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Exoplanet atmospheres: a brand-new and rapidly expanding research field

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Abstract

The field of exoplanets is quickly expanding from just the detection of new planets and the measurement of their most basic parameters, such as mass, radius and orbital configuration, to the first measurements of their atmospheric characteristics, such as temperature, chemical composition, albedo, dynamics and structure. Here I will overview some the main findings on exoplanet atmospheres until September 2010, first from space and just in the past two years also from the ground.

1 Introduction

The introduction of any general talk about exoplanets always includes an account of the number of planets found. The number of planets discovered as of mid-September 2010 was 490[1]. All exoplanets detected thus far, and recognized as such by the IAU, have been discovered within the past 18 years via a series of observational techniques, which have been quickly improving over time. That improvement is reflected in the histogram in Fig. 1, where one can not only see how the number of exoplanets discovered per year has been steadily increasing, but also the number of techniques with which exoplanets are being discovered.

The first four exoplanets acknowledged as such were discovered between 1992 and 1994 via periodic timing variations in the very precise signal of pulsars [49, 48]. Then, in 1995, the first planet about a star like the Sun was discovered [31]. This planet, similar in mass to our Jupiter and orbiting its host star with a period of about four days, was discovered via the radial velocity technique. This technique continues to be the most successful, scoring close to 80% of the exoplanets discovered to date. Three other techniques have accomplished

[1] http://exoplanet.eu

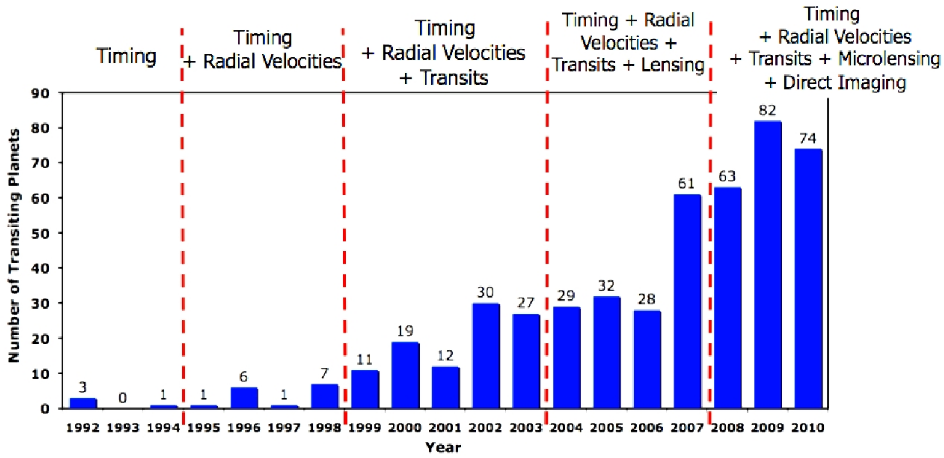

Figure 1: Histogram representing the number of exoplanets discovered per year since 1992 (last updated on September 2010; http://exoplanet.eu). On the top of the diagram are highlighted in chronological order the number of successful planet detection techniques. Each vertical dashed line indicates the year of the first discovery by each new technique, e.g. the first planet via the radial velocity technique was detected in 1995, and so on.

the detection of planets since then. In 1999 the discovery of the first planet via the transits technique was announced [5, 22]. Then, in 2004, the micro-lensing technique produced its first detection [2]. Finally, just two years ago, the first believed to be *bona-fide* imaged planets were detected via direct imaging [25, 30].

With close to 500 planets discovered so far, just finding another planet is no longer news, and we are witnessing a split of the field of exoplanets into two main directions: on one hand work continues on trying to detect new planets, but now focusing on finding the first Earth analogs. On the other hand, many efforts are being put into trying to unveil the physical properties of those planets, specially the physical characteristics of their atmospheres. This is how a new field, which some call *Exoplanetology*, is now being born.

