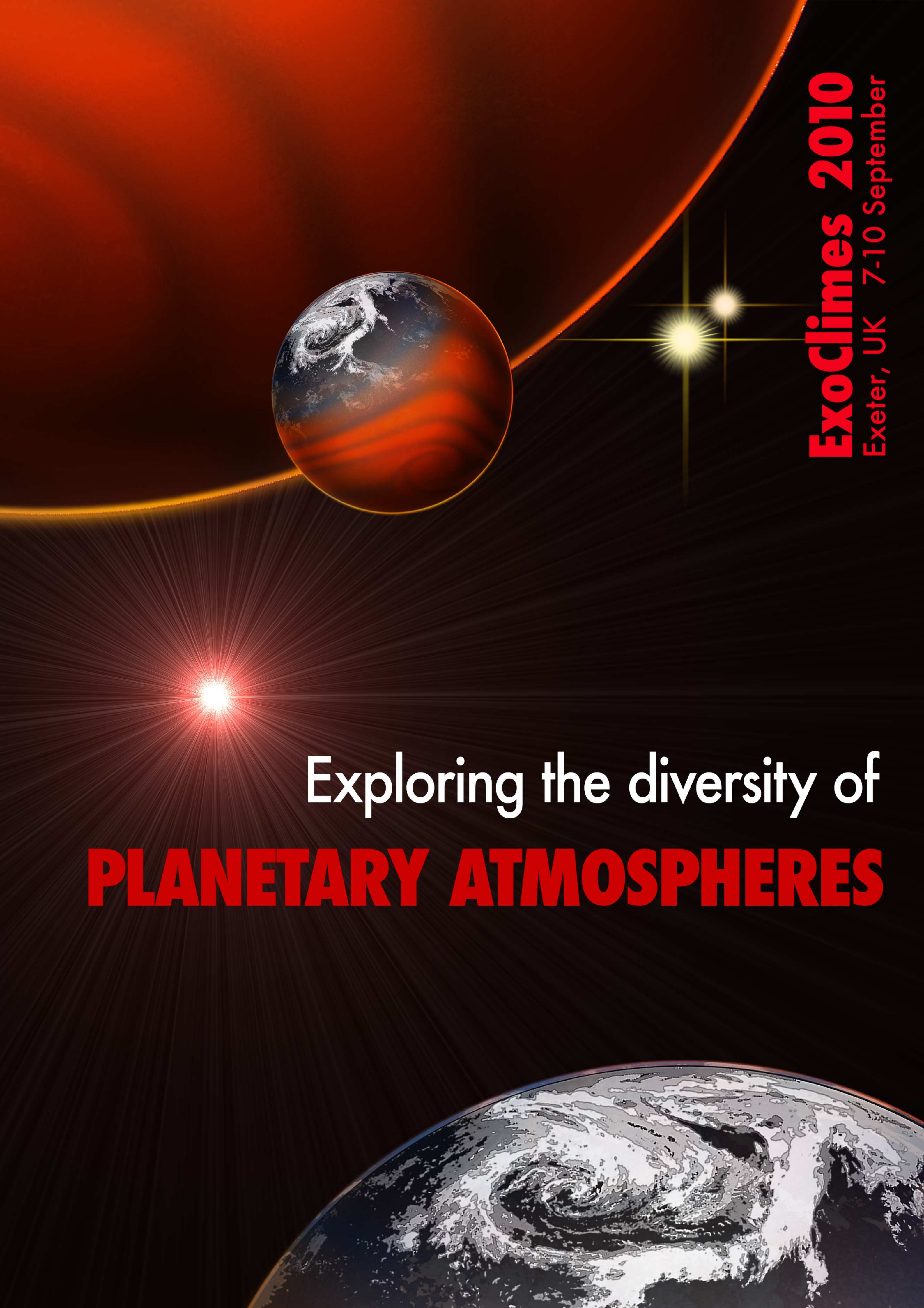

ExoClimes 2010

Exeter, UK 7-10 September

Exploring the diversity of

PLANETARY ATMOSPHERES

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Invited Speakers

Sushil Atreya – University of Michigan
Peter Cox – University of Exeter
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David Grinspoon – Denver NH Museum
James Kasting – Pennsylvania State University
Heather Knutson – UC Berkeley
Tim Lenton – University of East Anglia
Ralph Lorenz – JHU Applied Physics Lab
Kristen Menou – Columbia University
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Franck Selsis – University of Bordeaux 1
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Fred Taylor – University of Oxford

Scientific Organising Committee

Suzanne Aigrain (co-chair) – University of Oxford
Isabelle Baraffe – University of Exeter
Peter Cox – University of Exeter
François Forget – University Paris 6
Jonathan Lunine – University of Arizona
Frédéric Pont (co-chair) – University of Exeter
Adam Showman – University of Arizona
Christophe Sotin – Jet Propulsion Laboratory
Fred Taylor – University of Oxford
Roger Yelle – University of Arizona

Local Organising Committee

Suzanne Aigrain | **Aude Alapini Odunlade** (chair) | **Alasdair Allan** (IT) | **Susie Burdett** (secretary) | **Joanna Bulger** | **Rob De Rosa** (webcast) | **Nawal Husnoo** (website) | **Jenny Patience** | **Frédéric Pont**

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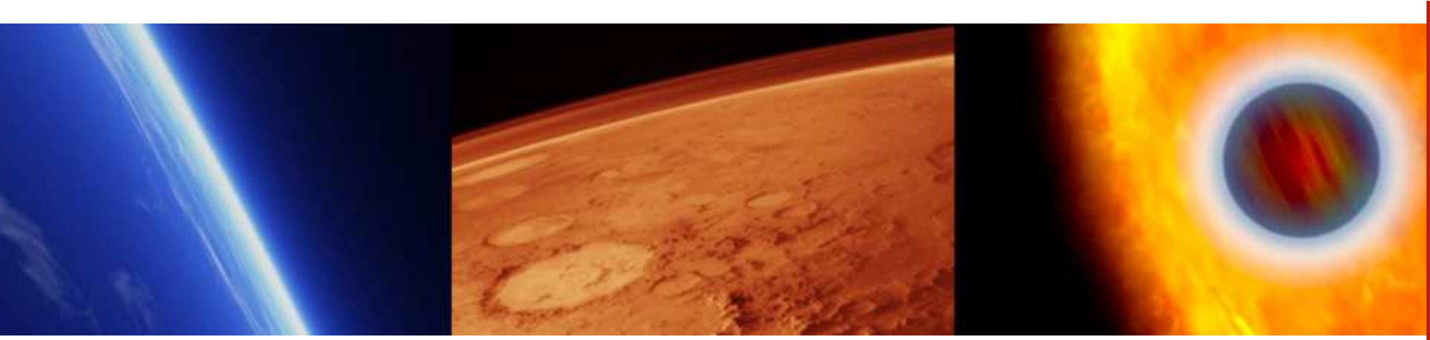

Introduction

Planetary atmospheres are complex and evolving entities, as mankind is rapidly coming to realise whilst attempting to understand, forecast and mitigate human-induced climate change. In the Solar System, our neighbours Venus and Mars provide striking examples of two endpoints of planetary evolution: runaway greenhouse and loss of atmosphere to space. The variety of extra-solar planets brings a wider angle to the issue: from scorching 'hot Jupiters' to ocean worlds, exo-atmospheres explore many configurations unknown in the Solar System, such as iron clouds, silicate rains, extreme plate tectonics, and steam volcanoes. Exoplanetary atmospheres have recently become accessible to observations.

This meeting in Exeter is designed to bring together Earth, Solar System and Exoplanet specialists to discuss recent results and the way ahead, and put our own climate in the wider context of the trials and tribulations of planetary atmospheres.

The conference themes are:

Extra-Solar planets
Atmosphere and circulation models of hot gas giants
The atmosphere-interior connection

Solar System planets
Comparative planetology, Mars, Venus, Earth, Titan

Bridging the Gap
Applying GCM to exoplanets, toy models, ocean planets
Super-Earths and lava worlds, formation of atmospheres

Living Atmospheres
Habitability, atmosphere-life co-evolution
Earth as a system, climate change

Venue

The city of Exeter, numbering a little over 100,000 inhabitants, is located in the South West of England, about 200 miles from London, a stone's throw from the South coast and the Dartmoor and Exmoor national parks. The town centre is clustered around its medieval cathedral and historic quayside, and still retains traces of its roman origins. The meeting will take place on the University's Streatham campus, on a hill overlooking the city and the Exe river estuary, about 15 minutes walk North from the city centre.

University of Exeter

Exeter is one of the UK’s most popular and successful universities with campuses in Exeter in Devon and near Falmouth in Cornwall. Students and staff enjoy some of the finest campus environments in the UK. The Southwestern counties of Devon and Cornwall boast an attractive mix of city life, countryside and coastline. The University of Exeter is currently ranked 12th out of more than 100 UK universities in the *Times* league table. It was the 2007/08 *Times Higher Education* University of the Year. The University is currently undergoing a series of major building developments throughout the Streatham Campus, such as the construction of the new Forum, the expansion of the Business School as well as the School of Biosciences and student residences.

Useful phone numbers

Peter Chalk (ExoClimes reception 7-10 Sept) 01392 723516
Holland Hall 01392 722330, Reed Hall 01392 215566
Exeter Gemini Taxi 01392 666666, Exeter Capital Taxi 01392 433433
Exeter Airport 01392 367433, Heathrow Airport 0844 3351801

Social events

Conference social events will take place on Monday, Tuesday and Thursday. We will enjoy welcome drinks in the Holland Hall bar on Monday evening and at the Imperial Pub on Tuesday evening. On Thursday afternoon, we will have a local food and drink tasting session and a walking tour of Exeter. At the tasting, there will be an opportunity to sample local cheeses, ales, ciders and preserves. The tours will be led by the local Red Coat tour guides and participants will be able to choose between tours with different themes, such as “Medieval treasures of Exeter”, “Exeter's Old and New”, “Cathedral to Quay”, and “Ghosts and legends”. The tours will be followed by the Conference Dinner at Michael Caines Restaurant at Abode Exeter on Cathedral Square.

Monday 6th

18:00 Social: Welcome Cocktails (Holland Hall bar)

Tuesday 7th

8:30 Registration opens
9:15 Introductory remarks

Session: Comparative planetology in the Solar System

9:30 Planetary atmospheres in the Solar System: ***Fred Taylor***

10:30 Refreshments

11:00 The changing appearance of Jupiter and Saturn: ***Leigh Fletcher***
11:30 The atmosphere of Titan: ***Sushil Atreya***

12:30 Lunch

14:00 The atmosphere of Venus: ***David Grinspoon***
15:00 The atmosphere of Mars: ***Peter Read***

16:00 Refreshments

16:30 The climate of early Mars through GCM: ***Robin Wordsworth***
17:00 Super-rotation of Venus and Titan with GCMs: ***Sebastien Lebonnois***
17:20 Inverse Energy Cascades in planetary atmospheres: ***David Choi***

18:00 Social: Welcome Drinks (The Imperial Pub)

Wednesday 8th

Session: Giant exoplanets

9:00 A survey of exoplanetary atmospheres: ***Heather Knutson***
9:50 Statistics of irradiated planet atmospheres from Spitzer: ***Joseph Harrington***

10:20 Refreshments

10:50 Characterizing exoplanet atmospheres through transmission spectroscopy: ***David Sing***
11:20 Observed spectra versus model atmospheres: ***Jonathan Fortney***
12:10 Detection of orbital motion and high altitude winds in HD209458b: ***Ignas Snellen***

12:30 Lunch

14:00 Atmospheric dynamics in hot Jupiters: ***Adam Showman***
14:50 3D atmospheric dynamics: ***Ian Dobbs-Dixon***
15:20 Evaporation of hot Jupiters: ***Alain Lecavelier***

15:50 Refreshments

16:30 The diagnostic value of polarization spectra: ***Daphne Stam***

Session: Terrestrial exoplanets

17:00 Formation of terrestrial planet atmospheres: ***Linda Elkins-Tanton***

Thursday 9th

Session: Terrestrial exoplanets (continued)

9:00 Atmospheres of short-period terrestrial exoplanets: ***Franck Selsis***
9:50 Exo-cartography: ***Nick Cowan***

10:20 Refreshments

Session: Bridging the gap

11:00 Exotic climates on exoplanets: ***Kristen Menou***
11:50 Hermean atmospheres of rocky exoplanets: ***Brian Jackson***
12:15 The atmosphere of the transiting super-Earth GJ1214b: ***Eliza Kempton***

12:30 Lunch

14:00 Global circulation models applied to exoplanets: ***François Forget***
14:50 Climate of Earth-like ocean planets at high obliquity: ***John Marshall***

15:20 Social: Local food tasting (Peter Chalk)
17:00 Social: Red Coat Tours (Cathedral Square)
19:00 Social: Conference Dinner (Abode)

Friday 10th

Session: Bridging the gap (continued)

9:00 Thermodynamics of planetary climate: ***Ralph Lorenz***
9:50 Idealized models for planetary climate and circulation: ***Jonathan Mitchell***

10:20 Refreshments

Session: Living planets

11:00 Habitability of exoplanets: ***James Kasting***
12:00 Accumulation of Hydrogen-rich atmospheres onto the Earth and exo-Earths: ***Masahiro Ikoma***

12:30 Lunch

14:00 The diversity of Earth's past and future atmospheres: ***Tim Lenton***
15:00 Climate Change and Exoplanet Sciences: ***Peter Cox***
16:00 Concluding remarks

16:30 Refreshments

List of Posters

Comparative planetology

1.1 Investigating the scattered light from planetary atmospheres with polarimetry
Esther Buenzli − ETH Zurich, Switzerland

1.2 A multidisciplinary investigation of Martian atmospheric chemistry
Maria Duffy − The Open University, UK

1.3 The Chemical Composition of Simulated Titan's Mid-Atmospheric Aerosols
Diana Laufer − Tel Aviv University, Israel

1.4 Seeing Double at Neptune's South Pole
Statia Luszcz-Cook − U.C. Berkeley, USA

1.5 Cyclostrophic wind in Venus mesosphere from the Venus Express temperature retrievals
Arianna Piccialli − Max Planck Institute for Solar System Research, Germany

