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# atmospheres

## THE PHYSICS AND CHEMISTRY OF PLANETARY GASEOUS ENVIRONMENTS

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**Analysis of Spectroscopic Observations of the Earth Atmospheres and of the Atmospheres of Other Planets of the Solar System (Titan and Jupiter)**

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**ABSTRACT**

Over the years the number of spectrally resolved observations of the Earth atmosphere and of the atmospheres of the planets and moons of the solar system has increased dramatically. To analyze them, more and more sophisticated retrieval methods have been developed. Usually, the Earth atmosphere and planetary atmospheres communities have worked in parallel, with few interactions among the two worlds. However, the physics underneath those observations is similar, and most analysis tools can be applied to both fields with a small effort. Here I will briefly describe a retrieval code for the analysis of InfraRed limb observations and show some results of the analysis of the limb measurements of a spectrometer orbiting around the Earth (MIPAS on board the ESA satellite ENVISAT). Then I will discuss how that retrieval code has been adapted for the analysis of planetary atmospheres limb measurements and show the results of its application to Titan's limb emissions, measured by the VIMS instrument on board the Cassini probe, and of Jupiter's limb emissions (measured by the JIRAM spectrometer on board the Juno probe).

**Large-Scale Planetary Atmospheric Dynamics "from Above"**

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**ABSTRACT**

Planetary atmospheric dynamics is governed by a common set of partial differential equations. For large-scale, neutral (un-ionized) phenomena, the appropriate equations are known as the "primitive equations". In this presentation, a broad overview of the physics of atmospheric dynamics is discussed for the different types of planets found in both the solar and extrasolar systems. The focus is on key physical parameters and their estimated typical values for the atmospheres. Crucial issues related to the accurate numerical solution of the equations and modeling of the atmospheres are also highlighted. Additionally, some critical topics and open questions are identified.

**3D atmospheric simulations of the lava planet K2-141b to interpret JWST observations**

*Mark Hammond, Shang-Min Tsai, Raymond Pierrehumbert
*Christ Church, Oxford, UK*

**ABSTRACT**

Lava planets have densities consistent with a rocky composition and extremely high surface temperatures. This makes them more readily observable than cooler terrestrial planets, and presents interesting questions about their atmospheric and surface properties. Their tidally locked orbital configuration should produce a distinctive day-night circulation.

The lava planet K2-141b will be observed with JWST with MIRI LRS (PI Lisa Dang) for three orbits for 21 hours. This program will use the resulting spectrally resolved phase curve to search for an atmosphere, in particular the 9 micron SiO spectral feature, using this to constrain the horizontal and vertical temperature structure of the atmosphere

Our contribution to this scheduled program is to use 3D simulations of potential atmospheres of K2-141b to understand the effect of a global circulation on the observations. We focus on how three cases — a bare rock, a thin outgassed day-side atmosphere, and a thick global atmosphere — produce different observational features. We show three strong indicators of a thick global atmosphere, which are i) significant night-side thermal emission, ii) east-west broadband phase curve asymmetry, and iii) asymmetry in the emission spectra of the east and west terminators.

In presenting this work, I will describe the modelling setup we use, describe how the results will be used to support the observations, and discuss how they relate to the global circulation of tidally locked planets in general. For example, K2-141b has a high rotation rate, which suppresses day-night heat transport and the formation of a hot-spot shift. Understanding the atmospheric circulation of observationally accessible tidally locked planets like K2-141b will be vital for understanding the circulation of cooler, potentially habitable planets.

**The C/O ratio and its influence on hydrodynamic escape of Super-Earth exoplanets**

Matthäus Schulik, Richard Booth and James Owen
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**ABSTRACT**

Photoevaporating planetary winds have been proposed as important mechanism contributing to the evolution of the volatile inventory in close-in planets, potentially explaining the observed radius valley for low-mass exoplanets at around r~ 1.7r_{Earth}.
Molecules originating a planets' lower atmosphere can be entrained in the escaping hydrogen wind and dissociated by energetic photons on their way to higher altitudes. This process results in outflows containing varying amounts of C and O atoms, in their neutral and ionized states.
These minor species can contribute strongly to the total cooling capability in the outflow, and hence impact the mass loss rates significantly.
In this work, we use a 1-D multi-species radiation hydrodynamics code in conjunction with photochemistry, in order to investigate the C/O-dependent mass loss-rates and thermal structure of outflows from those exoplanets.
We will discuss impacts of the birth properties of exoplanets, parameterized by their atmospheric C/O and C/H values. Furthermore we will investigate the evolution of exo-atmospheres under the UV-rich irradiation conditions of M and K dwarves. Finally, those radius evolution scenarios will give rise to predictions of the observable transit radii of planets at a given age. Incorporating constraints of C/O measurements from JWST as well as ground-based high-resolution spectroscopy will help test those predictions and understand the role of atomic cooling in planetary evolution.

**Photo-evaporation of hot rocky exoplanet**

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**ABSTRACT**

A short description: About 500 exoplanets whose radii are less than 2 Earth radii have radiative equilibrium temperatures high enough to melt and vaporize rock. Thus, if rocky exoplanets like CoRoT-7b, they likely have atmospheres composed of rocky materials. Such hot rocky exoplanets could evolve greatly through loss of planetary mass and atmospheric species if the rocky vapor atmosphere undergoes massive escape. In our study (Ito & Ikoma 2021, ApJ), we constructed an 1-D hydrodynamic model of the highly UV-irradiated, rocky vapor atmosphere, including detailed radiative processes and photo- and thermo-chemistry. Our simulation shows that the atmospheric escape occurs by a hydrodynamic/transonic wind. Almost all of the incident XUV energy is converted into the radiative emission of rocky vapors. Due to this, the mass loss rate is very low, but massive enough to remove completely the major species Na from the atmosphere. We suggest that the photo-evaporation affects the planetary mass only slightly, but may changes the atmospheric major species for hot rocky exoplanets with super-Earth-size/Earth-size.

**The legacy of HST/WFC3: a prototype for population studies of exoplanets with JWST and Ariel**

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**ABSTRACT**

Today, nearly 5000 exoplanets have been detected and, despite the significant progress in the field of atmospheric characterisation in the last decade, we still have a limited understanding for a small number of planets. Similarly to the field of exoplanetary detection, atmospheric population studies are the way forward in constraining, which is the current condition of planets, how did they form, and how have they evolved. One of the most successful instruments for observing exoplanetary atmospheres is the *Wide Field Camera 3* (WFC3) on-board the *Hubble Space Telescope*. In particular, the use of the spatial scanning technique has given the opportunity for even more efficient observations of the brightest targets, achieving the necessary precision of 10 to 100 ppm to the flux of the star. In this presentation, I will discuss the main discoveries made with the WFC3/IR instrument - including the first detection of water vapour in a habitable-zone planet - the process followed to develop an automatic analysis pipeline, and the lessons learnt from this process. Today, it is the moment to use this experience from HST and to follow a scalable approach as far as observation planning and data processing are concerned. This is vital now, as JWST is ready to start its breakthrough observations and Ariel is in preparation to provide a large number of observations, up to 1000 exoplanets starting from 2029. In addition, I will discuss the first results from the on-going JWST data challenge, organised by the exoplanet ERS team.

# A new view of Venus

D. Titov
*ESA/ ESTEC*

**ABSTRACT**

Venus appears to be an “alien” planet drastically and surprisingly different from the Earth. Space missions revealed the world with remarkably hot, dense, cloudy, and very dynamic atmosphere filled with toxic species. The spacecraft delivered comprehensive data on the temperature structure, the atmospheric composition, the cloud morphology, the atmospheric dynamics, the solar wind interaction and the escape processes. In many respects Venus can be considered as an archetype of terrestrial exoplanets. The talk will review the current knowledge of Venus and outline strategy of its future exploration.

**Oscillations and stability of the jupiter polar cyclones**

Alessandro Mura and the JIRAM team
*INAF IAPS*

**ABSTRACT**

The NASA spacecraft Juno discovered the presence of circumpolar cyclone structures on Jupiter in 2017, and it has been monitoring their evolution ever since. These cyclones are organized in structures shaped like regular polygons. Here we study the evolution of these structures over a period of almost four years, between February 2017 and November 2020. In this investigation we focus on the data provided by the JIRAM instrument (Jovian InfraRed auroral mapper), and in particular by the M-band imager, which detects the infrared radiance emitted in the wavelength range between 4.5 and 5µm. These observations have made possible to monitor the properties, position and evolution of cyclonic and anticyclonic structures at latitudes above 80° both in the North and South poles, regardless of illumination conditions.

Fundamental questions regarding Jovian cyclogenesis concern the formation mechanism and whether these cyclones are deep or shallow structures. Useful indications can be obtained by ascertaining the stability and rotation speed of these polar structures, and if vortices outside such polar structures, which naturally tend to migrate towards the poles, can easily enter these regular structures and merge with pre-existing cyclones. JIRAM's measurements show that any change in a structure (number of cyclones and/or shape) is an extremely unlikely event on an annual scale, which has only happened once, and only temporarily: a sixth cyclone joined the pentagonal structure in the south in 2019, but it has disappeared after a relatively short period of time without merging with the pre-existing cyclones. Neither the merging of two cyclones, nor the disappearing/creation of one stable cyclone has ever been observed. Additionally, the secular drift velocities of the structures are not compatible with the shallow hypothesis. The drift is much smaller than the typical scale velocities on Jupiter surface: two order of magnitude smaller than the zonal winds and much less than the drift velocities of smaller vortices observed equatorward.

Cyclones oscillate around what may seem like equilibrium positions, and these oscillations tend to propagate from one cyclone to another. These oscillations have almost equal timescales, and here we investigate the possible implications of such similarity. The two regular structures perform a slow rotational motion around their respective poles when measured in the SIII reference system, but with significantly different angular velocities.

Here we show also a new recent global picture of the North polar cyclones' structure, which was only partially covered since its discovery 5 years ago, and we find that it remained almost unperturbed just like the South one. Each cyclone has a peculiar morphology, which differs from the others and it is stable over the observed lapse of time in most cases.

