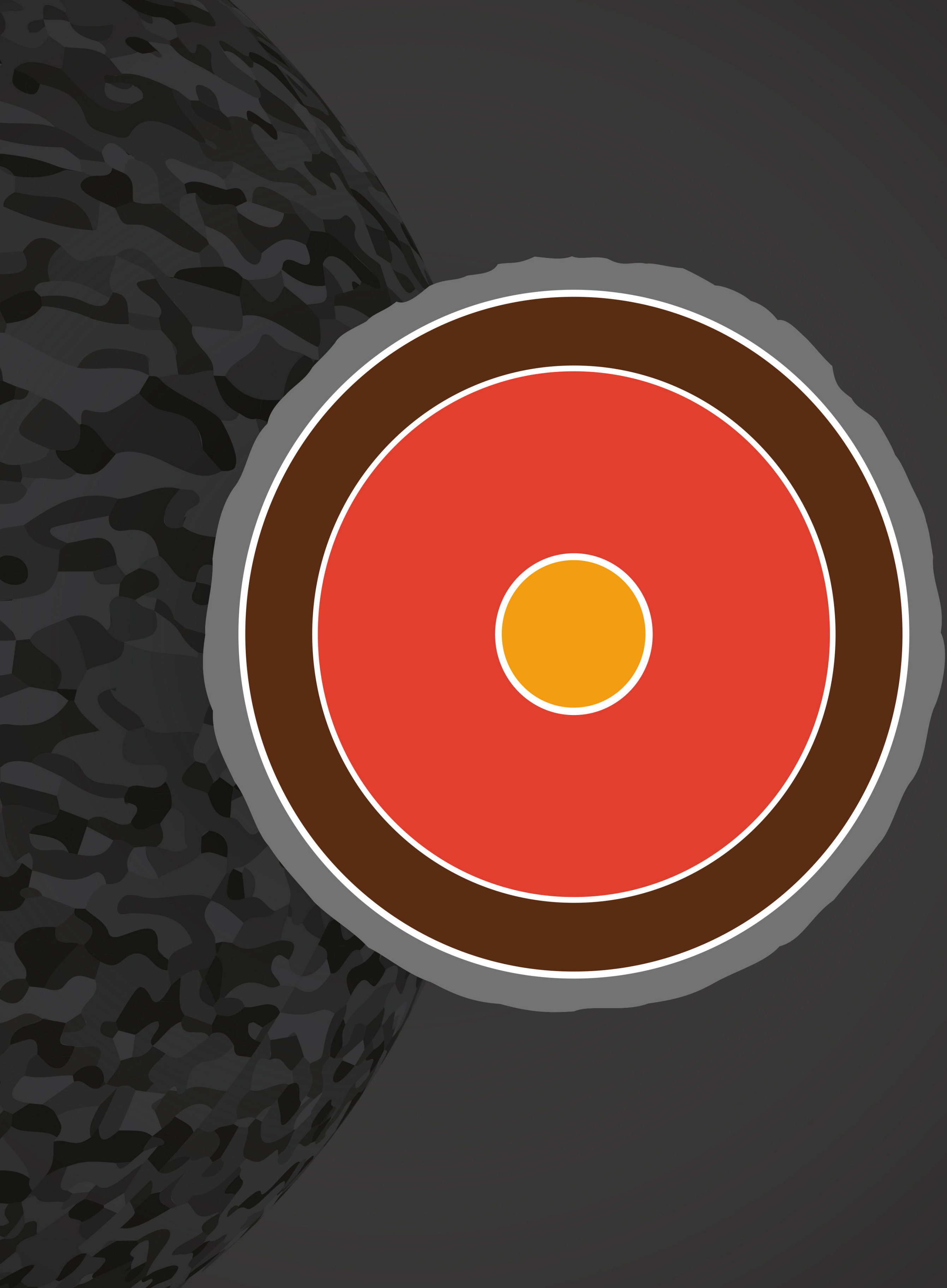
ROCKY WORLDS: *from the solar system to exoplanets*

6th - 8th January 2020 at the Kavli Institute, University of Cambridge



Abstracts

The organisers are committed to conducting meetings that are productive and enjoyable for everyone. This meeting is a place for the open exchange of scientific ideas. Harassment of participants in any form will not be tolerated. Thank you for helping make this a welcoming, respectful space for all.

The European Astronomical Society Council (EAS) Ethics Statement and Guidelines for Good Practice will apply during the conference. Participants are encouraged to read the document and follow its recommendations.
https://eas.unige.ch//documents/EAS_Ethics_Statement.pdf

Any participant who wishes to report any inappropriate behaviour is encouraged to speak, in confidence, to the LOC
E-mail rw2020@ast.cam.ac.uk

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Session Overview

MONDAY *06 JAN*	**TUESDAY** *07 JAN*	**WEDNESDAY** *08 JAN*
INTERIORS CHAIRED BY AMY BONSOR	**FORMATION CHAIRED BY PAUL RIMMER**	**ATMOSPHERES CHAIRED BY MIKHEL KAMA**
09:00 Registration Opens **09:30** Meeting starts with introductions Pg 14 **09:40** Jon Wade Pg 15 **10:20** Tim Lichtenberg	Pg 21 **09:00** Zoe Leinhardt Pg 22 **09:40** Lewis Watt Pg 23 **10:00** Marc Brouwers	Pg 29 **09:00** Robin Wordsworth Pg 30 **09:40** Nisha Katyal Pg 31 **10:00** Zahra Essack
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18:45
Pre-conference dinner drinks.
Pembroke College *(see map)*
(Dress code for evening receptions and conference banquet is smart/casual)

19:30
Conference dinner

** Please note: all information is subject to change; any updates will be announced via the Hoyle and Kavli reception monitors.*

Monday 6th January 2020
Session • Interiors
Chair • Amy Bonsor

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09:30	Meeting starts with introductions
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10:20	**Tim Lichtenberg:** Rocky (exo-)planet diversity from protoplanet solidification. *| Pg 15|*
10:40	Coffee break
11:00	**Fergus Horrobin:** Modelling Tidal Dissipation in Super-Earths with a Partially Molten Mantle. *| Pg 16 |*
11:20	**John Harrison:** Polluted White Dwarfs: Constraints on the Origin and Geology of Exoplanetary Material. *| Pg 17 |*
11:40	**Teresa Wong:** Plate Tectonics on Earth-Like Planets. *| Pg 18 |*
12:00	Lunch (12:00-13:40)
13:40	**Daniel Spencer:** Coupling volcanism and interior dynamics on Io. *| Pg 19 |*
14:00	**Sarah McIntyre:** Planetary magnetism as a parameter in exoplanet habitability. *| Pg 20 |*
14:20	Break-out sessions: **Laura Rogers, John Harrison and Alexander Mustill:** Insights into exoplanet compositions from the Solar System, exoplanet atmospheres, and host star abundances. *Kavli Ryle Rooms* **Dan Spencer:** Planetary Volcanism, linking interiors to atmospheres. *SLT* **Francis Nimmo:** Tidal heating in the solar system and elsewhere. *HCR*
15:40	Coffee break
16:00	Discussion (Chair: Helen Williams)
16:40	Poster Introductions (Chair: James Bryson)
17:00	Poster Session with Cheese & Wine
18:30	Close

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Session • Formation
Chair • Paul Rimmer

09:00	**Zoe Leinhardt:** The Birth and Death of Extrasolar Planets. *|Pg 21|*
09:40	**Lewis Watt:** Planetary Embryo Collisions in Extreme Debris Disks. *|Pg 22|*
10:00	**Marc Brouwers:** How planets grow by pebble accretion. *|Pg 23|*
10:20	Coffee break
10:40	**Mor Rozner:** The Ablation Barrier for the growth of Meter-Size Objects in Protoplanetary Disks. *|Pg 24|*
10:40	**Thomas Haworth:** Gravitationally stable massive discs around low mass stars. *|Pg 25|*
11:20	**Kathryn Dodds:** The early thermal evolution of planetesimals during accretion and differentiation. *|Pg 26|*
11:40	**Evgeni Grishin:** Seeding interstellar planetesimals in circumstellar discs. *|Pg 27|*
12:00	Photo
12:05	Lunch
14:00	Break-out sessions: **Tim Lichtenberg:** Bridging the gap from planet formation to rocky exoplanet evolution. *SPO* **Sarah McIntyre:** Multi-parameter Approach to Habitability (M-PAtH). *Kavli Ryle Rooms* **Thomas Haworth & Jeff Jennings:** Strengthening collaborations across the epochs of planetary system evolution: A broad outlook and case study in star formation and planet-forming discs. *SLT* **Evgeni Grishin:** Formation and properties of the first planetesimals. *HCR*
15:20	Coffee break
15:40	Discussion (Chair: Mark Wyatt)
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17:00	Close
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Chair • Mihkel Kama

09:00	**Robin Wordsworth:** Tracing the coupled evolution of water and oxygen on temperate rocky exoplanets. *| Pg 29 |*
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10:40	**Catriona Sinclair:** Terrestrial Planet Bombardment and Atmosphere Evolution. *| Pg 32 |*
11:00	**David Grinspoon:** The Evolution of Climate and a Possible Biosphere on Venus. *| Pg 33 |*
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14:00	Break-out sessions: **Victoria Hartwick:** Cloud Microphysics in Exoplanet Atmospheres. *Kavli Ryle Rooms* **Quentin Changeat:** Exploring degeneracies in atmospheric retrieval techniques. *SLT* **Paul Rimmer & Sang-Min Tsai:** Atmospheric Features as "Golden Spikes" for Exoplanetary Eons. *HRC*
15:20	Coffee break
15:40	Discussion (Chair: Oliver Shorttle)
16:10	**Vivien Parmentier:** Understanding the spectrum of far away worlds: lessons learned form hot giant planets. *| Pg 36 |*
17:00	Close

Local Information

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Internet Access
Internet access during the conference will be most easily achieved using eduroam: https://www.eduroam.org/
For those unable to use eduroam, we will issue wifi accounts at the registration desk.

IoA First Aiders:
Matt Bothwell • 01223 339279, Hoyle Rm 59
Cormac O'Connell • 07801707058 or 01223 337505, Observatory Rm 5
Monica Gamboa • 01223 337548, Hoyle Reception
Mark Hurn • 01223 337537, Library Office
Debbie Peterson • 01223 766643, Hoyle Rm 6

Location of First Aid Boxes:
Hoyle Building • Ground floor; between lift shaft & cleaning cupboard 1st floor; outside toilets
Observatory Building • In Kitchen and Librarian's Office
Kavli Institute Building • Ground floor; outside room K14 Upper first floor; outside room K34

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The nearest A & E Unit is at Addenbrooke's Hospital, Hills Road, Cambridge. If no First Aider is available the casualty should be escorted to the Hospital's Emergency Department. In a serious emergency you should always call 999.