1.6 Global GCM simulations of Jupiter's atmosphere
Roland Young − University of Oxford, UK

1.7 An analysis of Pluto occultation light curves using an atmospheric radiative-conductive model: troposphere case
Angela Zalucha − Massachusetts Institute of Technology, USA

Giant exoplanets

2.1 The atmospheres and orbital eccentricities of WASP planets
David Anderson − Keele University, UK

2.2 3D hydrodynamical simulations of substellar objects' atmospheres
Veronica Arias − Hamburger Sternwarte, Germany

2.3 Within the Atmosphere of WASP-14b
Jasmina Blecic − University of Central Florida, USA

2.4 The Orbit of WASP-12b
Christopher Campo − University of Central Florida, USA

2.5 Characterizing Planetary Atmospheres with Narrow-Band Transit Photometry
Knicole Colón − University of Florida, USA

2.6 Characterization of the extrasolar planet TrES-1b
Patricio Cubillos − University of Central Florida, USA

2.7 The effect of scattering clouds and dust on extrasolar planet emission spectra
Remco de Kok − SRON Netherlands Institute for Space Research, Netherlands

2.8 Optical and near-infrared measurements of dayside-emission from hot Jupiters Ernst de Mooij − Leiden Observatory, Netherlands

2.9 Ultraviolet transmission spectroscopy of the transiting exoplanet WASP-12b
Luca Fossati − The Open University, UK

2.10 A new look at NICMOS transmission spectroscopy
Neale Gibson − University of Oxford, UK

2.11 Secondary Eclipse Phase Measurements from the Spitzer ToO Program
Ryan Hardy − University of Central Florida, USA

2.12 Retrieval of Exoplanet Atmospheric Structure and Composition from Transit Spectroscopy Lee Jaemin − AOPP/Oxford, UK

2.13 A Ground-Based Optical Transmission Spectrum Survey of the Atmospheres of Transiting Exoplanets: Line Analysis and Future Work
Adam Jensen − Wesleyan University, USA

2.14 Three-dimensional atmospheric circulation of hot Jupiters on highly eccentric orbits Tiffany Kataria − University of Arizona, LPL, USA

2.15 Spitzer lightcurves of the ultrashort period, massive hot Jupiter WASP-18b
Pierre Maxted − Keele University, UK

2.16 Two Multi-Wavelength Secondary Eclipses of WASP-18b
Sarah Nymeyer − University of Central Florida, USA

2.17 Hot Jupiters in a tube and Hyperdog for planetary sniffing
Robert Peale − University of Central Florida, USA

2.18 On the radius of hot Jupiters
Frédéric Pont − University of Exeter, UK

2.19 A Ground-Based Optical Transmission Spectrum Survey of the Atmospheres of Transiting Exoplanets: First Results Seth Redfield − Wesleyan University, USA

2.20 Ground-based Photometric Detections of Thermal Emission from hot Jupiters Justin Rogers − Johns Hopkins University, USA

2.21 Spectral comparison of directly imaged, young substellar companions using integral field spectroscopy; construction of an empiric log g sequence
Tobias Schmidt − Astrophysical Institute Jena, Germany

2.22 Spectral and Polarimetric characterization of gaseous and telluric planets with SEE COAST Jean Schneider − Paris Observatory, France

2.23 Transmission spectroscopy of the sodium doublet in WASP-17b with VLT
Patricia Wood − Keele University, UK

Terrestrial exoplanets

3.1 The spectro-photometric variability of the globally-integrated infrared emission of terrestrial planets
Illeana Gomez − Laboratoire d'Astrophysique de Bordeaux, France

3.2 Spectropolarimetric signals of Earth-like exoplanets with clouds
Theodora Karalidi − SRON-Netherlands Institute for Space Research, Netherlands

3.3 Influence of clouds in atmospheres of Earth-like extrasolar planets
Daniel Kitzmann − Technische Universität Berlin, Germany

3.4 An Energy-balance model for tidally-heated ocean planets
Alastair McKinstry − National University of Ireland, Galway

3.5 Reflectance spectra of irradiated Earth-like exoplanets
Mariana Wagner − Sternwarte Hamburg, Germany

Bridging the gap

4.1 Extra-solar planetary interior and atmospheric structure models
Victoria Bending − The Open University, UK

4.2 Some Crucial Aspects of Exoplanet Atmosphere Dynamics Modeling
James Cho − Queen Mary, University of London, UK

4.3 Planetary Polar Vortices: Instabilities in Nature and in the Laboratory
Luca Montabone − LMD-Universite Paris VI / AOPP-University of Oxford

4.4 The impact of microphysics on optical properties of shallow cumulus clouds based on Large Eddy Simulations. The EULAG model and its ability to simulate exoplanets Joanna Sławińska − Institute of Geophysics, University of Warsaw, Poland

4.5 Planetary Atmospheric Circulation Regimes in a Simplified GCM
Yixiong Wang - University of Oxford, UK

Living planets

5.1 Earth Glint Observations Conducted During the Deep Impact Spacecraft Flyby
Richard Barry − NASA Laboratory for Exoplanets and Stellar Astrophysics, USA

5.2 Influence of the stellar spectral flux distribution on surface habitability and atmospheric dynamics of Earth-like extrasolar planets
Mareike Godolt − Zentrum für Astronomie und Astrophysik, TU Berlin

5.3 Response of ozone photochemical pathways to a doubling in CO_2
Mareike Godolt − Zentrum für Astronomie und Astrophysik, TU Berlin

5.4 Simulating Earth as an Extrasolar Planet
Tyler Robinson − University of Washington, USA

Talk abstracts

Comparative planetology

Planetary atmospheres in the Solar System [invited review]

Fred Taylor − Oxford University, UK

An introductory overview is given of the diversity of planetary atmospheres in the Solar System, with emphasis on their current climates, common physics, and likely evolution, as revealed by recent space missions.

The Changing Appearance of Jupiter and Saturn: Recent Results and Implications for Exoplanet Studies

Leigh Fletcher − University of Oxford, UK

Despite decades of intense research and observation, our understanding of the physics and chemistry of the giant planets of our solar system remains incomplete. And yet the origins, evolution, dynamics and composition of Jupiter and Saturn serve as the paradigm for the interpretation of exoplanetary spectra. This presentation will review recent studies of temporally evolving phenomena on a range of timescales, from hours to decades, observed by Galileo, Cassini, New Horizons and ground-based telescopes. These include (a) the global upheavals of Jupiter's banded appearance on quasi-periodic timescales and the recent ‘fading’ of the Southern Equatorial Belt; (b) the rate of asteroidal/cometary impacts and their effect on the atmospheric composition; (c) the polar vortices of both Jupiter and Saturn and their seasonal variability; and (d) the continuing evolution of Jupiter's giant anticyclones (reddening, strengthening and interactions). These are examples of the range of variability we detect in our own solar system through spatially-resolved observations. Depending on the observational geometry, such large-scale phenomena could lead to substantial variations in the disc-averaged spectra of exoplanets.

The atmosphere of Titan [invited review]

Sushil Atreya − University of Michigan, USA

Atmospheres have been discovered on only a handful of the one hundred and seventy or so moons in the solar system. Amongst them Titan is found to have the most massive and earth-like atmosphere of nitrogen, with a trace of methane thrown in for good measure. Methane to Titan is somewhat like water to Earth, displaying a cycle similar to the hydrological cycle. The combination of nitrogen and methane is responsible for Titan’s extensive photochemical “smog”, the hydrocarbon haze. In this talk, I will review our current understanding of the origin and chemical evolution of Titan’s atmosphere together with the moon’s hydrocarbon cycle, based on observations from Cassini-Huygens mission.

The atmosphere of Venus [invited review]

David Grinspoon − Denver Museum of Nature and Science, USA

Venus is commonly thought to have experienced a transition, early in its history, from a wet, more Earth-like environment to its current hot and highly desiccated state. A more recent global transition is indicated by the sparse, randomly distributed and relatively pristine crater population, which implies a rapid decrease in volcanic resurfacing rate between 300 and 1000 Myr ago. The accompanying precipitous decline in out-gassing 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 sulphuric acid cloud decks. Rapid loss of SO_2 to carbonates at the surface and H_2O to space strongly implies an active source for these gases on the scale of 10’s of million years. The stability of Venus’ climate is therefore dependent upon active volcanism and the sulphur cycle.

The atmosphere of Mars [invited review]

Peter Read − University of Oxford, UK

This talk will provide an overview of our understanding of the atmospheric circulation, meteorology and climate of Mars, based on the exploration and measurement of the Martian environment from ground-based, spacecraft and in situ platforms, and from numerical models. Many aspects of the Martian atmosphere and climate are similar in form and origin to those on the Earth, and emphasis will be placed on comparative aspects of both planets. Their mid-latitude meteorology in particular has many features in common between Mars and the Earth, although the Martian weather is significantly less chaotic than the Earth for reasons that are still imperfectly understood. Cyclic variations in the orbit and rotation of Mars have led to major changes in the state of the Martian climate on timescales of 10 Kyr - 2Myr, in ways that parallel the Milankovitch cycles on Earth. Dust and water play major roles in the Martian climate system, both today and in its past and likely future on geological timescales, and these will be explored in this talk. Finally, I will briefly discuss ongoing efforts to use simplified numerical models to capture the gross changes in circulation and climate between Earth, Mars and over a wide range of key parameters, with the eventual aim of putting Earth-like planets into a broader dynamical perspective.

Exploring the climate of Early Mars through GCM modeling

Robin Wordsworth − Laboratoire de Météorologie Dynamique, France

As we attempt to derive theoretical limits on the habitability of planets around other stars, understanding the evolution of the rocky planets in our own solar system becomes ever more critical. Mars contains abundant geological evidence for an ancient water cycle, so its history is of particular interest. Was the Martian climate once capable of supporting life? If so, why did it change? How important was the size of Mars to its evolution? Here we describe recent 3D modeling of climate scenarios for Mars as early as 4 Gyr. We analyse the effects of clouds (CO_2 and H_2O) and water vapour on the surface temperature in the primitive, denser Martian atmosphere, and discuss the likely nature of the early hydrological cycle. Finally, we assess the implications of our results in the more general context of exoplanet research.

Using both Venus and Titan's atmospheric GCM in the study of the super-rotation question

Sebastien Lebonnois − LMD / CNRS / UPMC, France

The super-rotation that is observed in the atmosphere of Venus and Titan is a specific feature that is not yet fully understood. The bulk of these atmospheres rotates much faster than the solid body of the planet, and the total angular momentum contained in the atmosphere is much larger than what would be contained if the atmosphere was rotating in average as the solid surface (which is the case for the Earth and Mars). Using Global Circulation Models of both Venus and Titan, we have obtained simulations that compare quite well with available observations for both atmospheres. Based on these simulations, we investigate some aspects of the super-rotation question, among which the respective role of rotation rate, thermal tides and other types of waves, the impact of seasonal variations on Titan, the role of the opacity layer located in altitude. Angular momentum exchanges with the surface and transport in the atmosphere are studied, as well as the influence of parameters such as the boundary layer scheme or the initial conditions. The similarities and differences between Venus and Titan illustrate the complexity of this circulation feature.

Inverse Energy Cascades in Terrestrial, Jovian, and Exoplanet Atmospheres

David Choi − University of Arizona, USA

The circulation of planetary atmospheres is often dominated by jet streams and vortices with large horizontal dimensions. The existence of such features, while potentially resulting from a variety of mechanisms, are promoted by the natural tendency of quasi-two-dimensional fluids − like atmospheres − to turbulently transfer energy from small length scales to large ones. Under appropriate conditions, this process − known as an inverse energy cascade − can generate meteorological features at the planetary scale even when the turbulent instabilities that energize the circulation exhibit very small length scales. In the context of exoplanets, such inverse cascades, if present, could play a crucial role by generating global-scale meteorology that is amenable to characterization via lightcurve mapping and other techniques that cannot resolve the planetary disk. Here, we examine the evidence for inverse energy cascades, and evaluate their potential for shaping the global-scale circulation, across planetary atmospheres. We first review observational and numerical modeling studies that have investigated the inverse cascade in Earth's atmosphere. Classic studies of atmospheric kinetic energy and passive tracers provide compelling evidence, though questions exist even for this best-studied case. Next, we evaluate the evidence at Jupiter and Saturn, where the weaker friction may better allow the unimpeded existence of an inverse cascade. We present a new observational data set, based on an analysis of Cassini images, supporting the existence of an inverse cascade in Jupiter's atmosphere. Finally, we survey the conditions that could allow inverse energy cascades to exist in typical exoplanetary atmospheres and discuss the observational implications.

Giant exoplanets

A Survey of Exoplanetary Atmospheres [invited review]

Heather Knutson − University of California in Berkeley, USA

The past decade has marked a period of great progress in our quest to discover and characterize the properties of the planets outside of our own solar system. Observations of transiting systems, in which the planet periodically passes in front of and then behind its star as seen from the earth, have allowed us to study the properties of these distant worlds in unprecedented detail. Most studies to date have focused on a class of close-in, gas-giant planets known as hot Jupiters, which typically have atmospheric temperatures ranging between 1000 and 2000 K, and are expected to be tidally locked. These planets present a considerable challenge for atmosphere models, as they occupy a physical regime that differs significantly from that of the solar system gas giants. In my talk I will discuss some of our initial observations of these unusual planets and our corresponding conclusions about their bulk compositions, atmospheric compositions, temperature profiles, and global circulation patterns. I will then discuss how large ongoing survey programs using the Spitzer Space Telescope will help to resolve some of the questions raised by these early observations and extend them to smaller and cooler planets.