2 Exoplanetology

As in other fields with a name ending in *-ology*, e.g. Biology, Geology, and so on, Exoplanetology treats exoplanets like a group of study *subjects* whose characteristics we want to understand in detail. The information about exoplanets that can be obtained using current techniques is definitely more limited than the information we can derive from the technically more accessible planets in our own Solar System. However, there are several properties of known exoplanets that can be readily obtained.

From the timing, radial velocity and micro-lensing techniques we can derive the minimum mass of the planets, $M \sin i$, where i is the inclination angle of the planet's orbit with respect to us as observers. We can also measure the orbital period of the planet P and its orbital separation from the host star a.

Transits and direct imaging provide a richer set of information. From transiting systems we can measure the orbital inclination of the system (and therefore the absolute mass of the planet whenever radial velocities are available), the radius of the planet, $R_{\rm p}$, (and from that mass and radius we can derive the density of the planet and determine if it is a rocky planet or a gas ball), the eccentricity of the orbit, e, and we can also begin measuring some of the planet's atmospheric characteristics. Via direct imaging we can measure accurate orbital parameters of the system, as well as the planetary atmosphere.

The atmospheric parameters that can be currently measured either through transits or direct imaging are:

- The atmospheric temperature of the planet, $T_{\rm p}$, as a function of wavelength, or equivalently, as a function of atmospheric height.
- Its bolometric albedo, A_B, which is the fraction of incident irradiation from the star on the planet's atmosphere that gets reflected back to space. This parameter gives us an idea of the presence or absence of clouds.
- The energy re-distribution factor, f or P_n[2], which gives information about what fraction of the incident stellar energy on the irradiated day-side of the planet is transported to the non-irradiated night-side (see also Sections 4 and 5). From the energy re-distribution factor we can infer the presence or absence of winds in the atmosphere of the planet. To get a sense of the scale of these parameters, $f = 2/3$ (or $P_n = 0$) indicates completely inefficient transportation of energy between the irradiated and non-irradiated sides of the planets, while $f = 1/4$ (or $P_n = 0.5$) indicates very efficient energy transportation.
- And, finally, we can also start obtaining information about the chemical composition of the planet's atmosphere.

3 Transiting planets

As technology improves, direct imaging will eventually become the technique of choice to characterize exoplanet atmospheres. In fact, the first results using this technique have already been reported [24], where from a spectrum between 3.88 and 4.10 μm of the directly imaged planet HR8799c [30], the study concludes that the continuum atmospheric emission from this planet differs significantly from existing models. However, direct imaging is still at its very early stages and, at present, transiting planets provide the richest source of information about exoplanet atmospheres. What makes a transiting planet so especial is that its orbital inclination, as seen from Earth, is such that the planet crosses in front and behind the star once every orbit, as illustrated in Fig. 2a. The passage of the planet in front of the star is called a transit (or *primary eclipse*), while the passage of the planet behind the star is usually called a *secondary eclipse.*

[2]See Appendix in [44] for a more detailed definition of these two parameters.

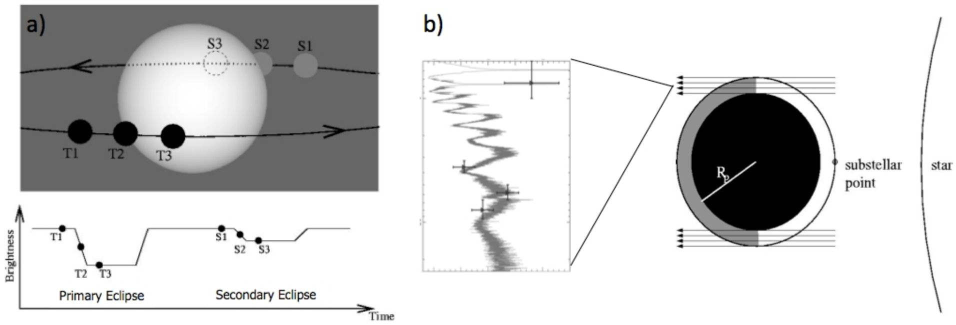

Figure 2: (a) Transiting planet system, where once every orbit the planet crosses in front of the star (primary eclipse) and behind the star (secondary eclipse); (b) when a planet crosses in front of the star, part of the stellar light crosses through the atmosphere of the planet and is absorbed by the chemicals in that atmosphere. That extra absortion of stellar light produces what is called the *transmission spectrum* of an exoplanet [47].

