

EPSC2017

EX4 abstracts

Thermal dependency of CO₂ VUV absorption cross section and application to warm exoplanetary atmospheres

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Abstract

Most of exoplanets detected so far have atmospheric temperatures significantly higher than 300 K. These exoplanets are often close to their star and thus receive an intense UV photons flux, triggering important photodissociation processes. However, the temperature dependency of VUV absorption cross sections, which are essential data to model photolyses in atmospheric models, are barely known. Thus, by lack of appropriate data, absorption cross sections at room temperature are used in photochemical models of extrasolar planets, leading to a non-measurable uncertainty. With the future space- or ground-based telescopes that will be developed in the coming years (JWST, E-ELT...) investigating these research fields becomes urgent [1]. In this context, we quantified the temperature dependency of the VUV absorption cross section of carbon dioxide (CO₂). We performed experimental measurements on the range (115-230 nm) between 150 and 800 K. The absorption cross section of CO₂ increases with the temperature (Fig. 1). At 200 nm, there are more than four orders of magnitude between the one at 300 K and the one at 800 K. We also determined a parametrisation to calculate the continuum of the absorption cross section on this wavelength range. We used these new data in our photo-thermochemical model for exoplanets [2] and studied the impact on the results (photolyses rates and chemical composition) as well as on the observables (synthetic transmission spectra) [3, 4]. We will present these experimental results and their consequences on the modelling of exoplanet atmospheres.

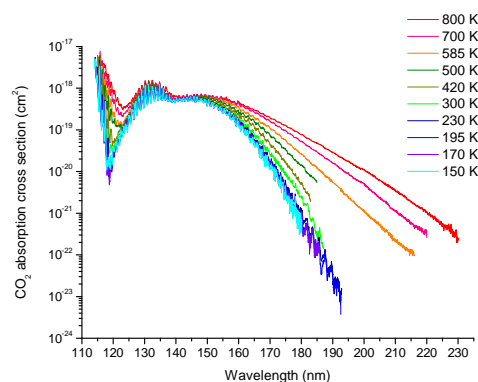


Figure 1: Absorption cross section of CO₂ (cm²) at temperature between 150 and 800 K.

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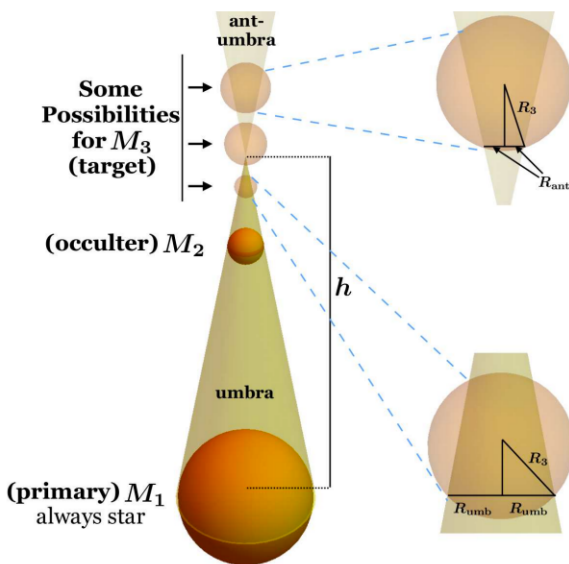
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How space probes view eclipses, transits and occultations at syzygy

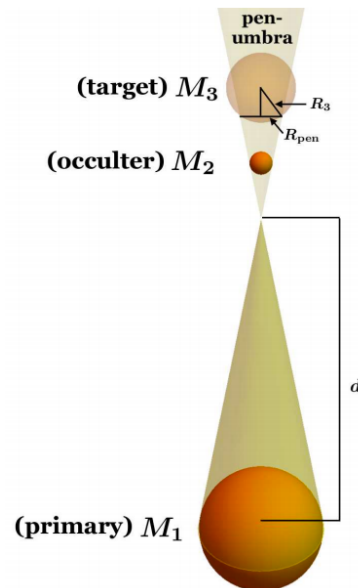
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 Based on MNRAS In Press (2017), arXiv:1703.03414

Abstract

Although conjunctions and oppositions frequently occur in planetary systems, eclipse-related phenomena are usually described from an Earth-centric perspective. Space missions to different parts of the Solar system, as well as the mounting number of known exo-planets in habitable zones and the possibility of sending featherweight robot spacecraft to them, prompt broader considerations. Here, we derive the geometry of eclipses, transits and occultations from a primarily exo-Earth viewpoint, and apply the formulation to the Solar system and three types of three-body extrasolar planetary systems: with 1 star and 2 planets (Case I), with 2 stars and 1 planet (Case II), and with 1 planet, 1 star and 1 moon (Case III). We derive the general conditions for total, partial and annular eclipses to



occur at syzygy and exo-syzygy, and implement them in each case in concert with stability criteria. We then apply the formalism to the TRAPPIST-1, Kepler-444

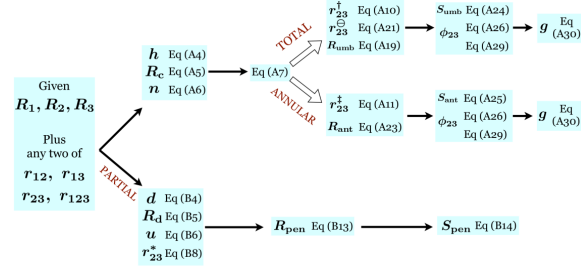


and Kepler-77 systems -- the first of which contains multiple potentially habitable planets -- and provide reference tables of both Solar system and TRAPPIST-1 syzygy properties. We conclude by detailing a basic algebraic algorithm which can be used to quickly characterize eclipse properties in any three-body system.

2. Specifics

In all cases, the radiation emanating from the primary will form two different types of cones with the occulter, because the latter is smaller than the former. The first type of cone, yielding total and annular eclipses, is formed from outer or external tangent lines (Figure on left). The second type of cone, yielding partial eclipses, form from the inner or internal tangent lines (Figure above). For all derivations, see [1].

As shown by the flow chart below, given the radii of the three objects in syzygy, plus any two of the distances, other relevant quantities, such as eclipse type and depth, can be derived.



This flowchart has enabled us to create tables of eclipses from various viewpoints [1], and can be used to quickly and algebraically obtain a first-order idea of what space probes sent to different bodies in the Solar system might see.

Acknowledgements

DV has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement no. 320964 (WDTracer).

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Modeling the albedo of magma ocean planets

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Abstract

1 Introduction

The modeling of telluric exoplanets at the beginning of their history, during their magma ocean stage, has been very active during the last decade. Such models usually consist in coupled models, with various sub-modules (interior, atmosphere) interacting with each others through matter and/or energy fluxes [1, 2, 3].

Here we present the newest updates to the 1d radiative-convective atmospheric submodule [7, 8] of a coupled interior-atmosphere model developed since 2010 [9, 12]. These newest updates consist in the inclusion of Rayleigh scattering, but mainly in the modeling of the reflectivity of the atmosphere in order to determine its albedo. This updated atmospheric model is therefore able to compute both the thermal outgoing longwave radiation ($OLR = \sigma T_{\text{eff}}^4$) of the planet, and the absorbed stellar flux ($ASF = \sigma T_{\text{eq}}^4$), thus allowing a self-consistent estimation of the secular cooling heat flux originating from the interior through the atmosphere, given by $\sigma (T_{\text{eff}}^4 - T_{\text{eq}}^4)$. Also, the determination of both thermal emission spectra and spectral reflectivity could help in constraining future exoplanet observations that would happen to currently experience their magma ocean stage.

2 Improvements

2.1 Rayleigh scattering

Rayleigh scattering opacity was added to the most recent version of the atmospheric submodule [8]. Cross-sections of N_2 , CO_2 and H_2O were assumed to follow a λ^{-4} spectral dependency so that spectral averaging within each of the 36 bands in both thermal ($0\text{--}10^4 \text{ cm}^{-1}$) and stellar ($2000\text{--}33000 \text{ cm}^{-1}$) components could be computed analytically. Preliminary testing shows that the influence of Rayleigh scattering

for the thermal component was indeed negligible for $\lambda > 1 \mu\text{m}$.

2.2 Spectral reflectivity

In the 36 stellar bands, opacity due to Rayleigh scattering (see above), clouds and gaseous species (CO_2 and H_2O) was considered. Clouds properties ($\varpi_0(\lambda)$, $Q_{\text{ext}}(\lambda)$ and $g(\lambda)$ assuming a Henyey-Greenstein phase function) were parameterized from Mie calculations given by [4], in the same way than for the already modeled thermal component. Gaseous opacities were extracted from the MT_CKD database [6] for the H_2O - H_2O continuum, and from Venusian observations for CO_2 - CO_2 . Line opacities were computed using KSPECTRUM [10], using the spectra already computed for similar pressures, temperatures and atmospheric composition by M. Turbet [11].

Spectral reflectivity in each of these bandes is then computed using a k -correlated code with 16 quadrature points in g -space, running DISORT [5] in the 4 streams approximation. Once spectral reflectivity is computed, the resulting albedo can be computed by weighting each band's reflectivity according to the Planck function for the star temperature.

3 Preliminary results

The work is still underprogress, but two features appear robust in our preliminary simulations: (1) for a given atmosphere (H_2O and CO_2 total pressures, surface temperature), the albedo is increasing with increasing stellar temperature. This is due to a global decrease in reflectivity with increasing wavelengths, since Rayleigh and/or cloud scattering becomes dominated by near IR absorption from H_2O (and CO_2 to a lesser extent); (2) for a given atmospheric inventory, a transition between a high albedo regime for relatively low surface temperatures and a lower albedo at higher surface temperatures can be observed. The transition temperature is close to the one observed for

the OLR[8]: for higher surface temperature, clouds are optically thin, and therefore the condensation cold trap becomes negligible, enabling “dark” water vapor to reach higher levels where it can efficiently absorb stellar light.

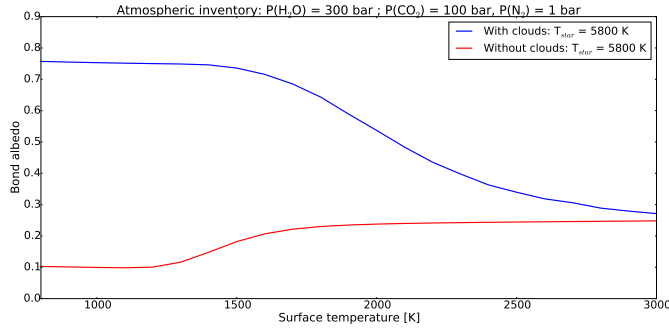


Figure 1: Preliminary modeling of the albedo of a H₂O-dominated atmosphere around a solar analog wrt. its surface temperature

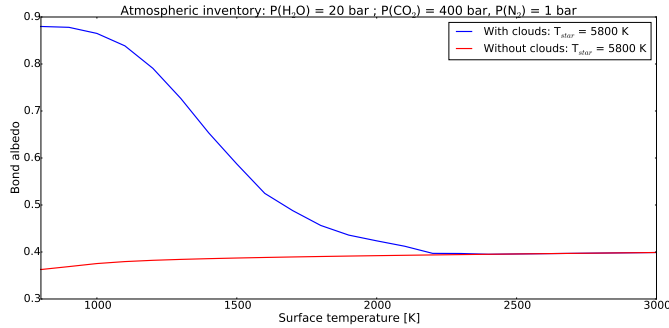


Figure 2: Preliminary modeling of the albedo of a CO₂-dominated atmosphere around a solar analog wrt. its surface temperature

4 Conclusion

Once finalised, the results from this model will be used as a benchmark for a new PhD project, aiming at using the LMD generic global circulation model in order to better model the transition between magma ocean planets (with a very high internal heat flux on par with stellar absorption) and mature telluric planets (with negligible internal heat flux) and thus investigate their habitability once atmospheric escape is taken into account.

Acknowledgements

This work has been supported by INSU through the Programme National de Planétologie.

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Occurrence of outgassed atmospheres on stagnant-lid Super-Earths

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Abstract

We explore volcanic outgassing on stagnant-lid exoplanets of different interior structures and compositions. We study planets of 1–8 M_{\oplus} (Earth masses) (Figure 1), that have refractory bulk abundances that are compatible with abundance proxies of planet-hosting stars (i.e., Mg/Si, Fe/Si). With a set of more than 1400 super-Earth cases, we study the influence of thermal, structural, and compositional parameters on volcanic outgassing. Besides thermal parameters, planetary mass crucially influences possible outgassing. At high masses (>6 – 7 Earth masses), the large pressure gradient in the lithosphere generally prohibits partial melting at depth. We also demonstrate how our findings provide interpretative means for the observational studies on exoplanet atmospheres.

1. Introduction

Our knowledge on the diversity of their interiors and atmospheres is limited, because exoplanet data are generally few and do allow for very different interior structures and compositions. The anticipated diversity of atmospheres on super-Earth exoplanets is subject to planet formation and evolution processes. Among the long-term processes, interior outgassing is relevant. Here, we study how outgassing on super-Earths scales for different interior structures and compositions.

2. Interior models

While accounting for high-precision astrophysical data and associated uncertainties (mass M , radius R , bulk abundances Mg/Si and Fe/Si) of super-Earths, we calculate for each synthetic planet the two endmember interiors that are those of maximum and minimum core size that fit data within the 1- σ uncertainty ($\sigma_M = 10\%$, $\sigma_R = 5\%$, $\sigma_{Fe/Si} = 20\%$, $\sigma_{Mg/Si} = 20\%$). More details in Dorn et al. (2015, A&A, 577, A83).

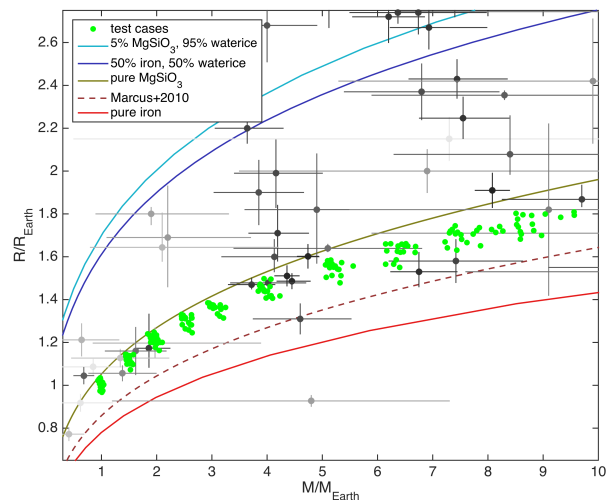


Figure 1: Masses & radii of considered planet cases (green dots) compared to mass-radius relationships of idealized compositions.

3. Convection model

We model convection in a compressible mantle in the 2-D spherical annulus geometry using the truncated anelastic liquid approximation. Reference profiles for temperature, density, gravity, and pressure, as well as material properties of thermal expansion coefficient, thermal heat capacity, and thermal conductivity are taken directly from the interior models (Section 2). Given these input profiles and imposed lateral variation fields for temperature, density, and pressure, the convection code solves the conservation equations for mass, momentum and energy.

3.1. Melting:

Varying mantle composition affect melting temperatures T_s , for which we derive an iron-dependent melting law for low pressures based on [1] and [2], where

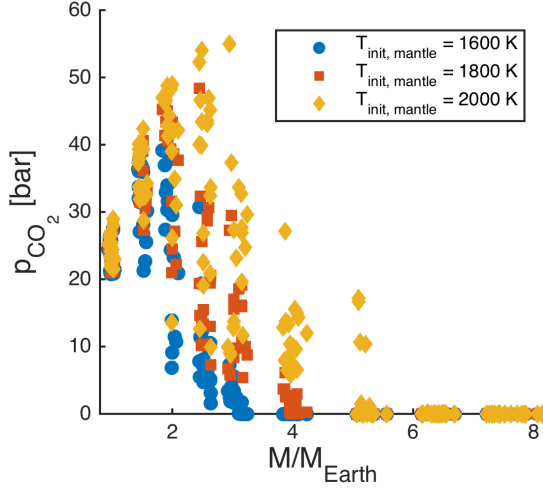


Figure 2: Influence of initial mantle temperature on outgassing. The amount of outgassing is in terms of partial pressure p_{CO_2} . Surface temperature T_{surf} is fixed to 280 K in all test cases.

