Transiting Planets
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The extrasolar planet atmosphere and exosphere: Emission and transmission spectroscopy

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Abstract. We have now entered a phase of extrasolar planets characterization: probing their atmospheres for molecules, constraining their horizontal and vertical temperature profiles and estimating the contribution of clouds and hazes. We review here the current situation with ground-based and space-based observations, and present the transmission spectra of HD189733b in the spectral range 0.5-24 microns.

1. Introduction

Extrasolar giant planets are now being discovered at an ever increasing pace (Butler *et al.*, 2007; http://exoplanet.eu). As a result, planetary scientists and astronomers are increasingly called upon to make the transition from *discovery* to *characterization*, so that we can begin the long task of understanding these planets in the same way that we understand those in our own Solar System. Using transit techniques, we can already probe the atmospheric constituents of a growing sample of giant extrasolar planets orbiting very close to their parent star. During the primary transit, we can indirectly observe the thin atmospheric ring surrounding the optically thick disk of the planet -the limb- while the planet is transiting in front of its parent star. This method was traditionally used to probe the atmospheres of planets in our Solar System and most recently, thanks to the *Hubble Space Telescope* and *Spitzer*, was successfully applied to a growing sample of giant exoplanets orbiting very close to their parent star - the so called "hot-Jupiters"-. The idea was first theoretically proposed by Seager and Sasselov in 2000, and confirmed experimentally by Charbonneau *et al.* in 2002, who first detected the presence of Sodium in the atmosphere of a hot-Jupiter.

In the secondary eclipse technique, we first observes the combined spectrum of the star and the planet. Then, we take a second measurement of the star alone when the planet disappears behind it: the difference between the two measurements consists of the planet's contribution. This technique was pioneered by two different teams in 2005, using the Spitzer Space Telescope to probe two hot Jupiters in the Infrared (Deming *et al.*, 2005; Charbonneau *et al.*, 2005). A similar measurement was performed by Harrington *et al.* (2006) on a non-transiting planet by monitoring through time the combined star-planet flux. The light-curve obtained in this way allowed an understanding of some thermal properties of the planet Upsilon Andromedae b.

Primary transit. The use of transmission spectroscopy to probe the outer layers of the transiting hot Jupiters has been particularly successful in the UV and visible spectral ranges (Charbonneau *et al.*, 2002; Vidal-Madjar *et al.*, 2003; Ballester, Sing & Herbert 2007; Ben Jaffel 2007, 2008; Knutson *et al.*, 2007a, Pont *et al.*, 2007, Redfield *et al.*, 2008). More recently it was attempted in the Near and Middle Infrared spectral window, producing novel and extremely interesting results (Richardson *et al.*, 2006, Deming *et al.* 2007, Knutson *et al.*, 2007b, 2008a, Beaulieu *et al.*, 2008, Tinetti *et al.*, 2007, Swain *et al.*, 2008a, Nutzman P., *et al.*, 2008, Agol *et al.*, Knutson *et al.*, this volume). Transmission spectra are sensitive to atomic and molecular abundances and less to temperature variation. Temperature influences the transmission spectrum by way of its influence on the atmospheric scale height (Brown 2001) and the absorbtion coefficients.

Secondary eclipse. With this method, we can probe the photons that are directly emitted (Charbonneau *et al.*, 2005, Deming *et al.*, 2005), or reflected by the planet (Cameron *et al.* 1999, Leigh *et al.*, 2003, Rowe *et al.*, 2006). So far, the focus has been on the brightest stars with transiting extrasolar planets, namely HD 209458b (Charbonneau *et al.*, 2000), HD 189733b (Bouchy *et al.*, 2005) and GJ436b (Butler *et al.*, 2004), HD 149026b (Sato *et al.*, 2005), TRES-1 (Alonso *et al.*, 2004).