Both primary and secondary eclipses give a wealth of information about the atmospheric characteristics of those planets, provided that we can detect the signals, which are typically of the order of 1% of the total light of the system for primary eclipses, and a small fraction of a percent (0.1–0.2 %), for the secondaries.

In the case of primary eclipses, we can measure the chemical composition of a planet's atmosphere, and the distribution of those chemicals with atmospheric height, from what is called its *transmission spectrum* (see Fig. 2b). When the planet passes in front of the star, light from the star crosses the thin layers of its atmosphere. The chemicals present in that atmosphere absorbe part of the stellar light, and their signatures, i.e. their transmission spectrum, can be identified by subtracting spectra of the system collected during transit from spectra collected outside of transit.

Secondary eclipse observations provide an even more powerful tool. To explain the concepts, although more detailed physical models are in fact used in the interpretation of secondary eclipse data, as will be shown later, we can assume that the planetary atmopshere behaves like a blackbody. From the secondary eclipse we can measure directly the flux coming from the atmosphere of the planet[3]. Inserting that flux into Planck's equation

$$F_{\rm P} = \frac{2h\nu^3}{c^2} \frac{\pi R_p^2}{e^{\frac{h\nu}{kT_{\rm P}}} - 1} \frac{1}{D^2} \quad ; \quad \nu = c/\lambda, \tag{1}$$

where we can estimate the blackbody temperature, $T_{\rm p}$, on the side of the planet that faces the star once we know the radius of the planet, $R_{\rm p}$, the distance of the planet-star system from Earth, D, and the wavelength of the observations, λ. Then, substituting that temperature into the energy balance equation

[3]In fact what we measure is the ratio of the planet-to-star fluxes, $F_{\rm P}/F_{\rm st}$, and then derive $F_{\rm st}$ from models or real observations when available.

$$T_{\mathrm{P}} = T_{*}\frac{R_{*}}{a}^{\frac{1}{2}}[f(1-A_B)]^{\frac{1}{4}}, \tag{2}$$

where R_*, T_*, and a are known, we can estimate the bolometric albedo and the energy redistribution factor of the planet (see [27] for more details). Note that to do these estimations we assume that $A_B \in [0,1]$ and $f \in [1/4, 2/3]$.

From secondary eclipses it is also possible to obtain the *emission spectrum* of the planet, either by measuring the spectrum directly, or by building up a composite spectrum using photometric observations from individual filters. However, spectroscopy is preferred to minimize the potential effects of variability in the planet's atmosphere (see end of Section 4).

Until here the introduction of the concepts and terminology that will be used in the remaining of the document. Let's now move to the main observational results so far in the study of exoplanet atmospheres. Notice that this is not a complete compilation of all results, but a brief summary of the ones I consider have been most relevant and illustrative. Notice also that this summary is based only on results published until September 2010.

