Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18 – 22, 2016, in Bilbao, Spain. S. Arribas, A. Alonso-Herrero, F. Figueras, C. Hernández-Monteagudo, A. Sánchez-Lavega, S. Pérez-Hoyos (eds.)

Exoplanet atmosphere highlights

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Abstract

In only two decades since the first identification of a planet outside the Solar System, and about one since the pioneering detection of an atmosphere, exoplanet science has established itself as a mature field of astrophysics. As the search of as-of-yet undiscovered planets goes on, the field is steadily expanding its focus from detection only to detection and characterization. The information to be grasped from exoplanet atmospheres provides valuable insight into the formation and evolution of the planets and, in turn, into how unique our Solar System is. Ultimately, a dedicated search for life in these distant worlds will have to deal with the information encoded in their atmospheres. In recent years there has been rapid progress on both the theoretical and observational fronts in the investigation of exoplanet atmospheres. Theorists are predicting the prevailing conditions (temperature, chemical composition, cloud occurrence, energy transport) in these objects' envelopes, and are building the frameworks with which to approach the interpretation of observables. In parallel, observers have consolidated the remote sensing techniques that were utilized during the early years, and are now venturing into techniques that hold great promise for the future. With a number of space missions soon to fly and ground-based telescopes and instruments to be commissioned, all of them conceived during the exoplanet era, the field is set to experience unprecedented progress.

1 Introduction

Exoplanet science is a rapidly advancing field of astrophysics. Two key questions: Is there life beyond Earth? and, How unique is our Solar System? are to a large extent responsible for the interest that exoplanets are receiving. To date, more then 3000 exoplanets have been confirmed.[1] Masses, radii and orbital parameters are available for many of these systems, from which it is possible to estimate bulk properties such as densities and, based on energy

[1]http://exoplanetarchive.ipac.caltech.edu

balance arguments, equilibrium temperatures. A quick look at Fig. 1 reveals the significant diversity amongst the already known exoplanets. Indeed, the word *diversity* probably conveys much of what has been learned during these initial years.

Figure 1 includes numerous planets with bulk densities less than Saturn's (towards the top left corner) that are expected to be mainly gaseous. Many others are characterized by bulk densities larger than Earth's (towards the bottom right corner) and are predominantly rocky. In between those two configurations, other bulk compositions (e.g. water planets) are possible. Color-coded, Fig. 1 shows also that the equilibrium temperature of these objects spans an order of magnitude. The broad range of densities and temperatures is indicative of the variety in the nature of these objects, and of the variety of physical and chemical processes occurring in their atmospheres (provided that an atmosphere exists). By investigating their atmospheres, we attempt to characterize the exoplanets current state, as well as their history and future evolution. The accuracy required to characterize an exoplanet atmosphere is typically a couple of orders of magnitude more than is required to detect the exoplanet. This technical challenge explains why the number of planets with atmospheric observations is smaller than the number of confirmed exoplanets.

2 Remote sensing techniques

To date, atmospheric characterization efforts have largely focused on obtaining transmission spectra of exoplanets during transit [25, 26]. Transiting exoplanets may also be seen in occultation, as the planet passes behind the star. At short wavelengths, occultations probe deeper into the atmosphere than transmission spectroscopy, a result of the different path lengths of photons in each view. At long wavelengths, occultations allow us to measure the color-dependent brightness temperature of the planet and therefore look into its thermal structure.

Both transiting and non-transiting exoplanets can be studied at arbitrary orbital phases when the planet, star and observer are not aligned. In this way, the observer gets simultaneous access to the planet day and night sides, and may spatially resolve the planet as it moves on its orbit. Like in occultations, the information inferred from the planet phase curve (brightness vs. star-planet-observer phase angle outside of transit and occultation) depends on the wavelength being probed. Unlike occultations, phase curves provide insight into both the day and night sides of the planet. All three perspectives (transit, occultation, phase curve) are complementary in terms of the physics that is investigated and the altitudes that are probed (Fig. 2).