**Study of Jupiter's auroral regions through the measurement of the Juno/JIRAM instrument**

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**ABSTRACT**

The Jovian Auroral Infrared Mapper (JIRAM) instrument aboard NASA's Juno spacecraft was designed to monitor the atmosphere of Jupiter and its aurorae with an unprecedented spatial resolution. In this work, JIRAM data measured over the polar regions have been used to derive quantitative information on the species CH4 and H3+ and on the variability of their spatial distribution. JIRAM spectra have been analysed in the spectral region 3-4 μm, that is particularly favourable for the study of the aurorae. Starting from the data previously analysed for the orbit JM0003, the dataset has been enlarged to include observations outside the auroral ovals with a lower signal and extending the analysis to successive orbits. The first Juno orbits, from JM0003 to JM0091, have been examined to find the most promising for the study of the aurorae. Along with the JM0003, the orbits JM0071 and JM0081 have been analysed for the south aurora. The selected spectra show H3+ and CH4 emissions in the auroral regions and have been analysed using an inversion technique based on a Bayesian approach. Preliminary tests have allowed to optimize for the new dataset the a-priori information vector and the corresponding error and limit the degrees of freedom of the information to just the abundances of the two species and H3+ temperature. The results have confirmed the presence of methane near both poles, within the auroral oval, and comparable abundances of H3+ in the two auroral regions, with values ranging between 2-2.8 × 1012 cm-2 and some peaks larger than 2.8 × 1012 cm-2. The H3+ temperatures appear lower in the south aurora, where the values do not exceed 825 K, while in the north aurora the temperatures span between 800 K and 950 K. The comparison of these results with the images obtained from the JIRAM's observations in the L band has also allowed to study the morphology of the Jovian aurorae and to highlight the displacement of a few degrees westward of the south aurora over the time.

**Water ice clouds detection with NOMAD LNO nadir channel on board ExoMars TGO**

Luca Ruiz Lozano[1,2], Ö. Karatekin[2], V. Dehant [1, 2], G. Bellucci[3], F. Oliva[3], F. Altieri[3], F. G. Carrozzo[3], E. D'Aversa[3], F. Daerden[4], I.R. Thomas[4], B. Ristic[4], Y. Willame[4], M. R. Patel[5], J.-J. López-Moreno[6] and A.C. Vandaele[4]

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## ABSTRACT

The Nadir and Occultation for Mars Discovery (NOMAD) is one of the four instruments on board 2016 ExoMars Trace Gas Orbiter. The instrument is a suite of three spectrometers, mainly designed to study minor atmospheric species at high spectral resolution. Nevertheless, Oliva et al. (2022) demonstrated the capability of NOMAD infrared nadir channel to investigate surface ice composition in the 2.3 – 2.6 µm wavelength range. Ice signatures have been also observed at mid/equatorial latitudes suggesting, after analysis, the first detection of CO2 ice clouds through the study of the narrow 2.35 µm absorption band. In this work, we also take advantage of NOMAD infrared LNO channel and present a new technique allowing to map Martian H2O ice clouds. For this study, we select LNO spectral orders 167, 168, 169 located close to the 2.7 µm ice absorption band. The acquisition of data during Mars Year 34 and 35 (March 2018 to February 2021) allows us to construct seasonal maps for H2O ice clouds. The results present a high sensibility to the Polar Hood clouds and limited detections in the Aphelion Cloud Belt (ACB). Indeed, previous OMEGA spectrometer observations (Olsen et al, 2019) show different physical properties between the two main Martian atmospheric structures. As a result, the ACB is generally less detectable in the infrared. We hence reach the LNO channel sensibility limit for these clouds.

Finally, this work can be adapted to other high-resolution spectrometers devoted to exoplanetary science for example. Using all the available spectral ranges, we will be able to investigate the exoplanet's atmosphere composition.

# Martian CO2 ice characterization through ExoMars/TGO NOMAD LNO channel nadir high resolution data

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## ABSTRACT

The main focus of NOMAD instrument suite aboard ExoMars/TGO spacecraft is the study of minor atmospheric species at high spectral resolution. Nevertheless, it also offers the opportunity to investigate surface composition and aerosols properties. In this work we demonstrate the instrument capability in detecting CO2 ice through the analysis of the infrared LNO channel nadir observations considering the spectral range 2.3 – 2.6 μm. We obtain seasonal maps for CO2 ice in the polar regions, in good agreement with predictions by a general climate model and with the Mars Express/OMEGA spectrometer observations. We also find CO2 ice signatures at mid/equatorial latitudes, that we interpret as ice cloud on the basis of surface temperature, local time and grain size considerations. This provides the first detection of CO2 ice clouds through the study of the narrow 2.35 μm absorption band, sampled by LNO order 189. Through radiative transfer considerations we verify that this spectral feature is possibly sensitive to nm-sized ice grains.

**Mars as an exoplanet**

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## ABSTRACT

The exoplanets studies are now allowing us to recover direct information of the exoplanetary atmospheres, both in terms of composition and dynamics. The main techniques used for this purpose rely on high-resolution optical and/or near-infrared spectroscopy, with observations taken either during an exoplanet transit (transmission spectroscopy) or near the secondary eclipse (emission spectroscopy).

While at the moment the exoplanetary atmospheres studies are mostly confined to gaseous, hot planets (where the atmospheric signal is stronger), we are slowly moving towards small rocky planets, with the end goal of observing atmospheres of Earth-twins.

Still, the interpretation of the atmospheric data is still problematic and not always straight-forward. A great help in better understanding the information we recover on the exoplanets' atmospheres may come from the Solar System objects.

In this study, we plan to use high resolution spectroscopic observations of Mars to study the planets' atmosphere with the same techniques used in exoplanet studies with emission spectroscopy. Our aim is to link the atmospheric properties to the geophysical and tectonics characteristics on Mars surface, in order to better understand the information we obtain from exoplanets' study.

As a first step, we will use archival Mars spectra taken with the near-infrared spectrograph GIANO-B at the Telescopio Nazionale Galileo as a test case for our procedure. Then we plan to use the same instrument to observe the martian polar regions.

If successful, this procedure may be applied to other Solar System bodies such as Venus or Jupiter's and Saturn's moons.

We hope to use our joint expertise in both the exoplanet's atmosphere and geophysics to bridge the gap between Solar System bodies and exoplanets.

**Upgrade of ASIMUT-ALVL to model the VIS-NIR Jupiter’s atmosphere spectrum**

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**ABSTRACT**

MAJIS (Moons And Jupiter Imaging Spectrometer) is one of the key instruments on board the Jupiter ICy Moons Explorer (JUICE), the next mission to the Jovian system. We would like to perform simulations of different test cases with respect to the viewing geometries of JUICE when observing Jupiter. For this purpose, we have upgraded ASIMUT-ALVL, a Radiative Transfer code Developed at BIRA-IASB and extensively used to characterize Mars and Venus atmospheres. We implemented the current knowledge of physical and chemical characteristics of Jupiter, including the Rayleigh scattering contribution due to dominant atmospheric species, the refractive index of Jupiter’s atmosphere, and the Collision-Induced Absorption (CIA) due to $H_2$-$H_2$ and $H_2$-He molecular systems. To model the aerosols and hazes, we use the microphysical parameters already defined by López-Puertas et al. 2018. We are particularly interested on the composition of Jupiter’s atmosphere, specifically on the $H_2O$ and $CH_4$ contents, the most abundant species in the troposphere as a whole, after $H_2$ and He. Therefore, we focus our model in the VIS-NIR spectral range of MAJIS (0.5m-2.35m). In this work, we will discuss the challenges faced during the implementation of Jupiter parameters in ASIMUT-ALVL, as well as the followed methodology to validate our model with respect to previous works. The next step will be to reproduce real observational data. Once fully validated, we will assess the performances of the MAJIS VIS-NIR channel to characterize the vertical structure of the Jovian atmosphere.

**Oscillations of the Martian Northern Hemisphere Polar Vortex, a Contour Dynamics Perspective**

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**ABSTRACT**

The oscillations of the Martian Northern Hemisphere polar vortex are examined by using the Kida vortex model to interpret the dynamics of the vortex in reanalysis data. The vortex nutating around a fixed angle with little variability in its aspect ratio is shown to be controlled by the Hadley cell and wavenumber-2 planetary-scale waves that are characterised with a stationary component that is shown to be linked directly to Martian topography. The wave forcing and the Hadley cell structure are modelled as a strain and a rotational flow in Kida's model. It is shown that the strain and rotational flow are strongly negatively correlated, acting against vortex elongation in Kida's model. The result suggests that periods of high topographic forcing events are accompanied with a weakening in the Hadley cell winds and thus provides an explanation why vortex splits are rare on Mars. The methodology described in this presentation might also be applied to such exoplanetary atmospheres where a near-elliptical polar vortex is present during a 'winter season' to highlight the role of surface topography in polar vortex variability.

**The Claritas Fossae Fault System (Mars): a potential enhanced pathway for fluids exchange between the inner planet and the Martian atmosphere**

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## ABSTRACT

The surface of Mars hosts several regionally sized geological features (e.g., Tharsis Volcanic Province–TVP, Valles Marineris–VM, Claritas Fossae–CF, Thaumasia Highlands–TH) associated with faults, fracture swarms and volcanic vents. These lasts are crustal discontinuities that on Earth are widely recognized as enhanced pathways for fluid exchanges between the inner planet and its atmosphere. Similarly, on Mars their study at regional scale is of utmost importance to provide new insight on the role of the tectonics on the evolution of the atmosphere and of its characteristics. In this work we analyse the morphotectonic structures outcropping in the area of the Claritas Fossae (40°–15°S; 110°–100°W) to explore their development at depth and their crustal relevance. The CF exceeds a length of 1000 km and a width of 150 km. It is characterized by a system of elongated, sharp and asymmetric scarp-bounded depressions considered the surface expression of N-S trending faults. In the central-northern part there are two main faults, the Western Fault (WF) and the Eastern Fault (EF), characterized by length of 200 and 800 km and by elevation change of the scarps of 1000 and 2000 m, respectively.