4 Results from space

From space we have already detected the atmosphere of about ten planets, the majority of them are Jupiter-mass targets orbiting their host star at very close distances, so-called *hot Jupiters*. They have the peculiarity of being tidally locked to their star, which means that, like in our own Earth-Moon system, the same side of the planet always faces the star. Therefore those planets have permanent day and night sides. The most relevant detections from space have been:

- Via primary eclipses:
  - The detection of Sodium (NaI) absorption in the atmosphere of the hot Jupiter HD 209458b, which was first reported in 2002 [6]. These authors detected the sodium with the Hubble Space Telescope (HST), by observing an extra dimming during primary eclipse at the wavelengths corresponding to the NaI-doublet, around 0.59 μm. This was the first time the atmosphere of an exoplanet was detected.
  - The second detection of an exoplanet atmosphere was reported five years later [47]. That study reported H_2O vapor in the atmosphere of another hot Jupiter, called HD 189733b, by measuring the transmission spectrum of the planet with the Spitzer Space Telescope (SST) at 3.6, 5.8 and 8.0 μm infrared wavelengths, and in the optical at ~ 0.76 μm, with HST. The following year a new study [45] claimed to not only see H_2O features in the transmission spectrum of HD189733b, but also methane (CH_4). They arrived to this conclusions from HST spectra between 1.5 and 2.5 μm. Notice however, that there is being some controversy around these detection claims, as described at the end of this section.
- Via secondary eclipses:

- Atmospheric emission from the hot Jupiters HD 209458b [13] and TrES-1b [7] with the SST. The detected emission of HD 209458b at 24 μm suggested a brightness temperature for the planet of about 1130 K. In the case of TrES-1b, the observed eclipse depths at 3.6 μm and 4.5 μm indicated a blackbody temperature of about 1060 K. These two were the first detections of atmospheric emission from exoplanets.

- Also, using the SST, variations in brightness as the day and night sides rotate into view have been measured for two planets. Observationally, this effect is similar to the changes in brightness with phase seen in Venus, but while with Venus we can observe the planet directly, in the case of extrasolar planets, the light from the star is always on the way. One of the planets observed is Ups And b, which shows brightness changes between the day and the night side of the planet with an amplitud of about 0.3% [20][4]. For the other observed planet, HD189733b [26], the change in brightness between the day and night sides is six times smoother, with an amplitude of only about 0.05%. Translating these differences in brightness into temperatures (assuming the planets emit as blackbodies), the atmosphere of Ups And b has a day-side temperature of about 1600K, while its temperature is $\sim$ 1000K cooler on the non-irradiated night-side. HD189733b, on the other hand, presents a more uniform temperature distribution, with a day-side at about 1200K, and a night-side only $\sim$ 240K cooler, or what is the same, HD189733b seems to very efficiently re-distribute the stellar incident energy around its atmosphere, while the same process seems very inneficient in Ups And b.

  This detection of the two outmost possible cases of stellar irradiated energy re-distribution efficiency at a so early stage in this field, has started a debate about whether there are two classes of irradiated hot Jupiters: one class where there is very little transport of irradiated energy to the night-side, and therefore the planets show very high brightness and temperature contrasts between their day and night sides, and another class where the energy gets quickly advected around the planets. A possible explanation for these effects is the presence, or absence, of *thermal inversion layers* in the upper atmosphere of those planets, similarly to the Ozone layer on the Earth's atmosphere, which absorbe and re-emit the incident stellar irradiation before it has time to penetrate into the planet's atmosphere and get advected. Ozone, however, cannot be responsible for those thermal inversion layers, because this molecule is unstable at the high temperatures observed in the upper atmospheres of hot Jupiters. The chemicals responsible for those thermal inversion layers remain unknown, although molecules such as TiO, VO or sulfur compounds have been suggested [15, 50].

- The detection at optical wavelengths of the secondary eclipses of the hot Jupiters CoRoT-1b, CoRoT-2b and HAT-P-7b using the CoRoT and Kepler satellite mis-

[4]Notice that Ups And b, although included in this section, in fact does not eclipse, but it was still possible to measure the variation between its day and night side emission by observing it at five different epochs, when the planet was expected to go through different *illumination* phases and therefore contribute by different amounts to the total light of the system.

