PLANETS DAY 2025

Meeting programme

08:45 – 09:15	Badge collection and coffee	
09:15 – 09:20	Welcome address	
09:20 – 10:00	**Theme 1** How can we understand complexity with necessarily-simple astrophysical observations?	*Chair:* Carly Howett *Speaker:* Jayne Birkby *Panel:* Jayne Birkby, Raymond Pierrehumbert, Bethan Gregory
10:00 – 10:40	**Theme 2** How are the building blocks of life delivered to and retained on planets?	*Chair:* Carly Howett *Speaker:* Claire Nichols *Panel:* Claire Nichols, Jon Wade, Benjamin Hess, Julie Cosmidis
10:40 – 11:10	Coffee	
11:10 – 11:50	**Keynote talk**	*Chair:* Tim Barraclough *Speaker:* Nick Lane
11:50 – 12:30	**Theme 3** What nano-scale physics underpins the origin and evolution of both unicellular and multicellular life forms?	*Chair:* Tim Barraclough *Speaker:* Sonia Antoranz Contera *Panel:* Sonia Antoranz Contera, Jon Bath
12:30 – 13:40	Lunch – Hall	
13:40 – 14:20	**Theme 4** How does life drive planetary evolution, and vice versa?	*Chair:* Andrew Davison *Speaker:* Ros Rickaby *Panel:* Ros Rickaby, Tamsin Mather
14:20 – 15:00	**Theme 5** To what extent is the co-evolution of life and planet driven by random chance?	*Chair:* Andrew Davison *Speaker:* Tim Coulson *Panel:* Tim Coulson, Frankie Dunn, Tim Barraclough
15:00 – 15:40	Collaboration activity part one	
15:40 – 16:00	Coffee	
16:00 – 17:00	Collaboration activity part two	
17:00	Poster reception	

Venue information

Cheng Kar Shun Digital Hub, Jesus College
Entrance (X) via Market Street (step free)
what3words: costs.stars.atoms
https://www.accessguide.ox.ac.uk/jesus-college

Talk abstracts

KEYNOTE

Revolution by Natural Selection: An astrobiological history of life from the inside

Nick Lane
Professor of Evolutionary Biochemistry
Director, UCL Centre for Life's Origins and Evolution

Complex (eukaryotic) cells arose just once in four billion years of life on Earth. This singularity cannot be explained by a simple exploration of genetic sequence space. I will show that the peculiar nature of membrane bioenergetics constrained the origin of life, the evolution of prokaryotes, and the singular emergence of eukaryotic complexity. The same principles likely apply to the origins of life on any of the ~40 billion wet, rocky planets in the Milky Way.

How can we understand complexity with necessarily-simple astrophysical observations?

Jayne Birkby
Associate Professor of Exoplanetary Science
Dept. of Physics – Astrophysics, University of Oxford

The search for life on other worlds has revealed an extraordinary and diverse population of planets. Planet formation creates numerous classes of planets, many with no analogue in our Solar system, from molten lava worlds, to enigmatic sub-Neptunes shrouded in hazes hosting possible liquid oceans, and to far-flung gas giants with the promise of potential icy moons. Despite this richness, most astronomical observations have to extract the information they need from a single pixel on a detector. In this talk, I'll give an overview of the observational data for planets beyond our Solar system and the information we can deduce from these necessarily simple observations, while contrasting this with the more detailed information we have obtained on Solar System planets from orbiters and landers.

How are the building blocks of life delivered to and retained on planets?

Claire Nichols
Associate Professor of the Geology of Planetary Processes
Dept. of Earth Sciences, University of Oxford

In order to understand how uniquely habitable Earth is, it is important to understand the planetary conditions required for the origins of life. The correct prebiotic chemistry must be available, as well as liquid water and a reduced atmosphere. Lightning strikes, meteorite impacts and igneous activity have all been proposed as important mechanisms for creating the right ingredients for life to begin. The origin of Earth's water remains debated, with some arguing that it can be exclusively supplied by a primordial hydrogen atmosphere while several lines of evidence suggest delivery from meteorites and (to a lesser extent) comets. Today, Earth's atmosphere is rich in oxygen, allowing complex life to thrive on the planet. However, in its past the atmosphere was highly reduced, with a composition dominated by hydrogen and methane. The reason for such a drastic shift in atmospheric composition is multi-faceted and in particular, the role of the magnetic field in mediating this process remains unknown. This talk will explore some of the current debates and remaining challenges in determining the planetary conditions required for life to emerge, take-hold and thrive and why, for now at least, Earth appears to be uniquely inhabited.