In the infrared spectral range, we can not only detect with this technique the molecular species showing a noticeable rotational/vibrational signature, but also constrain the bulk temperature and the vertical thermal gradient (Knuston *et al.*, 2007b, 2008b; Burrows *et al.*, 2007; Charbonneau 2008, Barman 2008, Harrington *et al.* 2006, 2007; Swain *et al.*, 2008b). Compared to transmission spectroscopy, emission spectroscopy may scan different regions of the atmosphere for molecular signatures and cloud/hazes contributions (Brown, 2001; Richardson *et al.*, 2007). Same considerations are valid in the UV-visible spectral range, except that the photons reflected by the planet do not bring any information about the planetary temperature and the thermal structure, but about the planetary albedo (Rowe *et al.*, 2006) and the presence of atomic/ionic/molecular species having electronic transitions.

Finally, with primary and secondary transit techniques we can observe different phases of the planet along its orbit, especially if the planet is tidally locked. During the primary transit we can sound the terminator, whereas during the eclipse we can mainly observe the day-side.

Light-curves. Monitoring the light-curve of the combined star-planet spectrum can be a useful approach both for transiting (Knutson *et al.*, 2007, 2008) and non-transiting planets (Harrington *et al.*, 2006). In the latter case the planetary radius cannot be measured, but we can appreciate the variations of temperature or albedo through time (depending if the observation is performed in the visible or infrared).

The problems that we can tackle with current telescopes are:

• Detection of the main molecular species in the hot transiting planets' atmosphere.

• Constraint of the horizontal and vertical thermal gradients in the hot exoplanet atmospheres.

• Presence of clouds or hazes in the atmospheres.

Today we can use two approaches to reach these objectives:

(*a*) Broad band photometry or low resolution-spectroscopy from a space based observatory. This can be accomplished by SPITZER or HST.

(*b*) High resolution spectroscopy from ground-based observatories in the optical and NIR.

The next steps with these indirect techniques will be:

• Detection of minor atmospheric species and constraint of their abundance.

• More accurate spectral retrieval to map thermal and chemistry gradients in the atmospheres.

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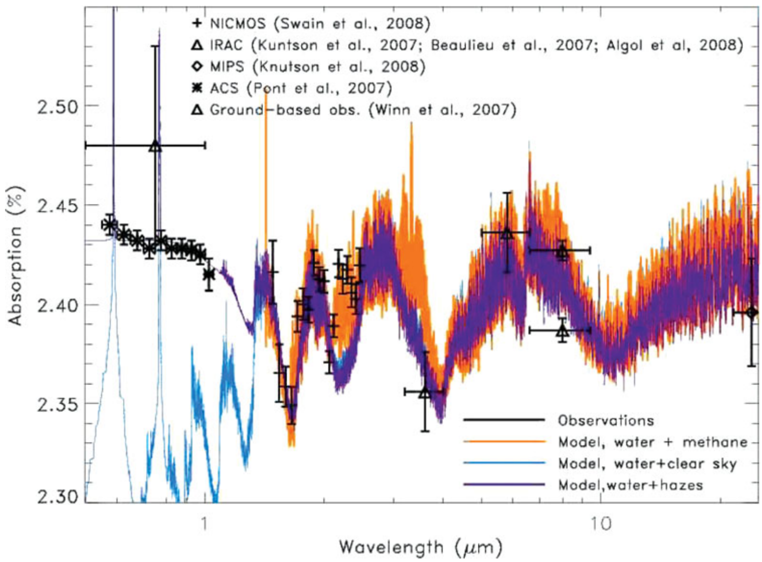

Figure 1. Simulated middle Infrared spectra of the transiting Hot Jupiter HD189733b in the wavelength range 0.5-25 μm together with HST ACS Measurements in the range $0.5 - 1\mu$m (Pont *et al.*, 2007), HST NICMOS at $1.5 - 2.5\mu$m (Swain, Vasisht, Tinetti, 2008), and Spitzer IRAC-MIPS measurements (Beaulieu *et al.*, 2008; Knutson *et al.*, 2007, 2008; Agol *et al.*, this volume). The overall transmission spectrum is shaped by the water absorption in the infrared (Tinetti *et al.*, 2007b) but methane is needed to explain the NIR (Swain, Vasisht, Tinetti, 2008). Notice that the different data collected by instruments over a wide wavelength range are giving consistent results. At shorter wavelength, the increasing flatness of the spectrum could be explained by hazes. In our simulation we have used a distribution of haze particles with size <1 μm. To better constrain the optical properties of the hazes, we should have additional data between 1 and 1.6 μm. With the current data, we cannot make any conclusive hypothesis about the haze chemical composition.

