Density Matters 2024:
Uncovering the Formation, Interior Structure and Evolution of Small Exoplanets

Abstract Booklet

R. Burn & R. Luque on behalf of the SOC
densitymatters2024@mpia.de

More information can be found on:
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About

With the launch of JWST and the increasing performance of ground-based facilities, the field of exoplanetary sciences has moved to the *characterization stage* of small planets.
The goal of this workshop is to gather researchers interested in the various aspects of the observed and theoretically-predicted properties of super-Earths and sub-Neptunes. Our aim is to foster meaningful exchanges among attendees, driving new developments on the various modeling aspects that incorporate the observational constraints that recent (and upcoming) studies provide.

Organizing committee

Name	Organization
Remo Burn	MPIA
Rafael Luque	University of Chicaco
Natalie Batalha	UC Santa Cruz
Hubert Klahr	MPIA
Enric Palle	Instituto de Astrofisica de Canarias
Allona Vazan	The Open University of Israel
Björn Benneke	University of Montreal
Julia Venturini	University of Geneva

List of Abstracts – Talks

Monday 5th

Formation

Remo Burn: A radius valley between migrated steam worlds and evaporated rocky cores I will present the work which motivated the proposal of this workshop. We recently showed, that the planetary radius valley can be explained as the transition from rocky super Earths to migrated (supercritical) water vapor worlds (here 'steam worlds'). This result is in agreement with planetesimal-based planet formation models including migration. However, there were several modeling challenges and we treated to us unknown ground in terms of atmospheric and internal modeling. Finally, the mass-radius relation of planets orbiting M dwarfs might help to unravel further detailed aspects on the planetary evolution.

Eve J. Lee: Radius, Mass, and Long Period Planets The exoplanet landscape in radius, mass, and period space reveals various peaks and valleys. The origin of such features remains debated. I will discuss how the exoplanet population beyond 30 days presents the more pristine laboratory of testing different formation channels. I will further examine ways in which upcoming missions can be leveraged to distinguish between different birth conditions of exoplanets.

Chris Ormel: Consumption and recycling of pebbles in pre-planetary atmospheres When planets grow massive in protoplanetary disks, they gravitationally attract the disks's gas to form an extended, hot envelope. For low-mass planets this envelope remains in pressure equilibrium with the disk gas. From hydrodynamical simulations it has been pointed out that there can nevertheless be a significant exchange of gas between disk and planet, which has important consequences for the thermodynamical evolution of these envelopes. We now have addressed whether such recycling flows can also operate on pebbles. To this effect, we have modified the Athena++ code to include sublimation and freezeout phase change processes, enabling us to understand the fate of pebbles accreting in these envelopes. We find that the simulations can be classified into two groups: "recycling-dominated", where ices sublimate and return to the disk and "vapor-dominated", where the amount of vapor increases gradually. The outcome suggests a compositional dichotomy, with the former group remaining dry (terrestrial) and the latter becoming wet (water worlds).

Octavio Miguel Guilera: The impact of the dust torque on the formation of low-mass planets Most of the works dealing with planet migration focus on the interaction between the planet and the gaseous disk, neglecting the role of the dust component. However, multifluid hydrodynamical simulations performed in the last quinquennium have shown that the dust can generate a non-negligible contribution to the total torque over the planet. We recently incorporated this phenomenon in our global model of planet formation. Thus, the aim of this talk is to show the impact of the torque exerted by the solid component of the disk on the migration of low-mass planets growing by pebble accretion.

Gijs D. Mulders: Where are the Water Worlds? Identifying the Exo-water-worlds Using Models of Planet Formation and Atmospheric Evolution Water worlds are an elusive group of planets whose existence has been predicted based on planet formation models. While direct evidence of such planets is hard to obtain due to degeneracies in internal structure models of planet cores with and without hydrogen atmospheres, it is likely that some of the observed transiting planets are indeed water worlds. By combining various planet formation models from the Genesis library with atmospheric escape models, we find that up to 20% of observable transiting planets could be water worlds. However, most of the water rich planets are predicted to be outside a period of 10 days, a slight mismatch with current observational strategies for radial velocity and spectroscopic follow-up.

Demographics

Natalie M. Batalha: Taking Measure of the Diversity of the Sub-Neptune Population of Exoplanets Kepler revealed the dramatic abundance of super-earth and mini-neptune sized planets in the galaxy (which we collectively refer to as sub-Neptunes) and provided survey data adequate for demographic studies. TESS detected hundreds of nearby transiting sub-Neptunes amenable to detailed characterization. JWST enabled studies of the atmospheric properties of the sub-Neptune population. We leverage data from all three space missions and ground-based doppler instruments to quantify the diversity of the sub-neptune population and compare empirical distributions with population synthesis models from theory. The long-term goal is to understand the nature of the sub-neptune population, their structure and volatile content, and the implications for habitability.

Johanna Teske: Population Surveys of Small Planet Densities and Atmospheres In this talk I will discuss the structure and latest results from a two-part "concentric" survey I am co-leading to measure small planet compositions (bulk densities and atmospheres) in a statistically robust framework. The Magellan-TESS Survey (MTS) and the COMPASS (Compositions of Mini-Planets for Atmospheric Statistical Study) Program utilize transiting (TESS, JWST) and radial velocity/Doppler (Magellan/PFS) techniques to try to connect observed planet distributions to the true underlying populations and the processes that shape them. Such population studies – and, importantly, how we construct them – will help hone in on where we should focus future efforts as we move deeper into the era of exoplanet characterization and towards uncovering Earth-like conditions on other worlds.