Statistics on Irradiated Atmospheres from the Spitzer Exoplanet ToO Program as of September 2010

Joseph Harrington − University of Central Florida, USA

The Spitzer Exoplanet Target of Opportunity Program's goal is to test models of irradiated atmospheres by gathering sufficient observations to do statistics. We now have results from many planets in all Spitzer channels (3.6, 4.5, 5.8, 8, 16, and 24 microns). We will present plots including predicted equillibrium versus observed brightness temperatures for all planets observed to date, and will discuss patterns emerging in those plots. We will also discuss lessons learned from analyzing exoplanet data that concern certain widely accepted analysis and modeling approaches.

Characterizing Exoplanet Atmospheres though Transmission Spectroscopy
David Sing − University of Exeter, UK

An ever growing number and diversity of short-period planet atmospheres are now accessible through the transit-radius spectra (transmission spectroscopy). Detections over the last decade have mainly been hot Jupiter gas giant planets, which have provided the first measurements of composition, structure, and dynamics of exoplanet atmospheres. I will discuss the current state of the art for these observations including HST, Spitzer and large ground-based telescopes, review what can be learned from these measurements, and examine what can be realistically achieved in the reasonably near future through this technique.

Observed spectra versus theoretical models [invited review]
Jonathan Fortney − University of California in Santa Cruz, USA

Space-based and ground-based telescopes have allowed astronomers to detect thermal emission from the close-in planets known as ‘hot Jupiters’ and ‘hot Neptunes’. Modeling these hot atmospheres requires an understanding of radiative transfer, chemistry, cloud formation (of rock and iron), and atmospheric dynamics. These planets are quite diverse in terms of the measured fluxes from their day and night sides. Using spectroscopy, molecules that have been detected via emission and transmission spectra include H_2O, CH_4, CO, and CO_2. I will discuss the spectra from 1D and 3D models of these atmospheres, and our growing understanding of these planets as a class of astronomical objects.

Orbital motion, absolute mass, and high-altitude winds on exoplanet HD209458b
Ignas Snellen − Leiden Observatory, Netherlands

We report on the first detection of the orbital velocity of an extrasolar planet, HD209458b. High dispersion ground-based spectroscopy during a transit of this planet reveals absorption lines from carbon monoxide produced in the planet atmosphere, which shift significantly in wavelength due to the change in the radial component of the planet orbital velocity. These observations result in an assumption-free mass determination of the star and planet using only Newton's law of gravity. A blueshift of the carbon monoxide signal with respect to the systemic velocity of the host star suggests the presence of a strong wind flowing from the irradiated dayside to the non-irradiated nightside of the planet within the 0.01-0.1 mbar atmospheric pressure range probed by these observations. The strength of the carbon monoxide signal suggests a CO mixing ratio of $1\text{-}3\times10^{-3}$ in this planet’s upper atmosphere.

Atmospheric Dynamics of Hot Jupiters [invited review]
Adam Showman − University of Arizona, USA

The stellar flux incident on hot Jupiters and hot Neptunes is expected to drive an atmospheric circulation that shapes the day-night temperature difference, infrared light curves, spectra, albedo, and atmospheric composition, and recent Spitzer infrared light curves seem to show evidence for dynamical meteorology in these planets' atmospheres. Here, I will survey basic dynamical ideas and detailed 3D numerical models that illuminate the atmospheric circulation of these exotic planets. I will describe the dynamical mechanisms for pumping and maintaining the fast jets that develop in these models, particularly the broad eastward (superrotating) equatorial jet that seems to be a near-universal feature of 3D models of synchronously rotating hot Jupiters on 2-4 day orbits. The role of friction in affecting the atmospheric circulation, and the conditions that promote time variability, will also be discussed. I will finish by discussing issues relevant to the atmospheric circulation regimes of super Earths, hot Neptunes, and planets on eccentric orbits. Relevant observational implications and tests will be summarized. Where appropriate, connections to giant planets in our Solar System – Jupiter, Saturn, Uranus, and Neptune – will be emphasized, since these planets provide a foundation for our understanding of giant planet circulation generally.

3D Atmospheric Dynamics
Ian Dobbs-Dixon − University of Washington, Seattle, USA

Close-in gas giant planets are now familiar members of the growing family of extra-solar planets. While their short period orbits and proclivity for transiting has made them the target of numerous observational campaigns and our knowledge of their structure and composition has increased dramatically, fundamental questions remain. I will present 3D radiative hydrodynamical simulations of atmospheric flows on a wide variety of such objects, ranging from the well-known HD209458b to the more exotic rapidly rotating or highly eccentric objects. Such objects exhibit a diverse range of unusual behaviors including supersonic winds, shocks and instabilities, and time dependent behavior.

Evaporation of Hot-Jupiters. HST Observations and models
Alain Lecavelier des Etangs − IAP/CNRS, France

We will review the observations and the corresponding models of the evaporation of ‘hot Jupiters’. The observations started with the discovery made with HST that the planet orbiting HD209458 has an extended atmosphere of escaping hydrogen. Subsequent observations obtained with STIS and ACS and most recently with COS confirm the escape of the gas. And, even more, oxygen and carbon have been shown to be present at very high altitude in the upper atmosphere. Observations of other targets like HD189733b and WASP-12 show that evaporation is a general phenomenon which could contribute to the evolution of planets orbiting close to their parent stars. To interpret these observations, we developed models to quantify the escape rate from the measured occultation depths. Numerous models have also been published to investigate mechanisms which can lead to the estimated escape rate. In general, the high temperature of the upper atmosphere heated by the far and extreme UV combined with the tidal forces allow a very efficient evaporation of the upper atmosphere. We will review the different models and their implications.

The diagnostic value of polarization spectra applied to the Solar System planets
Daphne Stam − SRON-Netherlands Institute for Space Research, Netherlands

Polarimetry is an intrinsic part of near future exoplanet detection instruments for the VLT (SPHERE) and the ELT (EPICS) because it facilitates distinguishing direct starlight, which is unpolarized, from the polarized starlight that is reflected by a planet. The polarized planetary signal can not only be used to find a planet, it also contains a wealth of diagnostic information about the planetary atmosphere. Just like a flux spectrum, a planet's polarization spectrum consists of a continuum with superimposed high-spectral-resolution features due to absorption by atmospheric gases and Raman scattering. Indeed, this polarization spectrum appears to be more sensitive to a planet's atmospheric composition and structure than the flux spectrum, especially at the phase angles where exoplanets are most likely to be observed. We will illustrate this point using numerically simulated polarization spectra of the different types of Solar System planets, complemented with available measured polarization spectra. We will also address the background polarization signal that can be expected from exozodiacal dust surrounding exoplanets.

Terrestrial exoplanets

Formation of terrestrial planet atmospheres [invited review]
Linda Elkins-Tanton − Massachusetts Institute of Technology

Planets may obtain atmospheres from three primary sources: Capture of nebular gases, degassing during accretion, and degassing from subsequent tectonic activity. Compositions of primitive and differentiated meteorites provide a range of reasonable starting bulk materials for planetary formation and atmospheric degassing; virtually all meteorites carry at least traces of water, carbon, and sulfur, while some contain as much as 20% water. Material delivered early is likely to have been processed through a planetary melting event (a magma ocean), which are assumed to occur one or more times during the first tens of millions of years of planetary formation through accretionary impacts. A very small initial water content (less than a half mass percent) in the accreting Earth can produce a dense steam atmosphere, while a small change in chemistry can produce a carbon-based atmosphere, such as that on Venus. Recent work indicates that the earliest atmospheres degassed from rocky planets may in fact be highly reducing, producing methane or carbon monoxide atmospheres. Because the greatest majority of volatiles are liberated into the planetary atmosphere at the time of accretion, subsequent cooling is likely to lead to surface fluid oceans of water or carbon compounds, that will remain in chemical communication with the early atmosphere. Only a small fraction of the original volatiles remain in the solid planet, available to be released into the atmosphere through later volcanism. The low initial volatile contents required to degas a massive initial atmosphere that will collapse upon cooling into an ocean indicate that rocky super-Earth exoplanets may be expected to commonly produce water oceans within tens to hundreds of millions of years of their last major accretionary impact.

Atmospheres of short-period terrestrial exoplanet [invited review]

Franck Selsis − Laboratoire d'Astrophysique de Bordeaux, France

Exoplanet searches have revealed an abundant population of low-mass planets (below 15 M_{Earth}) with very diverse properties in terms of their orbits, the characteristics of their parent stars, and the planetary system in which they are found. Until we develop instruments (nuller, coronograph, occulter...) able to achieve the direct detection of terrestrial exoplanets, the physical/chemical properties of these planets and their atmospheres will have to be inferred from combined light observation (i.e. from a mixture of the light from the star and the planet). Such characterization will be restricted to particular planet types. For instance, infrared observations will have to target planets with a large-enough radius (and therefore significantly more massive than Earth) and planets that exhibit a high enough contrast with their star, meaning hot planets. Only in the case of very-low mass stars can we hope to start probing the atmospheres of habitable worlds. Although less appealing than more earth-like objects, short-period super-earths do represent an important science case and some should be observable already with JWST. Their atmospheres constitute a link between the gaseous envelope of hot-Neptune/hot-Jupiters and the atmospheres of Earth-sized terrestrial planets. They are subjected to strong tidal forces that affect their orbital evolution, rotation, structure and climate. They are also subjected to intense XUV and particle irradiation threatening the survival of their atmospheres. Gathering even basic information about the occurrence and properties of Super-Earth atmospheres as a function of orbital distance, mass, and spectral type of their host stars will provide fundamental constraints to our understanding of the origin and evolution of planetary atmospheres.

Exo-Cartography

Nick Cowan − University of Washington, USA

One of the best constraints on climate models of exoplanets is the time-variability of disk-integrated brightness. At thermal wavelengths, these variations tell us about temperature inhomogeneities on the surface of the planet (hot spots, jet streams, etc.); at reflected wavelengths, they tell us about albedo markings on the planet (clouds, continents, oceans, etc.). I will describe the first successful applications of phase function mapping and eclipse mapping for a hot Jupiter, and will outline the prospects for applying similar techniques to directly imaged exoplanets.

Bridging the gap

Exotic Climates on Exoplanets [invited review]
Kristen Menou − Columbia University, USA

Various efforts and methodologies used to address atmospheric circulation and the climate on exotic versions of the Earth will be reviewed. In particular, unusual forcing regimes on oblique and eccentric versions of Earth will be addressed. Prospects and challenges for the characterization of climatic conditions on tidally-locked Earth-like planets in the near future will be emphasized.

Hermean Atmospheres of Hot Rocky Exoplanets
Brian Jackson − NASA/Goddard Space Flight Center, USA

Current detection biases mean that most of the initially discovered rocky exoplanets will probably be on very close orbits, with corresponding large surface temperatures. Such planets will likely have tenuous atmospheres composed of vaporized rocky material, similar to Mercury's exosphere. In fact, initial calculations suggest the atmospheres may have column abundances of volatiles, particularly sodium, exceeding the column abundance of Mercury's exosphere by many orders of magnitude. The volatiles likely present in the atmospheres of hot rocky exoplanets may be detectable through observations with sufficiently high spectral resolution. For example, at the column abundance of sodium predicted for CoRoT-7b's exosphere, optical depths at sodium's D1 and D2 resonant scattering features may approach 10^6. Consequently, the transit depth for CoRoT-7 b in the wavelengths of these features may be as much as 40% larger than out of the features. As for Mercury, detection of such an atmosphere around a hot rocky exoplanet would provide important constraints on the planet's composition. In this talk, we will present the results from models of such putative atmospheres for a range of hot rocky exoplanets orbiting a range of host stars and discuss their detectability.

The Atmosphere of the Transiting Super-Earth GJ1214b
Eliza Kempton (formerly Miller-Ricci) − UC Santa Cruz, USA

The planet GJ1214b is the first known transiting super-Earth requiring a significant atmosphere to explain its observed mass and radius. Models for the structure of this planet predict that it likely possesses a H-He envelope of at least 0.05% of the total mass of the planet. However, models with a significant water steam atmosphere are also permitted, given the planet's measured average density. We explore a range of possible atmospheres for the planet, and we present transmission and emission spectra for each of these cases. We find that, if GJ1214b possesses a hydrogen-rich atmosphere as predicted, then the primary transit depth for such an atmosphere would vary at a level of up to 0.3% as a function of wavelength, relative to the background light of its M-dwarf host star. Observations at this level of precision are obtainable with current space-based and ground-based instrumentation.

Global Climate models applied to exoplanets [invited review]
François Forget − LMD/IPSL, Paris, France

The possible climate conditions and habitability of extrasolar terrestrial planets have so far mostly been studied with simple 1D steady-state radiative convective models that simulate the global mean conditions. Much has been learned, but the next step is to perform 3D simulations using Global Climate models (GCMs) similar to those used on Earth for weather forecasts or climate evolution studies. Because these models are almost entirely built from physical equations (rather than empirical ones), they can be applied to many kinds of terrestrial planets. Indeed, a full GCM can be considered as a ‘planet simulator’ that aims to simulate the complete environment on the basis of universal equations only. Our team has developed GCMs for the terrestrial atmospheres in our solar system (Mars, Venus, Titan, Triton, Pluto). These projects have confirmed that many processes controlling the climate (e.g., large-scale dynamics, turbulence, storage and diffusion of heat in the subsurface, etc...) can be modelled using the same equations on most terrestrial planets. On this basis, we have developed a new ‘universal’ GCM, which by construction will be general enough to study a wide range of possible habitability scenarios. The real challenge has been to develop a radiative transfer code fast enough for 3D simulations and versatile enough to model any atmospheric cocktail / thick atmosphere accurately. We will present a study performed to represent the exoplanet Gliese 581d, on the outer edge of the habitable zone, and preliminary results on the behaviour of a planet near the inner edge of the habitable zone, with liquid water on its surface, but exposed to a stellar radiative flux larger than on the Earth.