χ_{Fe} is in wt%.

$$\begin{aligned} \Delta T_s &= (1.02 + 0.641P - 0.0362P^2) \\ &\quad \cdot (10 - \chi_{\text{Fe}}), \text{ if } P \leq 12 \text{ GPa} \\ \Delta T_s &= 3.6 \cdot (10 - \chi_{\text{Fe}}), \text{ else.} \end{aligned} \quad (1)$$

4. Results and Conclusions

We find that planet mass has a first order effect on outgassing. Above $\sim 7 M_{\oplus}$, outgassing becomes negligible in all test cases (note $T_{\text{surf}} = 280 \text{ K}$). Thermal parameters are of primary importance, since they extend the range of planet masses, where outgassing is observed (Figure 2). Variation of core sizes and mantle compositions seem to be of secondary influence on depletion and outgassing (Figure 3). Finally, secondary atmospheres on stagnant-lid planets only occur in a limited range of planet masses. The identification of secondary atmospheres beyond that limit implies different dynamic regimes (e.g., mobile lid). We propose a qualitative comparison of our findings with actual gained insights on the atmosphere types of observed exoplanets.

This analysis will inform the interpretation of determined thicknesses and compositions of exoplanet atmospheres, e.g. from future spectroscopic observations (e.g., E-ELT, JWST).

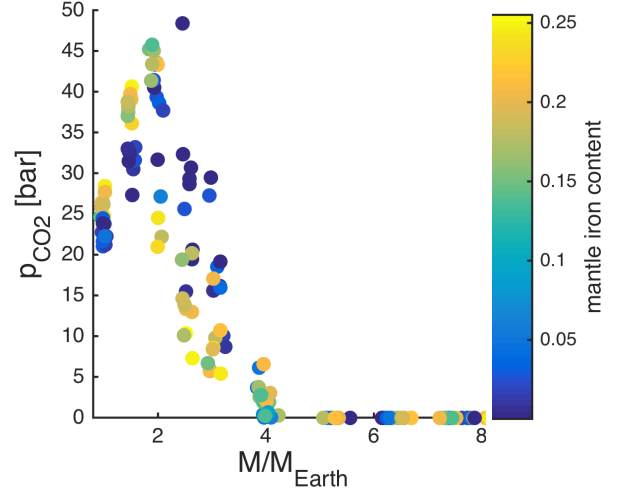


Figure 3: Influence of mantle iron content on depletion and outgassing for different planet masses and bulk compositions ($\text{Fe/Si} \in \{.5, 1., 1.5\}$ $\text{Fe/Si}_{\text{Sun}}$ and $\text{Mg/Si} \in \{.5, 1., 1.5\}$ $\text{Mg/Si}_{\text{Sun}}$).

Acknowledgements

This work was supported by the Swiss National Foundation under grant 15-144 and is MERAC-funded by Swiss Society of Astrophysics and Astronomy. It was in part carried out within the frame of the National Centre for Competence in Research PlanetS. L. Noack has been funded by the Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office through the Planet Topers alliance.

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Artificial Intelligence in planetary spectroscopy

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Abstract

The field of exoplanetary spectroscopy is as fast moving as it is new. Analysing currently available observations of exoplanetary atmospheres often invoke large and correlated parameter spaces that can be difficult to map or constrain. This is true for both: the data analysis of observations as well as the theoretical modelling of their atmospheres.

Issues of low signal-to-noise data and large, non-linear parameter spaces are nothing new and commonly found in many fields of engineering and the physical sciences. Recent years have seen vast improvements in statistical data analysis and machine learning that have revolutionised fields as diverse as telecommunication, pattern recognition, medical physics and cosmology.

In many aspects, data mining and non-linearity challenges encountered in other data intensive fields are directly transferable to the field of extrasolar planets. In this talk, I will discuss how deep neural networks can be designed to facilitate solving said issues both in exoplanet atmospheres as well as for atmospheres in our own solar system. I will present a deep belief network, RobERt (Robotic Exoplanet Recognition) [1], able to learn to recognise exoplanetary spectra and provide artificial intelligences to state-of-the-art atmospheric retrieval algorithms. Furthermore, I will present a new deep convolutional network [2] that is able to map planetary surface compositions using hyper-spectral imaging and demonstrate its uses on Cassini-VIMS data.

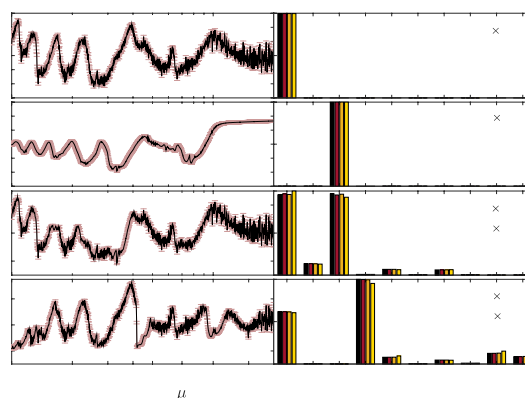


Figure 1: Left: simulated emission spectra of exoplanet atmosphere (normalised by the planetary black body). Right: RobERt estimated probability of molecules being present in the spectrum. In all cases molecules were detected accurately.

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The LAPS Project: A tutorial, online model to simulate the atmosphere of any terrestrial planet.

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The project

The **LAPS** (Live Atmospheres-of-Planets Simulator) is a live 1-D radiative-convective version of the LMD Global Climate Model [1,2,3]. The LAPS provides an accelerated and interactive simulation of the climate of any terrestrial planet and exoplanet. This tool was initially designed for students to explore the boundaries of the «Classical Habitable Zone», defined as the range of orbital distances within which a planet can maintain liquid water on its surface [4].

Capability of the model

The model faithfully reproduces both the inner edge and the outer edge limits of the Habitable Zone, and their dependencies to the type of star and the gas composition. It can also be used to recover the atmospheres of the Solar System terrestrial planets (Venus, Earth and Mars) and explore how they would evolve when exposed to different external conditions (different star, orbit, ...).

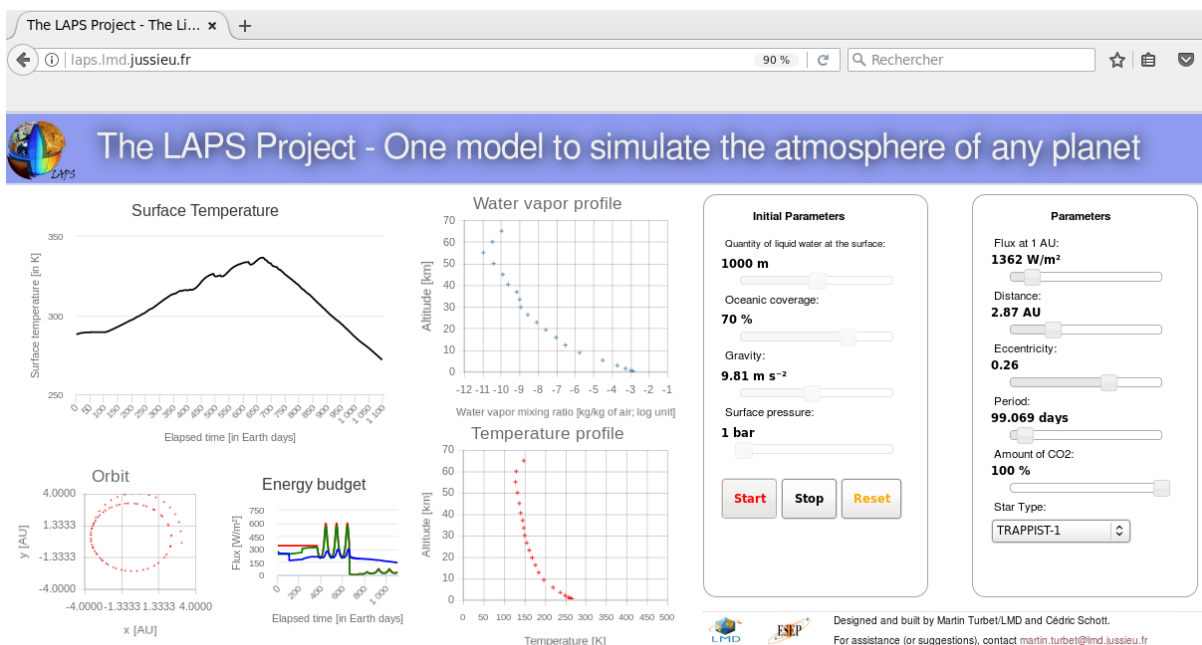


Figure 1: Screenshot of the online Graphical User Interface of the LAPS model. It presents the evolution of the surface temperature and the instantaneous vertical profile of temperature and water vapor during a simulation which typically achieve 10 Earth days per CPU seconds.. Throughout the simulations, the star insolation (i.e. the distance from the star), the type of star, the amount of CO2, ... can be modified.

The LAPS model provides a "hands on" experiment by showing how the surface and atmospheric temperatures as well as the profile of water vapor evolve through time when the external forcing (insolation, star spectrum, ...) or the planet (gravity, quantity of CO₂, initial amount of water reservoir, ...) is modified.

How to use it?

Just click on <http://laps.lmd.jussieu.fr/> !

Note that the tool will be presented on demand and on live during the EPSC-2017 poster session.

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Proxima Cen and TRAPPIST-1 exoplanetary systems: possible climates and observational constraints

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1. Introduction

The years 2016-2017 have been extremely fruitful in discoveries of interesting nearby Earth-size exoplanets. Radial velocity monitoring with HARPS has found the signature of a $M \sin i = 1.3 M_{\oplus}$ planet located within the Habitable Zone of Proxima Centauri, the closest star from the Sun [1]. Meanwhile, 7 transiting temperate Earth-size (at $\pm 30\%$) planets have been detected around the ultra-cool star TRAPPIST-1 [2-4]. The detections of Proxima Cen b and TRAPPIST-1 planets are major discoveries mostly because these – very likely rocky – planets are (and will stay) the best candidates for future atmospheric characterization by transit spectroscopy, direct imaging, or thermal phase curve with the forthcoming astronomical ground (e.g. E-ELT) or space-based (e.g. JWST) observatories [2,3,5-9]. These two systems are thus invaluable probes for planetary science outside our Solar System, and possibly habitability.

We explore here the possible climates of these planets, and produce observational constraints that should be used to discriminate between all the possible atmospheric states of the planets.

2. Environment / orbital evolution

Proxima Centauri and TRAPPIST-1 are very active stars, compared to our Sun. Recent work [10,11] have shown that the planets orbiting around them are exposed to X/UV irradiation 10^1 - 10^3 times larger than received on Earth. Moreover, during the 100My following their formation when TRAPPIST-1 and Proxima Cen were pre-main-sequence stars and their luminosity significantly higher than today, each of the planets could have faced a runaway phase where the most condensable volatiles (e.g. water) would have been vaporized, and exposed to atmospheric escape. As much as several Earth ocean hydrogen content could have been lost in the process

[10,12]. Note however that despite this hostile environment, density measurements – through TTV analysis [3,13] – of the TRAPPIST-1 system suggest that most of the planets could still be volatile-rich. Eventually, Proxima Cen b and all the 7 TRAPPIST-1 planets should be today in slow rotation (and very likely, in synchronous rotation) as expected for such planets influenced by gravitational tides [9,10].

3. Possible climates

We use here the 3D LMD Generic Global Climate Model (GCM) to simulate the atmosphere(s) of Proxima Cen b (and TRAPPIST-1efgh planets), for their two most likely rotation modes, and for various volatile (H_2O , CO_2 , CH_4 , N_2 , ...) contents.

We find that a broad range of atmospheric compositions allow surface liquid water for Proxima Cen b and TRAPPIST-1e. In particular, we find that *if Proxima Cen b or TRAPPIST-1e are 1) in synchronous rotation and 2) water-rich, then the planets should always have a patch of liquid water at least at their substellar point, whatever their atmosphere (as thick or thin as wanted)* [5,9]. All their possible climates are summarized in Fig 1.

Although a few bars of CO_2 [9] would suffice to sustain habitability on planets slightly less irradiated (e.g. TRAPPIST-1fg), these planets could likely be trapped in permanent snowball state, because it should be difficult for them to accumulate enough greenhouse gases like CO_2 or CH_4 . CO_2 would easily collapse in the nightside, forming CO_2 ice deposits that should be gravitationally unstable and get buried beneath the water ice shell in geologically short timescales [9,14,15]. Given TRAPPIST-1 planets large EUV flux (at least $\sim 10^3 \times$ Titan's flux), CH_4 and NH_3 should be photodissociated rapidly and thus be hard to accumulate in the atmosphere. This, and the radiative cooling effect of photochemical hazes/stratospheric

methane, would make it difficult for TRAPPIST-1fgh to sustain surface habitability.

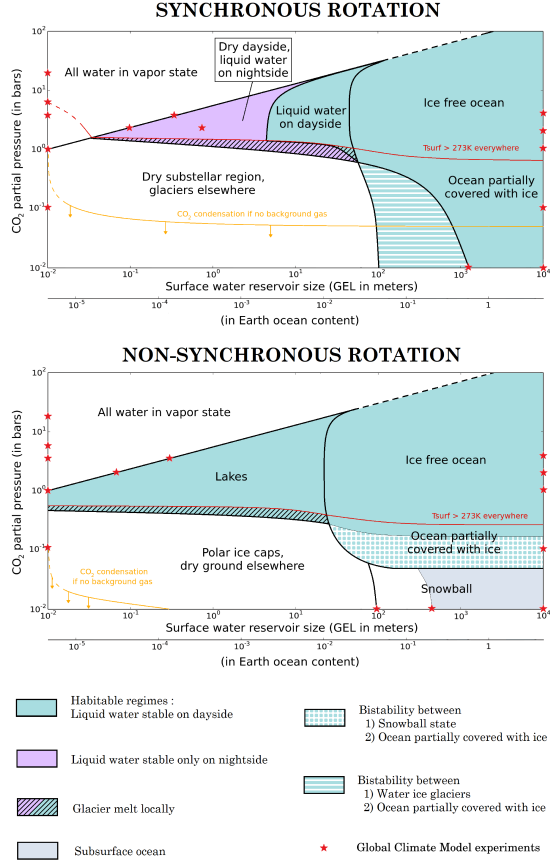


Figure 1: Schematic diagrams of the possible climate regimes reached by Proxima Cen b (and TRAPPIST-1e, by extension) as function of the available CO_2 and H_2O contents. More details can be found in [5].

4. Observational constraints

For each of the climate regimes obtained in our analysis, we produce synthetic observables that can be used to prepare future observations of the planets by either JWST or ELT-class telescopes. In the case of Proxima Cen b, we produced reflection and emission spectra, and phase curves for the simulated climates. We find that atmospheric characterization of the planet will be possible via direct imaging with forthcoming large telescopes. The angular separation of $7\lambda/D$ at $1\text{ }\mu\text{m}$ (with the E-ELT) and a contrast of $\sim 10^{-7}$ will enable high-resolution spectroscopy and the search for molecular signatures, including H_2O , O_2 , CO_2 ... The observation of thermal phase curves (see Fig 2) can

be attempted with JWST, thanks to a contrast of 2×10^{-5} at $10\text{ }\mu\text{m}$.