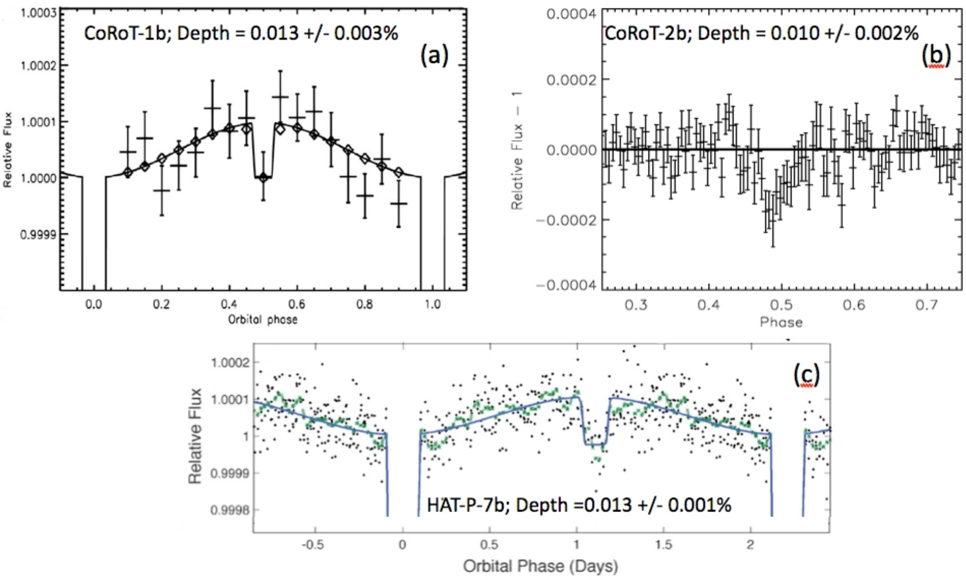

Figure 3: Secondary eclipses in the optical of the hot Jupiters (a) CoRoT-1b [41], (b) CoRoT-2b [42], both detected using the CoRoT Mission data, and (c) HAT-P-7b [3], detected using Kepler Mission data.

sions [41, 42, 3]. As shown in Fig. 3, the depths of the eclipses are of the order of 0.01%, and for two of the planets (CoRoT-1b and HAT-P-7b) one can nicely see curvatures in the light curve indicative of brightness variations with phase, which suggest that those planets have bright day sides versus significantly darker night sides and therefore might present thermal inversion layers in their atmospheres. The light curve of CoRoT-2b, on the other hand, appears flatter which can be interpret as a planet with more uninform temperature and no thermal inversion layer. An additional conclusion that can be derived from the very shallow optical depths of the eclipses is that all three planets have albedos close to $A_B = 0$.

The last set of results from space I present in this section is a combination of primary and secondary eclipse measurements of HD189733b, in the optical and near-infrared, to highlight the potential discovery of variability in the atmosphere of that planet. Shortly after [47] announced the detection of H_2O vapor in this planet via transmission spectra, another paper [18] claimed no sign of water in the emission spectrum of the planet during secondary eclipse. Another four papers had been published by the end of 2009, alternating water/no-water claims in the atmosphere of the planet [45, 33, 19, 38]. In a follow-up result the same group who had claimed no water detection reported new observations of the emission spectrum of the planet where they claimed strong water absorption features and attribute the previous non-detection to weather patterns in the atmosphere of the planet, which would cause its emission spectrum to vary over time [19]. The most recent result reports the absence of water absorption bands [38]. Instead, their data appear most consistent with a featureless spectrum like the one previously measured in the optical [33], and was attributed to some kind of haze in the upper atmospheric layers of the planet. This is an example of the kind of controversial findings that are starting to emerge in this novel field. Either the atmosphere of the planet is really varying, or perhaps what we are observing is stellar variability or systematics between the observational strategies and analyses performed by each group.

5 Results from the ground

The first successful detections using ground-based telescopes occured in 2008 and were done via transmission spectra during primary eclipse, again around the NaI doublet lines.