We applied a forward modelling based on the HCA method that allows replicating the superficial morphologies through the relative movement of crustal blocks separated by tectonic discontinuities (i.e., faults) with given geometry and displacement. Resultsindicate that the EF is a crustal listric fault that reaches the base of the crust at about 80 km of depth. This is in line with other studies based on geophysical data that suggest in this and in surrounding regions a similar crustal thickness. Results from the modelling of both the WF and the EF will allow preparing a tectonic evolutionary model of the trapezoidal-shaped region bounded by CF–TH–VM structures and to evaluate their role as conduits for enhanced fluid connections between the planet and the atmosphere.

**The pursuit of a meticulous chemical survey of exoplanet atmospheres**

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**ABSTRACT**

Thousands of exoplanets have now been discovered with a huge range of bulk parameters. However, the essential nature of these planets remains largely mysterious. We have poor observational insights into how the chemistry of a planet is linked to its formation environment, or how the host star drives the processes controlling the planet's birth and evolution.

Current facilities have begun the reconnaissance of exoplanetary atmospheres. HST has been utilised to conduct observations of tens of worlds. These data have allowed for the first “population” studies of exoplanet atmospheres to be undertaken. WFC3 G141, which provides sensitivity to water in these atmospheres, has been central to these efforts and has characterised planets in both transmission and emission.

I will discuss the latest outcomes of homogenous population studies with HST WFC3, highlighting the key results and findings in the search for chemical. Furthermore, the limitations of current approaches will be presented, including data quality, the potential biases in the current analysis methods, and lack of rigorous population-level target selection.

In the next few years, the quality and quantity of space-based data will drastically increase thanks to JWST, Twinkle and Ariel. These new facilities will probe the atmospheres of hundreds of planets in unprecedented detail, triggering a substantial shift in our understanding of planetary science. However, to maximise the science yield of these missions we must learn lessons from the currently available datasets.

I will discuss how we can use the results and, at times, failings of these previous endeavours to develop clear strategies for target selection. Additionally, I will present projects which seek to understand the key capabilities and niches of these observatories, to help develop strategies to exploit the synergies and complementarities between different facilities in an attempt to construct a meticulous chemical survey of exoplanet atmospheres.

**New retrievals from HST observations focusing on the chemistry of exoplanets**

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**ABSTRACT**

The field of exoplanet studies is in rapid evolution with the launch of the JWST and
new facilities are foreseen in the near future such as the new VLT instruments, Ariel, ELTs. The future observations performed with these instruments will provide data (i.e. planetary spectra) with unprecedent accuracy, allowing to determine the physical and chemical parameters of exoplanets with a much better accuracy than what is currently possible.
In preparation of future observations, we propose here a re-analysis of Hubble Space Telescope (HST) data of five hot Jupiters, combining multiple instruments. Our five targets are : HAT-P-12b, HD 209458b, WASP-6b, WASP-17b and WASP-39b, with atmospheric temperatures from 1000K to 1700K and radii from 0.9 to 1.9 Jupiter radius.
We started from raw data observations from the Space Telescope Imaging Spectrograph (STIS) G430L and G750L grisms (0.5-1µm) and from the Wide Field Camera 3 (WFC3) G102 and G141 grisms (1.1-1.7µm). We analyze these raw datasets using Iraclis (Tsiaras et al. 2016) and calstis pipelines. After data reduction, we proceed with a retrieval analysis with TauREx (Al-Refaie et al. 2019) to fit the transmission spectra. We tested different chemistry, TP profiles, and clouds parametrization.
For example, we run simulations coupled with ACE program (Agúndez et al. 2012) that calculate the chemical composition at thermodynamic equilibrium corresponding to the temperature profile found at each step of the calculation. As a result, we can have models that constrain the abundance profiles and contributions of the main molecules. We remark that for very hot planets, thermochemical equilibrium hypothesis is well describing the data.
This work will be continued in the near future in the frame of Ariel preparation.

**Ultra-hot Jupiters as laboratories for theories of atmospheric structure and planet formation**

Lorenzo Pino, Jean-Michel Désert, Matteo Brogi
*INAF-Arcetri, Italy*

## ABSTRACT

Ultra-hot Jupiters (UHJs; T_eq >~ 2500 K) are the hottest gaseous giants known. They emerged as ideal laboratories to test theories of atmospheric structure and its link to planet formation. Indeed, because of their high temperatures, (1) they likely host atmospheres in chemical equilibrium and (2) clouds do not form in their dayside. Their continuum, which can be measured with space-facilities, can be mostly attributed to H-opacity, an indicator of metallicity. From the ground, the high spectral resolution emission spectra of UHJs contains thousands of lines of refractory (Fe, Ti, TiO, …) and volatile species (OH, CO, …), whose combined atmospheric abundances track planet formation history in a unique way. In this talk, I will describe the state-of-the-art of atmospheric observations of hot and ultra-hot Jupiters with ground-based high dispersion spectroscopy. Thanks to recent advancements in this technique, our and other teams are reaching unprecedented precision on atmospheric properties, including atmospheric abundances of atoms and molecules, pushing towards Solar System-like precisions. Through this new observational window, in the next few years we will revisit open questions about atmospheric structure and planet formation from an unprecedented perspective. In this contribution, we will also take a deeper look at the optical emission spectrum of UHJ KELT-9b between secondary eclipse and quadrature: thanks to a novel technique, we can now observe its three-dimensional atmospheric structure, and winds . Finally, I will present a new ambitious observing program that I lead to observe optical emission spectra of 5 -10 UHJs with the best 8-meter class telescopes for this scope (VLT ESPRESSO, Gemini-N MAROON-X).
Ultimately, observations of UHJ atmospheres offer a new and unique take on formation and evolution of planets and their atmospheres. They are thus highly synergic with studies of atmospheres of different classes of Solar System and extrasolar planets.

**Towards phase-curve retrieval studies of exoplanets in the era of next-generation telescopes**

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*University College London, UK*

## ABSTRACT

In the last 10 years, the study of exoplanets has moved from their discovery to the characterisation of their atmospheres, in particular using transit and eclipse observations from the Hubble Space Telescope (HST) and the Spitzer Space Telescope (Spitzer). While those telescopes provided a first insight on chemical processes, thermal structures and cloud properties in those planets, the next-generation of space telescopes (NASA-JWST, BSSL-Twinkle and ESA-Ariel) will revolutionise our understanding of these worlds by providing high-quality data for thousands of targets. Via the phase-curve technique, which consist in following the planet's emission along an entire orbit, those telescopes will be sensitive to three-dimensional (3D) processes and provide insight into atmospheric dynamics, equatorial jets and even localise storms. However, as of today, most atmospheric retrieval techniques employ a one-dimensional geometry due to their large computing requirements. Such 1D model cannot be used for phase-curve data as they do not account for 3D effects and a new class of fast, more-than-1D models is required. In this talk, I will present a new 1.5D phase-curve model that has been developed and tested on a number of simulations and real data from HST and Spitzer.

**Remote-Sensing observations of exo-atmospheres in our galaxy**

Giovanna Tinetti

*University College London, UK*

**Warm-Jupiter Exoplanet Observations as Probes for Atmospheric Chemical Processes**

Patricio Cubillos[1,2], Ilaria Carleo[3,4], Gloria Guilluy[5]

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## ABSTRACT

Transmission observations of transiting exoplanets allow us to constrain the composition of their atmospheres. In particular, the GIANO-B high-resolution spectrograph can probe a wide range of the near-infrared spectrum with unprecedented detail (0.9--2.45 microns), being able to test for the presence of several molecular species such as H2O, CO, CO2, CH4, HCN, NH3, and C2H2. The simultaneous detection of multiple carbon-, oxygen-, and nitrogen-bearing species places direct constraints to infer which chemical processes shape the observed composition of a planetary atmosphere.

Here we report on the statistically significant detection of a rich atmospheric composition on two warm-Jupiters planets, WASP-69b and WASP-80b, from GIANO-B observations.

Having equilibrium temperatures near the CO--CH4 equal-abundance boundary (~1000 K), make the composition of these planets particularly sensitive to temperature, and thus favorable for characterization. By employing physically motivated models of the atmosphere and spectra, we explored the physical conditions (temperature and elemental composition) and chemical processes (equilibrium or disequilibrium) that are more consistent with the set of molecular detections (and non-detections). Our analysis suggests that the atmosphere of both planets is affected by disequilibrium-equilibrium processes and that WASP-69b possibly has a carbon-rich composition.

**Population study: exploring the transition from super-Earth to sub-Neptune with a Hubble transmission survey**

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**ABSTRACT**

Exoplanets with size between the Earth and Neptune (1-4R⊕) do not have any equivalent in our Solar System and remain challenging to characterise. Yet, there are ubiquitous in the Galaxy and their distribution (number of planets per star vs radius) is bimodal highlighting a gap in the number of planets around 1.7R⊕ (Fulton et al. 2017). Planets with a radius below 1.7R⊕ are thought to be rocky planets, and called Super-Earth, above this limit planets are most likely made of gas and called Sub-Neptune. We made use of the available data from the Hubble Space Telescope in the Near-Infrared and gathered 26 transmission spectra of planets with size below 6R⊕. To study the transition between rocky and gaseous planets, we used TauREx3 (Al-Refaie et al. 2019), a Bayesian retrieval code to test six atmospheric retrieval models, from primary to secondary and compared their results with the Bayesian Evidence. We confirmed the detection of an atmosphere for 11 planets in the sample and this corresponds to the planets with a radius above 1.7R⊕.

While HST data cannot be used to differentiate a light atmosphere with clouds from heavier atmospheric scenarios, we proved that a primary clear atmosphere is rejected with more than 3σ confidence for 25 planets in the sample. Even though a secondary, N2 rich atmosphere, or a pure H2O atmosphere, is never the best fit, we cannot rule out this possibility for most planets. We showed that, by extending the wavelength range of the spectrum using ARIEL, we will be able to distinguish between a primary and a secondary atmosphere. The detectability of intermediate-size planets in the Near infrared is linked to the amplitude of the water feature around 1.4 microns and, thus, we build a new metric to assess the size of this absorption. Using this metric, we studied the cloudiness of warm Sub-Neptune and compared observational values to simulated ones. We explored the correlation between the 1.4 micron's feature amplitude and the temperature by constructing a grid in irradiation, metallicity and cloudiness using Exo-REM (Baudino et al. 2015; Charnay et al. 2018), a self-consistent radiative, convective model.