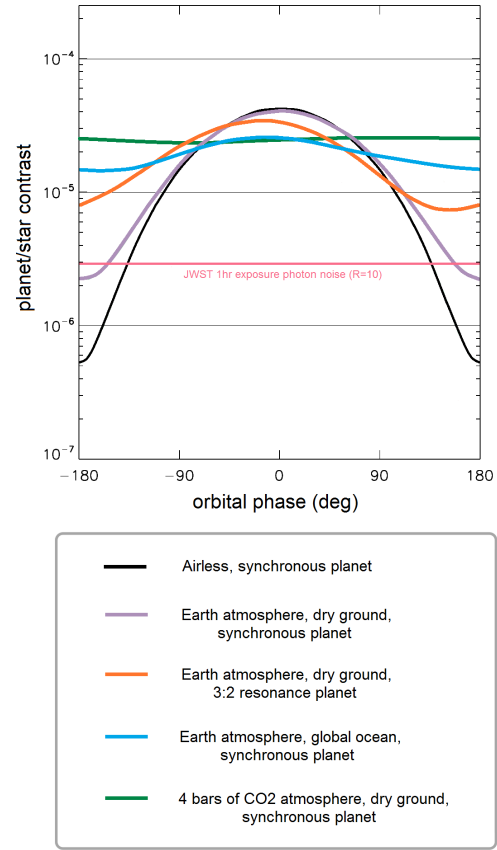


Figure 2: Thermal phase curves ($\sim 11.4\mu\text{m}$) for several configurations : airless planet, Earth-like planet with oceans, planet with a thick atmosphere ... The red curve roughly depicts the relative amplitude of the expected detection limit of JWST for an exposure of $\sim 1\text{h}$.

More results on Proxima Cen / TRAPPIST-1 systems will be discussed at the EPSC-2017 conference.

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Is the Super-Earth 55 Cancri e still a carbon-rich planet?

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Abstract

The Super-Earth 55 Cancri e forms one of the best cases for the study of planetary interiors, as its physical properties are known with an unrivaled precision. Using the latest estimates of these parameters, we investigate the composition and internal structure of 55 Cancri e as a solid silicate-rich planet and confirm that the planet is not dense enough to be purely rocky. A water-rich composition presents limitations, especially given the planet's surface conditions. The measured mass and radius of 55 Cancri e can however be reconciled by considering a composition based on carbon materials. As the latest measurements tend to discuss the likelihood of such an extremely carbon-rich composition, we think that 55 Cancri e constitutes a strong test case for the investigation of hybrid compositions containing both silicates and carbon molecules.

1. Introduction

Probing the composition of exoplanets is possible through the use of planetary interiors models, who allow to constrain the internal structure of these bodies. A precision of a few percent is required on the fundamental parameters (mass and radius) of an exoplanet to precisely derive its composition. The Super-Earth 55 Cancri e (hereafter 55 Cnc e) meets these requirements, as it orbits a bright and close solar-type star, 55 Cancri [1, 2]. The use of precise interferometric measurements and improved stellar models provided an error under 6% on the planet's mass, and 4.5% on its radius [3].

Here we perform a detailed study of 55 Cnc e's interior with these parameters, that is a mass of $8.631 \pm 0.495 M_{\oplus}$ and a radius of $2.031^{+0.091}_{-0.088} R_{\oplus}$ [3]. We first explore the case of a terrestrial planet (i.e. fully rocky) with a possible water envelope. A theoretical kind of planets is then considered, formed from different materials than those that predominate in the solar system, that is carbon-based molecules. We then discuss the legitimacy of the compositional parameters derived for 55 Cnc e in both cases.

2. Interior model and parameters

Our model is presented in [4], it computes the radius of a planet from its known mass and assuming a composition. A planet described by this model is constituted by three concentric and fully differentiated main layers: a core, a mantle, and an envelope. Depending on the kind of planet we consider, these layers are formed from different materials. For terrestrial planets, our model takes the Earth as a reference and these layers are made of metals (iron and iron alloy), silicate rocks, and water, respectively. The two latter layers may be divided into two sublayers each because of phase changes of the corresponding materials. The two mantle sublayers contain different silicate rocks, whereas the water envelope divides into a liquid water layer on top of a high-pressure ice layer. In the case of a carbon-rich planet, the core is also made of iron metals. The mantle is solely composed of silicon carbide SiC, surrounded by a pure carbon envelope. The carbon envelope may divide into graphite and diamond sublayers.

The composition of a planet is thus fixed by the mass of the three main layers, therefore we define two parameters in our model: the core mass fraction (CMF) and envelope mass fraction (EMF), that are varied in the 0 to 1 range. We exclude from our simulations planets that harbor a thick gaseous atmosphere. However, to allow the presence of liquid water at the surface of simulated terrestrial planets, we consider the surface conditions to be close to those of the Earth (1 bar pressure and 288 K temperature).

3. Results

We perform a simulation of the interior of 55 Cnc e for every composition allowed by the variations of the CMF and EMF. The parameter space formed that way is represented as a ternary diagram (see Figure 1). Here we present the results obtained for a terrestrial planet of a mass of $8.63 M_{\oplus}$. Two parameters allow to reduce the explored set of compositions and place constraints on the values of the CMF and EMF. The

first parameter is the planet’s radius, whose range estimated by [3] is plotted on Figure 1. The compositions located between the isoradius curves that show the 1σ values are those compatible with both a mass of $8.63 M_{\oplus}$ and a radius between 1.943 and $2.122 R_{\oplus}$. To lower the important degeneracy that appears, a second parameter is taken into account, namely the Fe/Si bulk ratio of the planet, which is assumed to be identical to the stellar value. Here we take $\text{Fe/Si} = 0.903 \pm 0.287$, derived from [5]. The grey area on the ternary diagram shows the 1σ values of the Fe/Si ratio. From these constraints, we derive the allowed ranges for 55 Cnc e’s CMF and EMF when considering terrestrial materials: 10–30% for the CMF, and 10–50% for the EMF (i.e. water mass fraction). With such a structure, 55 Cnc e cannot be fully rocky like the Earth. A significant water amount is needed to explain the planet’s radius and Fe/Si ratio.

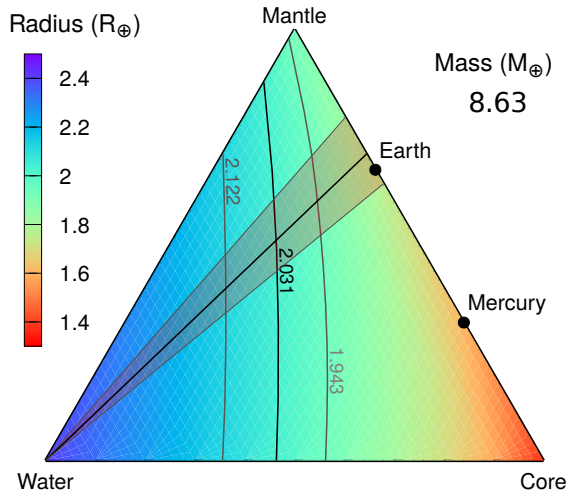


Figure 1: Ternary diagram displaying the compositional parameter space of a $8.63 M_{\oplus}$ 55 Cnc e. A colored map of the planet radii is shown, with isoradius curves denoting the central and 1σ values from [3]. The darkened area delimits which compositions are compatible with the stellar Fe/Si ratio from [5].

We use the same methodology in the case of a carbon-rich planet, and explore the ternary diagram of metallic core, SiC mantle, and pure carbon envelope. With the constraint from the planet’s radius, we obtain a range of 0–35% for the CMF, and 0–90% for the EMF. These results show that the measurement of the radius strongly constrains the CMF in the case of carbon-rich planets, compared to the EMF.

4. Discussion

We investigated the composition of the Super-Earth 55 Cnc e using updated stellar parameters. Assuming terrestrial materials imposes the planet to be an ocean world (at least 10% of water in mass). A fully rocky composition is excluded by the measured radius and stellar Fe/Si ratio. Following recent studies suggesting that 55 Cnc e is carbon-rich [6, 7], we explored the impact of such an enrichment on the planet. The modeling shows that the mass and radius of 55 Cnc e can be explained by a small metallic core surrounded by a mantle and an envelope of carbon materials. Although recent estimates of stellar abundances suggest that the planetary system is less enriched in carbon than previously reported [5], the planet has likely a hybrid composition with both oxygen and carbon-based molecules. Further studies have to be carried out to determine the structure of materials that would form in such conditions.

Acknowledgements

B.B. and O.M. acknowledge support from the A*MIDEX project (n° ANR-11-IDEX-0001-02) funded by the “Investissements d’Avenir” French Government program, managed by the French National Research Agency (ANR); O.M. and M.D. also acknowledge support from CNES.

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Constraints on low mass Exoplanets Interiors from Stellar Abundances

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Abstract

Through models of planetary structure, we can now probe the interior and composition of the hundreds of exoplanets with known masses and radii. In addition to the still limited precision on the fundamental parameters of these bodies, models are limited by the existence of degeneracies when deriving a planet's composition. Here we present a model of internal structure developed to study the interior of planets up to ~ 10 Earth masses. To break the degeneracy, the model takes into account the Fe/Si ratio of a simulated planet, assuming it is equal to that of the host star. This allows to precisely constrain the compositional parameters of the body, and shows the importance of measuring the elemental abundances of exoplanet-hosting stars.

1. Introduction

The huge diversity of detected exoplanets, in terms of physical and orbital parameters, has revealed that terrestrial and giant gaseous planets such as those in our system are not the only families of planetary bodies. In particular, Super-Earths and sub-Neptunes fill the gap that exists in the $1-10 M_{\oplus}$ range in the solar system. Knowing their composition brings key constraints to understand the formation conditions of the various planet families. The mean density of a planet only gives a rough estimate on its composition. Models of planetary interiors overcome this limitation by precisely constraining the composition and internal structure of a planet.

Here we present an interior model able to handle compositions as various as those of small planets and large satellites of the solar system. It uses an equation of state adapted to high-pressure materials, and is designed to explore a large range of compositions for solid terrestrial planets. A degeneracy inherent to such models however remains on a planet's composition, independently from the precision on its fundamental parameters. We show that taking into account

the bulk Fe/Si ratio of a planet, derived from stellar abundances, allows to break this degeneracy.

2. Interior model and parameters

All planets considered in our model are fully differentiated into three main layers: a metallic core, a silicate mantle, and a water envelope. The metallic core is composed of iron and iron alloy FeS. Depending on the pressure and temperature conditions, the mantle may be divided into two sublayers, that contain different phases of silicate rocks. Likewise, the water envelope can divide into a layer of high-pressure ice and a liquid water layer on top. The mass and size of these layers fix the composition of a planet, and they are linked through the model, which is able to reproduce the behavior of a given material. Moreover, the boundaries between two phases of the same material are computed from its phase change laws. Therefore, only the locations of the core-mantle and mantle-envelope boundaries are required to fix the composition of the planet. These variables are equivalent to the masses of the three main layers, and from mass conservation to the planet mass, the core mass fraction (CMF) and the water mass fraction (WMF). Therefore, in the following, the "composition" of an exoplanet refers to the pair (CMF,WMF).

The distribution of chemical species in the different layers and sublayers is described by another set of parameters [2], which do not have a significant influence on the computation of a planet's radius compared to the CMF and the WMF. Therefore, they are fixed to produce a distribution of materials which reflects that of the Earth [1]. For a given composition and planetary mass, the model computes the profiles of gravitational acceleration, pressure, temperature, and density inside the body, and computes the corresponding radius. In this work, we use the Vinet equation [3] as equation of state. It is more suited than other equations of state in describing the behavior of a given material, but also extrapolates better at large pressures [4].

3. Results

The parameter space formed by the variations of the CMF and the WMF can be represented as a ternary diagram (see Figure 1). For a given planet mass, each point on the diagram corresponds to a unique composition, and yields a planetary radius through the model. Isoradius curves can be drawn on the produced colormap, on which the planetary radius is constant. These curves show the degeneracy that exists when using a model of internal structure: a set of fixed planetary mass and radius can be explained by all the compositions located on the corresponding isoradius curve. To reduce this set of possible compositions, we fix limits on the CMF and WMF by considering formation conditions of the solar system. Reflecting the composition of the icy moons of Jupiter and Saturn, we place an upper limit of 50% on the WMF [1]. Similarly, the value of the Fe/Si ratio in the protosolar nebula allows to rule out compositions with a CMF larger than 65% [1]. The corresponding areas on the ternary diagram are shaded. However, these limitations are based on solar system conditions, which may not be relevant for a large part of known planetary systems, and other parameters better reduce the set of possible compositions.

The degeneracy on the composition can be broken by taking into account the bulk Fe/Si ratio of the planet. This planetary parameter cannot be measured, thus we assume its value to reflect the stellar ratio, a hypothesis that is verified by models of planetary formation [5]. As for the planet radius, the Fe/Si ratio of a planet can be computed for a given composition, and thus lines of constant Fe/Si ratio can be drawn on the ternary diagram. For a given set of planet mass, radius, and Fe/Si ratio, only one composition is possible.

4. Discussion

We have developed a model that allows to simulate the interior of planets with various compositions, from terrestrial (i.e. fully rocky) planets like the Earth or Mercury, to ocean planets that possess a massive envelope of water. Using the Vinet equation of state, our model is more adapted to describe planets with masses under $\sim 10 M_{\oplus}$ compared to previous studies. The degeneracy that exists on a planet's composition for a given set of mass and radius is efficiently broken with the incorporation of the body's bulk Fe/Si ratio, and is independent from solar system conditions. As this parameter is directly derived from the stellar abundances, we hereby show the importance of precisely measuring

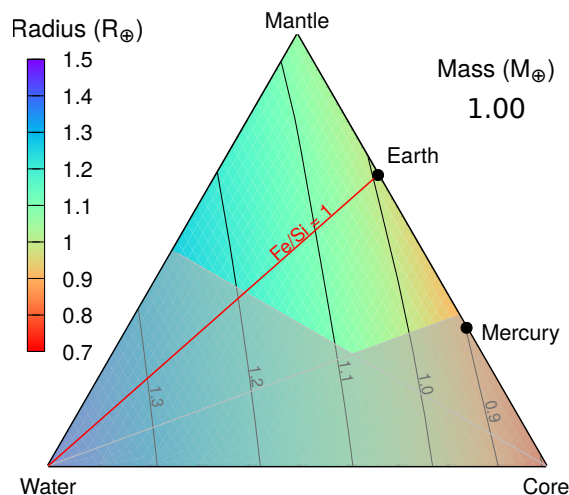


Figure 1: Ternary diagram displaying the compositional parameter space of a $1 M_{\oplus}$ planet. A colored map of the planet radii is shown, with isoradius curves and a line of constant bulk Fe/Si ratio. The grey areas correspond to compositional limitations based on solar-system formation.

the chemical composition of exoplanet-hosting stars.

Acknowledgements

B.B. and O.M. acknowledge support from the A*MIDEX project (n° ANR-11-IDEX-0001-02) funded by the “Investissements d’Avenir” French Government program, managed by the French National Research Agency (ANR). O.M. and M.D. also acknowledge support from CNES.

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The Interior of Kepler-406b, a high-density solid exoplanet

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Abstract

Using an interior model developed to investigate the interior of solid terrestrial planets, we provide precise constraints on the possible compositions and internal structures of Kepler-406b, which is a high-density exoplanet ($\rho = 11.82 \pm 2.70 \text{ g/cm}^3$). We find that, to account for its measured mass and radius, Kepler-406b has to possess a massive metallic core corresponding to at least 52% of the planet's mass. Solar system formation conditions set an upper limit to this fraction at 65%, however a limit more adapted to the Kepler-406 system needs to be brought from measurements of the elemental abundances of this host star.

1. Introduction

Diversity is the main characteristic that appears with the increasing number of detected exoplanets. Exotic worlds have been discovered, in terms of orbital and physical parameters, compared to the planets of our solar system. These parameters have been estimated for 49 planets within 22 planetary systems observed with the *Kepler* mission, most of them being small-mass exoplanets within the terrestrial to icy giant regime (masses under $\sim 20 M_{\oplus}$) [1]. Detections of planets with extreme mean densities have been reported, ranging from $0.90 \pm 0.21 \text{ g/cm}^3$, to $11.82 \pm 2.70 \text{ g/cm}^3$.