What nano-scale physics underpins the origin and evolution of both unicellular and multicellular life forms?

Sonia Antoranz Contera
Professor of Biological Physics
Dept. of Physics – Condensed Matter Physics, University of Oxford

The transition from unicellular to multicellular life was a crucial evolutionary step, enabling complex organisms like plants and animals to develop. While most studies focus on genetics and environmental influences, physics also plays a key role. The shapes of biological tissues result from interactions between physics, chemistry, and genetics, which control mechanical properties across different scales. Our study demonstrates that plant growth dynamics can be derived using the Onsager principle of non-equilibrium thermodynamics. We tested our theoretical predictions against experimental data in plants, revealing that stable multicellular growth and shape are constrained by specific energy gradients. Our findings suggest that plants can only grow and maintain stability within defined thermodynamic limits.

How does life drive planetary evolution, and vice versa?

Ros Rickaby
Chair of Geology, University College
Dept. of Earth Sciences, University of Oxford

Life and the planet's chemical environment are united in an inescapable feedback cycle. The presence of life in whatever form, involves a natural feedback cycle inherent to the complex system that is Earth. Evolutionary invention creates new waste, and this waste modifies the environment in ways that are challenging for contemporaneous life. Even oxygen, the by-product of the reductive chemistry of life, was initially toxic to the prevailing anaerobes. Together with energy, evolution finds a solution to manage and use that waste for new life chemistry, which then itself generates novel waste and so on: the drive for increasing complexity. This talk will explore the inevitability of the course of the chemical evolution of life and a planet, different strategies for life to adapt to changing environments and whether life can be thought of as stabilising or destabilising to the planet or life itself.

To what extent is the co-evolution of life and planet driven by random chance?

Tim Coulson
Professor of Zoology
Dept. of Biology, University of Oxford

The abiotic conditions on the earth were just right for life to emerge. Early life didn't have a significant impact on Earth, but as it gained in complexity and diversified it did. Stochasticity has played a key role in the coevolution of life and the planet, and I will provide some examples during this talk.

<u>Circulation models and simulated phase curves of WASP-76b</u>

John Allen
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

This study investigates the effect of varying internal heat flux and atmospheric drag on the observable properties of WASP-76b, showing the results of General Circulation Models (GCMs) and simulated phase curves to be compared with brand-new *James Webb Space Telescope (JWST)* data. We conduct a suite of GCMs, which solve the primitive equations of meteorology coupled to non-grey correlated-k radiative transfer with the SPARC/MITgcm. We represent the effect of Lorentz forces by changing a spatially constant drag timescale, and we vary the internal temperature across a range of predicted values for hot and ultra-hot Jupiters. We find that strong drag inhibits day-night heat transport, and the internal heat flux has a smaller effect on the observable properties of WASP-76b than atmospheric drag. We post-process our GCMs using the gCMRT radiative transfer code to produce simulated phase curves for comparison with new Cycle 3 *JWST/NIRSpec* data. This study builds on the work of May & Komacek et al. (2021) by incorporating non-grey radiative transfer through the SPARC scheme, helping to deepen our understanding of the effect of internal heat fluxes and atmospheric drag on the observable properties of ultra-hot Jupiters. We further compare our GCMs with an analytic model building upon our understanding of overturning circulations on Earth but applied to hot Jupiters. We model the divergent flow of the circulation of WASP-76b by coupling a heat engine model to the Held-Hou model for Hadley circulation, which is compared to the GCM outputs. The effect of atmospheric drag on this overturning circulation is further investigated by decomposing the GCM output for the planetary winds into their rotational and divergent components. This work further deepens our understanding of the atmospheric dynamics of hot and ultra-hot Jupiters by combing both large computationally intensive simulations and analytic theory.

<u>Exoplanetary ionospheres</u>

Richard D. Chatterjee
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

The pattern of airy and airless rocky planets presently being uncovered by the *James Webb Space Telescope* is a record of how ionospheres are pushed to the limits of survival by ionising radiation from their host stars. Orbiting as close to a red dwarf as the Parker Solar Probe's orbit that "touched" the Sun, a super-Earth could harbour liquid water oceans beneath an ionosphere much hotter than the host star's photosphere, exhibiting spectacular airglow and aurora. How prominent is this juxtaposition of potentially habitable surface climates and extreme space weather? I'll present results on the dynamics and escape of high-molecular-weight ionospheres, a key unknown for the Rocky Worlds Director's Discretionary Time (DDT) survey.