• Cloud microphysics: understanding the composition, location and optical parameters of cloud/haze particles.

• Cooler and smaller planets, possibly in the habitable zone.

Futher into the future, the James Webb Space Telescope or the JAXA/ESA SPICA mission concept (Nakagawa *et al.*, 2003) will be the next generation of space telescopes. They will guarantee high spectral resolution from space and the characterization of fainter targets, allowing us to expand the variety of "characterizable" extrasolar planets.

2. Temperature profiles

With photometry, or low resolution spectroscopy in the Near and Mid Infrared, we are today able to put some constraints on the thermal horizontal and vertical profiles of planetary atmospheres. For instance, we are already in a position of appreciating the differences between HD189733b (Knutson *et al.*, 2007b) and Upsilon Andromedae (Harrington, *et al.*, 2006): at 8 and 24 μm HD189733b shows a well-mixed temperature distribution between the day and the night side, while the opposite is seen for Upsilon Andromedae at 24 μm. HD209458b shows clear signs of a thermal inversion at relatively low altitude (Burrows *et al.*, 2007), the situation is different for HD189733b (Barman 2008, Swain *et al.*, 2008b). However, high-resolution spectroscopy is needed to perform a more accurate spectral retrieval and better constrain the dynamics of planetary atmospheres.

3. Molecules in the atmosphere of hot Jupiters

Water. In a star-planet system, a significant amount of water vapor can only exist in planetary atmospheres at orbital distances small enough (less than $\sim$ 1AU for a sun-like star). This closeness requirement is well met by hot Jupiters. According to photochemical models, H_2O should be among the most abundant species (after H_2) in the lower atmosphere of giant planets orbiting close to their parent stars (Liang et al., 2003; 2004). Moreover, according to our calculations (Tinetti *et al.*, 2007a), H_2O is the easiest of these species to detect in primary transit in the IR. A very accurate data list for water at hot Jupiter-like temperatures, has been calculated by Barber *et al.* (2006).

Carbon bearing molecules, such as CO, CH_4, CO_2, C_2H_2 are expected to be abundant as well, depending on the C/O ratio and the efficiency of the photochemistry in the upper atmosphere (Liang *et al.*, 2004). Especially for species that are supposed to be less abundant than water or with spectral signatures which are harder to detect, we need to make the leap to high-resolution spectroscopy. Also, improved line lists at high temperatures are needed to better interpret the measurements. From preliminary results and models, it is not excluded that the chemistry might vary substantially from the highly irradiated day-side to the non-illuminated night-side of these planets (Cooper and Showman, 2006; Swain *et al.*, 2008ab).

Nitrogen or sulfur-bearing molecules are also likely to be present in the atmospheres of hot-Jupiters, but their weaker signatures may be difficult to catch with a low resolving power (Sharp and Burrows, 2007).

H_3^+ – the simple molecular ion formed by the photo-ionisation of H_2 – could be a crucial indicator of the escape processes in the upper atmosphere (Yelle, 2004, 2006). Now that the HST/STIS instrument is no longer operative to observe the Lyman-alpha line in the UV (Vidal-Madjar *et al.* 2003, Ben-Jaffel, 2007), H_3^+ is the only molecular ion able to monitor the escape processes on hot Jupiters. So H_3^+ is a crucial detection target; even if detection is unsuccessful, such measurement provides at least an improved upper limit on its abundance (Shkolnik *et al.*, 2006). Calculations of the H_3^+ abundance on a hot-Jupiter (Miller *et al.*, 2000; Yelle, 2004) show that the contrast between H_3^+ emission and stellar brightness places it just on the current limit of detectability with a large ground-based telescope. We stress that even if it is a very challenging observation, it would be the best diagnostics to understand the properties of the upper atmospheres of Hot-Jupiters (Koskinen *et al.*, 2007) whereas observations of the Lyman alpha line could be partially or totally contaminated by energetic neutral atoms from charge exchange between stellar wind protons and neutral hydrogen from the planetary exospheres (Holmstrom *et al.*, 2008) or inadequately analyzed and understood as stressed by Ben-Jaffel (2008).

