Abbot Dorian - poster
University of Chicago

No Snowball Bifurcation on Tidally Locked Planets

I'm planning to present on the effect of ocean dynamics on the snowball bifurcation for tidally locked planets. We previously found that tidally locked planets are much less likely to have a snowball bifurcation than rapidly rotating planets because of the insolation distribution. Tidally locked planets can still have a small snowball bifurcation if the heat transport is strong enough, but without ocean dynamics we did not find one in PlaSIM, an intermediate-complexity global climate model. We are now doing simulations in PlaSIM including a diffusive ocean heat transport and in the coupled ocean-atmosphere global climate model ROCKE3D to test whether ocean dynamics can introduce a snowball bifurcation for tidally locked planets.

Abraham Carsten - poster
University of Victoria

Stable climate states and their radiative signals of Earth-like Aquaplanets

Over Earth's history Earth's climate has gone through substantial changes such as from total or partial glaciation to a warm climate and vice versa. Even though causes for transitions between these states are not always clear one-dimensional models can determine if such states are stable. On the Earth, undoubtedly, three different stable climate states can be found: total or intermediate glaciation and ice-free conditions. With the help of a one-dimensional model we further analyse the effect of cloud feedbacks on these stable states and determine whether those stabalise the climate at different, intermediate states. We then generalise the analysis to the parameter space of a wide range of Earth-like aquaplanet conditions (changing, for instance, orbital parameters or atmospheric compositions) in order to examine their possible stable climate states and compare those to Earth's climate states. The analysis allows for the calculation of possible radiative signals from aquatic exoplanets as would be observed by telescopes.

Adams Danica - poster
California Institute of Technology

Aggregate Hazes in Exoplanet Atmospheres

Photochemical hazes have been frequently used to interpret exoplanet transmission spectra that show an upward slope towards shorter wavelengths and weak molecular features. While previous studies have only considered spherical haze particles, photochemical hazes composed of hydrocarbon aggregate particles are common throughout the solar system. We use an aerosol microphysics model to investigate the effect of aggregate photochemical haze particles on transmission spectra of warm exoplanets. We find that the wavelength dependence of the optical depth of aggregate particle hazes is flatter than for spheres since aggregates grow to larger radii. As a result, while spherical haze opacity displays a scattering slope towards shorter wavelengths, aggregate haze opacity can be gray in the optical and NIR, similar to those assumed for condensate cloud decks. We further find that haze opacity increases with increasing production rate, decreasing eddy diffusivity, and increasing monomer size, though the magnitude of the latter effect is dependent on production rate and the atmospheric pressure levels probed. We generate synthetic exoplanet transmission spectra to investigate the effect of these hazes on spectral features. For high haze opacity cases, aggregate hazes lead to flat, nearly featureless spectra, while spherical hazes produce sloped spectra with clear spectral features at long wavelengths. Finally, we generate synthetic transmission spectra of GJ 1214b for aggregate and spherical hazes and compare them to space-based observations. We find that aggregate hazes can reproduce the data significantly better than spherical hazes, assuming a production rate limited by delivery of methane to the upper atmosphere.

Arcangeli Jacob - poster
University of Amsterdam

Phase Curve of an Ultra hot Jupiter: WASP-18b

We present the full-orbit phase curve of the ultra hot Jupiter WASP-18b, obtained with HST. Our data show a large day-night contrast coupled with a small westward offset to the hottest point, indicative of strong drag or dissipation on the day side atmosphere to maintain the >1500 K temperature contrast.
We compare our phase curve to 3D Global Circulation Models to explore the effect of drag on the circulation and estimate the required drag efficiency.
Our models show that Lorentz-force drag from a planetary magnetic field as weak as 10 Gauss could have the desired drag efficiency, although other sources of drag cannot be ruled out. These results hint at the complexity behind ultra hot Jupiter climates, as their extreme temperatures give rise to further physical and chemical effects on their atmospheres.

Barstow Joanna - poster
University College London

Cloudy hot Jupiters: maximizing information from retrievals

Recent primary transit observations have yielded some evidence of cloud or haze for a large fraction of hot Jupiters. Whilst some predictions of composition, size and distribution are available from chemical and circulation models, our knowledge of cloud formation processes on these planets is still very limited and gaining constraints from data is critical. Parameterised cloud models are required to extract information from spectra via retrieval methods, which involves simplification of cloud properties and the underlying physics, but allows the broad characteristics (e.g. vertical distribution, opacity) to be inferred directly from observations.
The choice of appropriate parameters in these models is critical to maximise information content, and the parameters selected will affect the cloud solution for the retrieval. I will present the results of an investigation into the most appropriate parameterisation of cloud for transiting exoplanet observations, including some discussion of the impact of spatially variable cloud cover.

Baudino Jean-Loup - poster
University of Oxford

Combining forward modelling and retrieval to extract the maximum of physics from exoplanet direct imaging observations

The characterisation of the exoplanets evolved recently thanks to the development of the second generation of direct-imaging instruments, especially SPHERE. The resolution and wavelength range available now gives access to an increase in accuracy and in the number of physical parameters that can be constrained. SPHERE observations are a combination of narrow band filters between J and K and spectroscopy between Y and H. We first show how a forward model (Exo-REM) may be used to obtain the physical parameters of the target. Then we use the results of this first approach as an a priori for the retrieval code (NEMESIS) on the same dataset. We also apply a Nested Sampling version of NEMESIS complementary to the more traditional Optimal Estimation mode. We compare the results of the various approaches highlighting the advantages of each. We give the resulting physical parameters constrained by these approaches to show what SPHERE can determine alone in terms of exoplanet characterisation.

Baxter Claire - poster
University of Amsterdam

A comprehensive survey of exoplanet atmospheres with Spitzer

Studying exoplanets affords us the opportunity to understand the sheer diversity of planets in different physical regimes; from close-in hot-jupiters to super-earths without solar system counterparts. We aim to use the statistical power of a large survey to test the theoretical predictions of exoplanet atmosphere properties. We classify the sample into groups and use the properties of individual planets within these groups to understand the collective diversity of our sample.
We use the Spitzer space telescope to observe the atmospheres of a diverse sample of two dozens of close-in gas giant exoplanets and we present our preliminary results. The sample spans ranges of mass and equilibrium temperature. The dominant absorbers at these observed wavelengths are water, methane and carbon monoxide, and we strive to test theoretical predictions of the abundances of these molecules using our survey. We conduct a uniform and detailed analyses of transiting exoplanet light curves using state-of-the art systematic corrections in the two warm Spitzer/IRAC bandpasses (at 3.6 and 4.5 microns). We compare our observations of the atmospheric signals to cloud-free atmospheric 1D models. Ultimately, our work places new constraints on diverse families of exoplanet atmospheres, as well as on possible formation and evolution scenarios.

Beltz Hayley - poster
University of Michigan

Making Every Dimension Count: Combining High Resolution Spectroscopy with a 3D GCM to Constrain Wind Speed and Rotation Rate for a Hot Jupiter

High resolution spectroscopy allows astronomers to probe the atmospheres of exoplanets. Once telluric and stellar lines are removed from the data, the dim planetary spectrum remains, but buried in the noise. In order to retrieve this signal, we use a cross-correlation method with synthetic spectra. Because of the inherently three dimensional structure of an exoplanet atmosphere, we employ a 3D general circulation model (GCM) for the Hot Jupiter HD 209458b to generate model spectra to use in the cross-correlation analysis of VLT/CRIRES high-resolution emission spectra for this planet. With an orbital period of just over 3.5 days, it is likely that HD 209458b is tidally locked into synchronous rotation, but this has yet to be empirically proven. We therefore run our GCM with 12 different rotation periods, ranging from 2.03 days to 9.08 days. From this suite of models we generate 12 sets of synthetic spectra which can then be used to cross-correlate with the data. From this, our goal is to constrain both wind speeds and the rotation rate of this Hot Jupiter. Our analysis is the first ever use of synthetic spectra from 3D GCMs for cross-correlation with high-resolution emission spectra, to empirically constrain winds and rotation of an exoplanet.

Benneke Björn - oral
Université de Montréal, iREX

A Sub-Neptune Exoplanet with Low-Metallicity Methane-Depleted Atmosphere and Mie-Scattering Clouds

With no analogues in the Solar System, the discovery of thousands of exoplanets with masses and radii intermediate between Earth and Neptune was one of the big surprises of exoplanet science. These super-Earths and sub-Neptunes likely represent the most common outcome of planet formation1,2. Mass and radius measurements indicate a diversity in bulk composition much wider than for gas giants3; however, direct spectroscopic detections of molecular absorption and constraints on the gas mixing ratios have largely remained limited to planets more massive than Neptune4–6. Here, we analyze a combined Hubble/Spitzer Space Telescope dataset of 12 transits and 20 eclipses of the sub-Neptune GJ 3470 b, whose mass of 12.6 M⊕ places it near the half-way point between previously studied exo-Neptunes (22-23 M⊕)5–7 and exoplanets known to have rocky densities (7 M⊕)8. Obtained over many years, our data set provides a robust detection of water absorption (>5σ) and a thermal emission detection from the lowest irradiated planet to date. We reveal a low-metallicity, hydrogen- dominated atmosphere similar to a gas giant, but strongly depleted in methane gas. The low, near-solar metallicity (O/H=0.2-18) sets important constraints on the potential planet formation processes at low masses as well as the subsequent accretion of solids. The low methane abundance indicates that methane is destroyed much more efficiently than previously predicted, suggesting that the CH_4/CO transition curve has to be revisited for close-in planets. Finally, we also find a sharp drop in the cloud opacity at 2-3 μm characteristic of Mie scattering, which enables narrow constraints on the cloud particle size and makes GJ 3470b a keystone target for mid-IR characterization with JWST.

Birkby Jayne - oral
Anton Pannekoek Institute for Astronomy, University of Amsterdam

Exoplanet atmospheres at high spectral resolution

High-resolution spectroscopy is a robust and powerful tool in exoplanet atmospheric characterization. Key to its success it resolving molecular features into a dense forest of thousands of individual lines arranged in unique patterns by wavelength. It uses either the change in the Doppler shift of a planet during its orbit to disentangle its spectrum from the glare of its host star, or takes advantage of the star-planet spatial separation when combined with high contrast imaging. The technique is sensitive to the depth, shape, and position of a planet's spectral lines, and thus reveals information about the planet's composition, atmospheric structure, mass, global wind patterns, and rotation. In this talk, I will review the ground-breaking advances that high resolution spectroscopy has made in the study of giant exoplanet atmospheres, and I will detail how this will further progress in the era of the ELTs, as well as its complementarity to JWST and other lower resolution data. I will end with a look to how this technique is being trained to be able to detect biosignatures in nearby rocky worlds in the future.

Blecic Jasmina – oral
New York University Abu Dhabi

Equilibrium and Kinetic Cloud Models in Retrieval

Clouds have shown to be essential in understanding exoplanetary spectra. They play a fundamental role in detecting and revealing the atmospheric chemical composition, as they often hide information from the deep atmospheric layers by dramatically smoothing the spectral features and increasing the amount of scattered light. In addition, they introduce compositional and morphological changes, by molding the planetary temperature and pressure structure and altering the planetary energy budget and dynamics. Clouds are notoriously hard to model even in the Earth atmosphere and particularly in exoplanetary retrieval as they add additional free parameters overburdening already highly computationally demanding calculations without adding much to the information criteria for poor quality data. Thus, the most commonly used cloud models in exoplanetary retrieval to date are either a simple constant cross-section, a gray cloud model, or an opaque cloud deck at a given pressure. In forward modeling, however, there are two approaches used to understand exoplanetary cloud formation in a self-consistent manner: (1) the phase-equilibrium concept of thermal stability, Ackerman and Marley (2001) and (2) the phase-non-equilibrium concept of microphysical dust formation, Helling et al.(2008). While the first approach describes the end state of the cloud formation, assuming that the gas is well mixed, transported above the cloud base and grains fall under the influence of gravity, the second approach explores the kinetic processes of cloud formation, where the dust particles form, fall down and grow, until they evaporate below the cloud base. Here, we present the implementation of both of these theoretical approaches in retrieval; the equilibrium approach as a parametrized model, and the kinetic approach as a fully self-consistent model. We apply these models to current Spitzer and Hubble data and synthetic James Web Space Telescope observations of several hot-Jupiters in 1D and 2D retrieval, providing detailed information about the cloud composition, extent, particle size distribution, and number density; and we compare our results with the 3D general circulation models with clouds.

Bott Kimberly – oral
University of Washington/VPL

Utility of Polarimetry in Studies of Exoplanet Atmospheres and Habitability

Polarimetry has been suggested as a means to detect oceans on terrestrial exoplanets, detect and retrieve the orbital parameters of strongly Rayleigh Scattering giant exoplanets, map exoplanets, and characterize clouds. The value of this method in comparison with other approaches, however has not been well quantified in the past.

In this talk we examine the utility of the method for studies of exoplanet surfaces, atmospheres, and condensates with current and near future telescope architectures. We also examine other uses for polarimetry in the near future for atmospheric characterization including spectropolarimetry for biosignatures.

Using a robust radiative transfer model with both polarized and non-polarized solutions, we provide comparisons of different exoplanet scenarios including archetypes of terrestrial planets based on realistic environmental scenarios, super Earths in contrast to sub-Neptunes, and giant planets in polarized light to aid in quantifying the advantage polarimetry might provide, and to identify which planetary scenarios are most likely to yield characterization results using this with planned polarimeters.

Brogi Matteo - poster
University of Warwick

Measuring temperatures and abundances of exoplanet atmospheres with high-resolution cross-correlation spectroscopy

Two decades of discoveries have allowed the scientific community to determine in exquisite detail the frequency and size distribution of exoplanets. And yet, their true nature still eludes our full understanding and requires accurate estimates of the atmospheric properties, i.e. chemical composition and thermal vertical structure. High-resolution spectroscopy (R > 25,000) has recently emerged as one of the leading methods to detect atomic and molecular species in the atmospheres of exoplanets. However, it has so far been lacking a robust method to extract quantitative constraints on temperature structure and molecular/atomic abundances. Here I present the first successful Bayesian atmospheric retrieval framework applicable to high-resolution spectroscopy and relying upon the cross-correlation between data and models to extract the planetary spectral signal. This method allows us to correctly determine Bayesian credibility intervals on atmospheric temperatures and abundances allowing for a quantitative exploration of inherent degeneracies. Furthermore, the new framework allows the direct combination of the complementary information carried by high- and low-res spectroscopy. Low-resolution spectroscopy measures variations over broad wavelength ranges whereas high-resolution focusses on the position, shape and strength of individual lines. Their combination - obtained trivially within the framework - allows us to extract the maximum amount of information from exoplanet atmospheres, leading to radical improvements in both metallicity and C/O ratio measurements. This framework is the first step towards a synergy between space and ground observations that will eventually lead to the characterisation of potentially habitable planets,

Casewell Sarah - oral
University of Leicester

Irradiated Brown Dwarfs

As brown dwarfs have atmospheres similar to those we see in Jupiter and in hot Jupiter exoplanets, irradiated brown dwarfs have been described as “filling the fourth corner of parameter space between the solar system planets, hot Jupiter exoplanets and isolated brown dwarfs”. Irradiated brown dwarfs are however, rare. There are only about 15 known around main sequence stars, and even fewer that have survived the evolution of their host star to form close, post-common envelope systems where the brown dwarf orbits a white dwarf. These systems are however, extremely useful. The white dwarf emits more at shorter wavelengths, where the brown dwarf is brightest in the infrared, meaning it is possible to directly observe the brown dwarf – something that is extremely challenging for the main sequence star-brown dwarf systems.
In this talk I will discuss the known white dwarf-brown dwarf binaries and how the brown dwarf’s atmosphere is being affected by orbiting its much hotter white dwarf companion. My observations of these systems have shown that emission lines are often present from the brown dwarf’s atmosphere – but that not all systems have emission from the same species. I have also shown that the ultraviolet irradiation from the white dwarf has the largest effect in the K and 4.5 micron bands, creating a brightening effect – the brown dwarf actively emitting much more in these wavelengths than it should be. I will discuss the causes of this brightening - which may be due to H_2 fluorescence, as has been suggested to be present in the atmospheres of exoplanets orbiting active M dwarfs, or due to H_3^+ emission, as is seen in the atmospheres of planets in our solar system (Jupiter, Saturn, Uranus).
This talk will also discuss the similarities and differences between the irradiated brown dwarf systems with different types of host star (white dwarf vs main sequence) and how the mass-radius relation of brown dwarfs is affected by irradiation.

Chachan Yayaati - poster
California Institute of Technology

A Hubble PanCET Study of HAT-P-11b: A Cloudy Neptune with a Low Atmospheric Metallicity

We present the first comprehensive look at the 0.35-5 μm transmission spectrum of the warm (~800 K) Neptune HAT-P-11b derived from thirteen individual transits observed using the H*ubble* and *Spitzer Space Telescopes*. Along with the previously published molecular absorption feature in the 1.1-1.7 μm bandpass, we detect a distinct absorption feature at 1.15 μm and a weak feature at 0.95 μm, indicating the presence of water and/or methane with a combined significance of 4.4 σ. We find that this planet's flat optical transmission spectrum and attenuated near-infrared molecular absorption features are best-matched by models incorporating a high altitude cloud layer. Atmospheric retrievals using the combined 0.35-1.7 μm *HST* transmission spectrum yield strong constraints on atmospheric cloud-top pressure and metallicity, but we are unable to match the relatively shallow *Spitzer* transit depths without under-predicting the strength of the near-infrared molecular absorption bands. HAT-P-11b's *HST* transmission spectrum is well-matched by predictions from our microphysical cloud models when sulphide condensates are removed, and that the physical properties of the condensates in these models are in good agreement with constraints obtained from retrievals using the Mie scattering formalism. Both forward models and retrievals indicate that HAT-P-11b most likely has a relatively low atmospheric metallicity (<55 $Z_\odot$ or < 28 Z_* with 95% confidence), in contrast to the expected trend based on the solar system planets. Our work also demonstrates that the wide wavelength coverage provided by the addition of the *HST* STIS data is critical for making these inferences.