Such extreme values of mean density raise the question about the composition of these exoplanets, which can be probed using models of planetary interiors. Here we perform the detailed study of one exoplanet among those with extreme densities detected by [1], namely Kepler-406b. This planet has a measured mass of $6.35 \pm 1.4 M_{\oplus}$, and a radius of $1.43 \pm 0.03 R_{\oplus}$, yielding a density of $11.82 \pm 2.70 \text{ g/cm}^3$ (which is above the density of pure iron at ambient conditions, 8.34 g/cm^3 [2]). Using an interior model of solid exoplanet, we derive constraints on the possible compositions and internal structures of Kepler-406b that are compatible with these measurements.

2. Interior model and parameters

A planet described by our model (see [3] for details) is constituted by three concentric and fully differentiated main layers: a metallic core, a silicate mantle, and a water envelope. The two latter layers may be divided into two sublayers each because of phase changes of the corresponding materials. The two mantle sublayers contain different silicate rocks, whereas the water envelope divides into a liquid water layer on top of a high-pressure ice layer.

Because the composition of a planet is fixed by the mass of the three main layers, we define two parameters in our model: the core mass fraction (CMF) and the water envelope mass fraction (WMF), that are varied in the 0–1 range. We exclude from our simulations planets that harbor a thick gaseous atmosphere. However, to allow the presence of liquid water at the surface of simulated terrestrial planets, we consider the surface conditions to be close to those of the Earth (1 bar pressure and 288 K temperature). The physical and orbital parameters of Kepler-406b and its host star Kepler-406 are summarized in Table 1.

Table 1: Physical and orbital properties of Kepler-406b and its host star Kepler-406 [1].

Parameter	Unit	Value
<i>Planet parameters</i>		
Orbital period	day	2.42629
Planet mass	M_{\oplus}	6.35 ± 1.4
Planet radius	R_{\oplus}	1.43 ± 0.03
Planet density	g/cm^3	11.82 ± 2.70
<i>Stellar parameters</i>		
Effective temperature	K	5538 ± 75
Star mass	M_{\odot}	1.07 ± 0.06
Star radius	R_{\odot}	1.07 ± 0.02

3. Results

We perform a simulation of the interior of Kepler-406b for every compositions allowed by the variations of the

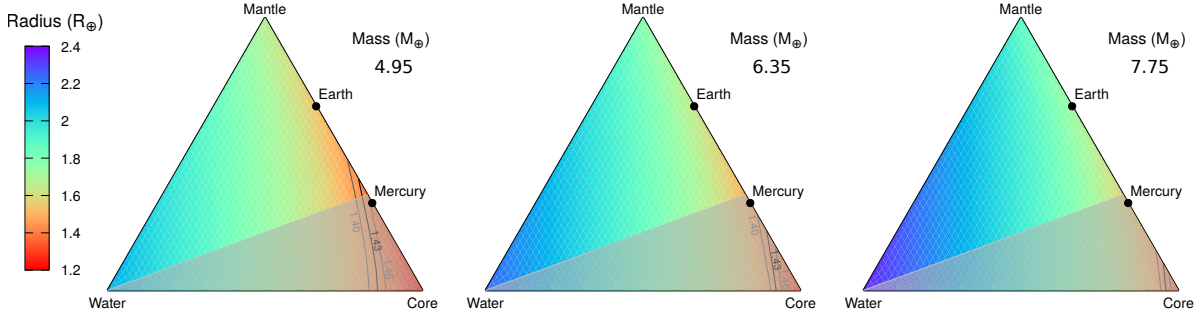


Figure 1: Ternary diagrams displaying the compositional parameter space explored for Kepler-406b, for three values of the planet mass: the minimum, central, and maximum values inferred by [1] using 1σ uncertainties. Also shown are the isoradius curves denoting the measured planet radius with its 1σ extreme values [1]. The shaded region covers compositions incompatible with solar system formation conditions.

CMF and WMF. The parameter space thus formed is represented by a ternary diagram (as those displayed in Figure 1). We explore the planet composition from its measured mass and associated 1σ error, giving 4.95, 6.35, and $7.75 M_{\oplus}$. The compositions located between the isoradius curves denoting the 1σ values on each ternary diagram of Figure 1 are those compatible with both a mass between 4.95 and $7.75 M_{\oplus}$ and a radius between 1.40 and $1.46 R_{\oplus}$. Our simulations show that Kepler-406b possesses a massive metallic core, with a CMF between 52% and 95%. In comparison, Mercury has a CMF of 68% [4]. Such high CMF values can be considered unlikely regarding the formation conditions of planets in the solar system. If one assumes that these planets have compositions derived from that of the protosolar nebula, CMF higher than 65% are then excluded [5]. The corresponding area on the ternary diagrams of Figure 1 is shaded. This assumption rules out an important part of the set of compositions derived for Kepler-406b, and the density measurement can only be explained if i) the planet’s mass corresponds the lowest value of the investigated mass range and ii) the CMF is between 52% and 65%.

4. Discussion

We investigated the internal structure and composition of Kepler-406b, under the assumption that it is a terrestrial planet with possible addition of water. To account for its measured mass and radius, Kepler-406b has to possess a massive metallic core corresponding to at least 52% of the planet’s mass. According to our study, this fraction may go up to 95%, which is incompatible with solar system formation conditions that exclude CMF values over 65%. Applying this as-

sumption to a planetary system different from the solar system is questionable, since the formation conditions of Kepler-406b may have been different. This can be investigated by measuring the elemental abundances of the host star Kepler-406, and in particular its Fe/Si ratio, which is shown to be identical for the host star and for orbiting planets [6].

Acknowledgements

B.B. and O.M. acknowledge support from the A*MIDEX project (n° ANR-11-IDEX-0001-02) funded by the “Investissements d’Avenir” French Government program, managed by the French National Research Agency (ANR). O.M. and M.D. also acknowledges support from CNES.

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A population study of hot Jupiter atmospheres

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Abstract

In the past two decades, we have learnt that every star hosts more than one planet. While the hunt for new exoplanets is on-going, the current sample of more than 3500 confirmed planets reveals a wide spectrum of planetary characteristics. While small planets appear to be the most common, the big and gaseous planets play a key role in the process of planetary formation. We present here the analysis of 30 gaseous extra-solar planets, with temperatures between 600 and 2400 K and radii between 0.35 and 1.9 Jupiter radii. These planets were spectroscopically observed with the Wide Field Camera 3 on-board the Hubble Space Telescope, which is currently one of the most successful instruments for observing exoplanetary atmospheres. The quality of the HST/WFC3 spatially-scanned data combined with our specialised analysis tools, allows us to create the largest and most self-consistent sample of exoplanetary transmission spectra to date and study the collective behaviour of warm and hot gaseous planets rather than isolated case-studies.

We define a new metric, the Atmospheric Detectability Index (ADI) to evaluate the statistical significance of an atmospheric detection and find statistically significant atmospheres around 16 planets. For most of the Jupiters in our sample we find the detectability of their atmospheres to be dependent on the planetary radius but not on the planetary mass. This indicates that planetary gravity is a secondary factor in the evolution of planetary atmospheres. We detect the presence of water vapour in all the statistically detectable atmospheres and we cannot rule out its presence in the atmospheres of the others. In addition, TiO and/or VO signatures are detected with 4σ confidence in WASP-76 b, and they are most likely present on WASP-121 b. We find no correlation between expected signal-to-noise and atmospheric detectability for most targets. This has important implications for future large-scale surveys.

Tidally driven evolution of differentiated terrestrial exoplanets

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Abstract

The number of confirmed extrasolar planets has already exceeded 3000, providing us with a wide statistical set for the study of their orbital dynamics. In contrast to gas giants, majority of low-mass, possibly terrestrial exoplanets orbits its host star on a circular or only slightly eccentric orbit, which may be a consequence of past or still ongoing tidal evolution. Tidal response has been traditionally described using models based on the assumption of either a constant phase lag or a constant time lag [1, 2], implying however simplified rheology. As these models are not generally applicable to terrestrial moons and planets with realistic properties, recent authors have proposed rheologically motivated analytical [3, 4, 5] or N-body numerical [6] treatment of tides.

Here, we present a numerical model of tidally driven orbital evolution based on the solution of continuum mechanics equations for a differentiated spherical body, whose mantle is governed by either the Maxwell or the Andrade viscoelastic rheology. The model enables generally heterogeneous structure of the mantle, making thus possible the assessment of coupling between the internal and the orbital evolution.

1. Model and Methods

Both the long-term orbital evolution and the concurrent despinning or spinning up of the planet is studied using the Gauss's planetary equations complemented with the evolution equation for the rotation rate derived from the conservation of the total angular momentum.

$$\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}} \left[eR \sin \nu + \frac{p}{r} S \right], \quad (1)$$

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{nae} \left[eR \sin \nu + \left(\frac{p}{r} - \frac{r}{a} \right) S \right], \quad (2)$$

$$\begin{aligned} \frac{d(C\Omega)}{dt} = & -\frac{1}{2} \frac{\mathcal{G}M_*m\sqrt{1-e^2}}{na^2} \frac{da}{dt} \\ & + \frac{M_*m}{M_*+m} \frac{na^2e}{\sqrt{1-e^2}} \frac{de}{dt}. \end{aligned} \quad (3)$$

Here, a, e, Ω are the semi-major axis, the orbital eccentricity and the spin rate of the planet, respectively, n is the mean motion, r and ν indicate the instantaneous star-planet distance and the true anomaly, $p = a(1-e^2)$ stands for the semilatus rectum of the orbit, C is the moment of inertia of the planet, \mathcal{G} the gravitational constant, M_* and m the masses of the star and the planet and R, S are the radial and the perpendicular component of the disturbing force.

The disturbance in the system is caused by tidal deformation of the planet. In order to estimate the boundary deflections, we utilize an extension of the tool and method described in [7, 8], which is based on the numerical solution of governing equations for a viscoelastic continuum,

$$\nabla \cdot \mathbf{u} = 0, \quad (4)$$

$$-\nabla \pi + \nabla \cdot \mathbf{D} + \mathbf{f} = \mathbf{0}, \quad (5)$$

complemented with the constitutive relation for either the Maxwell or the Andrade rheology. In the equations above, \mathbf{u} stands for the displacement vector, π and \mathbf{D} are the isotropic and the deviatoric part of the incremental stress tensor and \mathbf{f} is the force acting on the planet – in our case a combination of the tidal force, the centrifugal force and the self-gravity. The governing equations are solved in the time domain and discretized using a staggered finite difference scheme in the radial direction and a spherical harmonic decomposition in the lateral directions.

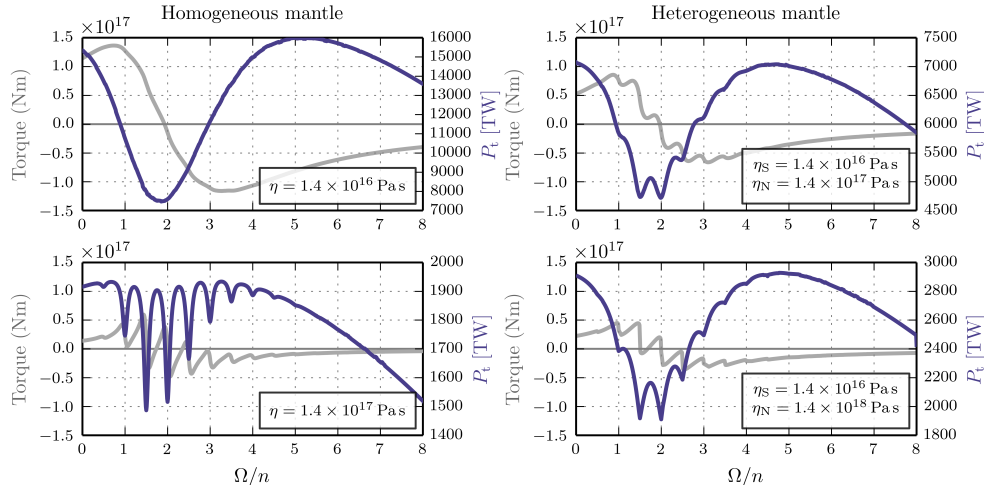


Figure 1: The tidal torque (gray) and the tidal heating (blue) as a function of the loading frequency and the mantle viscosity for a close-in Earth-size terrestrial exoplanet.

2. Results

Our model planet consists of a solid inner core, a liquid outer core and a deformable viscoelastic mantle, with possibly heterogeneous viscosity structure. We study the effect of the internal structure on the long-term orbital and rotational evolution, and compare our results with analytical tidal model of homogeneous viscoelastic planet. Furthermore, we compute the rate of the energy dissipation during the orbital evolution and evaluate its effects on the mantle's viscosity.

Figure 1 shows the spin-orbit ratio dependence of the tidal torque and the tidal heating in the case of either homogeneous or heterogeneous structure of the mantle, prescribed as a viscosity difference between the southern and the northern hemisphere. We may see that the energy dissipation inside of a planet with the north-south viscosity structure acquires values different from the results in the case of the homogeneous mantle with average viscosity (lower row). The number and the position of zero points of the tidal torque varies as well, affecting the stability of the corresponding spin states.

3. Summary and Conclusions

Numerical computation of tidal evolution may be of great importance when dealing with complex rheologies, planets with non-trivial internal structure or non-spherical shape, and with analytically challenging phenomena. Here, we have presented a method for the evaluation of tides on generally heterogeneous bodies,

enabling for example the analysis of coupling between the orbital and the internal evolution of differentiated terrestrial exoplanets and icy moons.

Acknowledgements

This work was supported by the Charles University grant SVV (260447/2017) and the IT4Innovations Centre of Excellence project (CZ.1.05/1.1.00/02.0070).

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Retrieving the cloud coverage on Earth-like exoplanets using polarimetry

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Abstract

Clouds in the atmospheres of exoplanets have a significant impact on the habitability of these bodies. Clouds can also introduce ambiguities in the retrieval of atmospheric properties, such as gas mixing ratios. We present here numerical models of different types of liquid water cloud covers on Earth-like exoplanets and the degree of linear polarization of starlight that they reflect. Our results show that the type of cloud cover and the amount of coverage on an exoplanet can be retrieved by using polarimetry at different wavelengths.

1. Introduction

Clouds have a large impact on the radiative balance of a planet and therefore on its climate and habitability. But they will also influence the retrieval of a planet's surface and atmosphere properties. They can, for example, create a bias in the retrieved surface temperature [2], and affect the depth of absorption bands in the IR [6] and in reflected sunlight [2]. Clouds will in particular create ambiguities when retrieving mixing ratios of biomarker gases like O_2 from the depth of e.g. the O_2 A-band [1]. Transit spectroscopy of exoplanets is also affected by clouds, as the spectral behavior of clouds on an exoplanet's limb can mimic a gaseous atmosphere with a high molecular mass [3]. In direct detections, clouds can hide potential biosignatures on the surface of an exoplanet, such as the red edge of (terrestrial) vegetation [4] or signatures of liquid surface water. Knowledge of the cloud coverage of an exoplanet is thus crucial in order to gain insight into its habitability.

2 Atmosphere and cloud models

To model the atmospheres of Earth-like exoplanets, we use an Earth-like surface pressure and temperature profile, and horizontally homogeneous liquid wa-

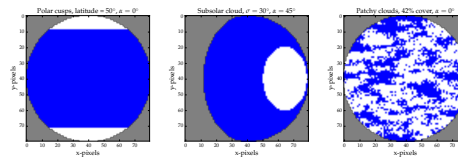


Figure 1: Illustration of the three cloud coverage types: polar cusps, sub-solar clouds and patchy clouds.

ter clouds ($r_{\text{eff}} = 8 \mu\text{m}$, $\nu_{\text{eff}} = 0.10$). The cloud resides at a pressure level p_{cloud} from 800 to 600 mb.