In the first detection, published with data from the 9.2-m Hobby-Eberly Telescope (HET)[34], they detected NaI absorption in the $\sim$ 0.59 μm doublet in the transmission spectrum of HD189733b. The signal was very small, only about 0.3% fainter than the spectral continuum, but they managed to produce a larger than 3σ detection. HD189733b is now the second planet with NaI detected in its atmosphere.

In the second detection [40], they revealed the NaI doublet in the transmission spectrum of HD209458b with a confidence level better than 5σ, using data from the 8.2-m Subaru Telescope. Although this was not a new finding, but a confirmation of the 2002 detection with HST [6], it represented a significant improvement on the detection of exoplanet atmospheric transmission features using ground-based telescopes.

The third detection not only found CO in the atmosphere of HD209458b, but also found that the CO absorption to be Doppler shifted by about 2 km s^{-1} (2σ), which suggests the presence of strong longitudinal winds between the irradiated and non-irradiated hemispheres of the planet [43].

The fourth, and last detection via transmission spectra was the identification of potassium absorption around 0.76 μm in the atmosphere of two different planets, XO-2b [39] and HD80606b [9]. Absorption by Potassium, together with Sodium, had been predicted ten years ago to be the most prominent features in the transmission spectrum of exoplanets [36].

Those four are, thus far, all the available detections of exoplanetary atmospheres from the ground via primary eclipses. Detections of planetary atmospheric emission via secondary eclipses have, on the other hand, rocketed since early 2009.

The first two ground-based detections of thermal emission from exoplanets were simultaneously announced in January 2009. The first of the two results reported the detection of the secondary eclipse of the hot Jupiter OGLE-TR-56b, observed with the 6.5-m Magellan Telescopes and the 8.2-m VLTs, in z'-band ($\sim$0.9 μm), with a depth of 0.036 ± 0.009 % [37]. The other detection, using the 4.2-m WHT, was also of a hot Jupiter, TrES-3b, but in the near-IR K-band ($\sim$2.2 μm), where they reported a depth of $\sim 0.24 \pm 0.04$ % [14].

Both detections are consistent with the irradiated atmospheres of the planets being hotter than 2000K, and with the planets having a very hot day-side versus a much colder non-irradiated night-side. This means that, for both planets, the re-circulation of energy from the day to the night side is very inefficient. The results are therefore consistent with both

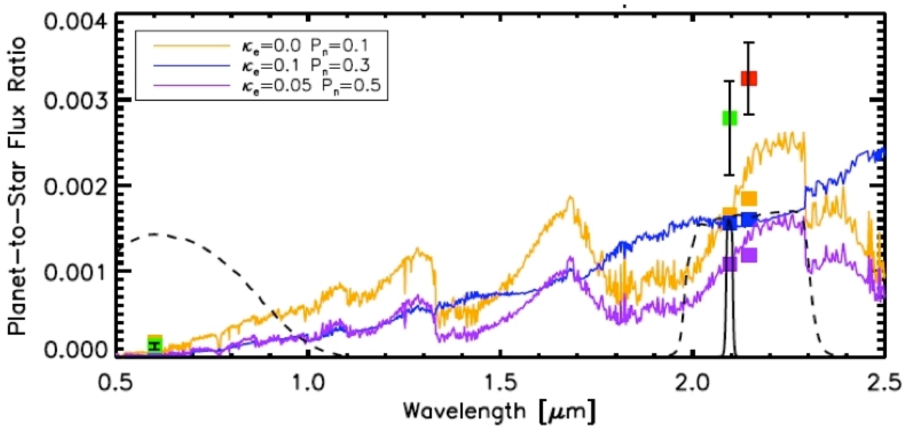

Figure 4: CoRoT-1b secondary optical and near-IR detections (green and red points), compared to models with different energy re-distribution parameters, P_n, and opacities, κ_e, which simulate the effect of thermal emission layers. None of the models, which assume the inversion layers at a height pressure of 1 mbar, can reproduce the two near-IR observations [35].

planets having thermal inversion layers in their upper atmosphere, similarly to the results found by SST for several other planets. However, these observations in the optical and near-IR prove different atmospheric depths (or pressure levels) than the SST observations.