2.1 Transmission spectroscopy

Transmission spectroscopy is better suited to probe the upper layers of an atmosphere, a result of the long optical paths of photons during the transit. Transmission spectroscopy has matured as a remote sensing technique, and comparative studies of exoplanets, mainly

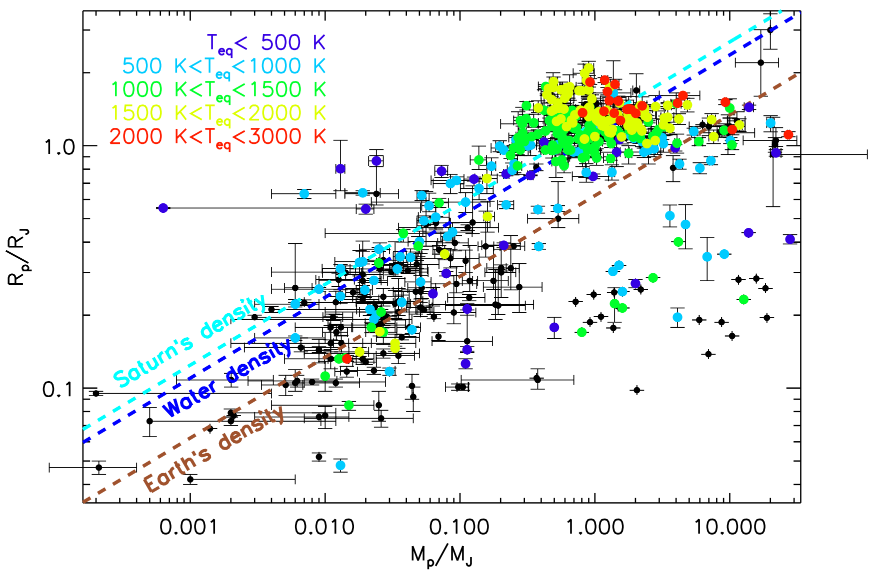

Figure 1: R_p–M_p diagram for currently known exoplanets. Information retrieved from the NASA Exoplanet Archive, http://exoplanetarchive.ipac.caltech.edu. The planet equilibrium temperatures are estimated from: $T_{\rm eq} = T_{\rm eff}(R_\star/2a)^{1/2}$, where $T_{\rm eff}$, $R_\star$ and a stand for the stellar effective temperature, the stellar radius and the orbital semi-major axis, respectively. The lines that cross the diagram follow a $M_p/M_J = C(R_p/R_J)^3$ law, where C is a constant specific to each of the indicated compositions (Earth, 100% water, Saturn).

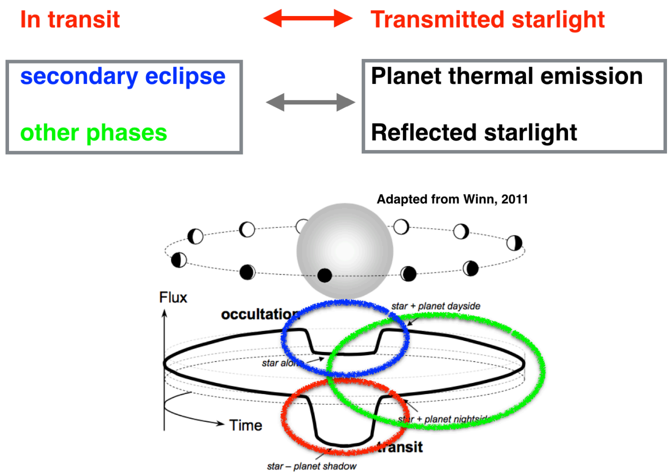

Figure 2: Transits and occultations present favorable conditions for the investigation of exoplanet atmospheres. At other phases, the atmosphere can also be investigated through the starlight reflected by the exoplanet or through the thermal radiation emitted by the exoplanet itself. Figure based on Ref. [32].

close-in gas giants, are now possible [26, 29].