We showed that photochemical hazes created by the photodissociation of methane in the high atmosphere of warm Sub-Neptune are likely required to explain the observations of flat transmission spectra in the Near infrared.

**Four-of-a-kind: Exploring the atmospheres of the HR8799 system with GRAVITY**

Evert Nasedkin
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**ABSTRACT**

High contrast imaging provides a novel window into the atmospheres of young exoplanets, though the robust interpretation of results comes with many challenges. In this talk I will explore the systematic characterization of the HR8799 system using new VLTI/GRAVITY data combined with new and archival data from SPHERE, GPI, CHARIS, ALES and OSIRIS in order to provide the best picture of the planetary atmospheres across a broad wavelength range. Using petitRADTRANS in a Bayesian retrieval framework, we compare a suite of state-of-the-art models applied to each of the targets in order to measure atmospheric properties. We present the first C/O ratios of each of these planets as derived through disequilibrium and free chemistry retrievals, and discuss potential formation mechanisms that could have led to the current planetary configuration.

**Modons and Other Storms on Hot Exoplanets**

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**ABSTRACT**

Hot-Jupiter atmosphere observations show large variations in the location of the “hot spot” as well as in the amplitude of spectral features. Thus far, atmospheric flow simulations of these planets have generally produced a large and monolithic patch of hot area located eastward of the substellar point with little spatial or temporal variability suggested from current observations. By performing very high-resolution numerically-converged pseudospectral simulations, we demonstrate the presence of intense highly dynamic storms as well as planetary-sized coupled storm pairs (known as “modons”) in the atmospheres of hot-Jupiters. Importantly, these large storms persistently redistribute hot and cold regions of the atmosphere around the entire planet, leading to discernible signatures in disk-averaged thermal flux. The storms on hot-Jupiters all act in concert to exhibit quasi-periodic life cycles within multiple equilibrium states – behavior which may be identifiable by next generation missions, such as JWST and ARIEL.

**Toward the Observational Studies of Exoplanet Habitability**

Renyu Hu
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**ABSTRACT**

JWST will provide revolutionary capabilities to characterize small exoplanets and open up pathways toward the observational studies of exoplanet habitability. Particularly, the temperate planets with radii between 1.7 and 3.5 times the radius of Earth (i.e., temperate sub-Neptunes) will be among the planets first observed for atmospheric signatures. Some of the temperate sub-Neptunes may support liquid-water oceans if they do not have massive $H_2$ atmospheres and are thus not too hot at the bottom of the atmospheres. The mass of the atmospheres is not directly measurable by transits but critical for habitability. I will present a novel method to combine transmission spectroscopy and planetary chemistry modeling to determine if temperate sub-Neptunes are capped by thick $H_2$ atmospheres or thinner atmospheres that could foster a habitable environment. This method will be applied to the JWST observations of K2-18 b and LHS 1140 b, harbingers of a growing list of temperate sub-Neptunes. Hotter rocky planets, on the other hand, may or may not have an atmosphere. Some of them are suitable for observations in the thermal infrared and thus provide a testing ground for models of atmospheric evolution and retention. I will discuss using planetary phase curves to constrain whether small exoplanets have atmospheres, and using thermal emission spectra to determine their surface or atmospheric composition. These methods, complemented by novel models of terrestrial exoplanets’ atmosphere, atmosphere-interior exchange, and evolution, will break new ground for exoplanet science in the coming decade.

Specifically,

Deep characterization of small exoplanets will soon open up pathways toward the observational studies of exoplanetary habitability. At the frontier, JWST will be capable of obtaining the spectra of temperate and $H_2/H_2O$-rich planets and hotter rocky planets. The temperate planets with radii between 1.7 and 3.5 times the radius of Earth (i.e., sub-Neptunes) are in many ways more favorable targets for atmospheric observations than smaller planets. Some of these planets may support liquid-water oceans if they do not have massive $H_2/He$ envelopes and are thus not too hot at the bottom of the envelopes. I will present a novel method to use transit observations to determine if temperate sub-Neptunes are capped by thick $H_2/He$ atmospheres or thinner atmospheres that could foster a habitable environment. My group will use JWST to apply this method to K2-18 b and LHS 1140 b, harbingers of a growing list of temperate sub-Neptunes.

**EOS-ESTM: a flexible climate model for habitable exoplanets**

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**ABSTRACT**

The quest for life outside the Solar System is one of the major scientific challenges of our time. This search has attracted the interest of astronomers for ages but it's only in the last decades that it is becoming feasible. To date, the best strategy to accomplish this task consists in using large observational campaigns in combination with surface/atmospheric models of exoplanets to identify Earth-like rocky planets that show the best characteristic of habitability over a wide range of climate factors. In this context, we have developed EOS-ESTM, a fast and flexible model aimed at simulating the climate of potentially habitable planets. The model is built on ESTM, an energy balance model with upgraded vertical and meridional transport, and EOS, a new procedure for calculating the radiative transfer in a variety of rocky planetary atmospheres (Simonetti et al. 2022).

As part of our effort, we updated the model introducing and improving several prescriptions that include (i) the dependence of the surface albedo on the instantaneous stellar zenith distance, (ii) the description of a variety of cloud properties and (iii) the dependence of the ice coverage on the planetary surface temperature. To calibrate the model, we used a large set of Earth's satellite data, including the mean annual global profiles of surface temperature, TOA albedo, OLR and ice coverage. We, then, tested the capacity of the model to simulate a broad spectrum of exoplanetary climates. Applications to non-terrestrial conditions yield predictions that are in line with similar tests obtained with more complex 3D climate models. The flexibility of the model can be used to explore in detail the habitability conditions of individual exoplanets or exploring the extension and location of the HZ in a multiparameter space.

**EOS: a new dawn on radiative transfer for habitable worlds**

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## ABSTRACT

The vertical radiative transfer (RT) is a fundamental component of climate simulations, since it takes care of calculating the outgoing longwave radiation (OLR) and top-of-atmosphere (TOA) albedo for a set of atmospheric and planetary input parameters. These simulations can then be used to reconstruct the physical state on exoplanetary surfaces by piecing together the limited available data. They are also fundamental in the study of the past climate states of Earth, Mars and Venus.

In this talk we present EOS, a new RT procedure for cool and warm rocky exoplanets based on the publicly available RT model HELIOS and the opacity calculator HELIOS-K. Originally developed for the study of Gas Giant planets, these codes have been upgraded and complemented with a set of prescription devised for habitability studies. In particular we: (i) added the treatment for the continuum absorption features of $H_2O$ and $CO_2$, (ii) expanded the treatment of the sub-Lorentzian line wing shapes of $CO_2$ and (iii) considered the effects of non-ideal behaviour of $CO_2$ and $H_2O$ on lapse rate at condensation conditions. We assessed the robustness of EOS with respect to changes in model variables and physical inputs and finally, we compared it to other RT models used in literature (SMART, SBDART, LBLRTM...). The advantages of EOS are twofold: (i) it is based on highly parallelized, GPU-accelerated codes and (ii) it can be applied to a variety of cases that would generally require custom-built solutions.

As a result, EOS produces lookup tables for OLR and TOA albedo that can be used directly in 2D and 3D climate simulation or indirectly to train a neural network. Specifically, we used it to update ESTM, which is an energy balance model with enhanced prescriptions for the meridional transport of heat (Biasiotti et al. submitted to MNRAS). The EOS-ESTM model is flexible and fast enough to be used in large scale explorations of the planetary parameter space in terms of habitability indices and atmospheric observability.

**The effect of late giant collisions on the atmospheres of protoplanets and the formation of cold sub-Saturn**

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**ABSTRACT**

We investigate the origins of cold sub-Saturns (CSS), an exoplanetary population inferred from microlensing surveys. If confirmed, these planets would rebut a theorized gap in planets' mass distribution between those of Neptune and Jupiter caused by the rapid runaway accretion of super-critical cores. In an attempt to resolve this theoretical-observational disparity, we examine the outcomes of giant collisions between sub-critical protoplanets. Due to the secular interaction among protoplanets, these events may occur in rapidly depleting discs. We show that impactors $\sim$ 5% the mass of near-runaway envelopes around massive cores can efficiently remove these envelopes entirely via a thermally-driven super-Eddington wind emanating from the core itself, in contrast with the stellar Parker winds usually considered. After a brief cooling phase, the merged cores resume accretion. But, the evolution timescale of transitional discs is too brief for the cores to acquire sufficiently massive envelopes to undergo runaway accretion despite their large combined masses.
Consequently, these events lead to the emergence of CSS without their transformation into gas giants. We show that these results are robust for a wide range of disc densities, grain opacities and silicate abundance in the envelope. Our fiducial case reproduces CSS with heavy ($\gtrsim 30M_\oplus$) cores and less massive (a few $M_\oplus$) sub-critical envelopes. We also investigate the other limiting cases, where continuous mergers of comparable-mass cores yield CSS with wider ranges of core-to-envelope mass ratios and envelope opacities. Our results indicate that it is possible for CSS and Uranus and Neptune to emerge within the framework of well studied processes and they may be more common than previously postulated.

**Mapping day-night variations in the stratosphere of the ultrahot Jupiter WASP-121b**

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## ABSTRACT

The dayside and nightside conditions of a hot Jupiter differ in the extreme, thanks to tidal locking of the planetary rotation and the resulting asymmetry in radiative forcing. To refine our global understanding of such atmospheres, phase curve measurements provide a unique means to probe the stratospheric emission of both the dayside and nightside hemispheres. I will present a spectroscopic phase curve measurement obtained for the ultrahot Jupiter WASP-121b using the Hubble Space Telescope WFC3 instrument, which probes dayside and nightside atmospheric properties across two orders of magnitude in pressure and a temperature range of 2000K. Variations observed for the 1.4 micron water vapor band throughout the planet's day-night cycle reveal a vertical temperature profile that transitions from warming with altitude on the dayside hemisphere to cooling with altitude on the nightside hemisphere. These data provide valuable constraints for the radiative and dynamical processes operating to maintain the atmosphere in thermal equilibrium. The phase-resolved spectra also inform our understanding of the 3D atmospheric chemistry, in particular the role played by thermal dissociation and ionisation as a function of longitude and altitude.