Magnetic monitoring of natural hydrogen production

Red Coleman
Dept. of Earth Sciences, University of Oxford

The hydrothermal alteration of mafic and ultramafic rock generates significant fluxes of hydrogen. These serpentinization reactions are central to the current origin of life hypothesis and may play an important role in the emergence of modern habitable planetary conditions. Unfortunately, the flux of hydrogen produced during serpentinization remains poorly defined. Reported rates of reaction in the literature vary by several orders of magnitude and fails to identify key reaction controls. This precludes an effective understanding of the impact and significance of the hydrogen flux produced during serpentinization.

Efforts to better constrain serpentinization, both in the lab and in the field, are often contradictory because of the slow reaction rates and high detection limits of hydrogen that make actively monitoring these reactions technically extremely challenging. To better understand serpentinization and its potential to impact planetary conditions, we must first be able to effectively track reaction progress.

The precipitation of magnetite, one of the reaction products, offers a novel approach to monitor the reaction rate. As reaction progresses the increasing magnetic moment of the capsule may be monitored providing a cheap, non-intrusive, and high-resolution technique to constrain serpentinization. This will allow the rate of reaction and key controls to be defined.

Isotopic clues to planetary origins: Tracing magnesium and silicon fractionation in early magma oceans

Bram de Winter
Dept. of Earth Sciences, University of Oxford

Silicon (Si) and magnesium (Mg) are two major building blocks of rocky planets, yet Earth's mantle is isotopically heavier in these elements compared to chondrites—the primitive materials from which planets are thought to have formed. While core formation and vapour loss have been proposed as explanations for this disparity, an alternative mechanism lies in the deep mantle: small-scale heterogeneities formed during magma ocean crystallization. Equilibrium isotope fractionation during this process could sequester lighter isotopes in hidden reservoirs, making them inaccessible in surface samples. In this study, we combine experimental and theoretical approaches to explore how Mg and Si isotope systematics can reveal new insights into the deep interior of our planet and its early evolution. Our findings provide a perspective on the role of magma oceans in shaping Earth's chemical and isotopic architecture.

Did the Eagle Station parent body generate a magnetic field?

Brandon Fish
Dept. of Earth Sciences, University of Oxford

Recent analysis of the metallic matrix of Oued Bourdim 001, the most recently added member of the Eagle Station Pallasite group, has revealed numerous regions of the "Cloudy Zone" microstructure. In the presence of a magnetic field, the "cloudy zone" may acquire a chemical transformation remanent magnetization (cTRM) through the spontaneous formation of single-domain islands of ferromagnetic tetrataenite during extremely slow sub-solidus cooling through 320°C. New cooling rate data acquired for Oued Bourdim 001 has revealed that the Eagle Station pallasites cooled over a range (8–21 KMa^{-1}) that places them in ideal conditions to record the paleomagnetic signature of a potential dynamo. If the Eagle Station parent body had a sufficiently large and convecting inner liquid core, its paleomagnetic signature may have been recorded during the formation of the cloudy zone.

Since a paleofield can only be recorded with sufficient distance away from its source, evidence of a paleomagnetic signature would indicate a formation mechanism far from the core-mantle boundary (CMB). However, if a stony-iron fragment formed at or near the CMB, it would be impossible to record a paleomagnetic signature due to its close proximity to the convecting core. The presence or absence of a recorded paleofield in Eagle Station pallasites would provide a major constraint in determining the possible formation mechanisms of the Eagle Station pallasites, size of the parent body core, and whether or not a magnetic field was generated in the Eagle Station parent body.

Modelling the influence of oxidative chemistry on trace gases in Mars' atmosphere

Bethan Gregory[1], Kevin S. Olsen[1], Ehouarn Millour[2], Megan Brown[3]
[1]*Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford*
[2]*Laboratoire de Météorologie Dynamique (CNRS/UPMC/IPSL)*
[3]*Centre for Atmospheric Science, University of Cambridge*

The *ExoMars Trace Gas Orbiter (TGO)*, operating since 2018, has detected and characterised trace gases in the Martian atmosphere over several Mars years. It has constrained upper limits of potential constituents, improved the accuracy of species concentration measurements, and observed seasonal and spatial variations in the atmosphere. The wealth of data it has obtained has addressed several key open questions about the nature of Mars' atmosphere, while other measurements have revealed much that remains poorly understood.