From a study of ten transiting hot Jupiters that incorporates observations from the UV to the IR, it has been suggested that water is not fundamentally absent from these objects [26]. The lack of strong water features at IR wavelengths is explained by the occurrence of high-altitude clouds and haze, evidence for which is seen at short wavelengths. Another comparative study [29] suggests that hotter exoplanets ($T_{\rm eq} \geq 700$ K) with larger gravities are more likely to have cloud-free atmospheres, and will therefore present better chances for IR water detection.

Comparative studies are particularly useful to form the bigger picture of exoplanet atmospheres. The conclusions drawn from such studies (in particular on the occurrence of clouds/haze) will help decide which planets are better suited for the spectroscopic investigation of their chemical composition with big facilities (e.g. JWST, E-ELT).

A few smaller exoplanets within the super-Earth and mini-Neptune range have been studied with transmission spectroscopy. GJ 1214b and GJ 436b are probably the best-known examples [14, 16]. The flat spectra measured in both cases are consistent with the occurrence of clouds/haze in their atmospheres that mute the signature of molecules (e.g. water) present.

The effect of refraction in exoplanet atmospheres may prevent the access to the more dense atmospheric layers with transmission spectroscopy [10]. This effect can compete with

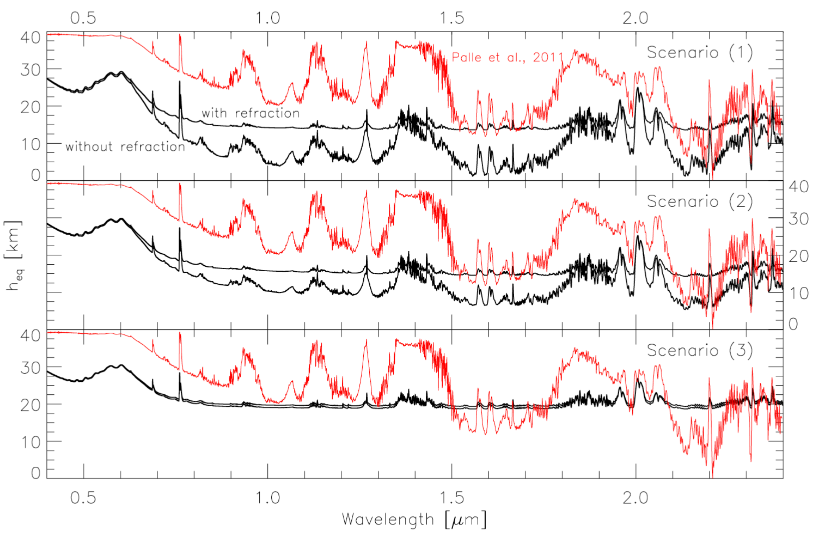

Figure 3: Refraction can potentially mute the spectroscopic signatures of long-period transiting planets. The black curves show the effect of refraction for the Sun-Earth system. Omitting refraction from transmission spectra models may lead to erroneous conclusions. From Ref. [10].

the masking introduced by clouds/haze and is particularly important for exoplanets on long-period orbits. For an Earth-Sun system, refraction will prevent the access to tropospheric altitudes (<12 km) and therefore to the layers where climate phenomena take place (Fig. 3).

Transmission spectroscopy at EUV wavelengths can probe the exosphere of hot exoplanets. The discovery of H I, O I and C II atom absorption to altitudes of a few planetary radii above the hot Jupiter HD 209458b [30, 31] triggered similar EUV observations targeting additional exoplanets and atomic features (e.g. Mg I, Si III). Interestingly, the Neptune-sized planet GJ 436b has been shown to have a cloud of H I atoms that dims the host star at Lyman-α during transits by ~60%, much more than the <1% dimming that occurs at optical wavelengths. EUV observations, together with energy considerations, constrain the evaporation rate of exoplanets, which is critical to understand the demographics of exoplanets.