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In the event of a fire alarm please evacuate the building by the nearest exit (please see pages 113 & 114 for locations). Do not stop to collect personal belongings and do not re-enter the building.

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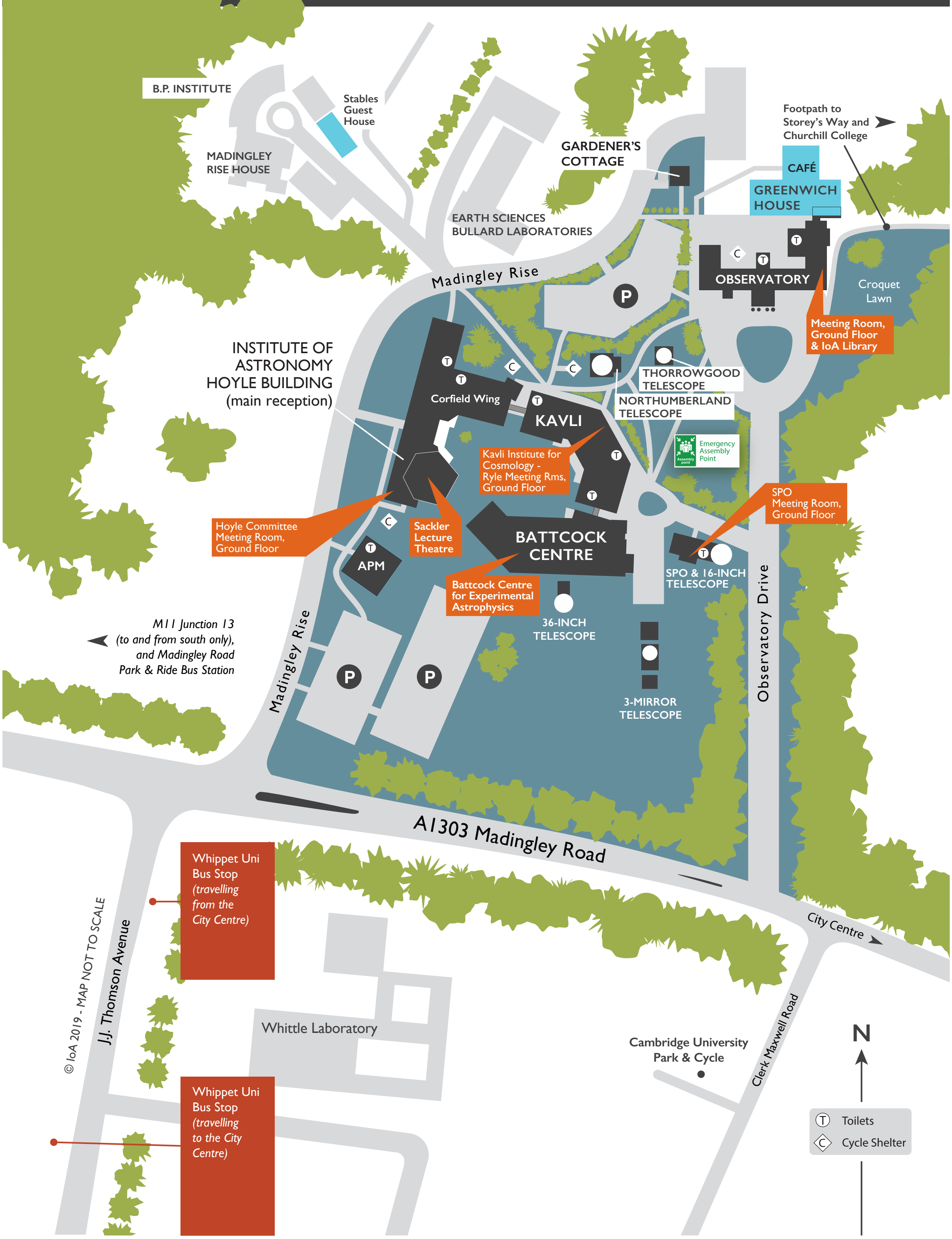
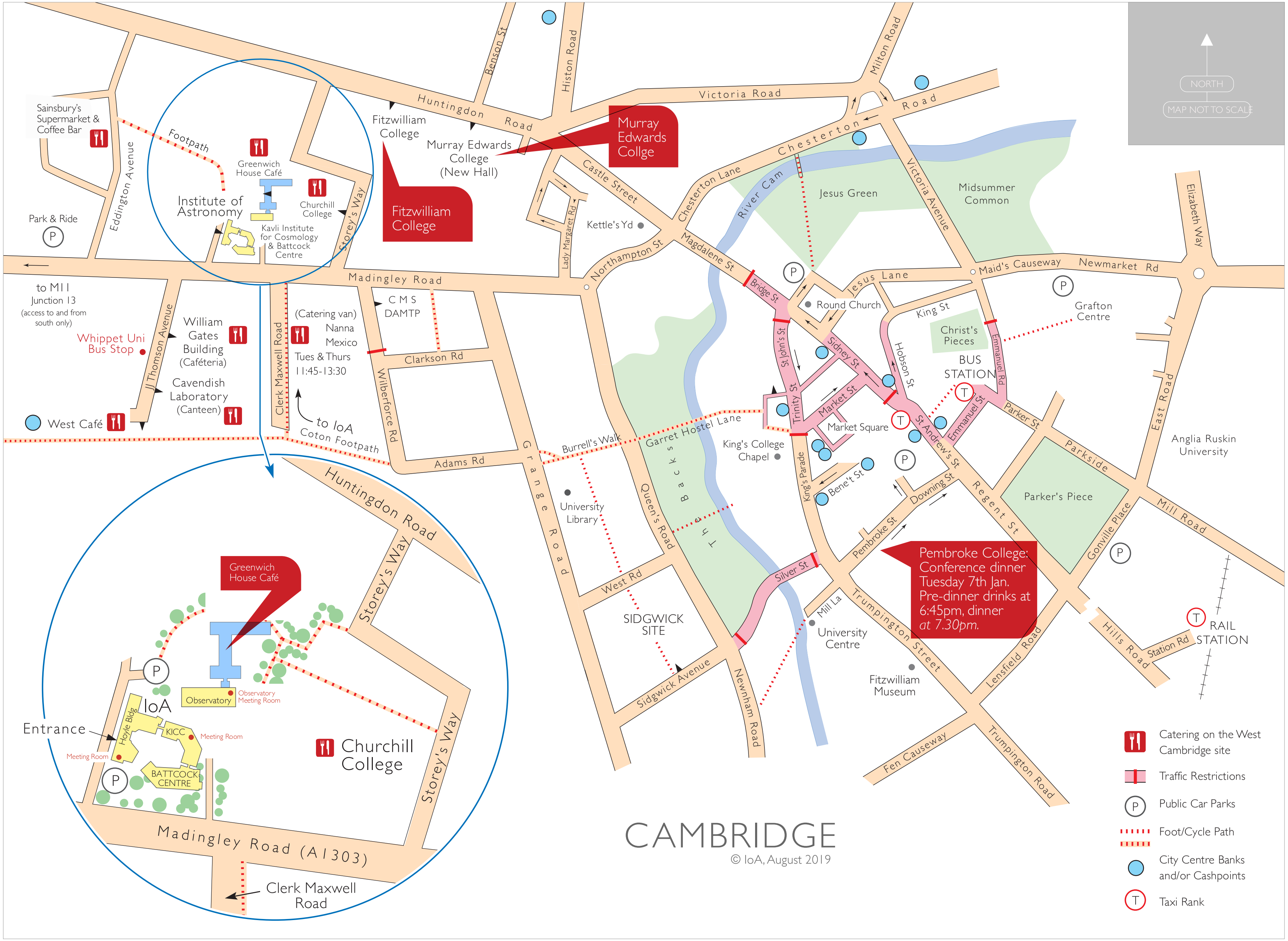
SITE MAP



B.P. INSTITUTE
Stables Guest House
MADINGLEY RISE HOUSE
GARDENER'S COTTAGE
EARTH SCIENCES BULLARD LABORATORIES
Footpath to Storey's Way and Churchill College
CAFÉ
GREENWICH HOUSE
OBSERVATORY
Croquet Lawn
Meeting Room, Ground Floor & IoA Library
Madingley Rise
INSTITUTE OF ASTRONOMY HOYLE BUILDING (main reception)
Corfield Wing
KAVLI
THORROWGOOD TELESCOPE
NORTHUMBERLAND TELESCOPE
Emergency Assembly Point
Kavli Institute for Cosmology - Ryle Meeting Rms, Ground Floor
Hoyle Committee Meeting Room, Ground Floor
Sackler Lecture Theatre
BATTCOCK CENTRE
SPO Meeting Room, Ground Floor
APM
Battcock Centre for Experimental Astrophysics
SPO & 16-INCH TELESCOPE
36-INCH TELESCOPE
3-MIRROR TELESCOPE
Observatory Drive
M11 Junction 13 (to and from south only), and Madingley Road Park & Ride Bus Station
Madingley Rise
A1303 Madingley Road
City Centre
Whippet Uni Bus Stop (travelling from the City Centre)
Whipple Laboratory
Whittle Laboratory
Cambridge University Park & Cycle
Clerk Maxwell Road
J.J. Thomson Avenue
© IoA 2019 - MAP NOT TO SCALE
Whippet Uni Bus Stop (travelling to the City Centre)
N
Toilets
Cycle Shelter