Enric Palle: THIRSTEE: constraining the observational properties of the water world population Very recently, we proposed that for M dwarf hosts, the radius valley might be a consequence of interior composition rather than an indicator of atmospheric mass loss. Strong evidence of a large population of water worlds orbiting M dwarfs was seen by refining the masses and radii of a few known planets. A similar result for FGK stars would transform our interpretation of Kepler-based planet demographics, but first, we need precise masses for a meaningful sample of high-value targets. We proposed to begin achieving this goal by 1) enlarging the sample of precisely-characterized water world/rocky planet candidates around M dwarfs, and 2) improving the mass determination of seemingly intermediate water mass fraction planets around FGK-type stars. To accomplished this goal, time has been awarded in 2023/24 at several facilities including ESPRESSO, HARPS, HARPS-N, HIRES and CARMENES. We report the new results on this characterization effort of the water world population.

Léna Parc: Exploring the observational and theoretical transition between Super-Earths and Sub-Neptunes around M- and FGK-stars With the updated PlanetS catalog of well characterized and reliable transiting planets, we revisit the bimodality of small planets orbiting M-dwarfs described by Luque & Pallé (2022) between terrestrial planets and water-worlds. By using more robust methods than the usual histograms, we draw the radius and density distribution of these planets and show the continuity of compositions between the two populations and the fading of the radius valley for low-mass stars. This enables us to explore the close connections between observations and theories related to the formation, evolution, and internal structure models. The study extends to FGK-dwarfs and the evolution of these results with the spectral type of the host star. Enlarging our samples is key to obtaining robust statistical results : we present the potential of the Near InfraRed Planet Searcher (NIRPS) spectrometer to determine and improve mass measurements of small planets in orbit around M-dwarf stars.

Jo Ann Egger: Hot water worlds: Populating forbidden regions in the mass-radius diagram for close-in planets A central question in exoplanetary research is the composition and internal structure of exoplanets, as it is one of the most promising strategies for constraining planet formation and evolution processes. However, especially for small exoplanets such as super-Earths and sub-Neptunes, a wide range of compositions is compatible with their observed densities. Usually, the best option is to use Bayesian inference to obtain a probability distribution of a planet's internal structure parameters.
This intrinsic degeneracy is complicating a direct comparison between theoretically modelled and observed exoplanet populations. As a possible solution to this problem, we identified regions in the mass-radius diagram where it is not possible for close-in planets to exist unless they contain volatiles, at least according to current evaporation theories. This makes planets located there promising water world candidates. Here, we present the science case of our CHEOPS GTO programme that aims to populate these "forbidden" regions with well-characterised planets, along with the new and improved Bayesian internal structure modelling framework that we developed.

Tuesday 6th

Atmospheres

Nikku Madhusudhan: Habitability in the Sub-Neptune Regime The search for life elsewhere is the holy grail of modern astronomy. The detection of atmospheric signatures of habitable Earth-like exoplanets is challenging due to their small planet-star size contrast and thin atmospheres with high mean molecular weight. The vast diversity of system parameters in the sub-Neptune regime opens new regimes of exoplanetary habitability, increasing the target volume in the search for life elsewhere. These include the recently proposed Hycean worlds, with habitable ocean-covered surfaces underlying hydrogen-rich atmospheres. We will discuss observational and theoretical developments in the atmospheric characterisation of temperate sub-Neptunes, and Hycean worlds in particular. Considering the JWST spectrum of K2-18b, we will discuss inferences of the atmospheric chemical composition and constraints on the temperature structure, clouds/hazes, chemical disequilibrium and interior/surface conditions. We will discuss future prospects and central questions in the search for habitable environments and biosignatures in temperate sub-Neptunes with JWST.

Eva-Maria Ahrer: A first look at water world candidates GJ9827d and GJ3090b with JWST In this talk I will discuss two water world candidates, GJ9827d and GJ3090b. I will present the properties of these planets which make them particularly enticing to study, which led them to be selected as targets for the JWST water world program (#4098, B. Benneke, T. Mikal-Evans). In this program, each water world candidate will be observed twice with each NIRISS/SOSS and NIRSpec/G395H, resulting in an overall wavelength coverage of 0.6 - 5.2 micron. Thus far we observed two transits of GJ9827d (with SOSS) and three transits of GJ3090b (two with G395H, one with SOSS), from which I will share preliminary results and discuss potential implications for these planets atmospheres.

Renyu Hu: Distinguish and Characterize Temperate and Para-temperate Water-rich Planets A handful of small (R_p < 2.5 $R_\oplus$) exoplanets that are temperate (T_eq < 320K) and para-temperate (T_eq < 400K) are suitable for detailed atmospheric characterization using JWST. The first-order question about these planets is to determine whether they have a massive He/He envelope, or a water-rich interior. This question is particularly important for temperate and perhaps para-temperate planets because temperate water-rich planets without massive gas envelopes can conceivably have observable liquid-water oceans. I will discuss ways to detect a water-rich interior by transmission spectroscopy, based on the exploration of climate states and atmospheric chemistry features of these planets using a new model called ExoPlanet Atmospheric Chemistry & Radiative Interaction Simulator (EPACRIS). The model successfully explains JWST's initial observations of K2-18 b, and proposes OCS and SO_2, in addition to the coexistence of CO_2 and CH_4, as evidence for a water-rich interior.

Björn Benneke: JWST Transit Observations of Temperate Rocky Worlds, Sub-Neptunes, and Potential Water Worlds The James Webb Space Telescope offers the first opportunity to characterize the transmission spectrum of temperate rocky planets, sub-Neptunes, and potential water worlds with sufficient precision to identify their detailed atmospheric compositions. In this presentation, I will discuss newly obtained high-precision JWST transmission spectra of planets in the rocky planet regime and around the radius valley between 1.1 and 2.5 Earth radii.