2.2 Occultations and phase curves

Occultations and phase curves yield valuable insight into exoplanet atmospheres, and allow detection of spectroscopically active molecules, measure temperature profiles, infer the occurrence of clouds/haze and build maps of molecules and temperatures on the planet. The interpretation of occultation and phase curve measurements, however, may be affected by degeneracies. Phase curves obtained over the full orbit have been obtained for a few close-in gas giant planets at optical wavelengths [1, 5, 6, 7, 27] and in the infrared [4, 13, 28]. In the infrared, thermal emission from the planet atmosphere typically dominates the signal. At the shorter wavelengths, both thermal emission and reflected starlight may contribute comparably, depending on the wavelength of the observations, on the equilibrium temperature and on the composition and occurrence of atmospheric condensates. For many hot Jupiters, a wavelength of about 1 μm separates the spectrum region where planet thermal emission and reflected starlight tend to prevail [25].

Focusing on occultations and phase curves at optical wavelengths, accurate broadband photometry of unresolved planet-star systems from space with CoRoT [27], Kepler [3], HST [8] and MOST [23] have provided unique insight into the albedos, temperatures, re-circulation of energy and the occurrence of clouds and haze on close-in exoplanets [1, 5, 6, 7, 12]. Additional optical data of occultations and phase curves together with a better understanding of their information content will help:

- better constrain the re-circulation of energy in exoplanet atmospheres, and the limitations of optical-only and infrared-only measurements [24].
- understand the nature and occurrence of exoplanet clouds, which is key towards follow-up spectroscopic characterization of the atmospheric gas composition.

With space missions such as CHEOPS (launch date: 2018), PLATO (2024) and TESS (2017) to fly within a decade, the immediate perspective for broadband optical investigations of exoplanets is very positive. Although none of these missions was devised for atmospheric studies, they will undoubtedly complement characterization efforts with JWST (2018) and +30-m ground-based telescopes (E-ELT, GMT, TMT).

Figure 4 is extracted from a recent work [11] that investigates the optical phase curve of hot Jupiter Kepler-7b [6]. The measured phase curve shows that the reflectivity of this planet is unusually high for a hot Jupiter [12] but comparable to that of Jupiter (for comparison, Kepler-7b's geometric albedo is $A_g \sim 0.3$, whereas that of Jupiter is $A_g \sim 0.5$). Interestingly, its brightness peak displays an offset with respect to superior conjunction, a feature that is not unique to this object [1, 7] and that may be indicative of either displaced hot spots or of clouds on the 'morning' hemisphere.

For Kepler-7b, the most plausible scenario to explain its optical phase curve calls for clouds on the morning hemisphere. Through detailed radiative transfer calculations of the multiple scattering problem, Ref. [11] has shown that the shape of Kepler-7b's optical phase curve contains valuable information on the nature of the cloud particles. Major conclusions from that work are: that the cloud particles must be of sub-micron size and that their imaginary refractive index must be small (which entails a single scattering albedo close to one, and narrows down the identity of the condensates). In the future, optical phase curves at multiple wavelengths (as provided by e.g. CHEOPS, TESS and PLATO) will offer additional diagnostics capabilities (Fig. 4, bottom).