NORTH
MAP NOT TO SCALE
CAMBRIDGE
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Pembroke College:
Conference dinner
Tuesday 7th Jan.
Pre-dinner drinks at
6:45pm, dinner
at 7.30pm.
Murray Edwards Collge
Fitzwilliam College
Murray Edwards College (New Hall)
Fitzwilliam College
Sainsbury's Supermarket & Coffee Bar
Park & Ride
Footpath
Greenwich House Café
Institute of Astronomy
Churchill College
Kavli Institute for Cosmology & Battcock Centre
to M11 Junction 13 (access to and from south only)
Whipper Uni Bus Stop
William Gates Building (Caféteria)
Cavendish Laboratory (Canteen)
West Café
(Catering van) Nanna Mexico Tues & Thurs 11:45-13:30
to IoA Coton Footpath
C M S
DAMTP
Huntingdon Road
Madingley Road
Storey's Way
Eddington Avenue
JJ Thomson Avenue
Clerk Maxwell Road
Clarkson Rd
Wilberforce Rd
Adams Rd
Grange Road
Benson St
Histon Road
Victoria Road
Milton Road
Chesterton Road
Castle Street
Lady Margaret Rd
Kettle's Yd
Northampton St
Chesterton Lane
Magdalene St
Bridge St
River Cam
Jesus Green
Victoria Avenue
Midsummer Common
Maid's Causeway
Newmarket Rd
Elizabeth Way
Jesus Lane
Round Church
King St
Christ's Pieces
BUS STATION
Grafton Centre
Emmanuel Rd
Emmanuel St
Parker St
Parkside
East Road
Anglia Ruskin University
Parker's Piece
Gonville Place
Mill Road
Hobson St
Sidney St
St John's St
Trinity St
Market St
Market Square
St Andrew's St
King's College Chapel
King's Parade
Bene't St
Downing St
Regent St
Pembroke St
Garret Hostel Lane
Burrell's Walk
The Backs
University Library
Queen's Road
West Rd
SIDGWICK SITE
Sidgwick Avenue
Silver St
Mill La
University Centre
Newnham Road
Trumpington Street
Fitzwilliam Museum
Lensfield Road
Hills Road
Station Rd
RAIL STATION
Fen Causeway
Trumpington Road
Observatory
Observatory Meeting Room
IoA
Entrance
Hoyle Bldg
KICC
Meeting Room
BATTCOCK CENTRE
Madingley Road (A1303)
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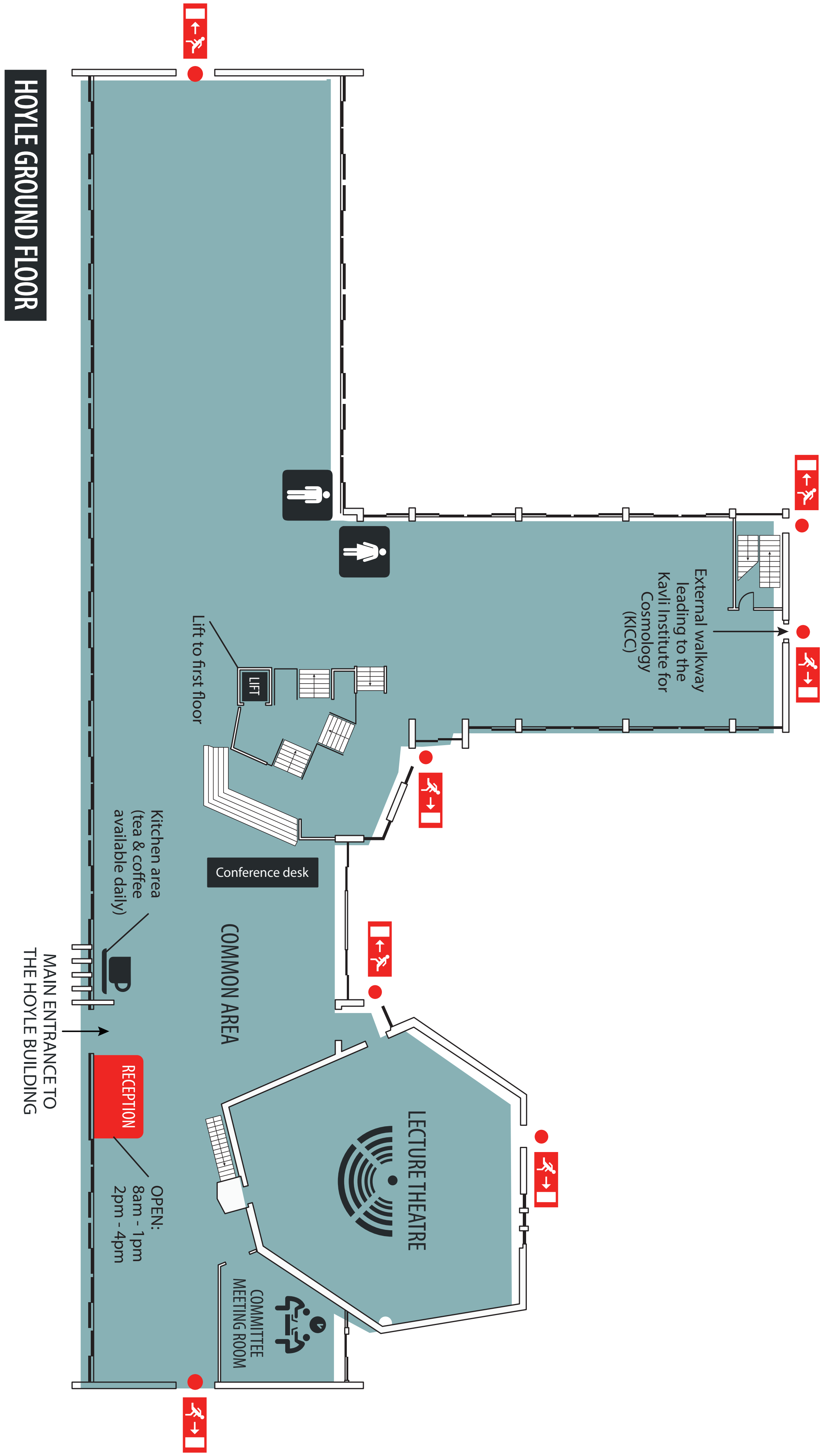
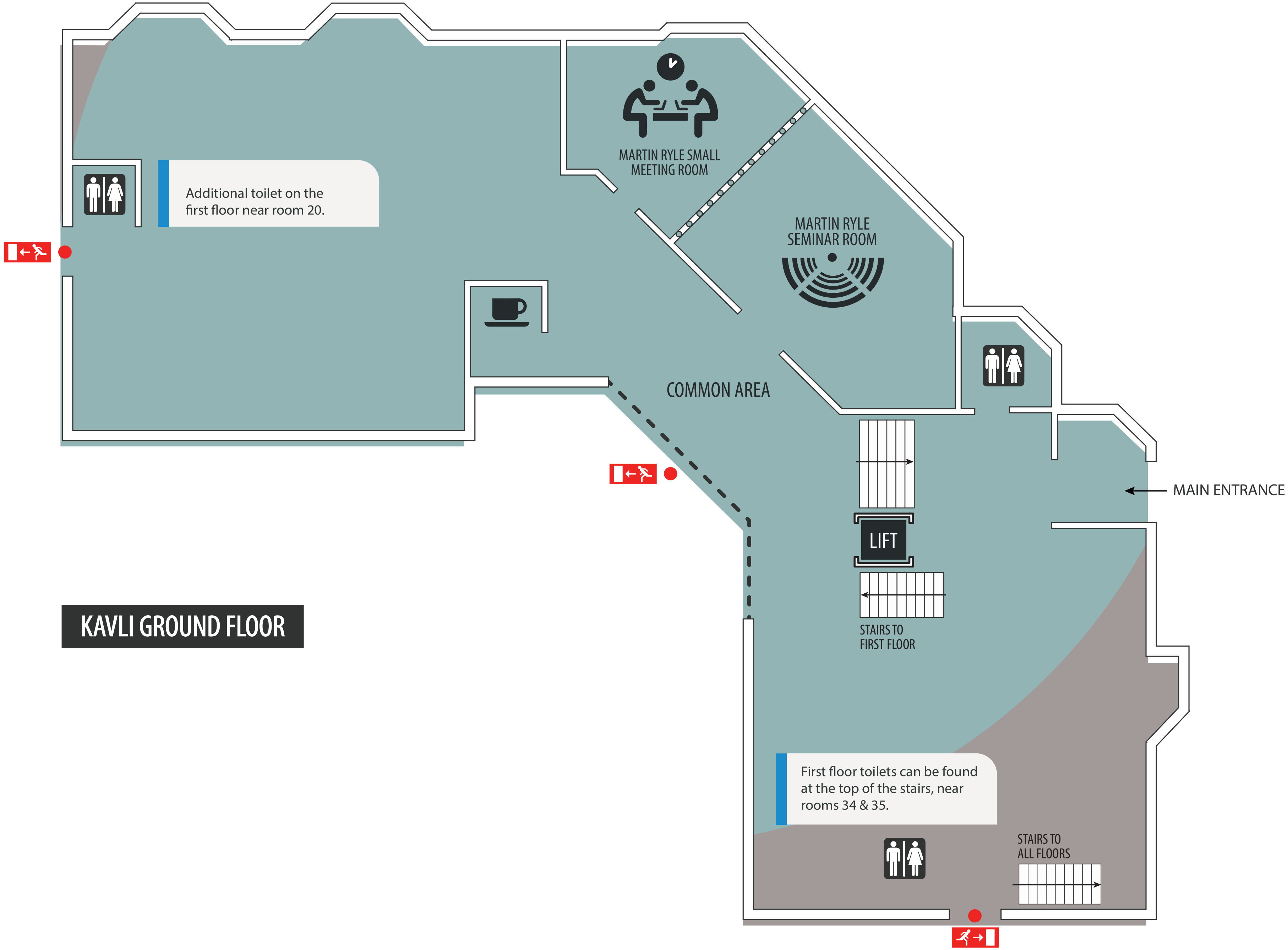

HOYLE GROUND FLOOR
External walkway leading to the Kavli Institute for Cosmology (KICC)
LIFT
Lift to first floor
Conference desk
Kitchen area (tea & coffee available daily)
COMMON AREA
MAIN ENTRANCE TO THE HOYLE BUILDING
RECEPTION
OPEN: 8am - 1pm 2pm - 4pm
LECTURE THEATRE
COMMITTEE MEETING ROOM