Explorations of the climates of earthlike ocean exoplanets at high obliquity

John Marshall − Massachusetts Institute of Technology, USA

One method of studying earth-like exoplanets is to view earth as an exoplanet and consider how its climate might change if, for example, its obliquity were ranged from 0 to 90 degrees. High values of obliquity particularly challenge our understanding of climate dynamics because if obliquity exceeds 54 degrees, then polar latitudes receive more energy per unit area than do equatorial latitudes. Thus the pole will become warmer than the equator and we are led to consider a world in which the meridional temperature gradients, and associated prevailing zonal wind, have the opposite sign to the present earth, and the equatorial Hadley circulation exists where it is cold rather than where it is warm. And all this is going on in the context of a very pronounced seasonal cycle. The problem becomes even richer when one considers the dynamics of an ocean, should one exist below. A central question for the ocean circulation is: what is the pattern of surface winds at high obliquities, as it is the winds that drive the ocean currents and thermohaline circulation? How do atmospheric weather systems growing in the easterly sheared middle latitude jets and subject to a global angular momentum constraint, combine to determine the surface wind pattern? Should one expect middle latitude easterly winds? If not, why not? Finally, a key aspect with regard to habitability is to understand how the atmosphere and ocean of this high obliquity planet work cooperatively together to transport energy meridionally, mediating the warmth of the poles and the coldness of the equator. How extreme are seasonal temperature fluctuations? Should one expect to find ice around the equator? Possible answers to some of these questions have been sought by experimentation with a coupled atmosphere, ocean and sea-ice General Circulation Model of an earth-like aqua-planet: i.e. a planet like our own but on which there is only an ocean but no land. The coupled climate is studied across a range of obliquities (23.5, 54 and 90). We present some of the descriptive climatology of our solutions and how they shed light on the deeper questions of coupled climate dynamics that motivate them. We also review what they tell us about habitability on such planets.

Thermodynamics of Planetary Climate [invited review]

Ralph Lorenz − JHU Applied Physics Laboratory, USA

Atmospheres are heat engines. Every raindrop that falls was first hoisted aloft subject to the laws of thermodynamics, which provide some insight into the potential vigour of a planetary climate. The generation of available potential energy − and thus the mechanical work and how this work is then dissipated − controls how interesting an atmosphere may be. Some examples will be discussed. The concept of habitability as a global property also merits some discussion. Even if the average surface temperature of a world permits liquid water, the presence of large horizontal temperature gradients may make large areas uninhabitable, and can sequester volatiles in the colder regions, dessicating the body as a whole. In this connection, it is useful to estimate the horizontal temperature gradients on a body. The flows in oceans and atmospheres may conspire − if dynamically permitted to do so − to maximize the entropy production by their heat transport. This notion will be presented and cautions on the application of this principle will be discussed.

Idealized models for planetary climate & circulation: from Earth to Titan
Jonathan Mitchell − UCLA, USA

Titan is in many respects the most Earth-like environment in the Solar System. Its thick, nitrogen atmosphere is laden with methane vapor which is an active thermodynamic (and radiative) constituent, thus playing the role of water vapor in Earth's atmosphere. I will show how idealized climate models can be usefully applied to Titan's climate and atmospheric circulation. In the first part, I will use a steady theory for Earth's tropical circulation and an idealized, moist GCM to characterize Titan's weather and climate. In the second part, I will use a dry GCM to show the transition from an Earth-like wind pattern to a Titan-like wind pattern, the latter being characterized by atmospheric angular momentum exceeding solid-body rotation, i.e., superrotation.

Accumulation of hydrogen-rich atmospheres onto the Earth and exo-Earths
Masahiro Ikoma − Tokyo Institute of Technology, Japan

Hydrogen-rich atmospheres of disk (or nebular) origin could affect our understanding of the origin and evolution of terrestrial planets. It is a natural by-product of planet formation. It is, however, unresolved whether the Earth had such a primordial atmosphere. That hydrogen atmosphere may have brought water, and also affected the orign and evolution of life. Recently, we have faced a new problem as to transiting exoplanets; hydrogen causes degeneracy in inferred compositions of exoplanets with measured masses and radii. In this talk, with our simulations of accumulation of atmospheres of disk origin, I constrain the amout of hydrogen that Earth-like planets should retain.

Living planets

Habiability of Exoplanets [invited review]
James Kasting − Pennsylvania State University, USA

In order to be considered habitable by terrestrial standards, an exoplanet must lie within the conventional habitable zone (HZ) around its parent star, defined as the region where liquid water is stable at the planet’s surface. Other types of planets – for example, those with subsurface liquid water – might be habitable; however, it would be difficult to detect life remotely on such planets, and hence they are of limited interest. Our models of the HZ have remained more or less the same for almost 20 years. They are defined for Earth-like planets with N_2-CO_2-H_2O atmospheres. The inner edge of the HZ is defined by loss of water, either by a runaway greenhouse, or by a variant thereof termed a ‘moist greenhouse’. The outer edge is defined by the distance at which CO_2 begins to condense on a planet’s surface. All calculations thus far have been done with 1-D climate models. Improved 3-D climate models for addressing this question are still in development. Some authors have published HZ models that depend more strongly on the nature of the planet. Such models, however, can only be applied if the planet’s characteristics have already been determined, and so they are of limited utility for guiding future searches. Although this theory of the HZ is attractive, it may well be over-simplified, as it does not seem to account for the climates of either early Earth or early Mars. Mars looks as if it was habitable early in its history, yet it falls outside of the Kasting et al. (1993) boundaries. Attempts to explain the warmth of early Mars by adding additional greenhouse gases to its atmosphere have for the most part been unsuccessful (as have models in which early Mars was generally cold). Early Earth was well within the published HZ boundaries; however, past CO_2 concentrations derived from paleosols and, more recently, from banded iron-formations are significantly lower than those required to compensate for the reduced luminosity of the young Sun. Additional surface warming could have been provided by reduced greenhouse gases, including both CH_4 and NH_3, by enhanced pressure-broadening by N_2, or by cloud albedo feedbacks. An attempt will be made to sort out this confusion and to explore the implications for the prospects of finding habitable planets elsewhere.

The diversity of Earth's past and future atmospheres [invited review]

Tim Lenton − University of East Anglia, UK

As James Lovelock pointed out in 1965, the extreme thermodynamic disequilibrium of the Earth's present atmosphere reveals that life is abundant at the surface. The search for life on extra-solar planets might best be achieved by looking for atmospheric disequilibrium. At the same time, Lovelock cautioned not to assume that life elsewhere would look anything like that on the Earth. By extension, the atmospheres of other living planets could be quite different to our own. Indeed, by looking back at Earth history we can get a sub-sample of some of the alternative atmospheres that a thriving biosphere can support. The talk will review what we know about those past atmospheres, and what models project for the future atmosphere of the Earth. Oxygen is of particular interest as it is widely assumed to be a bio-signature – although really it is the co-existence of methane and other reduced gases with it that is most revealing of life. Importantly, the current oxygen-rich (15-30%) atmosphere is the exception rather than the rule – it has only been present for about a tenth of the planet's history. Oxygen has risen in a series of steps. Prior to the origin of oxygenic photosynthesis, roughly 2.7 billion years ago, it was a negligible constituent. Then for hundreds of millions of years, oxygen flickered around a part per million of the atmosphere and methane was more chemically dominant. At the 'Great Oxidation', 2.4-2.2 billion years ago, oxygen increased by orders of magnitude and the ozone layer formed, in what appears to have been a permanent, irreversible transition. Still oxygen probably remained only about 1% of the atmosphere – for the next 1.5 billion years we really have rather poor constraints. Recent evidence suggests several 'Lesser Oxidations' happened between about 700 and 400 million years ago. Finally we get the charcoal record reliably indicating oxygen above 15% of the atmosphere for the past 370 million years. In the long-term future, oxygen is forecast to decline. Generalising beyond the Earth reveals two key points: (1) The process of oxygenic photosynthesis, which is absolutely necessary to produce an oxygen-rich atmosphere, is extremely difficult to evolve and might only be expected to arise on a tiny fraction of planets that have evolved prokaryote life. (2) Even where oxygenic photosynthesis does evolve, there is no guarantee that a Great Oxidation will occur – it could be delayed beyond the habitable lifetime of a terrestrial planet. Consequently, we have to conclude that looking for oxygen is not the best way to look for life elsewhere.

Climate Change and Exoplanet Sciences, what can they learn from each other? [invited review]

Peter Cox − University of Exeter, UK

Global warming since the industrial revolution on Earth is almost certainly due to anthropogenic emissions of greenhouse gases − the underlying climate science is well-founded in the physics of the 19th and early 20th centuries. However, there are still significant uncertainties in projections of how the Earth's climate will evolve under feasible socioeconomic scenarios, and these uncertainties become very pronounced as the climate is pushed beyond its current regime of operation. Is it possible that the Earth's climate could "runaway" or flip to a new "hothouse" stable state under scenarios of increased greenhouse gas emissions? The rapidly emerging science of Exoplanets has the potential to help by providing information on a spectrum of planetary climates spanning a wide range in atmospheric composition and orbital parameters. Equally, the science of climate change may cast light on important processes on Exoplanets, such as the processes controlling planetary energy balances (including greenhouse gases and atmospheric aerosols), and pole-to-equator transfer of heat. This talk will attempt to highlight important potential synergies between the sciences of climate change and Exoplanets, drawing on the results presented at this conference.

Comparative planetology

1.1 Investigating the scattered light from planetary atmospheres with polarimetry

Esther Buenzli – ETH Zurich, Switzerland

The polarization of light reflected from a planet provides unique information on the atmosphere structure and scattering properties of particles in the upper atmosphere. The solar system planets show a large variety of atmospheric polarization properties, from the thick, highly polarizing haze on Titan and the poles of Jupiter, Rayleigh scattering on molecules on Uranus and Neptune, to clouds in the equatorial region of Jupiter or on Venus. Polarimetry is also a promising new technique to study extra-solar planets. The future VLT planet finder instrument SPHERE will be equipped with a polarimetric mode for the search and characterization of extra-solar giant planets around nearby stars, while polarimetric observations of hot Jupiters have already been attempted with existing instruments. For the preparation of the SPHERE planet search program we have made a suite of polarimetric observations and models for the solar system gas giants. For the outer planets, observations from Earth measure mainly backscattered light that is generally unpolarized. However, a second order scattering effect produces a measurable limb polarization for resolved planetary disks. We have made detailed models for the spectropolarimetric signal of the limb polarization of Uranus and the poles of Jupiter between 520 and 935 nm, to derive scattering properties of haze and cloud particles. Additionally, we have calculated a large grid of polarization phase curves for simple atmosphere models. We discuss the diagnostic potential of polarimetric observations and the expected polarization of extrasolar giant planets.

1.2 A multidisciplinary investigation of Martian atmospheric chemistry

Maria Duffy – The Open University, UK

For many years the Mars exploration program has focused on the mantra “follow the water” as a means of unraveling key questions about the red planet such as whether the surface has ever supported life and what the ancient climate could have been like. However, with discoveries such as the seasonal plume of methane and sulfate-bearing soil, many have now turned to “follow the chemistry” as being the true way to make progress. It is clear that the interaction of the atmosphere and the lithosphere and any potential biosphere will mark the atmosphere in ways we can only speculate about at present. Currently, there are many proposals for possible missions to monitor trace gases in the Martian atmosphere with a view to studying these possible interactions. The aim of these missions will be to constrain the possible reactions taking place in the Martian system and to finally allow us to begin answering some of these questions. The current project will investigate the chemistry of the Martian atmosphere through laboratory-based simulation and with computational experiments using a Mars General Circulation Model. Plasma discharge experiments have been used with Mars-like gas mixtures to gain insight into the possible reactions occurring in the atmosphere and their rates under different conditions. Eventually these experiments will be scaled up to use in the Open University Mars Simulation Chamber complete with Mars analogue soil and a Solar UV simulator. The data collected will be used in the Mars GCM to investigate how the trace species are transported around the planet from potential surface source regions and calculate their lifetimes and distributions in the atmosphere. It is hoped that these simulations will constrain some of the reactions occurring between trace species in the atmosphere and identify their sources and sinks be they geological or biological in origin. An understanding of the reactions involved is necessary to gain knowledge not just of Mars but other planets in our own solar system and beyond. To identify biosignatures such as ozone and methane on other worlds we must first understand their presence in the Martian system, a system for which detailed, high-resolution observation is possible.

1.3 The Chemical Composition of Simulated Titan's Mid-Atmospheric Aerosols

Diana Laufer – Tel Aviv University, Israel

The research focuses on the chemical composition of Titan's aerosols, formed by UV irradiation under the conditions of Titan's troposphere. A large fraction of the major unsaturated species: C_2H_2 C_2H_4, HCN and HC_3N, with mixing ratios of about $3x10^{-6}$, 10^{-7}-10^{-8}, $3x10^{-7}$ and 10^{-9}-10^{-10} respectively, reside in Titan's atmosphere between 150-500 km, before they condense near the tropopause. A large flux of medium wavelength UV penetrates down to the troposphere, resulting in the polymerization of these unsaturated compounds and the formation of aerosols. In our experiments, the analysis of the resulting products by UV photolysis at 1849Å and 2537Å of different mixtures of C_2H_2 with N_2 and C_2H_2 with CH_4, HCN and C_2H_4, was carried out by Mass Spectrometer and Supersonic Gas Chromography Mass Spectrometer, compared with the NIST library, as well as Elemental Analysis and Direct Chemical Ionization. In the gas phase, C_2H_2 photolysis results in unsaturated C_4 species which, upon further addition of C_2 form the cyclic benzene. These gas-phase intermediates are consumed when an acetylene-poor gas mixture is irradiated for a long time, giving rise to larger solid-state species, mainly by addition of C_2, followed by further cyclization. The largest species formed was the condensed 5-ring benzopyrene. Another fraction of the polymers consists of polyvinyl and vinyl acetylene chains, which are cross linked due to their labile π electrons and form an insoluble solid matrix. This explains the reduction of the C:H ratio from the condensed aromatics of 1.2 to the measured C:H = 1.013±0.001 in the polymers. The formation of aerosol particles and their agglomeration to fractal particles were modeled and found to agree very well with DISR observations.