Challener Ryan - poster
University of Central Florida

A Comprehensive Spitzer Study of the GJ 436b Eclipses

GJ 436b is one the most observable transiting Neptune-sized planets, with hundreds of hours of Spitzer observations, including 16 transits and 24 eclipses over 6 photometric channels, some of which have not been published. We jointly fit the eclipse light curves, using advances in correlated-noise removal techniques to achieve the best, but realistic, signal-to-noise ratios. We then determine updated orbital parameters, atmospheric composition, and thermal structure, and discuss these results in the context of past work. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Astrophysics Data Analysis Program grant NNX13AF38G.

Checlair Jade – oral
University of Chicago

Testing the weathering feedback with LUVOIR and Habex

Traditional habitable zone theory assumes that the silicate-weathering feedback regulates the atmospheric CO2 of planets within the habitable zone to maintain surface temperatures that allow for liquid water. There is some non-definitive evidence that this feedback has worked in Earth history, but it is untested in an exoplanet context. A critical prediction of the silicate-weathering feedback is that, on average, within the habitable zone planets that receive a higher stellar flux should have a lower CO2 in order to maintain liquid water at their surface. We can test this prediction directly by using a statistical approach involving low-precision CO2 measurements on many planets with future observing facilities such as JWST, LUVOIR, or HabEx. The purpose of this work is to carefully outline the requirements for such a test.
First, we use a radiative-transfer model to compute the amount of CO2 necessary to maintain surface liquid water on planets for different values of insolation and planetary parameters. We run a large ensemble of Earth-like planets with different masses, atmospheric masses, inert atmospheric composition, cloud composition and level, and other greenhouse gases. Second, we post-process this data in a statistical framework to determine the precision with which future observing facilities such as JWST, LUVOIR, and HabEx could measure the CO2. We then combine the variation due to planetary parameters and observational error to determine the number of planet measurements that we would need in order to effectively marginalize over uncertainties and resolve the predicted trend in CO2 vs. stellar flux.
The results of this work may influence the usage of JWST and will enhance mission planning for LUVOIR and HabEx,

Darveau Bernier Antoine - poster
Université de Montréal

High-dispersion transit/emission spectroscopy with SPIRou (Spectro-Polarimètre InfraRouge) at the Canada-France-Hawai-Telescope (CFHT).

SPIRou has recently been installed at the CFHT. Its unique wavelength coverage (1 - 2.35 µm) and its high-resolution (~75,000) make this instrument highly suitable for exoplanets atmospheric characterization via transit and emission spectroscopy. Its broad spectral range gives access to the signature of many different species simultaneously, which is very convenient to compare their relative abundances. Moreover, its high-resolution enables us to distinguish the planet signal from the earth atmospheric absorption and the star signal because of the doppler-shift. I will present an overview of SPIRou's performances to characterize exoplanets atmospheres by showing real transit and emission data.

Deibert Emily - poster
University of Toronto

Investigating the Presence of HCN in the Atmosphere of 55 Cancri e

We present our recent analysis of high-resolution, near-infrared spectra of 55 Cancri e: an extremely hot, low-density super-Earth orbiting a nearby Sun-like star. Following up on Tsiaras et al. (2016), who used observations from WFC3 (HST) to report the detection of an atmosphere around this exoplanet, we investigate the possibility that HCN can explain the features detected by Tsiaras et al. (2016) at 1.42 and 1.54 μm. With 10 transits in the near-infrared obtained from the CARMENES (Calar Alto) and SPIRou (CFHT) instruments, we make use of the Doppler cross-correlation technique pioneered by Snellen et al. (2010) to search for the thousands of absorption lines caused by HCN in the near-infrared. Our method simultaneously takes advantage of the extremely high spectral resolution and broad wavelength coverage of our observations to provide an unprecedented look at the atmosphere of a super-Earth. We are able to rule out a wide range of HCN models in 55 Cancri e's atmosphere, and provide the most stringent constraints to date on the atmospheric makeup of this enigmatic exoplanet.

Egan Arika - poster
University of Colorado, Boulder

The Colorado Ultraviolet Transit Experiment (CUTE)

The Colorado Ultraviolet Transit Experiment is a CubeSat designed to characterize the interaction between close-orbiting exoplanets and their host star via low-resolution transit spectroscopy. Inflated and escaping atmospheres on short-period exoplanets have been observed in both the far-ultraviolet (FUV) and near-ultraviolet (NUV). The inflation and outflow are driven by the extreme irradiation these planets experience as a result of their proximity to the host star. However, the physics of this star-planet interaction is difficult to constrain due to the relatively few ultraviolet transit observations published. CUTE is a dedicated, NUV CubeSat mission that will observe 6 - 10 transits of more than a dozen bright exoplanetary systems of a range of masses, thereby increasing the observational basis for atmospheric escape studies. The 250 – 330 nm bandpass is host to several atomic and molecular transitions, including Mg I, Mg II, Fe I, Fe II, and OH. These diagnostics enable us to quantify the transit ingress, egress, and depth of exoplanet light curves as a function of wavelength, allowing us to determine the planetary mass loss rates, constrain the atmospheric composition, and search for the presence of bow shocks. CUTE is planned for launch in 2020 for a seven-month nominal mission. Its flexible observing schedule allows for coordinated observations of interesting targets with a number of facilities. This presentation details the CUTE instrument and mission design, displays performance curves, and discusses predicted science results for several representative exoplanetary systems.

Evans Tom - oral
MIT

Hubble spectroscopic phase curve observations for the ultrahot Jupiter WASP-121b

WASP-121b is an extreme system, even by exoplanet standards. With a radius 1.8x that of Jupiter, it is one of the most inflated planets known, and orbits a bright F6 star only ~15% beyond its Roche limit, where it is subjected to intense tidal forces and the atmosphere is heated to ~2700K. Radiation from the dayside hemisphere has been measured using Hubble and Spitzer, revealing spectral features due to H- ions, H2O, and CO. Notably, these features are observed in emission rather than absorption, providing the first definitive evidence for a thermal inversion in an exoplanet atmosphere. This dayside thermal inversion is likely caused by strong absorption of incident stellar radiation at optical wavelengths, a picture supported by the Hubble transmission spectrum, which probes the atmospheric opacity at the day-night boundary. It shows evidence for significant absorption across the optical, possibly due to VO gas, as well as a dramatic near-UV absorption signal, not seen before for any other planet. We will present new observations of WASP-121b, in the form of a full-orbit spectroscopic phase curve acquired with Hubble at near-infrared wavelengths. Phase curves provide information about the circulation and 3D properties of the atmosphere, unobtainable through primary transits and secondary eclipses alone. In particular, phase curves allow the day-night brightness contrast to be determined and can reveal evidence for advective heat transport in the form of the dayside hot spot being offset from the substellar point, both constraining atmospheric dynamics. The new phase curve data will also track how the H2O band within the Hubble bandpass transitions from being in emission on the dayside to absorption on the cooler nightside, producing a longitudinally-resolved map of WASP-121b's vertical thermal structure. Through detailed comparison with 3D circulation models, these measurements will provide valuable new insights into the efficiency with which optical absorbers such as TiO and VO are removed from the upper atmosphere via condensation cold-trapping.

Feng Kat - poster
UCSC

Testing Assumptions in Retrievals of Spectroscopic Phase Curves

From Jupiter's banded structure and iconic Great Red Spot, to Earth's constantly changing cloud patterns, planetary atmospheres are complex 3D structures. With the upcoming JWST, we will obtain data from exoplanet atmospheres of higher precision than ever before. Given this opportunity, we must understand the accuracy of our data interpretation. Our model-driven interpretation of an atmosphere's spectrum fuels our understanding of the day-night heat redistribution and establishes chemical abundance estimates, which impact theories on planet formation.

Without the ability to spatially resolve exoplanet atmospheres, we often approximate them as 1D and uniform to model hemispherically-averaged spectra. Retrieval models have traditionally followed this assumption. Could our inferences be biased as a result? In 2016, I pioneered an investigation for hot Jupiters, which have large day-night temperature contrasts due to close-in, tidally-locked orbits. I showed that one can fundamentally mischaracterize planetary abundances when relying on a 1D model for atmospheres made up of half-hot and half-cool regions.

In my poster, I will discuss my latest work in preparation for the era of high-precision spectra. How does the 1D assumption bias our estimates of planetary composition as a function of orbital phase? HST has obtained "spectroscopic phase curves" for a small number of planets, but JWST will study more targets with higher quality observations. What reliable inferences can be made across the orbit? I consider synthetic data taken both with HST and future data expected from JWST. I also demonstrate the effect on actual Hubble phase curve data of a hot Jupiter WASP-43b. With JWST-quality data, our simplifying 1D assumptions always lead to incorrect estimates of all molecules, compared to a more realistic 2D temperature structure. The need for more accurate models is clear. The framework I will present is also ideal for incorporating patchy clouds, hot spots, and chemical gradients.

Fisher Chloe - poster
University of Bern

Supervised machine learning for interpreting ground-based high-resolution transmission spectra

No abstract

Fortney Jonathan – oral
University of California, Santa Cruz

The Radiative-Convective Boundary in Giant Planet Atmospheres

The visible atmosphere can often be a window into processes happening deeper within the atmosphere, or interior. Indeed, in most cases for giant planets, the properties of the radiative atmosphere entirely regulate the cooling of deeper planetary layers. Hot Jupiters are often thought to have deep radiative atmospheres due to their high incident stellar fluxes, with the radiative-convective boundary (RCB) found at 1 kbar, far below the visible atmosphere. However, the idea of a deep RCB rests on the assumption of little intrinsic flux from the interior. Here we show instead that high intrinsic fluxes are actually quite typical, given the large radii (and hot interiors) of these planets. This can move the RCB to pressures of less than ten bars. This shallow RCB has a number of important ramifications. 1) It may dramatically alter vertical and horizontal atmospheric circulation in these planets compared to previous calculations which placed the RCB at great depth. One should think of these atmospheres as being radiative-convective, not merely radiative. 2) At near-infrared wavelengths, where atmospheric opacity sources (such as water vapor) are often at their minima, one can see relatively deeply into a planet's atmosphere. Through the use of 1D models we show that in the NIR one can sometimes observe flux that emerges from below the radiative-convective boundary, which is a direct probe of the interior entropy of these planets, which will place new constraints on the radius inflation mechanism. 3) Planets on eccentric orbits can have this eccentricity damped, in which orbital energy is converted to thermal energy in the planetary interior. This thermal flux can heat interiors well in excess of that expected for simple cooling models, by orders of magnitude, leading to shallow RCBs and detectable fluxes from the deep interior. Inferring these fluxes from spectra can lead to a direct constraint on a planet's tidal quality factor, Q, which is typically not a measurable quantity.

Gaidos Eric - poster
University of Hawaii at Manoa

Singlet helium in the atmospheres of young planets: upper limits and stellar false positives

We obtained infrared spectra of a transiting Neptune-size planet around a solar-type star in the 650 Myr-old Hyades cluster using the IRD spectrograph on the Subaru telescope. Despite the expectation that this planet would be losing a H-He atmosphere in the presence of elevated XUV emission from the young, active host star, we detected no significant changes in the He I triplet around 10830 A. We consider possible explanations for this result: the planet possesses no such atmosphere; the atomsphere is not escaping; or there is insufficient EUV radiation to excite helium to the 23S ground state of the transitions. We also consider the limiting effect of variations in the He I line across the stellar disk on detecting low-level absorption in any planetary atmosphere.

Gibson Neale - poster
Trinity College Dublin

Comparing low- and high-resolution transmission spectra of hot Jupiters: What do we really know?

Observing the atmospheres of transiting planets is extremely challenging. Time-series systematics limit our ability to achieve photon-limited spectroscopy of their atmospheres, and in the worst cases can mimic spectral features leading to spurious conclusions, making it impossible to get a reliable chemical inventory of their compositions. We have developed some of the leading methods to mitigate systematics in the spectral extraction process (e.g. Gaussian processes); nonetheless, significant limitations remain with these techniques, and to fully optimise the enormous archive of space- and ground-based datasets we need to update our spectral extraction routines and cross-validate results from multiple sources.
I will present new results from both low- and high-resolution ground-based followup of atomic and molecular features found with the Hubble Space Telescope. For example, using HST/STIS, we found a huge potassium feature in the atmosphere of the hot-Jupiter WASP-31b, although curiously no sodium, as well as Rayleigh and Mie-scattering indicating a haze and cloud deck. We re-observed the spectrum using VLT/FORS2, confirming the scattering signals but failing to find potassium. Since then, we have performed high-resolution followup with VLT/UVES. We have also followed up the ultra-hot Jupiter WASP-121b that was found to have evidence for TiO, VO, and perhaps even SH, as well as a thermal inversion in its atmosphere. We have re-observed multiple transits using both Gemini/GMOS and VLT/UVES, targeting Na, K, TiO and VO. I will present these results, and discuss their implications for our current understanding of hot-Jupiters. I will finish with a discussion of future prospects in observational techniques to fully optimise archival HST and ground-based observations.

Goldblatt Colin -oral
University of Victoria

Stable climate states and their radiative signals of Earth-like Aquaplanets

The Sun was dimmer earlier in Earth history, but glaciation was rare in the Precambrian: this is the "Faint Young Sun Problem". Most solutions rely on changes to the chemical composition of the atmosphere to compensate via a stronger greenhouse effect, whilst physical feedbacks have received less attention. Here we show that a strong negative feedback from low clouds has had a major role in stabilizing climate through Earth's history. We perform Global Climate Model experiments in which a reduced solar constant is offset by higher CO2, and find a substantial decrease in low clouds and hence planetary albedo, which contributes 40% of the required forcing to offset the faint Sun. Through time, the climatically important stratocumulus decks have grown in response to a brightening Sun and decreasing greenhouse effect, driven by stronger cloud-top radiative cooling (which drives low-cloud formation) a stronger inversion (which sustains clouds against dry air entrainment from above). This demonstrates the importance of physical feedbacks on long-term climate stabilization, and a reduced role for geochemical feedbacks.

Graham RJ - poster
University of Oxford

Pressure-dependence of silicate weathering may be weaker than usually assumed

The silicate weathering feedback is thought to control the CO_2 partial pressure of Earth's atmosphere on long timescales. The same mechanism is hypothesized to operate on rocky exoplanets with exposed land and abundant surface liquid water. In addition to a direct temperature dependence, representations of silicate weathering in climate modeling include a dependence on CO_2 partial pressure, with weathering rate proportional to $(pCO_2)^{\beta}$ The value of the exponent β is taken to be somewhere between 0.3 and 0.5 in most studies of rocky planet climate. Based on a survey of the literature on laboratory experiments that have quantified the dissolution rate of a variety of silicate minerals, we argue that β could fall well below 0.25. Simple calculations show that this has important implications for the location of the outer edge of the "liquid water habitable zone" and the likelihood of snowball limit cycling on rocky planets. Further, we argue that the particular surface mineral composition of a rocky planet may impact the strength of its silicate weathering feedback due to differences in the temperature- and pH-dependence of the dissolution rates of different silicate minerals.

Guilluy Gloria - poster
Università degli Studi di Torino (UNITO)

A GIARPS view of the extended atmosphere of HD 189733b

High-resolution transmission spectroscopy of hot giant exoplanets allows for both precise determinations of atmospheric chemical abundances and accurate measurements of proxies for atmospheric escape phenomena and mass-loss mechanisms. I will present results obtained within the GAPS 2.0 long term programme for atmospheric characterization of the highly irradiated hot Jupiter HD 189733b using the Telescopio Nazionale Galileo (TNG) in the simultaneous GIARPS (GIANO-B + HARPS-N) observing mode. I will report on the results obtained based on a convergent multi-technique approach to the analysis of the GIARPS high-resolution spectra with the aim of 1) studying the extended atmosphere of HD 189733b using the Helium absorption triplet at 10833 Angstrom and 2) distinguishing the atmospheric absorption signals from the stellar contamination.

Hammond Mark - poster
University of Oxford

The role of the meridional circulation in the formation of zonal flow on tidally locked planets

Understanding the global circulation of tidally locked planets is crucial to interpreting their observations, climates and habitability. GCM simulations, phase curve measurements and other studies have led to a picture of their circulation as dominated by an eastward equatorial jet, with a hot-spot east of their substellar point and two cold cyclones on their night-side.

We use a rotating shallow-water system as a 2D model of the atmosphere of a tidally locked planet, to explain this circulation. We linearize this model about the equatorial jet to focus on its effect on the circulation, and find the stationary solution with a spectral method. I will show how this solution matches results from non-linear shallow-water simulations and full GCM simulations. I will also show how this model predicts how observable quantities such as hot-spot shifts and day-night contrast scale with planetary parameters such as rotation rate and temperature. The model also predicts properties of the free and unstable modes of such a planet's atmosphere, which I will compare to GCM simulations of such atmospheres.