KAVLI GROUND FLOOR



Eco-friendly Notice

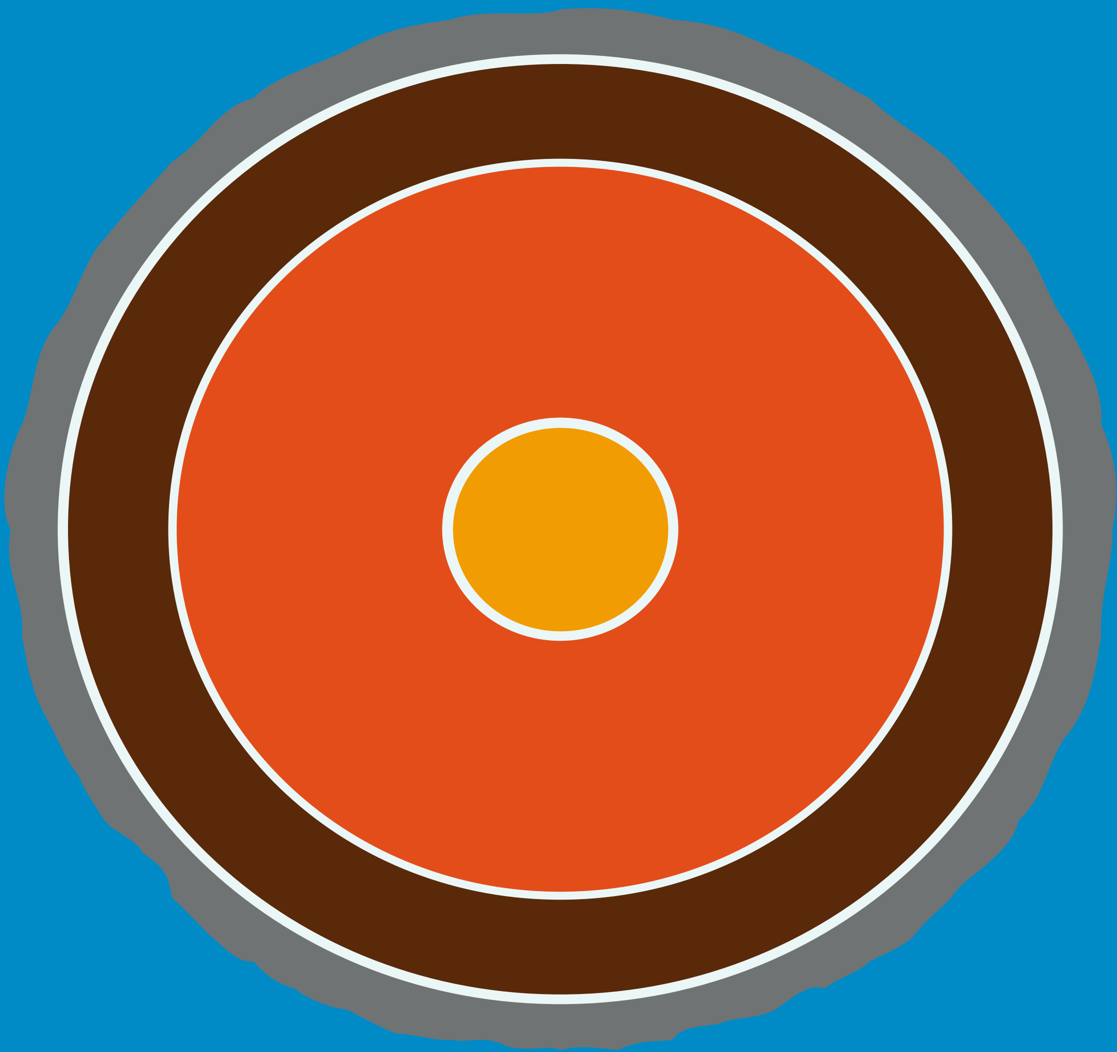
While the organization of the Rocky Worlds produces a carbon footprint that is higher than we would wish, we have implemented some measures to promote eco-friendly policies:

• We have reduced our colour printing by providing an online abstract book.

• Complementary pens are partially made of recycled plastic

• We have attempted to minimize any single use, disposable napkins, cutlery and crockery.

• Please observe the different types of bins at IoA and KICC and dispose of your trash accordingly.



TALK AND POSTER ABSTRACTS

The role of core formation in planetary habitability and the development of complex life

INTERIORS

Jon Wade • University of Oxford

Earth and Mars both possessed ample surface water very soon after formation, yet while oceans still cover around 70% of the Earth's surface, Mars has lost the majority of its surface water, leaving it inhospitable for the development of complex life. What happened to surface water on Mars? While the Martian water inventory was undoubtedly depleted by loss to space following the collapse of the planet's magnetic field, the presence of hydrated clays and the widespread serpentinisation of surface basalts attests to water-rock reactions playing a critical role in its sequestion. This, then, leads to an obvious question - why has Earth remained habitable for life, and Mars became barren? This is problematic, especially given the secular evolution of the Earth, and the presence of active water transport mechanisms, such as plate tectonics, to the Earth's essentially dry lower mantle.

One possible explanation concerns iron, the one major rock forming element whose mantle concentration varies significantly across the terrestrial bodies. We show how this subtle chemical variation, set by the differing conditions of planetary accretion and core formation, plays a disproportionate role in subsequent planetary development and habitability. The ability of a planet's surface to retain water over geological timescales is therefore a result of the stochastic processes that resulted in planetary core formation. Furthermore, we suggest that the Earth's mantle iron content provides a key evolutionary driver for the development of complex, multicellular life.

In summary, it is likely that planetary habitability may not simply be a case of "right ingredients and distance from star" but rather the correct "recipe" of planet accretion.

NOTES:

Rocky (exo-)planet diversity from protoplanet solidification

INTERIORS

Tim Lichtenberg • University of Oxford

The census of currently known rocky exoplanets has proven vastly more diverse than anticipated and we do not understand which are the main physical mechanisms to form 'Earth-like' planets. In this talk I will describe current efforts to establish a general modeling framework for the transition of rocky planets from the disk-stage accretion phase to their long-term evolution, bridging the gap between theories of planet formation and the reality of exoplanet data. The model framework spatially resolves the cooling and volatile partitioning of a rocky planet from the core-mantle boundary to the top of the atmosphere using a non-grey radiative transfer scheme for non-ideal atmospheres. I will outline how the stochasticity of accretion, such as drastically varying volatile mixing ratios, planet-star distance, late-stage giant impact rate, or planet mass, can play a crucial role in setting the stage for the long-term evolution of a rocky planet, and how future observations from ground and space-based telescopes may make use of such models to distinguish between rocky planets like and unlike Earth.

NOTES:

Modelling Tidal Dissipation in Super-Earths with a Partially Molten Mantle

INTERIORS

Fergus Horrobin • University of Toronto

Astronomers have typically treated tidal dissipation using a simple constant dissipation value and have used tidal dissipation to explore the orbital evolution of super-Earths under tides. This approach is fundamentally flawed when regions of the planet begin to melt, as has been shown in recent geophysical research. In this work, we present a self-consistent numerical model to determine how dissipation proceeds in the presence of melt on tidally-heated rocky exoplanets. We model the feedback effects between tidal heating and melt to discuss where tidal heating happens, how much dissipation can occur and how much melt is generated and transported. To do this, we combine models for rocky planet rheology, tidal dissipation, and melt transport. We evaluate the effectiveness of our model using Io and show that modelling melt is important to reproduce the correct surface heat flux. We then apply the model to rocky planets to determine where and how much dissipation occurs and answer a fundamental question: is tidal heating a runaway process, or is it confined to a region of the interior due to a regulating mechanism.

NOTES:

Polluted White Dwarfs: Constraints on the Origin and Geology of Exoplanetary Material

INTERIORS

John Harrison • IoA, University of Cambridge

White dwarfs that have accreted rocky exoplanetary debris offer a unique insight into the bulk composition of exoplanetary material. Understanding the range of bulk compositions possible for rocky bodies in exoplanetary systems will significantly aid our understanding of the interiors of extrasolar terrestrial planets, in an analogous way to how the solar system meteorite suites provide insights into the interior compositions of the terrestrial planets. We have created a Bayesian framework which can take observed polluted white dwarf atmospheric abundances and output constraints on the temperature experienced by the polluting material and the geological and collisional history of the polluting material. Our analysis suggests that all the polluted white dwarf atmospheric abundances observed to date can be explained using a solar system-like differentiation model, hinting that exoplanetary geologies may not be dissimilar from the geologies of rocky bodies in the solar system. The atmospheric abundances present in many polluted white dwarfs can only be explained if solar system-like differentiation and collisional processing is commonplace exoplanetary systems. We also find evidence that the material that pollutes white dwarfs can have a wide range in formation temperatures, ranging from icy volatile-rich material (analogous to Kuiper belt objects) to refractory enhanced volatile-poor material (analogous to objects primarily composed of calcium aluminium inclusions).

NOTES:

Plate Tectonics Initiation on Earth-Like Planets - Insights from Numerical Analysis of Convection-Induced Lithospheric Failure

INTERIORS

Teresa Wong • University of Munster

Plate tectonics is central to many aspects of the geology and evolution of terrestrial planets, yet it is only observed on the Earth while all other known planets are covered with a stagnant lithosphere. Plate motions on the Earth are mostly driven by the pull of subducting slabs, therefore understanding the initiation of subduction is crucial to understanding plate tectonics initiation. On a one-plate planet which lacks the forces due to plate motions, some other mechanisms will have to cause the first episode of subduction to mobilize the surface. Sublithospheric convection has been proposed as a possible mechanism that induce stresses in the lithosphere. The question is whether these stresses can initiate subduction. We develop scaling laws for the criterion of lithospheric failure from single-cell steady-state convection, which has more controlled flow and thus easier to analyse. We show that these scaling laws are applicable to time-dependent convection. We extrapolate the scaling laws to planetary conditions to assess the feasibility of plate tectonics for terrestrial planets.

NOTES:

Daniel Spencer • University of Oxford

Previous models of Io have assumed the presence of a magma ocean or high melt fractions [1][2][3]. Here we demonstrate that observations can be satisfied by a two-phase fluid dynamical model which does not invoke a magma ocean, a feature that would be unlikely to form due to the resultant strong density inversion. We also demonstrate the importance of magmatic emplacement in Io's lower lithosphere. High eruption rates with no volcanic emplacement lead to unrealistically thick lithospheres. This also means that the heat profile of Io's lithosphere could deviate significantly from a high-Peclet number problem such as those previously expected [4]. We argue most of Io's mantle is partially molten to a low melt fraction (2-5%) and that a thin, high melt fraction layer inferred from magnetometer data [3] can be understood as a decompacting boundary layer, but importantly this does not have an important effect on Io's eruption system.

[1] Bierson & Nimmo, 2016 Icarus [2] Tyler, Henning, & Hamilton, 2015[3] Khurana et al, 2011, Science[4] Kirchoff & McKinnon, 2009

NOTES:

Sarah McIntyre • Australian National University

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 with radii $R_p \leq 1.23\ R_\oplus$. 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.

NOTES:

The Birth and Death of Extrasolar Planets

Zoe Leinhardt • University of Bristol

Extrasolar planets are a diverse population along all dimensions from individual physical characteristics such as mass and mean density to the dynamical characteristics of the planetary system such as semi-major axis and number of planets. The ease with which extrasolar planets seem to form has resulted in discoveries of planets around unlikely host stars such as tight binaries and evolved post main sequence remnant stellar cores. In order to understand the diversity of the extrasolar planet population we need to understand planet formation in detail. However, most of the process is difficult to observe directly. In this talk I will review numerical results of planetary evolution and also highlight a few particularly interesting observations of potentially extreme events from violent collisions to the death of a solar system that may help tie our theoretical evolution models to reality.

NOTES:

Planetary Embryo Collisions in Extreme Debris Disks

FORMATION

Lewis Watt • University of Bristol

Planetary collisions are an expected process in the formation of terrestrial planets, but observations of such events are lacking. Recent observations of extreme debris disks ID8 and P1121 suggest a massive amount of millimetre and micron sized dust are added and then removed in a short time period. We use numerical simulations to test the hypothesis that these events were caused by large planetary scale collisions. For the collisions we use Mars to Earth-mass impactors with varied velocities and impact parameters.

From the simulations we find that the escaping dust after a collision has a velocity dispersion which is independent of the specific impact energy but does depend on whether the impact parameter is greater than the critical value, therefore, a population of velocity dispersions can be modelled by two normal distributions. The velocity dispersion when normalised by the Keplerian velocity of the progenitor only varies with the semi-major axis. As a result, flux variations due to the collision point and anti-collision line are restricted to small semi-major axes.