**Characteristics and applications of the Meso-NH mesocale model applied to the Earth atmosphere**

Didier Ricard
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**ABSTRACT**

Meso-NH (Lac et al., 2018) is an atmospheric non hydrostatic research model, developed for more than 20 years, initially by the CNRM (CNRS/Météo-France) and the LAERO (UPS/CNRS). It is an attractive community model currently used in research institutes around the world integrating the developments of dozens of researchers. It is dedicated to a broad range of resolutions, from planetary waves to near-convective scales down to turbulence scales. It is possible to study scale interactions over large grids or via two-way grid nesting. The model can be used both as a cloud-resolving model and a large-eddy simulation, as well as a direct numerical simulation. It is designed for studies of physics and chemistry of Earth atmosphere with advanced diagnostics.

It is a grid-point limited-area model based on anelastic equations, which are written on the conformal plane to take into account the Earth's sphericity. Based on a highly parallel code in an open access framework, it uses advanced numerical techniques allowing high computational performance.

It includes state-of-the-art physics parameterization schemes: radiation, turbulence, microphysical, convection schemes that are important to represent convective-scale phenomena and turbulent eddies. It is on-line coupled with the surface model SURFEX (Masson et al. 2013) to represent the influence of planetary surfaces or sub-surfaces with very different physical characteristics like forests, deserts, oceans, glaciers, or urban areas on the atmosphere. All these parameterizations are also used in the Numerical Weather Prediction model AROME (Seity et al., 2011), running operationally at Météo-France since 2008 at kilometric resolution.

In addition, Meso-NH has been expanded to provide capabilities for a range of Earth system prediction applications such as chemistry and aerosols, electricity and lightning, hydrology, optical turbulence for astronomy, wildland fires, volcanic eruptions, and cyclones with ocean coupling.

**Data Assimilation in atmospheric models: from operational applications to the impact assessment of future satellite measurements**

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With data assimilation we mean a family of methods to optimally combine observations with numerical models of any (more or less) complex phenomena of interest. In atmospheric science, it is one of the main approaches to rely on for improving the knowledge of the atmospheric state at a given reference time or time-interval, at a given spatial resolution.

Through this process, analyses are generated ingesting from a few to a myriad of heterogeneous observations (e.g., from classic meteorological stations on land or on ship, to radar systems or satellites), typically available on an irregular grid, to produce a representation of the atmospheric state over a regular grid. Global analyses are valuable in a number of different contexts, from climate studies to operational forecasts, where they provide initial and boundary conditions.

The same holds for “local” analyses, that is analyses performed on limited spatial domains. In this latter case they can be specifically applied to improve the reliability of short-term forecasting and nowcasting, a hot topic for present meteorology when dealing with the prediction of extreme events, in the context of a changing climate.

However, in atmospheric science and operational applications, it is known that any assimilation of data does not guarantee an improvement in the model simulation results. In complex systems like the (Earth) atmosphere, it can depend on a number of reasons, such as the measurement types, their errors and density, the assimilation methods, the magnitude of the differences between the measurements and the corresponding model values, and some others. In this talk, after a short recap of the main theoretical bases, some numerical experiments on data assimilation will be presented for limited area model simulations, using different measurements and methods, for two main objectives: improving the operational meteorological forecasts and assessing the potential impact of assimilating measurements of future satellite missions on atmospheric modelling and predictions.

The latter objective is approached through an Observing System Simulation Experiment (OSSE), a generic framework of wide applicability, for generating synthetic measurements and evaluating the impacts of their assimilation in forecasting some atmospheric features of primary interests.

**The use of spectrally resolved observed radiances to test and improve the representation of the Earth's atmosphere in climate models**

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**ABSTRACT**

The Outgoing Longwave Radiation (OLR), defined as the Earth's energy emitted at top of the atmosphere (TOA) in the spectral range 100 – 2500 $cm^{-1}$ (4 - 100 μm), is a key quantity controlling the Earth energy budget and its accurate representation by global climate models (GMCs) is crucial to have reliable historical and future simulations. In this framework, the integrated broadband OLR fluxes provided by the Earth Radiation Budget Experiment (ERBE) and the more recent Cloud and Earth Radiant Energy System (CERES) mission constitute the standard reference to investigate the evolution of the Earth's energy balance and represent the target dataset for climate models tuning. However, despite the comparison of simulated and observed energy fluxes integrated over the whole Earth emission spectrum [W $m^{-2}$] provides fundamental information to assess climate models performance, it makes
difficult the detection of biases masking possible compensation errors that may occur in different spectral regions. Conversely, comparing simulated to observed spectra [W $m^{-2}$ $sr^{-1}$ $cm^{-1\ (-1)}$] allows to point out the potential model criticalities in particular spectral bands containing the signatures of specific climate variables.
From the mid of 2000s stable hyperspectral observations of the Earth emission spectrum in the Mid-Infrared region (667 to 2750 $cm^{-1}$) have been providing by different sensors (IASI, AIRS, SCIAMACHY, etc) opening interesting perspectives for climate study applications. In addition, the FORUM mission, selected to be the ninth ESA Explorer mission, will measure from 2027 the spectrally resolved radiances of the Earth's emission spectrum at the TOA, from 100 to 1600 $cm^{-1}$, filling the existing observational gap of the far-infrared region (FIR), from 100 to 667 $cm^{-1}$.
In this work, in anticipation of FORUM measurements, we compared ten years of IASI existing observations to synthetic radiances extracted from the EC-Earth GCM (version 3.3.2), a recent European model based on ECMWF's Integrated Forecasting System (IFS) for the atmosphere–land component.
In order to extract simulated spectra from the climate model, EC-Earth has been used along with the CloudFeedback Model Intercomparison Project (COSP), a simulator package able to map the model state into synthetic observations from different satellite-borne active (CloudSat (radar) and CALIPSO (lidar)) and passive (ISCCP, MISR and MODIS) sensors. We have further developed the package by implementing inside COSP the radiative transfer model σ-FORUM, a monochromatic code able to reproduce synthetic radiances in the Far-Infrared and Mid-Infrared regions compatible with future FORUM and existing IASI observations.
Due to the high computation cost of the operation, the efficiency of the EC-Earth model equipped with the new COSP module has been improved by modifying the σ-FORUM original code structure and by the number of grid-points where the spectrum is computed. Therefore, on-line simulations provided by the EC-Earth model equipped with the new COSP + σ-FORUM module have been performed in clear-sky conditions with prescribed sea surface temperature and sea-ice cover every 6 hours, over a timeframe consistent with the availability of IASI data.
Systematic comparison between observational data and model outputs have been performed over spectral bands of 10 $cm^{-1}$ on a global and regional scale by distinguishing the types of surface (land, sea) of the emitted radiances in order to address the existing model biases in different spectral bands to specific climate variables. The long term analysis shows a warm bias of the climate model in the roto-vibrational water vapour

bands and in the $CO_2$ absorption band, which represents a strong evidence of model bias in the upper-troposphere and stratosphere, while a cold bias in the atmospheric window occurs over land, suggesting the existence of compensation errors in the broadband flux.

## Stellar activity through simultaneous multiband photometry: V1298 Tau case study

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### ABSTRACT

A reliable modeling of stellar activity is fundamental to observe and characterize exoplanets and their atmospheres, especially for planets around young stellar objects (YSO). Since active regions, such as faculae and spots, have different temperatures with respect to the photospheric surface we expect different stellar flux variations in different photometric bands. For this reason, we plan to observe a sample of active stars through simultaneous multiband photometry, using Johnson B, V, R and I, Sloan g', r' and z' together with J, H, and K bands.
We are currently testing our method observing V1298 Tau, a very active young stellar object hosting 3 confirmed planets. Preliminary results indicate that the activity is dominated by spots contribution. By using MCMC (Markov Chain Monte Carlo) fitting procedure we are able to determine the size and the position on the stellar surface of the dominant spots and estimate their temperature.

**Extreme ultraviolet and X-rays driven photochemistry of gaseous exoplanets.**

Daniele Locci
*Università di Palermo, Italy*

**ABSTRACT**

The interaction of exoplanets with their host stars causes a vast diversity in bulk and atmospheric compositions, and physical and chemical conditions. Stellar radiation, especially at the shorter wavelengths, drives the chemistry in the upper atmospheric layers of close orbiting gaseous giants, providing drastic departures from equilibrium. We unfolded the effects caused by photons in different spectral bands on atmospheric chemistry, in particular we focused on the effects induced by X-rays.

The weak X-ray photoabsorption cross-sections of the atmospheric constituents boost the gas ionization to pressures inaccessible to vacuum and extreme ultraviolet photons. Although X-rays interact preferentially with metals, they produce a secondary electron cascade able to ionize efficiently hydrogen and helium bearing species, giving rise to a distinctive chemistry. We aim at finding chemical signatures in synthetic spectra that allow us to assess the level of ionization induced by X-rays.

**Preliminary results of atmospheric parameters varying with LT around volcanoes from PFS-MEx observations**

Paulina Wolkenberg[1], Marco Giuranna[1], Davide Grassi[1], Aymeric Spiga[2], Alejandro Cardesin-Moinelo[3], Donald Merritt[3], Julia Marin-Yaseli de la Parra[3]
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## ABSTRACT

We present a new type of observations (scan mode) to study atmospheric parameters varying with LT over volcanoes in the Tharsis region. Scan orbits are measured by the Planetary Fourier Spectrometer (PFS) across the track of Mars Express spacecraft. We focus on observations from the southern summer season in MY 35. In order to improve fits between modeled and observed spectra, a correction on surface pressures was introduced. We found a hot air close to the top of Olympus while the cold air is observed at 40 – 50 km of altitude. As a result, potential temperatures are almost constant from 15 to 30 km of altitude. Thus, the very deep vertical mixing layer occurs there.