We use three types of coverage: (1) sub-solar clouds, extending an angle σ_c away from the sub-solar point; (2) polar caps, with clouds covering everything above threshold latitude L_t ; (3) patchy clouds. For each type of coverage, F_c indicates the fraction of the planetary surface that is covered by clouds.

We compute the starlight reflected by our planets by dividing the planet as seen by the observer, thus at a given phase angle α , in a grid of square pixels. The cloud optical thickness in cloudy pixels is 6.0, a typical value at visible wavelengths, while it is zero in the cloud-free pixels. We use the adding-doubling method to then compute the locally reflected Stokes vectors for the center of each pixel. These local Stokes vectors are rotated to a common reference frame before being summed to obtain the disk-integrated values of I , Q , U , and V .

3. Results

The degree of linear polarization $P = \sqrt{Q^2 + U^2}/I$, of planets with the three types of cloud coverages for similar values of F_c is shown in Fig. 2 at 300 nm and at 500 nm.

First, we'll discuss the 500 nm case. As can be seen, a sub-solar cloud should be quite obvious to detect since it disappears from sight as the planet rotates and the polarization becomes determined by the

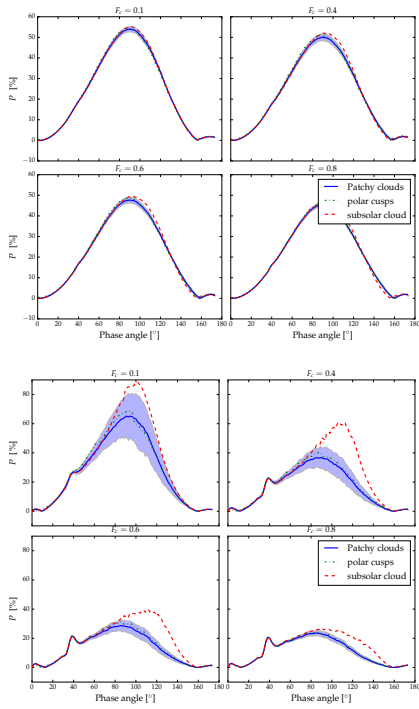


Figure 2: Degree of polarization P as a function of phase angle for different F_c and different cloud coverage types at $\lambda = 300$ nm (top) and 500 nm (bottom). Shaded areas indicate the 2σ variability in the signal of the patchy cloudy planet due to 300 randomly chosen patterns.

Rayleigh scattering of the cloud-free pixels. The phase angle where this transition occurs depends on σ_c . The polar caps and patchy clouds have a similar average polarization pattern, but a large variability in the signal would indicate patchy clouds as it would result from different distributions of cloud patches across the planet.

For all three coverage types, the rainbow ($\alpha \approx 40^\circ$) is visible (especially for large F_c) and with a similar strength regardless of the coverage type; as it depends on the refractive index and cloud particle size and shape, it could be used to retrieve cloud microphysical properties, independent of the cloud pattern. We've identified some ambiguities in particular the patchy cloud coverage, because P is also determined by the cloud top altitude, with lower clouds usually yielding higher values of P . Variability in P could thus also be caused by variations in cloud top altitudes. Observations at different wavelengths could be used

to solve this ambiguity, as Rayleigh scattering above the clouds is sensitive to the wavelength, as can also be seen in Fig. 2. Observations in gaseous absorption bands could also provide additional information [1].

4. Observational strategy

When observed in the blue, the different cloud coverage types appear nearly identical: at 300 nm, Rayleigh scattering above the clouds dominates the signal and makes the clouds nearly invisible. In the blue, one could assume a purely gaseous atmosphere to retrieve the planet's orbital parameters from polarimetry. Estimates of the cloud cover and composition could be made from the interpretation of observations at longer wavelengths, and used to refine the retrieval of the orbital parameters in an iterative process.

We intend to further investigate this by applying this retrieval method to simulations of possible polarization signals of Proxima b, using models for the possible climate and clouds on this recently discovered exoplanet [5].

Acknowledgements

We acknowledge the support of the Dutch Scientific Organization (NWO) through the PEPSci network of planetary and exoplanetary science.

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Cloud modelling for brown dwarfs and young giant exoplanets

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Abstract

We implemented a cloud scheme in ExoREM, a 1D radiative-convective developed for young giant planets. This model computes cloud condensation, sedimentation and mixing. The vertical mixing is parameterized with 3D simulations of convection. The radius of cloud particles is either fixed as a free parameter or determined by comparing the characteristic timescales. The model can also simulate an inhomogeneous cloud cover.

We validated the model by reproducing the LT transition for brown dwarfs. Then, we applied it to young giant planet observed with the VLT-SPHERE instrument.

1. Introduction

Many exoplanets observed by direct imaging seem cloudy as most brown dwarfs or transiting exoplanets. These clouds affect chemistry, temperature and observational spectra. Models used for atmospheric characterization must therefore properly simulate clouds in order to allow atmospheric retrieval and an accurate determination of planetary parameters.

1.1 ExoREM

ExoREM is a 1-D radiative-equilibrium model for young giant exoplanets that we started developing in LESIA [1]. ExoREM solves for radiative-convective equilibrium, assuming that the net flux (radiative+convective) is conservative. The model is essentially valid for planets with effective temperatures between 400 and 1800 K. Opacity sources include the H₂-He collision-induced absorption and molecular lines from H₂O, CO, CH₄,

NH₃, VO, TiO, Na and K. The vertical profiles of the different absorbers are calculated for a given temperature profile assuming non-equilibrium chemistry for C-, N- and P-bearing compounds by comparing chemical time constants with vertical mixing time.

2. 3D simulations of convection

In order to parameterize the vertical mixing coefficient K_{zz} (for clouds and chemical non-equilibrium), we performed 3D simulations with a non-hydrostatic mesoscale model [2]. The 3D model is forced with radiative tendencies from the 1D model. Convective cells form in the convective region and gravity waves propagate above. We derived the root mean square of the vertical velocity and parameterized the K_{zz} profile according to this velocity profile ($K_{zz} = H * w_{rms}$). We also explored the evolution of the fraction of updrafts compared to downdrafts with the effective temperature. This updraft fraction might be related to the cloud fraction.

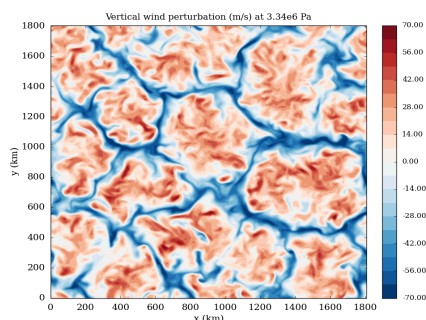


Figure 1: horizontal cross-section of the vertical wind in the convective region (red color for upward winds, blue color for downward winds)

3. 1D Cloud modelling

We implemented a cloud model that takes into account condensation, sedimentation and vertical mixing. We simulate Fe, Mg_2SiO_4 , Na_2S , KCl, ZnS and H_2O clouds. The size of cloud particle can be:

- 1) Fixed as a free parameter
- 2) Determined by fixing τ_{sed} (the ratio of sedimentation velocity by vertical mixing velocity)
- 3) Determined by comparing the timescale of condensation, coalescence, sedimentation and mixing

We compared these 3 assumptions by simulating the photometry of brown dwarfs and the LT transition (figure 2). While the first two methods are more adapted for retrieval, the third one naturally reproduces the LT transition. With this self-consistent cloud modelling, we also predict that low gravity objects as young giant planets should be redder. Such a trend seems to be observed.

The model can also simulate an inhomogeneous cloud cover, allowing investigating the variability of brown dwarfs and young giant planets.

After validating our cloud model with brown dwarfs, we applied it to young directly imaged planets observed in particular with VLT-SPHERE. Most of these objects appear cloudy and ExoREM seems efficient for characterizing them and for determining their planetary parameters.

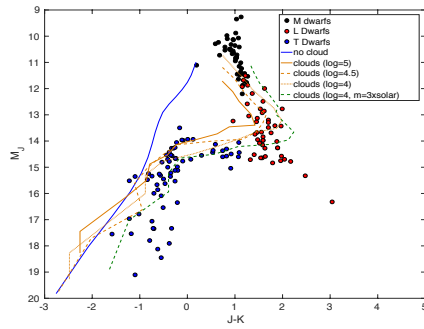


Figure 2: Magnitude-color diagram of brown dwarfs showing the LT transition. Solid and dashed lines are computed with ExoREM with/without Fe and Mg_2SiO_4 clouds.

4. Summary and Conclusions

We developed a cloud model for ExoREM that is realistic, physical and simple in order to be used both for forward modelling and retrieval. The model is validated by reproducing the LT transition for brown dwarfs and appears as an efficient tool for characterizing young directly imaged planets.

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Geometric effects on the flux and polarization signals of Jupiter-sized exoplanets

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Abstract

The direct detection of reflected starlight from exoplanets marks the beginning of a new era in the characterization of extrasolar planetary atmospheres. The flux and in particular the linear polarization signals from such planets are sensitive to atmospheric structure and composition, but other effects may also contribute to observed signals. We investigate the influence of an exoplanet's shape and orbit orientation on its flux and polarization signature, and compare it against the influence of a variable cloud cover.

1. Introduction

The linear polarization of light has played a key role in the characterization of planetary atmospheres at least since its contribution in determining the composition and size of Venus' cloud particles from Earth-based disk-integrated observations across a wide phase angle range, and at a few wavelengths [1]. Since then, the interpretation of polarization observations with simulations of scattering in planetary model atmospheres has been applied successfully to various solar system bodies.

Polarimetry could also be used as a method for determining the composition of exoplanetary atmospheres [see e.g. 4]. Indeed, it has several advantages over photometry when applied to the direct detection of extrasolar planetary systems, as light from the host star tends to be unpolarized, whereas starlight that is scattered in the planetary atmosphere will usually pick up a degree of polarization which facilitates the detection of planetary light. While the outer planets in our solar system present very low polarization signals when observed from Earth because of the illumination and viewing geometries, the illumination and viewing geometries of exoplanets favor relatively high

degrees of polarization. In [4], the strong dependence of the linear polarization on the composition and structure of Jupiter-like model planets with purely gaseous atmospheres, or with clouds and hazes added, is shown. The model planets were, however, assumed to be spherical and the effect of inhomogeneous cloud coverage was not considered.

A planet's shape may be oblate (squashed at the poles) due to rotation, but it may also be deformed by tidal interactions with the host star if it is in a close-in orbit. Such tidal forces will give the planet an ellipsoidal shape, the major axis of which will point towards the star under some angle. When in addition, we vary the obliquity of the planet, we also change the cross section of the disk at a given phase angle (i.e. the angle star-planet-observer) and so may introduce a comparable effect to oblateness.

The simulations conducted in this study extend the work in [4] to include ellipsoidal Jupiter-sized planets with non-zero obliquities. In addition, the effect of a spatially extended stellar disk has been included so that scattering simulations could be made for tidally deformed hot-Jupiters orbiting very close (< 0.1 AU) to their host stars (for planets in wide orbits, the incident starlight can be assumed to be unidirectional, see [4]).

2. Results

As demonstrated for self-luminous, hot exoplanets [3], and for directly imaged homogeneous planets [2], increasing oblateness introduces a slight increase in the planet's linear polarization. Figure 1 shows that this effect is minor relative to the effects of varying inhomogeneous cloud cover.

We find that the effect of obliquity on the linear polarization is of the same order of magnitude as oblateness. This is illustrated in Figure 2, showing the linear polarization against the normalized flux for

both spherical and oblate models at three obliquities. Note that the flux of the star itself is not included in the signal.

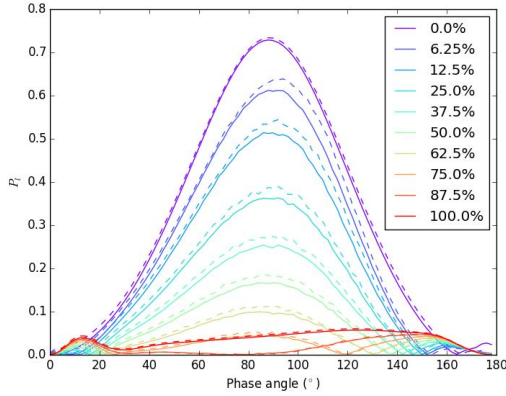


Figure 1: The variation of total linear polarization with percentage inhomogeneous cloud cover for spherical (solid) and oblate (dashed) model planets.

For hot-Jupiters around solar-type host stars, we detect little change in the polarization signal with tidal deformation, but there are some interesting effects as a result of the planet's close proximity to its star (< 0.1 AU). Figure 3 shows an enhanced reflected flux at large phase angles for close-in planets as compared to a planet in a wide orbit. This enhancement is further increased with increasing oblateness (not shown), and may lead to an underestimation of an exoplanet's radius from observations if not taken into account.

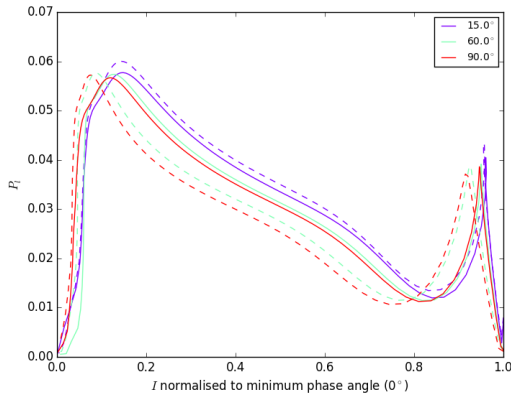


Figure 2: Variation with obliquity of linear polarization plotted against normalized intensity for spherical (solid) and oblate (dashed), 100% cloudy model planets.

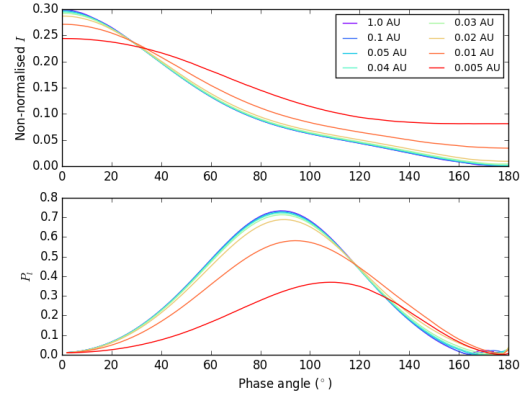


Figure 3: Variation of flux (top) and linear polarization (bottom) with distance from the star.

3. Conclusions

This work demonstrates that geometrical influences on the direct detection of exoplanets in polarized light tend to be at an order of magnitude below the influence of atmospheric composition and structure, so may be ignored in first order characterizations for exoplanets in wide orbits. For close-in planets, the spatial extension of the stellar disk should be taken into account.

Acknowledgements

C. Palmer would like to thank D. Stam and L. Rossi for their continued support in his master thesis work.

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Feasibility and benefits of pulsar planet characterization

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Abstract

Planet orbiting neutron stars seem to be rare, but all the more interesting for science due to their origins. Characterizing the composition of pulsar planets could elucidate processes involved in supernova fallback disks, accretion of companion star material, potential survival of planetary cores in the post-MS phase of their stars, and more. However, the small size and unusual spectral distribution of neutron stars (NS) make any spectroscopic measurements very difficult if not impossible in the near future. In this work, we set to estimate the feasibility of spectroscopy of planets orbiting specifically pulsars, and to review other possible methods of characterization of the planets, such as emissions caused by aurorae.