Clouds and hazes. At the spectral resolution that can be obtained today from space, the best we can do is to assess their presence, as they are supposed to flatten the spectral signatures or modify the spectral shape. In the case of transmission spectroscopy, they cause the atmosphere to be opaque at higher altitudes (Brown, 2001). The HST observations from Pont *et al.*, (2008) show an almost featureless transmission spectrum in the range $0.5 - 1\,\mu$m, which may suggest the presence of hazes.

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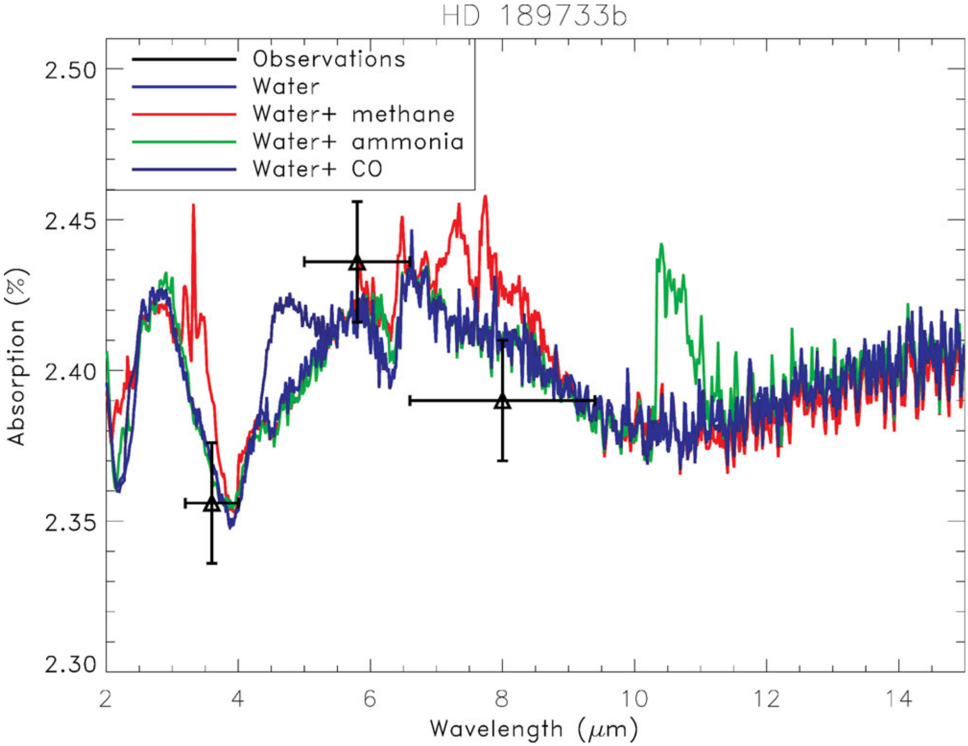

Figure 2. Simulated middle Infrared spectra of the transiting Hot Jupiter HD189733b in the wavelength range 2-15 μm together with IRAC measurements (Beaulieu *et al.*, 2008, Knutson *et al.*, 2007, Tinetti *et al.*, 2007b). Water is giving the main pattern of the spectra. Notice that to distinguish the different additional molecules, photometry is not enough, highly resolved spectra are needed.