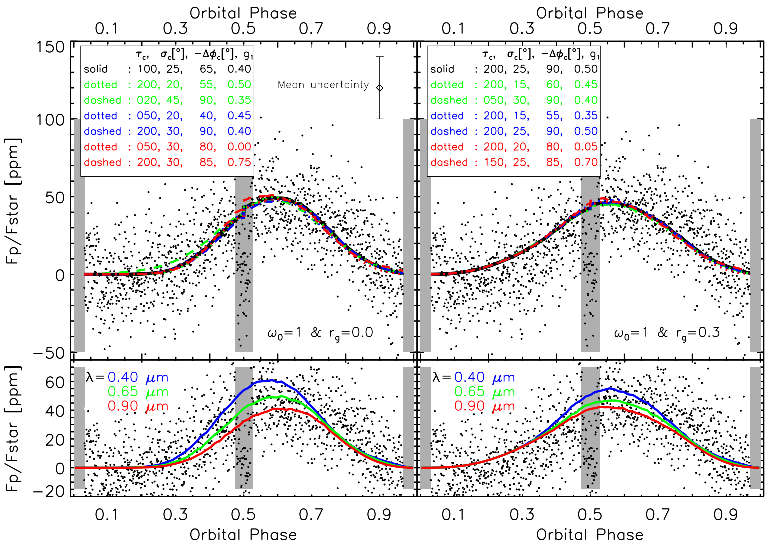

Figure 4: Observations [6] and models for the optical phase curve of Kepler-7b. The color curves at the top show model phase curves based on different cloud configurations. All color curves lead to a comparably good fit of the observations, which reveals that degeneracies exist in the interpretation of phase curves. However, Ref. [11] shows that a few robust conclusions can be drawn on the nature of the cloud particles of Kepler-7b (and in particular on the particle size and refractive index). Adapted from Ref. [11].

3 Modeling

Models are essential in the prediction and interpretation of observables. Models of exoplanet atmospheres are often based on past work on solar system planets and/or on models of stellar and sub-stellar objects. It is not always clear how model-dependent some of the conclusions drawn from the observation of exoplanet atmospheres may be, and where to place the limit on the information that can be extracted from near-future observations. For these reasons, the modeling of exoplanet atmospheres is a very active field.

3.1 Chemistry

Chemical models predict atmospheric compositions, and are useful to guide the search of atoms and molecules in exoplanet atmospheres. Assumptions such as thermo-chemical equilibrium may be valid under conditions of high temperatures and pressures in the atmospheres but may be questionable otherwise [21]. In the more general case, photochemistry calculations that resolve the competing kinetics and transport processes of all gas species are needed.

Chemical models are roughly divided depending on the range of altitudes they focus on. Lower atmosphere chemical models focus on the major molecular and atomic species that are probed at optical and infrared wavelengths [17, 20]. Upper atmosphere chemical models focus mainly on processes that are probed at EUV wavelengths. In the latter case, the conversion from molecules to atoms is quick, the gas can be ionized, and bulk advection that drives the atmospheric escape must be considered [9, 15, 33]. These models may include hundreds of gas species and up to thousand of chemical reactions. Chemical models are the basis for microphysics models that predict the occurrence of aerosols in exoplanet atmospheres.

3.2 General Circulation Models

General Circulation Models (GCMs) predict in a more or less integrative way the dynamics, thermal structure and composition of exoplanet atmospheres. Although still in their infancy, GCMs are critical in the investigation of exoplanets as observations of these objects will be limited to globally-integrated features in the foreseeable future. GCM simulations define expected atmospheric patterns that can guide interpretation efforts of transmission spectra and measured phase curves. In the latter case, GCMs provide clues on the peak-to-peak amplitude of the phase curves at various wavelengths and whether these peaks are in phase or out of phase with the illuminated fraction of the planet visible from the observers location.

3.3 Inversion models

The interpretation of a measured spectrum is not straightforward. Beyond observational uncertainties (Fig. 5), there are additional challenges associated with the relevant physics. To extract the full information contained in the spectra, while avoiding over-interpretations, inversion models are needed that identify the best-fitting solution(s) while exploring potential

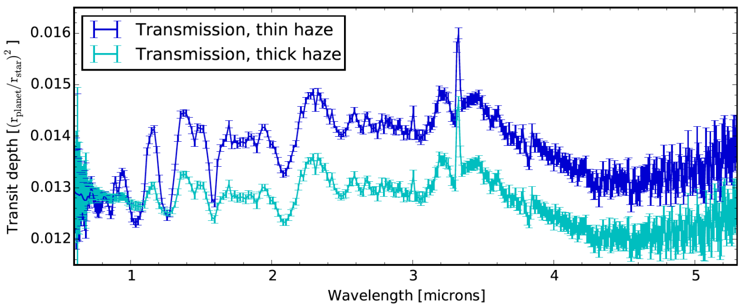

Figure 5: Simulation of a transit observation of GJ1214b with the JWST/NIRSpec instrument. Error bars are one sigma noise based on the SNR computed for a single transit observation. Adapted from Ref. [22].