**Transmission spectroscopy of exoplanetary atmospheres at high spectral resolution**

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**ABSTRACT**

Transiting exoplanets offer the best opportunity for an atmospheric characterization: transmission spectroscopy is now the most powerful technique to investigate exoplanetary atmospheres. During a planetary transit, a fraction of the light coming from the host star is filtered through the planet's atmosphere, thus providing hints of its composition. With resolving power R>50,000, a lot of information and robust constraints on fundamental parameters of exoplanet atmospheres can be retrieved. Due to their unique fingerprint at high dispersion, molecular and atomic species can be robustly identified by cross-correlating hundreds of resolved individual transitions or by isolating their line profile for the ones with the largest cross-sections, in contrast to the potential ambiguities in the interpretation of planet spectra observed at low dispersion or with sparse photometric bands. This allows one also to characterize many atmospheric properties, such as composition, winds, temperature-pressure profiles. In this contribution I will review the state of the art of high-resolution transmission spectroscopy, showing the last recent results and focusing on the striking detection of atomic oxygen in the hottest known exoplanet, that followed the prediction by a sophisticated state-of-the-art atmospheric model.

**ANDES: the ArmazoNes high Dispersion Echelle Spectrograph for the European Extremely Large Telescope**

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## ABSTRACT

ANDES (ex HIRES) is an optical-infrared High Resolution Spectrograph for the ELT which is expected to start construction in early 2022 to arrive at the telescope in early 2030. The ANDES project is carried out by an international consortium composed of 33 institutes from 13 countries of which INAF is the leading technical institute.
I will present an overview of the project, describing science cases and the baseline design. The top science cases of ANDES will be the detection of life signatures from exoplanet atmospheres, tests on the stability of Nature's fundamental couplings, and the direct detection of the cosmic acceleration. However, the science requirements of these science cases enable many other ground-breaking science cases. The baseline design, which allows to fulfil the top science cases, consists of a modular fibre-fed cross-dispersed echelle spectrograph providing a simultaneous range of 0.4-1.8 µm with a goal of 0.35-2.4 µm, at a resolution of 100,000 and with several observing modes. ANDES will be provided both in seeing- and diffraction-limited modes, the latter being characterised by a unique high resolution IFU, capable of a simultaneous wavelength coverage of 1-1.8 µm, which is particularly suited for the study of exoplanets atmospheres in reflection.

**Characterizing the atmospheres of cold and temperate exoplanets with direct imaging observations in reflected starlight**

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## ABSTRACT

The discovery of about 5000 exoplanets has unveiled a wide diversity of worlds, many of which have no analogue in the Solar System. Characterizing their atmospheres is a key to understand their formation mechanisms, evolution and possible habitability conditions. Up to date, the set of exoplanets accessible for atmospheric characterization has remained generally limited to hot and short-period planets due to the technology available. Cold and temperate exoplanets on long-period orbits are currently out of reach for atmospheric studies. Upcoming direct-imaging instruments observing exoplanets in reflected starlight will start overcoming these biases, enabling the atmospheric characterization of mature long-period exoplanets. These facilities will probe the outer regions of planetary systems and will ultimately be able to observe low-mass planets in the habitable zone of Sun-like stars.

The first space-based instrument devoted to directly imaging exoplanets in reflected starlight will be the coronagraph instrument aboard the Nancy Grace Roman Space Telescope, planned for launch in the mid-2020s. This coronagraph will act as a technology demonstrator for next-generation missions such as the Large IR/O/UV Space Telescope recommended by the US Astro2020 Decadal Survey, a synthesis of the previous LUVOIR and HabEx concepts. In this talk we discuss, based on atmospheric retrieval exercises from simulated measurements, the prospects for atmospheric characterization of cold and temperate exoplanets with direct imaging observations in reflected starlight. We analyse the challenges for the interpretation of these observations, in particular for the case of non-transiting exoplanets that lack a measurement of the planet radius. We also show how different observing strategies can help improve the atmospheric characterization. Finally, we present
several examples of known exoplanets that will be accessible for atmospheric characterization with this technique and discuss their detectability with different direct-imaging facilities.

**How to measure spectra of planetary atmospheres in the laboratory ?**

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**ABSTRACT**

The habitability of (exo)planets depends on many factors, including the properties of the atmosphere. Spectra of planetary atmospheres are useful for the determination of the composition of the atmosphere, the detection of clouds, and the study of dynamical processes. Furthermore spectra taken in atmospheric transparency windows can shed light on low clouds and the surface of the planet.
The interpretation of spectral data requires accurate molecular constants for the species involved, as well as a theoretical comprehension of the phenomena contributing to the emission and absorption process occurring in various layers of the atmosphere. Although these data are available for the terrestrial atmosphere, the conditions in terms of density and temperature of many solar and extra solar planets are often very different from the Earth, and adequate data and theory are insufficient to describe emission and absorption processes properly.
Laboratory experiments can be useful to fill the gap in our knowledge and provide new spectral data that might also contribute to an improvement of theoretical models.
Here I will present some experimental techniques and recent laboratory measurements in conditions similar to the atmosphere of Venus.

**Laboratory investigation on the atmospheric chemistry of Titan waiting for the NASA Dragonfly mission: the formation of unsaturated dinitriles**

Nadia Balucani, Demian Marchione, Luca Mancini, Pengxiao Liang, Gianmarco Vanuzzo, Giacomo Pannacci, Marzio Rosi, Piergiorgio Casavecchia
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## ABSTRACT

Following the successful Cassini mission and the landing of the Huygens probe in 2005, in 2034 the Dragonfly mission will explore again Titan, the massive moon of Saturn. The mission features a lander which will allow sampling various regions of Titan's surface by landings in different locations. After the huge amount of data collected by the Cassini-Huygens mission, we now know that Titan is characterized by a nitrogen-dominated atmosphere showing the richest chemistry among all planets/moons of the Solar System and by an icy surface covered by abundant organic molecules and lakes formed by liquid methane and ethane. At the moment, Titan is the best object to explore the prebiotic chemistry that might have preceded the emergence of life on Earth.

In our laboratory, we have already investigated several gas-phase reactions leading to the formation of N-containing molecules which have been detected or that are alleged to be present in the upper atmosphere of Titan. The further evolution of those species can explain the formation of the N-rich organic macromolecules that form the haze layers of Titan. In view of the Dragonfly mission, we have continued a systematic investigation of the reactions involving also minor components. A combined experimental and theoretical approach has been used to characterize these gas-phase reactions. At the same time, we have developed a flow micro-reactor cryogenically cooled to the temperature typical of Titan's surface to characterize a possible chemistry occurring in liquid methane.
In this contribution, we will present results concerning the formation of unsaturated dinitriles, namely dicyanoacetylene and dicyanoethylene, by the reactions between the CN radicals and cyanoacetylene or cyanoethylene. The implications for the chemistry of Titan and Dragonfly mission will also be noted.
The authors wish to thank the Italian Space Agency for cofounding the Life in Space project (ASI N. 2019-3-U.0).

**A laboratory investigation of the reaction N($^2$D) + benzene and implications for the atmospheric chemistry of Titan**

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**ABSTRACT**

Titan, the massive moon of Saturn, is characterized by a nitrogen-rich dense atmosphere while minor constituents include organic molecules, such as methane and higher hydrocarbons.The observation of nitriles and other molecules containing a C-N bond suggest that active forms of nitrogen can react with methane and/or the other hydrocarbons present in trace amounts. Atomic nitrogen is produced in the upper atmosphere of Titan by EUV photodissociation of molecular nitrogen or other processes induced by energetic particles. Notably, nitrogen atoms can be formed in both the ground, 4S, and the first electronically excited, 2D, states, the latter being a metastable state with a very long radiative lifetime.
In our laboratory we have investigated several bimolecular reactions involving N($^2$D) and aliphatic hydrocarbons by means of the crossed molecular beam (CMB) technique with mass spectrometric detection and time of flight (TOF) analysis, in order to identify the primary products and determine their relative yield.
In all cases, the investigated reactions were observed to lead to the formation of N-containing organic molecules. More recently, we have employed the same experimental approach to investigate the reactions of N($^2$D) with other species known to be present in the atmosphere of Titan. In this contribution, I will present the results concerning the reaction with benzene. Benzene has been established to be quite abundant in the atmosphere of Titan. The experimental results have been complemented by electronic structure calculations and statistical estimates of the product branching ratios. According to our study, the N($^2$D)$C_6H_6$ reaction is barrierless and lead dominantly to HCN+$C_5H_5$(cyclopentadienyl). Interestingly, the product species can further react in the conditions of the upper atmosphere of Titan possibly contributing to the growing up of the large N-rich organic macromolecules constituting the haze aerosols of the moon.

**Planetary Atmosphere Simulation System for Spectroscopy (PASSxS), a laboratory set up used to characterize the optical properties of gases at typical planetary conditions**

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**ABSTRACT**

The optical properties of gases at typical planetary conditions are of major importance to provide the input parameters to the radiative transfer models, especially in the regions where the present databases lack of information. The experimental data can support either the study of our solar system bodies and also contribute significantly to the understanding of the exoplanets spectroscopy. In this work we describe this experimental set up designed to measure the optical properties of gases such as $CO_2$, $CH_4$, $H_2$, $H_2$+He or their combinations, performed in an ample range of pressure and temperature. The experimental set-up is composed by a custom vacuum double chamber, perfectly designed to be coupled to a Fourier Transform-InfraRed (FT-IR) spectrometer. The chamber is designed to sustain pressures in a range from vacuum up to 70 bar and temperatures ranging from 100 up to 500 K. The chamber is equipped with a multi pass absorption gas cell, characterized by an optical path of about 9 m, mounted in the inner part. The inner chamber is inside another vacuum vessel able to insulate thermally the gas cell. Thanks to the FTIR, the absorption coefficients of the gases can be measured in a wide spectral range (1250 - 25000 $cm^{-1}$) with a spectral resolution from 0.07 to 10 $cm^{-1}$. In this work we describe the setup and present preliminary results of the $CO_2$ Fermi Triade bands measured in the IR spectral region at different densities and temperatures.

**Experimental activity at the atmospheric simulation chamber ChAMBRe**

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## ABSTRACT

Atmospheric simulation chambers (ASCs) are laboratory facilities devoted to the investigation of chemical and physical processes occurring in the atmosphere. Inside ASCs, the atmospheric conditions can be controlled and monitored in real time for periods long enough to mimic realistic environments and to study interactions among the atmospheric constituents. The high versatility of ASCs allows for a wide application in many fields of atmospheric sciences.