Harrington Joseph - oral
University of Central Florida

Systematics, Instrument Modes, and Their Effect on JWST Eclipse Retrievals

We recently detected spurious exocomet-like features in Spitzer Proxima Centauri b data. They were due to image vibrations at 10+Hz. We now expect systematics-related problems from Spitzer, which was designed for 1% relative photometry. The James Webb Space Telescope (JWST) is designed for greater precision, and has undergone extensive ground-based testing. However, given the rewards for major exoplanet discoveries, we will push even JWST's performance to its limits, characterizing ever cooler and smaller planets.
We are thus developing a simulator for multiple JWST instruments that simulates the data at the sub-pixel level. By connecting ExoSim, which simulates instrument data for the Ariel mission and others; JOSE, Joe and John's Optimal Spectrum Extractor; POET, our Photometry for Orbits, Eclipses, and Transits package; and BART, our Bayesian Atmospheric Radiative Transfer retrieval algorithm, we can estimate the impact of potential systematics on atmospheric retrievals. For example, while JWST's pointing accuracy is much better than Spitzer's, its pixels are similarly smaller, making the pointing accuracy per pixel about the same. How will the inevitable spacecraft vibrations affect retrievals? What photometric and spectroscopic extraction methods will reduce these effects the best? Only by putting a known answer into the data and trying to retrieve it can we know.

Hayworth Benjamin – oral
Pennsylvania State University
NO2 as a biosignature

The process of how a planet's magnetic field impacts its atmospheric chemistry by regulating the atmosphere's interaction with space weather has recently been explored by Airapetian et al. [1] in the context of the early Earth. These authors point out that a more active young Sun would have experienced more frequent coronal mass ejections (CMEs), which can shear-open the Earth's magnetic field, bombarding the upper atmosphere with SEPs. According to the authors, these particles helped drive atmospheric chemistry, resulting in heightened concentrations of nitrous oxide, N2O, which contributed to warming the planet and offsetting the Sun's decreased visible luminosity.

In the context of exoplanetary science, N_2O is a sought after biosignature, as no abiotic source currently produces it in astronomically observable quantities [2-3]. If the mechanism of Airapetian is correct, the atmospheric chemistry associated with space weather may act as a false positive for life on extrasolar planets. This could mean that any planet lacking a magnetic field – or around an active star – would build up substantial abiotic levels of N_2O. Whether this buildup would be observable is not clear. To answer this question, we model the production rate of N_2O as a function of SEP flux and magnetic field strength, as well as determining whether the resulting concentration of N2O will be observable by future space tele-scope missions such as NASA's HabEx or LUVOIR.

Looking for the spectral signature of N_2O could also serve as an indirect method of detecting planetary magnetic fields. To our knowledge, no observational techniques currently exist for detecting magnetic fields around rocky exoplanets. That is unfortunate, as a planet's current habitability, as well as its future atmospheric evolution, may depend on its possessing a global geodynamo [4]. Proposed methods for detecting an exoplanet's magnetic field involve measuring the interaction between the host star's stellar wind and planet's magnetic field. This can be done, in principle, by measuring electron synchrotron radiation [5], by observing transit luminosity asymmetry caused by the bow shock [6], or by using observable Lyman-alpha signatures to infer hydrogen escape constrained by the magnetosphere's interaction with the solar wind [7]. Unfortunately, for terrestrial planets all of these methods fall below current detection thresholds. So, instead, we propose inferring the existence of exoplanetary magnetic fields by observing differences in their atmospheric spectra. For example, N_2O, NO, and HCN should be more abundant if a planet lacks a magnetic field, if the formation mechanism proposed by Airapetian et al. [1] is correct. As a potent greenhouse gas, N_2O also has direct implications for habitability. These same active stellar environments are also favorable for organic haze production [8]. Organic haze could provide N_2O the UV shielding it needs to be present in high concentrations and to contribute to greenhouse warming of the planet's surface. We investigate the relationships between stellar activity, organic haze production, and atmospheric N_2O accumulation and to thereby reevaluate the habitability of hazy extrasolar worlds.

[1] Airapetian et al. (2016) Nature Geo., 9, 452-455. [2] Lovelock, J.E. (1975) Proc. R. Soc. Lond. B Biol. Sci., 189, 167-181. [3] Meadows, V. (2017) Astrobio., 17(10). [4] Lundin et al. (2007) Space Sci. Rev., 129, 245-278. [5] Zarka, P. (2004) ASP Conf. Proc., 321, 160. [6] Vidotto et al. (2011) MNRAS, 411(1), L46-L50. [7]

Kislyakova et al. (2014) Science, 346(6212), 981-984. [8] Arney et al. (2017) ApJ, 836(1).

Heavens Nicholas - poster
Hampton University/Space Science Institute

Evaluating a One-Dimensional Scenario for Cold Trap Breakdown on the Archaean Earth in a Three Dimensional Framework: Progress and Prospects

On present day Earth, atmospheric water poorly mixes into the middle atmosphere. There is a strong contrast between water vapor mixing ratios typical of the troposphere (~1000 ppmm) and water vapor mixing ratios near the Earth's mesopause (~5 ppmm), where the photodissociation of water by solar radiation at Lyman α wavelengths takes place. A parallel contrast exists between water vapor concentrations near the surface and in the upper troposphere (~10000 ppmm vs. ~ 100 ppmm in the tropics). This strong contrast in water vapor concentrations between the near-surface atmosphere and the mesopause is one factor that limits hydrogen escape from the Earth's atmosphere today. These contrasts are driven by the freeze drying effect of Earth's cold tropical tropopause (the so-called "cold trap") and the barrier to mixing created by the warm, stable stratosphere above it. In the Archean, matters could have been much different. It has been proposed that radiative heating of the atmosphere by methane in the visible/near-infrared and low ozone concentrations would result in an atmospheric thermal structure without a cold trap or a stratosphere. I have been testing this idea by developing a version of the Community Earth System Model (CESM) that uses an idealized, flux-corrected slab ocean component, uses a version of the Rapid Radiative Transfer Model for Global Climate Models (RRTMG) that has been tailored for high methane and carbon dioxide concentrations, and is coupled to the Whole Atmosphere Community Climate Model (WACCM). The goal is to test both the mechanism for more thorough vertical mixing of water in the Archean atmosphere as well as quantify the potential consequences of high amounts of mesospheric water for atmospheric escape of water, methane, and xenon. Because of technical barriers, I have not managed to develop the full framework contemplated but have obtained a variety of interesting preliminary results, which I will present here.

Helling Christiane - poster
Centre for Exoplanet Science, University of St Andrews

Dayside ionospheres and nightside lightning on ultra-hot Jupiters

Global atmosphere dynamics simulations point to a diversity of flow regimes on giant gas planets that will be imprinted in their appearance through cloud formation, which influences the amount of gas that is observationally accessible. Super-hot Jupiters have emerged as a class of exoplanets that has challenged retrieval approaches, demonstrating the need for complex modelling that includes gas and cloud chemistry consistently. Such consistent models enable us to understand the profound day/night differences in atmospheric ionisation and in the occurrence of lightning, in addition to the details of the cloud and gas chemistry.
The combination of results from 3D atmosphere models with our kinetic cloud formation model enables us to present detailed analysis of global cloud properties, and tied to it, the composition of the gas phase for planets like WASP-18b and HAT-P-7b. A distinct difference between the very hot day-side and the very cold night-side emerges. The clouds form mainly on the nightside where cloud particles acquire electrostatic charges through, for example frictional interaction. The resulting discharges occur as lightning inside the clouds. Lightning can then triggers the formation of potentially long-lived tracer molecules like HCN and H3+ and derivates thereof (Helling \& Rimmer 2019, submitted). The dayside it too hot for cloud particles to form and thermal ionisation increases the local gas ionisation to a level comparable to Jupiter's upper atmosphere (Helling et al. 2016, Surv. Geophys. 37; Helling et al. 2019, arXiv:1901.08640).

Christiane Helling et al.

Hood Callie - poster
UCSC

Can We Characterize the Haziest Sub-Neptunes with High Resolution Spectroscopy?

Observations to characterize planets larger than Earth but smaller than Neptune have been inconclusive due to hazes or clouds that obscure molecular features in their spectra. However, high-resolution spectroscopy may enable us to probe the regions in these atmospheres above the clouds where the cores of the strongest spectral lines are formed. We will present models of transmission spectra for a suite of sub-Neptune planets from 1 - 5 microns at a range of resolutions relevant to current and future ground-based spectrographs. We are particularly interested in the cloudiest planets where low-resolution transmission spectroscopy has yielded no constraints. The models will be for GJ1214b-like planets with photochemical hazes, as well as for planets with 0.3x and 3x GJ1214b's irradiation. Furthermore, we will also compare the utility of the cross-correlation function and the new likelihood function derived for this technique when detecting opacity sources in these spectra. We will investigate the effect of these different characteristics, as well as varying noise levels, on the resulting detection strengths to aid in planning future observations.

Horst Sarah -oral
Earth & Planetary Sciences, John Hopkins University

Photochemical Hazes

No abstract

Joshi Manoj - poster
University of East Anglia

Using Earth's polar night boundary layer to estimate dark-side inversions on tidally-locked terrestrial exoplanets

An important factor in determining the potential habitability of tidally-locked planets is the strength of the atmospheric boundary layer inversion between the cold dark side surface, where gases might condense, and the warmer free atmosphere, We analyse data obtained from polar night measurements at the South Pole and Alert Canada, which are the closest analogues on Earth to conditions on the dark sides of tidally locked exoplanets. On Earth, such inversions rarely exceed 25 K in strength, suggesting a similar constraint to near-surface dark side inversions. Our results demonstrate the importance of comparisons with Earth data in exoplanet research, and highlight the need for further modelling studies of the exoplanet atmospheric collapse problem.

Kane Stephen - poster
University of California, Riverside

Venus as a Laboratory for Exoplanetary Science

A fundamental aspect of understanding the limits of habitable environments and detectable signatures is the study of where the boundaries of such environments can occur, and the conditions under which a planet is rendered into a hostile environment. The archetype of such a planet is Earth's sister planet, Venus, and provides a unique opportunity to explore the processes that created a completely uninhabitable world and thus define the conditions that can rule out bio-related signatures. In this talk I will describe the gaps in our knowledge regarding Venus and how this is impacting our ability to model exoplanet atmospheres and interiors. I will outline the premise behind the "Venus Zone" and how testing the conditions of runaway greenhouse is an essential component of understanding the development of habitable conditions. I will present several detected potential Venus analogs including climate simulations that constrain their surface environments, simulated transmission spectra, and occurrence rate calculations. Finally, I will summarize the need for a return mission to Venus and the primary questions that need to be addressed.

Katyal Nisha - poster
TU Berlin

Evolution of atmosphere of early Earth with a coupled interior-outgassing and atmospheric model

The evolution of Earth's early atmosphere and the emergence of habitable conditions on our planet are intricately coupled with the development and duration of the magma ocean phase during the early Hadean period (4 to 4.5 Ga). We study the evolution of a pure steam atmosphere during the magma ocean period. The thermal emission also known as the outgoing longwave radiation from the planet is calculated using a line-by-line radiative transfer code GARLIC. Our study suggests that for an atmosphere consisting of pure H2O, built as a result of outgassing, the solidification of the magma ocean takes place in about 1 Myr. We show the variation of surface temperature and emission spectra as a function of magma ocean solidification time. We also study the effect of thermal dissociation of H2O at higher temperatures by applying atmospheric chemical equilibrium which results in the formation of H2 and O2 during the early phase of the magma ocean. As a result, a 1-6% reduction in the OLR is seen associated with the decrease in the surface temperature. Due to the difference in the absorption behaviour at different altitudes, the spectral features of H2 and O2 are seen at different altitudes of the atmosphere. We then obtain the effective height of the atmosphere from the calculated transmission spectra for the whole duration of the magma ocean. We observe that as the magma oceans cools down, the atmospheric transmission height or the depth of the water bands are reduced from a few thousand km to a few hundred km. Furthermore, we study the effect of varying mantle redox state on the atmospheric composition. Our results suggest that the mantle oxidation state (i.e. the oxygen fugacity of the system) is a central parameter affecting the outgassing hence atmospheric composition and extent.

Kawashima Yui – oral
SRON Netherlands Institute for Space Research

Effect of UV irradiation intensity, metallicity, and eddy diffusion on transmission spectra of hazy exoplanet atmospheres

Recently, properties of exoplanet atmospheres have been constrained via multi-wavelength transit observation, which measures an apparent decrease in stellar brightness during planetary transit in front of its host star (called transit depth). Sets of transit depths so far measured at different wavelengths (called transmission spectra) for some exoplanets are featureless or flat, inferring the existence of haze particles in the atmospheres. Previous studies that addressed theoretical modeling of transmission spectra of hydrogen-dominated atmospheres with haze used some assumed distribution and size of haze particles. In Kawashima & Ikoma (2018), we developed new photochemical and microphysical models of the creation, growth, and settling of haze particles for deriving their size and number-density distributions in close-in warm (< 1000 K) exoplanet atmospheres.

In this study, we explore the dependence of the production rate of haze and the resultant transmission spectra on UV irradiation intensity, metallicity, and eddy diffusion coefficient. We find that the difference in the UV irradiation intensity yields the diversity of transmission spectra observationally suggested. We also demonstrate that the photodissociation rates of the hydrocarbons, which are related to the haze monomer production rate, are basically smaller for higher metallicity in spite of their increased abundances. This is because of the enhanced photon-shielding effect by the major photon absorbers, H2O, CO, CO2, and O2, existing at higher altitudes than the hydrocarbons. Thus, the transmission spectrum for higher metallicity atmosphere is less affected by haze. Moreover, we find that the efficient eddy diffusion yields a steep Rayleigh-scattering slope in the optical and more prominent molecular-absorption features, which is the dependence opposite of condensation clouds.

Kite Edwin - poster
University of Chicago

The transition from primary to secondary atmospheres

I will use basic models to address two questions. The first is the biggest open question for the atmospheres of TESS/Keplersuper-Earths: whether or not they exist. The second may be the biggest open question for the atmospheres of sub-Neptunes: how does magma-atmosphere exchange set the composition of the atmosphere? These questions are related: both involve coupling between magma ocean evolution (chemical and thermal), and H2-rich atmospheres. (1) After stellar XUV flux declines, Super-Earth volcanism continues for Gyr. This late volcanism might rejuvenate atmospheres, but only if the solid mantle has enough volatiles. Volatiles that have high-molecular-mass (high-μ) are delivered in the first ~108 yr. This is the timescale, for short-period exoplanets, on which early-accreted nebular atmospheres are ablated. (In contrast, for the inner Solar System, nebular gas escaped in <107 yr). Thus, rocky exoplanet high-μ volatiles might be entrained by escaping H2. The extent of high-μ loss depends crucially on magma ocean crystallization timescales. If crystallization is slow (due to the H2 greenhouse effect), then because the atmosphere and magma are equilibrated, as much as 100% of the high- μ volatiles can escape (depending on H2 escape flux). Bare rocks result. However, early crystallization favors later existence of an atmosphere. This is counter-intuitive, because crystallization drives most volatiles to the surface, where they are vulnerable to XUV. However, the (small) fraction of volatiles which are trapped within the crystals are shielded (due to the long timescale of solid-state mantle convection) during the early era of high XUV. Because the timing of magma ocean crystallization is sensitive to stellar luminosity, this model suggests a period-mass threshold for atmosphere presence-absence on Super-Earths. (2) Sub-Neptunes are mostly magma by mass, and are mostly atmosphere by volume. However, the effect of the magma on the atmosphere is little-explored. There are two sources of atmosphere - gas from nebula accretion, and volatiles released from solids. For the Fe-Mg-Si-O-H system, I show that on sub-Neptunes, the fate of H (and the atmosphere's composition) is set by magma oxidation state. In turn this oxidation state is set by the details of planet assembly. Depending on the oxidation state of the magma, a nebular-derived atmosphere can masquerade as an outgassed atmosphere and vice versa. Fortunately, planet radius and atmosphere scale height can be used to distinguish between these scenarios. H2O dissolved in the magma is a major H sink for sub-Neptunes: the total volatile budget can be mostly dissolved H2O even when μatm ~2. Because of this magma H sink, the amount of H2 needed to explain the radius of sub-Neptunes is much greater than usually assumed. The maximum radius boost from outgassing of volatiles released by solids is probably insufficient to explain sub-Neptunes. Worlds in the Habitable Zone bigger than this maximum must retain significant nebula volatiles - i.e., they are "nebula-choked" and cannot have Earth-like atmospheres. These results point the way to future modeling work, combining magma-ocean chemistry with fractionating escape during the transition from primary to secondary atmospheres.

Koll Daniel - poster
MIT

Hot Hydrogen Climates near the inner edge of the Habitable Zone; Implications for origin-of-life scenarios on Earth and Super-Earths

Young terrestrial planets can capture or outgas hydrogen-rich atmospheres with tens to hundreds of bars of H2, which persist for 100 Myrs or longer. Although the earliest habitable conditions on Earth and terrestrial exoplanets could thus arise while the atmosphere is still dominated by H2, the climatic effects of H2 remain poorly understood. Previous work showed that H2 induces strong greenhouse warming at the outer edge of the habitable zone. Here we use a 1D radiative-convective model to show that H2 also leads to strong warming near the inner edge of the habitable zone. Unlike H2's greenhouse warming at the outer edge, however, its effect near the inner edge is driven by thermodynamics: H2's large thermal scale height allows the atmosphere to store more water vapor than either a pure-H2O atmosphere or an atmosphere with a heavy background gas, such as N2 or CO2, thereby amplifying the greenhouse effect of H2O. Using idealized grey calculations, we then present a general argument for how different background gases affect the inner edge of the habitable zone. H2 stands out for its ability to induce novel 'Soufflé' climates, which further support its warming effect. Our results show that if the earliest conditions on a planet near the inner edge of the habitable zone were H2-rich, they were likely also hot: 1 bar of H2 is sufficient to raise surface temperatures above 340 K, and 50 bar of H2 are sufficient to raise surface temperatures above 450 K.