1.4 Seeing Double at Neptune's South Pole

Statia Luszcz-Cook – U.C. Berkeley, USA

Keck near-infrared images of Neptune from UT 26 July 2007 show that the cloud feature typically observed within a few degrees of Neptune's south pole had split into a pair of bright spots. A careful determination of disk center places the cloud centers at −89.07±0.06 and −87.84±0.06 degrees planetocentric latitude. If modeled as optically thick, perfectly reflecting layers, we find the pair of features to be constrained to the troposphere, at pressures greater than 0.4 bar. By UT 28 July 2007, images with comparable resolution reveal only a single feature near the south pole. The changing morphology of these circumpolar clouds suggests they may form in a region of strong convection surrounding a Neptunian south polar vortex.

1.5 Cyclostrophic wind in Venus mesosphere from the Venus Express temperature retrievals

Arianna Piccialli – Max Planck Institute for Solar System Research, Germany

Cyclostrophic balance is a special approximation of the thermal wind equation that implies the balance between the equator-ward component of the centrifugal force and the meridional pressure gradient. This equation gives a possibility to reconstruct the zonal wind u − if the temperature field is known − together with a suitable lower boundary condition on u. Leovy (1973) first noted that the strong zonal winds at the cloud tops in Venus atmosphere are well described by the cyclostrophic approximation. Venus is not the only body in the solar system where cyclostrophic approximation is valid. Saturn’s satellite Titan, like Venus, is a slow rotator and the strong zonal winds in its stratosphere are in cyclostrophic balance. The cyclostrophic approximation is also valid on smaller scales, such as in Earth cyclones or Mars and Earth dust devils. Here we present retrievals of the cyclostrophic wind in Venus mesosphere derived from VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) and VeRa/Venus Express temperature soundings. VIRTIS probes Venus south hemisphere in the altitude range 65-90 km with a very good spatial and temporal coverage. VeRa (Radio Science Experiment) observes both north and south hemispheres between 40-90 km of altitude with a vertical resolution of ~100 m. Thanks to Venus Express capabilities, the variability of zonal wind with latitude, altitude and local time was analyzed in detail. The main features of the retrieved winds are: 1) a mid-latitude jet with a maximum speed up to 140±15 m/s which occurs around 50°S latitude at 70 km altitude; 2) the fast decrease of the wind speed from 60°S toward the pole; 3) the decrease of the wind speed with increasing height above the jet. Cyclostrophic wind shows satisfactory agreement with the cloud-tracked winds derived from the Venus Monitoring Camera (VMC/VEx) UV images. A disagreement is observed at the equator and near the pole due to the breakdown of the cyclostrophic approximation. Knowledge of both temperature and wind fields allowed us to study stability of the atmosphere with respect to convection and turbulence. The Richardson number was evaluated from zonal field of measured temperatures and thermal winds. The atmosphere is characterized by a low value of Richardson number from ~45 km up to ~60 km altitude at all latitudes that corresponds to the lower and middle cloud layer, indicating an almost adiabatic atmosphere. A high value of Richardson number was found in the region of the mid-latitude jet, indicating highly stable atmosphere. The necessary condition for barotropic instability is satisfied on the pole-ward side of the mid-latitude jet, indicating the possible presence of wave instability.

1.6 Global GCM simulations of Jupiter's atmosphere

Roland Young – University of Oxford, UK

The mechanisms responsible for the formation and maintenance of the ubiquitous zonal jets on the giant planets, of which Jupiter's are the most spectacular example, are still poorly understood. Of particular interest is how energy is injected into the system at small scales. Well established results in turbulence theory can be used to argue that such an energy injection combined with a planetary beta-effect can lead to an inverse cascade of energy to large scales resulting in planetary-scale zonal jets. Observations of lightning on the giant planets suggest that moist convection might be the dominant process responsible. These jets can be reproduced qualitatively using idealised models such as the 2D non-divergent equations on a sphere, and recently using quasigeostrophic and simpified General Circulation Models (GCMs). A GCM for giant planet atmospheres has been developed in Oxford over the last several years based on the dynamical core of the UK Met Office Unified Model. Recent work has applied this model to the troposphere and stratosphere of Jupiter including simple parameterisations of cloud formation and moist convection. These simulations have been carried out over a limited area in latitude encompassing the south equatorial and temperate belts and the Great Red Spot. We report on our progress in extending this model to a global domain using a supercomputing cluster available in Oxford. With these developments we hope to be able to resolve the zonal jets on a global scale and hence investigate Jupiter's global dynamics using a more realistic model.

1.7 An analysis of Pluto occultation light curves using an atmospheric radiative-conductive model: troposphere case

Angela Zalucha – Massachusetts Institute of Technology, USA

Ground based observations of stellar occultations by Pluto have been a major source of information about Pluto's atmosphere over the past two decades. Along with spectroscopic observations, modeling studies have shown that Pluto's atmosphere is primarily made of N_2 with trace amounts of CH_4 and CO, but the abundances are not precisely known. The vertical temperature structure consists of a stratosphere (temperature increasing with height) and a mesosphere at higher altitudes (temperature constant or decreasing with height). Pluto's lower atmosphere remains enigmatic, in part because stellar occultations have difficulty probing deep into the atmosphere. The depth of the troposphere, if it exists at all, has yet to be constrained. Similarly, surface pressure is not well known and is also complicated because it may be changing with time (possibly because of an N_2 frost cycle, analogous to the Martian CO_2 cycle). Pluto's surface radius, which may be inferred from occultation studies or mutual events with its moon Charon, is still uncertain to within several kilometers. Using the radiative-conductive model of Strobel et al. 1996 (Icarus, 120, 266-289), now with a convective troposphere feature, I have analyzed Pluto stellar occultation light curves from the years 1988, 2002, 2006, and 2008. From these I am able to place constraints on surface pressure, surface radius, and troposphere depth. This study uses a sophisticated radiative transfer model, with the requirement of radiative equilibrium, unlike previous studies using idealized models.

Giant exoplanets

2.1 The atmospheres and orbital eccentricities of WASP planets

David Anderson – Keele University, UK

We present recent ground-based and space-based observations of occultations of WASP planets by their host stars. We combine measured occultation depths with atmosphere models to infer the properties of planetary atmospheres. We also combine the timing of occultations with high-precision radial velocimetry to determine planetary orbital eccentricities. These are necessary to determine the contributions of tidal heating to the planets' energy budgets, thus permitting a testing of the hypothesis that tidal heating is responsible for the bloatedness of some exoplanets.

2.2 3D hydrodynamical simulations of substellar objects' atmospheres

Veronica Arias – Hamburger Sternwarte, Germany

Since the 1995 discovery of the first Brown Dwarf and the first Extrasolar Giant Planet, hundreds of these sub-stellar objects have been detected. With surface temperatures below 2000 K, convection is the dominant energy transport mechanism and plays a key role in the thermal structure and chemical mixing of their atmospheres. Modeling such cool atmospheres has proven to be challenging. An enormous progress has been made in the treatment of opacities and in the development of an Equation of State (EOS), but the Mixing Length Theory is still widely used as an approximation for convection. We treat convection in a more realistic way. We use the FLASH Code to perform 3D hydrodynamical simulations in order to study the various effects of convection in the sub-stellar objects's atmospheres. Since molecules form at such low temperatures and these chemical processes can energetically play an important role for the onset of convection, the choice of the EOS is crucial. We have coupled to the FLASH code a realistic and detailed EOS, which is a module of the PHOENIX code. This EOS can handle the low temperatures encountered in the sub-stellar objects' atmospheres through a detailed treatment of the physical and chemical phenomena. We will present the advantages and limitations of this approach, and the current status of project.

2.3 Within the Atmosphere of WASP-14b

Jasmina Blecic – University of Central Florida, USA

Having a mass and density that exceeds most of the known extrasolar planets, a significant orbital eccentricity that suggests the possible existence of a companion, and being in very close proximity to its host star, the hot Jupiter WASP-14b represents one of the most interesting objects for atmospheric analyses. We will present analyzed photometric data obtained in 2009 during the cryogenic mission with the Spitzer Exoplanet Target of Opportunity Program. Observations in two wavelength ranges, 4.5 and 8.0 microns, led us to the detection of two secondary eclipses. Analytic light curve models fit the data using a Metropolis-Hastings Markov Chain Monte Carlo (MCMC) algorithm that incorporates corrections for systematic effects. We will discuss these corrections and present estimates of infrared brightness temperatures and constraints on atmospheric composition. Support for this work is provided by the Spitzer operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

2.4 The Orbit of WASP-12b

Christopher Campo – University of Central Florida, USA

We observed two secondary eclipses of the exoplanet WASP-12b using the Infrared Array Camera on the Spitzer Space Telescope. The close proximity of WASP-12b to its G-type star results in extreme tidal forces capable of inducing apsidal precession with a period as short as a few decades. This precession would be measurable if the orbit had a significant eccentricity. The ground-based secondary eclipse phase reported by Lopez-Morales et al. (0.510±0.002) implies eccentricity at the 4.5 sigma level, and the spectroscopic orbit of Hebb et al. has eccentricity 0.049±0.015, a 3 sigma result, and predicts an eclipse phase of 0.509±0.007. Our eclipse phases are 0.5012±0.0006 (3.6 and 5.8 microns) and 0.5007±0.0007 (4.5 and 8.0 microns). These values are inconsistent with the ground-based data, but marginally consistent with the spectroscopic orbit. Considering the unlikely possibility that precession brought the long axis of the orbit into alignment during our observations, a model considering these points and transit times from professional and amateur observers estimates orbital precession at 0.02±0.01 deg/d. This implies a tidal Love number of 0.15±0.08, indicating a very centrally condensed planet. However, if the orbit is actually eccentric, we have observed it at a remarkably special time to find eclipse phases consistent with apsidal alignment. Future observations can decide between these possibilities.

2.5 Characterizing Planetary Atmospheres with Narrow-Band Transit Photometry

Knicole Colón – University of Florida, USA

Increasing numbers of transiting extrasolar planets are having their atmospheres characterized via both ground-based and space-based observations. We present a unique technique that will allow us to characterize the atmospheres of transiting exoplanets using high-precision narrow-band photometry with large ground-based telescopes. Specifically, we will discuss our use of the tunable filter imaging mode of the OSIRIS instrument installed on the 10.4-meter Gran Telescopio Canarias and how we use this instrument to take observations at different wavelengths nearly-simultaneously throughout a transit event. Each observation has a small bandpass (FWHM ~ 1.2 nm), so we can use the data acquired at multiple wavelengths to gain spectral information about atomic and/or molecular absorption features. We are currently using this technique to measure absorption due to potassium (K I) in the atmospheres of exoplanets. We will discuss preliminary results as well as our future plans for this project.

2.6 Characterization of the extrasolar planet TrES-1b

Patricio Cubillos – University of Central Florida, USA

The space-based telescope observations of secondary eclipses have allowed the identification of several molecules in extrasolar planet atmospheres. Here, as part of the Spitzer Target of Opportunity program, we will present an analysis of three secondary eclipse light curves of the extrasolar planet TrES-1b at 16 microns using the Spitzer's InfraRed Spectrograph instrument, reporting its brightness temperature. Complementing with existing data from other Spitzer channels, we compare the results with planetary models to characterize its atmosphere.

2.7 The effect of scattering clouds and dust on extrasolar planet emission spectra

R. de Kok (1), C. Helling (2), D.M. Stam (1), P. Woitke (3) – (1) SRON-Netherlands Institute for Space Research, Utrecht, Netherlands ; (2) SUPA, University of St. Andrews, UK ; (3) UK ATC, Royal Observatory, Edinburgh, UK

The dayside emission spectrum of a transiting extrasolar planet can be determined by measuring its secondary eclipse at different wavelengths. From this, properties about the planet's atmosphere can be derived, such as temperature and composition. Almost all the transiting extrasolar planets discovered so far orbit close to their star, giving rise to high dayside temperatures. This in turn means that the planet emits most of its thermal radiation at relatively short wavelengths (near-infrared). Hence, scattering of this thermal radiation by clouds and dust might be more important than for solar system planets. The scattering nature of the clouds might significantly affect the emission spectrum and hence determinations of temperature and composition from this spectrum. We use the planet atmospheres generated by the DRIFT-PHOENIX code (e.g. Helling et al., ApJ 675, L105, 2008) as a basis for spectral calculations that fully include scattering of thermal radiation. In DRIFT-PHOENIX temperatures, gas concentrations and dust and clouds are self-consistently calculated for a given effective temperature, gravity and metallicity. The dust particles compose a mixture of grains with different composition. We use these pre-calculated model atmospheres to calculate disc-integrated emission spectra using a doubling-adding scattering code (Wauben et al., A&A 282, 277-290,

1994) and so quantify the effect of these realistic scattering particles on the emission spectra at near-infrared wavelengths.

2.8 Optical and near-infrared measurements of dayside-emission from hot Jupiters

Ernst de Mooij – Leiden Observatory, Netherlands

We have obtained measurements of the secondary eclipses of exoplanets with both ground- and space-based observatories at optical and near-infrared wavelengths. These observations probe the thermal emission of hot Jupiters at, and beyond the peak of their spectral energy distribution, providing complementary information to Spitzer Space Telescope observations.

2.9 Ultraviolet transmission spectroscopy of the transiting exoplanet WASP-12b

Luca Fossati – The Open University, UK

WASP-12 is a 2 Gyr old solar type star, hosting WASP-12b, one of the most irradiated transiting planets currently known. We observed WASP-12 in the UV with the Cosmic Origin Spectrograph (COS) on HST. The light curves we obtained in the six covered UV wavelength ranges, all of which contain many photospheric absorption lines, imply effective radii of $2.69\pm0.24\ R_J$, $2.18\pm0.18\ R_J$, and $2.66\pm0.22\ R_J$, suggesting that the planet is surrounded by an absorbing cloud which overfills the Roche lobe. We detected enhanced transit depths at the wavelengths of resonance lines of neutral sodium, tin and manganese, and at singly ionised ytterbium, scandium, manganese, aluminum, vanadium, iron and magnesium.