The only Italian ASC, ChAMBRe, is installed at the Genova Section of INFN and it is managed in collaboration with the Environmental Physics Laboratory of the Physics Department-University of Genoa. ChAMBRe (Chamber for Aerosol Modelling and Bio-aerosol Research) is an indoor chamber, made in stainless steel and with a volume of about 2.2 $m^3$. The chamber is equipped with on-line monitors of the internal temperature, pressure and relative humidity, gas analyzers and particles counters (a Scanning Mobility Particle Spectrometer, an Optical Particle Sizer and a Wideband Integrated Bioaerosol Sensor). Three Photoacoustic Extinctiometers measure aerosol optical properties and filter samplers are also available to collect particles for off-line analysis. The air inlet is throughout a five-stage filtering inlet system (including a HEPA filter), which reduces the ambient relative humidity to about 15 % (possibly lowered down to 0% by using synthetic air) and ensures

an excellent purification of the air entering the chamber. Gas and particles composition in ChAMBRe can be controlled by specific injection systems. A Solar simulator mimics the sun light in the UV-IR window.

Most recent studies at ChAMBRe focused on the optical properties of atmospheric aerosols and the interaction between bioaerosol and the other atmospheric constituents.

We will introduce the facility and its main features and possible applications, even through the Trans National Access (TNA) supported by European research programs.

**Impact of magnetic fields and cosmic rays in the context of star formation and exoplanetary systems**

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**ABSTRACT**

Our understanding of the processes that govern star formation and the life of exoplanets has been revolutionised by observations in the last two decades. These fields will continue to benefit from next-generation missions such as JWST and Ariel. I will review the important role that magnetic fields and cosmic rays play in star formation and exoplanetary systems. I will discuss the impact of both stellar and Galactic cosmic rays for protoplanetary disks and exoplanets. In particular, I will focus on how cosmic rays are an important source of ionisation for these disks and how magnetic fields can influence protoplanetary disk formation and evolution. I will describe how the flux of cosmic rays reaching an exoplanet is expected to vary during its life and the implications this has for chemistry in the exoplanet's atmosphere. Finally, I will mention what we might expect from upcoming observations and important open questions in the field.

**The evolution and stability of $CO_2$-$CH_4$-$H_2O$ atmospheres**

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**ABSTRACT**

We follow up on an overlooked class of atmosphere pointed out by Woitke et al.(2020), primarily composed of $CO_2$, $CH_4$, $H_2O$, and $N_2$ based on thermochemical equilibrium. The coexistence of $CO_2$ and $CH_4$ by thermodynamics has critical implications for false positives of biosignature gases. In this work, we extend the previous study by considering chemical kinetics and a realistic 1D atmosphere structure.
The timescale is first estimated and compared to the planetary system. We find that thermochemistry is too sluggish and chemical equilibrium is irrelevant in the loosely habitable temperature regime. Nevertheless, there exists a sweet spot at higher temperatures that permits the coexistence of $CO_2$ and $CH_4$ as the planet cools and the atmospheric constituents quenched after formation. Using a photochemical model (VULCAN; Tsai et al. 2021) coupled to a radiative-transfer model HELIOS (Malik et al. 2019), we investigate the photochemical steady state of this type of $CO_2$-$CH_4$-$H_2O$ atmosphere in the context of considering $CO_2$-$CH_4$ as a biosignature pair.
The sensitivity to stellar irradiation and surface interactions are also explored.

**The transmission spectrum of WASP-17 b from the optical to the near-infrared wavelengths: combining STIS, WFC3 and IRAC datasets**

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**ABSTRACT**

In the last two decades the Hubble and the Spitzer Space telescopes have pioneered exoplanet atmospheric studies through transit and eclipse spectroscopy. Among the hot-Jupiters, an exotic class of planets that do not have a counterpart in our solar system, we find the so-called ‘puffy’ hot-Jupiters. Their hot inflated atmosphere and consequently large scale height boosts the S/N ratio of the observations, allowing us to easily probe their
atmosphere.
In this context, I will present the transmission spectrum of the inflated hot-Jupiter WASP-17 b, one of the least dense gas giants discovered so far. The exoplanet was observed with the STIS (gratings G430L, G750L) and WFC3 (grisms G102, G141) instruments aboard the Hubble Space Telescope, allowing for a continuous wavelength coverage from 0.4 to 1.7 μm. I also include the observations taken with IRAC channel 1 and 2 on the Spitzer Space Telescope, which add photometric measurements at 3.6 and 4.5 μm. Thanks to the availability of a large breadth of observations, this is a rare opportunity to investigate the spectrum of WASP-17 b from the optical to the near-infrared wavelengths.
I will describe how the HST spectral data was analysed with Iraclis, an open-source pipeline specialised on the reduction of STIS and WFC3 observations. Moreover, I will present a machine learning approach to the data reduction of Spitzer photometric data, by employing the Transit Light Curve Detrending LSTM method.
The modelling of this exoplanetary spectrum proves challenging, with two of the STIS datasets producing incompatible results. Hence, I will discuss what can be inferred from the spectrum of this intriguing planet, from the potential presence of aluminium oxide (AlO) and titanium hydride (TiH) to an extreme photospheric activity of its companion star.
The study is of particular interest as it: a) demonstrates the issues faced when combining data from a variety of instruments; b) presents the benefits of achieving a large wavelength coverage; c) allows to investigate the activity of the host star.
The lessons learned from the combination of different instruments are exceptionally timely given the similar challenges that JWST data will bring in the near future.

**ESPRESSO transmission spectroscopy of WASP-54 b and GJ 436 b**

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**ABSTRACT**

We observed two primary transits of the hot Jupiter-size and warm Neptune- size exoplanets WASP-54 b and GJ 436 b using the ESPRESSO spectrograph on the VLT. The data cover the 380 - 780 nm wavelength range. The host stars have very different spectral types: F8 and M3, respectively. The two transits were acquired on two different occasions separated by 1 (WASP-54 b) and 2 (GJ 436b) months. The mean S/N of the individual spectra is 40 - 50 (WASP-54 b) and 35 - 45 (GJ 436 b) at 550 nm. GJ 436 b is known for its escaping atmosphere (Ehrenreich et al. 2015). We searched for atomic and molecular species in the planetary atmospheres using both the direct detection of absorption features and the cross-correlation methods. We also used the two transits per planet to investigate whether there is any atmospheric variability.

## The transmission spectrum of the ultra-hot Jupiter WASP-76b

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## ABSTRACT

The atmosphere of WASP-76b has been explored during the last years in the search for both molecular and atomic features. The transmission spectrum of this Ultra-hot Jupiter has a rich chemical inventory containing a plethora of atomic species like Li, Na, Ca, Fe, among others. Here we report on the transmission spectrum of WASP-76b as studied by the ESPRESSO consortium. In summary, thanks to the ESPRESSO data it has been possible to extract two transmission spectra of WASP-76b with a nominal R≈140000.
These two transmission spectra continuously cover the full ESPRESSO wavelength range (3800-7880 Å). We show that the technique employed can detect features down to the level of 0.1%. Finally, we discuss the presence of atomic and molecular features in the atmosphere of WASP-76b.

**Architecture of planetary systems with giant planets in outer orbits**

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**ABSTRACT**

In recent years, our knowledge about planetary systems has expanded in a way that could not have been foreseen when the first exoplanet was detected in 1995. In spite of this, today there are still several questions that we are trying to answer. In Italy, most of the scientists working in this field cooperate inside the GAPS team (General Architecture of Planetary Systems).
In this context, we will present preliminary results obtained within the KP (Known Planets) sub-program: the aim is to investigate the influence of giant planets in outer orbits on the presence and characteristics of planets in closer orbits, in particular on the possibility of hosting planets in the habitable zone. The KP objects are characterized by the fact that they are giant planets with periastron greater than 1 A.U. around low-activity stars for which only a few or low-quality data were available before the beginning of the GAPS project. Taking this into account, we are putting together all the available radial velocity measurements in the literature for these targets and perform orbital fits over a timespan of several years to determine whether these objects have undetected companions either in the habitable zone or beyond the snow line. In particular, a few potential candidates with periods longer than the already known planets have already been identified.

**Predicting the optical performance of the Ariel Telescope using PAOS**

Andrea Bocchieri

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**Abstract:**

Ariel, the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey, is the M4 mission in ESA's Cosmic Vision program and will provide the first unbiased spectroscopic survey of transiting exoplanets' atmospheres. PAOS, the Physical Ariel Optics Simulator, is an end-to-end Physical Optics Propagation (POP) model of the Ariel telescope and subsystems. It propagates the complex wavefront through the Ariel optical chain and delivers realistic PSFs at the intermediate and focal planes. PAOS performs detailed analyses on diffraction and aberrations impacting the Ariel optical performance before having a system-level measurement, to ensure that the optical quality, complexity, costs, and risks are not too high.

**Atmospheric composition of giant planets: the effects of chemical diversity in protoplanetary discs**

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## ABSTRACT

The composition of giant planet atmospheres is linked to the planet formation process and arises from the interplay between the migration and accretion of gas and solids by giant planets across the native protoplanetary discs. As migrating giant planets can interact with diverse chemical environments, the final composition of their atmospheres can be used as a proxy into their formation and migration histories once its link to the disc chemistry is fully understood. We investigate the effects of the different chemical scenarios of the host protoplanetary disc (chemical composition inherited by the native molecular cloud or resetted to atomic components by the young protostar) on the final composition of giant planets, exploring the possibility of a wide planetary formation region (5-130 AU) as suggested by recent observations and focusing on four elemental tracers in the planet atmosphere: C, O, N, and S. In all disc chemical scenarios, we find that the elemental ratios of our four tracing elements in the giant planet's atmosphere are strongly influenced by the formation and migration process but that, while connected to it, they are not a direct reflection of the disc chemical structure. We show how the elemental ratios of our four tracing elements vary with the radial migration and how referring their values to the stellar abundance ratios provides direct insights into the source of the planetary metallicity and the planet formation history. Our results and methods have direct application to future spectral observations, like those that JWST and Ariel will perform, and illustrate how the retrieval of the main molecular carriers of C, O, N, and refractory elements like S will allow to directly constrain the formation history of giant planets.