Peter Gao: The Transmission Spectrum of the Super Puff Kepler-51b as Observed by JWST NIRSpec PRISM One of the strangest discoveries of the Kepler mission is a rare class of low mass, large radius, and low-density planets that has been nicknamed "Super Puffs". These objects challenge formation and evolution theories due to their inferred large gas mass fractions, which could be an order of magnitude higher than those of the smaller and much more numerous - but similar mass - sub-Neptunes. Here we reveal the 1-5 micron transmission spectrum of Kepler-51b as observed by JWST, with the aim of looking for signatures of hazes, rings, and atmospheric molecules. We find clear signatures of molecular absorption in our preliminary analysis, as well as tentative hints of hazes and/or rings. The molecular absorption will allow us to constrain the atmospheric metallicity and C/O of Kepler-51b, finally shedding light on the origins and evolution of this enigmatic class of exoplanets.

Internal

Lorena Acuña: Water content trends in low-mass multiplanetary systems Both rocky super-Earths and volatile-rich sub-Neptunes have been found simultaneously in multi-planetary systems, suggesting that these systems are appropriate to study different composition and formation pathways within the same environment. To estimate their composition, we present an interior structure model for water-rich planets that includes self-consistently an atmosphere in radiative-convective equilibrium. We use our interior-atmosphere model within a Bayesian adaptive Markov Chain Monte Carlo (MCMC) for the detailed analysis of individual planets, allowing to estimate the uncertainties of the compositional parameters, core mass fraction and water mass fraction, given the error bars of the observed mass and radius.

In this talk, I will focus on the homogeneous analysis of a sample of multi-planetary systems hosting 5 or more exoplanets. Their composition gives us clues about their possible formation site in the protoplanetary disk and their formation mechanisms, including atmospheric escape. I will also discuss the uncertainties and degeneracies interior models face when estimating the volatile content of low-mass planets, and how JWST and further modelling work can help narrow down their possible compositions.

Martin Turbet: Mass-radius relationships for small planets with water-rich atmospheres In this presentation, I will review our team's recent results in modeling water-rich planetary atmospheres, and their effects on mass-radius relationships of small planets.
First, I will describe the conditions necessary for a planet to have its own reservoir of water in the form of vapor. We have recently shown that in most cases, the water condensation limit (Turbet et al. 2021, 2023) is a more relevant criterion than the runaway greenhouse limit (Leconte et al. 2013, Kopparapu et al. 2017, Chaverot et al. 2023).
Next, I will present the effect of these vapor-dominated atmospheres on mass-radius relationships. Assuming vigorous convection in the lower atmosphere, we first showed (Turbet et al. 2019, 2020) that the impact of steam atmospheres on planetary density can be enormous. However, we recently showed (Selsis et al. 2023) that water vapor absorption lines and continuum can prevent most incoming stellar radiation from penetrating the deep atmosphere (typically > 1 bar), which tends to suppress convection and make the deep atmosphere colder and isothermal, which in turns reduce the extension of the atmosphere. This last result opens up new questions, as it shows that the mass-radius relationships of water-rich planets strongly depend on their internal heat flux, and therefore on their age. It also modifies the conditions leading to surface and mantle melting, and hence the interaction between internal and atmospheric water reservoirs.

Allona Vazan: Rain of rocks in sub-Neptunes Planet formation models of rocky sub-Neptunes show that most of the accreted rock (silicate) is in vapor form at the end of the planet formation phase. This vapor will rainout (condense and settle) as the planet cools. We implement the silicate rainout mechanism in the thermal evolution model and examine its effect on the observed radius-mass relation. We find that the duration of the rainout in sub-Neptunes is on $\sim$Gyr timescale and is shorter for smaller planets. The rainout mechanism naturally explains diluted cores in Neptunes, and core-envelope structure in super-Earths. The energy released by the rainout inflates the planet's radius. Accounting for the radius inflation reduces the inferred amounts of hydrogen-helium in sub-Neptunes by up to a factor of two (compared to the standard core-envelope model). For planets formed with envelope masses below 0.4 $M_\oplus$, we anticipate that the inflation of the planet's radius caused by rainout will enhance mass loss by a factor of 2–8 compared to planets with non-polluted envelopes. Our model provides an explanation for bridging the gap between the predicted composition gradients in massive planets and the core-envelope structure in smaller planets.

Raymond T. Pierrehumbert: Atmosphere-interior thermochemical evolution Astronomical observations probe only the outer atmosphere of a planet with a significantly thick atmosphere. From such data what can we infer about planetary interiors? For example, if observations such as those of K2-18b indicate a hydrogen-dominated atmosphere with water below the detection threshold, can that be consistent with a water-dominated interior? Can the water take the form of a liquid ocean, or must it be supercritical? The answer to such questions requires models of volatile cycling between deep interiors and the outer atmosphere, taking into regard constraints from climate physics, bulk density and thermochemical evolution models, as well as formation scenarios. The lack of precise knowledge of interior opacities, as well as equations of state for mixtures, is a major source of uncertainty.

Matthew Nixon: New insights into the internal structure of GJ 1214 b informed by JWST Recent JWST observations of the sub-Neptune exoplanet GJ 1214 b suggest that it hosts a high-metallicity, hazy atmosphere. Emission spectra of the planet show molecular absorption features, with H2O as the most likely candidate species. The observations are consistent with the planet being either a "water-world" consisting of a steam atmosphere above a substantial layer of H2O ice, or a "gas dwarf" with an atmosphere consisting largely of H2 in combination with other molecules. In light of this new information, we conduct a thorough reanalysis of the internal structure of the planet. We use a range of atmospheric models consistent with the JWST observations as boundary conditions for interior models in order to constrain the bulk composition and internal structure of the planet. We consider whether a water-world with a steam atmosphere is consistent with the known properties of the planet and explore the range of feasible water mass fractions. For the gas dwarf scenario, we explore how the atmospheric composition influences the possible interior composition of the planet.