Komacek Thaddeus – oral
University of Chicago

The atmospheric circulation and climate of terrestrial exoplanets over a broad range of planetary parameters

The combination of detections of nearby stellar systems with Earth-sized exoplanets in the habitable zone and the upcoming launch of the James Webb Space Telescope drive the need for a detailed understanding of the climate of terrestrial planets. In this work, we determine properties that control the atmospheric circulation of terrestrial exoplanets and the impact of the circulation on observable properties of the planet. To do so, we simulate the atmospheric circulation of terrestrial exoplanets over a broad range of planetary and host stellar parameters using the General Circulation Model ExoCAM in an aquaplanet configuration. We run three suites of models for planets orbiting different stellar types, including a late M-dwarf, early M-dwarf, and a Sun-like star. In each of these three model suites, we separately vary the incident stellar flux, planetary rotation period (set equal to the orbital period for tidally-locked planets around M-dwarf stars), planetary radius, surface pressure, and surface gravity, keeping all other parameters fixed to Earth-like values. We show how properties of the atmospheric circulation and climate (e.g., day-night and equator-pole temperature contrasts, cloud coverage, wind speeds) depend on planetary parameters. We compare our results to analytic theory for baroclinic criticality in the atmospheres of fast-rotating planets orbiting Sun-like stars. We find that this theory predicts the scaling of equator-to-pole temperature contrast and bulk lapse rate with planetary rotation rate and surface pressure found in our ExoCAM simulations. Additionally, we calculate model full-phase light curves (or "phase curves") and JWST/NIRSpec transmission spectra from our simulations in order to ascertain how planetary properties may be manifest in observations. We find that varying planetary parameters causes noticeable changes to the amplitude and morphology of the phase curves, with the incident stellar flux and rotation rate playing the largest role. Lastly, we find that water clouds greatly reduce the amplitude of molecular features in transmission spectra. As a result, it will be challenging to detect molecules other than CO2 in the atmospheres of terrestrial exoplanets in the habitable zone with JWST.

Kozakis Thea - poster
Carl Sagan Institute, Cornell University

Dying to Live: Post-Main Sequence Habitability

During the post-main sequence phase of stellar evolution the orbital distance of the habitable zone, which allows for liquid surface water on terrestrial planets, moves out past the system's original frost line, providing an opportunity for outer planetary system surface habitability. We use a 1D coupled climate/photochemistry code to study the impact of the stellar environment on the planetary atmospheres of Earth-like planets/moons throughout its time in the post-main sequence habitable zone. We also explore the ground UV environments of such planets/moons and compare them to Earth's. We model the evolution of star-planet systems with host stars ranging from 1.0 to 3.5 M$_\odot$ throughout the post-main sequence, calculating stellar mass loss and its effects on planetary orbital evolution and atmospheric erosion. The maximum amount of time a rocky planet can spend continuously in the evolving post-MS habitable zone ranges between 56 and 257 Myr for our grid stars. Thus, during the post-MS evolution of their host star, subsurface life on cold planets and moons could become remotely detectable once the initially frozen surface melts. Frozen planets or moons, like Europa in our Solar System, experience a relatively stable environment on the horizontal branch of their host stars' evolution for millions of years.

Lacy Brianna - poster
Princeton University

Combined Effects of Aerosols and Day-Night Temperature Gradients on Transit Spectra

Many exoplanet atmospheres show evidence of clouds in their transmission spectra. These observable metrics include the slope at optical wavelengths, the uniformity or non-uniformity of this slope, and the presence of condensate-specific features in the infrared wavelengths. Previous works have explored the influence of cloud characteristics, such as condensate species, particle size distribution, depth, and patchiness. We present a replication and extension of these studies, exploring the effect of varying the temperature-pressure profile of the atmosphere and varying the steepness of the day-night temperature gradient, in addition to those factors listed above. We also provide a new grid of cloudy models against which one might carry out retrievals from JWST or other transmission spectroscopy.

Leconte Jeremy - oral
CNRS | Bordeaux University

Weird convection regimes in hydrogen dominated atmospheres: from solar system giant planets to brown dwarfs.

J. Leconte, F. Selsis, and T. Guillot

On Earth, moist convection is a very efficient process, not only because condensing water releases plenty of latent energy to power the motion, but also because water vapor is lighter -- in the sense that it has a lower mean molecular weight -- than air. In hydrogen dominated atmospheres, however, water vapor is much heavier than the background gas, which creates a strong barrier that convection needs to overcome. Here we will show how this can lead to peculiar convection regimes and considerably alter the standard temperature profiles assumed for Solar System Giant planets. We will also discuss potential implications for JUNO and its measurement of deep water abundance.
In brown dwarfs, the situation is made even more complex by the fact that thermochemistry alone can modify the composition -- hence the molecular weight -- of the atmosphere. It has been hypothesized that this could trigger a thermochemical instability that would enhance atmospheric mixing and explain some observed features of the transitions between different types of brown dwarfs. Using both analytical theory and experimental results, we will argue that if such instabilities can indeed occur, their effects cannot explain the observed transitions.

Lee Graham Kim Huat - poster
University of Oxford

DMC - A Kinetic, Bin Resolving Cloud Formation Model

We present a new, flexible spectral (bin) based cloud formation model DMC.
DMC simulates detailed kinetic microphysical condensational processes, with consistent eddy diffusive mixing, cloud particle settling and element depletion.
We present cloud structure results for representative atmospheric profiles of Brown dwarfs and hot Jupiter atmospheres.

LeFevre Maxence -oral
AOPP

Three-dimensional turbulence-resolving modeling of Proxima-B exoplanetary atmosphere

The role that convection plays in cloud feedback on Earth climate is still not fully understood. Numerous observed exoplanets are in synchronous rotation with its host star. To understand the impact on climate of such extreme insolation from different star type, Global Circulation Model (GCM) is used. The representation of turbulence requires in such model a parametrization to represent the turbulence smaller than the size of the grid. These representations are based on Earth convection. The extreme insolation on those exoplanets could lead to a different convective activity, height and thickness of the cloud layer and that could lead to a change in the stability of the surface liquid water. We present results on the convective activity of Proxima-b using turbulent-resolving model (WRF) with realistic radiative transfer and microphysics. The versatility of the model allows a large spectrum of atmospheric composition.

Lewis Neil Tamas - poster
University of Oxford

What controls the strength of super-rotation in terrestrial atmospheres?

An atmosphere can be expected to super-rotate when its thermal Rossby number is large (Mitchell and Vallis, 2010), and when acceleration of zonal flow at the equator, associated with the presence of equatorial waves, overwhelms deceleration due to the dissipation of waves propagating out of the mid-latitudes (Laraia and Schneider, 2015). At present, however, there exists no predictive theory for super-rotation, or scaling that describes how the strength of super-rotation varies with planetary parameters.

In this work, we present results from a series of idealised GCM experiments where the planetary rotation rate is varied between $\Omega = \Omega_E$ and $\Omega = \Omega_E / 2048$, where Ω_E is the Earth's rotation rate. To do this we use Isca; a framework for building three-dimensional models of planetary atmospheres (Vallis et al., 2018). The model configuration used here is based on the Held–Suarez benchmark for an Earth-like atmosphere.

In these experiments the strength of super-rotation is found to increase proportionally with 1.2 until a critical rotation rate is reached (Ω_E /16), below which it remains constant as is further reduced. To understand this behaviour, we investigate the zonally-averaged zonal momentum budget in each of our experiments. Early analysis suggests that the critical rotation rate is reached when the horizontal eddy scale, which is found to scale with the equatorial deformation radius, reaches the planetary scale.

The strength of super-rotation on Venus exceeds the limiting value found in our idealised experiments by a significant factor (~7 times greater). This is not surprising, given the differences between our model atmosphere and Venus' atmosphere. However, we hypothesise that an upper limit on super-rotation strength, of the type found in our experiments, is ubiquitous across terrestrial atmospheres with the exact value set by atmospheric composition and structure.

Lian Yuchen - poster
Peking University, China

A model for Hot Jupiter with bottom thermal perturbation

Hot Jupiters are one of the few types of planets that can currently be observationally characterized. Under strong external radiation forcing, Hot Jupiters show a variety of atmosphere circulation pattern. Due to spectrum exhibits information and our knowledge in atmosphere dynamic of the Hot Jupiter, some researchers create the atmosphere models, for understanding the observations and the physics of these planets generally, but almost all models ignore---or treat in a very simplified fashion--the interaction of the interior convection zone with the deep, thick stratified atmosphere. Here, we take the small-scale thermal perturbation into account, and import a spatially and temporally noise, which is horizonally isotropic, as forcing parameter into 3D primitive equation model for influencing the temperature at convective-radiation boundary layer. In some cases, the random thermal perturbation give limited impact on pattern ------ a significant temperature increase near the hot spot, while the others does not have much influence on the top layer pattern, which shows hot spot shift with super-rotation on equator at top layers, when star radiation becomes stronger.We draw a conclusion that the flow does not vary in time until the perturbation reach 0.0001 K/sec. We assume the model relax the radiation forcing by Newtonian cooling scheme to equivalent temperature in various radiative time scale on different levels.Perhaps we predict more time variability if atmospheres are strongly enough forced by convection, and we hope get new information from spectrum to prove the result.

Lichtenberg Tim - poster
University of Oxford

A water budget dichotomy of rocky protoplanets from Al-26 heating

In contrast to the water-poor planets of the inner Solar System, stochasticity during planetary formation and order-of-magnitude deviations in exoplanet volatile contents suggest that rocky worlds engulfed in thick volatile ice layers are the dominant family of terrestrial analogues among the extrasolar planet population. However, the distribution of compositionally Earth-like planets remains insufficiently constrained, and it is not clear whether the Solar System is a statistical outlier or can be explained by more general planetary formation processes. Here we use numerical models of planet formation, evolution and interior structure to show that a planet's bulk water fraction and radius are anti-correlated with initial 26Al levels in the planetesimal-based accretion framework. The heat generated by this short-lived radionuclide rapidly dehydrates planetesimals before their accretion onto larger protoplanets and yields a system-wide correlation of planetary bulk water abundances, which, for instance, can explain the lack of a clear orbital trend in the water budgets of the TRAPPIST-1 planets. Qualitatively, our models suggest two main scenarios for the formation of planetary systems: high-26 Al systems, like our Solar System, form small, water-depleted planets, whereas those devoid of 26Al predominantly form ocean worlds. For planets of similar mass, the mean planetary transit radii of the ocean planet population can be up to about 10% larger than for planets from the 26Al-rich formation scenario.

Lobo Ana - poster
California Institute of Technology

Seasonal Cycles on Other Earths

Radiative imbalance at the top-of-atmosphere drives the general circulation of planetary atmospheres. Yet, how fundamental atmospheric features, such as the Hadley cell and extratropical eddies, respond to different radiative forcing and impact the surface climate and the hydrological cycle remains poorly understood. This is particularly true when seasonal cycles are being considered.
Here, we use an idealized GCM in aquaplanet configuration with a seasonal cycle, building on previous work that considered the impact of obliquity on planetary climate, to address the dynamic response to radiative changes in a broader context. In particular, we explore the response of the large-scale circulation, and associated climate, to perturbations in both the shortwave radiation, through obliquity changes, and perturbations in longwave radiation through changes in the meridional and vertical structure of the imposed optical depth. We focus on seasonal phenomena that are not captured by annual mean forcing and that might involve nonlinear responses.
Increasing obliquity results in increasingly stronger and broader seasonally reversing cross-equatorial Hadley circulations. Embedded in the ascending branches of these cells is a broader and poleward-shifted ITCZ, which does not coincide with maxima in near-surface temperature. Polar precipitation increases, as a consequence of increased MSE during the summer and condensation of precipitable water as temperatures drop rapidly at the end of the season. We also note a significant decrease or disappearance in storm tracks, which is due to two major factors: changes in moisture distribution, which is strongly tied to temperatures, and changes in extratropical baroclinic eddies, which are tied to meridional temperature gradients. As obliquity is increased, latent heat release from polar precipitation can compensate for radiative cooling in the winter and reduce or even reverse the meridional temperature gradient and hinder the formation of baroclinic eddies for a significant portion of the winter.

Loftus Kaitlyn – oral
Harvard University

Sulfate Aerosol Hazes and SO2 Gas as Constraints on Rocky Exoplanets' Surface Liquid Water

Despite surface liquid water's importance to habitability, observationally diagnosing its presence or absence on exoplanets is still an open problem. Inspired within the Solar System by the differing sulfur cycles on Venus and Earth, we investigate thick sulfate (H2SO4-H2O) aerosol haze and high trace mixing ratios of SO2 gas as observable atmospheric features whose sustained existence are linked to the near absence of surface liquid water. We examine the fundamentals of the sulfur cycle on a rocky planet with an ocean and an atmosphere in which the dominant forms of sulfur are SO2 gas and H2SO4-H2O aerosols (as on Earth and Venus). We build a simple but robust model of the wet, oxidized sulfur cycle to determine the critical amounts of sulfur in the atmosphere-ocean system required for detectable levels of SO2 and a detectable haze layer. We demonstrate that for physically realistic ocean pH values (pH $\geq$ 6) and conservative assumptions on volcanic outgassing, chemistry, and aerosol microphysics, surface liquid water reservoirs with greater than 10^{-3} Earth oceans are incompatible with a sustained observable H2SO4-H2O haze layer and sustained observable levels of SO2. Thus, we propose the observational detection of a H2SO4-H2O haze layer and of SO2 gas as two new remote indicators that a planet does not host significant surface liquid water.

Lorenz Ralph - poster
Johns Hopkins

Dragonfly : In-situ measurements of Titan's Meteorology

NASA's latest New Frontiers mission, Dragonfly, will explore Titan in 2034 with landed meteorology and geophysical/geochemical investigations, imaging (geomorphology) and flights to profile the structure of the lower atmosphere.

Lorenz Ralph
Johns Hopkins University

Energetic of Convection and Lightning

No abstract

Lothringer Joshua - poster
University of Arizona

A New Look at Ultra-Hot Jupiters using the PHOENIX ExoplaneT Retrieval Algorithm (PETRA)

We describe the PHOENIX ExoplaneT Retrieval Algorithm, or PETRA, a new atmosphere retrieval analysis code built around the well-tested and widely-used PHOENIX atmosphere model. PETRA is capable of retrieving atmospheric properties from irradiated and self-luminous exoplanetary, brown dwarf, and stellar atmospheres using low- and high-spectral resolution observations. We use PETRA to develop a novel technique to probe the ion chemistry in ultra-hot Jupiters (>2000K). Retrieving the abundances of select ions will grant insight into the importance of MHD effects in shaping the circulation of ultra-hot atmospheres, while providing measures of the composition and temperature structure.

Louden Tom - oral
University of Warwick

An equatorial jet and polar flow on WASP-49b

I will present a new analysis of the high resolution spectrum of WASP-49b using Terminator, a code developed to spatially resolve the atmosphere's of exoplanets. Simulations of hot Jupiters with GCM's predict the presence of a strong equatorial jet, as well as a day-to-night flow. Without spatial resolution, it is only possible to measure a global average velocity of the planet, and hence it is not possible to disentangle these contributions. Transit Limb Scanning makes it possible to spatially resolve the atmosphere of an exoplanet during transit, by modelling the differential weighting of the contributions of different regions of the planet's atmosphere during transit. This technique was first used in Louden & Wheatley 2015 to spatially resolve the atmosphere of the hot Jupiter HD\,189733b and detect the presence of an equatorial jet. Here, I build upon this technique and show for the first time that it is also possible to separate out contributions from polar and equatorial regions of the planet. I will present an analysis of the sodium line of WASP-49b showing 3 distinct velocity regions in the atmosphere; eastern and western equatorial regions with velocities of - 3±1 and 1±1 km/s, and a polar region with an average velocity of -1\ ±1 km/s. This is only the second time that an equatorial jet has been directly measured on exoplanet, and is the first evidence of a distinct polar region.

Malik Matej - poster
University of Maryland, College Park

Analyzing Atmospheric Temperature Profiles and Spectra of M dwarf Rocky Planets

The highly anticipated launch of JWST will open up the possibility of comprehensively measuring the thermal emission spectra of rocky terrestrial exoplanets orbiting M dwarfs to detect and characterize their atmospheres. In preparation for this opportunity, we present model atmospheres for three M-dwarf planets particularly amenable to secondary eclipse spectroscopy -- TRAPPIST-1b, GJ 1132b, and LHS 3844b. Using three limiting cases of candidate atmospheric compositions (pure H2O, pure CO2 and solar abundances) we calculate temperature-pressure profiles and emission and reflection spectra in radiative-convective equilibrium, including the effects of a solid surface at the base of the atmosphere. Our results differ appreciably from simpler parameterized models of super-Earth atmospheres in terms of the overall temperatures and the temperature gradient, which has important observational consequences. We find that the atmospheric radiative transfer is significantly influenced by the cool M-star irradiation; H2O and CO2 absorption bands in the near-infrared are strong enough to absorb a sizeable fraction of the incoming stellar light at low pressures, which leads to temperature inversions in the upper atmosphere. The non-gray band structure of gaseous opacities in the infrared is hereby an important factor. Opacity windows are muted at higher atmospheric temperatures, so we expect temperature inversions to be common only for sufficiently cool planets. We also find that pure CO2 atmospheres exhibit lower overall temperatures and stronger reflection spectra compared to models of the other two compositions. We estimate that for GJ 1132b and LHS 3844b we should be able to distinguish between different atmospheric compositions with JWST. The emission lines from the predicted temperature inversions are currently hard to measure, but high resolution spectroscopy with future ELTs may be able to detect them.