**Reduced atmospheres on post-impact worlds: The early Earth**

Jonathan Itcovitz

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## ABSTRACT

Impacts may have had a significant effect on the atmospheric chemistry of the early Earth. Reduced phases in the impactor (e.g., metallic iron) can reduce the planet's $H_2O$ inventory to produce massive atmospheres rich in $H_2$. Whilst previous studies have focused on the interactions between the impactor and atmosphere in such scenarios, we investigate two further effects, 1) the distribution of the impactor's iron inventory during impact between the target interior, target atmosphere, and escaping the target, and 2) interactions between the post-impact atmosphere and the impact-generated melt phase. We find that these two effects can potentially counterbalance each other, with the melt-atmosphere interactions acting to restore reducing power to the atmosphere that was initially accreted by the melt phase. For a $\sim 10^{22}$ kg impactor, when the iron accreted by the melt phase is fully available to reduce this melt, we find an equilibrium atmosphere with $H_2$ column density $\sim 10^4$ moles cm$^{-2}$ ($pH_2 \sim 120$ bars, $XH_2 \sim 0.77$), consistent with previous estimates. However, when the iron is not available to reduce the melt (e.g., sinking out in large diameter blobs), we find significantly less $H_2$ ($7\times10^2-5\times10^3$ moles cm$^{-2}$ , $pH_2 \sim 60$ bars, $XH_2 \sim 0.41$). These lower $H_2$ abundances are sufficiently high that species important to prebiotic chemistry can form (e.g., $NH_3$ , HCN), but sufficiently low that the greenhouse heating effects associated with highly reducing atmospheres, which are problematic to such chemistry, are suppressed. The manner in which iron is accreted by the impact-generated melt phase is critical in determining the reducing power of the atmosphere and re-solidified melt pool in the aftermath of impact.

## ArielRad : the Ariel Radiometric Model

Lorenzo Mugnai

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### ABSTRACT

ArielRad, the ARIEL radiometric model, is a simulator developed to address the challenges in optimising the space mission science payload and to demonstrate its compliance with the performance requirements. During its 4 years primary operation, ARIEL, the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey, will provide the first unbiased spectroscopic survey of a large and diverse sample of transiting exoplanet atmospheres. To allow for an accurate study of the mission, ArielRad uses a physically motivated noise model to estimate contributions arising from stationary processes, and includes margins for correlated and time-dependent noise sources. We show that the measurement uncertainties are dominated by the photon statistic, and that an observing programme with about 1000 exoplanetary targets can be completed during the mission lifetime.

## Alfnoor : Assessing the Information Content of Ariel's Low-resolution Spectra with Planetary Population Studies

Lorenzo Mugnai

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### ABSTRACT

The Ariel Space Telescope will provide a large and diverse sample of exoplanet spectra, performing spectroscopic observations of about 1000 exoplanets in the wavelength range 0.5–7.8 μm. In this work, we investigate the information content of Ariel's Reconnaissance Survey low-resolution transmission spectra. Among the goals of the Ariel Reconnaissance Survey is also to identify planets without molecular features in their atmosphere. In this work, (1) we present a strategy that will allow us to select candidate planets to be reobserved in Ariel's higher resolution tier, (2) we propose a metric to preliminary classify exoplanets by their atmospheric composition without performing an atmospheric retrieval, and (3) we introduce the possibility to find other methods to better exploit the data scientific content.

**High temperature VUV cross section measurements for the study of hot exoplanets: new line list and temperature dependance of $A^1\Pi$-$X^1\Sigma^+$ + CO transition, 3 ≤ v' ≤ 10 and v'' = 0, 1**

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## ABSTRACT

The large diversity of planetary worlds has been firmly established, since the discovery of the first exoplanet in 1995. Some planets have the size of Jupiter and orbit at very close distances from their host star, making them "Hot Jupiter" with atmospheric temperatures as high as 2000 K. To understand how such diversity can be, we need more information about the physical and chemical characteristics of those planets. This is one of the main goals of the JWST mission and will be the main objective of the Ariel mission. The observations of these telescopes will be interpreted thanks to photo/thermochemical kinetics models, that calculate the atmospheric abundance profiles. Unfortunately, such models need input data like UV absorption cross sections of gases and most of them are unknown at high temperatures.
Our group has started some years ago the determination of absorption cross sections at high temperatures showing on $CO_2$ how huge the variations can be as compared to ambient ones (Venot et al. 2013, 2018). Nevertheless, in those laboratory measurements, one of the uncertainties remains the determination of the temperature of gas inside the oven. To overcome this, we have studied the absorption cross section of CO in the $A^1\Pi$-$X^1\Sigma^+$ transition between 68 000 and 78 000 $cm^{-1}$ (128 to 147 nm), at different temperatures between 300 and 800 K. This work led us derive a new line list of the rovibrational transitions with 3≤v'≤10 et v''=0, 1. This line list was then used to determine the temperature of gas inside the oven.
Our study shows that CO can be used as a direct temperature probe of the gas inside our oven. Since this line list was tested over a large domain of temperatures, it can be extrapolated to higher temperatures with confidence. It will be made available to the community for astrophysical studies.
In addition to the work on CO, we will also present our new VUV experiment developed at LISA to systematically determine temperature variations of gas absorption cross sections in this wavelength domain.

**Thermally driven hydrodynamic escape stripping lunar-mass objects - an application to Ganymede and Titan**

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## ABSTRACT

The solar system gas giant moons Titan and Ganymede are remarkably similar in mass, mean density and semimajor-axis distance to their host planets, yet Titan harbours a massive atmosphere, while Ganymede does not.
Assuming identical formation conditions for both of those moons, this is a puzzling conundrum. A mechanism to explain this atmospheric dichotomy has been qualitatively proposed in the past. The culprit is supposed to be the large difference in thermal formation heat fluxes emanating from their host planets. This idea however, to the extent of our knowledge, has never been tested quantitatively.
In this work we present simulations to test this idea. We discuss the dramatic impact of different molecules on the efficiency of the outflow and follow the atmospheric mass-loss over the history of the early solar system, as the efficiency of escape races against the rapid cooling of their host planets.

**Metabolic Signatures of Aerial Biospheres in the Clouds of Venus & Venus-like Exoplanets**

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**ABSTRACT**

Life in the clouds of Venus, if present in sufficiently high abundance, must be affecting the atmospheric chemistry. It has been proposed that abundant Venusian life could obtain energy from its environment using three possible sulfur-based metabolisms. These metabolisms raise the possibility of Venus's enigmatic cloud-layer SO2-depletion being caused by life. We couple each metabolic pathway to a photochemical-kinetics model and self-consistently predict the composition of Venus's atmosphere under the scenario that life produces the observed SO2-depletion. Using this photo-bio-chemical kinetics model, we show that all three metabolisms can produce SO2-depletions, but do so by violating other observational constraints on Venus's atmospheric chemistry. We can therefore place limits on the maximum possible biomass density of sulfur-metabolising life in the clouds, before violating observational constraints. The methods employed are equally applicable to aerial biospheres on Venus-like exoplanets, planets that are optimally poised for atmospheric characterisation in the near future.

**The exposure platforms OREOcube and Exocube on the International Space Station: Photochemistry and in-situ spectroscopy of planetary atmospheres**

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## ABSTRACT

OREOcube (Organics Exposure in Orbit cube) and Exocube (Exposure of Organics/Organisms cube) experiments will both be part of the new European Space Exposure Platform EXPO to be mounted on the outside of the International Space Station (ISS), allowing the exposition of chemical and biological samples to elevated levels of
electromagnetic- and space radiation in Low Earth Orbit (LEO). Exocube consists of two payloads: ExocubeBio monitors the growth and adaptation of microorganisms via colorimetry and fluorescence while ExocubeChem measures the photostability of organic molecules via infrared spectroscopy. The experimental design of OREOcube is similar to ExocubeChem but makes use of the UV-Vis spectroscopy measurement technique instead.
Both ExocubeChem and OREOcube study astrobiologically and astrochemically relevant organic compounds, so called biomarkers, either in a pure form or in connection with inorganic material such as iron oxides or minerals.
To obtain uniform sample films, the organic and inorganic molecules will be deposited by controlled thermalevaporation onto transparent window substrates, which can then be hermetically sealed to form sample cells, allowing the control of different gas atmospheres and pressures. In this way the organic thin films be exposed to specific gas mixtures giving the possibility to mimic different planetary atmospheres. This will allow us to investigate the behavior of specific organic compounds, known to be building blocks of life as we know it, in a specific gas atmosphere via in-situ spectroscopy. Due to their leak rates of below 10-10 mbar*l/s, the sample cells are designed to maintain a stable atmosphere for the experimental period outside the ISS over the course of 12 months.

Studying the interaction of organics and inorganics will provide information about the role that inorganic material, such as solid mineral surfaces, play in the transport and distribution as well as the photochemical evolution of organics in our solar system. Keeping track of changes in the gas atmosphere within the sample cells during the experiment gives us additional information about by-products of chemical reactions and thus spectral signatures of decay products in the gas phase. In laboratory simulations, biomarkers such as amino acids, pigments and polycyclic aromatic hydrocarbons have been deposited on inorganic material such as iron oxides (FexOx), titanium oxides (TiO2) and minerals, which can all be found on the Martian surface. The samples can then be kept in a custom-designed Martian atmosphere (p=6mbar, 95.9% $CO_2$, 2% Ar, 1.9% $N_2$, 0.14% $O_2$) and exposed to the conditions on the Martian surface (i.e. temperature, radiation environment, surface) while measuring changes in thin films and atmosphere in-situ. In further experiments, it has been shown that with the existing experimental setup, it is possible to assemble samples cells containing an $N_2$/$CH_4$ mixture as it can be found in higher atmospheric layers of Titan, a moon of Saturn. Besides Earth, Titan is the only body in the solar system with an $N_2$ dominated atmosphere and the investigation of the behavior of its atmosphere under certain conditions could give indications about how early Earth transformed into a planet on which life developed.