NOTES:

How planets grow by pebble accretion

Marc Brouwers • University of Cambridge

Proto-planets embedded in their natal disks acquire hot envelopes as they grow and accrete solids. This ensures that the material they accrete - pebbles as well as (small) planetesimals - will vaporize to enrich their atmospheres. Enrichment modifies an envelope's structure and significantly alters its further evolution.

We have developed a model for the evolution of planets with polluted planets, and find that it follows four distinct phases. Initially, the central core grows directly through impacts and rainout. The inner envelope absorbs increasing amounts of solids as vapor and eventually halts the growth of the core. A planet reaches runaway accretion when the sum of its core and vapor mass exceeds a value that we refer to as the critical Z mass. We derive an expression for this criterion that supersedes the traditional critical core mass. We then identify the decline of the mean molecular weight - dilution - as a mechanism that limits gas accretion during a polluted planet's embedded cooling phase. When the disk ultimately dissipates, the vapor rains out, augmenting the mass of the core. This is a process that takes several Gyr to complete. The energy release that accompanies it does not result in significant mass-loss, as it only occurs after the planet has greatly contracted.

Our model provides a natural explanation for the relative abundance of Super-Earths and Sub-Neptunes at short orbital distances. In our model, the small core masses of the giant planets are a result of their accretion history, rather than later core erosion.

The presented results draw from our self-consistently coupled impacts and planetary structure models from (Brouwers et al. 2018), as well as from our analytical calculations (Brouwers & Ormel, submitted), and from new numerical simulations (Ormel et al in prep).

NOTES:

The Ablation Barrier of Meter-Size Objects in Protoplanetary Disks " to "
The Ablation Barrier for the growth of Meter-Size Objects in Protoplanetary-Disks

FORMATION

Mor Rozner • Technion, Israel Institute of Technology

Ablation is a destructive process which can erode small-size planetary objects. Ablation operates in a wide range of environments and under various conditions, from atmospheric entry of meteoroids to ablation in planetary envelopes. Here we point out that ablation of pebbles and small planetesimals in protoplanetary disks,that can constitute a significant barrier for the early stages of planet formation. We use analytic calculations to show that the typical gas densities and the relative velocities between planetesimals and gas make small bodies ranging in size between cm up to even tens of meters highly susceptible to gas-drag ablation. At these size ranges ablation can efficiently erode the planetesimals down to cm-size. In particular, the ablation timescale is sufficiently short as to quench any further growth of such few-cm up to tens of meters planetesimals. On the other hand, this grinding-down ablation mechanism could populate protoplanetary disks with pebble-size planetesimals, thereby boosting pebble-accretion growth at later stages of planet formation, once large planetesimals and planetary embryos exist in the disk.

NOTES:

Gravitationally stable massive discs around low mass stars

FORMATION

Thomas Haworth • QMUL

A large mass in planets is being discovered around low mass stars (e.g. Trappist-1) requiring a high planet formation efficiency. This is made even more challenging because some fraction of the (potentially planet-forming) mass is accreted and stripped through processes like photoevaporation. The oft-assumed upper limit on the disc mass is around a tenth of the stellar mass, since above this gravitational instability is expected to onset. However self-gravitating discs around low mass stars have not been formally studied.

I will present new models addressing this, which demonstrate that low mass stars can actually support axisymmetric discs with higher disc-to-star mass ratios than naively anticipated. This could help to alleviate the mass budget problem for planet formation around low mass stars.

NOTES:

The early thermal evolution of planetesimals during accretion and differentiation

FORMATION

Kathryn Dodds • Department of Earth Sciences, University of Cambridge

Over the past decade, there has been an increase in the number of paleomagnetic studies of meteorites in which their primary remanence has been linked to dynamo activity on their parent bodies. This signal has been found in differentiated meteorites as well as in some chondrites, potentially providing evidence for partially differentiated parent bodies. The earliest period of dynamo activity from 5 – 20 Myr after Solar System formation has been attributed to dynamos driven by thermal convection in a molten core, instead of compositional convection during core solidification. However, generating a dynamo from thermal convection alone is difficult as the density differences induced by cooling are small. In planetesimals, this requires fast (>5 KMyr^{1}) core cooling rates which are only likely generated during early periods in which the body loses heat to the surface via convection in a semi-molten magma ocean.

To better constrain this process, we model the 1D thermal evolution of planetesimals from accretion through to the shut-down of convection in the magma ocean for a range of proposed accretionary scenarios. The heat source of these bodies is the decay of the short-lived radiogenic isotope, ^{26}Al. We model accretion timescales from 500 years (i.e., instantaneous) to 4.5 Myr and over radii from 50 km to 600 km. We use scaling laws from magnetohydrodynamic simulations to determine if these bodies generate a thermal dynamo, and the characteristics of the magnetic field. During differentiation, ^{26}Al partitions into the silicate mantle that heats up the magma ocean, causing a stable stratification to be introduced at the top of the core. This stratification inhibits dynamo generation. In the 'instantaneously' accreting bodies, this introduces a delay (>5Myr) to convection in the core whilst this stratification is removed. However, gradual differentiation in bodies that accrete over >0.7 Myr can destroy this stratification by adding cold material to the top of the core. Our model also produces partially differentiated planetesimals with a core and mantle overlain by a chondritic crust for accretion timescales >2 Myr. By comparing the results of the model to the paleomagnetic record of meteorite groups, we can constrain the physical properties (such as size) and the accretional history of their 23parent bodies.

NOTES:

Seeding interstellar planetesimals in circumstellar discs

FORMATION

Evgeni Grishin • Technion, Israel Institute of Technology

The formation of planetesimals is thought to be rapid, while they are still embedded in a gaseous protoplanetary disc. However, small planetesimals experience collisions and gas drag that lead to their destruction on short time-scales, not allowing, or requiring fine-tuned conditions for the efficient growth of ~metre-sized objects. Here we show that ~10^4 interstellar objects such as the recently detected 1I/2017-U1 ('Oumuamua) could have been captured. The capture rates are robust even for conservative assumptions on the protoplanetary disc structure, local stellar environment, and planetesimal interstellar medium density. 'Seeding' of such planetesimals then catalyses further planetary growth into planetary embryos, and potentially alleviates the main challenges with the metre-sized growth barrier. In addition, interstellar and loosely bound exo-Kuiper belt and exo-Oort cloud objects can be captured onto the scaled-down gaseous disc around a white dwarf star, providing additional channel for the influx of solids. For a gaseous disc which extends much beyond its Roche limit, capture is more probable than disruption at the Roche limit and linearly increases with the radial extent of the disc. Even in systems without minor planets, capture of smaller bodies will change the disc size distribution and potentially its temporal variability. The discovery of the intact minor planet embedded in the debris disc orbiting SDSSJ1228+1040 could also potentially be explained by the capture mechanism.

NOTES:

Formation pathways of rocky planets

Sean Raymond • Laboratoire d'Astrophysique de Bordeaux

It is seductive to imagine super-Earths as scaled-up versions of our Solar System's rocky planets. However, the central processes involved in the growth of different populations of planets are likely very different. For example, simple scaling arguments show that migration played a dominant role in the final assembly of super-Earth systems whereas it was likely of little importance in the growth of our terrestrial planets. In this talk I will review models for the growth of rocky planets in different astrophysical settings, including mechanisms for water delivery.

NOTES:

Tracing the coupled evolution of water and oxygen on temperate rocky exoplanets

ATMOSPHERES

Robin Wordsworth • Harvard University

Water (H2O) and oxygen (O2) are two compounds of particularly special relevance to habitability and the search for life on exoplanets. Surface liquid water is essential for all known forms of life, but its remote detection using current or future observational techniques is incredibly challenging. Oxygen is important to the habitability of complex life and is also regarded as a potential atmospheric biosignature, but abiotic ways of generating O2-dominated atmospheres are also theorized to exist. Here I describe our recent efforts to understand the evolution and observabiity of the water and oxygen inventories on rocky exoplanets. I discuss recent coupled atmosphere-interior modeling of abiotic oxygen buildup via water photolysis that we have used to assess the viability of O2 as a biosignature. I also discuss recent work that we have performed to investigate whether sulfate aerosol hazes can be used as a remote diagnostic of surface liquid water. Finally, I will briefly discuss some of the key theoretical advances that need to occur to improve terrestrial exoplanet characterization prospects over the next decade.

NOTES:

Effect of Secondary Outgassing on
Atmospheric Evolution of Terrestrial Planets

ATMOSPHERES

Nisha Katyal • TU Berlin

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. In this work, we study the evolution and spectral response of steam based atmospheres which are outgassed from the mantle in the interior of the planet. 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 observe that as the magma oceans cools down, the atmospheric transmission height or the depth of the water bands gets lower from a few thousand km to a few hundred km. In this talk, I will also show the effect of varying redox state of the mantle (fugacity) on the atmospheric evolution which has implications for formation of water oceans. Using atmospheric loss processes, I will present an interesting interplay between the outgassing and escape of water.

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Low Albedo Surfaces of Lava Worlds

ATMOSPHERES

Zahra Essack • MIT

Hot super Earths are exoplanets with short orbital periods (< 10 days) whose rocky surfaces can reach temperatures high enough to become molten. There are a few hot super Earths that exhibit high geometric albedo values (> 0.4) in the Kepler band (420-900 nm). Sources of reflected light that may contribute to the high albedos include: Rayleigh scattering in an atmosphere that may contain visible wavelength absorbers, reflective clouds, and/or the planetary surface. In this study, we focus on reflection from planetary surfaces. We aim to determine whether specular reflection from molten lava and quenched glass (a product of rapidly cooled lava) on the surfaces of hot super Earths may be sources of reflected light that contribute to the high geometric albedos. We experimentally measure the specular reflection from rough and smooth textured quenched glass, and survey non-crystalline solids literature for specular reflectance values from molten silicates as a proxy for specular reflectance values for lava. Integrating the empirical glass reflectance function and non-crystalline solids reflectance values over the dayside surface of the planet at secondary eclipse yields an upper limit for the albedo of a lava-quenched glass planet surface of ~ 0.1. We conclude that lava planets with solid (quenched glass) or liquid (lava) surfaces have low albedos, and the high albedos of some hot super Earths are most likely explained by atmospheres with reflective clouds, or even possibly a calcium/aluminum oxide melt surface. Our future work includes measuring the albedo of molten lava to determine if our current low albedo surface result holds, and identifying potential lava worlds in TESS data for follow-up observations and future characterization.