Manjavacas Elena - poster
University of Arizona

Cloud Atlas: Rotational Spectral Modulations and Potential Sulfide Clouds in the Planetary-mass, Late T-type Companion Ross 458C

We have discovered rotational modulations on the planetary-mass brown dwarfs ROSS458C. We have discovered a sinusoidal modulation with an amplitude of 2.8% in its white light curve, and a rotational period estimated in ~7h. This rotational modulation might be a confirmation of the existence of sulfid clouds in planetary-mass brown dwarfs.

Mansfield Megan - poster
University of Chicago

Finding Atmospheres on M Dwarf Terrestrial Planets

In the near future, the James Webb Space Telescope (JWST) will provide the capability for atmospheric characterization small, rocky planets around M dwarfs. However, it is currently unknown whether such planets can retain atmospheres. The high X-ray and ultraviolet flux of M dwarfs may completely strip the atmospheres off small, close-in planets.

I will present the results from a multi-institution collaboration in which we propose a rapid test for the presence of an atmosphere. The test relies on secondary eclipse photometry with JWST, which measures a planet's dayside brightness temperature. We argue that an atmosphere will reduce the dayside temperature of a tidally locked planet relative to that of a bare rock, either because the atmosphere transports heat to the night side of the planet or because atmospheric scatterers such as clouds will increase the planet's Bond albedo. If a planet's dayside was then observed to be significantly cooler than a bare rock, this implies that the planet has a substantial atmosphere.

We investigate the promise and limits of this technique with simulated JWST observations of three high-priority warm super-Earths: TRAPPIST-1b, GJ1132b, and LHS3844b. Our simulations are based on general circulation models and state-of-the-art radiative-convective models (see poster by Matej Malik). We also investigate geological false positives using Solar System analogs and laboratory data for potential high-albedo surfaces. We find that for all three planets JWST could identify an O(1) bar atmosphere in as little as one eclipse, while atmospheric detection with other techniques typically requires more effort.

The TESS mission is expected to find >100 hot rocky planets by the time JWST launches, and observing them with this technique would have major astrobiological implications. For example, if atmospheres are common on hot M dwarf planets, then cooler, potentially habitable planets around these stars will also likely have atmospheres.

Marquette Melissa - poster
McGill University

Characterizing hot Jupiter atmospheres through high resolution eclipse spectroscopy

By combining analysis conducted using simplified toy models, full blown GCMs, and ultimately real data, we aim to explore the limits of what atmospheric conditions are detectable in the spectra of hot Jupiters. Given that multiple molecular species, including H2O and CO (Brogi et al. 2013), have already been robustly detected using high resolution spectroscopy (Birkby 2018), we seek to push these detections further by using high resolution spectra taken during secondary eclipses to infer how these spectral lines may have been altered by the conditions under which they were produced (e.g. their shape, depth) and use that to inform us about atmospheric characteristics. To do this, we combine simplified toy models that demonstrate the scale of the effects of atmospheric conditions on spectral lines with full blown GCMs capable of creating a more realistically complex portrait of what these effects might look like in the resulting spectra we observe. This will inform our target selection and observational strategy to conduct future observations using the SPIRou spectopolarimeter on the Canada-France-Hawaii telescope, as well as our ultimate handling of the data to enable us to extract as much information as possible.

Mayorga Laura - poster
Center for Astrophysics | Harvard & Smithsonian

The Reflected Light Variations of Terrestrial Exoplanets: Lessons from the Galilean Satellites

Direct observation of the disk-integrated brightness of bodies in the Solar System, and the variation with illumination and wavelength, is essential for both planning imaging observations of exoplanets and interpreting the eventual datasets. In my previous work, I used the Imaging Science Subsystem cameras aboard Cassini to determine the disk-integrated and wavelength-dependent variations of Jupiter, which will serve to inform observations of gas-giant exoplanets. Here, I present the derived illumination and rotation variations of the four Galilean satellites, which are useful proxies for icy exoplanets with little or no atmosphere and will help constrain surface contamination in patchy cloud scenarios. The data span a range of wavelengths from 400 - 950 nm and predominantly phase angles from 0 - 140 degrees. Despite the similarity in size and density between the moons, surface inhomogeneities result in significant changes in the disk-integrated reflectivity with planetocentric longitude and phase angle. This implies that future exoplanet observations with sufficient precision could exploit this effect to deduce surface variations, determine rotation periods, and infer surface composition.

McIntyre Sarah - poster
Australian National University

Planetary Magnetism as a Parameter in Exoplanet Habitability

Evidence from the solar system suggests that, unlike Venus and Mars, the presence of a strong magnetic dipole moment on Earth has helped maintain liquid water on its surface. Therefore, planetary magnetism could have a significant effect on the long-term maintenance of atmosphere and liquid water on rocky exoplanets. We use Olson & Christensen's (2006) model to estimate magnetic dipole moments of rocky exoplanets. Even when modelling maximum magnetic dipole moments, only Kepler-186 f has a magnetic dipole moment larger than the Earth's, while approximately half of rocky exoplanets detected in the circumstellar habitable zone have a negligible magnetic dipole moment. This suggests that planetary magnetism is an important factor when prioritizing observations of potentially habitable planets.

McIntyre Kathleen - poster
University of Central Florida

The Current State of Spitzer Secondary Eclipse Analyses: HD 209458 b

Kathleen J. McIntyre, Joseph Harrington, Ryan C. Challener, Matthew Reinhard, Raechel Green, Zacchaeus Scheffer, Cody Jordan, Parker Jochum, and Catherine Millwater.

The Spitzer Space telescope has been the workhorse for exoplanet secondar eclipse observations for more than a decade. Despite this, we are still uncovering and understanding new methods for moderating systematics in our analyses. Here we present the test case of HD 209458 b, one of the most observed, published, and highest signal-to-noise exoplanets discovered to date. We compare the effect of different methods, for example, BiLinearly-Interpolated Subpixel Sensitivity (BLISS) and Pixel-Level Decorrelation (PLD), on the resulting light curves across all of Spitzer's IRAC channels. One such systematic that can mimic the features of a secondary eclipse or small primary transit is vibrations of the spacecraft that manifest as changes in the point spread function. Previously utilized metrics of interpreting noise pixel do not account for the systematic's presence when there is no accompanying increased contribution to the noise. This omission with will impact published results. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G.

Metchev Stanimir - poster
University of Western Ontario

Ultra-cool dwarfs viewed equator-on: a Spitzer survey of the best host stars for biosignature detection in transiting exo-Earths

There are nearly 200 known planets around M dwarfs, but only one system around an ultra-cool dwarf (spectral type >M7, effective temperature < 2700 K): Trappist-1. Ultra-cool dwarfs are arguably the most promising hosts for atmospheric and biosignature detection in transiting planets because of the enhanced feature contrast in transit and eclipse spectroscopy.

We present first results from a Spitzer survey to continuously monitor 15 of the brightest ultra-cool dwarfs over 3 days each to detect transits of planets as small as Mars. To maximize the probability of detecting transiting planets, we have selected only ultra-cool dwarfs seen close to equator-on. Spin-orbit alignment expectations dictate that the planetary systems around these ultra-cool dwarfs should also be oriented nearly edge-on. Any planet detections from this survey will be high priority targets for JWST transit spectroscopy. No other telescope, present or within the foreseeable future, will be able to perform a similarly sensitive and dedicated survey for characterizeable Earth analogs.

Miguel Yamila - oral
STRW, University of Leiden, The Netherlands

Juno and Jupiter

The key to understand our origins is in the interiors of the giant planets. Because Jupiter and Saturn were the first planets to form, their primordial envelopes -accreted from the primitive solar nebula- contain crucial information to understand the physics and the chemistry of the protosolar disk that gave birth to the solar system. Heavy elements, even though they are a smaller constituent, are an important input in formation models and therefore crucial to understand the formation history of the giant planets.

Recent measurements provided by Juno and Cassini Grand Finale missions (Bolton et al. 2017; Iess et al. 2018; 2019) have lead to a radical change of our knowledge of the giant planets' interiors. The highly accurate gravity data, allows us to calculate new models to understand Jupiter and Saturn's interior structure and atmospheric dynamics. These models are used to determine the amount of heavy elements and its potential distribution in the interior of the planets (Miguel et al. 2016; Wahl et al. 2017; Guillot, Miguel et al. 2018; Kaspi et al. 2018; Galanti et al. 2019). In this talk I will present our calculations that also explore the effect of different model parameters, towards a better determination of the mass of heavy elements and its distribution in the giant's interiors.

Miles Brittany - poster
UC Santa Cruz

Non-Equilibrium Chemistry of the Coolest Brown Dwarfs: Implications for Directly Imaged Exoplanets

The Y-dwarf spectral class is composed of only ~23 brown dwarfs with effective temperatures below 450 K and atmospheres rich in gaseous methane, ammonia, and water. Y-dwarfs are colder than any current directly imaged exoplanet, offering previews into the atmospheric physics of gas giants that will be discovered and characterized in the future with JWST and SCALES. The coldest brown dwarf WISE 0855 (250 K) showed water absorption and evidence of clouds across its M-band (4.5 – 5.0) spectrum. In addition to this, WISE 0855 is also only ~100 K hotter than Jupiter, yet its lack of phosphine absorption means that it has significantly different atmospheric mixing properties than Jupiter. This difference implies that there could be a large degree of variation in atmospheric physics at extremely cool temperatures. In this work, we expand the sample of cool brown dwarf M-band spectra to cover the temperature range of 250 K – 700 K by taking low resolution Gemini/GNIRS spectra of 4 T/Y-dwarfs (50 hours, WISE 1541, WISE 2056, WISE 0313, UGPS 0722) and placing them in context to previously published spectra (WISE 0855, 2MASS 0415, Gl 570D). With the exception of Gl 570D, cloud-free, solar metallicity brown dwarf models do not accurately fit the spectral slopes of our sample and better fits are achieved when non-equilibrium abundances of carbon monoxide are added into the atmospheric models. Atmospheric mixing can bring up warmer carbon monoxide gas and our sample suggests that mixing becomes stronger at cooler effective temperatures. We discuss why these types of atmospheric analyses are essential for 1) planning and interpreting higher quality JWST Y-dwarf observations and 2) predicting what may be observable on cooler, low-gravity gas giant exoplanets.

Mitchell Jonathan - poster
UCLA

Terrestrial Planetary Atmospheres and Climate Extremes: Titan's surface methane hydrology

Titan's global-scale topography, with high-latitude lowlands and low-latitude highlands, and its limited methane reservoir result in cold-trapped volatile storage near the poles. However, idealized GCM simulations of Titan's climate reveal the need for a more dispersed component of methane evaporation at high latitudes and surface infiltration at low latitudes, which indicate the need for realistic surface hydrology (Lora & Mitchell 2015; Mitchell & Lora 2016). We have developed a global land hydrology for the Titan Atmosphere Model (TAM; Lora et al. 2015) that includes surface and subsurface liquid transport and a "ground methane evaporation" from a near-surface methane table (Faulk et al. 2019). Sensitivity simulations indicate that lateral-flow dominant hydrology overproduce surface lakes and seas, while infiltration-dominant simulations faithfully capture the observed sea distribution. Our results also indicate a much larger methane reservoir than is present on the surface is likely hidden in Titan's subsurface methane aquifer.

Mollière Paul – oral
Leiden Observatory

Isotopologues at High Spectral Resolution

The cross-correlation technique is a well-tested method for exoplanet characterization, having lead to the detection of various molecules, and to constraints on atmospheric temperature profiles, wind speeds, and planetary spin rates. A new, potentially powerful application of this technique is the measurement of atmospheric isotope ratios. In particular HDO/H2O ratios can give unique insights in the formation and evolution of planets and their atmospheres.
I will report on the detectability of molecular isotopologues in the high-dispersion spectra of exoplanet atmospheres. I will show why we expect to see 13CO already with the class of current telescopes, once instruments such as CRIRES+ become available. The more exciting detection of HDO will be more challenging, but it could become a prime science case for the first-light instrument METIS on the European ELT: for Proxima Cen b, a single night of observation may be enough to detect HDO if the planet is water rich. For more massive self-luminous planets the HDO detection may help to constrain the planets accretion history. Finally, I will discuss the detection of which other isotopologues may be feasible, and what we can learn from them.

Moore Keavin - poster
McGill University

Water Cycling and Loss on M-Earths

M-dwarfs are the most common stars in the Galaxy, and are host to many rocky planets; if the planets are Earth-like, they are referred to as M-Earths. The volatile budget of an M-Earth importantly determines the amount of water in various reservoirs, from the surface oceans to the large volume sequestered in the mantle. This water is constantly cycled between these reservoirs, by regassing from the surface to the mantle through subduction of hydrated oceanic crust, and degassing from the mantle to the surface by mid-ocean ridge volcanism. Water may also be lost from the surface through the atmosphere, due to the large flux of XUV radiation which can photo dissociate water molecules, during the early evolution of the host M-dwarf, which can critically impact the climate of the planet. I aim to create a coupled model of water cycling and atmospheric loss on M-Earths to determine the planetary water distribution, including surface water content, throughout the planet's lifetime.

Moran Sarah - poster
Johns Hopkins University, Earth and Planetary Sciences

Chemistry of Temperate Exoplanet Atmospheric Hazes from the Laboratory

Very little experimental work has been done to explore the properties of photochemical hazes formed in atmospheres with very different compositions or temperatures than that of the outer solar system or of early Earth. With extrasolar planet discoveries now numbering thousands, this untapped phase space merits exploration. This study presents the first chemical composition results of haze particles produced from exoplanet laboratory studies. We used very high resolution mass spectrometry to measure the chemical components of solid particles produced in atmospheric chamber experiments in the Johns Hopkins University PHAZER lab. Many complex molecular species with general chemical formulas $C_wH_xN_yO_z$ were detected. Of interest, our detections include multiple molecular formulas with prebiotic implications. Additionally, we found that the experimental exoplanetary haze analogues exhibit diverse solubility characteristics, which could provide insight into the possibility of further chemical or physical alteration of photochemical hazes in the atmospheres of super-earth and mini-neptune exoplanets. Our results suggest that further studies investigating this complex chemistry and its subsequent effects on exoplanetary atmospheres are warranted. These analogue particles can help us better understand chemical processes happening in exoplanet atmospheres and are a possible source of prebiotic chemistry on distant worlds.

Morley Caroline - oral
University of Texas at Austin

Clouds on terestrial planets, prospects for observations

An exciting and imminent frontier of exoplanet science is the characterization of Earth-sized planets. The most amenable planets for characterization in the coming decades are transiting planets orbiting the smallest stars. During the past two years, nine planets close to Earth in radius have been discovered around nearby M dwarfs cooler than 3300 K. These planets include the 7 planets in the TRAPPIST-1 system and two planets discovered by the MEarth survey, GJ 1132b and LHS 1140b. A number of other such planets are expected to be found by the TESS mission and ground-based surveys like MEarth and SPECULOOS. Some of these planets orbit as distances potentially amenable to surface liquid water, though the surface temperatures will depend strongly on the albedo of the planet and the thickness and composition of its atmosphere. The stars they orbit also vary in activity levels, from quiet M dwarfs like LHS 1140 to more active stars like TRAPPIST-1. This set of planets will form the testbed for our first chance to study the diversity of atmospheres around Earth-sized planets. Here, we will present model spectra of the nine currently-known temperate terrestrial worlds amenable to atmosphere characterization. We also present model spectra of an additional set of simulated planets from the Barclay et al. 2018 catalog, which represent the best new planets that TESS will find, as well as actual TESS planets as they are discovered. We show the distributions of planet radii, orbital periods, temperatures, host star temperatures, and distances for the predicted sample of TESS terrestrial planets that provide the best opportunities for measuring their atmospheres. We vary both composition and the surface pressure of the atmosphere, basing our elemental compositions on outcomes of planetary atmosphere evolution in our own solar system. We present both thermal emission spectra and transmission spectra for each of these objects, and we provide predictions for the observability of these spectra with future space missions including JWST and the Origins Space Telescope mission concept, as well as the ground-based Giant Magellan Telescope. We show which big questions in terrestrial planet science are likely to be studied with JWST and which can be studied in the more distant future.

Nortmann Lisa - poster
Instituto de Astrofisica de Canarias

High-resolution studies of the He I absorption feature in multiple planets

The CARMENES* consortium (*Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs) is using the instrument to study the atmospheres of a growing number of exoplanets. In particular, the high-resolution coverage of the near infrared allows us to resolve the helium I triplet lines at 1083 nm and study the dynamics of the gas in the extended atmosphere. For the Saturn-mass planet WASP-69b we find that the material is accelerated away from the planet towards the observer, which manifests in a net blue shift of the measured He I lines of several km/s. Further, a well-sampled light curve reveals the planetary helium to trail behind the planet in form of a comet-like tail. We yield further detections of helium I in the hot Jupiter planets HD189733b and HD209458b and derive upper limits for GJ436b and KELT-9b, which challenge current literature predictions. A look into the host stars of this yet small sample of targets hints at a correlation between the strength of the helium I absorption with host star activity and stellar extreme UV flux received by the planet, unveiling formation processes of this line in atmospheres of exoplanets.

