math.cas.cz

Habitability of the Earth and other planets depends on a lot of physical processes, including a probable presence of the small-scale cosmological effects, such as the local Hubble expansion. The problem of local Hubble expansion was studied for almost nine decades [1] but remains a very controversial subject till now [2, 3]. A new impetus to this idea was given by the concept of "Dark Energy" (or the effective Λ-term in Einstein equation), which became a commonly-accepted paradigm in cosmology in the last two decades: Since the Λ-term is distributed perfectly uniform everywhere, the cosmological effects could be expected at any scales [4], and self-consistent treatment in the framework of General Relativity confirms this option [5].

As regards application to the problem of habitability of planets, the presence of local Hubble expansion enables us to easily resolve the so-called Young Faint Sun paradox, i.e., the impossibility of existence of a liquid water on the Earth 2–3 billion years ago, which was necessary for the emergence of the life [6, 7]. In this case, the insufficient luminosity of the Sun was compensated by a shorter distance to the Earth at that time [8, 9]. The same effect should be evidently expected for exoplanets. In fact, this enables us to formulate a new version of the so-called Anthropic Principle, i.e., the statement that emergence and development of the life on a planet is possible only at the specific, quite narrow range of values of the fundamental physical constants. As follows from our treatment of the Young Faint Sun paradox, this set of constants should include also the local value of the Hubble parameter.

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Space environment and magnetospheric Poynting fluxes of the exoplanet Tau Boötis b

F. Elekes[1] and J. Saur[1,2]

[1]*Institute forGeophysics and Meteorology, Univ. of Cologne, Cologne, Germany*
email: f.elekes@uini-koeln.de
[2] *email: jsaur@uni-koeln.de*

The first tentative detection of a magnetic field on the Hot Jupiter exoplanet Tau Boötis b was recently reported by Turner et al. (2020)[1]. The planetary magnetic field was inferred from observations of circularly-polarized radio emission obtained with the LOFAR telescopes. The observed radio emission is possibly a consequence of the interaction of the surrounding stellar wind with the planet's magnetic field. Therefore, we perform magnetohydrodynamic simulations to better understand the space environment around Tau Boötis b and its interaction with the stellar wind. We investigate the magnetospheric energy fluxes and effects of different magnetic field orientations in order to understand the physical origin and the mechanisms that may lead to the observed radio emission given the proposed magnetic field strength in Turner et al. (2020). We find in our simulations that the interaction is super–Alfvenic and energy fluxes generated by the stellar wind–planet interaction are energetically consistent with the observed radio powers in Turner et al. (2021) for a magnetospheric Poynting flux–to–radio efficiency > 1e−3. In case of a magnetic polarity reversal of the host star from an aligned to anti-aligned magnetic field configuration, expected radio powers in the magnetospheric emission scenario fall below the observable limits.

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Climates of short-period tidally locked exoplanets

J. Lirawi[1], T.F. Illenseer[1] and W.J. Duschl[1,2]

[1] *University of Kiel, Institute of Theoretical Physics and Astrophysics, Kiel, Germany*
[2] *The University of Arizona, steward Observatory, Tucson, AZ, USA*

The habitability of tidally locked exoplanets has been studied extensively recently. In many cases, attention has been paid to the loss of liquid water, which can occur through escape mechanisms or by freezing out as ice. When considering the freezing out of water on the nightside of tidally locked exoplanets, the dynamics of the atmosphere and ocean play an important role. These dynamics change significantly for tidally locked exoplanets when they have very short orbital periods [1]. Nevertheless, the climate systems in this "fast-rotator" regime are yet not well understood.

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The Impact of Clouds on the Radius Evolution of Hot Jupiters

A. J. Poser [1], N. Nettelmann [2], and R. Redmer [1]
[1]Institute of Physics, University of Rostock, Rostock, Germany
[2]Institute of Planetary Research, German Aerospace Center, Berlin, Germany

Giant planets may inhibit valuable information on formation processes in their interiors and atmospheres [1]. Their current internal structure and today's observed luminosity is especially determined by their long-term internal evolution due to contraction and cooling. For cooler gas giants (T_{eq}<1000K), evolutionary calculations can predict today's measured luminosity and radius. But for warmer planets (T_{eq}>1000K), additionally extra energy mechanisms are needed to explain the measured radius [3,4]. Slowing down contraction due to higher atmospheric opacities and a consequently reduced cooling rate has been discussed previously as a possible contributing mechanism to the observed radius inflation. An enhanced opacity in the atmosphere can be due to a higher metallicity [5] or due to clouds and hazes as expected to be found in almost all giant planets.

Of particular interest to us is in what way an opacity enhanced atmosphere due to additional absorbers such as clouds influence the planetary thermal evolution, particularly the radius evolution. Therefore we couple the thermal evolution, interior structure models and atmospheric models, as in Poser et al. (2019) [6] . To approximate the long-term atmospheric evolution, we simulate cloud decks in an ad-hoc manner via the semi-analytical model by Heng et al (2010) [7,8] . In detail, the cloud deck location and the cloud opacity are tagged along the thermal evolution. This allows us to study at first order how time-varying cloud decks may influence the radius evolution of giant planets. We look into the effects of different cloud deck locations and opacities on the radius for the young TOI-1268b (T_{eq}=919K) and evolved WASP-39b (T_{eq}=1116K) , both Saturn-like [9,10].