NOTES:

Terrestrial Planet Bombardment and Atmosphere Evolution

ATMOSPHERES

Catriona Sinclair • IoA, University of Cambridge

We investigate how the bombardment of terrestrial planets by populations of planetesimals left over from the planet formation process affects the evolution of their atmospheres, through both impact induced atmospheric mass loss and volatile delivery. This work builds on previous studies of this topic by combining prescriptions for the atmosphere loss and mass delivery derived from hydrodynamic simulations with results from dynamical modelling of a realistic population of impactors. The effect on the atmosphere predicted by the hydrodynamical simulations performed by Shuvalov (2009) as a function of the impactor and system properties are incorporated into a numerical model for the atmospheric evolution. The effects of stochastic giant impacts, that can cause non-local atmosphere loss, are also included using the prescription from Schlichting et al. (2015), and aerial bursts and fragmentation of smaller impactors in hot and dense atmospheres is included using the prescription derived from further simulations performed by Shuvalov et al. (2014). We compare the impact induced atmosphere evolution of Earth, Venus and Mars using impact velocities and probabilities inferred from the results of dynamical models of the population of left over planetesimals in the early solar system from Morbidelli et al. (2018). The effect of the variation in the distribution of the impactor material properties is investigated, and the results discussed in light of observational constraints regarding the composition of the material delivered to Earth as the late veneer.

NOTES:

David Grinspoon • Planetary Science Institute

Of the three local terrestrial planets, two have lost their oceans either to a subsurface cryosphere or to space, and one has had liquid oceans for most of its history. It is likely that planetary desiccation in one form or another is common among extrasolar terrestrial planets near the edges of their habitable zones. As our understanding of terrestrial planet evolution has increased, the importance of water abundance as a substance controlling many evolutionary factors has become increasingly clear. This is true of biological evolution, as well as geological and climatic evolution. Water is among the most important climatically active atmospheric gasses on the terrestrial planets. It is also a controlling variable for tectonic style and geologic processes, as well as a mediator of surface-atmosphere chemical reactions. Thus, understanding the sources and sinks for surface water and characterizing the longevity of oceans and the magnitude of loss mechanisms on terrestrial planets of differing size, composition and proximity to stars of various stellar types, and the range of physical parameters which facilitates plate tectonics is key to defining stellar habitable zones. Venus almost surely experienced a transition, early in its history, from a wet, more Earth- like environment to its current hot and highly desiccated state. The timescale is disputed, but recent results using 3D GCM's suggest that, depending on ancient rotation rate and topography, an ancient ocean may have persisted for ~ 2 GY. A more recent global transition is indicated by the sparse, randomly distributed and relatively pristine crater population, which implies a decrease in volcanic resurfacing rate between 300 and 1000 Myr ago. The accompanying decline in outgassing rate may have caused large climate change. Geological evidence for dramatic changes in resurfacing rate implies large amplitude climate changes which may have left a record of synchronous global deformations and other climatically forced geological signatures. These two transitions may have been causally related if the loss of atmospheric and interior water caused the transition from plate tectonics to single plate behaviour. Today ongoing volcanism most likely provides the ingredients for the global sulfuric acid cloud decks. Rapid loss of SO2 to carbonates at the surface and H2O to space strongly implies an active source for these gases on the scale of 10's of MY, a result consistent with surface data suggesting the presence of active volcanism. The stability of Venus' climate is therefore likely dependent upon active volcanism and the sulfur cycle. For much of solar system history Earth may have had a neighbouring planet with life- supporting oceans. During this time the terrestrial planets were not isolated. Rather, due to frequent impact transport, they represented a continuous environment for early microbial life. Life, once established in the early oceans of Venus, may have migrated to the clouds which, on present day Venus, may represent a habitable niche. Though highly acidic, this aqueous environment enjoys moderate temperatures, surroundings far from chemical equilibrium, and potentially useful radiation fluxes. Observations of unusual chemistry in the clouds, puzzling patterns of unidentified solar absorbers, and particle populations that are not well characterized, suggest that this environment must be explored much more fully before biology can be ruled out. A sulfur-based metabolism for cloud-based life on Venus has been proposed. While speculative, these arguments, along with the discovery of terrestrial extremophile organisms that might survive in the Venusian clouds, establish the credibility of astrobiological exploration of Venus. Given that many exoplanets are sure to be "Venus like" in many respects, the exploration of this climate history and of a possible cloud-based biosphere, has implications for terrestrial planets and habitability throughout the galaxy.

NOTES:

Hydrologic Control of Silicate Weathering and Rocky Planet Climate Stability

ATMOSPHERES

Robert Graham • University of Oxford

The classical concept of the "liquid water habitable zone" relies on the silicate weathering feedback to stabilize climate across a range of instellations. However, the representation of the silicate weathering feedback that is typically used in rocky exoplanet weathering and climate stability studies does not account for the limit on the concentration of silicate weathering products in runoff that emerges due to thermodynamic equilibrium between silicate mineral dissolution and clay precipitation in weathering systems (Maher & Chamberlain 2014). The maximum solute concentration is determined by pCO_2 and the stoichiometry of dissolution/precipitation reactions in the weathering system. We constructed a coupled zero-dimensional CO_2- and energy-balance model with simple representations of hydrology and surface properties that includes this parameterization of silicate weathering. Including the thermodynamic limit on solute concentration causes modeled global weathering fluxes to be controlled by a combination of runoff, CO_2 partial pressure, and surface properties like soil age and porosity. In our simulations, the outer edge of the habitable zone (defined as the instellation where planetary temperature falls below freezing) is more sensitive to land fraction and CO_2 outgassing rate than previous exoplanet weathering studies have indicated. The habitable zone outer edge is also very sensitive to hydrology and planetary surface properties, which have not been considered in previous exoplanet weathering studies. This suggests that the climate stability of ocean- and land-bearing exoplanets is determined by a complex interplay of poorly-understood factors.

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ATMOSPHERES

ARIEL, a mission to unravel the atmospheric composition of a large number of super-Earths

Quentin Changeat • University College London

Ariel has been selected as ESA's M4 mission for launch in 2028 and is designed for the characterization of a large and diverse population of exoplanetary atmospheres to provide insights into planetary formation and evolution within our Galaxy.

Here we explore the mission capability to perform an in-depth survey into the atmospheres of smaller planets, which may be enriched or secondary. Earth-sized planets and super-Earths with atmospheres heavier than H/He will be more challenging to observe spectroscopically. However, a recent assessment of the mission performances in Phase B has found that Ariel could have substantial capability for providing in-depth observations of smaller planets. Trade-offs between the number and type of planets observed will form a key part of the target selection process and this list of planets will continually evolve with new exoplanet discoveries replacing predicted detections.

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Understanding the spectrum of far away worlds: lessons learned form hot giant planets.

ATMOSPHERES

Vivien Parmentier • University of Oxford

Each exoplanet is a unique world to explore surrounded by a complex three-dimensional atmosphere. Yet, observations of these atmospheres are often low signal-to-noise, cover a limited range of wavelengths and are the average of different parts of the atmosphere with potentially very different properties. I will discuss the challenges and many pitfalls faced in interpreting the observations of hot, giant exoplanets in the past decade and which lessons should be kept in mind when the atmospheres of rocky worlds will become accessible.

NOTES:

Halogen solubility in silicate melts

1

Richard W Thomas & Bernard J Wood • University of Oxford

The Halogens (F, Cl, Br and I) are typically found as minor components in many magmatic and hydrothermal systems. Despite their relatively low abundances, they are thought to influence greatly the chemical and physical properties of melts [1], the genesis and evolution of magmas and their eruptive processes [2]. Understanding these effects requires knowledge of the thermodynamic properties of halogens in silicate melts and determining these properties is the principal aim of our study. In order to measure halogen activities, we added halogen buffers such as Ag/AgCl and Ag/AgBr in which the metal (as oxide) is virtually insoluble in silicate melt under the conditions of the experiment. The buffer controls the fugacity of the halogen of interest. Experiments were performed at 1.5GPa and temperatures of 1300-1500°C in a piston-cylinder apparatus. Oxygen fugacity in most experiments was controlled at the C-CO2 buffer. Our experiments show (1) that chlorine solubility in haplobasalt at 1.5GPa/1400°C can reach 5 weight%, even at Cl2 fugacities as low as 0.0035 bar. (2) reducing the oxygen fugacity increases the Cl content significantly. This indicates that Cl and O occupy similar sites in the silicate melt. (3) The chlorine content, at fixed Cl2 fugacity, increases with CaO and FeO contents of the silicate. The former observation is consistent with XANES spectroscopic measurements indicating the presence of Ca-Cl complexes in the silicate melt. The latter finding may bear particular importance for petrogenesis on Mars (where melts are known to have a higher relative abundance of Cl and Fe than terrestrial magmas [3]). Preliminary additional measurements indicate (1) that Br is significantly less soluble than Cl when Br2 and Cl2 have similar fugacities and (2) that Cl content is a strong positive function of temperature.

[1] Filiberto, & Treiman., (2009). The effect of chlorine on the liquidus of basalt: First results and implications for basalt genesis on Mars and Earth. Chemical Geology, 263, 60–68. [2] Aiuppa, et al., (2009). Halogens in volcanic systems. Chemical Geology, 263(1–4), 1–18. [3] Filiberto, et al., (2014). Effect of chlorine on near-liquidus phase equilibria of an Fe–Mg-rich tholeiitic basalt. Contributions to Mineralogy and Petrology, 168, 1027.

Coupling volcanism and interior dynamics on Io

2

Daniel Spencer • University of Oxford

Previous models of Io have assumed the presence of a magma ocean or high melt fractions [1][2][3]. Here we demonstrate that observations can be satisfied by a two-phase fluid dynamical model which does not invoke a magma ocean, a feature that would be unlikely to form due to the resultant strong density inversion. We also demonstrate the importance of magmatic emplacement in Io's lower lithosphere. High eruption rates with no volcanic emplacement lead to unrealistically thick lithospheres. This also means that the heat profile of Io's lithosphere could deviate significantly from a high-Peclet number problem such as those previously expected [4]. We argue most of Io's mantle is partially molten to a low melt fraction (2-5%) and that a thin, high melt fraction layer inferred from magnetometer data [3] can be understood as a decompacting boundary layer, but importantly this does not have an important effect on Io's eruption system.[1] Bierson & Nimmo, 2016 Icarus[2] Tyler, Henning, & Hamilton, 2015[3] Khurana et al, 2011, Science[4] Kirchoff & McKinnon, 2009.

Plate tectonics initiation as a random outcome of time-dependent convection

3

Teresa Wong • University of Munster

We investigate the time-dependent behaviour of convection to understand the factors controlling the timing of lithospheric failure. We find that the variation in timing not only systematically depends on the physical parameters of the convecting mantle but also, for convective systems with the same set of parameters, small variations in initial conditions result in different structures of the lithosphere, thus changing the stresses in the lithosphere and give rise to different timing of lithospheric failure. This study suggests that it is important to address the question of when plate tectonics can initiate on a planet, in addition to finding favourable conditions for lithospheric failure. We estimate whether plate tectonics can happen in reasonable planetary lifetimes.