Here, we use the Planetary Climate Model—a 3D global climate model that includes a photochemical network—to explore some *TGO* observations that require new atmospheric photochemical interactions. These include the spatial and temporal variability of hydrogen chloride (HCl)—the first new gas detected by *TGO*—which has been investigated recently using the mid-infrared channel on *TGO*'s Atmospheric Chemistry Suite. Observations show a strong seasonal dependence of HCl in the atmosphere, with almost all detections occurring during the latter half of the year between the start of dust activity and the southern hemisphere autumnal equinox. We will investigate potential source and sink mechanisms accounting for this pattern, beginning with the role of heterogeneous chemistry involving ice and dust aerosols, which affects the abundances of oxidative species such as OH, HO_2, O, and O_3, as well as potentially serving as a mechanism for direct release and sequestration of HCl from the atmosphere. We will also explore potential mechanisms behind the annual occurrence of spatially-constrained aphelion HCl, and investigate the interplay between chlorine-bearing species and OH, HO_2, O, and O_3.

Understanding the role of oxidative chemistry on HCl and other trace gases is key to achieving a more complete picture of processes occurring in the present-day Mars atmosphere, as well as processes that have shaped its evolution and habitability.

Tidal heating and habitability in tightly-packed planetary systems

Hamish Hay
Dept. of Earth Sciences, University of Oxford

Significant internal tidal heat generation is available to bodies in tightly-packed planetary systems, due to close proximity to a star/planet, and the orbital excitation induced by mean-motion resonances with neighbouring objects. The prime example of this is Jupiter's moon Io, with ancient, global volcanism driven by tidal deformation, which is controlled by orbital interactions with the other Galilean satellites. I will review approaches to determining the tidal heat generation of planetary bodies, including those with fully- and partially-molten interiors. I will describe an appropriate method to apply these tidal heating models to exoplanetary systems, where crucial details of the rheology and thermal state of these planets is often lacking. Finally, this poster will describe the implications of tidal heating, as one of the few universal internal heating mechanisms available to planets, for the habitability of terrestrial and ocean planets and moons.

Interstellar object chemodynamics

Matthew Hopkins
Dept. of Physics – Astrophysics, University of Oxford

The Milky Way is thought to host a huge population of interstellar objects (ISOs), numbering approximately 10^{15} per cubic parsec in the vicinity of the Sun, formed and shaped by a diverse set of processes ranging from planet formation to Galactic dynamics. This range of dependences mean that the ISO population that will be observed by the *Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST)* can be compared to predictions to test hypotheses in both planetary and Galactic physics. We present a novel prediction of the composition and velocity distribution of the ISO population in the Solar neighbourhood, made by combining a protoplanetary disk chemical model with measurements of stellar metallicities and velocities from *Gaia*. The predicted distribution is compatible with the known properties of the current observed ISO population, 1I/'Oumuamua and 2I/Borisov. Similar to the stars they formed around, ISOs show a correlation between dynamics and composition, with water-poor ISOs from thin disk stars having a lower velocity dispersion than water-rich ISOs from thick disk stars. The Sun's motion relative to the local standard of rest causes water-poor ISOs to cluster around the Solar apex; this correlation has important implications for the *LSST* selection function which depends on both velocity and composition. Studying the properties of the ISO population discovered by *LSST*, informed by *Gaia*, provides a chance of novel constraints on the Milky Way's history of star and planet formation.

Thermal surface mapping of Europa using *Galileo* PPR

Sarah Howes
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

Europa is an ice-covered Galilean moon, with evidence of housing an ocean underneath its thick ice shell – a potential site for habitability in our Solar System. One of the key criteria for habitability in this environment is energy transport between the surface and interior, which can be observed during thermal surface measurements as local hotspots. Using data from *Galileo*'s photopolarimeter-radiometer (PPR) instrument, we map the variance in brightness temperature, thermal inertia, and bolometric albedo across Europa's surface in order to search for possible regions of endogenic heating. In addition, we perform a sensitivity study by adding synthetic thermal anomalies to the data in order to investigate the detection limits of the PPR instrument. This study will aid in constraining the extent of thermal activity within Europa's recent geological history and prepare for future missions to the Galilean satellite, such as *Europa Clipper*.

