Nature versus Nurture: The Effect of Stellar Irradiation on Atmospheric Evolution

The discovery of planetary systems around other stars has transformed planetary science over the last 20 years, and challenged our understanding of how planets work. From hot, Jupiter-sized bodies that orbit their stars in a little over a day to cloudy worlds resembling miniature Neptunes, these exoplanets and their atmospheres demonstrate astounding variety. The key question for the next decade is which factors are responsible for driving these differences, and in particular what is the role of irradiation from the parent star? A comparative study of known planets, including those in the solar system, can provide answers. New and proposed space and ground-based telescopes will open up the field of exoplanet atmospheres and further our understanding over the next decade, and it is essential to develop techniques to exploit these observatories. I have a background in both planetary science and exoplanet research, providing me with a unique range of expertise that makes me ideally suited to comparative, multidisciplinary studies of this kind.

Introduction: With nearly 2000 exoplanets confirmed, the next step is to characterise these exotic worlds. The most successful method is transit spectroscopy; as a planet passes in front of (transits) or is eclipsed by its parent star, the amount of light coming from the system is reduced. Small wavelength-dependent fluctuations in the transit depth contain information about absorbing gases within the planet's atmosphere. The process of inferring atmospheric properties from these observations is called spectral retrieval; using this technique we can determine the temperature structure and composition of an atmosphere. Tools such as *NEMESIS* [1], an optimal estimation retrieval program, may be used to extract atmospheric information from noisy spectra [2].

Towards a broader picture of exoplanet atmospheres: Direct imaging of exoplanets has also recently emerged as a powerful characterisation tool. Hot, young planets far from their stars can be observed by using coronagraphs to block out the radiation from the star. These young planets are less irradiated than their transiting cousins in close orbits, so they more closely resemble **brown dwarfs** – isolated, failed stars. By comparing the climates of **transiting** and **directly imaged extrasolar planets** with brown dwarfs and with the smaller, cooler **solar system** planets we gain a much broader view of planetary science. Together, these objects provide a laboratory to explore the effects of **surface gravity**, **temperature**, and **size**, and especially the influence of the parent star (Figure 1). The amount of **stellar irradiation** a planet receives is a key driver of atmospheric chemistry and dynamics, and a continuum of objects enables us to investigate this process.

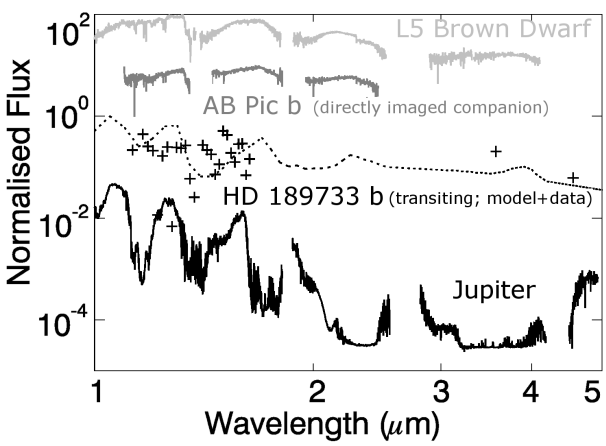

Figure 1: near-infrared observations of Jupiter, a transiting hot Jupiter, a directly-imaged substellar companion and an L5-type brown dwarf. Spectral characteristics are varied; for example, only Jupiter's spectrum is completely dominated by reflected sunlight. These spectra allow us to infer the atmospheric properties of the observed bodies. Currently, spectra of transiting planets like HD 189733b are far noisier and less complete than for other objects, but models indicate what will be possible in the near future. Data are from the IRTF spectral library (brown dwarf and Jupiter), [3] (AB Pic b), and [4,5] (HD 189733b).