1. Introduction

There are five key ways how a pulsar may acquire planets: i) they could be remnants of planetary cores of objects formed in-situ, ii) they could be objects formed in-situ from the fallback debris after a supernova explosion, iii) they could be objects formed in-situ from a debris disk from a merger of two white dwarfs, which also gave existence to the pulsar, iv) they could be remnants of a stellar companion that lost most of its mass to the pulsar, v) they could be captured objects, most likely from a companion star, less likely rogue planets; however, the scenarios can be distinguished more finely (see [6]). Considering the PSR B1257+12 system [10], Podsiadlowski [6] concluded that a white dwarf (WD) merger is the likeliest scenario. Margalit and Metzger [4] proposed a formation by tidal disruption of a C/O white dwarf companion by the pulsar, specifying a more general companion disruption scenario [11] and providing valuable scenarios of disk evolution for both WD-NS merger disks, but also supernova fallback disks.

The nearly coplanar orbits of the three planets around PSR B1257+12 also suggest formation in-situ. This possibility is further supported by the discovery of a

circumstellar disk of the magnetar 4U 0142+61 [9], and a tentative asteroid belt around the millisecond pulsar B1937+21 [7]. PSR B1620-26 b is a circumbinary planet orbiting a pulsar and a white dwarf, and likely formed around the white dwarf precursor, with its system later captured by the pulsar, giving rise to a binary, while the pulsar's original stellar companion was ejected [8]. In a globular cluster with high star density, where this system is present, such an event is more likely than in the galactic disk. Finally, the PSR J1719-1438 system contains most likely a remnant of a disrupted WD companion that narrowly avoided its complete destruction, based on its minimum density [1].

These three known systems represent three of the possible means of origin of pulsar planets. Formation in disks from WD-NS mergers as opposed to supernova fallback disks is also supported by the observed rarity of pulsar planets [2,4]. But we cannot completely discount the option of planetary cores surviving an (asymmetric) supernova explosion, however unlikely it seems. In this scenario, the planets' composition would be heavily altered by the event. Not only would likely only cores of massive and preferably distant planets survive, but the conditions during a supernova explosion, especially the strong neutrino flow, could change the core's chemical make-up as well. However, a detailed model of the compositional changes is out of the scope of this study.

Planets formed from the supernova fallback material – if possible despite its low angular momentum – would also exhibit likely very distinct properties; we could expect metal-rich composition and a variety of short-lived isotopes. Planets arising from WD disruption disks can be expected to have a predominantly carbonaceous composition – essentially to be “diamond planets” [3,4]. On the other hand, planets captured after the explosion would not possess the above-described distinct properties. Finally, planets arising directly from WDs would be recognizable by their extremely high density. Characterization of pulsar planets would be

valuable for distinguishing these mechanisms more reliably and constraining the systems' evolution.

2. Characterization feasibility

Due to the small size of neutron stars (approx. 20km diameter), transit probabilities are many magnitudes lower than for planets around MS stars, and unlike them, influenced heavily by the planet's size. Combined with the star's spectrum and known systems' distance, it makes the chance of transmission spectroscopy negligible. The distance and spectral distribution also make potential reflectance spectroscopy extremely unlikely. However, if the planet possesses a magnetic field, cyclotron maser emissions (less likely also optical effects) from its aurorae could be detectable in principle. Pulsar wind charged particles or remnants of supernova fallback/companion disruption disk could provide sufficient environment for this mechanism. Estimating a planet's magnetic field could at least constrain its composition and dynamics. Finally, thermal emissions could be useful for detecting young planets around nearby neutron stars, although their potential for more detailed characterization is rather limited.

3. Conclusions

We conclude that spectroscopic characterization of pulsar planets is highly unlikely to be achieved in the near future, though not entirely impossible, but possible auroral emissions and thermal emissions present more feasible means of at least roughly characterizing planets in pulsar systems. Moreover, they could in theory reveal planets around young pulsars where there is too much timing noise compared to "recycled" millisecond pulsars. While researching pulsar planetary systems could hardly be further from the popular search for "Earth 2.0", it could yield extremely valuable data for planetary science, radio astronomy, astrophysics and other fields, and it could help us answer some fundamental questions about exoplanetary origins and evolutions. For these reasons, we think it worthwhile to pursue this topic.

Acknowledgements

We would like to thank Dr. Paul B. Rimmer for his valuable advice on the topic.

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Atmospheric Composition Retrieval from Transit Spectra of Terrestrial Exoplanets: A Feasibility Study using Earth Observations

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Abstract

For an assessment of the detectability of molecular concentrations from transit spectra of Earth-like exoplanets, occultation spectra observed by an operational Earth observation satellite mission have been modeled with a line-by-line infrared radiative transfer code. Retrieval of atmospheric composition utilizing a nonlinear least squares fit of degraded spectra allows to infer detection limits for different spectral regions, resolution and noise levels.

1. Introduction

With more than 3600 exoplanet known today, including some dozen Earth-like and super-Earths, the characterization of their atmospheres has come into the focus of current research. Despite the limited quality of currently available exoplanet spectral observations, the methodology developed for Earth and Solar System Planet remote sensing can be readily applied to the analysis of terrestrial extrasolar planet data. For the retrieval of atmospheric composition, transmission spectroscopy analyzing the attenuation of stellar light along its optical path through the planet's atmosphere is particularly suited. In this contribution we use a high resolution line-by-line infrared radiative transfer code to model co-added occultation measurements in order to assess the feasibility to quantify the concentration of atmospheric constituents.

2. Radiative Transfer Modeling

The Generic Atmospheric Radiative Transfer Line-by-Line Infrared Code — GARLIC [1] has been developed with emphasis on efficient and reliable numerical algorithms and a modular approach appropriate for simulation and/or retrieval in a variety of applications (observation geometry, instrumental spectral response and field-of-view). The core of GARLIC's

subroutines constitutes the basis of forward models used to implement inversion codes to retrieve atmospheric state parameters from limb and nadir sounding instruments. Furthermore, GARLIC has been used for a variety of exoplanetary atmosphere studies, e.g. [2].

3. Earth Observation Data

Limb sounding in the microwave, infrared, and ultraviolet-visible spectral range is a well-established approach for the characterization of Earth's atmosphere, in particular for remote sensing of the stratosphere and mesosphere with high altitude resolution. The effective height spectra generated by integrating (summing) a limb sequence of infrared spectra over all tangent heights serve as transit spectra expected to be observed for an Earth-like atmosphere.

4. Results

Using a nonlinear least squares optimization solver coupled to the GARLIC radiative transfer code we have retrieved the atmospheric composition from Earth's transit spectra. For an assessment of the detectability of atmospheric constituents from realistic exoplanet observations, the high-quality Earth observations have been smeared to lower resolution by convolution with appropriate spectral response functions and further deteriorated by adding noise.

5. Summary and Conclusions

Transit spectra of Earth's atmosphere observed by an operational satellite instrument have been modelled by our high resolution code GARLIC. The comparison of modelled and observed spectra clearly indicates the impact of various molecular species as well as continuum-like contributions. Varying the spectral range, spectral resolution, and noise level allows to quantify the detection level for various molecules.

Acknowledgements

Financial support by the Deutsche Forschungsgemeinschaft — DFG (project SCHR 1125/3-1) is gratefully acknowledged.

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Transmission spectroscopy of a tidally distorted extremely hot Jupiter

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Abstract

During planetary transit, stellar light is filtered through an exoplanet's atmosphere, revealing the planet's atmospheric properties through wavelength-dependent absorption features. An increasing number of transmission spectra have been observed to date, forming a key data set for constraining planetary atmospheric compositions and have also revealed atmospheric aerosols in the form of clouds and hazes as a common feature in exoplanet atmospheres. We have been conducting a survey of transmission spectra of a sample of hot giant planets with large ground-based facilities, using FORS2 at the ESO VLT and GMOS at the Gemini telescope.

In this talk, we present the first high-precision transmission spectrum of WASP-103b, showcasing the performance of ground-based multi-object spectroscopy for the characterization of planetary atmospheres. WASP-103b, a planet which is at the brink of tidal disruption by its host star, is one of the most massive ($1.5 M_J$) and hottest (2500 K) planets characterized so far through transmission spectroscopy. We will present results on the Na and K absorption features in the planetary atmosphere and discuss these measurements in context, comparing WASP-103b to other hot Jupiters in their final stages of life.

Traces of exomoons in flux and polarization signals of starlight reflected by exoplanets

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Abstract

The detection of moons around extrasolar planets is one of the main focuses of current and future observatories. These silent companions contribute to the planets' observed signals but are barely detectable with current methods. Numerous gaseous exoplanets are known to orbit in the habitable zones of stars, and the expected abundance of natural satellites and their diversity in composition make them ideal targets when looking for habitable celestial bodies. And moons are suspected to play key roles in stabilizing a planet's rotational axis and hence its climate. We show that an exomoon orbiting an Earth-like exoplanet could be identified by measuring the flux and polarization of starlight reflected by the planet-moon system, allowing the characterization of their orbital motions and physical properties.

1. Introduction

Current instruments such as Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) on the Very Large Telescope (VLT) and Gemini Planet Imager (GPI) on the Gemini North telescope, together with the Exoplanet Imaging Camera and Spectrograph (EPICS) on the future European Extremely Large Telescope (E-ELT), have capabilities to perform high-contrast, direct imaging and characterization of exoplanets, both through spectroscopy and polarimetry.

Previous modelling of light curves and polarization signals [3, 9, 10, 8] shows that polarimetry not only increases the contrast between the exoplanet and its star, but can also unveil the structure and composition of the atmosphere and surface. Here, we take one step further by analysing how the presence of an exomoon influences the flux and polarization signals of an Earth-like exoplanet. The influence is two-fold: 1. the flux reflected by the planet-moon system increases according to the moon's reflection properties, and 2. the transits and eclipses between the moon, planet, and star modulate the observable signal (see Fig. 1).

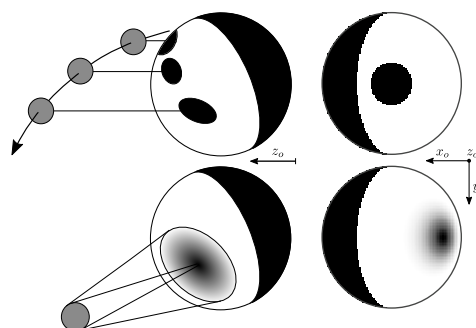


Figure 1: Sketches of a lunar transit of the planet (top left), an eclipse (bottom left), the discretization during a lunar transit (top right), and during a planetary eclipse (bottom-right). The z_o -axis points towards the observer.

2. Numerical model and results

We describe the flux and polarization of starlight that is reflected by a spatially unresolved planet-moon system by a Stokes vector [2] computed using and adding-doubling radiative transfer model [1], assuming the starlight is unpolarized [5]. Our model planet has a Lambertian surfaces with horizontally homogeneous atmospheric layers filled with gas and/or aerosol particles on top, and our model moon has a Lambertian surface without atmosphere.

The observable Stokes vectors at a certain epoch are a function of the illumination and viewing geometries of each body, which depend on the bodies' phase angle α (the angle between the direction to the star and the observer measured from the centre of the body), and on the orbital geometry of the bodies involved, as that can lead to situations in which they interfere with each other. In particular, we have modelled the following interferences (see Fig. 1):

- A transit: the interposition of a body between the observed target and the observer, partially (or to-

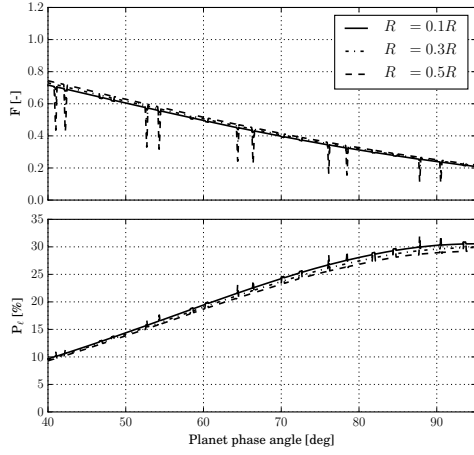


Figure 2: Flux (top) and degree of linear polarization (bottom) of an edge-on system consisting of an Earth-like planet and an exomoon with surface albedo 0.1, for different moon radii R_m expressed in the planet radius R_p .

tally) blocking the light that is reflected by the target while adding reflected light from the body.

- An eclipse: the interposition of a body between the star and the observed target, casting a shadow on (part of) the reflecting target.

We compute the orbital dynamics and geometries using the ‘nested two-body’ model introduced in [7, 6], that is based on the assumption that the motion of the planet and moon around the planet-moon system barycentre, as well as the motion of this barycentre around the star, can be described by Keplerian orbits.

Fig. 2 shows the flux and degree of linear polarization obtained as the exoplanet and moon transit and eclipse each other in a zero-eccentricity, system that is viewed edge-on, for different moon radii R_m .

3. Discussion

The traces of exomoons that we find in our numerical simulations (see Fig. 2), show up as remarkable signatures in the signal of the spatially unresolved planetary system. The flux and polarization variations due to eclipses and transits are of the same order of magnitude as the overall signal and can span several hours (depending on the moon radius with respect to the planet and the orbital periods). The observable signals appear similar to those obtainable with the well-

known transit photometry technique applied on stars except for delivering enhanced contrast between bodies and a greater frequency of observation, although with much less photons and thus requiring much larger telescopes.

4. Conclusion

We aim to investigate the correlation between the flux and degree of polarization of the reflected starlight and the orbital characteristics of the planet-moon system. The results obtained for an Earth-like planet will be compared to those for a giant Jupiter-like planet, analysing the impact of using varying atmospheric models. We also aim at estimating the required instrument radiometric and polarimetric accuracy, assessing the feasibility of exomoon discoveries through polarimetry with current and future technology [4].

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Spectroscopic observations of Hot-Jupiters with the Hubble WFC3 camera

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Abstract

We report here the analysis of the near-infrared transit spectrum of the hot-Jupiter HAT-P-32 b which was recorded with the *Wide Field Camera 3* (WFC3) on-board the *Hubble Space Telescope* (HST). HAT-P-32 b is one of the most inflated exoplanets discovered, making it an excellent candidate for transit spectroscopic measurements. To obtain the transit spectrum, we have adopted different analysis methods, both parametric and non parametric (Independent Component Analysis, ICA), and compared the results. The final spectra are all consistent within 0.5σ . To interpret the spectrum of HAT-P-32 b we used \mathcal{T} -REx, our fully Bayesian spectral retrieval code. As for other hot-Jupiters, the results are consistent with the presence of water vapor ($\log H_2O = -3.45^{+1.83}_{-1.65}$), clouds (top pressure between 5.16 and 1.73 bar). Spectroscopic data over a broader wavelength range will be needed to de-correlate the mixing ratio of water vapor from clouds and identify other possible molecular species in the atmosphere of HAT-P-32 b.

1. Introduction

In the past decade the *Hubble Space Telescope* has been an invaluable observatory to study the properties of exoplanetary atmospheres. The majority of the planets observed to date are hot and gaseous as they are the easiest targets to probe. Transit observations in the UV, VIS and IR have started to provide important insights into the chemical composition and structure of the atmospheres of gas-giants orbiting very close to their star.

In this work we analyze the near-infrared transit spectrum of the hot-Jupiter HAT-P-32 b ($T_{eq} = 1786$ K) (Hartman et al., 2011) obtained with the WFC3 camera on-board the HST. HAT-P-32 b is one of the most inflated exoplanets discovered, being less massive than Jupiter ($M_p = 0.79 M_{Jup}$) but having

almost twice its radius ($R_p = 1.789 R_{Jup}$). The atmosphere of HAT-P-32 b has been observed with ground-based instruments in the optical wavelengths, revealing a featureless transmission spectrum (Gibson et al., 2013; Zhao et al., 2014; Nortmann et al., 2016; Mallonn & Strassmeier, 2016). In addition, Zhao et al. (2014) suggested the presence of a thermal inversion in the atmosphere of HAT-P-32 b to interpret eclipse observations.