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SPP 1992 - Exploring the diversity of extrasolar planets

T. Schumann[1] **and L. Scheibe**[1]

[1] *Technische Universitaet Berlin, Zentrum für Astronomie und Astrophysik, Germany*

One of the most exciting recent discoveries in astronomy is the existence of a huge variety of extrasolar planets orbiting other stars, including numerous multi-planet systems. Exoplanets can be very different to those found in our Solar System in terms of size, composition and system architecture.

This Priority Programme aims to explore such diversity, understand its origins and wants to make substantial contributions to answering the following fundamental questions: What does the diversity of exoplanets tell us about their formation processes and the evolution of planets and planetary systems? What can we learn about the astrophysical conditions necessary to harbour life and are these conditions common in our Milky Way?

This requires combined efforts across disciplines, linking observational planet detection and characterization to theory. Science areas addressed in this SPP 1992 therefore include: the detection of exoplanets and observational characterization of their properties such as orbit, mass, radius, atmosphere; and the modeling of exoplanet properties in terms of evolution processes, planetary interiors, habitability, formation and atmospheres.

Within the SPP 1992, 51 projects at 17 research institutions all over Germany have been funded by the German Research Foundation, establishing and strengthening collaboration between different sites of exoplanet research.

Structure around LBV: astrospheres or more?

K. Weis[1] and D.J. Bomans[1]

[1]*Astronomical Insitute, Ruhr University Bochum, Bochum, Germany*

The winds of stars have a large impact on the both the evolution of the star and the surrounding ISM. For massive stars, which drive the strongest winds, our understanding of the mass loss and impact on the ISM is essential to also understand the evolution of the internal stellar structure. LBVs are evolved massive stars which loose mass by enhanced mass loss phases and in eruptive events.
I will summarize the nature of these stars and their circumstellar environment in connection or contrast less massive main-sequence and supergiant stars. A short overview will be given about what are Luminous Blue Variables (LBVs). Presented are the observational characteristics that are unique to LBVs. Are the structures around LBVs astrospheres from the strong stellar winds, circumstellar denser nebulae or are both components present. How do these nebulae look like and what does that imply for the formation mechanism. Furthermore their evolutionary status is put into context with other phases of massive stars and their influence on the surrounding starforming regions is discussed.

Determination of rare SPE spectra with application to Earth and the extrasolar gas giant HD209458b

J.M. Wissing[1], A.J. Poser[1], O.S. Yakovchuk[1], and R. Redmer[1]

[1]*University of Rostock, Rostock, Germany*

Extreme solar particle events (SPEs) are rare by definition. In our solar system, satellites offer measurements of a couple of major SPEs, but the really extreme ones can only be found in historical data such as ice cores. Unfortunately, it seems that spectral information cannot be retrieved from such archives. Nevertheless, the shape of the spectrum is crucial for the vertical ionization profile. In the terrestrial example, an offset of some kilometers in atmospheric altitude may lead to photolytic destruction or tropospheric wash out of chemical follow-ups. For HD209458b, we found that a significant fraction of the particles' energy is reflected into space.

Our approach is, first, to determine the probability of rare solar particle events by a statistical approach using in-situ particle measurements. This allows the determination of particle spectra for events happening once in a thousand years or even once per 10ka.

In a second step, these SPE spectra will then be applied to the planetary atmospheres of Earth as well as the gas giant HD209458b also known as "Osiris", an exoplanet with a close orbit around a sun-like star.
These calculations are performed by the Geant4-toolkit and result in ionisation spectra. The vertical pressure-temperature structure of HD209458b is derived by fitting a semi-analytical T(P) function to previously published profiles [1, 2].
An inter-comparison of the different setups and their results will be discussed.

References

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Exploration of best-practice telluric correction methods to optimize ground-based exoplanet spectroscopy for the detection of biosignatures

J. Wokittel[12] **and K. Poppenhaeger**[2]

[1] *Geographical Institute, Humboldt-University, Berlin, Germany*
[2] *Leibniz-Institute for Astrophysics Potsdam, Potsdam, Germany*

The presence of atmospheric chemical disequilibrium has generally been proposed as detectable biosignature for exoplanets. However, our knowledge of exoplanet atmospheres is either limited by the resolution capacity of the telescopes and spectrographs in space or, for ground-based observations by the absorption and scattering due to Earth's atmosphere. Ground-based high-resolution observations will remain the key tool for probing exoplanet atmospheres for the foreseeable future, for example with the PEPSI high-resolution spectrograph at LBT. Thus, it is necessary to explore and quantify the performance of different approaches that remove absorption and scattering features due to the Earth's atmosphere from spectroscopic transit observations (so-called telluric lines). Physical models of the Earth atmosphere can be used to treat tellurics in observations, but they depend on the completeness of the used telluric line atlas based on LBLRTM and an atmospheric pressure profile, such as Molecfit [1]. Alternatively we can use statistical approaches analysing the variability of the observed spectra themselves throughout the observation, such as Sysrem [2], or our purely data-based approach [3]. In our approach, we analyze the behavior of each individual spectral pixel throughout the observing night and approximate its changes in flux with a low-order smoothing spline. Our preliminary results show that this approach can remove tellurics from the exoplanet transmission spectrum efficiently, while leaving exoplanetary signals mostly intact. We compare this to the tellurics removal performed by ESO's molecfit tool.

References

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