I will develop modelling techniques for consistent interpretation and analysis of exoplanet, brown dwarf and solar system spectra. My initial focus will be brown dwarfs and solar system planets, for which high quality spectra exist, and recent exoplanet spectra from the Hubble Space Telescope [e.g. 6], the Very Large Telescope [e.g. 7] and Gemini [e.g. 8]. I will perform a comparative study of brown dwarfs, solar system planets and exoplanets to achieve a deeper understanding of how the presence of and proximity to a star drives atmospheric chemistry, dynamics, structure and evolution, and of the importance of other factors such as surface gravity and temperature. The high quality of current brown dwarf and solar system data makes these objects an ideal training set for atmospheric models. This model development will be a useful step in preparation for exoplanet observations with the James Webb Space Telescope, due to launch in 2018.

Since entering the field in 2011 I have made substantial contributions to exoplanet remote sensing. I was a Science Team Working Group Lead for the proposed Exoplanet Characterisation Observatory, studying the application of atmospheric retrieval techniques to data [9,10], and I recently published a similar analysis for JWST [11]. I am a co-developer of the NEMESIS radiative transfer and retrieval tool for exoplanet atmospheres [1], and was the first to perform a retrieval analysis for cloudy atmosphere models of the super-Earth GJ 1214b [12]. I have extensive experience in modelling hot Jupiter atmospheres [13,14,15] and am modelling Co-I on accepted proposals for similar objects (HST Cycle 23, PIs: Evans, Wakeford; VLT P96, PIs: Evans, Nikolov). My PhD thesis at the University of Oxford dealt with remote sensing of the sulphuric acid cloud on Venus, during which I was involved in the VIRTIS instrument team for the ESA Venus Express mission. I have recently used data from the VIMS instrument on the Cassini spacecraft to constrain the properties of Saturn's tropospheric cloud and haze. Other current work includes producing atmospheric models of the irradiated brown dwarf WD0137-349B [16] to compare with recently-obtained spectra, examining the potential of observing terrestrial planet atmospheres with JWST, and investigating the impact of clouds on exoplanet observations with JWST.

Modelling clouds is a key challenge in exoplanet spectroscopy to emerge in recent years. Clouds, dust and haze present in exoplanet atmospheres affect radiative balance and atmospheric chemistry, and also obscure absorption features and prevent remote sensing of deep regions of the atmosphere [e.g. 12]. The broad wavelength coverage of new observatories such as JWST will better enable the effect of clouds to be disentangled from other atmospheric properties. Clouds are ubiquitous in the Solar System, and whilst their nature is partly understood for most planets, their presence also obfuscates the retrieval process here [17]. Brown dwarfs are known to be cloudy, and there is evidence that young, hot, directly-imaged planets like those in the HR 8799 system are also cloudy [8]. Any model attempting to reproduce spectra of these objects must include clouds, and innovative, minimally-parametric approaches to discover their nature are required [e.g. 18]. Temporally or spatially variable clouds add another layer of complexity to the issue.
* Following on from my pioneering work presented in [17,12,15], I will develop a new, hierarchical modelling and retrieval scheme for cloudy atmospheres. This will enable cloud model complexity to be tuned according to the information content of the observations, avoiding the twin problems of model over fitting and over simplification. Limb or transit observations place tight constraints on cloud top altitude, whereas thermal emission observations are more sensitive to composition, so different observation geometries can constrain different aspects of the cloud model. Clouds and hazes on some solar system bodies are photochemical in origin (e.g. Titan tholins) so the study of clouds will form a key part of this fellowship as their presence may be linked to stellar irradiation.