degeneracies. There has been a rapid development in such modeling frameworks in the last years, that are being used to characterize exoplanets but also brown dwarfs [2, 18, 19]. The basis of inversion techniques is to connect different spectroscopic features to a variety of physical phenomena (absorption, scattering, thermal emission) and the atmospheric altitude range where they occur. Figure 6 sketches some of these ideas. The level of sophistication of inversion models that are used for exoplanets is comparable or higher than what is being used in solar system planets and Earth observations.

4 Perspectives

The investigation of exoplanet atmospheres has come a long way, and this rapid progression will continue in the near future. This progress will come hand-in-hand with new observations provided by space missions and telescopes that were, at least partly, planned after the field of exoplanets emerged. The observation of exoplanets based on direct imaging, high-spectral resolution spectroscopy and polarimetry will contribute to other techniques that are now more established. Modeling will be an essential part of these efforts, and will provide the theoretical foundation to put empirical findings into perspective.

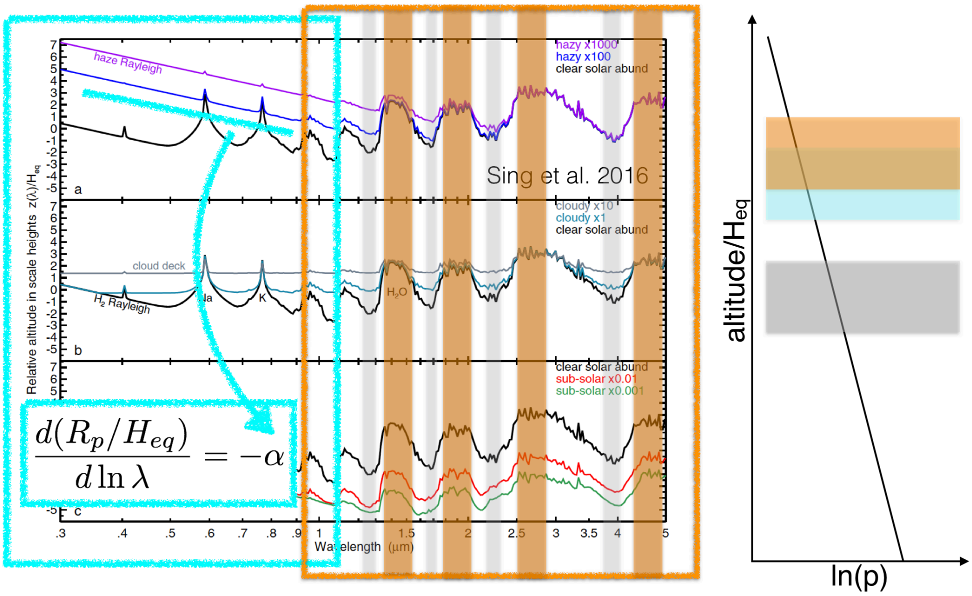

Figure 6: Roughly, the information contained in a transmission spectrum is encoded into both broadband and narrowband features. Broadband features such as the Rayleigh slope that occurs at optical and ultraviolet wavelengths may be indicative of clouds/hazes at relative high altitudes. Narrowband features are sensitive to the occurrence and abundance of spectroscopically-active molecules and atoms. Broadband features can mask the narrowband features, which may cause degeneracies in the interpretation of the spectra.

Acknowledgments

Desde aquí van mis gracias al comité organizador por una magnífica reunión y por la posibilidad de presentar una breve perspectiva de un campo tan dinámico como el de las atmósferas de exoplanetas. I gratefully acknowledge Prof. Heike Rauer for continued support.

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