We used our dedicated WFC3 pipeline (Tsiaras et al., 2016a) to extract the transit light-curves per wavelength channel and obtain the planetary spectrum. We used in parallel Independent Component Analysis to correct for the instrumental systematics, and investigate the effect of different analysis techniques on the same data set. The final spectrum was analyzed using our fully Bayesian spectral retrieval code, \mathcal{T} -REx (Waldmann et al., 2015a,b).

2. Data Analysis

The spatially scanned spectroscopic images of HAT-P-32 b were obtained with the G141 grism and are available from the MAST archive¹. Before extracting the light-curves (white and spectral), all frames were reduced using the routines described in Tsiaras et al. (2016a). HAT-P-32 A has an M1.5 stellar companion, HAT-P-32 B ($T_{eff} = 3565 \pm 82$ K, Zhao et al., 2014). The dispersed signals from HAT-P-32 A and B are blended when using the scanning mode. However, these two stars are separated enough ($2''.923 \pm 0''.004$, Zhao et al., 2014) to avoid blending when the differential reads (the difference between two consecutive non destructive reads are considered. Then was determined the photometric aperture and the signal was extracted. It is known that instrumental systematics (known as “ramps”) affect the WFC3 infrared detector both in staring and scanning modes. We fitted the ramps on

¹<https://archive.stsci.edu/>

the white light-curve using a similar approach to [Kreidberg et al. \(2014\)](#), i.e. we adopted an analytic function with two different types of ramps, short-term and long-term, to correct the data:

$$R(t) = (1 - r_a(t - t_v))(1 - r_{b1}e^{-r_{b2}(t-t_0)}) \quad (1)$$

where, t is the mid-time of each exposure, t_v is the time when the visit starts, t_0 is the time when each orbit starts, r_a is related to the long-term ramp and r_{b1}, r_{b2} are related to the short-term ramp.

Finally, for each wavelength bin we divided the spectral light-curve by the white light-curve ([Kreidberg et al., 2014](#)) and fitted a linear trend simultaneously with a relative transit model:

$$n_\lambda(1 + \chi_\lambda)(F_\lambda/F_W) \quad (2)$$

where n_λ is the normalization factor that needs to be calculated for each bin, χ_λ is the wavelength-dependent linear ramp ([Tsias et al., 2016a,b](#)), (F_λ/F_W) is the ratio between the spectral light-curve and the white light-curve.

3. ICA

Independent Component Analysis (ICA) is a blind signal-source separation (BSS) technique which is able to separate the source signals in a set of observations without any prior knowledge about the signals themselves or their mixing ratios. ICA has been used to remove instrument systematics and other astrophysical signals in exoplanetary light-curves. In this paper, we discuss a similar approach to the analysis of spectroscopic time series obtained with *HST*/WFC3 using the scanning-mode technique.

The main steps of the algorithm are:

1. ICA decomposition;
2. Fitting;
3. Finalizing the parameter error bars.

4. Atmospheric retrieval

To interpret the spectrum of HAT-P-32 b, we use *T*-REx ([Waldmann et al., 2015b,a](#)), a Bayesian spectral retrieval code which uses line lists provided by ExoMol, HITEMP and HITRAN. With the exception of water vapor, the fitted values for all the other molecular mixing ratios are smaller than 10^{-7} . This result means that they are not detectable from this dataset. The water vapor mixing ratio oscillates, instead,

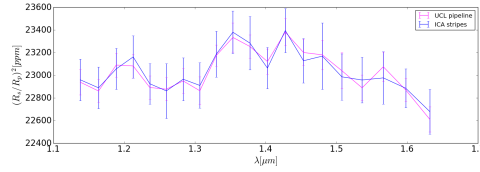


Figure 1: Spectra obtained with the UCL pipeline (magenta) and with stripe-ICA (blue).

between $\log H_2O = -3.45^{+1.83}_{-1.65}$ depending on the clouds' top pressure, which could occur between 5.16 and 1.73 bar.

5. Summary and Conclusions

We have reported here the analysis of the near-infrared transit spectrum of the hot-Jupiter HAT-P-32 b which was recorded with the *Wide Field Camera 3* on-board the *Hubble Space Telescope*. To interpret the spectrum of HAT-P-32 b, we used *T*-REx, a fully Bayesian spectral retrieval code.

As for other hot-Jupiters, the results are consistent with the presence of water vapor ($\log H_2O = -4.66^{+1.66}_{-1.93}$) and probably clouds (top pressure between 5.16 and 1.73 bar). Spectroscopic data over a broader wavelength range will be needed to decorrelate water vapour's mixing ratio from clouds and identify other possible molecular species in HAT-P-32 b atmosphere.

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Exo-Planetary high-Temperature Hydrocarbons by Emission and Absorption Spectroscopy (the e-PYTHEAS project)

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Abstract

The e-PYTHEAS is a multidisciplinary project which combines theoretical and experimental work with exoplanet modelling applications. It sits on the frontier between molecular physics, theoretical chemistry and astrophysics. It aims at enhancing our understanding of the radiative properties of hot gaseous media to allow for improved analysis and interpretation of the large mass of data available on the thousands of exoplanets and exoplanetary systems known to date. Our approach is to use theoretical research validated by laboratory experiments and to then inject it into models of the atmospheres of the giant gaseous planets in the solar system and other planetary systems. This will help to analyse data and address essential questions on the formation and evolution of planetary systems.

1. Introduction

Most of the exoplanets are hot and therefore their spectra are very complex and contain numerous unassigned features [1]. The large number of exoplanetary observations acquired via a combination of new, larger telescopes and space missions will therefore only be exploitable if and only if the adequate laboratory and theoretical data

are made available for their analysis, without the current limitations.

Our consortium of five French laboratories and multiple associated partners proposes to improve the existing high-temperature spectroscopy data for several molecular species detected in exoplanets. Our strategy consists in producing experimental and theoretical data that are then applied to observations.

The provision of infrared (IR) laboratory data of methane, acetylene, ethylene and ethane, between 500 and 2500 K will help to refine thermal profiles and provide information on the gaseous composition, the hazes and their temporal variability.

2. Present status

Currently available data are insufficient in several ways:

- All datasets are affected by large gaps below 1.65 μm , an important region in observations;
- High-temperature spectroscopic data cannot be extrapolated from low-T atmospheric databases such as HITRAN and GEISA. Such extrapolations fail to reproduce high J rovibrational transitions and hot band transitions involving highly excited

vibrational levels and thus opacity calculations at high temperatures present large uncertainties;

Accurate molecular models are still missing to generate complete high- T line lists for hydrocarbon absorbers which dominate the spectrum of brown dwarfs, exoplanets and Asymptotic Giant Branch stars and play a primary role in the physical chemistry of their outer atmospheres.

3. Methodology

Based on state-of-the-art theoretical calculations and new models, extensive line lists (including positions, intensities, profiles, *etc.*) will be generated and validated by laboratory experiments: (i) emission spectroscopy at thermal equilibrium above 500 K in the 1.4–17 μm region [2]; (ii) high sensitivity laser absorption spectroscopy by Cavity Ring Down Spectroscopy (CRDS) in non-thermal equilibrium and hypersonic relaxation in the 1.5–1.7 μm region [3]; (iii) direct absorption and CRDS at high sensibility from 500 to 1000 K in the 1.26–1.71 μm region for weak line measurements [4]; (iv) room temperature absorption down to 0.8 μm to reach highly excited vibrational states. These complementary interdisciplinary researches will permit a breakthrough towards interpretation of high-resolution exoplanetary observations (see Figure 1).

The feasibility of this challenging project is attested by our previous successful experience and established expertise in experiments, spectra analyses and theory: our low- T experimental data and *ab initio* predictions for methane, ethylene and their isotopologues are currently the most accurate available [5].

4. Expected results

The first CH_4 line lists produced already at 2000 K above 2 μm within this program show good agreement with observations [6], as well as C_2H_4 hot- T list up to 700 K [7].

At the end of our project, the scientific community will benefit from experimental and synthetic spectra in the 0.8–17 μm region for hydrocarbons and their isotopologues ($^{12}\text{CH}_4$, $^{13}\text{CH}_4$, CH_3D , C_2H_2 , C_2H_4 and C_2H_6) in large temperature ranges (up to 2500 K). For each of these species, we will provide rovibrational assignments, broadening coefficients

(by H_2) and cross-sections, directly usable in radiative transfer codes.

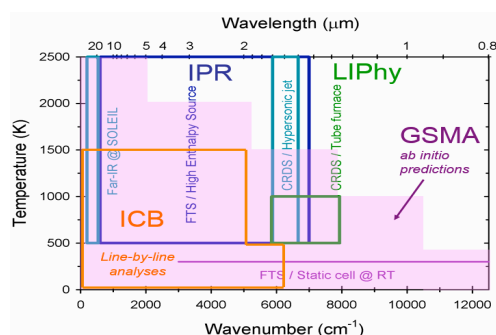


Figure 1: Schematic of the project's experimental and theoretical set up, available means and proposed contributions per team involved. The spectral zones indicated in pink and orange correspond to the theoretical work in the case of methane.

Our consortium seeks to establish the framework for a large international collaboration, which will benefit from the sharing of unique access to observations, special facilities, manpower, software and experimental means.

For more information, see the e-PYTHEAS Web site:

<http://e-pytheas.cnrs.fr>

Acknowledgements

Our consortium wishes to thank the French National Research Agency (ANR) for funding this project (contract ANR-16-CE31-0005-03).

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Transit spectroscopy of a temperate Jupiter

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Abstract

In this study, we consider the expected infrared transmission spectrum of a temperate Jupiter, with an equilibrium temperature ranging between 350 and 500 K, and we analyse the best conditions for the host star to be filled in order to optimize the S/N ratio of its transmission spectrum. According to our analysis, temperate Jupiters around M stars could have an amplitude signal higher than 10^{-4} in primary transits, with revolution periods of a few tens of days and transit durations of a few hours. In order to enlarge the sampling of exoplanets to be observed with ARIEL (presently focussed on objects warmer than 500 K) [1], some of these objects could be considered as additional possible targets for the mission.

1. Introduction

Temperate Jupiters, with equilibrium temperatures ranging between 350 and 500 K, are not expected to exist according to the standard nucleation model, which requires that giant planets are formed at large distances from their host star. However, some objects of this type have been found around solar-type stars, with expected equilibrium temperatures ranging between 250 and 500 K (Table 1). If such objects are also transiting around low-mass stars, they would be suitable targets for transit spectroscopy. Future surveys with space missions like GAIA, but also CHEOPS, TESS or PLATO, are likely to provide new targets for this class of exoplanets.

Table 1

Examples of temperate giant exoplanets detected around F, G and K stars, with a mass larger than 0.5 Jovian mass and an eccentricity smaller than 0.1 (from www.exoplanets.eu). The equilibrium temperature is calculated assuming an albedo $a = 0.03$ and a fast-rotating planet [2].

Name	$M_p(M_J)$	P(d)	D(AU)	T_p (K)
HD 134113 b	47	202	0.64	295
HD 233604 b	6.6	192	0.747	434
HD 28185 b	5.7	383	1.03	320
HD 32518 b	3.04	157	0.59	395
HD 159243 c	1.9	248	0.8	338
HD 9446 c	1.82	193	0.654	342
HD 141399 c	1.33	202	0.69	390
HD 231701 b	1.08	142	0.53	419
Kepler-11 g	0.95	118	0.46	392
HD 92788 c	0.9	162	0.6	392
HD 37124 b	0.675	154	0.53	331
HD 45364 c	0.66	343	0.897	252
Mu Ara d	0.52	310	0.92	306

2. The infrared spectrum of a temperate Jupiter

According to thermochemical equilibrium, we expect CH_4 , NH_3 and H_2O to be the main minor tropospheric species (after H_2 and He) of a temperate Jupiter. The main difference with the true Jupiter is that there is no cold trap at the tropopause, so the three molecules are expected to keep a constant mixing ratio with the altitude. We assume their relative abundances to be consistent with the cosmic abundances, i.e. $\text{H}_2\text{O}:\text{CH}_4:\text{NH}_3 = 2:1:0.1$. Their relative abundances are expected to stay unchanged even in the case of a higher metallicity (as in the case of Jupiter).

Above the tropopause, photo-dissociation products are expected: C_2H_2 and C_2H_6 (from CH_4 photo-dissociation), CO and CO_2 (from H_2O photo-dissociation). By analogy with the case of Jupiter, we assume the following abundances in the stratosphere: $\text{CH}_4:\text{C}_2\text{H}_2:\text{C}_2\text{H}_6 = 1:10^{-4}:2 \cdot 10^{-3}$, and $\text{H}_2\text{O}:\text{CO}:\text{CO}_2 = 1:1:0.2$. Calculations show that CO and CO_2 contribute as minor absorbers in the infrared spectrum, while the contribution of hydrocarbons is negligible (Figure 1).

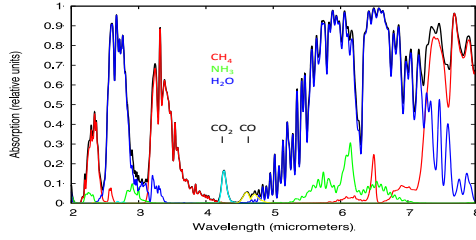


Figure 1. A typical absorption spectrum (primary transit) for a temperate giant exoplanet, including the effect of photochemistry. The contribution of hydrocarbons is negligible. The full scale is equal to the amplitude of the primary transit absorption A , as calculated in Table 2.

What could be the condensates present in a temperate Jupiter? For temperate objects colder than 500 K, there are few expected condensates, except possibly hydrated silicates; in addition, all ices are in gaseous form. We can thus expect temperate Jupiters to be relatively free of condensates [3]. As a result, the albedo of such a planet can be expected to be very low, as has been actually observed on hot Jupiters, for which typical values of 0.03 have been derived.

3. Primary transit spectroscopy of a temperate Jupiter

The amplitude of the primary transit absorption of a hydrogen-rich Jupiter-like exoplanet can be approximated as follows [1]: $A = 1.94 \cdot 10^{-7} \times T_p / \rho R^*$, where T_p is the planet's equilibrium temperature and R^* is the radius of the star (in solar radii). In order to get A larger than 10^{-4} , we need to consider temperate Jupiters around low-mass stars.

Table 2

Estimated revolution period, amplitude of primary transit signal, and transit time for a Jovian-like exoplanet transiting around a star of spectral type between G2 and M8. Two cases are considered: $T_p = 350$ K and $T_p = 500$ K. The fast rotator case is favoured for G2 to M0 stars (M0 stars are actually an intermediate case); the tidally locked object case is favoured for M5 and M8 stars.

Spectral type	R (Rs)	M (Ms)	P (d)	A	Transit time (h)
G2 ($T_p = 350$ K)	1.0	1.0	180	$6.78 \cdot 10^{-5}$	10.3
G2 ($T_p = 500$ K)			61	$9.69 \cdot 10^{-5}$	7.1
G5 ($T_p = 350$ K)	0.93	0.93	159	$7.84 \cdot 10^{-5}$	9.4
G5 ($T_p = 500$ K)			54	$1.12 \cdot 10^{-4}$	6.6
K0 ($T_p = 350$ K)	0.85	0.78	117	$9.38 \cdot 10^{-5}$	8.3
K0 ($T_p = 500$ K)			40	$1.34 \cdot 10^{-4}$	5.8
K5 ($T_p = 350$ K)	0.74	0.69	94	$1.24 \cdot 10^{-4}$	7.0
K5 ($T_p = 500$ K)			32	$1.77 \cdot 10^{-4}$	4.9
M0($T_p = 350$ K)	0.63	0.47	48	$1.71 \cdot 10^{-4}$	5.4
M0($T_p = 500$ K)			17	$2.44 \cdot 10^{-4}$	3.9
M5($T_p = 350$ K)	0.32	0.21	18	$6.64 \cdot 10^{-4}$	2.6
M5($T_p = 500$ K)			6	$9.50 \cdot 10^{-4}$	1.7
M8($T_p = 350$ K)	0.13	0.10	6	$3.98 \cdot 10^{-3}$	1.0
M8($T_p = 500$ K)			2	$5.70 \cdot 10^{-3}$	0.6

4. Sensitivity estimate

As a calibrator, we use the exoplanet WASP-76 b as described in the ARIEL proposal [1]. The amplitude of its primary transit is 10^{-3} and the transit time is 3.4 hours. A summation of 25 transits (corresponding to a total integrating time of 85 hours) is needed to achieve a S/N of about 10. According to our calculations, with a total observing time of 100 hours, a S/N of 2.5, 9.5 and 57 can be reached for temperate Jupiters around M0, M5 and M8 stars, respectively. In all cases, the observing time of 100 hours could be achieved within a total time of 3 years, compatible with the expected lifetime of ARIEL.