2.10 A new look at NICMOS transmission spectroscopy

Neale Gibson – University of Oxford, UK

I present a re-analysis of HST/NICMOS transmission spectroscopy of several exoplanet systems, from which detections of several molecules, including H_2O, CH_4 and CO_2 are claimed. Given the variation of all reported signals from NICMOS are approximately the same amplitude, I discuss the possibility that the signals are due to instrumental systematic noise, rather than a real signal from the planets' atmospheres.

2.11 Secondary Eclipse Phase Measurements from the Spitzer ToO Program

Ryan Hardy – University of Central Florida, USA

The timing of exoplanet secondary eclipses provide a direct constraint on orbital eccentricity, and can be combined with other data to increase the precision of orbital solutions. We present dynamical constraints and complete orbital fits from Spitzer secondary eclipse observations for the orbits of several planets studied by the Spitzer Target of Opportunity Program in 2010, including WASP-12b, WASP-14b, WASP-18b, GJ436b, and HAT-P-13b. We discuss the dynamical implications for selected planets, methods of joint orbital fitting, and the possibility of detecting apsidal precession in short-period exoplanets.

2.12 Retrieval of Exoplanet Atmospheric Structure and Composition from Transit Spectroscopy

Lee Jaemin – AOPP/Oxford, UK

Recent spectroscopic observations of transiting hot Jupiters have permitted the derivation of molecular and atomic abundances (H_2O, CO, CH_4, CO_2 and alkali metals) in these extreme atmospheres. In this presentation we will describe the development of a suite of radiative transfer and retrieval tools for exoplanet conditions, building upon software used extensively in solar system studies (e.g. NEMESIS). We discuss the build-up of molecular linelists for high temperature application, compare the use of different radiative transfer models (line-by-line and correlated-k) and compare our calculated spectra with previous transit observations. We rigourously derive the sensitivity of these spectra to the atmospheric temperature profile and gaseous distribution, and assess the degeneracy of possible interpretations of spectral features observed in the hot Jupiters.

2.13 A Ground-Based Optical Transmission Spectrum Survey of the Atmospheres of Transiting Exoplanets: Line Analysis and Future Work

Adam Jensen – Wesleyan University, USA

Observations with the Hobby-Eberly Telescope (HET) were used to make the first ground-based detection of a specific element, sodium, in an exoplanetary atmosphere (Redfield et al. 2008). We are now in possession of a rich dataset of similar high-resolution (R~60,000) optical spectra from the HET. Our survey includes multiple in-transit and out-of-transit observations of four different exoplanetary systems with observations under way on a fifth system. This dataset provides very high signal-to-noise coverage of the spectral region from ~5000-9000 angstroms and is a wonderful opportunity for comparative exoplanetology. We will discuss in detail our investigation into these systems, including the data reduction processes and details of the transmission spectrum line analysis. Special attention is paid to the resonant lines of alkali metals (especially Na I and K I) that we expect to see at the temperatures of these exoplanets, which are all hot Jupiters or hot Neptunes. We will also discuss potential long-term prospects of our work, including deriving complete optical atmospheric transmission spectra of these exoplanets and searching for exospheric absorption.

2.14 Three-dimensional atmospheric circulation of hot Jupiters on highly eccentric orbits

Tiffany Kataria – University of Arizona, LPL, USA

Of the ~400 exoplanets detected to date, over one-tenth of these are on highly eccentric orbits ($e>0.5$). Such scenarios lead to highly time-variable stellar heating on the giant planet, which has a large effect on its meteorology. However, little is known about the basic dynamical regime of such planets, and how it may compare to the dynamics of giant planets on more circular orbits. Therefore, we present three-dimensional atmospheric circulation models that include radiative transfer (the Substellar and Planetary Atmospheric Radiation and Circulation Model) for generic hot Jupiters over a wide range of eccentricities. We compare the atmospheric circulation of the planet when placed in highly circular ($e=0$) up to highly eccentric ($e=0.75$) orbits in synchronous and pseudo-synchronous rotation around their parent stars. In particular, we analyze the temperature structure of each of these cases, as well as the jet streams, waves, and interactions between the two that arise for each scenario. Furthermore, we discuss the observational implications and extent to which light curves and spectra of planets on highly eccentric orbits will allow their meteorological properties to be inferred.

2.15 Spitzer lightcurves of the ultrashort period, massive hot Jupiter WASP-18b

Pierre Maxted – Keele University, UK

WASP-18b is a massive hot Jupiter exoplanet (10 Jupiter masses) which orbits an F6 star with an orbital period of only 0.94 days. We present preliminary results from a Spitzer campaign to observe lightcurves at 3.6 microns and 4.5 microns covering an entire orbit of the planet. The principal aim of these observations is to map the distribution of thermal emission from the planet over its surface from the phase variation observed in these lightcurves. This phase variation gives a direct measurement of the efficiency of heat distribution from the day-side to the night-side of the planet. The phase variation may also show on offset in the position of the hot-spot on the planet's surface from the sub-stellar point due to zonal winds.

2.16 Two Multi-Wavelength Secondary Eclipses of WASP-18b

Sarah Nymeyer – University of Central Florida, USA

The Spitzer Exoplanet Target of Opportunity Program observed secondary eclipses of WASP-18b using Spitzer's Infrared Array Camera (IRAC) in the 3.6-μm and 5.8-μm bands on 2008 December 20, and in the 4.5-μm and 8.0-μm bands on 2008 December 24. We present a pressure-temperature profile, eclipse depths and brightness temperatures of WASP-18b, which is one of the hottest planets yet discovered (as hot as an M-dwarf star).

2.17 Hot Jupiters in a tube and Hyperdog for planetary sniffing

Robert Peale – University of Central Florida, USA

Laboratory results of hot vapor emission spectroscopy with relevance to atmospheres of hot jupiters are presented. Species include titanium and vanadium oxides, silicates perovskiite and enstatite, hydrogen and its various ions, metals (Na, K, Mg, Ca, Al, Fe), steam, sulfur compounds, carbon monoxide, carbon dioxide, ammonia, methane, ethylene, acetylene, and hydrogen cyanide. Mixtures are made to mimic suspected composition of actual exoplanets. A high resolution Fourier transform spectrometer with resources to cover the UV to far-IR range is used in conjunction with a microwave discharge apparatus and a furnace in order to achieve temperatures in the range 1000-3000 K. In addition, a prototype of a long-wave infrared intracavity laser absorption spectrometer based on quantum cascade lasers and a scanning Fabry-Perot spectrometer is described with potential for detecting ultratrace vapors in extraterrestrial environments.

2.18 On the radius of hot Jupiters

Frédéric Pont (1) and Suzanne Aigrain (2) – (1) University of Exeter, UK ; (2) University of Oxford, UK

Many gas giant planets orbiting close to their host star ('hot Jupiters') have anomalously large radii – up to 70% larger than expected. Studying the distribution of radii for known transiting exoplanets, we find that the distribution of anomalous radii can be satisfactorily account for by a coupling of radiative forcing from the stellar irradiation and tidal dissipation inside the planet. If the mechanical work carried out by the planetary atmosphere to bring heat from the day side to the night side is used to keep the planet out of tidal equilibrium, the resulting increase in internal entropy will result in an inflated planet. The distribution of observed radii as a function of incoming stellar irradiation, planet mass and orbital distance are in good agreement with this picture.

2.19 A Ground-Based Optical Transmission Spectrum Survey of the Atmospheres of Transiting Exoplanets: First Results

Seth Redfield – Wesleyan University, USA

We present details of a ground-based program designed to do a comparative analysis of the atmospheres of transiting exoplanets. We have obtained ultra-high signal to noise transmission spectra of four transiting systems. We combine multiple in-transit observations taken by the 9.2-m Hobby-Eberly Telescope (HET) and compare directly with out-of-transit observations. Together with high resolution UV spectrographs in space, and infrared photometry, observations in the visible, provide an opportunity to probe important components of exoplanetary atmospheres. We discuss our observations of neutral sodium, the strongest signature in the visible for hot giant planets, and provide a comparative analysis among the exoplanets in our sample. In addition, we discuss prospects for a complete optical transmission spectrum, limits on the extent of any exospheres, as well as, the challenges of such ground-based observations. Measurements, and even upper limits, of atmospheric lines should provide important constraints on models of giant exoplanet atmospheres, including for example, temperature inversions, cloud cover altitudes, atomic and molecular composition, and temperature profiles.

2.20 Ground-based Photometric Detections of Thermal Emission from Hot Jupiters

Justin Rogers – Johns Hopkins University, USA

One of the most powerful method of exploring the physics of exoplanetary atmospheres is via the direct measurement of a planet's thermal emission during a secondary eclipse. A number of such detections have been made from space with the Spitzer, Hubble, CoRoT, and Kepler satellites, and in just the past two years, detecting these tiny (~0.1%) signals has become possible with ground-based instruments. We recently announced three ground-based detections: OGLE-TR-56b in z'-band with Magellan, and two with the ARC 3.5-m telescope: CoRoT-1b in Ks-band and WASP-12b in z'-band. For CoRoT-1b we combined our detection with three others in the optical to near-infrared, and compared the depths to various atmospheric models. Neither blackbody models nor state-of-the-art physical models can fully explain the observed thermal emission of CoRoT-1b around 2.0 microns. The closest physical model suggests an inefficient transport of heat from the planet's dayside to nightside, and a thermal inversion layer with an optical absorber added near the 0.1-bar pressure level − deeper in the atmosphere than the absorbers in the models used for mid-infrared Spitzer detections of other irradiated hot Jupiters. We will also discuss additional observations at APO and the VLT, and summarize the picture emerging from ground-based eclipse photometry of hot jupiters and the surprising challenges they pose for atmospheric models.

2.21 Spectral comparison of directly imaged, young substellar companions using integral field spectroscopy; construction of an empiric log g sequence

Tobias Schmidt – Astrophysical Institute Jena, Germany

About 15 substellar companions with large separations (>50 AU) to their young primary stars and brown dwarfs are confirmed by both common proper motion and late-M / early-L type spectra. The origin and early evolution of these objects is still under debate. While often these substellar companions are regarded as brown dwarfs, they could possibly also be massive planets, the mass estimates are very uncertain so far. They are companions to primary stars or brown dwarfs in young associations and star forming regions like the TW Hya association, Upper Scorpius, Taurus, Beta Pic moving group, TucHor association, Lupus, Ophiuchus, and Chamaeleon, hence their ages and distances are well known, in contrast to free-floating brown dwarfs. An empirical classification is not possible, because a spectral sequence that is taking the lower gravity into account, is not existing. This problem leads to an apparent mismatch between spectra of old field type objects and young low-mass companions at the same effective temperature, hampering a determination of temperature and surface gravity independent from models. Now that about 15 such substellar candidates are found in associations of different ages, 1-35 Myrs, it is possible to study their spectra in comparison to each other using the advantage of light concentration by an adaptive optics system with their primary as guide star. Therefore we have begun the construction of an empirical log g sequence from homogenous observation of all these substellar companions using the AO-assisted integral field spectrograph SINFONI at VLT (ESO).

2.22 Spectral and Polarimetric characterization of gaseous and telluric planets with SEE COAST

Jean Schneider – Paris Observatory, France

The prime objective of SEE COAST (Super Earth Explorer Coronagraphic Off-Axis Space Telescope) is to contribute to the understanding of the formation and evolution of planetary systems. Exploring the diversity of these objects is therefore the main driver to define the instrumentation. In the next decade the improvement of radial velocity instruments and obviously temporal coverage will provide us with a large numbers of long period giants as well as telluric planets, namely Super Earths. Obtaining the spectral and polarimetric signatures of these objects in the visible range to measure atmospheric parameters (molecular composition, clouds, soils) will be unique and with important scientific returns. A space mission complementary to near-IR instruments like SPHERE, GPI, JWST and later ELTs for the full characterization of giants and Super Earths is a first secure step towards the longer term goal that is the characterization of telluric planets with mass and atmosphere comparable to that of the Earth. An overview of the astrophysical motivation and the trade-off that lead to a simple integrated concept of a space-based high-contrast imaging instrument will be given.

2.23 Transmission spectroscopy of the sodium doublet in WASP-17b with VLT

Patricia Wood – Keele University, UK

The detection of increased sodium absorption during primary transit implies the presence of an atmosphere around an extrasolar planet, and enables us to infer the structure of the atmosphere. WASP-17b is the least dense planet currently known. It has a radius of 1.77R_J and orbits an F6-type star. The transit signal is expected to be ~3 times larger than that observed in HD209458b (0.135% at bandwidth 1.5Å). We obtained 24 spectra with the GIRAFFE spectrograph on the VLT, of which 8 were during transit. Integrated flux was measured at bandwidths 0.75, 1.5, 3.0, and 6.0Å, the last 3 coinciding with bandwidths used by Snellen et al. for HD209458b. For 0.75, 1.5, and 3.0Å, two half-bandwidths were centred on each component of the sodium doublet (5895.92 and 5889.95Å), and 6.0Å was centred midway between the components. We find a transit depth of 0.40±0.15% at 1.5Å. This suggests that, like HD209458b, WASP-17b has an atmosphere depleted in sodium. Systematic errors prevent significant detection of the transit in wider bandwidths. A transit depth measurement in such a narrow bandwidth is affected by the rotation of the star (Rossiter-McLaughlin effect). We are developing a model to account for this. An improved observing strategy should enable us to detect the transit at wider bandwidths. We also have Spitzer data for the secondary eclipse of WASP-17b at 3.6 and 4.5 microns. The combination of these data and models will enable us to accurately characterise the atmosphere of this hot Jupiter.