Lunar tides of a molten iron core beneath a basal magma ocean

Murray Kiernan, Richard Katz, Hamish Hay, David Rees Jones, James Bryson
Dept. of Earth Sciences, University of Oxford

The tidal potential of an orbiting moon can perturb the immiscible interface between a liquid metal core and a basal magma ocean, driving flows within the core. Could such flows provide the turbulent kinetic energy required to drive a dynamo and create a magnetic field? We derive and analyse a theory for such flows, predicting sharply shearing boundary layers. This may provide a mechanism for the geodynamo early in Earth history, prior to formation

of the inner core. It may be relevant for planetary bodies large enough to form a basal magma ocean and where one or more moons is present.

Simulating the climates and thermal emission of prime nearby temperate rocky exoplanet candidates

Tad Komacek
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

A panoply of habitable worlds orbiting M dwarf stars exist in our galaxy. A subset of those that are nearby are pristine targets for the NASA *James Webb Space Telescope* and upcoming ground-based Extremely Large Telescopes (ELTs) and future space mission concepts including *MIRECLE*, the *Habitable Worlds Observatory*, and eventually the *Far-IR Surveyor* and *LIFE* flagships. The upcoming observational characterization of these planets necessitates the development of detailed theoretical expectations for their atmospheric conditions, including composition, thermal structure, cloud cover, and resulting observable properties. We have simulated the atmospheric circulation and climate of a set of seven prime temperate rocky exoplanets, including LP 890-9c, TRAPPIST-1e, GJ 1002b, Proxima Centauri b, Wolf 1069b, GJ 1061d, and Teegarden c. Specifically, we conducted three ExoCAM General Circulation Model simulations for each planet assuming spin-synchronization for varying partial pressures of carbon dioxide (2 bars, 0.1 bars, and 1e−4 bars), assuming 1 bar of background N_2. We find that the simulated climates of these exoplanets differ strongly depending on their instellation and CO_2 complement, with especially large changes in the spatial extent and optical thickness of water cloud coverage. We then post-processed these ExoCAM simulatons with the Planetary Spectrum Generator (PSG) to predict thermal emission phase curves and spectra for each object with a *MIRECLE*-like mid-infrared observatory. We predict strong CO_2 features for three targets, Proxima Cenaturi b, GJ 1061d, and GJ 1002b, that would be detectable with a *MIRECLE*-like observatory in 30 days of observation regardless of the partial pressure of carbon dioxide. We additionally find that CO_2 could be detectable on Teegarden c and Wolf 1069b if the partial pressure of CO_2 is sufficiently high, greater than approximately 0.1 bars. Our findings imply that characterization of nearby non-transiting temperate planets in mid-infrared thermal emission can reveal their atmospheric composition and climate state.

Primordial or modern features? Insights into lowermost mantle composition and mineralogy from seismic tomography

Justin Leung[1], Andrew M. Walker[1], Paula Koelemeijer[1], Federica Restelli[2], D. Rhodri Davies[3]
[1]*Dept. of Earth Sciences, University of Oxford*
[2]*Dept. of Earth Sciences, Royal Holloway University of London*
[3]*Research School of Earth Sciences, The Australian National University*

Large low velocity provinces (LLVPs) are seismically dominant features in Earth's lowermost mantle, but their detailed thermochemical nature remains a topic of discussion. Seismic observations to characterise the thermochemical nature of LLVPs are further complicated by the mineral phase transition of bridgmanite to post-perovskite, but due to large uncertainties in mineral physics, the details of this phase transition and its seismic expression remain uncertain. Robust constraints on the origin of these lowermost mantle structures would shed light on large-scale dynamic processes in the mantle, with implications on the thermal and dynamic evolution of the planet. Few studies have examined the combined effects of both chemical heterogeneity and phase transitions on lowermost mantle seismic signatures. Here, we investigate the tomographic signatures expected from a range of scenarios for the stability of post-perovskite within models of different lowermost mantle temperatures and compositions. We calculate synthetic velocity fields from existing temperature and compositional fields as predicted by geodynamic simulations and recent thermodynamic data. These are filtered to account for the limited resolution of seismic tomography, allowing us to quantitatively compare predicted and observed seismic tomography models. By rejecting synthetic velocity models that do not fit within the uncertainties of the Backus-Gilbert based model of Restelli et al. (2024; EPSL), we quantitatively show the following: (i) velocity anomalies cannot be entirely explained by LLVPs with a primordial composition; and (ii) ratios and correlation of velocity anomalies require bridgmanite and post-perovskite to co-occur at depth in the mantle. This implies that the effects of post-perovskite need to be accounted for when modelling dynamic processes in the deep mantle.