As an illustration, we present the transmission spectrum of HD189733b in the wavelength range $0.5 - 25\,\mu$m in Figure 1. The overall transmission spectrum is shaped by the water absorption in the infrared. H2-H2, methane and alkali metals absorptions are included, as well as a crude simulation of hazes opacity. Notice that the different data collected by instruments over a wide wavelength range are giving consistent results. Most probably additional molecules are present, but we are unable to appreciate their presence at this spectral resolution. For instance, in Figure 3, we show the additional contribution of a variety of plausible molecules as a function of wavelength: the contributions of methane at 3.2 μm, CO at 4.5 μm and ammonia at 11 μm are quite noticeable in the models. Although water can be detected with broad band photometry, it is clear that spectral resolution is needed in order to probe for different species.

4. Towards smaller mass planets

For both primary and secondary transit methods, smaller size/colder planets will increase the challenge. Transmission spectroscopy can benefit from very extended atmospheres : this scenario can occur if the main atmospheric component has a light molecular weight and a high temperature. The lighter, the hotter and the smaller the core, the easier is the observation in transmission spectroscopy (i.e. the more detectable are the spectral features). In the case of secondary eclipses, the parameters playing the major role are

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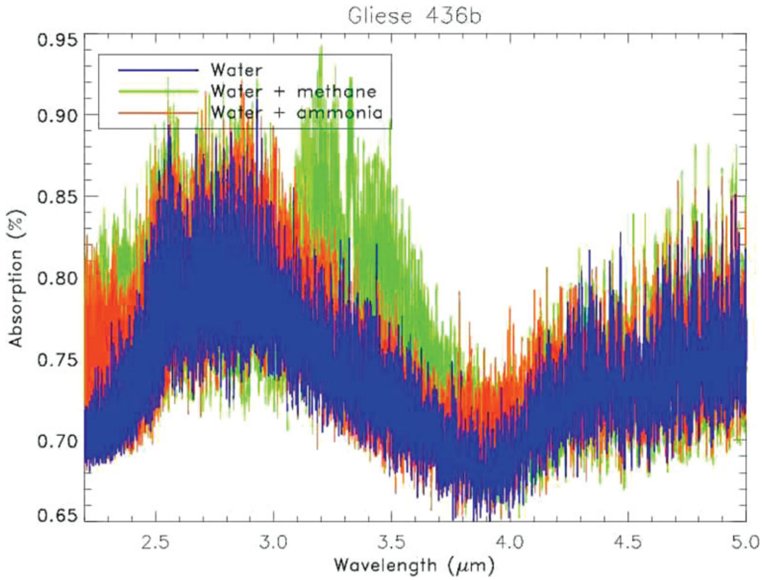

Figure 3. Middle Infrared spectrum of the transiting Hot Neptune GJ436b in the wavelength range 2.5-4.5 μm. The blue curve is due to water alone, the red curve to water and methane. The Strongest signature of Methane in the MIR is at 3.3-3.4 μm. Water mixing ratio is supposed to be 5 10^{-4}, methane mixing ratio 10^{-5}. If the methane mixing ratio is decreased or increased, the red plot will change accordingly.

the size of the planet compared to its parent star, and the planetary temperature for observations in the IR or the albedo in the visible.

With current telescopes, we can already approach the case of hot Neptunes transiting late-type stars, e.g. Gliese 436b (Deming *et al.*, 2007). Figure 3 shows a simulated transmission spectrum of Gliese 436b. Note that even if the transit depth is smaller than a hot Jupiter one (0.7 %), molecules such as methane could leave signatures of similar order of magnitude (∼0.05 %).

For Earth-size planets and/or colder atmospheres, we need to wait for JWST (Cornia and Tinetti, 2007; Cavarroc *et al.*, 2006, 2008).

5. Conclusion

Probing the atmospheres of exoplanets with transiting techniques has a bright and exciting future, both from space and from the ground. There are two main approaches: primary and secondary transit methods. In this proceeding we have reviewed how they can be complementary, and what are their inherent limitations. Taken together, and over a broad spectral range, these methods allow us to reach for a similar level of knowledge for exoplanet atmospheres as scientists had of the planets in the Solar System at the time of Voyager 1.

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