Spectroscopic analysis of exoplanet atmospheres
Ground-based high-resolution atmospheric characterization of hot Jupiters using near infrared spectroscopy

Emelie Stoltz Årevik
Feb 25, 2015

Abstract
This report is exploring the possibility of characterizing hot Jupiter atmospheres using ground-based high-resolution spectroscopy. The ESO CRIRES infrared spectrometer is selected as the observing tool. Simulated observations are computed for known transiting systems. The properties of observations (noise, spectral coverage, resolution) are estimated with the CRIRES Exposure Time Calculator. An inverse method is used for reconstructing the transmission spectra of exoplanetary atmospheres and identifying spectral features. The possibility of using this method for non-transiting systems is examined. Three exoplanets are deemed possible to reconstruct the spectrum of.

Sammanfattning

Bachelor degree project, 15 HP
Uppsala University
Department of Physics and Astronomy
Supervisor: Nikolai Piskunov
Subjectreader: Kjell Eriksson
Acknowledgements

I wish to thank Nikolai Piskunov, Erik Aronson, Kjell Eriksson and Gabriella Andersson for their help, patience and support throughout this project.
## Table of Contents

1. Introduction ..................................................................................................................... 1
2. Background ....................................................................................................................... 2
   2.1 Spectroscopy .............................................................................................................. 3
   2.2 The transit method .................................................................................................. 3
   2.3 The reflective method .............................................................................................. 4
3. Method ................................................................................................................................ 6
   3.1 Derivation .................................................................................................................. 6
   3.2 Choosing planet candidates ....................................................................................... 9
   3.3 Planet choices .......................................................................................................... 10
   3.4 Assumed radii for non-transiting planets ................................................................. 11
   3.5 Observing time and wavelength region ..................................................................... 12
   3.6 CRIRES Exposure Time Calculator ......................................................................... 13
4. Results ............................................................................................................................. 14
5. Discussion ......................................................................................................................... 16
6. Conclusions ....................................................................................................................... 17
7. References ......................................................................................................................... 19
8. Appendix 1 ....................................................................................................................... 21
9. Appendix 2 ....................................................................................................................... 23
1 Introduction
Just over the last 20 or so years the subject of exoplanets in astronomy has grown significantly. After the first discovery of a planet outside our solar system in 1992 (Wolszczan & Frail, 1992), new instruments and methods have been developed to examine these new worlds. A few exoplanets even have had their atmosphere studied. This project will study the possibility to examine the chemical contents of exoplanetary atmospheres using an inverse method for reconstructing the electromagnetic spectrum of the light that have passed through the atmosphere.

The project is mainly focused on the type of exoplanet called hot Jupiters, which as the name suggests have characteristics similar to those of Jupiter; that is they are gas giants with a mass similar to, but in general larger than, Jupiter. They range from about one Jupiter mass to about 30MJ. Hot Jupiters orbit close to their host star, approximately 0.015 to 0.5 astronomical units (the Earth orbits the Sun at 1 astronomical units), which naturally make them very hot, thereof the name.

The choice of studying hot Jupiters is motivated because they are the easiest exoplanet to discover in general, and from the Earths point of view they often tend to pass in front of their host star which is a requirement for the transitional method of observation and characterization.

The results from observing hot Jupiters can help us determine their origin as they cannot, according to our theories, form at their current distance to their host star. Finding out what these distant worlds are made of can also help us in the understanding of our own solar system, and the evolution of planetary systems overall. Learning how to observe and analyze the data for the contents of a hot Jupiters atmosphere can help us learn how to analyze smaller planets in the future.

More specifically this project will focus on simulating the optimal wavelength range as well as the optimal size ratio of planet and host star for characterizing the atmospheres of hot Jupiters. An inverse method for reconstruction of the planetary spectrum will be used for ground-based high-resolution instruments to find if it is applicable for proper observations.

Thus the goals of this project are

- To find the optimal wavelength range of observation for characterizing the atmospheres of hot Jupiters using an inverse method for reconstruction of the spectrum.
- To find the necessary size ratio between the planet and the host star for the same characterization.
- To consider non-transiting planets as well as transiting planets and see if it is possible to reconstruct the spectrum by increasing the signal to noise through more observing time.
- To see if the chosen method could be applicable for the considered exoplanets.

In order to reach these goals several real planetary systems will be considered for simulated observations. The contrast between the planet and the star will be estimated and non-specific instrumental noise will be added to compare systems with each other, including non-transiting systems.
2 Background

An exoplanet is a planet outside our own solar system, orbiting another star. There are several kinds of exoplanets, such as Earth-like rocky planets (like Earth or Mars), ice giants (like Neptune or Uranus) and gas giants (like Jupiter or Saturn).

There are 1890 confirmed exoplanets (2015-02-25, exoplanet.eu). 592 of them have been discovered using a method of radial velocity (RV) which was the first commonly used method as it could relatively easily find exoplanets around main sequence stars. When a planet orbits around a star both bodies will move around a common center of gravity. This will cause the star to wobble and as it is moving back and forth in the radial direction its light will be Doppler shifted. This can be detected using instruments like HIRES at the Keck observatory or HARPS at La Silla Observatory. In 1995 this method was used to find the first exoplanet orbiting a main-sequence star, 51 Pegasi b (Mayor & Queloz 1995). RV is a useful way to discover exoplanets; however it doesn’t give many physical properties of the planet other than the minimal mass (the inclination of the orbit is needed to determine the actual mass). There are a few properties about the orbit that can be found though, for example the orbital period, eccentricity and the semimajor axis (the separation between planet and star).

The majority of the discovered exoplanets, namely 1189 of them, have been discovered using the transit method where a planet passes in front of its host star. The amount of planets discovered by this method has increased dramatically just over the last few years with the Kepler spacecraft designed specifically for this task. The first exoplanet to be observed by the transit method was HD 209458 b (Charbonneau, et al. 1999) which was also the first planet to be confirmed by more than one method since it had previously been discovered with the RV method as well. Combining these two methods can reveal a lot more information about the planets, for example the radius of the planet alongside its mass, which in turn give its average density. Additionally if the planet has a secondary transit, that is it gets covered behind the star during a part of its orbit, we can find the eccentricity of the orbit as long as there are no other planets around. Moreover the atmosphere of the planet can be examined spectroscopically during the transit by analyzing the absorbed molecular lines in the light that passes through it.