Thermal modelling of a binary asteroid flyby: How Selam's presence changed *Lucy*'s encounter with Dinkinesh

Duncan Lyster
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

The Lucy mission's first asteroid flyby provided a unique and unexpected opportunity to study a binary asteroid system up close. Originally expected to encounter a single target, Dinkinesh, the discovery of its small moon, Selam, introduced additional opportunity and complexity to the flyby observations. We present thermal modelling of the system, quantifying how the presence of Selam influenced radiance measurements and its possible impact on thermal inertia estimates. Modelling the flyby geometry and instrument measurements using the new TESBY module of TEMPEST, we simulate expected thermal radiance from both bodies and assess their combined effect on *L'TES (Lucy Thermal Emission Spectrometer)* data interpretation. Our results demonstrate the importance of considering complex geometry in flyby planning and analysis, informing analysis techniques for upcoming encounters such as the flyby of asteroid DonaldJohanson on 20 April 2025. This work highlights how even a small moon can significantly impact spacecraft observations, shaping our understanding of asteroid surface properties and thermal environments.

Convective shutdown in the atmospheres of lava worlds

Harrison Nicholls
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

Atmospheric energy transport is central to the cooling of primordial magma oceans. Theoretical studies of atmospheres on lava planets have assumed that convection is the only process involved in setting the atmospheric temperature structure. This significantly influences the ability for a magma ocean to cool. It has been suggested that convective stability in these atmospheres could preclude permanent magma oceans. We develop a new 1D radiative-convective model in order to investigate when the atmospheres overlying magma oceans are convectively stable. Using a coupled interior-atmosphere framework, we simulate the early evolution of two terrestrial-mass exoplanets: TRAPPIST-1 c and HD 63433 d. Our simulations suggest that the atmosphere of HD 63433 d exhibits deep isothermal layers which are convectively stable. However, it is able to maintain a permanent magma ocean and an atmosphere depleted in H_2O. It is possible to maintain permanent magma oceans underneath atmospheres without convection. Absorption features of CO_2 and SO_2 within synthetic emission spectra are associated with mantle redox state, meaning that future observations of HD 63433 d may provide constraints on the geochemical properties of a magma ocean analogous with the early Earth. Simulations of TRAPPIST-1 c indicate that it is expected to have solidified within 100 Myr, outgassing a thick atmosphere in the process. Cool isothermal stratospheres generated by low molecular-weight atmospheres can mimic the emission of an atmosphere-less body. Future work should consider how atmospheric escape and chemistry modulates the lifetime of magma oceans, and the role of tidal heating in sustaining atmospheric convection.

Tackling supergranulation in Earth-twin surveys using the *HARPS-N* solar data

Niamh O'Sullivan
Dept. of Physics – Astrophysics, University of Oxford

In recent years supergranulation has emerged as one of the biggest challenges for the detection of Earth-twins in radial velocity (RV) planet searches. Supergranulation introduces RV variations on timescales of 1-2 days with amplitudes of 0.5-1 m/s, considerably larger than the expected 10 cm/s signal from Earth-like planets. I will use Gaussian Processes (GPs) applied to the *HARPS-N* solar data sets, and show how supergranulation varies in phase with the activity cycle of the Sun. I will also discuss observational strategies that can be employed to characterize supergranulation in other stars, a critical step in the search for Earth-twins. Finally, I will show that by modelling the supergranulation signal in this way, we can improve the detection of planets with smaller RV signals, bringing us closer to identifying Earth-like exoplanets.