Crystallization of a model silicate Moon

4

Edward Baker • Oxford Earth Science

Simulations of the hypothesised moon forming event reproduce the physical properties of the Earth-Moon system, but do not constrain the fraction of the Moon which came from the impactor. Similarities of the Earth and Moon in refractory element and isotopic ratios of a number of elements suggest however that silicate Moon is dominantly comprised of pre-impact silicate Earth. A zeroth-order model would therefore equate the silicate Moon with Earth's peridotitic mantle. Arguments against such a simplistic approach are firstly the low concentrations of volatile elements in lunar basalts and secondly the apparent enrichment of silicate Moon in Fe and Ti relative to terrestrial peridotite. In order to determine how close compositionally the source regions of lunar basalts are to terrestrial peridotite we have experimentally investigated the fractional crystallization of a magma ocean comprised of fertile, volatile-depleted pyrolite at reducing conditions and pressures appropriate to the early Moon. The approach was to start with the putative lunar peridotite composition and perform a series of stepwise crystallisation experiments. Starting at 2 GPa and 1625°C, the pressure and temperature were decreased systematically at each step to yield a crystal fraction of approximately 9% in each of 11 steps. The composition of the remaining melt fraction in each experiment was measured by electron microprobe and used as the starting composition for the next step in the series. Our results show that during fractional crystallisation of a peridotitic magma ocean the residual the melt composition evolves to refractory element concentrations similar to those observed in lunar mare basalt. Mixing of this residual melt with more olivine-rich material can account for much of the lunar surface material; it is therefore broadly possible, after extensive fractional crystallization to form the Mare Basalts from a fertile terrestrial peridotite.

Infrared Variability in Dusty White Dwarfs

5

Laura Rogers • IoA, University of Cambridge

Evidence for the survival of outer planetary systems to the white dwarf phase comes from observations of planetary material polluting the atmospheres of white dwarfs. These observations are unique in providing the composition of exo-planetary material. Infrared observations of dust very close to white dwarfs reveal how planetary material arrives in the atmospheres of white dwarfs. We expect the scattering of planetary bodies that leads to pollution to be a stochastic process, with the potential for variability on human timescales. Such variability has been found for the white dwarf WDJ0959-0200 among others, where a drop in K band flux of 20% was observed within one year. I present the results from a large scale near-infrared monitoring campaign of ~80% of all known dusty white dwarfs using UKIRT (WFCAM) over a baseline of 3 years. I address the following questions: How often do dust discs vary? In what way do they change? Are all discs capable of varying?

Wet Planetesimals around White Dwarfs

6

Matthew Hoskin • University of Warwick

I will summarise key findings on water-rich planetary material around white dwarfs. Through the analysis of photospheric pollution caused by accretion of planetary debris we are able to determine the composition of exo-planetesimals, and to date have identified four systems that are actively accreting material with a large (~10s of per cent) mass fraction of water. Hydrogen accreted in the form of water lingers in the atmosphere of a white dwarf for the remainder of its evolution. Detecting this pollutant hydrogen within the white dwarf population provides evidence of the ubiquity of water in planetary material, and we are beginning to constrain the masses of water that survive into this end phase of stellar evolution. This directly informs our understanding of the availability of water-bearing bodies early in planetary evolution, which are vital to render dry planets habitable.

Modelling Tidal Dissipation in Super-Earths with a Partially Molten Mantle

7

Fergus Horrobin • University of Toronto

Astronomers have typically treated tidal dissipation using a simple constant dissipation value and have used tidal dissipation to explore the orbital evolution of super-Earths under tides. This approach is fundamentally flawed when regions of the planet begin to melt, as has been shown in recent geophysical research. In this work, we present a self-consistent numerical model to determine how dissipation proceeds in the presence of melt on tidally-heated rocky exoplanets. We model the feedback effects between tidal heating and melt to discuss where tidal heating happens, how much dissipation can occur and how much melt is generated and transported. To do this, we combine models for rocky planet rheology, tidal dissipation, and melt transport. We evaluate the effectiveness of our model using Io and show that modelling melt is important to reproduce the correct surface heat flux. We then apply the model to rocky planets to determine where and how much dissipation occurs and answer a fundamental question: is tidal heating a runaway process, or is it confined to a region of the interior due to a regulating mechanism.

Delivering rocky planets and asteroids to white dwarfs

8

Alex Mustill • Lund University

Around half of all white dwarfs have atmospheres polluted by elements heavier than helium, brought to the white dwarf by the recent accretion of asteroids, comets or planets. By analysing the composition of the accreted material, one has a powerful tool to determine the bulk composition of extra-Solar asteroids, comets and planets. This material must be brought close to the white dwarf by dynamical interactions with large bodies that survive the evolution of the host star. I describe a scenario for dynamical delivery where stellar mass loss as the white dwarf is formed destabilises multi-planet systems, which then scatter large numbers of asteroids to the white dwarf.

Rapid seeding, core segregation, and volatile loss of planetesimal belts isolated in space and time

9

Tim Lichtenberg • University of Oxford

Multiple recent observations from astronomical surveys and geochemical studies are in tension with our current theoretical understanding of the accretion process. Radiometric dating suggests that rocky protoplanet accretion in the Solar System was long underway after 1–2 Myr after CAIs, which is supported by evidence for rapid dust coagulation during the earliest, embedded disk phases of young protostars in nearby star-forming regions. In contrast, planetesimal formation from, e.g., streaming instability, requires elevated solid densities, which typically necessitates major redistribution of dust mass during the class II disk stage. Furthermore, overcoming the earliest accretion stages before a potential onset of effective pebble accretion may be too slow to satisfy geochemical constraints on early core segregation in the non-carbonaceous meteorite reservoir. Here, we suggest that an early planetesimal formation burst during the disk infall stage can overcome some of these challenges. We combine models of dust coagulation and planetesimal formation with their subsequent thermochemical evolution to show that such early-formed, water-rich planetesimals rapidly dehydrate due to ^{26}Al heating and undergo efficient metal-silicate separation due to the build-up of internal magma oceans during the first $\approx$ 1 Myr after CAI formation, consistent with geochemically-inferred metal-silicate segregation ages. Furthermore, a second planetesimal burst from dust pile-up at a later inwards-moving snowline during the class II stage displays characteristics representative of the carbonaceous chondrite meteorite reservoir, including the build-up of cores between $\approx$ 2–3 Myr after CAIs, again consistent with geochemical constraints. Such a two-step process may rapidly seed and facilitate the accretion of the Solar System terrestrial planets prior to the gas and ice giants, and thus alleviate the tension between the inferred water inheritance during Earth's main accretion phase and the rapid water incorporation of embryos nucleated beyond the snowline.

Planet formation in the context of stellar clusters

10

Thomas Haworth • QMUL

I will summarise a series of recent papers studying the role of radiation environment in sculpting the evolution of planet-forming discs. This has particular importance for planet formation around low mass stars where the discs are weakly bound.

X-ray photoevaporation's limited success in forming planetesimals by the streaming instability

11

Jeff Jennings • IoA, University of Cambridge

The streaming instability (SI) is often invoked as a solution to the fragmentation and drift barriers in planetesimal formation, catalyzing the aggregation of dust on kyr timescales to grow km-sized cores. Yet there remains a lack of consensus on the physical mechanism(s) responsible for initiating it. One potential avenue is disc photoevaporation, wherein the preferential removal of relatively dust-free gas increases the disc metallicity. Late in the disc lifetime photoevaporation dominates viscous accretion, creating a local pressure maximum that collects drifting dust particles and may trigger the SI. Using a 1D viscous evolution model of a disc subject to internal X-ray photoevaporation, I will summarize our findings on the inefficacy of this process to build planetesimals. The amount of dust mass converted into planetesimals is often <1 Earth mass and at most a few Earth masses spread across tens of AU, suggesting that photo-evaporation may at best be relevant for the formation of debris discs, rather than a common mechanism for the formation of planetary cores. As a null result this further restricts the viable mechanisms to overcome the fragmentation and drift barriers.

Rapid Formation of Rocky Planets by Chondrule Accretion

12

Åke Nordlund • Niels Bohr Institute

Recently performed nested-grid, high-resolution hydrodynamic and radiation-hydrodynamics simulations of gas and particle dynamics in the vicinity of Mars- to Earth-mass planetary embryos (Popovas et al 2018MNRAS.479.5136P and 2019MNRAS.482L.107P) have provided quantitatively robust estimates of accretion rates for planet embryos formed inside a pressure trap. The simulations extended from the resolved surfaces of the embryos to several vertical disk scale heights, with a vertical dynamic range exceeding 1e5. Heating due to the accretion of solids caused vigorous convective motions, however even convection driven by a nominal accretion rate one Earth mass per Myr did not significantly alter the pebble accretion rate. Ray-tracing radiative transfer showed that rocky planet embryos embedded in protoplanetary disks can retain hot and light atmospheres throughout much of the evolution of the disks.

Importantly, the results showed that particles larger than the chondrules ubiquitously observed in meteorites are not required to explain the accretion of rocky planets such as Earth and Mars within the lifetime of the disk. Due to cancellation effects, accretion rates of a given size particles are nearly independent of disk surface density, while proportional to the dust-to-gas ratio. As a result, accurate growth times for specified particle sizes may be estimated. For 0.3-1 mm size particles, and assuming a dust-to-gas ratio of 1:100, the growth time from a small seed is ~1.5 million years for an Earth mass planet at 1 AU and ~1 million years for a Mars mass planet at 1.5 AU.

Åke Nordlund • Niels Bohr Institute

The magnitude and robustness of the accretion rate estimates hinges on the assumption of the embryo residing in a pressure trap. A vertically projected dust to gas ratio of 1:100 is thus a lower limit, with continued trapping of mm-size particles expected to accelerate accretion. This mechanism is therefore a prime candidate to explain rapid formation of rocky planets, leaving open only the question of by which mechanism the accretion is quenched, thus determining the final mass.

The Democratic Heliocentric Encke Method: A High Fidelity Tool for Rapidly Modelling the Planetary Formation Process

13

Peter Bartram • University of Southampton

The Democratic Heliocentric Encke Method (DHEM) is a new tool for rapidly modelling the formation of planetary systems. The effective simulation of the late stages in protoplanetary disk evolution poses three key challenges: 1) invariant conservation over the entire period required for formation; 2) ensuring correct handling during close encounters; and 3) insufficient particle numbers to resolve the effects of dynamical friction, due to computational costs.

Here we present a non-symplectic model that builds on the success of Everhart's Radau integrator: the combination of this already effective integration routine with our new formulation of a classic perturbation method allows for runtime decreases of a factor of three when compared to other non-symplectic routines such as Everhart's Radau itself. Close encounters are handled naturally and long term energy conservation is observed to allow for formation timescales to be studied precisely.
Typically, modelling of the final assembly phase of planetary formation falls firmly in the domain of symplectic integrators such as those found in MERCURY6. However, with recent advances in computational power, even with their much higher runtimes, it is now becoming feasible to achieve more precise simulation results through the use of non-symplectic methods. Further enabling this is what the DHEM aims to achieve.