However, not every planet transits in front of its star from our viewpoint from the Earth, which severely limits the amount of exoplanets that can be examined spectroscopically. Thus there are attempts at characterizing atmospheres using the reflected day side spectrum of planets, such as for 51 Pegasi b mentioned above (Brogi et al. 2013). Considering the close orbit of hot Jupiters the starlit part of their surface will reflect enough light for our spectrometers to pick up. But one of the major problems of observing exoplanets is that we cannot observe them directly. Since they orbit stars, which are always so much brighter than any object nearby, we can never observe the light of the planet on its own. Any contribution to the total light from the planet will be drowned in the light of the star. This means that the light that has passed through or have been reflected of the atmosphere of the planet will always be in a combined spectrum with the host star. Thus we have to develop ways to separate the two. For the case when we consider the reflected light of the side of the planet, it will be moving through its orbit as we are observing it, and during this movement the reflected light will be slightly Doppler shifted. Using this fact we can separate the reflected light of the planet from the starlight which in turn allows absorption lines to be detected. Observing the orbital motion around the star by following the changes in its day side spectrum can also allow us to determine the planets orbital inclination and mass (Brogi et al. 2012). For transiting cases it’s more of a case of seeing what in the spectrum is different while the planet is transiting compared to other parts of its orbit.
2.1 Spectroscopy

Spectroscopy is the study of the interaction between matter and radiation as a function of its wavelength or frequency. Observed light is represented in the form of a spectrum. For astronomers this study has been, and still is, important considering electromagnetic radiation is the only information accessible to us from outer space.

There are two important aspects of spectroscopy that are used when considering the atmospheric content of an exoplanet. Firstly, since the part of the spectrum that comes from the planet will be Doppler shifted it can be possible to distinguish the planetary spectrum from the stellar one. The Doppler effect is caused by the movement of the planet in its orbit around the star.

Secondly, the actual molecular content could be observed in the absorption lines of the planetary spectrum. As light hits a gaseous cloud there is a chance that the molecules will scatter or absorb different quanta of light, possibly reemitting it in another direction. This will cause the light we pick in our spectrometers to be significantly dimmer in particular wavelengths or frequencies corresponding to the quantum that was removed. This forms an absorption spectrum (Figure 1) and since we know from labs on Earth what quanta corresponds to what molecule we can find out what molecule most likely caused the brightness dip in the spectrum.

![Figure 1. A continuous spectrum (top) and an absorption spectrum (bottom) of visible light.](image)

2.2 The transit method

Due to the close orbits of hot Jupiters they have a large chance of transiting in front of their host stars from our point of view which makes them interesting to study by the transit method. They block out part of the light from the star, eclipsing it. This will result in a dip in observed flux from Earth and is thus a good way of detecting exoplanets. To find the light that has passed through the atmosphere of the exoplanet two different points of the orbit is considered. Basically we look for what is different between the combined planet-star spectrum from when the planet is transiting compared to any other point of its orbit. By taking the spectrum of the host star while the planet is next to the star (for example) and comparing that to one taken while the planet is in front, transiting the star, the result will be the light of the star that has passed through the atmosphere of the planet (if it has one). In this spectrum we could potentially see absorption lines of molecules, which would inform us of their presence in the atmosphere of the planet.

For gaseous planets we don’t know where the atmosphere starts or its height. A way to find out is to observe the planetary disk as it transits the star in different wavelengths. More penetrating, longer, wavelengths will reach deeper into the atmosphere before being absorbed or scattered. Thus if the observation is done over a large wavelength range we can tell when the planet is completely opaque and at which height the result comes back as just the spectrum of the star.

As hot Jupiters are orbiting close to their star the eclipse will cover a large part of the orbit of the planet. This might cause some trouble when interpreting the spectrum of the transit. As the planet comes into view from our viewpoint it will be moving slightly towards us as the orbit is elliptical, causing the light to be blue-shifted. After it has passed the point straight in front of the star from our point of view it will start moving away and red-shifting the light. This makes the spectrum difficult to analyze because the molecular bands will be moving if we observe over a long period of time. This effect is negligible if we make sure to take many and short exposures.

Additionally the effect of limb darkening should be considered. This is what describes how a star’s intensity will differ depending on where you are looking at the star (Figure 2). On the outer edges of the stellar disk from our point of view we are looking through fewer layers of the star, which means that it does not shine with the same intensity as it would if...
we were looking right at the center of the star. This is because the deeper layers are closer to the core and thus hotter, so there is a temperature drop as we look further from the center of the star. When observing a big transiting planet the light passing through the atmosphere will be affected by the variation in intensity. This will also change over time as the planet moves across the stellar disk, which complicates the analysis.

For the method of transmission there is a preference in observing exoplanets in near infrared light (~0.7µm – 2.5µm) because there are interesting molecular bands in this wavelength range, for example H₂O (at 0.92 – 0.95µm for hot Jupiters (Cahoy et al. 2010)), O₃, CO₂, CH₄ and HNO₃. These are of course interesting because they are reminiscent of our own solar system. Several of these are expected to be present in exoplanetary atmospheres because it is what we see in our solar system, our only reference point.

2.3 The reflective method
One way of observing exoplanets is to use the fact that they reflect light from their host stars of their cloud layer, and depending on how much they reflect and what absorption lines we can see in the reflected spectrum we can draw conclusions about their composition. The light of the star when the planet has its night side directed toward our point of view will be compared to the light when the planets day side contributes to the total emitted light. The difference will be the reflected spectrum of the planet combined with the thermal emission spectrum which appears since hot Jupiters will emit heat along a Planck curve like a (poor) black body (Figure 3). We can differentiate this spectra from the starlight by looking at what spectral lines are Doppler shifted over a full orbit of the planet. We can thus separate the part of the spectrum that moves from the static telluric and stellar spectral lines.
The reflective properties of a planet depend on many parameters but first and foremost on how much light is available. If the planet orbits around a bright star there will be many more photons that hit the surface so that more photons can get reflected in our direction. The distance from the star also matters since the flux will be lower the further away from the star the planet is. Another important aspect is how the planet is directed from the viewpoint of the Earth. If it is behind, but not eclipsed, by its star from our point of view it will reflect light across its entire surface, like the full moon, which increases the amount of light we receive. If a planet orbit is situated in an orbital plane perpendicular to our line of sight it will instead only reflects light across half of its surface. The latter is not an ideal scenario for detection of exoplanets because the amount of light added from the presence of the planet does not change over time, there will be no Doppler shift, and is therefore not detectable.