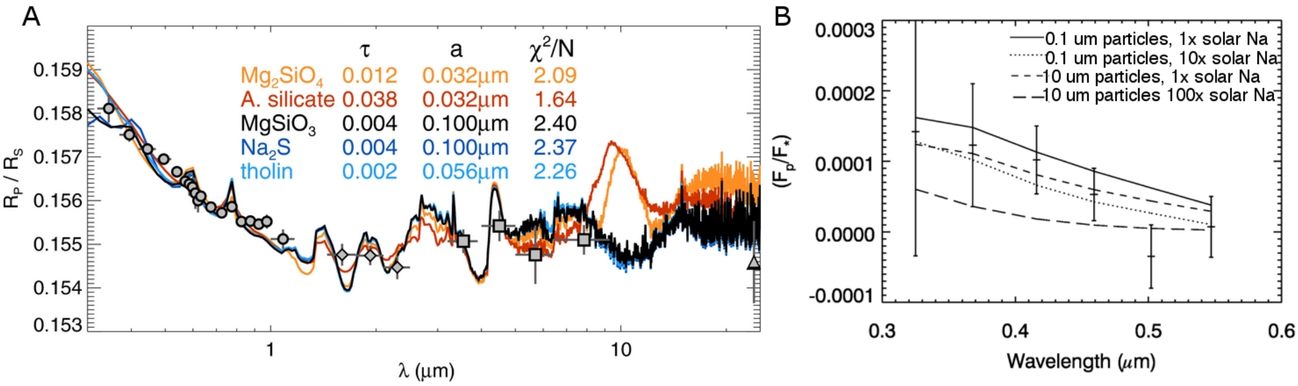

Figure 2, A: spectral models with different cloud compositions compared with the observed transmission spectrum of hot Jupiter HD 189733b, from [19]. B: spectral models with different cloud particle sizes and sodium abundance, compared to the reflection spectrum of HD 189733b [15]. Several models provide a good fit in both cases, showing the degeneracy of the problem.

Hot Jupiters (high irradiation): Transit and eclipse spectra have been obtained for a few tens of hot Jupiters, many coming from large HST surveys [e.g. 6]. However, they are generally noisy, with limited spectral resolution and range. Analysis can be complicated further by the presence of clouds (e.g. Figure 2). A new cloud retrieval scheme will improve our ability to reliably contstrain the atmospheric state for cloudy Hot Jupiters. Hot Jupiters are heavily irradiated as well as hot, and so they provide an opportunity to study the balance of thermo- and photochemical processes.
* Using data from large-scale published surveys such as [6] and smaller HST and VLT programmes, I will develop and test a new retrieval model for cloudy exoplanets including accurate spectral line data provided by the ExoMol team at UCL. Data reduction will be performed in conjunction with the UCL ExoLights group and current observational collaborators at Oxford and Exeter. The next few years will see several discoveries by planet surveys such as SuperWASP (hot Jupiters), Next Generation Transit Survey (planets around cool stars), the Kepler K2 mission

and the Transiting Exoplanets Survey Satellite (planets around bright stars). I will evaluate follow-up potential of these objects and seek new spectral data.

Studying moderately-irradiated solar system planets has the advantage of data quality (for Venus, Mars, Jupiter, Saturn and larger satellites) that far outstrips that of exoplanets and brown dwarfs; these objects have all been subject to the scrutiny of visiting spacecraft. However, with few objects to study, the solar system must be viewed in the context of other planetary systems.
* I will use the detailed satellite data of solar system planets as a test bed for the new cloudy planet models and retrieval algorithms. In addition, solar system planets cover an important region of planetary parameter space – that of cool, irradiated planets over a large surface gravity range. Solar system atmospheric processes are largely driven by photochemistry, e.g. hazes on Venus and Titan, and the ozone layer on the Earth. Comparing these planets to the more exotic exo-worlds will tell us about the relative importance of these processes at different temperatures.

***Directly imaged exoplanets (low irradiation)*:** Young planets in wide orbits can be observed by blocking out the light from the star. They occupy parameter space between isolated brown dwarfs and much closer in hot Jupiters. Recently, the Gemini Planet Imager [8] and the SPHERE instrument on the VLT [7] have dramatically improved the quality of directly imaged planet spectra.
* To date, the retrieval method has been seldom used for directly imaged planets [20], with the exception of [21]. I will use NEMESIS to analyse existing Gemini and VLT observations for a range of directly imaged planets, including the HR 8799 system and Beta Pictoris b, in a manner consistent with the analyses of transiting exoplanets and brown dwarfs.