Other secondary eclipse detections since then have been:

- The third ground-based detection of emission from an exoplanet's atmosphere was announced in June 2009 [17]. The planet in this case was CoRoT-1b, and they detected its secondary with the VLT, using a narrow-band filter centered at 2.09 μm. The depth of the eclipse that they measured was $\sim 0.278 \pm 0.054$ %. Shortly after, the detection of that secondary was confirmed in K-band ($\sim$2.2 μm) with observations from the 3.5-m telescope at Apache Point Observatory (APO) [35]. This new study not only detected a secondary $\sim 0.336 \pm 0.042$ % deep, but also combined their result with the previous narrow-band filter detection [17] and the detection in the optical described in Section 4[41] to compare, for the first time, observations of the atmospheric emission of an exoplanet in the optical and near-IR to current theoretical models. The result of that comparison, shown here in Fig. 4, is that, while the optical flux of the planet fits the models fairly well, the near-IR flux is at least twice larger than predicted by models. Such high near-IR flux also exceeds what would be expected for a planet with $A_B = 0$ and $f = 2/3$. Therefore, not only the atmosphere of CoRoT-1b seems to have thermal inversion layers, but also could have some emission mechanism which makes the irradiated side of the planet appear too bright in the near-IR.

- Emission detections from several other planets have been announced in 2010:

  - In early 2010 the detection of thermal emission in z'-band (~ 0.9 μm) from the hot Jupiter WASP-12b was announced, using data from the 3.5-m in APO [28]. They detected an eclipse depth of $\sim 0.082 \pm 0.015$ % and also claimed a slight eccentricity of the planet's orbit, in agreement with the eccentricity claimed in the discovery paper [21]. Subsequent studies [4, 23, 12] have disputed that eccentricity result. The last of those works, [12], also detects the thermal emission of WASP-12b in the near-IR J, H and K_s-band, and concludes that the higher pressure, deeper atmospheric layers of the planets probed by the J and H-band observations seem to be cooler, and more temperature homogenized than the higher atmospheric layers probed by K_s-band, where the observed emission from the planet is consistent with inefficient day-to-night redistribution of the irradiated heat, and low albedo.

- Shortly after, two independent detections of thermal emission from WASP-19b, one in H-band ($\sim 1.60\ \mu m$) and the other one using a narrowband NB2090 ($\sim 2.09\ \mu m$) filter where announced [1, 16]. Both results were obtained with the VLT. The depths of both eclipses, $\sim 0.366 \pm 0.072$ % in NB2090 and $\sim 0.259 \pm 0.045$ % in H-band, are consistent with a very low albedo, and very inefficient atmospheric energy re-distribution of the irradiated stellar energy. In addition, the emission of the planet in both filters give an atmospheric temperature for the planet of about 2600 K, which indicate that WASP-19b, likewise CoRoT-1b as explained before, is brighter in the near-IR bands than predicted by any existing model.
- Results for another two planets, TrES-2b and TrES-3b, were reported in the Spring of 2010 [10, 11]. In the case of TrES-2b they detected an eclipse depth of $\sim 0.062 \pm 0.012$ % in K_s-band, which gives a day-side blackbody temperature for this planet of about 1600 ± 100 K. This K_s-band emission, when combined with the SST secondary eclipse detections [32], suggests that the atmosphere of TrES-2b exhibits relative efficient day-to-night side re-distribution of heat. This is the first planet with a secondary eclipse observed from the ground for which an atmopheric thermal inversion layer might not be required to explain the observed flux. In the case of TrES-3b, these authors detected a K_s-band eclipse depth of $\sim 0.133 \pm 0.017$ %, which is about half the depth previously reported [14]. They also tried to detect the thermal emission of the planet in H-band and could only come up with a 3σ upper limit of 0.051%. This new K_s-band detection requires very efficient energy re-distribution in the atmosphere of TrES-3b. In addition, the authors speculate with the possible presence of a highly absorbent molecule, such as methane, to explain the non-detection of emission in H-band.