In addition to the amount of available light, the distance and orientation, the albedo plays a part. The albedo is the reflection coefficient or whiteness of the reflective surface which varies between 0 for dark non-reflecting surfaces to 1 for completely reflecting surfaces. For example a high geometric albedo, indicate the presence of a cloud layer or an icy surface. A space-weathered surface without much of an atmosphere, like the Moon, has a low albedo. Due to their close orbits hot Jupiters are generally expected to have low geometric albedo since strong stellar winds will blow away any potentially forming clouds.

The infrared part of the spectrum is perhaps not ideal to study using a method of reflection since the planets being so close to their host stars would have their reflected spectra dominated by thermal emission. This adds an additional unknown parameter which makes the analysis of the spectrum more difficult. Although the thermal emission from hot Jupiters could also contain information of absorption of molecules in the atmosphere these kinds of planets are so hot that the thermal emission will be moved towards shorter wavelengths. This can result in the emission covering parts of the reflected starlight spectrum of the planet which is troublesome because the two will mix and separating them is difficult.

Figure 3. Two Planck curves for a black object with $T = 5700$ K (star) and one with $T = 1200$ K (possible planet contribution)
First at a distance of about 1 AU the spectrum of gas giants orbiting a solar-like star will be dominated by reflected light to even beyond 1µm (Cahoy et al. 2010) which depends in part on the fact that clouds of water can form at this distance. One of the most contributing effects to the albedo of a gaseous planet is the presence or absence of clouds and as hot Jupiter most likely don’t have much clouds as mentioned above they generally have a lower albedo and appear dark. It is also more difficult to detect the planets at longer wavelengths when the planet has such a close orbit.

3 Method

The main method that will be used (Arons et al. in prep) is an inverse method which is able to reproduce a transmission spectrum of an exoplanet’s atmosphere over a large wavelength range in the near-infrared using high-resolution spectrometers. The advantage of the inverse method approach is that there will be much less model dependence as it has a higher resolution. For this method many short exposures instead of a few long ones are required.

The input variables are stellar flux and specific intensity spectra of the observed star as well as a telluric transmission spectrum. It also requires a high spectral resolution of at least 25 000 (to be able to differ between the spectral lines in the telluric atmosphere) as well as a wavelength coverage of at least 0.1 µm in a single exposure and a S/N per resolution element per exposure that is reasonable for analysis. The S/N depends strongly on the relative size between the exoplanet atmosphere and the star.

This method will be tested on parameters taken from real observed exoplanetary systems with the intent to simulate observations of said systems and use the method to reconstruct the spectrum of the exoplanets atmosphere.

The telluric transmittance that was used in the simulations was calculated using LinePak (Gordley et al. 1994) based on the U.S. Standard Atmosphere. The altitude of the atmosphere was set to 2.6 km, and the water vapor concentration was set to 20%.

The atmospheric structure of the hot Jupiter model spectra was taken from Miguel and Kaltenegger 2014. Clouds are not included and the atmosphere height is set to 5600 km on top of an opaque core with radius 90 000 km.

3.1 Derivation

The simulated spectrum $S$ of a star with a transiting exoplanet will be

$$S = (F^S - I^S A^P At^P + I^S A^E P^E) T$$  \hspace{1cm} (1)

Where $F$ = flux, $I$ = specific intensity, $A$ = relative area to stellar disk, $E$ = exoplanetary transmission and $T$ = telluric transmission while the sub/superscripts denote $S$ – stellar, $P$ – planetary and $At$ – planetary atmosphere respectively. $I$, the specific intensity, refers to the limb darkening effect of the star which varies over phase. $I$ is a function of $\mu$ (limb distance) and $\mu$ is taken from the position of the planet on the stellar disk. The areas are expressed as fractions of the stellar disk area.

The equation takes all the flux from the star, subtracts the light covered by the planet with the atmosphere included and then adds back the part of the light that passed through the atmosphere in the third term. All of this is multiplied with the telluric transmission to find the spectrum, $S$, that we would observe from the surface of the Earth.

The simulation needs to be considered over many phases, while also accounting for the Doppler shift in the stellar spectrum relative to the telluric spectrum from the rotation of the Earth as well as the Doppler shift from the planets radial velocity. On top of this noise has to be added which would originate from our theoretical spectrograph, but in this project the instrumentation will be non-specific and the only noise considered will be the shot noise which only depends on the incident flux. For real observations one also should consider the dark current and the read-out noise which are instrument specific. When considering all of the above an observation will be produced that can be used to recreate the planetary spectrum by solving (1) for $E$.

However doing this straight up will result in an unstable formula for the risk of dividing by zero where the telluric transmittance is close to non-existent. This will amplify the noise and the solution will oscillate in regions where the
telluric transmittance is low. To get around this an inverse problem can be solved. Here there is instead an optimization problem where we wish for the following expression to be minimized.

\[
\Omega \equiv \sum_{\lambda \theta} \left( E^P T - \frac{S_n + \frac{E^P F + f_{A_p} T}{\lambda^2 A_\Lambda}}{I^2 A_\Lambda} \right)^2 + \sum_{\lambda} \left( \frac{dP}{d\lambda} \right)^2 \Lambda = \min \tag{2}
\]

The summation is done over the different wavelengths and exposures during the transit. The first term in (2) is just (1) solved for E where the spectrum S now has become being affected by noise, renamed \(S_n\). The second term is a regularization term and the \(\Lambda\) is a free parameter which controls the importance of the regularization. This term has to be chosen and in a simulated observation can be found the optimal value of when comparing the result with the original input spectrum. The effect of the regularization can be seen as a smoothening of the resulting spectrum. Having a \(\Lambda\) that is too small only results in a spectrum filled with noise and absorption bands cannot be seen through this, but a \(\Lambda\) too large can flatten out the spectrum to just a line (see Figure 4).

For more in-depth understanding I refer to the unpublished paper by Aronson et al. 2015.
Figure 4. Simulation of WASP-80b with a regularization of $\Lambda = 10$, 1000 and 100000 in the J-band. The white represents the atmosphere of the Earth, the dark red is the actual exoplanet atmosphere and the lighter red line is the reproduced spectrum.
Choosing planet candidates

The exoplanet candidates that will be considered for the simulations should have parameters optimal for resolving the planet from its host star. As the planet is in certain phases of its orbit (in front of the star, transiting, or next to its star, reflecting starlight in our direction) the total observed spectrum will contain both the spectrum of the star and of the planet. The spectrum of the planet must be strong enough so that we can clearly see it through the noise. Thus it is important that the contrast between a planet and its star is large.