Atmospheric modeling

Duncan Christie: CAMEMBERT: A Mini-Neptunes General Circulation Model Intercomparison With observatories such as JWST, astronomers are now attempting to better understand the previously inscrutable atmospheres of mini-Neptunes, the smaller and often cooler cousins of the better-studied hot Jupiters. General circulation models (GCMs) are an essential part of the toolset used to improve that understanding, from both the perspective of theoretical investigations and in support of observation. It is only recently, however, that the exoplanet community has begun to benchmark and study the behaviour of our GCMs through intercomparisons, a practice that has been going on in the Earth sciences community for decades. With that in mind, we present CAMEMBERT (Comparing Atmospheric Models of Extrasolar Mini-Neptunes Building and Envisioning Retrievals and Transits), a community effort to compare the many of the GCMs used in studies of mini-Neptunes using common parameters and targets in hopes to better understand differences between our models and to better inform the interpretations of our results. This talk will cover the protocol as well as preliminary insights from the project. CAMEMBERT is a part of the CUISINES meta-framework, which also includes the THAI, SAMOSA, CREME, and MOCHA GCM intercomparisons.

James Owen: Using age to understand mass-loss and reveal the composition of sub-Neptunes The majority of the observed exoplanet population is billions of years old. However, many critical evolutionary processes happen before the planets are detected. I will discuss how a hydrogen-dominated sub-Neptuned atmosphere evolves through a combination of core-powered mass-loss, photoevaporation, and thermal contraction. Using models of this process, I will argue that by studying the exoplanet population as a function of age, we can break many of the compositional degeneracies present at a few billion years and show that seeing if and how rapidly the sub-Neptune population contracts can determine if the population hosts hydrogen dominated atmospheres or not.

Daria Kubyshkina: The atmospheric evolution of intermediate-mass planets: impact of the primordial parameters and atmospheric evolution Exoplanets in the mass range between Earth and Saturn show a wide spread in radius, and thus in density, for a given mass. This spread is commonly attributed to the diversity of planetary atmospheres in terms of sizes and/or compositions. Given that the exoplanetary population known to date is mainly comprised of Gyr-old planets, the distribution of their radii and masses can be affected both by the primordial properties of the planets and the long-term evolution of their atmospheres (atmospheric escape), closely connected to the evolution of their host stars. To get insights into the relative input from these factors for planets of different types (in terms of mass, orbit, and stellar host), we perform atmospheric evolution modeling for planets in the range 1-100 Mearth with equilibrium temperatures between 500-1700 K orbiting Sun-like star or an M-dwarf (0.4 $M_{\odot}$). Because high-energy stellar radiation affects atmospheric evolution, we consider different rotation evolution histories for both stars. We assume that planets are born with hydrogen-dominated envelopes and use analytical approximations based on formation models to set the parameters of their primordial atmospheres. We compare our results to the mass-radius distribution of the observed planets whose mass and radius were measured to the ≤ 45 % and ≤ 15 % levels, respectively, and which fall in the parameter range similar to our test planet set.

James Rogers: Fleeting but not Forgotten: the Imprint of Escaping Hydrogen Atmospheres on Super-Earth Interiors Small, close-in exoplanets are divided into two sub-populations: super-Earths and sub-Neptunes. In the scenario of atmospheric escape, most super-Earths are thought to have lost their primordially accreted hydrogen-dominated atmospheres via thermally driven winds. In this work, we consider the global chemical equilibrium of super-Earths and the lasting impacts of their fleeting hydrogen atmospheres. We find that hydrogen is efficiently sequestered into the interior, oxidising iron and endogenously producing $\sim$ 0.5 - 1.0% water by mass. Once the majority of the hydrogen has escaped the planet, we predict steam-dominated atmospheres, with other carbon-bearing gaseous species such as CO and CO2 present at the $\sim$ 0.1 - 1% level by atmospheric mass. One of the main effects of efficient sequestration of hydrogen into the interior is to produce an under-dense bulk interior compared to that of Earth. We predict bulk densities of super-Earths to be $\sim$ 5.0 g cm^{-3} for an Earth-mass planet, consistent with high-precision mass measurements and population-level inference analyses from atmospheric escape models.

Matthäus Schulik: New atmospheric escape models reveal the transition to metal-rich atmospheres in Super-Earths Close-in, rocky exoplanets suffer intense, hydrogen-dominated mass-loss through sustained high-energy irradiation. While there are strong indications that this process can transform large Sub-Neptunes into small Super-Earths, it is unclear whether this mass-loss can terminate, and what the elemental composition of the remnant atmosphere could be. Using a new set of 1-D radiation hydrodynamics evolutionary calculations which include multi-component mass-loss and photochemistry, I show how line cooling from dragged heavy atoms and ions impacts the hydrogen-escape rates and how the relative composition of the outflow changes as the atmosphere evolves and the planet contracts. I discuss how this results in a carbon-depleted and oxygen-rich phase of a low-mass planets life, before ultimately also this primary atmosphere is lost, consistent with recent non-detections of thick atmospheres around such worlds. Retaining a finite amount of atmosphere is restricted only to a combination of low irradiation levels, low mixing and deep gravitational potentials. Particularly residual hydrogen will be important as greenhouse gas and impact the further evolution of the lower atmosphere, which we comment on.

Alejandro Sánchez López: Robustness Challenges in Exo- Atmosphere Research: A Simulator-Driven Analysis Understanding the reliability and significance of atmospheric signals is key for robust findings. We will present a state-of-the-art simulator of exoplanet observations to investigate the variability in signal detection under different observing conditions. Based on a large (N=1000) ensemble of simulated observations, we explore the statistical significance of atmospheric signals employing different instrumental properties, telluric corrections, and detection metrics (from S/N evaluation to full retrievals). Our findings illustrate core statistical physics in state-of-the-art procedures, underscore the sensitivity of exoplanet signal detection to minor noise fluctuations, and highlight the need for refined analysis techniques. This study provides insights into the robustness of atmospheric detections and advances our ability to characterise these distant worlds with current and future instrumentation.