Nugroho Stevanus Kristianto - poster
Queen's University Belfast

High-resolution TiO signature in the emission spectrum of WASP-33b: New result using updated TiO line list

Recently, direct detection of the molecular signature in exoplanet atmosphere using high-resolution spectroscopy is a hot topic in the exoplanet characterisation research field. Unlike low-resolution spectroscopy, it is able to resolve molecular bands into individual absorption lines. By observing the planet during its orbital movement, it is possible to distinguish the exoplanet lines from telluric and stellar lines owing to the variation of Doppler shifts and detect specific molecule unambiguously, which is why it is called planet radial velocity (PRV) technique. It has been predicted that titanium oxide (TiO) and/or vanadium oxide (VO) causing thermal inversions in the atmosphere of the the very hot Jupiters. To find the thermal inversion agent, we observed WASP-33 b before its secondary eclipse using High Dispersion Spectrograph (HDS; R~165,000) on Subaru telescope in the wavelength range of 0.62-0.88 μm. We remove the systematics from the instrument, the telluric and stellar lines using SYSREM and cross-correlate it with model spectrum. We are able to detect TiO emission signature and confirm the existence of stratosphere in the dayside atmosphere of WASP-33b (one of the hottest Hot Jupiter, Teq= 3300 K) by 4.8 sigma. This is the first direct detection of TiO emission signature in the dayside of exoplanet atmosphere using PRV technique in the optical wavelength regime. Our result strengthens the prediction that cold trap effect is inefficient in the atmosphere of a very hot Jupiter (Teq > 2500K) and demonstrate the capability of HDS on Subaru telescope to do PRV observation. Here we also updated our result using new TiO line list.

Ohno Kazumasa - poster
Tokyo Institute of Technology

Atmospheric Circulation and Thermal Light Curves of Eccentric-Tilted Exoplanets

Relatively long-period planets potentially retain the primordial rotation, eccentricity, and obliquity that might encapsulate the information of the planetary climate and formation history.
Recent observational efforts have extended known exoplanet catalog to such long-period exoplanets, motivating us to study atmospheric circulations on them that is strongly associated to the climate and observable signature.
Here, we investigate the atmospheric dynamics of non-synchronized exoplanets across various radiative timescales, eccentricities, and obliquities using a shallow water model.
We found that the dynamical pattern can be demarcated into five regimes in terms of radiative timescal τ_{rad} and obliquity θ.
The atmosphere with τ_{rad} shorter than a planetary day usually exhibits a strong day-night temperature contrasts and a day-to-night flow pattern.
In the intermediate τ_{rad} regime between a planetary day and a year, the atmosphere is dominated by steady temperature and jet patterns for θ ≤ 18° but shows a strong seasonal variation for θ ≥18°.
If τ_{rad} is larger than a year, seasonal variation is very weak.
In this regime, eastward jets are developed for θ ≤ 54° and westward jets are developed for θ ≥ 54°.
These dynamical regimes are also applicable to the planets in eccentric orbits.
We also calculated the synthetic thermal light curves of the simulated planets for various viewing geometries.
We found that the peak of the light curve occurring after the secondary eclipse potentially indicates the obliquity of θ >18° if the planet is in a circular orbit or in a configuration that the periapse takes place before the secondary eclipse.
Our results could help to constrain exoplanet obliquities in future observations.

Oklopcic Antonija – oral
Harvard University

Atmospheric Escape and evolution via He I Line observations

Atmospheric escape is an important process in the evolution of atmospheres of extrasolar planets, especially those orbiting very close to their host stars. However, many aspects of atmospheric escape remain poorly understood, in part due to a small number of direct observations that have been available until recently, obtained mostly via transit spectroscopy in the difficult-to-observe hydrogen Lyman-alpha line. In recent theoretical work (Oklopcic & Hirata, 2018), we demonstrated that the absorption line of helium at 1083 nm can be used as a powerful new diagnostic of escaping atmospheres. Since then, excess absorption in the helium 1083 nm line has been observed in several exoplanets, using both space- and ground-based telescopes. These observations opened a new wavelength window into escaping atmospheres that can help us improve our understanding of the physical processes that drive atmospheric mass loss and, consequently, affect planetary evolution and demographics of planetary systems. In my presentation, I will demonstrate how we can use theoretical models of upper planetary atmospheres to interpret the observed 1083 nm transit absorption signatures and place constraints on the physical properties of extended exoplanet atmospheres and their mass loss rates.

Okuya Ayaka - poster
Tokyo Institute of Technology

Habitability of S-type tidally locked planets: effects of a binary companion star

Planets in the ``habitable zones'' around M-type stars are important targets for characterization in future observations. Due to tidal locking in synchronous spin-orbit rotations, the planets tend to have a hot dayside and a cold nightside. On the cold nightside, water vapor transferred from the dayside can be frozen in (``cold trapping'') or the major atmospheric constituent could also condense (``atmospheric collapse'') if the atmosphere is so thin that the redistribution of heat is not efficient. This is one of the crucial problems for the habitability of a planet around a single M-type star (e.g., Joshi et al. 1997; Leconte et al. 2013).
Motivated by the abundance of binary star systems (Raghavan et al. 2010), we investigate the effects of irradiation from a G-type companion star on the climate of a tidally locked planet around an M-type star through simulations of the 2D energy balance model (e.g., North 1975).
We find that the irradiation from the G-type star is more effective at warming up the nightside of the planet than the dayside. This contributes to the prevention of the irreversible trapping of water and atmosphere on the cold nightside, broadening the parameter space where tidally locked planets can maintain surface liquid water on stable orbits. Tidally locked ocean planets with $\sim \leq 0.3$ bar atmospheres or land planets with $\sim\leq 3$ bar atmospheres can produce a temperate climate with surface liquid water when they are also irradiated by a companion star with a separation of 1 - 4 au. We also demonstrate that planets with given properties can be in the Earth-like temperate climate regime or in a completely frozen state under the same total irradiation.

Owen James – oral
Physics, Imperial College London

Atmospheric Escape

Understanding the evolution of exoplanet atmospheres requires modelling a multitude of different processes. One of the most important of those is atmospheric escape, wherein the upper layers of a planet's atmosphere unbind themselves from the planet's gravity and are lost. Atmospheric escape has sculpted the atmospheres of terrestrial solar-system planets; however, given many exoplanets are extremely highly irradiated atmospheric escape is likely to be even more important for exoplanet atmospheres. In this talk, I will review some of the basic theory of atmospheric escape indicating that it begins almost immediately after the planet has finished it formation. I will discuss work on the loss of primordial H/He atmospheres, including potentially habitable worlds around Mstars. I will also discuss water loss, and heavy element loss from ultra-short period planets and discuss areas that need more theoretical attention. In particular, with respect to atmospheric escape of secondary atmospheres and the interplay between resupply and loss that is likely to set the outcome of atmospheric evolution for close-in terrestrial planets.

Pahlevan Kaveh - poster
Arizona State University

Magma ocean outgassing and the evolution of primordial atmospheres

Terrestrial planet accretion is associated with melting and magma oceans, core-mantle differentiation, and the outgassing of volatiles into a primordial atmosphere. A critical parameter that governs volatile outgassing is the oxygen fugacity (fO_2), which influences the quantity and species of volatiles that are outgassed. The range of fO_2s expected during terrestrial planet formation ranges from reducing conditions (near the iron-wustite (IW) buffer) where H_2 and CO dominate the gas phase, to oxidizing conditions (near the quartz-fayalite-magnetite (QFM) buffer) where H_2O and CO_2 are the dominant volatiles. Because the terrestrial mantle today is oxidized, scenarios of primordial planetary climates have centered on oxidized (H_2O-CO_2-rich) outgassed atmospheres, which readily lead to water oceans and massive CO_2 greenhouses, as apparently occurred in the case of early Earth. By contrast, the presence of metallic cores in all Solar System terrestrial planets points towards the likelihood of reducing conditions during primordial outgassing. Despite their likely abundance on early terrestrial planets, such primordial reducing greenhouses have not been well-studied. Here, I explore some of the behaviors of reducing outgassed atmospheres, including primordial H_2 greenhouses, delayed water ocean formation, and a new end-state for terrestrial planet evolution not encountered in the Solar System: the CO desert planet. Finally, I conclude by identifying isotopic and spectroscopic signatures of the evolution of primordial atmospheres in the Solar System and exoplanetary systems, respectively.

Panwar Vatsal - poster

Gemini/GMOS Transmission Spectroscopic Survey of Gas Giant Exoplanets

No abstract

Parmentier Vivien - poster
University of Oxford

From hot to ultra hot Jupiters

Hubble and spitzer space telescope observations of ultra-hot hot Jupiters (Teq>2000K) have revealed a lack of strong molecular features similar to the ones seen in cooler hot Jupiters (Teq<2000K). Many explanations have been proposed for these blackbody-like spectra, including the presence of a quasi-isothermal dayside atmosphere, the presence of a high C/O ratio or the presence of non-solar abundance ratio between water and other molecules such as VO or FeH. Using the case of WASP-121b, I will show that at these high temperatures the thermal dissociation of water fundamentally shapes the emission spectra.
Considering the vertical gradient of water and the presence of additional molecules predicted by chemical equilibrium calculations, I will show that both the emission and the transmission spectra of WASP-121b can be well reproduced by the outputs of a global circulation model assuming solar abundances and taking into account molecular dissociation and condensation of material at the limb of the planet. Finally, I will put WASP-121b into context, and discuss for which planets molecular dissociation is going to play a fundamental role and needs to be incorporated into atmospheric retrieval models.

Pino Lorenzo - poster
University of Amsterdam

Emission from metal atoms from the day-side of Kelt-9b

We present the first detection of emission lines from metals in atomic form from the photosphere of a planet. This was obtained by applying the cross-correlation technique to HARPS-N high spectral resolution (R>100,000) data targeting the day-side of the ultra-hot Jupiter KELT-9b (4,000 K). Iron and other metals were previously detected in the transmission spectrum of the planet, that probes the day-night transition region at low pressures (P < mbar). Our complementary observations probe deeper in the atmosphere, and well in the day-side, where chemical equilibrium is expected to hold. The data is consistent with a strongly inverted temperature-pressure profile and stellar abundance of iron. In combination with the existing transmission spectroscopy data, our observations provide the chance to map the 3D structure of the planet.

Pluriel William - poster
Bordeaux Laboratory for Astrophysics

Unravelling the biases of transmission spectroscopy due to the three-dimensional structure of exo-atmospheres

Transmission spectroscopy provides us with information on the atmospheric properties at the limb, which is often intuitively assumed to be a narrow annulus around the planet. This is why all existing retrieval algorithms used so far to constrain the atmospheric composition from data rely either on i) a single 1D forward model, thus assuming a uniform limb or ii) a linear combination of 1D models to account for heterogeneities between different regions of the limb (e.g. east vs. west). Even full three-dimensional atmospheric models (GCMs) commonly use only the atmospheric columns at the terminator to predict the observable transmission spectrum for a given simulation.
Here, we will demonstrate that the region probed in transmission actually extends significantly toward the day and night sides of the planet and that, as a result, the real transmission spectrum computed from a GCM simulation with our new fully 3D radiative transfer differs significantly from results obtained with the usual assumptions. This comes from the fact that the terminator of hot, synchronously rotating planets is a region exhibiting sharp thermal and compositional gradients. Finally using both real-planet examples and more idealized case, we will demonstrate how this effect can lead to strong biases is the temperature and abundances retrieved from actual data—biases that will need to be addressed and corrected for if we want to be able to make robust inferences from future JWST and ARIEL data.
W. Pluriel, J. Leconte, A. Caldas, F. Selsis, I.P. Waldmann, P. Bordé, M. Rocchetto, B. Charnay, V. Parmentier

Poser Anna Julia - poster
University of Rostock

The effect of clouds on the inferred metallicity of giant exoplanets

Atmospheres regulate the planetary heat loss and therefore influence planetary thermal evolution. Within an analytic atmosphere model, we here investigate the influence that different opacities, and in particular different cloud opacities and cloud depths can have on the thermal evolution of irradiated extrasolar gas giants. We show that thin, high clouds of short optical depth have negligible influence on the planet evolution, whereas deep-seated thick silicate clouds can lead to warmer deep tropospheres and therefore up to several 10 M_E higher bulk heavy element mass estimates. We discuss our interior model results with respect to the known age of the young hot Jupiter WASP-10b, for which accurately measured mass and radius values exist, and of WASP-39b whose observationally derived metallicity seems higher than predicted by current models.

Powell Diana - poster
UC Santa Cruz

Transit Signatures of Inhomogeneous Clouds on Hot Jupiters: Insights from Microphysical Cloud Modeling

Clouds on hot Jupiters are likely spatially inhomogeneous. Such cloud inhomogeneity can substantially impact the planetary climate and, when not accounted for, lead to incorrectly inferred planetary properties from limb-averaged observations. We determine the observability of inhomogeneous cloud cover on the limbs of hot Jupiters in transmission with JWST through post processing a general circulation model to include cloud distributions computed using a cloud microphysics model. In particular, we present a robust transit signature of cloud inhomogeneity that leverages information in the chromatic shape of the transit light curve. These simulated observations are statistically robust in retrieval even with limited wavelength coverage, uncertainty on limb darkening coefficients, and imprecise transit times. We further describe specific transmission signatures of condensational clouds including broad silicate and aluminum features in the infrared and show that the transit depths differed by up to 5% for realistic cloud particle size distributions compared to a mean particle size.

Ranjan Sukrit – oral
MIT

UV Light and Life in the Universe

The detection of life beyond our solar system is a key goal of exoplanet science. This quest is intimately coupled to the study of the emergence of life on Earth (abiogenesis): theories of abiogenesis provide informative priors for biosignature search target selection and signal interpretation, while the detection of life on exoplanets would strongly constrain theories of abiogenesis. In this talk, I will review progress in these fields, unified by the key role UV radiation plays in both. In particular, I will review recent advances in (1) our understanding of the geochemical context in which life arose on Earth and the implications for proposed prebiotic chemistries, (2) the UV environment on prebiotic Earth versus on M-dwarf exoplanets, and the implications for UV-dependent origin of life scenarios, and (3) efforts to refine and expand the inventory of gases whose detection could be a signpost of life (biosignature gases). I will focus especially on the favorable nature of M-dwarf exoplanets for biosignature detection, and as potential test cases for theories of abiogenesis.

Rauscher Emily - oral
Astronomy, University of Michigan

Hot Jupiters: Dynamics, Chemistry & Clouds

Hot Jupiters are often the first planets targeted with any new, cutting-edge characterization method. Is this just because they are the biggest and brightest, or is there still anything left to learn about these absolutely-not-Earthlike planets? In this review talk I will argue that our "standard picture" of hot Jupiters, which we have developed over almost two decades, is great but still missing potentially first-order pieces of physics. While challenging, hot Jupiters continue to stretch our understanding of planetary physics into a truly exotic regime. I will highlight recent work and current outstanding questions as to the atmospheric states of hot Jupiters. I will particularly focus on the influence of chemistry and clouds on the atmospheric dynamics, and vice versa, as well as observational implications. There is much we still need to learn!

Ridden-Harper Andrew - poster
Cornell University

Improved limits on Na and Ca in the exosphere of 55 Cancri e from new and archival data

It is thought that hot rocky super-Earths may have atmospheres that are produced by the vaporization of their surfaces. Furthermore, such atmospheres may be sputtered by the intense stellar winds of their host stars, potentially leading to large exospheric clouds consisting of elements such as sodium, calcium and potassium (e.g. Schaefer & Fegley 2009, Mura et al. 2011). Ridden-Harper et al. (2016) used high spectral resolution observations to search for sodium and ionized calcium surrounding the hot (T > 2000K) short period (P = 0.74 day) super-Earth, 55 Cancri e. With data from VLT/UVES, ESO 3.6-metre telescope/HARPS and TNG/HARPS-N, they found a tentative ~3 sigma absorption signal from the sodium D lines, after averaging over five transmission spectra. Additionally, they report a ~5 sigma absorption signal from the ionized calcium H and K lines in only one of four transmission spectra that included those spectral lines, potentially suggesting that 55 Cancri e's exosphere is variable.
We report on a follow up search (in prep.) that uses unpublished VLT/UVES and Calar Alto 3.5m telescope/CARMENES data, along with archival data from several other telescopes. While no signals such as those seen in Ridden-Harper et al. (2016) are present in the new data, the combination of all available data sets yields unprecedented limits that can significantly constrain the atmospheric properties of this enigmatic planet.

Robinson Tyler - poster
Northern Arizona University

Constraining Exoplanet Habitability with HabEx

A habitable exoplanet is a world that can maintain liquid water on its surface. Motivated in large part by the success of NASA's Kepler mission, many recent studies have substantially developed our understanding of how a world can become, and remain, habitable. Now, the next step towards completing a census of Earth-like planets orbiting stars in the solar neighborhood will be to build instruments that can characterize exoplanet environments and determine if certain worlds are habitable.