The contrast of a transiting planet is proportional to the thickness of the atmosphere squared, and can be expressed as the radius excluding atmosphere subtracted from the total radius, over the radius of the star squared.

\[ C_t \propto \frac{(R_p + R_a)^2 - R_p^2}{R_s^2} \] (3)

Thus when searching for transiting exoplanets they are preferred to orbit small stars while having a large radius themselves. The size of an exoplanets atmosphere cannot be known though. As mentioned in the Background it is possible to probe the height of the atmosphere using a significantly large wavelength range to observe at what wavelength the planet is opaque and at what point only the star spectrum is acquired. However, for this project a reasonable assumption is that the atmosphere is about 1% additional depth of the planet radius as we cannot perform these kinds of observations.

The contrast of a reflective planet is slightly different and is proportional to the radius of the planet \((R_p)\) divided by the distance to the star \((a)\) squared, times the geometric albedo \((p)\) of the planet surface. It does also depend on the phase of the planet, where full face means a fully lit surface in the direction of the observer. This is the only case that is considered in this project, although it does vary as the planet moves through its orbit.

\[ C_r \propto p \times \left(\frac{R_p}{a}\right)^2 \] (4)

Thus planets that are to have their reflective light observed are preferred to have a large radius, which is a difficult parameter to know for non-transiting planets, while also orbiting close to their star. Their geometric albedo should be large as well which is uncommon for hot Jupiters. In fact they are specifically known to have very low albedos, especially in the near-infra red, between 0.06-0.35 (Demory & Seager, 2010). This is mainly due to alkali metals, TiO and VO molecular absorption bands. As mentioned in the Background hot Jupiters tend to not have any reflective clouds in the atmosphere because of the stellar wind disbanding them. Marley M. S. Et al (1999) make it clear that the geometric albedo is significantly lowered for longer wavelengths and assuming no high-atmospheric reflective clouds the geometric albedo can be considered to be <0.1 for the near infra-red. When calculating the reflective contrast of the chosen planets the albedo will be assumed to be 0.1 for all planets.

Simulations will be performed in the near-infrared for several reasons. As mentioned in the Background there are several interesting absorption lines in this wavelength range. There is also the fact that the near infrared is what is called an infrared window. This means that there are several wavelength bands in this region which doesn’t get absorbed and thus not emitted from the atmosphere of the Earth. The infrared windows are regions in the telluric transmission where infrared radiation from outer space can reach the surface of the Earth without significant interference. This means that this region is fit for ground-based astronomical observations, and thus fit for observing exoplanetary atmospheres. As discussed in the introduction the near infrared might not be the ideal wavelength range for observing the reflective properties of hot Jupiters, some even say the albedo in this wavelength range is negligible (Sudarsky, Burrows & Pinto, 2000), while others think that the sensitivity in the observations of thermal emission is greater for small and cool planets (Crossfield, 2013). This certainly does not apply to hot Jupiters; still there will be an attempt to resolve reflective spectra of hot Jupiters since this would be a valuable outcome.

Also to reduce the noise from the observations the host star is preferably bright in the wavelength area we are observing in. This ensures that the telescope obtains plenty of photons, as the noise scale with \(\sqrt{\text{photon count}}\). As we observe in the near infra red the host stars are preferably bright in the J-, H- and K-bands. These bands are well-defined passbands.
or filters sensitive to a certain radiation of certain wavelengths. The wavelength ranges for the bands are 1.13-1.37 µm for the J-band, 1.50-1.80 µm for the H-band and finally 2.01-2.42 µm for the K-band.

### 3.3 Planet choices

As this project is focused on the potential for reconstruction of the exoplanet spectrum using the inverse method previously presented, several actually observed planetary systems will be considered. The input variables, such as the radius of the planet and its separation from the host star, will be taken from Eunkyu, H., et al 2014. However, as there is no possibility for real observations a single artificially produced spectrum of a hot Jupiter will be used in every case for analyzing. The systems will be chosen such that the contrast times the signal to noise ratio is as large as possible. See Table 1. for planet parameters being referred to in the following section. Here are the planets that were chosen:

- **HD 189733 b** is a well-studied planet, its discovery was announced at the same time as HD 209458 b, and it is the closest known hot Jupiter to Earth just 19.45 pc away. The light that is reflected of its surface has been studied spectroscopically and detection of water has been reported (Birkby et al 2013). It is the first exoplanet to have its colour, blue, determined (Berdyugina et al, 2011). The planet is transiting its host star, which itself is very bright, covering about 15% of the disk during the transit.

- **HD 209458 b** is also a well-studied planet and the first transiting planet to be discovered (Charbonneau et al. 1999). It has been studied spectroscopically from its transits and has a confirmed atmosphere (Charbonneau et al 2001). The planet is thought to have a geometric albedo of about 0.038 (Rowe et al 2008) and is quite large in relation to its host star which is relatively bright.

- **KELT-2 A b** does not have the ideal radius ratio with its host star as it is relatively small, and the separation is large as well, however the star is bright in the near infrared wavelength regime. It is said to be the ninth brightest star overall with a transiting planet, and is part of a binary system (Beatty et al 2012).

- **Kepler-7 b** is a hot Jupiter that has an unusually high geometric albedo of about 0.35 (Demory, et al, 2013) which can potentially be explained by the presence of high reflective clouds in the atmosphere. The cloud layer could possibly be silicon-based. This is the first planet to have a crude map of its cloud layer produced (Demory et al, 2013). Of the chosen transiting planets Kepler-7 b has a relatively small R_p/R_s ratio and has quite a large semi-major axis.

- **WASP-12 b** is a transiting planet which has been studied spectroscopically and has been found to potentially contain water (Mandell et al 2013), is abundant in CO and enhanced in methane (Madhusudhan et al 2010). It is an inflated planet (due to its very short distance from the star) and is also currently being consumed by its star (Lai et al, 2010).