All the secondary eclipse detections described above have been done photometrically, using either standard broadband or narrowband photometric filters. However, the first result at the next level, i.e. a spectro-photometric detection of emission from an exoplanet, has been already announced using the median-size 3-m InfraRed Telescope Facility (IRTF) [46]. They detect emission from the hot Jupiter HD189733b in two different spectroscopic windows, between 2.0–2.4 μm and 3.0–4.1 μm, with an average spectral resolution of $R = 470$. By binning these low resolution planetary spectra into the equivalent of nine narrowband filters, they detect eclipse depths from just a fraction of a percent, to a $\sim 1.0\%$ depth in the bin centered around 3.3 μm. These results are illustrated in Fig. 5, where the authors compare the new ground-based measurements to previous detections of emission from this planet with

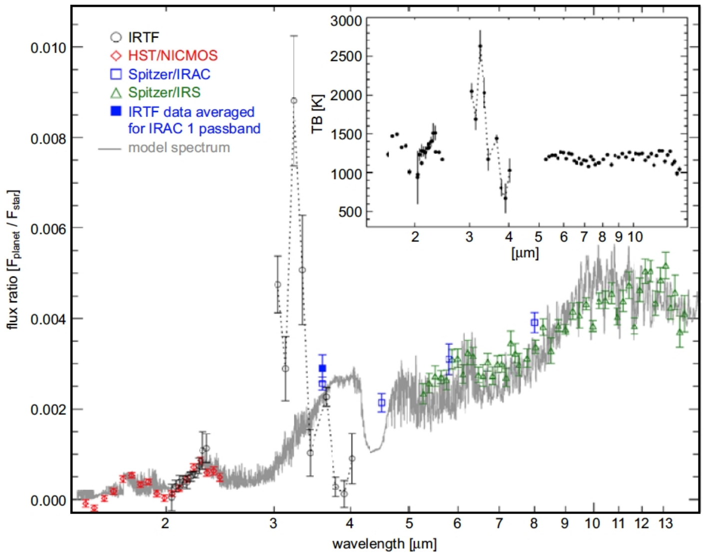

Figure 5: Emission spectrum of HD189733b observed with the 3-m IRTF (open circles), compared to previous HST observations (red), SST observations (blue and green), and a radiative transfer model (grey solid line) assuming LTE and adjusted to the HST and SST data. Reproduced from Fig. 2 in [46].

the HST [45] and the SST [8], and with *Local Thermodynamical Equilibrium* (LTE) models which reproduce well those data. They find that the ground-based observations between 2.0 and 2.4 μm are both consistent with the HST observations and LTE models. However, the spike observed around 3.2–3.3 μm cannot be modeled by thermal emission alone. The suggested explanation is the presence of non-LTE emission processes in the atmosphere of HD189733b, which would cause methane fluorescence around those wavelengths. Although this would be the first time fluorescent methane emission is detected in an exoplanet, this effect has been seen in our Solar System in the atmosphere of Jupiter, Saturn and Titan[5].

6 Summary

The detection and characterization of exoplanet amospheres is a brand new field which has started to bloom just in the past 3–4 years, thanks first to the advent of the SST, and most recently to the quick start off of successful detections with telescopes on the ground. Basically all atmospheres detected thus far are of hot Jupiters, but these detections are just the tip of the iceberg for what is yet to come. In the next few years, with more advanced instruments coming online, and the rapid improvement of analysis techniques, the characterization of exoplanet atmospheres will soon start to advance towards the lower mass planets regime, with the final goal in mind being the detection and characterization of Earth-like atmospheres.

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