Habitability can be detected or constrained by directly detecting surface liquid water, directly measuring the surface pressure and temperature of an exoplanet, and/or by using a combination of observed factors that, taken as a whole, indirectly indicate a habitable surface environment. The first two of these approaches were first demonstrated by Sagan et al. (1993), who used data from two flybys of Earth by NASA's Galileo spacecraft. Here, a surface liquid was directly detected using observations of specular reflectance (i.e., glint), and the composition of this liquid was determined using spectral features of water ice. Additionally, spectral retrievals using the Galileo observations indicated surface temperatures that spanned 240–290 K and surface pressures greater than 0.2 bar, which are both consistent with surface habitability.

From the perspective of exoplanet science, the Sagan et al. results are missing a key complication. Namely, exoplanet observations will not be spatially resolved, as were the Galileo Earth data. Thus, the characterization of habitability for distant Pale Blue Dots will be complicated by the blending of scenes that are cloudy and clearsky, warm and cold, humid and arid, and ocean-covered and land-covered.

In this presentation, we will discuss key ideas related to characterizing exoplanets for habitability. Observational and instrumental constraints will be derived and related to the Habitable Exoplanet Observatory (HabEx) and the Large UltraViolet-Optical-InfraRed explorer (LUVOIR), which are concepts currently under study for the Astronomy and Astrophysics 2020 Decadal Survey.

A number of observational techniques are relevant to the characterization of the atmospheres and surface environments of potentially habitable exoplanets: transit spectroscopy, high contrast imaging, and secondary eclipse spectroscopy. The first of these (transit spectroscopy) can potentially constrain near-surface temperatures and pressures and, thus, habitability. However, probing the near-surface environment may be difficult or impossible due to aerosol or gas opacity and refraction (which is especially problematic for Sun-like stars).

At thermal wavelengths, high contrast imaging and secondary eclipse spectroscopy may provide constraints on surface temperature and pressure, even at low spectral resolution and moderate signal-to-noise. For wavelengths relevant to HabEx and LUVOIR (the visible and near-infrared), surface temperature constraints are unlikely. Here, though, observations of ocean glint or polarization could directly reveal the presence of surface liquid water.

Detecting or constraining the habitability of a distant exoplanet will be a challenging and critical step towards understanding the frequency of the origin of life on other worlds. The most convincing constraints on habitability will likely come from multiple lines of evidence using a variety of approaches brought to bear on a distant Pale Blue Dot.

Roman Michael - poster
University of Leicester

GCM simulations of Hot Jupiters with Variable Clouds

Using a GCM with parameterized, radiatively-active cloud models, we explore the effects of different cloud species on potential visible and thermal phase curves. We model clouds as temperature-dependent condensates with Mie scattering properties appropriate for each species given assumed particles sizes and vertical extents. We start by modeling Kepler-7b--a hot Jupiter with an asymmetric reflected light phase curve suggesting heterogeneous clouds. We find that clouds form along the western terminator and nightside, producing visible phase curves roughly consistent with the observations, and we highlight the effect of radiative-feedback on the cloud distribution and consequent visible and thermal phase curves. Finally, we expand our model to include additional cloud species, covering a broader range of condensation temperatures and scattering properties. We apply then model to investigate the effects of clouds over a wider range of temperatures and gravities and compare resulting phase curves to observations and previous modeling.
M.T. Roman (1), E. Rauscher (2), & E. Kempton (3)
(1) The University of Leicester, UK; (2) University of Michigan, Ann Arbor, MI, USA;
3) University of Maryland, College Park, MD, USA

Sainsbury-Martinez Felix - poster
Maison de la Simulation - CEA Paris-Saclay

Exploring the internal structures of hot Jupiters using the GCM DYNAMICO: Deep, hot, adiabats as a possible solution to the radius inflation problem

The anomalously large radii of highly irradiated exoplanets have long remained a mystery to the Exoplanetary community, with many different solutions suggested and tested. These solutions have included tidal heating of the atmosphere, or ohmic heating from a strong magnetic field. Another solution was also suggested by Tremblin et Al. (2017): The inflated radii of highly irradiated exoplanets can be explained by the advection of potential temperature, via mass and longitudinal momentum conservation, leads to the deep atmosphere attaching to a hotter adiabat than would be suggested by 1D models, thus implying an inflated radius. In that paper this mechanism was tested using 2D steady-state models, and successfully reproduced an inflated HD209458b scenario. Here we extend this work to both the time-dependent and 3D regimes using the GCM Dynamico (Itself developed as a new dynamical core for LMD-Z, and verified against Hot Jupiter benchmarks as part of this work), exploring the evolution of the deep P-T profile, and the stability of a deep adiabat as the steady state solution. As a result of these calculations we confirm that a deep, hot, adiabat is both the target of long term evolution of the deep atmosphere, and is stable against typical forcing expected at deep pressures - we also note that this deep adiabat takes a very significant time to form from an isothermal initial condition (hence why it has not previously been seen in GCM simulations beyond a kink in the deep profile), and suggest that future GCM models should use an adiabatic profile to initialise the deep atmosphere. Taken as a whole, our results confirm the theory of Tremblin et Al. (2017): the inflated radii of highly irradiated exoplanets can be explained by connecting the atmosphere with a deep, hot, internal adiabat.

Sakuraba Haruka - poster
Tokyo Institute of Technology

Effects of core formation and impact-induced atmospheric erosion on Earth's volatile composition

Unveiling the sources of Earth's volatile elements is crucial to understanding how Earth developed its habitable environment. The volatiles in rocky planets are thought to have been delivered by chondritic materials. However, the elemental composition of the bulk silicate Earth (BSE) shows the depletion of carbon (C) and nitrogen (N) relative to hydrogen (H), a high C/N ratio, and a low C/H ratio compared to chondrites. We study the effects of the elemental partitioning, impact-induced atmospheric erosion, and core segregation during and after the magma ocean stage on the volatile abundances of BSE. We modeled both the main accretion stage and the late accretion stage. The former considered the elemental partitioning between the atmosphere, magma ocean, and metal which segregates into the core. The latter considered the partitioning between the atmo- sphere, oceans, and carbonate (the crust). By calculating the evolution for the range of partitioning coefficient, solubilities, and impactor properties, we evaluated how the resulting volatile composition of BSE depends on these input parameters.
As a result, we succeeded to reproduce the elemental composition of major volatile elements in current BSE when we chose the appropriate parameter values. While the elemental fractionation during the main accretion ended up with the excess of N/C, the preferential loss of N from the atmosphere during the late accretion reproduced BSE's volatile pattern. During the main accretion, C was most affected by the core segregation because C is the most siderophile among the volatile elements. During the late accretion, N was most affected by the atmospheric erosion because C and H were trapped in the surface reservoirs.

Samra Dominic - poster
University of St. Andrews

Mapping the atmospheric properties and chemical composition of the ultra-hot Jupiter HAT-P-7b

Dominic Samra, Christiane Helling, Nicolas Iro, Lia Corrales, Kazumasa Ohno, Munazza Alam, Maria Steinrueck, Ben Lew, Karan Molaverdikhani, Ryan MacDonald, Oliver Herbort, Peter Woitke, Vivien Parmentier.

HAT-P-7b is a tidally locked ultra-hot Jupiter with day/night temperatures varying by ~ 2000K. The intense stellar irradiation provides an ideal virtual laboratory to probe our physiochemical atmosphere models. Phase curves and spectra from ultra-hot Jupiters suggest relatively poor day-night circulation (Wong et al. 2016), and super-solar atmospheric metallicities (Evans et al. 2017, Sheppard et al. 2017). However, previous models have not included the impact of cloud formation on gas-phase abundances.
To model gas-phase and cloud properties across HAT-P-7b, we use results from a cloud-free 3D GCM (Parmentier et al.) as input to a kinetic non-equilibrium cloud formation model linked to gas-phase equilibrium chemistry (Helling and Woitke). We produce both global maps at given pressure levels, and radial maps for lines of longitude or latitude, allowing us to interrogate the 3D structure of atmospheric properties.
We show that cloud formation only occurs on the nightside, except when cool gas is transported across the terminator. Maps around the terminator display a distinct asymmetry: Clouds are located only on the morning side, due to winds flowing with planetary rotation. We find the C/O ratio to be a good tracer for clouds, with nightside values significantly enhanced above solar abundances from oxygen depletion by cloud formation. We predict transmission spectra of HAT-P-7b will exhibit a strong signature of 'patchy clouds' (Line & Parmentier, 2016), with observations at 0.6-20 μm inhibited by clouds above ~1 mbar.
This type of mapping analysis provides a powerful tool to infer the atmospheric and cloud properties of ultra-hot Jupiters. They highlight the day/night asymmetry of these planets, with the resulting terminator properties being potentially observable by photometry without the need for detailed spectroscopy.

Schaefer, Laura Kay - oral
Stanford University

Feeling hot,hot,hot! Magma ocean evolution on rocky exoplanets

Magma oceans are a stage of rocky planetary evolution in which much of the planet is molten. Volatiles are soluble in the silicate melt that makes up the bulk of the planet, making atmosphere-interior exchange extremely important for the atmospheric evolution in this stage of planet formation. Magma oceans in the Solar System were likely short-lived (~1-5 Myr for Earth, 50-100 Myr for Venus), but this is likely not true for the currently known exoplanet population. Most known rocky exoplanets are inwards of the runaway greenhouse boundary, indicating that a substantial atmosphere could produce a surface magma ocean, even for exoplanets with equilibrium temperatures below 1000 K. I will discuss the range of magma ocean planets that may be in our current sample and some of the implications for atmospheric composition and long-term evolution of these planets. Atmospheric erosion of these planets may leave them significantly different in bulk composition than the planets of our Solar System. I will discuss aspects of atmosphere-magma ocean exchange, mantle influence on atmospheric composition, and atmospheric escape.

Schlichting Hilke – oral
UCLA

Observational Signatures of the Core-Powered Mass-Loss Mechanism: The Radius Valley as a Function of Stellar Properties

The assembly of planetary cores results in core temperatures of about 10,000 to 100,000 Kelvin. Furthermore, if this assembly takes place in the presence of a gas disk, planetary cores not only accrete H/He atmospheres, but they are also prevented from cooling significantly since the optically thick H/He envelopes act like thermal blankets regulating the heat loss from both the core and envelope at the radiative-convective boundary. As a result the cores and envelopes take Gyrs to cool. We have recently shown that cooling luminosity of the core (core-powered mass-loss) can play an important role in the thermal evolution of the super-Earths and sub-Neptunes and that it yields a bimodal distribution in exoplanet radii consistent with observations. I will explain what physical process gives rise to the bimodality and show that slope and location of the radius valley depend, to first order, only on the planet properties and the bolometric luminosity of the host star. I will further show that this results in a shift of the radius valley to larger planet radii as a function of stellar mass. I will conclude with discussing what these findings imply for observed correlations of planet size and stellar mass and other stellar properties, highlight the importance of combining photoevaporation and core-powered mass-loss models when interpreting the observations.

Seeley Jacob - poster
Harvard University

What determines the tropical tropopause temperature on Earth?

Several recent modeling studies have found that the tropopause temperature on Earth is independent of surface temperature. However, we have been unable to extrapolate this empirical result to other planets because we have lacked a theory for the tropopause. Here I present a theory for the tropopause for atmospheres dominated by condensing greenhouse gases (i.e., those that are governed by Clausius-Clapeyron, such as water vapor on Earth or methane on Titan). Given the spectroscopy of the absorber (i.e., the absorption coefficient as a function of wavenumber), the theory predicts the tropopause temperature, and also reveals the circumstances under which one should expect a fixed tropopause temperature. I verify the predictions of the theory with the results of an iterative 1D radiative-convective model with line-by-line radiative transfer.

Seidel Julia Victoria - poster
University of Geneva

Wind of Change: retrieving the atmospheric structure of exoplanets from high-resolution transmission spectroscopy

The sodium doublet in the optical is one of the most powerful probes of exoplanet atmospheric properties, when observed in transmission spectroscopy during transits. Recent high-spectral resolution observations of the sodium doublet in hot gas giants allowed us to resolve the line shape, opening the way for extracting thermospheric properties using line-profile fitting.
I will present the latest results from the HEARTS survey for hot exoplanetary atmospheres at high-spectral resolution with HARPS and HARPS-N (Seidel et al. 2019a, submitted to A&A) which found a strongly broadened sodium doublet in the ultra-hot Jupiter WASP-76b. I interpret the findings via a retrieval method exploiting the resolution of the line profile to determine the temperature-pressure profile and the velocity of high-altitude winds in the thermosphere of WASP-76b and similar planets. The method could be applied to the whole sample of planets from the on-going HEARTS & SPADES survey for hot exoplanetary atmospheres at high-spectral resolution with HARPS and HARPS-N, and to the observations with next generation spectrographs like ESPRESSO. With the thus determined temperature-pressure profile and velocity of high-altitude winds I will create a clearer picture of the impact of winds and stellar irradiation on planetary upper atmospheres (Seidel et al. 2019b, in prep.).

Sergeev Denis - oral
University of Exeter

Simulations of moist convestion on exoplanets

On extrasolar planets, many aspects of non-rotating atmospheric dynamics, such as convection, play a crucial role in determining circulation regimes and ultimately their potential habitability. A few previous studies have already hinted at the importance of choosing the convective parameterisation scheme for correct estimates of the onset of runaway greenhouse effect on exoplanets.
Broadly, my research aims at a better understanding of the interaction between convective processes, different cloud condensates, and the large-scale state of the surface on terrestrial planets. While there are plenty of in-situ and remote observations on Earth to constrain and validate convection parameterisation schemes, no such measurements are available for exoplanets yet. Hence the next best option is to run convection-resolving simulations in a limited-area domain, which in turn can be compared to global model output and used to tune convective parameterisations.
I address these questions by employing the latest version of the UK Met Office Unified Model, adapted for exoplanet simulations; in the so-called nesting suite set-up allowing for a seamless approach to atmospheric modelling at different scales. Sensitivity simulations with parameterised or explicitly resolved convection are carried out for a range of temperature regimes, stellar parameters, planet rotation rates, atmospheric compositions.

Shaefer Laura – oral
Stanford Earth, University of Stanford

Magma Oceans

Magma oceans are a stage of rocky planetary evolution in which much of the planet is molten. Volatiles are soluble in the silicate melt that makes up the bulk of the planet, making atmosphere-interior exchange extremely important for the atmospheric evolution in this stage of planet formation. Magma oceans in the Solar System were likely short-lived (~1-5 Myr for Earth, 50-100 Myr for Venus), but this is likely not true for the currently known exoplanet population. Most known rocky exoplanets are inwards of the runaway greenhouse boundary, indicating that a substantial atmosphere could produce a surface magma ocean, even for exoplanets with equilibrium temperatures below 1000 K. I will discuss the range of magma ocean planets that may be in our current sample and some of the implications for atmospheric composition and long-term evolution of these planets. Atmospheric erosion of these planets may leave them significantly different in bulk composition than the planets of our Solar System. I will discuss aspects of atmosphere-magma ocean exchange, mantle influence on atmospheric composition, and atmospheric escape.

Showman Adam - oral
University of Arizona

Oscillations in Gas Giants

Brown dwarfs and directly imaged giant planets exhibit significant evidence for active atmospheric circulation, which induces a large-scale patchiness in the cloud structure that evolves significantly over time, as evidenced by infrared light curves and Doppler imaging maps. These observations raise critical questions about the fundamental nature of the circulation, its time variability, and the overall relationship to the circulation on Jupiter and Saturn. Jupiter and Saturn themselves exhibit numerous robust zonal (east-west) jet streams at the cloud level; moreover, both planets exhibit long-term stratospheric oscillations involving perturbations of zonal wind and temperature that propagate downward over time on timescales of ~4 years (Jupiter) and ~15 years (Saturn). These oscillations, dubbed the Quasi Quadrennial Oscillation (QQO) for Jupiter and the Semi-Annual Oscillation (SAO) on Saturn, are thought to be analogous to the Quasi-Biennial Oscillation (QBO) on Earth, which is driven by upward propagation of equatorial waves from the troposphere. To investigate these issues, we here present global, three-dimensional, high-resolution numerical simulations of the flow in the stratified atmosphere—overlying the convective interior—of brown dwarfs and Jupiter-like planets. The effect of interior convection is parameterized by inducing small-scale, randomly varying perturbations in the radiative-convective boundary at the base of the model. Radiative damping is represented using an idealized Newtonian cooling scheme. In the simulations, the convective perturbations generate atmospheric waves and turbulence that interact with the rotation to produce numerous zonal jets. Moreover, the equatorial stratosphere exhibits stacked eastward and westward jets that migrate downward over time, exactly as occurs in the terrestrial QBO, Jovian QQO, and Saturnian SAO. This is the first demonstration of a QBO-like phenomenon in 3D numerical simulations of a giant planet.

Spring Eleanor - poster
University of Amsterdam

Constraining 51 Pegasi b’s albedo & radius by searching for reflected light with high-resolution spectroscopy

The detection of the stellar light reflected by an exoplanet can provide a wealth of insight into that planet's atmosphere, internal heat and fundamental structure. Unfortunately such a signal is challenging to isolate, and the reflected light has only previously been detected a couple of times in the optical regime. Highly-resolved spectral data, however, reveal a finely spaced forest of molecular lines. The reflected spectrum from an orbiting exoplanet is far more significantly Doppler shifted than that of its relatively stationary parent star. At high resolution, the spectral lines are deep and sharp enough that the Doppler shifted spectrum reflected from an exoplanet can be disentangled from the stellar spectrum. Thus high resolution spectroscopy offers the possibility of extracting the elusive stellar reflection - and insights into the composition and structure of the exoplanet itself.
There is a necessity to perfect robust methods for characterising planetary atmospheres, including composition, structure and dynamics. Happily, when a star's reflection is captured from a planetary mirror, that planet's signature will be written into the light. I am using high-resolution data from HARPS-N of 51 Pegasi b - the first exoplanet and hot Jupiter ever discovered orbiting a Sun-like star. 51 Peg does not transit, therefore this high resolution method offers a new means of detecting the planet's signal and learning about its atmosphere. By cross correlating my data with models I can test the presence of a planetary signal to very high significance - drawing this planetary mirror out of the darkness.