- **WASP-17 b** has a very large size ratio and has a long transit duration which is great for our studies. It has been observed spectroscopically and has been found to potentially contain water (Mandell et al 2013). It is an unusual exoplanet in that it orbits its star in a retrograde orbit (Bayliss et al, 2010), which means that it is orbiting the opposite way of the rotation of the star.

- **WASP-19 b** has an extremely small semi-major axis and transits its star. Along with the short distance between it and the star it also has a short orbital period. It has been studied spectroscopically and has a broad absorption feature in its spectrum that probably originates from the presence of water (Mandell et al 2013).

- **WASP-80 b** is a transiting planet with one of the largest R_p/R_s ratios found so far (about 17%). It orbits a small cool star and a transmission spectrum has yet to be found (Mancini et al 2014).
- **WASP-103 b** is another transiting planet with a very short orbital period. Like WASP-12 b it resides close to its star and is thus highly irradiated, slightly inflated and possibly being consumed by the star (Gillon et al 2014).

- **XO-1 b** is a transiting planet that has been observed using infrared transmission spectroscopy and it has been found to contain water (Deming et al, 2013), methane, carbon dioxide and it could potentially also contain carbon monoxide (Tinetti et al, 2010). It orbits a relatively bright star at a large distance.

- **51 Peg b** orbits a very bright star and is not transiting in front of it. The planet has been studied spectroscopically from its dayside reflective properties and has been found to contain carbon monoxide and water (Brogi et al, 2013).

- **HD 73256 b** has the shortest semi-major axis of the chosen non transiting planets and has a very short orbital period (Udry et al, 2003).

- **HD 187123 b** orbits a solar twin (Butler et al, 1998) which is a quite bright star in the near infrared regime. Transits from this planet has not been found suggesting it is not particularly inflated (Castiliano, 2000), and thus it will be studied for its reflective properties.

- **τ Boo b** is a well studied non transiting exoplanet orbiting a very bright star. Its reflective side has been studied spectroscopically and there have been detections of both water (Lockwood et al, 2012) and carbon monoxide (Rodler, Lopez-Morales, Ribas, 2012).

- **υ And b** is the first discovered and innermost non-transiting exoplanet around the star υ Andromedae, although there are at least three more exoplanets in the system (Curiel et al 2010). The star is very bright at 3.0 magnitudes in the H-band.

### 3.4 Assumed radii for non-transiting planets

To be able to calculate the reflective contrast for the non-transiting planets their radius is needed, but most often it is unknown. In this project I choose to compare certain other known parameters to planets where the radius is known and proceed to use that radius for the reflective planet candidates as an approximation.

The first intuitive thing to consider is the mass of the planet and then compare it to our own Jupiter neighbour, however, there are great variations in the densities of gaseous exoplanets, especially for hot Jupiters (Figure 5) and there are discussions as to why. Tidal heating and enhanced opacity sources in the planet atmosphere are some of the possibilities discussed (Leconte et al. 2010) but also the incident flux (Weiss et al 2013). The incident flux is increased for planets residing close to a hot star. This would result in a constant flow of stellar flux which, if the planet has an atmosphere, increases the temperature of the gases contained in the atmosphere. This inflates the planet, increasing its radius but lowering its density drastically.

For this comparison the mass will still be used in case the chosen planets are not special cases of inflated giant planets. The other two parameters, the (surface) temperature of the host star and the distance between star and planet, are chosen since they could potentially prevent inflation of the planets. If the star is not very hot it may not inflate the planet as much as a hotter star would, and of course if the planet is further away there is a smaller risk that the planet will be inflated. See Table 2. for these planets and their parameters.
3.5 Observing time and wavelength region
The chosen wavelength bands, the J-, H- and K-band, in the near-infrared are known as infrared “windows” because the light passes through the atmosphere of the Earth (unlike longer infrared wavelengths) (see Appendix 1). The sky itself does not radiate much light in these wavelengths either, making them ideal for ground-based observations. Even so, it is not possible to get much observing time at one of the state-of-the-art telescopes today, and in this project I will consider a photon count similar to about 3 nights of photon collecting, unless otherwise stated (see below). If the planet has a short period more nights could be considered.

Refer to Table 3. for the information provided below.

- HD 189733 b has a quite short transit duration of just one hour and 49 minutes with a period of a little more than two days. Three nights of observation should be possible.

- HD 209458 b has a more reasonable transit duration of about 3 hours and should be possible to observe three times with a period of three and a half days.

- KELT-2 A b has a very long transit duration, more than five hours, but also a long period of more than 4 days. It is similar to the planet Kepler-7 b in transit duration and period, and to compare the two I will use three nights for KELT-2 A b and two for Kepler-7 b.
- Also WASP-12 b, WASP-17 b, WASP-80 b and XO-1 b will be observed three times. WASP-17b has a relatively long duration time.

- WASP-19 b and WASP-103 b could possibly be observed four times due to their very short orbital period, which could also be needed considering their relatively short transit durations.

The reflective planets all could be observed at least three times per month as they are not restricted by orbital phase and could potentially be observed during several hours. In this project five hours per night will be considered, so all the non-transiting planets will be considered over an observation time of five hours over three nights.

3.6 CRIRES Exposure Time Calculator

To obtain values for an individual planet’s potential signal, an online exposure time calculator from eso.org was used. More specifically the exposure time calculator for the CRIRES.

The CRIRES (CRyogenic high-resolution InfraRed Echelle Spectrograph) is as the name suggests a high-resolution infrared spectrograph on the VLT (Very Large Telescope) with a primary mirror 8.2 m across. This instrument works well for exoplanet observations.

To make sure all the data for the exoplanets were equivalent most of the input variables were kept constant. These parameters are such as the sky conditions, that is airmass and seeing for example, keeping adaptive optics on the same natural guide star and neglecting Doppler shift. The target magnitude was changed for each filter and the star was assumed to be a blackbody. The standard setting for the reference wavelength was used and changed to the appropriate wavelength for each bandpass filter.

The “requested wavelengths” are for the J-band 1.2407 microns, for the H-band 1.5555 microns and for the K-band 2.1376 microns. This means that the simulator will return values corresponding to these three wavelengths specifically. The proper simulations would of course contain areas of the spectrum where Earth has a large contribution but for the collection of the signal data these three wavelengths were chosen because they are located where the telluric absorption is low to acquire an as unbiased signal as possible. For a look on the telluric transmission lines, and where in that spectrum the chosen wavelengths reside, the reader is referred to Appendix 1

Each planet was observed for 30 seconds and the signal per second in each wavelength was noted. The shot noise was calculated as the square root of the signal and tabulated (Table 1).