Formation & Evolution

María Paula Ronco: The radius valley across stellar types The radius valley separating super-Earths from mini-Neptunes is a fundamental benchmark for theories of planet formation and evolution. Motivated from observations indicating that the position of the radius valley decreases with decreasing stellar mass and with increasing orbital period, we extend our previous research on the radius valley for Solar-mass stars, to cover stellar masses ranging from 0.1 to 1.5 $M_{\odot}$. We find that the location of the radius valley is in excellent agreement with observations. We also find very good agreement with the dependence of the radius valley on orbital period, both for FGK- and M-dwarfs. Additionally, we note that the radius valley gets filled towards low stellar masses (0.1-0.4 $M_{\odot}$). Furthermore, we find that for planetary equilibrium temperatures above 400 K, the water in the volatile layer exists fully in the form of steam, puffing the planet radius up compared to condensed-water worlds. As with Sun-like stars, pebble accretion leaves its imprint on the overall exoplanet population as a depletion of planets with intermediate compositions (0 - 20% water mass fraction), carving a planet-depleted diagonal band in the mass-radius diagram. This band, better visualised when plotting the planet mean density in terms of Earth-like composition, makes the valley emerge for all stellar masses.

Andrin Kessler: Uranus formation: Challenges of current planet formation theory Current planet formation theories are able to explain many parts of the observed exoplanet population as well as the general architecture of the Solar System with some rocky planets in the inner system and Giant gas planets outside. However, the existence of Uranus and Neptune is much harder to explain in the context of current theory given their mass and distance to the Sun. In this ongoing work, we look for Uranus-like planets in different synthetic populations that we generate using a global planetary formation and evolution model where we consider planet formation via planetesimals and/or pebbles. Preliminary results show that there is no viable formation pathway for Uranus in smooth disks when planetary migration is considered. Most of the promising Uranus candidates rather end up in the warm/hot sub-Neptune regime. We cautiously conclude that the apparent missing links in the formation theory of the Solar System ice giants are also important for the formation of closer-in planets in general.

Martin Schlecker: Bioverse: Probing the Habitable Zone Inner Edge Discontinuity in the Radius/Density Distribution Studying planetary habitability has become a major emerging research area, with critical implications for future exoplanet exploration and ambitious ground- and space-based telescopes. Yet, habitability remains challenging to determine for individual planets. We present Bioverse, a framework to quantify the diagnostic power of next-generation exoplanet surveys. Bioverse assesses the detectability of population-level trends injected in simulated planet populations as a function of sample selection and survey design. Here, we apply it to examining the inner edge of the habitable zone. We show that, through probing a discontinuity in bulk planet properties, the first empirical test of the habitable zone hypothesis may be imminent.

Nicolas Kaufmann: Population level study of the influence of planetesimal fragmentation on planet formation The size distribution of solids in the protoplanetary disk is still ill constrained and evolves significantly throughout plant formation by various processes. As the planets grow, they excite the mutual random velocities among planetesimals, making collisions between them destructive. This leads to their fragmentation changing the typical size of solids accreted by protoplanets. I will show the impact planetesimal collisional fragmentation has on planet formation employing a population synthesis approach. The synthesis is performed by varying the initial conditions based on observations of disks to generate synthetic exoplanet populations. Our results show that planetesimal fragmentation, in conjunction with radial drift and the interactions with the gas disk, can either promote or hinder planet formation, depending on the typical size of fragments produced in collisions. In addition, the enhanced radial drift of the smaller fragments also changes the typical origin of accreted solids affecting the composition of the forming planets.

Jesse Weder: Moving towards planetary population syntheses in MHD wind-driven discs - Revisiting planetary migration within the new paradigm Recently, MHD wind-driven disc evolution has attracted much attention as it has proven to be a viable alternative to the classical viscous disc paradigm. The evolution of the protoplanetary disc is of fundamental importance for planet formation. It's gravitational interaction leads to planetary migration, thus setting the stage for the formation. Moving towards MHD wind-driven discs with low levels of turbulence introduces several new effects that influence the migration processes. So far, however, global models for planet formation still rely on the viscous disc evolution paradigm. In an attempt to move towards planetary population syntheses in MHD wind-driven discs, we investigate the effects of low turbulence and MHD wind-driven disc evolution on planet migration within the population syntheses framework.

Wednesday 7th

Internal

Tim Lichtenberg: Internal fractionation of atmospheric volatiles on molten exoplanets Low-mass exoplanets in a fully to partially molten state open a novel window into key processes that shape the earliest, high-temperature evolutionary regimes of rocky worlds and their long-lived climate states. I will outline how magma ocean dynamics and core-mantle chemical segregation influence the feedback mechanisms between largely molten interiors and volatile envelopes. The physical and chemical coupling between magma layers and their equilibrating atmospheres can fractionate the dominant volatiles observable in the upper atmosphere to a degree that is testable with current instrumentation. As a key example, nitrogen species can be suppressed in H-dominated atmospheres if the volatile envelope is in direct contact with a chemically reduced molten interior. With a focus on the high-priority targets K2-18 b, 55 Cnc e, GJ 367 b, and TOI-561 b, I will outline observational tests to distinguish internal phase state and evolutionary scenarios.