Tan Xianyu - poster
University of Oxford

Intrinsic variability in cloudy atmospheres of brown dwarfs and directly imaged extrasolar giant planets

Light-curve variability at infrared wavelengths is common among brown dwarfs over a wide range of spectral types. There has been rich evidence suggesting the strong role of clouds in shaping the thermal structure and spectral properties of atmospheres of brown dwarfs and directly imaged extrasolar giant planets. Radiative cloud effects can also induce intrinsic variability. In this work, we show the spontaneous variability driven by clouds using a time-dependent one-dimensional model that incorporates a self-consistent coupling between the thermal structure, convective mixing, cloud radiative heating/cooling, and condensation/evaporation of clouds. Mechanism responsible for the intrinsic variability as well as sensitivity studies over a wide parameter space will be discussed. Our novel, self-consistent mechanism has important implications for the observed flux variability, especially for objects whose variability evolves on short timescales. It is also a promising mechanism for cloud breaking, which has been proposed to explain the L/T transition of brown dwarfs.

Taylor Jake - poster
University of Oxford

Understanding and Mitigating Biases when Studying Emission Spectra with JWST

Planets are 3D. Current retrieval techniques used to study the atmospheres of exoplanets tend to use 1D models. We present the optimal wavelength region, signal-to-noise and observing modes of JWST/NIRSpec needed to detect 2D effects in a single emission spectrum that has an inhomogeneous temperature structure. We also explore the origins of biases in retrieval and how to best mitigate them as we move into a new regime of space based observations.

Thompson Maggie – oral
University of California, Santa Cruz

Meteorite Outgassing Experiments to Inform Chemical Abundances of Super-Earth Atmospheres

At present, there is no first-principles understanding of how to connect a planet's bulk composition to its atmospheric properties. Since low-mass exoplanets likely form their atmospheres through degassing (Elkin-Tanton & Seager 2008), a logical first step to build such a theory for super-Earths is to assay meteorites, the left-over building blocks of planets, by heating them to measure the outgassed volatiles. Our Solar System presents a wide variety of meteorite types, including chondrites which are primitive unaltered rocks believed to be representative of the material that formed the rocky planets. We present the current results of our meteorite outgassing experiments in which we heated a variety of chondritic meteorite samples at carefully controlled rates to temperatures from 200 to 1200 °C and measured the partial pressures and relative abundances of the outgassed volatile species (e.g., CO2, H2O, CH4, H2, O2, S, Na) as a function of temperature and time. Our experimental set-up consisted of a residual gas analyzer connected to a furnace to heat samples at specified rates. We compare the results of these experiments to Schaefer and Fegley's prior theoretical chemical equilibrium and kinetics calculations which modeled thermal outgassing for a wide variety of chondrites to predict the composition of terrestrial atmospheres formed via outgassing of specific types of meteorites (Schaefer & Fegley 2007, Schaefer & Fegley 2010). In addition to testing and validating Schaefer and Fegley's models, the results from our experiments inform the phase space of chemical abundances used in atmospheric models of super-Earth exoplanets.

Todorov Kamen O. - poster
Universiteit van Amsterdam

Ground-based spectrophotometry of hot Jupiters using the MOS technique.

Transiting exoplanet observations using space-based facilities like HST and Spitzer have revealed the compositions and thermal properties of some of these objects. However, ground-based facilities can also be used successfully for exoplanet spectral characterization studies. Here, we show a visible-light spectrum of the hot Jupiter HAT-P-1b obtained with the ground-based Gemini Multi-Object Spectrograph (GMOS). Looking forward to the upcoming ELT and JWST facilities, we comment on several subtle systematic effects, some unique to Earth-bound transit observations, whose careful treatment is critical to the robustness of our analysis. We compare the transmission spectrum to atmospheric models and interpret the results in terms of the content of alkali metals and the amount of hazes in the atmosphere, placing HAT-P-1b in the broader context of comparative exoplanetology.

Tremblin Pascal - oral
CEA

Thermo-compositional diabatic convection in the atmospheres of brown dwarfs and in Earth's atmosphere and oceans

By generalizing the theory of convection to any type of thermal and compositional source terms (diabatic processes), we show that thermohaline convection in Earth oceans, fingering convection in stellar atmospheres, and moist convection in Earth atmosphere are deriving from the same general diabatic convective instability. We show also that ”radiative convection” triggered by CO/CH4 transition with radiative transfer in the atmospheres of brown dwarfs is analog to moist and thermohaline convection. We derive a generalization of the mixing length theory to include the effect of source terms in 1D codes. We show that CO/CH4 “radiative” convection could significantly reduce the temperature gradient in the atmospheres of brown dwarfs similarly to moist convection in Earth atmosphere thus possibly explaining the reddening in brown-dwarf spectra. By using idealized two-dimensional hydrodynamic simulations in the Ledoux unstable regime, we show that compositional source terms can indeed provoke a reduction of the temperature gradien. The L/T transition could be explained by a bifurcation between the adiabatic and diabatic convective transports and could be seen as a giant cooling crisis: an analog of the boiling crisis in liquid/steam-water convective flows.
This mechanism with other chemical transitions could be present in many giant and earth-like exoplanets. The study of the impact of different parameters (effective temperature, compositional changes) on CO/CH4 radiative convection and the analogy with Earth moist and thermohaline convection is opening the possibility to use brown dwarfs to better understand some aspects of the physics at play in the climate of our own planet.

Tsai Shang-Min - poster
AOPP, Oxford

Photochemical modelling of exoplanet atmospheres in 1D, 2D, and 3D

Determining the chemical composition is the primary focus in atmospheric characterisation. Photochemical models track the kinetics of the gas-phase species and are able to compute the steady-state abundances under the influence of atmospheric dynamics and photolysis. However, the classic 1D models may suffer from neglecting the 3D circulation while applying the model to the diversity of exoplanets. To improve this limitation, I introduce a 2D photochemical model that enables direct implementation of the wind from 3D GCM output. It helps us understand how the composition varies from the hot dayside to the cold nightside and the transition at the terminators. Finally, I apply a simplified chemical relaxation scheme in a 3D GCM of WASP-43b to show the disequilibrium effects of CO, CO2, H2O, and CH4. The chemical relaxation scheme is based on the work of Cooper & Showman 2006, which seeks to enhance the computational efficiency by replacing the chemical network with a handful of independent source/sink terms. The method is validated for the first time against full chemical kinetics calculations and is generalised to CH4, CO, CO2, H2O, NH3, and N2. A pathway analysis tool is also developed to identify the rate-limiting reactions, which allows practical estimation of the chemical timescale.

Turbet Martin – oral
Astronomy, University of Geneva

Modelling Terestrial Targets

As of August 2019, astronomers have already detected about forty temperate exoplanets, with masses or radii or sometimes even both that are similar to the Earth. Most of these recently detected exoplanets -- among which Proxima b, our closest neighbour, and the seven transiting TRAPPIST-1 planets -- are orbiting around nearby, low mass stars. These planets are potentially very important because they are the first terrestrial-type, temperate exoplanets that are and will be suitable for in-depth atmospheric characterization with current and forthcoming telescopes, with a broad range of techniques such as transit spectroscopy, direct imaging, secondary eclipse or thermal phase curves.

I will first review in my presentation the full hierarchy of numerical climate models (from simplified 1-D radiative-convective models to sophisticated, full 3-D Global Climate Models) that have been developed and used over the last years to simulate the possible atmospheres of exoplanets.
I will then review all we have learnt -- at least, all we think we have learnt -- from these modeling efforts applied to the study of temperate, terrestrial-type planets orbiting low mass stars. I will show and discuss how crucial these models are to propose, prepare and interpret future telescopic observations that are likely to lead to the first characterizations of exoplanets similar in size and insolation to the Earth.

Last, I will share my more personal point of view on the future pathways for this modelling work.

Wakeford Hannah – oral
Space Telescope Science Institute, Baltimore

Giants, Rocks, and Giant rocks? Observing Terrestrial Exoplanet targets

In the past three decades over 4,000 exoplanets, planets orbiting stars beyond our solar system, have been discovered. These planets are helping us answer a profound question: How did we get here? By looking beyond our solar system at the structure and composition of exoplanets and their systems we are able to put our planet into a wider context. With the ever-growing number of exoplanets being discovered the main challenge comes in characterising them and understanding the diversity of exoplanet masses, radii, and their atmospheric compositions to better examine their formation, history, and the probability for life. In this talk I will take us through the diversity of characterisable exoplanets. We will explore the current observations of planets below 4 Earth radii and ask questions about their atmospheres, composition, and links to formation. I will discuss the different effects we have to consider when observing small exoplanets orbiting cool stars. I will finish by looking to the future of big telescopes, planned observations, and the search for life in the habitable universe.

Way Michael – oral
NASA Goddard Institute for Space Studies

Modeling Venus-like Worlds Through Time:

What they may tell us about the evolution of Venus's atmosphere over 4Gy, and application to exoVenus worlds. Using a modern three-dimensional general circulation coupled atmosphere/ocean model [1] we recently demonstrated [2] that climatic conditions may have permitted liquid water on Venus' surface for ~2 billion years in its early history. Several assumptions were made based on what little data we have for early Venus such as; the type of solar spectrum extant at that time, orbital parameters, estimates of a shallow ocean from D/H measurements, topography, and atmospheric composition. I will discuss the motivations behind these assumptions and additional parameter space studies with direct relevance to hypothetical exoplanetary Venus-like worlds found at the inner edge of the liquid water habitable zone. Finally, I will show how our studies demonstrate that the reason for Venus' present climatic state is unlikely to be related to the gradual warming of our sun over the past 4Gyr as is commonly believed.

[1] Way, M.J. et al. (2017) Astroph Journ Suppl, 231, 1
[2] Way, M. J., et al. (2016) Geophy Res Lett, 43, 8376

Weller Matt - poster
Current: University of Texas at Austin Institute of Geophysics; at time of conference: Brown University

A Tale of Fire and Ice: Habitability (Life) Potential in a Non-Plate Tectonic World

A key observation is that the Earth exhibits plate-tectonics and a buffered climate allowing liquid water to exist over geologic lifetimes. While we know the Earth operates within plate-tectonics, the timing of its onset, the length of its activity, and its prevalence outside the Earth are far from certain. Recent work suggests that the Earth has not always been within a plate-tectonic regime, and that it has evolved over time. Multiple lines of geochemical and geologic evidence, as well as geophysical models of planetary evolution, suggest the Earth went through an "adolescent" episodic-lid, before settling into a "mature" modern style of plate-tectonics. This implies that life and habitable conditions have existed on the Earth during episodic behavior. Currently, observations of Venus shows no clear evidence of Earth-like plate tectonic activity or surface conditions. Observations of a thick 92 bar atmosphere, surface temperatures of ~740 K, and vast volcanic plains (80% of the surface; emplaced 300 – 1000 Mya), along with inferences of limited large scale shortening, are consistent with suggestions of an episodic-lid regime. If an early episodic Earth could support a habitable climate, what of Earth's "twin", Venus? Could an episodic Venus have been habitable? We assume a proxy climate system, that is Earth-like in land/water distribution and initial surface temperatures, assuming early Earth and Venus are otherwise identical (e.g., not a runaway greenhouse), consistent with inferences from models of planetary evolution and the suggestion of liquid water in Venus' past. In general, distance acts as a proxy for luminosity (time). Therefore, Venus' response at 0.72 AU acts as an older Earth. Increasing pCO_2 for an early Earth distance planet (1 AU) results in an early potential for a snowball state, but an increasing potential for climates that allow for liquid water as the solar luminosity increases (bottom to top branch as the Sun ages. In comparison, Venus type solutions, have a decreased likelihood for temperatures that allow for global glaciations, and instead favor temperatures in the past that allow for liquid water, suggesting early Venus may have had an advantage over the early Earth for predicted surface temperatures, and the potential for liquid water. This work suggests that an episodic Venus has the potential to allow for liquid water, and consequently habitability. If Venus could support life, it suggests a fundamental rethinking of plate-tectonics links to habitability, and how habitable zones are defined, that is Venus is at the edge of the current habitable zone because it currently does not have liquid water, not because it is inherently incapable of having liquid water at present. The potential of a life-bearing Venus illustrates the pressing need to constrain the tectonic and atmospheric evolution of Venus, in order to validate, or refute these ideas. If episodic, as has been recently suggested, blocks of intact surface can survive episodic resurfacing over geologic time scales, indicating that a record of older terrains, formed potentially under different atmospheric and tectonic conditions, are waiting to be discovered at the surface.

Wing Allison - oral
Earth, Ocean & Planetary Science, Florida State University

Convective Aggregation

Convection in Earth's atmosphere organizes on a variety of spatiotemporal scales, from mesoscale systems like squall lines, synoptic scale systems like tropical cyclones, and the planetary scale Madden-Julian Oscillation. There are many processes capable of organizing convection, such as wind shear and sea surface temperature gradients, but here I instead discuss a different type of organization that represents a fundamental instability of tropical climate: "self-aggregation". Convective self-aggregation is the spontaneous organization of convection into one or several long-lasting clusters surrounded by large areas of dry air that occurs despite spatially homogeneous boundary conditions and forcing. This phenomenon is found to occur in idealized numerical simulations configured in a state of radiative-convective equilibrium (RCE), an idealization of the climate in which convection balances the radiative heat loss of the atmosphere. Self-aggregation arises due to interactions between radiation, environmental moisture, circulation, and the convection itself. In this talk, I will briefly review RCE and the spacial characteristics of moist convection, then will describe the physical mechanisms leading to convective self-aggregation and the impact of aggregation on the large-scale energy budget. I will also explore how to relate what we've learned from idealized numerical simulations to Earth's real atmosphere.

Wordsworth Robin – oral
Harvard

Planetary oxidation

Planetary oxidation is critical to the evolution of terrestrial-type atmospheres and consequently to astrobiology and the search for biosignatures. The atmospheres and surfaces of all rocky planets oxidize to some degree due to gravitational differentiation: hydrogen is lost to space and iron moves to the core, leaving more electronegative elements, particularly oxygen, in their wake. Under some conditions, this process may continue until abiotic O2-dominated atmospheres form. To understand this important phenomenon in detail, we have performed the first fully coupled atmosphere-interior modeling of the oxidation of Earth-like planets around different star types. We include atmospheric photochemistry, diffusion and escape, line-by-line climate calculations and interior thermodynamics and chemistry, which allows self-consistent calculation of a planet's atmospheric and mantle redox state as a function of time. We find that planets that receive a low stellar flux and/or have high H2O, N2 and mantle Fe inventories are least likely to build up abiotic O2 atmospheres. In particular, the transiting exoplanets LHS1140b and TRAPPIST-1f and g have low probability of abiotic O2 buildup via water loss, making them important future targets for ground-based biosignature searches. Furthermore, our predictions for hotter planets such as GJ1132b provide a way to test our model via observations in future, without the confounding influence of a possible biosphere on the results.

Wyttenbach Aurélien - poster
Leiden University

CHESS: CHaracterization of Exoplanetary and Stellar Spectra

KELT-9 b (the hottest known hot Jupiter) is the archetype of the new class of ultra hot Jupiter (Teq>2000-2500 K). These planets are thought to be in chemical equilibrium and for the hottest one to have an atmosphere dominated by neutral and ionized atomic species, such as FeI, FeII, TiI, TiII, etc., some of which were recently detected in KELT-9 b. Recently, H and H have also been detected in the KELT-9 b atmosphere. Particularly, the H absorption hints that the hydrogen is filling the planetary Roche lobe and can escape from the planet, confirming that such object undergoes evaporation. In this work, we study the Balmer lines (H to H) in the optical transmission spectrum of KELT-9 b obtained with the HARPS-N spectrograph. We found significant absorptions for H, H and H, and hint of absorption for H. The absorptions level of those lines allowed us to put new constraints on the hydrogen population in the KELT-9 b atmosphere, on its temperature and its evaporation rate.

Zhang Xi - poster
University of California Santa Cruz

Large Eddy Simulation of Cloudy Atmospheres on Exoplanets and Brown Dwarfs

Large Eddy Simulation of Cloudy Atmospheres on Exoplanets and Brown Dwarfs
Xi Zhang (UC Santa Cruz), Tianhao Le (Caltech), Cheng Li (Caltech)
Clouds significantly influence the thermal structure and dynamics in planetary and brown dwarf atmospheres. Current 1D radiative-convective models with cloud formation assume diffusive tracer transport, but the assumed vertical diffusivity is largely uncertain. Here we present a new framework to investigate cloud formation and its impact on the atmospheric structure without the prescribed eddy diffusivity. We perform large eddy simulations on radiative-convective atmospheres using a local 3D non-hydrostatic model with a fine horizontal resolution including moist convection, simple cloud formation microphysics, and multi-scattering radiative transfer. We show preliminary results of Mg_2SiO_3 cloud formation and time evolution. Cloud feedback is found to play an important role in regulating the thermal structure and dynamics on those atmospheres and thus the interpretation of their observed light curves and spectra.