Brown Dwarfs (no irradiation): Despite their isolation, brown dwarfs have dynamic atmospheres with clouds and weather, driven by internal heating not stellar irradiation. With some exceptions, e.g. [16], they lack photochemistry. It is easier to obtain high quality spectra for brown dwarfs than for exoplanets, due to the lack of contaminating starlight. Instruments such as Magellan/FIRE [e.g. 22] and VLT/XSHOOTER have provided many high quality spectra [e.g. 23]. Except [24], previous analyses of brown dwarf spectra have simply compared existing models with observations; a retrieval approach contains fewer assumptions, allowing full exploration of parameter space and providing a data-driven solution [24] which can be compared with results from physical models.
* I will collaborate with colleagues at Oxford in adapting NEMESIS for analysis of brown dwarf spectra, including exploration of Monte Carlo retrieval approaches, then use it to infer atmospheric structure, composition and cloud properties for a range of brown dwarfs of different temperatures and ages, including special cases [e.g. 16]. The outcome will be an understanding of how brown dwarf chemistry and dynamics correlate with age.

Timeline: **Year 1** will focus on cloud model development and testing on solar system observations; model/retrieval comparisons and blind tests with collaborators at UCL, in the Netherlands and at NASA Ames; and application to existing and new HST and VLT observations of ~10 hot Jupiters. **Year 2** will build on this work, applying retrieval methods to available brown dwarf datasets (e.g. [23]), public observations of directly-imaged planets (e.g. [8]) and new transit spectra from HST and VLT, as well as preparing for the first JWST call in November 2017. New targets from TESS, NGTS and K2 can be explored for follow-up potential. In **Year 3** I will compare results from studies of different classes of object and complete a comparative study of atmospheric composition, day/night side differences (where possible), temperature structure, clouds and stellar characteristics (if relevant/where available). I will compare observations of a few 10s each of brown dwarfs and exoplanets, over a range of temperatures and sizes, with the solar system planets. Throughout the fellowship I will continue my work in support of the UCL-led ARIEL and Twinkle missions.

The strength of the retrieval approach for a comparative study such as this is the opportunity it affords to analyse planets and brown dwarfs with the same model in an entirely consistent way. With seven years of experience in applying spectral retrieval techniques to atmospheres of solar system planets, exoplanets and brown dwarfs, I am the ideal person to undertake this research.

1 Irwin+ 2008, JQSRT, 109, 1136; **2** Rodgers 2000, pub. World Scientific; **3** Bonnefoy+ 2014, A&A, 562, 127; **4** Crouzet+ 2014, ApJ, 795, 166; **5** Knutson+ 2012, ApJ, 754, 22; **6** Sing+ 2015, Nature, in press; **7** Hinkley+ 2015, ApJ, 805, L10; **8** Ingraham+ 2014, ApJ, 974, L15; **9** Barstow+ 2013a; **10** Barstow+ 2014b; **11** Barstow+ 2015; **12** Barstow+ 2013b; **13** Gibson, Aigrain, Barstow+ 2013a; **14** Gibson, Aigrain, Barstow+ 2013b; **15** Barstow+ 2014a; **16** Casewell+ 2015, MNRAS, 447, 3218; **17** Barstow+ 2012; **18** Irwin, Tice, Fletcher, Barstow**+** 2015; **19** Lee, Irwin, Fletcher, Heng, **Barstow** 2014; **20** Crossfield 2015, ApJ, arxiv:1507.03966; **21** Lee+ 2013, ApJ, 778, 97 **22** Burgasser+ 2011, ApJ, 735, 116; **23** Marocco+ 2015, MNRAS, 449, 3651; **24** Line+ 2015, ApJ, 807, 183