Some transiting planets will be analyzed reflectively as well to find out if it is possible to find a contrast times signal to noise ratio that equal that of the transit.
4 Results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transiting planets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD 189733 b</td>
<td>1.14</td>
<td>0.16</td>
<td>0.76</td>
<td>0.03</td>
<td>5.6</td>
<td>206 – 267 – 154</td>
</tr>
<tr>
<td>HD 209458 b</td>
<td>1.36</td>
<td>0.12</td>
<td>1.16</td>
<td>0.05</td>
<td>6.4</td>
<td>164 – 186 – 106</td>
</tr>
<tr>
<td>KELT-2 A b</td>
<td>1.29</td>
<td>0.07</td>
<td>1.83</td>
<td>0.06</td>
<td>7.4</td>
<td>99 – 117 – 67</td>
</tr>
<tr>
<td>Kepler-7 b</td>
<td>1.48</td>
<td>0.09</td>
<td>1.84</td>
<td>0.06</td>
<td>11.6</td>
<td>15 – 17 – 10</td>
</tr>
<tr>
<td>WASP-12 b</td>
<td>1.79</td>
<td>0.11</td>
<td>1.63</td>
<td>0.02</td>
<td>10.2</td>
<td>27 – 32 – 18</td>
</tr>
<tr>
<td>WASP-17 b</td>
<td>1.93</td>
<td>0.17</td>
<td>1.20</td>
<td>0.05</td>
<td>10.5</td>
<td>27 – 31 – 19</td>
</tr>
<tr>
<td>WASP-19 b</td>
<td>1.39</td>
<td>0.15</td>
<td>0.99</td>
<td>0.02</td>
<td>10.6</td>
<td>23 – 27 – 15</td>
</tr>
<tr>
<td>WASP-80 b</td>
<td>0.95</td>
<td>0.17</td>
<td>0.57</td>
<td>0.03</td>
<td>8.5</td>
<td>49 – 70 – 40</td>
</tr>
<tr>
<td>WASP-103 b</td>
<td>1.53</td>
<td>0.11</td>
<td>1.44</td>
<td>0.02</td>
<td>10.9</td>
<td>21 – 23 – 13</td>
</tr>
<tr>
<td>XO-1 b</td>
<td>1.21</td>
<td>0.13</td>
<td>0.93</td>
<td>0.05</td>
<td>9.6</td>
<td>36 – 43 – 24</td>
</tr>
<tr>
<td><strong>Non-transiting planets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51 Peg b</td>
<td>~1.39</td>
<td>0.14</td>
<td>1.03</td>
<td>0.05</td>
<td>4.2</td>
<td>394 - 511 - 355</td>
</tr>
<tr>
<td>HD 73256 b</td>
<td>~1.34</td>
<td>0.12</td>
<td>1.22</td>
<td>0.04</td>
<td>6.4</td>
<td>157 – 185 – 106</td>
</tr>
<tr>
<td>HD 187123 b</td>
<td>~1.24</td>
<td>0.11</td>
<td>1.14</td>
<td>0.04</td>
<td>6.4</td>
<td>164 – 186 – 106</td>
</tr>
<tr>
<td>τ Boo b</td>
<td>~1.29</td>
<td>0.09</td>
<td>1.42</td>
<td>0.05</td>
<td>3.5</td>
<td>654 – 707 – 404</td>
</tr>
<tr>
<td>υ And b</td>
<td>~1.65</td>
<td>0.12</td>
<td>1.38</td>
<td>0.06</td>
<td>3</td>
<td>786 – 890 – 509</td>
</tr>
<tr>
<td><strong>Reference planets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WASP-13 b</td>
<td>1.39</td>
<td>0.10</td>
<td>1.14</td>
<td>0.05</td>
<td>9.2</td>
<td>-</td>
</tr>
<tr>
<td>TrES-3 b</td>
<td>1.34</td>
<td>0.17</td>
<td>1.83</td>
<td>0.02</td>
<td>10.7</td>
<td>-</td>
</tr>
<tr>
<td>HAT-P-1 b</td>
<td>1.24</td>
<td>0.11</td>
<td>1.51</td>
<td>0.06</td>
<td>8.9</td>
<td>-</td>
</tr>
<tr>
<td>HAT-P-16 b</td>
<td>1.29</td>
<td>0.11</td>
<td>1.24</td>
<td>0.04</td>
<td>9.6</td>
<td>-</td>
</tr>
<tr>
<td>WASP-54 b</td>
<td>1.65</td>
<td>0.09</td>
<td>0.81</td>
<td>0.05</td>
<td>9.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Planet parameters with assumed radii for the non-transiting planets as well as the signal to noise in each of the considered wavelength bands.

The stellar brightness in the H-band is shown in Table 1 for an indication of the brightness of the star in NIR. General information about the chosen planet candidates are shown, with a separation between first the transiting planets, next the non-transiting planets and lastly the planets used for assuming the radii of the non-transiting ones.

<table>
<thead>
<tr>
<th>Planet</th>
<th>Stellar T [K]</th>
<th>Planet mass [M$_J$]</th>
<th>a [au]</th>
</tr>
</thead>
<tbody>
<tr>
<td>51 Peg b</td>
<td>5790</td>
<td>0.46</td>
<td>0.05</td>
</tr>
<tr>
<td>WASP-13 b</td>
<td>5830</td>
<td>0.48</td>
<td>0.06</td>
</tr>
<tr>
<td>HD 73256 b</td>
<td>5640</td>
<td>1.87</td>
<td>0.04</td>
</tr>
<tr>
<td>TrES-3 b</td>
<td>5650</td>
<td>1.91</td>
<td>0.05</td>
</tr>
<tr>
<td>HD 187123 b</td>
<td>5820</td>
<td>0.51</td>
<td>0.04</td>
</tr>
<tr>
<td>HAT-P-1 b</td>
<td>5980</td>
<td>0.53</td>
<td>0.05</td>
</tr>
<tr>
<td>τ Boo b</td>
<td>6390</td>
<td>5.95</td>
<td>0.05</td>
</tr>
<tr>
<td>HAT-P-16 b</td>
<td>6160</td>
<td>4.20</td>
<td>0.04</td>
</tr>
<tr>
<td>υ And b</td>
<td>6210</td>
<td>0.67</td>
<td>0.06</td>
</tr>
<tr>
<td>WASP-54 b</td>
<td>6100</td>
<td>0.63</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2. Planets with similar parameters as the non-transiting planets where the radii are known.