Terrestrial exoplanets

3.1 The spectro-photometric variability of the globally-integrated infrared emission of terrestrial planets

Illeana Gomez – Laboratoire d'Astrophysique de Bordeaux, France

The detection of the infrared emission of earth-like planets should become possible with JWST for hot super-Earths around K stars and for cooler planets around M stars. Our interest is focused on the characterization of these types of planets with very low spectral resolution observations. We present an analysis of the globally-integrated far-infrared flux using emission maps (longitude, latitude, time) either from satellite observations in the case of the Earth and from 3D atmospherical models in the case of solar system planets or exoplanets. Our model calculates at any time the fraction of the planetary disk exposed to a remote observer and computes the integrated flux to simulate the point-ilke signal detected by the observer. We have studied the annual, seasonal and diurnal variability to determine which planetary and atmospheric properties (rotation, temperature, radius, climate, atmospheric composition) can be inferred according to the instrument used (JWST, ELT, Darwin/TPF) and the quality of the signal (time resolution, signal to noise ratio). In the case of the Earth, we have found that the daily variations in longwave emitted radiation have an amplitude of several percent, which is comparable to that of the seasonal variations. It is important to remark, however, the strong influence of the weather patterns in the diurnal variability of the emitted flux, which are sometimes able to completely obscure the 24-hour rotation periodicity signal for several days at a time. We find that the analysis of the time series and light curves allows us to determine the 24-hour rotation period of the planet. The influence of solar illumination does not play a key role on the infrared emission, except for introducing a seasonal variability in the Earth's case due to the inhomogeneous distribution of land masses. The study of the combined signal of the Earth-Moon system, the limb darkening effect and the signal to noise ratio is in progress. The comparison with the 3D Global Circulation Model results will be presented. We will discuss the relevance of several effects on the signal: atmospheric thickness, density, clouds, the spectral band range of the observations, the distribution of surface features and the instrumental requirements.

3.2 Spectropolarimetric signals of Earth-like exoplanets with clouds

Theodora Karalidi – SRON-Netherlands Institute for Space Research, Netherlands

Studies of the Earth and other Solar System planets have shown the strong influence that clouds have on the radiative budget in an atmosphere, hence on the planet's climate, weather, and the dynamical processes that take place. They also influence photolysis rates, hence the photochemistry and chemical processes in the atmosphere. The precise effects of clouds depend on their altitude, their horizontal and vertical extension, and the number density, size, composition, and shape of the cloud particles. The detection and characterisation of clouds on an exoplanet would thus provide us with crucial information on the conditions in the planet's atmosphere and on its surface (if there is any). For this detection and characterisation, polarimetry will be important, as has already been shown in remote-sensing of the Earth and other Solar System planets. Here we will present numerically simulated flux and polarisation signals of exoplanets with (liquid) water clouds, for wavelengths from 0.3 μm to 1.0 μm, for both horizontally homogeneous and horizontally inhomogeneous planets (with broken cloud decks). We will show the effects of the cloud top altitude and cloud particle sizes on the flux and polarisation signals, and compare the effects of broken cloud decks on the flux and polarisation signals. We will discuss the prospects of deriving cloud and other planetary parameters from combining exoplanet flux and polarisation observations.

3.3 Influence of clouds in atmospheres of Earth-like extrasolar planets

Daniel Kitzmann – Technische Universität Berlin, Germany

The climate of Earth-like planets results from the energy balance between absorbed stellar radiation and the loss of thermal radiation emitted from the surface and the atmosphere to space. Cloud particles reflect the stellar radiation back towards space, thereby reducing the stellar energy available for heating the surface (albedo effect), but on the other hand also reduce the loss of thermal radiation to space (greenhouse effect). Clouds can have a strong influence on the radiation budget in planetary atmospheres, which directly affects the surface temperatures and, therefore, can influence the position and the extension of habitable zones around different central stars. The effectiveness of the albedo and the greenhouse effect depend on the strongly wavelength dependent optical properties of the cloud particles in combination with the spectral distribution of the incident stellar and atmospheric thermal radiation. Besides these climatic effects, clouds do also affect the planetary reflection and thermal emission spectra by e.g. dampening the spectral bands of molecules, or increasing the back-scattered stellar radiation. The climatic effects and the impact on the planetary spectra induced by cloud layers are closely related. In this contribution we studied the impact of low-level water droplet and high-level ice clouds on the surface temperatures and the planetary emission and reflection spectra in atmospheres of Earth-like extrasolar planets orbiting different types of main sequence dwarf stars. To investigate these effects, a parametric cloud description, accounting for the two considered different types of clouds and their partial overlap has been developed. This multi-layered cloud model is based on observations in the Earth's atmosphere and has been coupled with a one-dimensional radiative-convective climate model. In dependence of the coverages of the two different cloud types the resulting surface temperatures and the corresponding low-resolution spectra are presented and the the effectiveness of the greenhouse and the albedo effect is discussed.

3.4 An Energy-balance model for tidally-heated ocean planets

Alastair McKinstry – National University of Ireland, Galway

GJ1214b represents a new class of planet: close-in ocean planet or mini-Neptune. Close-in to an M-class star, it has very large tidal forcings as well as significant stellar heating. Such planets can be expected to be tidally locked, with the existence of an ocean dependent on zonal heat transfer. A new Energy-balance model is presented, to describe the 2D heat transfer and dissipation of tidally generated energy within a hypothesised ocean. On such planets, the climate will be dominated by the nature of the ocean, which is currently poorly understood. The exact heat distribution is seen to depend critically on the nature of the ocean mixing and dissipative mechanisms. For a air-liquid phase transition to exist, a high albedo and hence cloud cover is required. The cloud cover and albedo are hence modelled for two cases: that of a Neptune-like H_2 / CH_4 / H_2O atmosphere, and that of a CO_2-dominated super-Earth.

3.5 Reflectance spectra of irradiated Earth-like exoplanets

Mariana Wagner – Sternwarte Hamburg, Germany

The research field of exoplanets is rapidly advancing, at present over 450 objects are known. In order to optimize instrumental design for the detection of Earth-like exoplanets there is a mounting need for theoretical assistance. Provided a terrestrial exoplanet harbours an optically thin atmosphere, could different surface textures, e.g. ocean surface or soils be seen in its spectrum? And what kind of instrument would be needed to detect them? To answer this question we are using the stellar atmosphere code PHOENIX in the 1D spherical mode. It is a powerful tool to calculate radiation transport in i.a. planetary atmospheres even down to very low temperatures. The calculation of cool objects is challenging, because of the much more complex chemistry, i.e. the strong molecular abundances als well as the occurrence of dust formation. A reflection at the planetary surface serves as the inner boundary condition. This requires follow-up adjustements in order to get the planets atmosphere to coverge to stability. We are testing the specifications on an Earth-twin around a Sun-like star for a better comparison to real data and on a different types of exoplanets around M-dwarfs.

Bridging the gap

4.1 Extra-solar planetary interior and atmospheric structure models

Victoria Bending – The Open University, UK

We seek to develop simplified models of exoplanet atmospheres and interiors with a particular focus on giant planets, exploiting recent observations to provide guidance to our modelling studies. We use a simplified Global Climate Model (GCM), based on techniques developed for the Earth and, more recently, Mars and Venus, to study the atmospheric flow and heat transport with varying planetary parameters. Atmospheres are modelled with an idealised representation of radiative transfer processes. Critical parameters are varied, focussing on stellar irradiation, planetary rotation rate, orbital eccentricity and obliquity. The emerging physical properties of exoplanets also motivate exploratory studies of the interior structures of gas giant planets, covering a wider parameter space than present models of solar system planets. We make use of an up-to-date planetary structure model by adapting an existing Henyey-type low mass star code with a suitable equation of state. An ultimate aim of the project is to loosely couple the upper boundary of the interior model with the lower boundary of the neutral atmosphere represented in the GCM. Model predictions are intended to feed into planning and interpreting current and future observations.

4.2 Some Crucial Aspects of Exoplanet Atmosphere Dynamics Modeling

James Cho – Queen Mary, University of London, UK

Several crucial aspects for modeling the dynamics of extrasolar planet atmospheres are presented. These include both physical (e.g. stability, waves, and ionization) and numerical (e.g. dissipation, resolution, and initialization) aspects. Their effects on predictability and accuracy of large-scale dynamics are discussed.

4.3 Planetary Polar Vortices: Instabilities in Nature and in the Laboratory

Luca Montabone – LMD-Université Paris VI / AOPP-University of Oxford

Polar vortices are swirling regions of the atmosphere at a planet’s poles bounded by a circumpolar jet. The circumpolar jet develops as a result of conservation of angular momentum on a rotating planet. Earth’s stratospheric jets bound approximately circular-shaped vortices at both poles, which are relatively stable (depending on the season), except during episodes of “sudden stratospheric warming”. These are events characterized by a weakening, break-up, or temporary reversal of Earth’s polar vortices, associated with a weakening of the polar jet and changes in mid-latitude weather patterns. A number of phenomena are known to affect polar vortices on the Earth, which might include planetary waves, gravity waves, and possibly global warming (related to polar stratospheric cooling). Beyond Earth, the instabilities that affect the planetary polar vortices tend to produce a rich variety of different dynamical structures. ESA’s Venus Express spacecraft observed a double-lobed structure at the South Pole of Venus (as did Pioneer Venus Orbiter in the ’70s), which appears to be metastable. The so-called “dipole” is probably the most observed shape, but transitions to a tripole and to fairly circular shape are also likely. At the North Pole of Saturn, the NASA/ESA Cassini spacecraft observed a striking hexagonal structure within the polar vortex, which measures almost 250,000 km across. This structure does not seem to have changed since the observations of NASA’s Voyager spacecraft in the ’80s. Finally, instabilities similar to those observed in planetary polar vortices beyond Earth have also been observed in the central core of hurricanes on Earth, as well as in small-scale laboratory experiments, thus encompassing a range of scales varying by a factor of over 100 million. These instabilities seem to be related to the strong horizontal wind shear which can be produced between the circumpolar jet and the vortex interior. Barotropic instability arises when the horizontal velocity gradients are too strong, and energy is removed from the zonal flow and stored in large-scale, coherent eddies. We review some results from laboratory experiments at different scales on the barotropic instability of circumpolar jets and we put them in the context of the observations of planetary polar vortices in the Solar System.

4.4 The impact of microphysics on optical properties of shallow cumulus clouds based on Large Eddy Simulations. The model EULAG and its ability to simulate exoplanets.

Joanna Sławińska – Institute of Geophysics, University of Warsaw, Poland

Recent modelling studies demonstrate that assumptions concerning the microphysical evolution of natural clouds − the homogeneity of the cloud-environment mixing in particular − significantly affect the simulated albedo of a field of shallow convective clouds. In addition, in-cloud activation of cloud droplets (i.e. activation well above the cloud base) has been argued to also play a significant role. In-cloud activation and cloud-environment mixing interact with each other and their impact on cloud characteristics is difficult to separate in either observations or model simulations. Understanding the microphysical properties of such clouds has important implications for the cloud physics in general and for clouds-in-climate problem in particular. Results concerning aerosol concentration, activation and the homogeneity of mixing would be reported, with the particular emphasis on impact on microphysical and macrophysical (i.e. radiative) properties of shallow convective clouds. The Eulerian version of the three-dimensional anelastic model EULAG (EUlerian/semi-LAGrangian) is used. The model EULAG is used to solve multiscale flows in atmospheric and planetary physics. The EULAG model is an ideal virtual laboratory to perform and visualize numerical experiments in the fields of atmospheric and oceanic dynamics, turbulence, and atmospheric and stellar convection. In particular, this model has been proven to be a reliable tool for global simulations, and as such constitutes a prospective tool for modelling the atmospheres of exoplanets. Abilities of the EULAG model to simulate exoplanets would be described, with results of some test runs (i.e. Held-Suarez for Mars) given.

4.5 Planetary Atmospheric Circulation Regimes in a Simplified GCM

Yixiong Wang – University of Oxford, UK

Explorations of terrestrial planets within our own Solar System have revealed great diversity in global scale atmospheric circulation regimes, suggesting that a systematic study of the underlying dominating parameters is necessary. Preliminary studies have shown some clear trends among the various circulation patterns of Venus, Titan, Mars and the Earth, in which planetary rotation rate has been noticed to be one of the most crucial factors. On the other hand, laboratory studies of stratified rotating baroclinic fluids under a considerable range of parameter conditions have been investigated in detail for quite a long time, producing a series of well-defined regime diagrams depicting the parameter dependence of the fluid behaviour. This inspires us that similar studies on the parameter dependence of planetary atmospheric circulations could be conducted numerically using simplified GCMs which, like the rotating annulus in laboratory experiments, capture only the essential physics of the general circulation system. In this contribution, an exploration of the parameter space constructed by several defining non-dimensional planetary parameters has been made by using PUMA (Portable University Model of the Atmosphere), a simplified GCM with Newtonian cooling and Rayleigh friction, which could be viewed as a “prototype” terrestrial planetary atmosphere with no specific configuration of any individual planet. The dependence of atmospheric behaviours on planetary rotation rate, radiative relaxation timescale, and frictional timescale etc. has been investigated. And non-dimensional parameters involving these planetary factors have been constructed. The trends observed in these results show that the ability to predict at least qualitatively the structure of atmospheric circulations of other terrestrial planets outside the Solar System is possible. Future work will investigate a much wider domain of parameter space, including planetary obliquity, diurnal cycle, seasonal variation, and tidally-locked orbits so that more exotic conditions of the planets yet to be discovered can be encompassed by this framework.