Characterising exoplanet atmospheres in the M-band as a pathfinder for biosignatures with the extremely large telescope

Luke Parker
Dept. of Physics – Astrophysics, University of Oxford

High resolution spectroscopy (HRS; R~100,000) combined with adaptive optics on the worlds largest optical telescopes has been enormously successful in advancing our knowledge of exoplanet atmospheres. This powerful technique has explored the atmospheric chemistry, rotation, and dynamics of Jupiter-mass exoplanets in detail. Pushing this characterisation to Earth-mass planets is now the most ambitious science cases for the Extremely Large Telescopes (ELTs), which will see first light by the end of the decade. This will include the search for biosignatures (e.g. CO_2, H_2O, and CH_4) between 3-5 μm (M-band) in the atmospheres of the nearest rocky exoplanets with first-light instruments such as *METIS/ELT*. However, HRS beyond 3.5 μm presents significant challenges from thermal background noise and telluric contamination from the Earth's spectral features. We present ongoing projects to explore this spectral range prior to first light of the ELTs. First, we show *CRIRES+/VLT* R=100,00 M-band observations of the archetypal young giant exoplanet beta Pic b, detecting CO and H_2O in its atmosphere, and measure the planet spin rate, demonstrating the potential of HRS in the M-band. Second, we present the first results from a survey of directly imaged planets at M-band wavelengths, aiming to detect gaseous SiO in their atmospheres. SiO has distinct spectral features in the M-band and acts as both a probe of clouds and condensation, and as a tracer of the accretion history of giant exoplanets. This work paves the way for the ELT which, with its superior spatial resolution and collecting area, will allow HRS in the M-band to push to the characterisation of rocky exoplanets, from lava planets to potentially habitable worlds.

Anti-diffusive transport of angular momentum and super-rotation in planetary atmospheres

Peter Read
Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics, University of Oxford

Observations show that most known planetary atmospheres tend to rotate faster on average than their underlying planet. In practice this may be manifest as a global and/or localised excess of angular momentum compared with the corresponding value obtained in co-rotation with the bulk of the planet. Excesses of angular momentum are typically quite small for rapidly rotating planets such as the Earth (around a few per cent) but can be very large (O(10)) for slow rotators such as Venus or Titan. Such a phenomenon cannot be consistent with down-gradient diffusive transport of angular momentum and depends on strongly counter-gradient, anti-diffusive transport due to nonlinear wave-zonal flow interactions. We review a range of possible mechanisms for atmospheric super-rotation and present some recent work which attempts to develop scaling arguments to account for variations with parameters such as planetary size and rotation rate.

The Weird and the Wonderful in Our Solar System with the *Vera C. Rubin Observatory*

Brian Rogers
Dept. of Physics – Astrophysics, University of Oxford

We present a novel method for anomaly detection in solar system object data in preparation for the *Legacy Survey of Space and Time* to be carried out at the *Vera C. Rubin Observatory*. We train a deep autoencoder for anomaly detection and use the learned latent space to search for other interesting objects. We demonstrate the efficacy of the autoencoder approach by finding interesting examples, such as interstellar objects, and show that by using the autoencoder, further examples of interesting classes can be found. We also investigate the limits of classic unsupervised approaches to anomaly detection through the generation of synthetic anomalies and evaluate the feasibility of using a supervised learning approach.

Unlocking planetesimal water contents using their dynamo generation histories

Hannah Sanderson
Dept. of Earth Sciences, University of Oxford

In the early Solar System, planetesimals formed in two distinct reservoirs: non-carbonaceous (NC) in the inner Solar System and carbonaceous (CC) in the outer Solar System. It is unclear whether these two sets of planetesimals formed simultaneously in two different temperature regions (silicate condensation line for NC and water snowline for CC) or formed sequentially as the water snowline migrated outwards. In the migrating water snowline hypothesis, both NC and CC planetesimals accreted water, whereas in the two snowline hypothesis NC planetesimals were always dry. Therefore, resolving this question is crucial for understanding the source of water in the terrestrial planets, as well as mechanisms for planet formation. Here, we use a refined thermal evolution and dynamo generation model to predict differences in the dynamo and thermal histories between NC and CC achondrite parent bodies due to their differences in volatile content.

We present predictions for thermal and dynamo histories for NC and CC achondrite parent bodies. We discuss the differences in planetesimal composition required for these histories to measurably differ. Comparing our predictions to paleomagnetic measurements in NC and CC achondrites can provide insight into the differences in planetesimal formation between these reservoirs. Our model results will enable multiple strands of experimental evidence to be drawn together to investigate planetesimal formation in the inner and outer Solar System. It can further shed light on the first processes in planet formation and the implications for the origin of Earth's water.