In keeping with the theme of the conference, results are presented from simulations of terrestrial planets of our own Solar System. Furthermore, links to the problem of space debris are made showing possible new applications of the accurate long term integrations common in astronomy. (contributors: Dr Alexander Wittig. University of Southampton, Southampton; Dr Hodei Urrutxua. European Institute for Aviation Training and Accreditation, Univer-sidad Rey Juan Carlos, Madrid, Spain)

(Contributors: Dr Alexander Wittig. University of Southampton, Southampton; Dr Hodei Urrutxua. European Institute for Aviation Training and Accreditation, Univer-sidad Rey Juan Carlos, Madrid, Spain)

The sulfur content of rocky planets

14

Mihkel Kama • IoA, University of Cambridge

The sulfur content of a planet factors into the evolution of its internal structure and atmosphere. In the inner solar system, rocky planets appear to be sulfur-rich, but this may not be a universal outcome as volatile interstellar sulfur needs to be converted to mineral forms during star and planet formation. We investigate the range of possible sulfur content of rocky worlds. To this end, we present recent findings on the nature of sulfur reservoirs in protoplanetary disks and model the processing of sulfur during planet formation. From this we obtain a range of feasible sulfur abundances for planetary interiors modelling and suggest what types of planetary systems might be most likely to include planets with particular compositions.

(Contributors: Mihkel Kama, Shrishmoy Ray, Oliver Shorttle, Richard Booth, Cathie Clarke)

Methane absorption mechanisms on Mars

15

Sarah McIntyre • Australian National University

Increased methane levels have been discovered in the atmosphere of Mars. One of the main problems with the discovery is that the currently known loss pathways (gas phase oxidations, photolysis) operate on a lifetime on the order of hundreds of years, whereas shorter timescale loss processes are needed to explain the current observations. One possible sink that is not well quantified is the heterogeneous interaction with the dusty Martian surface. Here we investigate whether non-negligible adsorption reactions could be the explanation for a CH4 loss mechanism with a shorter lifetime that could potentially account for the observed fluctuations in methane levels in the Martian atmosphere. We conduct a series of lab experiments to analyse levels of methane adsorption in Martian simulated basalts in a variety of situations – including impactors, magmatic processes, hydrologic, and photochemical reactions – to investigate the heterogeneous interaction between methane and the Martian surface.

Sequestering Water in the Mantle to Keep M-Earths Habitable

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Keavin Moore • McGill University

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 photodissociate water molecules, during the early evolution of the host M-dwarf, which can critically impact the climate of the planet. We propose that an M-Earth can sequester water in its mantle, and that through degassing, the planet can recover an ocean on a desiccated surface once loss to space diminishes. We 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.

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

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Shang-Min Tsai • AOPP, Oxford

I will present the updated version of the open-source, photochemical kinetics code– VULCAN, with a N-C-H-O network and including photochemistry. Instead of the common approach of parametrizing atmospheric transport with only eddy diffusion (Kzz), we incorporate advection in our model and demonstrate the implication for shaping the ammonia distribution in deep Jupiter. We perform a set of tests to explore the dependence of initial conditions and the implication of the atmospheric evolution. A tentative kinetics of titanium and vanadium is also implemented to study the disequilibrium outcome of TiO and VO. Finally, we build model grids across atmospheres of hot Jupiters to super-Earths/mini-Neptunes around sun-like stars to explore chemical trends and spectral observables.

Pale Red Dots: An Investigation of Land Planet Climate Diversity

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Victoria Hartwick • NASA Ames Research Center

In this study we use an advanced 3D general circulation model to study a poorly characterized category of terrestrial climates, the land-planet, over a broad range of planetary and orbital regimes. Based on insights garnered from research on the present-day Martian climate and motivated by the seeming ubiquity of exoplanetary clouds in observations, we focus on the tight coupling between the dust and hydrology cycles. We investigate the impact of radiatively active clouds and attempt to answer fundamental science questions about the nature of precipitation. Here, we present initial results on the response of clouds and aerosols on Mars-like land planets to planetary size, distance from the sun, orbital obliquity, and surface pressure. To reduce planet-specific forcing, we first simulate an idealized Mars-type exoplanet with flat topography, zero obliquity and eccentricity, and Mars surface pressure. We assume present-day solar forcing. We then assess the impact of planetary size and orbital period and produce planetary spectrum as GCM outputs.

Can volcanism build hydrogen-rich early atmospheres?

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Pip Liggins • University of Cambridge

Hydrogen in rocky planet atmospheres has been invoked in arguments for extending the habitable zone via N2-H2 and CO2-H2 greenhouse warming, and providing atmospheric conditions suitable for efficient production of prebiotic molecules. On Earth and Super-Earth sized bodies where hydrogen-rich primordial envelopes are quickly lost to space, volcanic outgassing could act as a hydrogen source, provided it can match the loss rate from the top of the atmosphere. However, the volume of volcanic hydrogen emitted is strongly controlled by the oxidation state of the degassing melt, and the surface pressure of the planet. Here, we use a thermodynamic model of magma degassing and diffusion-limited atmospheric escape to determine which combinations of magma oxidation and hydrogen escape efficiency can build up appreciable levels of hydrogen in a secondary atmosphere. Using the modern Earth's diffusion limited escape rate, mixing ratios of 1-5 % can only be achieved by the most strongly reduced melts at low degassing pressures. Melts this reduced are very unlikely to have been present on Earth beyond the magma ocean stage, but fall at the lower end of the redox states recorded by the shergottite meteorites for Mars. Using Martian diffusion rates, a ~50 % reduction in escape efficiency compared to the diffusion limited escape rate would be required to build up a 10 % hydrogen atmosphere. We will also present results from an atmospheric model detailing the potential chemical makeup of such an atmosphere with results pertaining to prebiotic molecules.

Towards a more complex description of chemical profiles in exoplanet retrievals: A 2-layer parameterisation

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Quentin Changeat • University College London

State of the art spectral retrieval models of exoplanet atmospheres assume constant chemical profiles with altitude. This assumption is justified by the information content of current datasets which do not allow, in most cases, for the molecular abundances as a function of pressure to be constrained. In the context of the next generation of telescopes, a more accurate description of chemical profiles may become crucial to interpret observations and gain new insights into atmospheric physics. We explore here the possibility of retrieving pressure-dependent chemical profiles from transit spectra, without injecting any priors from theoretical chemical models in our retrievals. The "2-layer" parameterisation presented here allows for the independent extraction of molecular abundances above and below a certain atmospheric pressure. By simulating various cases, we demonstrate that this evolution from constant chemical abundances is justified by the information content of spectra provided by future space instruments.

Towards a more complex description of chemical profiles in exoplanet retrievals: A 2-layer parameterisation *continued...*

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Quentin Changeat • University College London

Comparisons with traditional retrieval models show that assumptions made on chemical profiles may significantly impact retrieved parameters, such as the atmospheric temperature, and justify the attention we give here to this issue. We find that the 2-layer retrieval accurately captures discontinuities in the vertical chemical profiles, which could be caused by disequilibrium processes – such as photo-chemistry – or the presence of clouds/hazes. The 2-layer retrieval could also help to constrain the composition of clouds and hazes by exploring the correlation between the chemical changes in the gaseous phase and the pressure at which the condensed phase occurs. The 2-layer retrieval presented here therefore represents an important step forward in our ability to constrain theoretical chemical models and cloud/haze composition from the analysis of future observations.

Atmospheres of Volatile-free Hot Rocky Exoplanets: Theoretical Thermal Structures and Emission Spectra

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Yuichi Ito • Department of Physics & Astronomy, University College London

Until today, over 1000 exoplanets whose radii are less than 2 Earth radii have been discovered. About 50% of those planets have substellar equilibrium temperatures high enough to melt and vaporize rock. Thus, if rocky like CoRoT-7b, they likely have atmospheres composed of rocky materials. Performing gas-melt equilibrium calculations (Schaefer & Fegley 2009) showed that the main constituents of the atmosphere are Na, O2, O, and SiO gas on magma without highly volatile elements. I call such an atmosphere a mineral atmosphere. In this presentation, I will show about the one-dimension theoretical thermal structures and emission spectra of mineral atmospheres of our model(Ito et al. 2015), mainly. Also, I will show that our feasibility assessment demonstrates that the identification of mineral atmospheres on hot rocky super-Earths in secondary transit, especially the spectral feature of SiO, is possible via observation from space telescopes. Furthermore, I'll discuss the variety of atmospheric composition on not only volatile-free but volatile-rich hot rocky exoplanets.

Outgassing of Common Rock and the Stability of Liquid Water

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Oliver Herbort • University of St Andrews

Little is known about the interaction between atmospheres and crusts of exoplanets so far, but future space missions and ground-based instruments are expected to detect molecular features in the spectra of hot rocky exoplanets. We aim to understand the composition of the gas in an exoplanet atmosphere which is in equilibrium with a planetary crust. Methods. The molecular composition of the gas above a surface made of a mixture of solid and liquid materials is determined by assuming phase equilibrium for given pressure, temperature and element abundances. We study total element abundances that represent different parts of the Earth's crust (CC, BSE, MORB), CI chondrites and abundances measured in polluted white dwarfs. For temperatures between ~ 600 K and ~ 3500 K, the near-crust atmospheres of all considered total element abundances are mainly composed of H2 O, CO2 , SO2 and in some cases of O2 and H2 . For temperatures 500 K, only N2 -rich or CH4 -rich atmospheres remain. For ~ 3500 K, the atmospheric gas is mainly composed of atoms (O, Na, Mg, Fe), metal oxides (SiO, NaO, MgO, CaO, AlO, FeO) and some metal hydroxides (KOH, NaOH). The inclusion of phyllosilicates as potential condensed species is crucial for lower temperatures, as they can remove water from the gas phase below about 700 K and inhibit the presence of liquid water. Measurements of the atmospheric composition could, in principle, characterise the rock composition of exoplanet crusts. H2O, O2 and CH4 are natural products from the outgassing of different kinds of rocks that had time to equilibrate. These are discussed as biomarkers, but do emerge naturally as result of the thermodynamic interaction between crust and atmosphere. Only the simultaneous detection of all three molecules might be a sufficient biosignature, as it is inconsistent with chemical equilibrium.

Atmospheric modelling using a chemical kinetics code

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Richard Hobbs • University of Cambridge

Chemical compositions of exoplanets can provide key insights into their physical processes, and formation and evolutionary histories. Atmospheric spectroscopy provides a direct avenue to probe exoplanetary compositions. However, whether obtained in transit or thermal emission, spectroscopic observations probe limited pressure windows of planetary atmospheres and are directly sensitive to only a limited set of spectroscopically active species. It is therefore critical to have chemical models that can relate retrieved atmospheric compositions to an atmosphere's bulk physical and chemical state. To this end we have created a chemical kinetics code for modelling exoplanetary atmospheres, which can calculate the gas phase hydrogen, oxygen, carbon, and nitrogen chemistry in planetary atmospheres.

https://www.kicc.cam.ac.uk/events/rocky-worlds-from-the-solar-system-to-exoplanets