Lena Noack: Rocky super-Earths might have reducing interiors and atmospheres In the last couple of years, the atmospheric characterization of selected super-Earths by observations started to become a reality. The first surprising results, including the non-detection of thick CO_2 envelopes

around the two innermost TRAPPIST-1 planets, showed the increased need for coupled interior-atmosphere models to understand potential evolutionary pathways for the atmosphere shaped amongst others by volcanic outgassing from the interior. Especially for super-Earth planets, it is still an open question, how the strength and chemistry of volcanic outgassing should vary depending on planetary mass and composition.
One major factor, that directly influences the mantle redox state (and hence the expected abundances of various gases in the atmosphere), is the extraction of reducing iron into a metal core. However, massive super-Earths experience high pressures and a strong compressibility in their interior, which can impact the core formation and therefore mantle redox state of the planet, favouring a more reducing atmosphere (possibly even up to the extreme case of a secondary outgassed H_2-dominated atmosphere). Preliminary results on core formation efficiency and their implications on the atmospheric evolution of massive super-Earths will be presented.

Chanoul Seo: Atmospheric H-C-O ratio for super-Earth/sub-Neptune with rocky core The majority of exoplanets with the radii larger than 1.6 $R_\oplus$ are more inflated than bare-rock planets with the same mass, indicating the substantial amount of volatile. The origin of volatile nor the planet bulk composition cannot be constrained from the mass-radius relation alone, and the spectral characterization of their atmospheres are expected to be solve this degeneracy. Previous models pointed out that the interaction between the accreted volatile and the likely molten rock (i.e., magma) beneath the atmosphere would have large impact on the atmospheric composition. However, previous models do not clarify the dependence of the atmospheric compositions with major spectral fingerprints on the observable planetary parameters. In this work, we explore the possible range of H, O, C in the atmosphere of exoplanets as a function of observable planetary parameters (mass, radius, equilibrium temperature) using a simple chemical equilibrium model. Consistent with the previous work, we show that the water fraction in contact with magma ocean is the order of 0.01-0.1 if the dry planetary core accretes the nebula gas, regardless of the planetary parameters. Due to the difference of solubility of H-bearing and C-bearing species into molten rock, C/H shows the increase of 3-20, where the low values correspond to H2-rich atmospheres while the high values (larger than the order of magnitude difference) correspond to the planets with the thin atmosphere with $P < 1000$ bar. Therefore, the C/O remains relatively low in most of the parameters range considered, below one-tenth of the nebula gas value if the atmospheric H_2O fraction is over about five percent. This trend provides a clue to verify or falsify for the formation scenario of sub-Neptunes from atmospheric compositions. We also highlight the need for the further constraints on the material properties at high pressure, which can substantially affect the interpretation of the atmosphere.

Brandon Park Coy: Signatures of Magma Ocean-Hydrogen Envelope Interaction on Gas Dwarfs Despite early results from JWST, the true nature of sub-Neptunes—their origins, atmospheres, and interior compositions—remains elusive. Most known sub-Neptunes are expected to house silicate-rich magma oceans overlain by a massive hydrogen-dominated envelope. Early models treated these two as fully differentiated, non-interacting layers. However, more recent work shows that large-scale interaction between these two media has multiple consequences for sub-Neptunes, impacting mass-radius relationships, converting hydrogen gas to dissolved water and metal oxides to hydrides, and forming exotic silicate gas species. However, interaction could self-limit if a ‘fuzzy layer’ of intermediate density forms, which may prevent large-scale mixing and interaction by inhibiting convection in both layers.
Can JWST test if there is significant interaction between the atmosphere and interior of sub-Neptunes? Chemical interaction can greatly impact commonly retrieved observables like the

atmospheric metallicity and C/O ratio. However, these observables are also impacted by a host of unrelated processes, including fractionating atmospheric escape, formation location, and planetesimal contamination, and the question remains whether such signatures are discernable from other processes. We investigate the feasibility of searching for signatures of magma-atmosphere interaction with JWST and highlight work needed to constrain evolutionary models of sub-Neptune atmospheres and interiors.

William Misener: Coupled chemistry and structure of hydrogen-silane-water atmospheres One model consistent with observations of sub-Neptunes is that these planets consist of silicate cores surrounded by hydrogen envelopes. At the conditions of the magma-atmosphere interface of sub-Neptune planets, substantial silicate vapor is expected to be in chemical equilibrium in the atmosphere. These species could greatly alter the atmospheric structure and evolution of these exoplanets, but previous models have neglected this compositional coupling. I present a coupled chemical equilibrium and atmospheric structure model, including silicate gas and its interactions with the background hydrogen. We find that silane, SiH_4, and water, H_2O, are the main products of atmosphere-interior interactions in sub-Neptune planets. These vapor products act as condensable species, decreasing in abundance with altitude. The resultant mean molecular weight gradient inhibits convection at temperatures above ~ 2500 K, inducing a non-convective layer near the magma surface. This layer decreases the planet's radius compared to a planet with the same base temperature and a convective, pure H/He atmosphere. Therefore, we expect silicate vapor to have major effects on the inferred envelope mass fraction of sub-Neptune planets, and on their thermal and mass evolution. The presence of silicon species in the atmosphere may also be observable, allowing a window into the interiors of these planets.

Atmospheres

Hamish Innes: Exploring the effects of non-dilute water vapour on the atmospheres of temperate sub-Neptunes Sub-Neptunes with Earth-like instellations and higher than solar metallicity are likely to have condensing water vapour in non-dilute concentrations in their atmospheres. I will present work utilising both 1D radiative-convective models and 3D General Circulation Models (GCMs) to explore the effect of non-dilute water vapour on their atmospheres. Our 1D simulations of sub-Neptunes with surface oceans, "Hycean Worlds", suggest that the inhibition of convection in the lower atmosphere could push the inner edge of the habitable zone outwards. To complement this work, we are also developing the ExoFMS GCM to handle the compositional gradients induced by condensing water vapour. Preliminary results show that the inhibition of convection in the weather layer can lead to a sharp contrast in water vapour content between the lower and upper atmosphere. I will discuss how this affects the atmospheric dynamics of sub-Neptunes and observable features, such as water clouds.