The parameters that were compared between the planets chosen for radii assumption and the non-transiting ones are shown, keeping the pairs of planets that were compared with each other next to each other in the table.
Here a value called X is introduced, which is a relative value of how easy a particular planetary system could be observed. The value is calculated through $X = C \times \frac{S}{N} \times \sqrt{N_{\text{obs}}}$ where C is the contrast of the system (calculated with (3) and (4)) and $N_{\text{obs}}$ is the number of observations performed. As there are two different contrasts depending on if we view the system through a transit or just reflected light the transiting planets will have two different values of X, displayed as diamonds and triangles respectively. The non-transiting ones will only have reflective values of X and are shown in the right hand side in the figure. A high value of X suggests that if an observation would be made the system would give a better and clearer result than a system with a lower value.

HD 189733 b and HD 209458 b are planets that stand out with the value of X an order of magnitude higher than the rest. The most reflective transiting planets acquire a higher reflective X than their corresponding value for their transit. These are the planets WASP-12b, WASP-19b and WASP-103b. Out of the non-transiting planets τ Boo b and ν And b have the highest values of X, close to that of the most high value transiting planets.

<table>
<thead>
<tr>
<th>Planet</th>
<th>Period [days]</th>
<th>Transit duration [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transiting planets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD 189733 b</td>
<td>2.22</td>
<td>1.82</td>
</tr>
<tr>
<td>HD 209458 b</td>
<td>3.52</td>
<td>3.08</td>
</tr>
<tr>
<td>KELT-2 A b</td>
<td>4.11</td>
<td>5.17</td>
</tr>
<tr>
<td>Kepler-7 b</td>
<td>4.89</td>
<td>5.19</td>
</tr>
<tr>
<td>WASP-12 b</td>
<td>1.09</td>
<td>2.93</td>
</tr>
<tr>
<td>WASP-17 b</td>
<td>3.74</td>
<td>4.42</td>
</tr>
<tr>
<td>WASP-19 b</td>
<td>0.79</td>
<td>1.57</td>
</tr>
<tr>
<td>WASP-80 b</td>
<td>3.07</td>
<td>2.11</td>
</tr>
<tr>
<td>WASP-103 b</td>
<td>0.93</td>
<td>2.59</td>
</tr>
<tr>
<td>XO-1 b</td>
<td>3.94</td>
<td>2.94</td>
</tr>
<tr>
<td>Non-transiting planets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51 Peg b</td>
<td>4.23</td>
<td>-</td>
</tr>
<tr>
<td>HD 73256 b</td>
<td>2.55</td>
<td>-</td>
</tr>
<tr>
<td>HD 187123 b</td>
<td>3.10</td>
<td>-</td>
</tr>
<tr>
<td>τ Boo b</td>
<td>3.31</td>
<td>-</td>
</tr>
<tr>
<td>τ And b</td>
<td>4.62</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Planet’s orbital periods and transit durations.

Figure 6. Value X for all simulations of all planets.
Images of the attempted reconstruction of the planet spectrum as a result of the simulations (including the most optimal regularisation parameter) for each wavelength range are shown in Appendix 2. Only the simulations that gave any kind of visible result of absorption is shown in Appendix 2. In the following images are different simulations with varying results as an attempt to show what simulations were deemed good enough for the planet to be considered detectable. The name of the planet, wavelength band and regularization parameter are shown. The white represents the atmosphere of the Earth, the dark red is the input exoplanet atmosphere and the lighter red line is the reproduced spectrum.

![Graph](image)

Figure 7. Comparison between different levels of results in the H-band. Red – satisfactory, magenta – acceptable, blue – poor.

The satisfactory results (red line, the result of HD 189733b, shown as an example in Figure 7.) are the ones that are thought to be possible to observe for real using this method. The reconstructed spectrum, the red line, is straight in all places that do not have any absorption bands, and clearly dips down in places where there are absorption bands.

The acceptable results (magenta line, the result of XO-1b, shown as an example in Figure 7.) are good enough for absorption bands to be seen visibly, however the reconstructed spectrum is wobbly and drawing conclusions without the input spectrum as a reference could result in false assumptions. The exoplanets with acceptable results are still not assumed to be possible to observe unless the S/N is increased through for example more observing time.

The poor results (the blue line, the result of WASP-12b, shown as an example in Figure 7.) do not show any absorption in the reconstructed spectrum and would not be possible to observe.

5 Discussion

The exoplanets that in these simulations may be observable (consider Figure 6) will during a proper observation probably be less likely to show a promising result. During an observation additional noise will be added from the instrument and other sources, turning absorption lines that in the simulations might be detectable into something that probably will be discarded as noise.

As we can see (Appendix 2), the absorption lines in the input exoplanet spectrum are few (water absorption only) and often overlapping with the absorption lines of Earth. In the J-band, for example, there is no absorption except in the area from ~ 1350 nm where the interference from the atmosphere of the Earth is great. Because of this any potential absorption in this wavelength region will be difficult to resolve. Also in the H-band there is an overlap around ~1780nm
making absorption in the region hard to determine. Only in the K-band does this simulated hot Jupiter provide us with information that can be distinguished from the atmosphere of the Earth. Nevertheless results from all three wavelength bands will be considered as they could still be of interest when observing exoplanets with different molecular contents to the simulated hot Jupiter.

Out of the exoplanets chosen for these simulations there are three planets that suggest the possibility of finding molecular absorption in their atmospheres using this inverse method of spectrum recovery. These are the well-studied planets HD189733b and HD209458b as well as the large planet WASP-80b. Depending on the amount of added noise both HD209458b and WASP-80b may however give uncertain results in the K-band, which seems to be the most difficult wavelength region of the three examined. Out of the ten exoplanets simulated only the abovementioned three showed any absorption in the K-band, compared to six of the planets in the J-band, and seven in the H-band (see Appendix 2). This is due to the fact that most planets had very low signal/s in the K-region specifically. The highest signal/s was exclusively in the H-band.