Modelling non-equilibrium slurries in planetary cores

Andrew M. Walker[1], Chris J. Davies[2], Alfred J. Wilson[2] and Michael I. Bergman[3]
[1]*Dept. of Earth Sciences, University of Oxford*

[2]*School of Earth and Environment, University of Leeds*
[3]*Simon's Rock College*

We describe a model of the formation of iron snow zones in planetary cores which have implications for the long timescale thermal evolution of planets and on the generation of an internal magnetic field. These two-phase "iron snow zones" are composed of a mixture of light-element enriched liquid and a small fraction of solid iron crystals. We focus on the seismically observed F-layer, a 150-400 thick region of unexpectedly low P-wave velocity at the base of Earth's outer core and assume that the F-layer consists of a slurry. In contrast to most previous descriptions, we focus on modelling the physics controlling the growth and sinking of individual iron crystals and do not assume that the slurry layer is in phase equilibrium. This means that our model does not require the temperature and solid volume to be linked through a liquidus relation and yields a size distribution of solid grain sizes and their falling velocities throughout the layer.

We consider the layer as a liquid iron-oxygen alloy cooled below the liquidus temperature such that solid iron crystals can form. Each crystal sinks because it is denser than the surrounding liquid. As the crystal sinks it also grows because of the chemical potential difference between iron in the solid and liquid phases. Growing crystals reject oxygen, moving the system towards equilibrium, but this equilibration is limited by the intrinsic growth kinetics of iron and by the need for iron to diffuse through an oxygen enriched boundary layer around the falling crystal. We model the layer as a collection of independently falling crystals which form throughout the layer and only interact by collectively changing the composition and temperature of the liquid. Assuming the layer is in steady state and imposing a suitable parameterisation of classical nucleation theory allows us to solve for the volume fraction of solid in the layer, the temperature and composition of the liquid, the size distribution of crystals. We also recover the rate of latent heat release in the layer and the growth rate of the Earth's inner core that is attributable to sedimentation.

List of participants

Dept. of Biology
Tim Barraclough
Willem Bonnaffé
Tim Coulson
Tom Pavey

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Dept. of Oncology
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Dept. of Psychiatry
Rachel Lin

Kennedy Institute of Rheumatology
Tal Arnon

Weatherall Institute of Molecular Medicine

Marta Arachi
Lucia Chen
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Li-Hsin Chang
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J. Heather Vedovato dos Santos

Museum of Natural History

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Łukasz Kowalski

Faculty of Theology and Religion

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Dept. of Earth Sciences

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Krisztina Sarkozi
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Andrew Walker
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Tesfahiwet Yemane
Lai Yiming

Dept. of Physics – Astrophysics

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Oscar Barragán
Jayne Birkby
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Chloe Fisher
Ryan Griffiths
Matthew Hopkins
Chris Lintott
Erik Meier Valdes
Niamh O'Sullivan
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Sofia Platymesi
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Geert Jan Talens
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Dept. of Physics – Atmospheric, Oceanic, and Planetary Physics

John Allen
Benjamin Bell
Richard Chatterjee
Bethan Gregory
Claire Guimond
Namrah Habib
Riya Hai
Fiona Henderson
Sarah Howes
Carly Howett
Tad Komacek
Shubham Kulkarni
Colette Levens
Duncan Lyster
Alex McGinty
Harrison Nicholls
Raymond Pierrehumbert
Peter Read
Andrew Wells

Dept. of Physics – Condensed Matter

Jon Bath
Sonia Contera
Qizheng Li

Mathematical Institute

Clive Bowman
Ian Hewitt
Callum Marsh

Other

Kyran Grattan *(Breakthrough Initiatives)*
Michael Gross *(independent science writer)*
Nick Lane *(University College London)*
Karl Massey *(Dept. of Physics development board)*
Gurinder Punn *(Oxford University Innovation Ltd.)*

Scientific organisation committee

Claire Guimond, Mark Hammond, Hamish Hay, Ross Anderson, Hal Drakesmith, Claire Nichols, Raymond Pierrehumbert, Jayne Birkby

Local organisation committee

Claire Guimond, Mark Hammond, Hamish Hay, Tad Komacek, Harrison Nicholls, Tobias Meier, Hannah Sanderson, John Allen, Richard Chatterjee, Alex McGinty, Ross Anderson, Hal Drakesmith, Claire Nichols, Raymond Pierrehumbert, Jayne Birkby