Living planets

5.1 Earth Glint Observations Conducted During the Deep Impact Spacecraft Flyby

Richard Barry – NASA Laboratory for Exoplanets and Stellar Astrophysics, USA

We describe observations of Earth conducted using the High Resolution Instrument (HRI) – a 0.3 m f/35 telescope – on the Deep Impact spacecraft during its recent flybys. Earth was observed on five occasions: 2008-Mar-18 18:18 UT, 2008-May-28 20:05 UT, 2008-Jun-4 16:57 UT, 2009-Mar-27 16:19 and 2009-Oct-4 09:37 UT. Each set of observations was conducted over a full 24-hour rotation of Earth and a total of thirteen near-IR spectra were taken on two-hour intervals during each observing period. Photometry in the 450, 550, 650 and 850 nm filters was taken every fifteen minutes and every hour for the 350, 750 and 950 nm filters. The spacecraft was located over the equator for the three sets of observations in 2008, while the 2009-Mar and 2009-Oct were taken over the north and south polar regions respectively. Observations of calibrator stars Canopus and Achernar were conducted on multiple occasions through all filters. The observations detected a strong specular glint not necessarily associated with a body of water. We describe spectroscopic characterization of the glint and evidence for the possibility of detection of reflection from high cirrus clouds. We describe implications for observations of extrasolar planets.

5.2 Influence of the stellar spectral flux distribution on surface habitability and atmospheric dynamics of Earth-like extrasolar planets

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Most previous works investigating the effect of different central stars upon the atmospheres of Earth-like planets in the habitable zone have been restricted to column model studies. Usually 3D General Circulation Models (GCMs) employ broad-band (two to six bands) parameterisations for the shortwave radiative transfer. We use the state-of-the-art GCM EMAC (ECHAM/MESSy) to study the influence of a stellar flux distribution corresponding to a K-type star on atmospheric dynamics and surface conditions of an Earth-like planet in the habitable zone. Our model includes the radiative transfer module FUBRAD, which calculates the incoming stellar radiation (UV to near-IR) in 52 bands for pressures below 70hPa. The higher band resolution of FUBRAD can lead to pronounced differences in heating rates and stratospheric temperatures compared to broad band schemes. Furthermore, we compute Sea Surface Temperatures interactively by coupling the atmosphere to a mixed layer ocean. Atmospheric composition and surface configurations as well as the total stellar energy input are assumed to be as for modern Earth.

5.3 Response of ozone photochemical pathways to a doubling in CO2

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Ozone is an important biomarker (life-indicator) on the Earth which influences UV hence potentially affects many atmospheric species. Photochemical pathways which remove ozone are potentially complex. We present results from a new diagnostic tool which sheds light on ozone photochemistry in the atmosphere. The tool − the Pathway Analysis Program (PAP) − automatically identifies and quantifies chemical pathways for ozone production and loss based on output from a coupled climate-photochemical model. We have analysed modern-day and doubled carbon dioxide conditions. Results are a valuable aid to understanding the potentially complex catalytic processes which affect atmospheric ozone and their response to carbon dioxide increases. The PAP tool has already been applied with success to modern Earth conditions in the stratosphere.

5.4 Simulating Earth as an Extrasolar Planet

Tyler Robinson – University of Washington, USA

The NASA Astrobiology Institute's Virtual Planetary Laboratory 3-D line-by-line, multiple-scattering spectral Earth model generates spatially- and temporally-resolved synthetic spectra and images of Earth. The model can be used to simulate the spectrum of Earth as it would appear to a distant observer at arbitrary viewing geometry over wavelengths from the far-ultraviolet to the far-infrared on timescales from minutes to years. We have validated our model against data from NASA's EPOXI mission, which obtained spatially- and temporally-resolved visible photometric (0.3-1.0 µm) and near-infrared spectroscopic (1.05-4.8 µm) observations of Earth on three dates (3/19/08, 5/29/08 and 6/5/08). Further validations include comparisons to photometric Earthshine observations (0.4-0.7 µm) which span a wide range of Earth phase as well as comparisons to date-specific, high spectral resolution mid-infrared observations (6-15 µm) of Earth acquired by the Atmospheric Infrared Sounder aboard NASA's Aqua satellite. To reproduce the available observations, we have run the model at a spatial resolution of almost 200 pixels, an atmospheric resolution of 48 pixels, and a cloud treatment with 4 categories of water clouds. Our validated model can now be used as a tool for feasibility studies for future space-based planet detection missions (e.g. NASA's Terrestrial Planet Finder). The model can also be used to better understand sensitivity to global signatures of habitability and life in disk-integrated spectra of Earth. Example applications that we will discuss include an investigation into the ability of Earth's atmosphere and clouds to obscure direct surface temperature measurements from thermal-infrared observations as well as a study of the phase-dependent contribution of Earth’s ocean “glint spot” to the overall brightness of the planet. The "glint spot" is generated by the specular reflection of sunlight from Earth's oceans and has been proposed as a mean of detecting oceans on extrasolar planets. In some cases, clouds exhibit similar behaviors to glint and could mimic or obscure its detection. We will use the realistic treatment of cloud scattering and glint in our model to investigate the significance of these two competing effects in Earth's disk-integrated spectrum.

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Transport

Town centre to the University

The town centre is a 20-minute walk from the University. Alternatively the D Bus goes regularly from the town centre to the university, except on Sundays. The bus can be caught from the High Street (outside Starbucks), Queens Street or opposite Exeter Central Station, as well as other stops along the route. During the conference the bus goes at half hour intervals, normally at 5 past and 35 past the hour from the High Street. At the University, the D Bus stops just in front of the Peter Chalk Centre. The ride between the University and High Street (town centre) costs £0.95, payable to the bus driver (exact change not required).

Exeter St David's Train Station to the University

There is a taxi rank outside the station. The ride to the University costs around £5.

The University runs a mini bus service between Exeter St David's Station and the University for staff and students. Participants could if they choose use this service. The bus stop is located behind the taxi rank outside the station (you should be able to see a sign with the Exeter University logo from the entrance of the station). It operates between 7.45am and 10.30 pm, and at half hour intervals from 4.00pm till 5.30pm from the layby outside the Geoffrey Pope Building. In the mornings, participants are advised to ask the driver to stop outside the Peter Chalk Centre as they reach the top of the hill.

Alternatively, participants can walk to the conference venue from the station. It is about 15 minutes walk, but participants should be warned it is uphill all the way. Maps of the university can be found at the end of this booklet.

Exeter Airport to the University

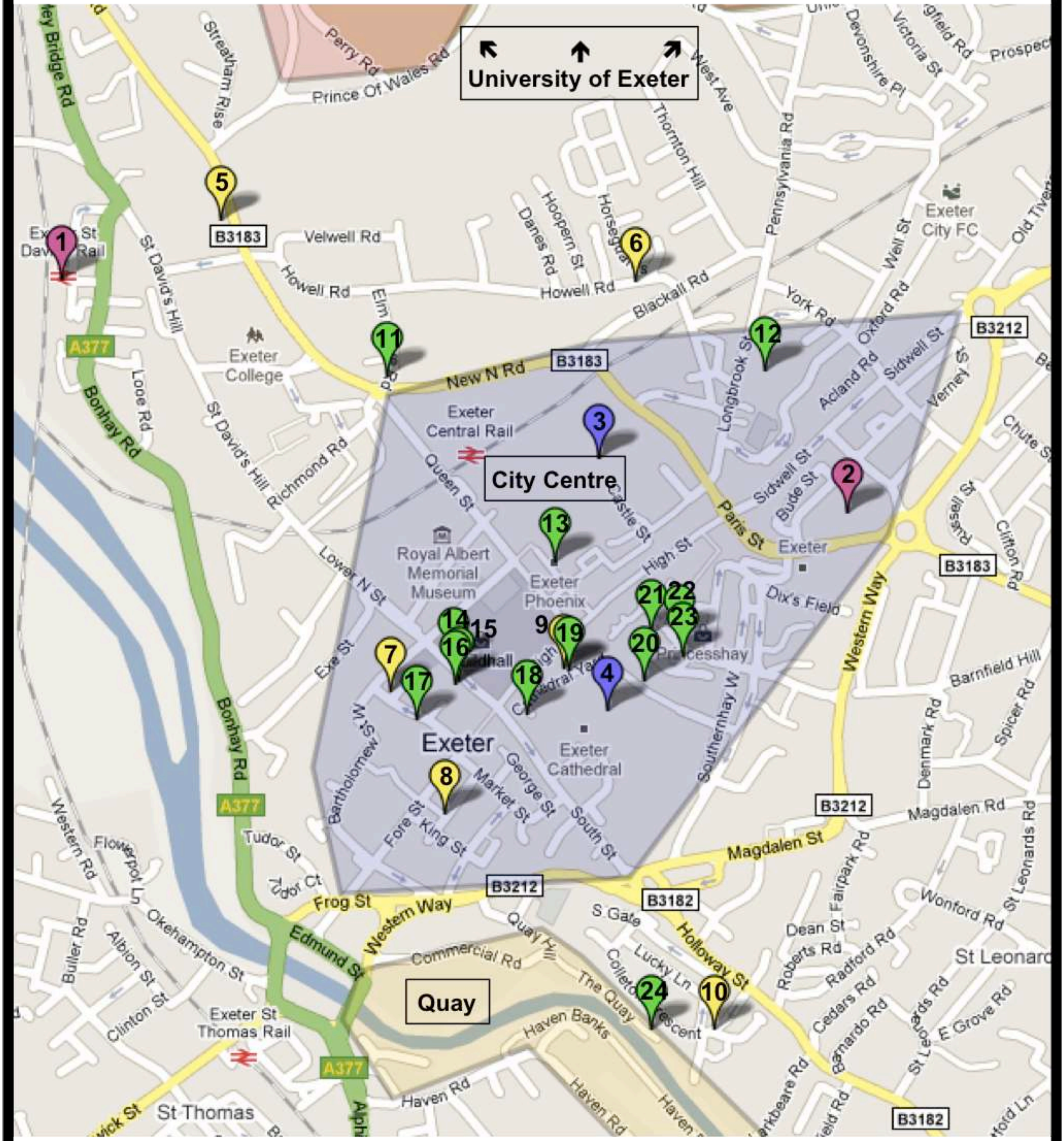
Taxis

There are Arrivals taxi bays located outside the airport. Exeter Airport Taxis are the only company permitted to use these. They recommend booking ahead by ringing 01392 234100 or online.

Buses

Two buses leave the airport for Exeter. Service 56 (56A 60B) runs Monday to Saturday between Exeter St. David's Station and Exmouth and Service 379 runs on Sunday between Exeter St. David's Station and Sidmouth. They are both run by Stagecoach Buses and go to Exeter bus station before arriving at Exeter St David's Station.

Exeter City Centre



- 1 St Davids Train Station
- 2 Central Coach Station
- 3 Rougemont Castle
- 4 Exeter Cathedral
- 23 La Tasca
- 24 On The Waterfront
- 5 Imperial Pub
- 6 Rusty Bike Pub
- 7 Mama Stones
- 8 Fat Pig Pub
- 9 Well House Tavern
- 10 Hour Glass Pub
- 11 The Gandhi
- 12 Harry's Restaurant
- 13 Zizzi
- 14 Herbies
- 15 Tiger Bill
- 16 The Conservatory
- 17 St Olaves
- 18 Al Farid's
- 19 Abode Exeter
- 20 Ask
- 21 Wagamama
- 22 Café Rouge

Exeter, and Devon in general, are famous for their many good pubs and restaurants.

Pubs

Locals are the best source of advice, but favorites very near campus include the ***Imperial Pub*** on New North Road (big, lovely garden), the ***Rusty Bike Pub*** on Howell Road (small and cosy), and ***Harry's Restaurant*** on Longbrook Street (booking recommended). In the centre of town, the cathedral square has a number of restaurants (Italian, British, Moroccan, Thai) as well as the ***Well House Tavern*** (don't miss the skeleton in the basement!). There are also a number of options on the quayside, most enjoyable in good weather. A little more out of the way but well worth a detour are the ***Hourglass Pub*** on Melbourne Street, the ***Fat Pig Pub*** on John Street, and ***Mama Stones*** (live music from 9pm) on Mary Arches Street.

Restaurants

	Type	**Address**	**Phone**
The Conservatory	Fine dining	18 North Street	01392 273858
St Olaves	Fine dining	12-22 Mary Arches Street	01392 217736
Harry's Restaurant	American / Mexican	86 Longbrook Street	01392 202234
Al Farid	Moroccan	3 Cathedral Yard	01392 494444
Ask	Italian	5 Cathedral Close	01392 427127
Zizzi	Italian	21-22 Gandy Street	01392 274737
On the Waterfront	Italian	4-9 The Quay	01392 210590
Café Rouge	French	92 Queen Street	01392 211778
La Tasca	Spanish	26 Bedford Street	01392 434488
Tiger Bills	Thai / American	7-8 North Street	01392 215499
Wagamama	Japanese	16 Bedford Street	01392 274810
The Gandhi	Indian	7 New North Road	01392 439703
Herbies	Vegetarian	15 North Street	01392 258473

Things to do

If you have a moment free or you can spend a day or two in the area before or after the conference, there are plenty of things to do:

Cycling or canoeing along the Estuary

You can hire a bicycle or a canoe from "Saddles and Paddles" on the Quayside. There are a couple of pubs along the Estuary (the Double Locks and the Turf Lock) which make nice stop-off points. You can also catch a boat ride on the Estuary from the Turf Lock, Topsham or Exmouth (the latter two are a short train ride from Exeter Central station).

The beach

The sea is at its warmest at this time of year. Both Exmouth and Dawlish, either side of the Estuary, are a short train ride from Exeter. If you have access to a car, there are beautiful beaches around Lyme Regis (Jurassic Coast World heritage site), secluded coves in fractal estuaries in South Devon (in particular Salcombe and Dartmouth), or wild, ocean-facing beaches in North Devon.

Hiking in Dartmoor

You can get a bus from Exeter to Moretonhampstead or Bovey Tracey, and members of the LOC will be more than happy to advise on where to go and what to do. There are also many nice pubs to restore yourselves in after a nice walk.

Old stones

Visit one of the many castles, abbeys and other buildings of interest in the area, such as Powderham Castle, Bickleigh Castle or Buckfastleigh Abbey.

The Tarka line Pub Crawl

Discover the rolling mid-Devon countryside at the leisurely pace of this old single-track railway, sampling pubs along the way and ending at the North Devon coast.

Notes