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The Atmosphere and Internal Structure of GJ 1132 b

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Abstract

We aim at investigating the possible internal structures of the exoplanet GJ 1132 b whose physical properties have been recently refined from multi-wavelength observations of a series of transits. Because this planet potentially harbors an atmosphere, we also discuss the influence of hydrodynamic escape on its internal structure.

Introduction

Discovered transiting exoplanets are known for their very small orbital periods. A planet with an Earth-like mass is then much closer to its host star than planets in the Solar system, and thus receives a much higher amount of irradiation. Therefore, such a planet experiences a very high XUV-driven escape of gases from its exosphere, which leads to major changes in the composition of the atmosphere. Here we aim at investigating the possible internal structures of the exoplanet GJ 1132 b whose physical properties have been recently refined from multi-wavelength observations of a series of transits [1]. Because this planet potentially harbors an atmosphere [1], we also discuss the influence of hydrodynamic escape on its internal structure.

Model

We refer the reader to [2,3] for a full description of the interior model used in this work. Following [1], we assume that the atmosphere of GJ 1132 b is dominated by H₂, with a limited amount of H₂O. We also postulate that hydrodynamic escape is favored by the high equilibrium temperature of the planet (~644 K [1]) and that the escaping hydrogen atoms drive off heavier atoms (here oxygen) through drag effects. Under those circumstances, we assume that the gas-loss is energy-limited, meaning that the different species are fully dissociated in atoms in the atmosphere. The energy input received by the planet is given by the prod-

uct $L_{XUV} \left(\frac{R_p}{2a} \right)^2$, where L_{XUV} is the host star XUV luminosity, R_p and a are the planet's radius and semi-major axis, respectively. The mass-loss rate \dot{m} (kg s⁻¹), determined from the balance between the energy input times an efficiency factor ϵ and the gravitational energy of escaping atoms, can be expressed as:

$$\dot{m} = \epsilon \frac{L_{XUV} R_p^3}{\mathcal{G} M_p (2a)^2} . \quad (1)$$

where M_p is the planet's mass. The total mass loss is then computed by integrating \dot{m} over time. The efficiency coefficient ϵ is assumed to be 0.1, based on the work of [4] who computed its value as a function of a planet's mass and radius. The total mass loss flux F_M (kg s⁻¹ m⁻²) can be expressed as the sum of the mass loss fluxes of all atoms:

$$\begin{aligned} F_M &= F_H + F_O + \dots \\ &= m_H f_H + m_O f_O + \dots \end{aligned}$$

where m_X is the mass and f_X is the atomic flux (atoms s⁻¹ m⁻²) of the atom X . The total mass loss flux is related to the mass loss rate by $\dot{m} = F_M (4\pi R_p^2)$. Because hydrogen is the dominant escaping atom that drags away all the other heavier species [5], its mass loss rate is then [5,6]:

$$F_H = \frac{F_M + m_O x_O (m_O - m_H) \frac{b_O g}{kT}}{1 + \frac{m_O x_O}{m_H x_H}} , \quad (2)$$

where x_X is the fraction of atom X in the atmosphere ($x_O = 1/3$ for water), k is the Boltzmann constant, T is the exosphere temperature, g is the surface gravity and b_X is the collision parameter between hydrogen and the atom X [7]. All the other mass loss fluxes can be easily determined from F_H and some parameters. With this toy model, one can compute the loss of any species present in the planet's atmosphere, provided that hydrodynamic escape was effective.

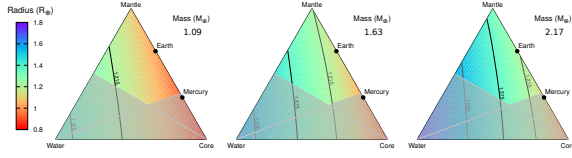


Figure 1: Ternary diagrams displaying the investigated compositional parameter space of GJ 1132 b for three values of the planet’s mass: the minimum, central, and maximum values inferred by [1], using 1σ uncertainties. Also shown are the isoradius curves denoting the planet’s surface radius measured by [1] with the 1σ extreme values. Two areas of the diagrams are excluded from the study, based on assumptions on the solar system formation (darkened zones; see [3] for details).

Results

Figure 1 shows the possible interiors of GJ 1132 b, assuming its mass and surface radius are $1.63 \pm 0.54 M_{\oplus}$ and $1.375 \pm 0.16 R_{\oplus}$, respectively [1]. The uncertainties on the determination of the planet’s physical parameters are too large to allow disentangling between fully rocky interiors and interiors containing a substantial portion of water. Figure 2 represents the amount of hydrogen atoms that could escape via blow-off from GJ 1132 b. It shows that 100 EOH of hydrogen can be lost by GJ 1132 b in less than ~ 100 Myr at its current orbit.

Discussion

The important loss of oxygen atoms via hydrodynamic escape suggests that the planet’s atmosphere could be fed by a substantial hydrosphere. If hydrodynamic escape is an effective mechanism, then GJ 1132 b would more likely belong to the family of ocean planets than any other type of solid planets.

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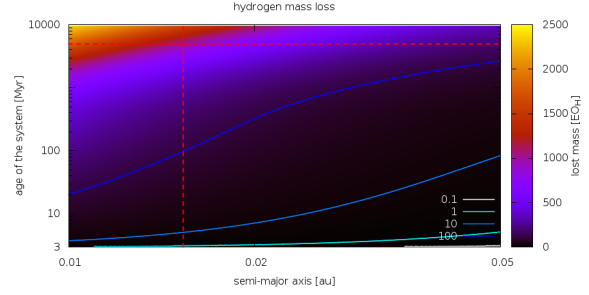


Figure 2: Mass of hydrogen lost by escape expressed in unit of Earth Ocean equivalent content of Hydrogen (EOH) as a function of time and distance from the host star ($1\text{EOH} = 1.53 \times 10^{23}$ g).

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Twinkle – A Low Earth Orbit Visible and Infrared Exoplanet Spectroscopy Observatory

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Abstract

Twinkle is a space mission designed for the observation of the atmospheres of extrasolar planets through the use of optical and infrared spectroscopy. The mission implementation is based upon an approach that has been successfully applied in other demanding space disciplines. Twinkle is also pioneering a new international access model, designed to provide access to cutting-edge science to researchers worldwide.

The study of exoplanets has been incredibly successful over the past 20 years: over 3000 planets have been discovered in our galaxy, and along with these discoveries fundamental parameters such as the planetary mass, size and distance to the parent star have been acquired. In the past decade, pioneering results have been obtained using transit spectroscopy with the Hubble and Spitzer Space Telescopes and ground-based facilities, which have enabled the detection of a few of the most abundant chemical species, hazes and condensates, and have also permitted the study of the planetary thermal structure.

The next step is Twinkle: a small dedicated satellite designed to understand the make-up of the many newly found worlds through the measurement of their atmospheric signatures. Twinkle will observe the chemical composition and weather of 100+ exoplanets in the Milky Way, including super-Earths (rocky planets 1-10 times the mass of Earth), Neptunes, sub-Neptunes and gas giants like Jupiter. It will also be capable of follow-up photometric observations of 1000+ exoplanets in the visible and infrared, as well as observations of Solar system objects, bright stars and disks. Twinkle is a cost-effective space mission taking advantage of lowered costs of access to space. The Twinkle satellite is being built in the UK and will be launched into a low-Earth sun-synchronous polar orbit in 2020, using

flight proven spacecraft systems designed by Surrey Satellite Technology Ltd and high Technology Readiness Level science payload components. The Twinkle science payload is composed of a visible-IR spectrograph (between 0.4 and 4.5 μ m) with resolving power $R \sim 70$ -300.

Early-results from SHINE, the SPHERE High-Contrast Imaging Survey for Exoplanets

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Abstract

With the development of high contrast imaging techniques and instruments, vast efforts have been devoted during the past decades to detect and characterize lighter, cooler and closer companions to nearby stars, and ultimately image new planetary systems. Complementary to other planet-hunting techniques, this approach has opened a new astrophysical window to study the physical properties and the formation mechanisms of brown dwarfs and planets. With the SPHERE XAO instrument first Light at VLT in May 2014, we have initiated with SHINE, the Sphere High-contrast-ImagInG survey for Exoplanets, a systematic characterization of 400-600 young, nearby stars close environment aimed at hunting and studying the physical and statistical properties of the giant planet population at wide orbits (>5 AU) between 2015 and 2020. In this talk, we will briefly present the main properties of the SHINE sample, the observing and data reduction and analysis strategy, the current detection performances achieved with the combination of both near-infrared instruments IRDIS and IFS, finally the key early-results obtained so far with the characterization of giant planets, the study of planetary system architectures, finally the first exploitation of the statistical information after 2.5 years of operation.

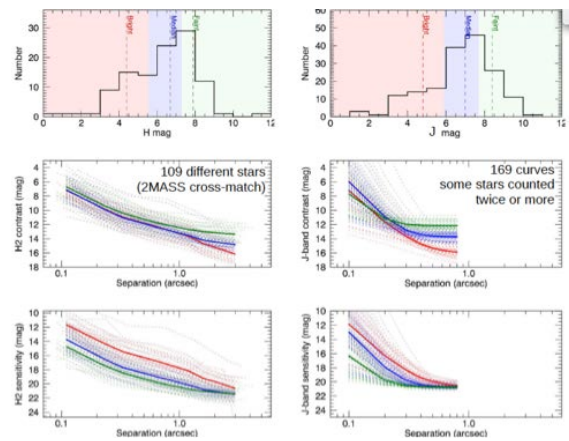


Figure 1: Detection limits for IRDIS (Right) and IFS (Left) for the SHINE sample (medium conditions)

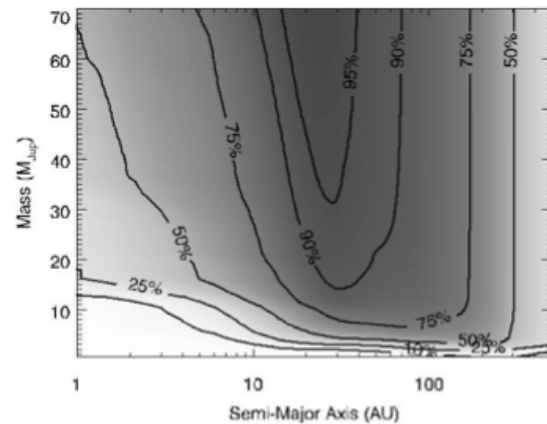


Figure 2: QMESS (Bonavita, 2013) average detection probability for SHINE using observed targets

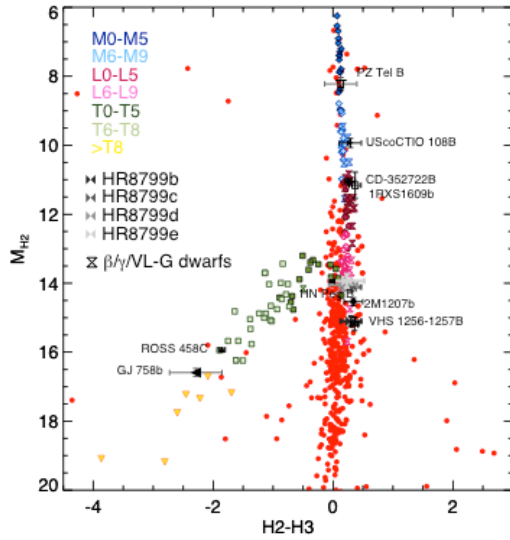


Figure 3: Color-magnitude diagram including all SHINE candidates and example of known systems.

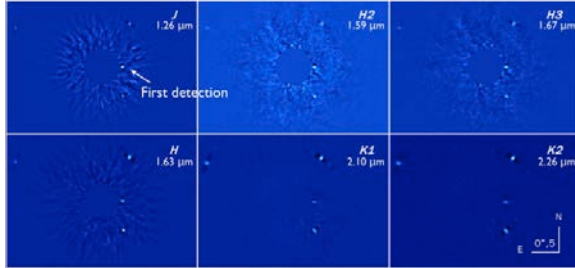


Figure 4: Illustration of the SHINE capability for the famous HR8799 exoplanetary system (Zurlo 2015, Bonnefoy 2015).

Conclusions

The SHINE program is a large high-contrast near-infrared survey of 600 young, nearby stars. Aiming at searching for and characterizing new planetary systems using VLT/SPHERE, it achieves unprecedented high-contrast and high-angular resolution imaging capabilities which bring new statistical constraints on the occurrence and orbital properties of the giant planet population at large orbits as a function of the stellar host mass and age.

Acknowledgements

We acknowledge financial support from the Programme National de Planétologie (PNP) and the Programme National de Physique Stellaire (PNPS) of CNRS-INSU. This work has made use of the the SPHERE Data Centre, jointly operated by OSUG/IPAG (Grenoble), PYTHEAS/LAM/CESAM (Marseille), OCA/Lagrange (Nice) and Observatoire de Paris/LESIA (Paris). We thank P. Delorme and E. Lagadec (SPHERE Data Centre) for their efficient help during the data reduction process. SPHERE is an instrument designed and built by a consortium consisting of IPAG (Grenoble, France), MPIA (Heidelberg, Germany), LAM (Marseille, France), LESIA (Paris, France), Laboratoire Lagrange (Nice, France), INAF-Osservatorio di Padova (Italy), Observatoire de Genève (Switzerland), ETH Zurich (Switzerland), NOVA (Netherlands), ONERA (France) and ASTRON (Netherlands) in collaboration with ESO. SPHERE was funded by ESO, with additional contributions from CNRS (France), MPIA (Germany), INAF (Italy), FINES (Switzerland) and NOVA (Netherlands). SPHERE also received funding from the European Commission Sixth and Seventh Framework Programmes as part of the Optical Infrared Coordination Network for Astronomy (OPTICON) under grant number RII3-Ct-2004-001566 for FP6 (2004–2008), grant number 226604 for FP7 (2009–2012) and grant number 312430 for FP7 (2013–2016).

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Towards The Exo-Earth Era

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Abstract

In the past few years, the number of planets discovered orbiting other stars has grown dramatically, and newly discovered planets are now announced on an almost daily basis.

In this presentation, I will describe how simulations of the orbital evolution of such planets can help us to better constrain their orbits, and even allow us to identify systems that are not all they seem to be. In addition, in coming years it is likely that the first truly Earth-like exoplanets will be discovered, and I will describe how those same dynamical tools will prove vital in assessing which of those planets are the most promising targets in the search for life beyond the Solar system.

Finally, at the University of Southern Queensland, we are in the process of building MINERVA-Australis - a dedicated Australian Exoplanet Observatory designed to follow-up and characterise Earth-like planets around the brightest stars. MINERVA-Australis will eventually feature six telescopes, all feeding to a single high-quality spectrograph. Capable of taking both spectroscopic and photometric observations, MINERVA-Australis will be a versatile and powerful planet detection and analysis machine.

MINERVA-Australis will be a key facility in the follow-up and analysis of planets discovered in the next wave of Exoplanet discovery, and will see first light in late 2017.