Shang-Min Tsai: Biosignature gases on sub-Neptune water worlds – lessons from K2-18 b Theoretical predictions and observational data indicate a class of sub-Neptune exoplanets likely have water-rich interiors and hydrogen-dominated atmospheres. Provided suitable climate conditions, such water worlds could host surface oceans, and have been termed "Hycean" (hydrogen-ocean) planets. The possibility of Hycean worlds has sparked great interest in the atmospheric characterization and habitability assessment of temperate sub-Neptune exoplanets. Motivated by recent JWST observations of a Hycean planet candidate, K2-18 b, we model the photochemistry and detectability of biosignature gases, including organic sulfur, in the H_2-atmospheres of similar temperate sub-Neptunes. Today on Earth, organic sulfur compounds (e.g., dimethyl sulfide and methanethiol) are primarily produced by marine biota, but they are rapidly destroyed by photolysis and other photochemical processes before these gases can accumulate to significant levels. In this study, we explore biogenic sulfur gases across stellar UV environments and biological production rates. Critically on tidally-locked planets, the main photochemical sinks removing organic sulfur gases are absent on the permanent nightside. Therefore, we further perform a 3D GCM and 2D photochemical modeling to simulate the global distribution of biogenic gases and determine whether they can accumulate to detectable levels on the terminators, as seen via transmission spectra.

Anjali Piette: Rocky Planet or Water World? The Observability of Low-Density Lava World Atmospheres An emerging population of low-density super-Earths may be explained by volatile-rich interiors. Among these, low-density lava worlds have dayside temperatures high enough to evaporate their surfaces, providing a unique opportunity to probe their interior compositions and test for the presence of volatiles. Using self-consistent 1D atmosphere-interior models, we explore the atmospheric observability of low-density lava worlds, focusing on three case studies with sub-stellar temperatures spanning 1900-2800 K: HD86226c, HD3167b and 55Cnce. Given the possibility of mixed volatile and silicate interior compositions for these planets, we consider a range of mixed volatile and rock vapor atmospheric compositions. We find that H2O and/or CO_2 could be detected with as few as $\sim$5 JWST secondary eclipses. Several observations of low-density lava worlds in JWST Cycles 1 and 2 will therefore be sensitive to the presence of volatiles in their atmospheres, testing the presence of volatile-rich interiors among the super-Earth population.

Artem Aguichine: Revisiting Exoplanet Mass-Radius Relations: Energetics of Water Worlds Exoplanet mass-radius relationships serve as fundamental tools for deciphering the compositions and structures of distant worlds. However, uncertainties persist regarding the validity of these relationships, prompting a deeper exploration into the underlying physics governing planetary interiors. Focusing on water worlds, we will explore some aspects of their energetics, and the dynamic interplay between the atmosphere and the interior. By scrutinizing the effects of atmospheric cooling rates on planetary radius variations, we challenge conventional mass-radius paradigms, highlighting the dynamic nature of exoplanetary interiors. Furthermore, our investigation into alternative interior compositions, including ammonia (NH3) and methane (CH4), underscores the necessity of refining mass-radius relations to capture the diverse range of exoplanetary compositions. Through our research, we aim to redefine our perception of exoplanetary interiors, paving the way for a more nuanced understanding of these enigmatic celestial bodies.

Jegug Ih: Do Rocky Planets Around M Stars Have Atmospheres? A Statistical Approach to the Cosmic Shoreline JWST has enabled the atmospheric characterization of terrestrial planets orbiting M dwarfs, with spectroscopic observations producing the first unambiguous detections of atmospheres as well as detections of bare rocks. Synthesizing these observations, it is natural to then ask under what conditions these planets can host atmospheres and what further observations are necessary to establish a population-level trend. The Solar system trend in the insolation-Vesc plane that separates airless bodies, or the so-called "Cosmic Shoreline", may not hold around M stars due to the harsher XUV environment. We simulate a survey of potential targets by combining planet formation/evolution and atmospheric observation models and apply a hierarchical model to test whether hypotheses can be distinguished. We also use bootstrapping to identify the most informative targets and observing modes. We discuss potential applications of this approach to designing surveys for other classes of extrasolar objects.

Thursday

Demographics

Julia Venturini: The radius valley for single and binary stars The existence of a radius valley in the size distribution of exoplanets, which separates super-Earths from mini-Neptunes, stands as one of the most important observational constraints to understand the origin and composition of exoplanets with sizes below Neptune. The most accepted models to explain the radius valley predict that mini-Neptunes are dry, which is at odds with predictions from pure formation models. In this presentation, I will first briefly show results of combined formation and evolution calculations that predict that mini-Neptunes are mostly water-worlds. In a second part, I will describe a new observational program that we are pursuing with CHEOPS to characterise the radius valley for binary stars.

Ian J.M. Crossfield: The TESS-Keck Complete Mass Catalog Currently, our best window into the composition of exoplanets relies on the synergy of precise radii and mass, which are enabled chiefly by transit surveys and high resolution, ground-based spectroscopic followup. I will share the system architectures revealed by the TESS-Keck Survey (TKS): a significant radial velocity follow-up effort aimed at measuring the masses and orbital properties of 86 TESS Objects of Interest. This work represents the largest uniform analysis of TESS-discovered planets to date: nearly 10,000 RVs resulting in mass, radius, and orbital constraints for 127 planets. TKS has achieved at least a 3-sigma mass constraint for 74 planets, in addition to confirming 33 new planets. We find that the Chen & Kipping (2017) mass-radius relation systematically underestimates planet mass, which may have implications for future survey planning.

Joseph Murphy: TAC-curate or Accurate? An Investigation into the Effects of Time-sampling and Undetected Companions on the Accuracy of Radial Velocity Mass Measurements Precise mass measurements are key to interpreting the transmission spectra of planets smaller than Neptune. Over the last five years, Doppler surveys of TESS planet candidates have diligently worked toward providing the community with such measurements. However, even mass measurements of purportedly high precision may be subject to inaccuracy due to poor phase coverage or model misspecification. Inaccurate mass measurements pose the threat of misleading future observations planning and misrepresenting planet bulk composition. As TESS follow-up continues to populate the sub-Neptune regime of the mass-radius diagram, care should be taken to ensure that these mass measurements are not only precise, but robust to imperfect time-sampling and undetected companions. In this talk, we investigate the effects of time-sampling and additional, undetected companions on the accuracy of radial velocity (RV) mass measurements. First, we present new RV observations for a handful of systems with previously published planet mass measurements or mass upper limits. Next, we apply a data resampling framework to real RV time series and conduct a suite of injection-recovery tests on synthetic data to explore how observing cadence and model misspecification affect recovered planet mass measurements. These tests provide useful guidelines for informing future RV observing proposals and justifying time requests.

Jaume Orell-Miquel: The MOPYS project: No evidence of enhanced evaporation in young planets During the early stages of planetary formation, planets suffer severe changes in their physical properties due to internal and external forces, which also affect their primordial atmospheres. The study of planets at early stages and its comparison with the already mature planet population is crucial for a better comprehension of different processes, such as: planet formation, evaporation of primary atmospheres of rocky planets, gas accretion or inflation. As part of a large project to investigate the evolution, out-flow, and evaporation of exoatmospheres, we present the first results of the MOPYS survey. We observed +20 young exoplanets, mainly sub-Neptunes, targeting the two principal ground-accessible evaporation tracers: H-α, and He triplet. We complemented our survey with available literature results. This broad range of studied planets allow us to obtain a general view of evaporation processes across planetary parameters, and find novel relationships to explain the evaporation processes.

Solène Ulmer-Moll: Exploring the interior composition of warm giants Warm giant planets provide a unique opportunity to better understand the formation and evolution of planetary systems. Their atmospheric properties remain largely unaltered by the impact of the host star or by inflation mechanisms. Thanks to several years of photometric and radial velocity campaigns, the sample of warm giant planets is steadily increasing, bridging the gap between the well-known hot Jupiters and the Solar System giants. Combining precise masses, radii, and ages with a planetary evolution model, we estimate the interior composition of warm gas giants. In this talk, I present the impact of several modeling assumptions (e.g. H/He equation of state, core mass). I infer the metal enrichment of the newly discovered temperate giants and explore their influence on the mass-metallicity correlation of giant planets.

List of Participants

Renyu Hu	NASA Jet Propulsion Laboratory
Tim Lichtenberg	University of Groningen
James Rogers	UCLA
Anjali Piette	Carnegie Earth & Planets Laboratory
Daria Kubyshkina	Space Research Institute, Graz, Austria
Raymond T. Pierrehumbert	University of Oxford
Peter Gao	Carnegie Earth & Planets Laboratory
Lorena Acuña	MPI for Astronomy
Enric Palle	Instituto de Astrofisica de Canarias
Thomas Henning	MPI for Astronomy
Johanna Teske	Carnegie Earth and Planets Lab
James Owen	Imperial College London
Remo Burn	MPI for Astronomy
Allona Vazan	The Open University of Israel
Natalie Batalha	UC Santa Cruz
Jo Ann Egger	Universität Bern
Eve J. Lee	McGill University
Léna Parc	University of Geneva
Martin Turbet	LMD, IPSL, LAB, CNRS
Björn Benneke	University of Montreal
Artem Aguichine	University of California, Santa Cruz
Gijs D Mulders	Universidad Adolfo Ibáñez, Chile
Octavio Miguel Guilera	Astrophysical Institute of La Plata
Shang-Min Tsai	UC Riverside
Nikku Madhusudhan	University of Cambridge
Nicolas Kaufmann	University Bern
Alejandro Sánchez López	Instituto de Astrofísica de Andalucía (IAA-CSIC)
Jesse Weder	University of Bern
Ian Crossfield	University of Kansas
Lena Noack	Freie Universität Berlin, Germany
Chris Ormel	Tsinghua University
William Misener	University of California, Los Angeles
Martin Schlecker	University of Arizona
Andrin Kessler	University of Bern
Matthew Conor Nixon	University of Maryland
Joseph M. Akana Murphy	UC Santa Cruz
Brandon Park Coy	University of Chicago
Eva-Maria Ahrer	MPI for Astronomy
Chanoul Seo	SOKENDAI/NAOJ
Hamish Innes	Freie Universität Berlin, Germany
Solène Ulmer-Moll	Bern and Geneva Universities
María Paula Ronco	Instituto de Astrofísica de La Plata
Duncan Christie	MPI for Astronomy
Shang-Min Tsai	UC Riverside
Matthäus Schulik	Imperial College/UCLA
Ryan Cloutier	McMaster University

Useful Information

There will be a welcome reception on Sunday evening

Talks should be 12 min + 3 min for questions

We will have discussions on Thursday and Friday based on participants answering the form on:
https://survey.sci-an.com/dYWpS4yQPUuocIDJ
The link will stay available during the full conference and all participants are encouraged to answer multiple times, e.g., after they thought of something new triggered by a talk.

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The answers will be manually and automatically analyzed powered by sci-an.com

On Wednesday afternoon, we plan an excursion to the nearby Wallberg, good shoes are useful this or other endeavors in your free time

Wi-Fi will be available during the conference.

The **Bavarian Evening** will be on Thursday, Participants are encouraged to dress in traditional style.

How to get to the Ringberg Castle?

The conference address is Schlossstrasse 20, 83708 Kreuth, Bavaria, Germany Directions can be found on the webpage of the castle (https://www.schloss-ringberg.de/convention-site/contact). We will organize a transport from the airport.

Support

The Density Matters Workshop is supported by the Ernst-Rudolf-Schloeßmann-Stiftung