When comparing the properties of the before mentioned planets to the rest there is one planet that stands out, namely KELT-2Ab. All the planets with poor results have a low S/N except from KELT-2Ab which has one of the highest values. WASP-80b, has a lower amount of S/N per exposure, a dimmer star, and a significantly smaller amount of exposures but is still considered observable (Table 1, Figure 6). A major difference between the two planets is that WASP-80b has the highest size ratio between itself and the host star of the exoplanets examined, while KELT-2Ab has the lowest. This suggests that the R_p/R_s, ratio, and thus the contrast, is an important property to consider, while the amount of exposures is not, to the same degree. This makes sense as the signal to noise is proportional to the contrast as well as the square root of the number of observations.

KELT-2Ab can also be compared to HD209458b as they have quite similar properties but one of them shows potential and the other does not. The only clear difference between them is that HD209458b has a slightly larger size ratio and fewer exposures even if the difference is not as large as in the case with WASP-80b. Again, the planet with a higher contrast and a smaller amount of exposures is the one deemed observable.

Another interesting comparison to make is that of WASP-80b and WASP-19b. They both have a high size ratio and thus a high contrast for their transit and a small amount of available exposures. The biggest difference between them is the brightness of their star, and thus their S/N (Table 1). Although the difference is not very large it seems to be enough to leave WASP-19b as no candidate in either wavelength band while WASP-80b could possibly provide a satisfactory result in all.

Also worth mentioning is the comparison between KELT-2A b and Kepler-7b who have very similar parameters (Table 1, Table 3). For KELT-2A b photons were collected for three days, while Kepler-7b only had two to see the difference this would make. As we can see in Figure 6 the value of X for KELT-2A b is higher possibly as a result of this. One must also consider that KELT-2A b has a brighter star in the near infra red wavelength regions in which the simulations were performed.

6 Conclusions

As the program that was used attempted to find the optimal regularization by considering the least square fit between the solution and the input exoplanetary spectrum some conclusions could be drawn about the regularization parameter. If the best fit is very large, above Λ ≈ 10 000, the result has been smoothened to the point where visual analysis would fail to acknowledge any absorption bands. In general, the optimal regularization is a regularization as low as possible and one higher than a couple of thousands does not improve the chances of finding any absorption lines. If an exoplanet has a reasonable high S/N (≥ 100) the parameter Λ should be up to about 5000 at most, or there is a risk of drawing false conclusions.

When considering which near infrared wavelength range is optimal for these kinds of simulations, the lack of results in the K-band suggests this wavelength range is not ideal. It would seem the stars we can expect around exoplanets release a low amount of photons in the K-band. The J-band is also not preferred for ground-based observations because of the relatively high amount of disturbance from the atmosphere of the Earth. Considering this the H-band is the wavelength
range to go for, although when looking for specific absorption bands doing so in the other bands would still provide a result worth considering.

A large size ratio seems to be necessary for reliable observations, but it is not possible from this project to find the necessary ratio specifically, as there are many other factors that weigh in on whether the planet spectrum can be reconstructed or not.

Looking at the relative value that is contrast times the signal to noise ratio times time of observation in seen in Figure 6 it becomes clear that the three planets HD209458b, HD189733b and WASP-80b have the highest values in all three wavelength bands. It would appear that the lowest value of a possible successful observation is at about X = 0.8 (J-band value for WASP-80b), while a more reliant observation would have a value X ≥ 1.6 (J-band value for HD209458b).

This then leads to the conclusion that recovering the planetary spectrum from the reflective effects of an exoplanet using this method could be possible for some of the planets considered. The relative reflective contrast times S/N and number of observations, the value X, in Figure 6, for the transiting planets show that the highest value is for HD189733b in the H-band at about 0.78 after three observations of five hours. This is at the lower limit and could potentially give some result, however with the additional noise added from a proper observation the result would not be trustworthy. Also seen in Figure 6, for the non-transiting planets, there are two planets with values ≥ 0.8 in at least two bands, Tau Boo B and Upsilon And b. A reconstructed spectrum from these two planets is a possibility; though results might be poor in the K-band. It must also be considered that the non-transiting planets contrast is uncertain from assuming their radii and since the contrast seems to be a quite important aspect for a successful simulation these results are more doubtful.

To directly consider the goals of the project:

- The optimal wavelength region for characterizing the hot Jupiter atmospheres using this inverse method for spectrum reconstruction is the H-region due to a stronger signal/s. The K-band also works but low signal/s can be expected here. The J-band has too much absorption from the atmosphere of the Earth to get a reliable result from ground based observations.

- The necessary size ratio cannot be determined; however it is clear a large ratio significantly increases the possibility of reconstructing the spectrum of the exoplanet in question as the contrast between planet and star is increased.

- To reconstruct the spectrum of non-transiting exoplanets using the same method does seem possible for at least two non-transiting planets of the ones considered, after three five hour exposures. It is however not certain as the radii, and thus the contrast, is approximated for these planets.

- The method could in total possibly be applicable on five of the considered exoplanets, namely HD 209458b, HD 189733b and WASP-80 b from transit data, and τ Boo b and υ And b from reflective data. This is concluded from that the planets have values of X ≥ 0.8 in most wavelength regions, with HD 209458b and HD 189733b having values above the more reliant value of X ≥ 1.6.
7 References

Aronson, E., Piskunov, N., Waldén, P., in prep


8 Appendix 1

Atmospheric transmission in the near infrared (J-band).

Atmospheric transmission in the near infrared (H-band).
Atmospheric transmission in the near infrared (K-band).
9 Appendix 2
Here are some of the figures produced from the simulations presented, only the exoplanets with a visible result are shown here. There is one figure per planet and wavelength band and all figures have the most optimal regularization, $\Lambda$. The white represents the atmosphere of the Earth, the dark red is the input exoplanet atmosphere and the lighter red line is the reproduced spectrum.

HD 189733b:

J-band, $\Lambda = 380$

H-band, $\Lambda = 840$
K-band, $\Lambda = 5590$

**HD 209458b:**

J-band, $\Lambda = 680$
H-band, $\Lambda = 4700$

K-band, $\Lambda = 10000$

WASP-17b:
J-band, $\Lambda = 10\ 000$

H-band, $\Lambda = 10\ 000$
K-band, $\Lambda = 100\ 000$

**WASP-80b:**

J-band, $\Lambda = 1000$
H-band, $\Lambda = 1000$

K-band, $\Lambda = 10\,000$

XO-1b:
J-band, $\Lambda = 5000$

H-band, $\Lambda = 10\ 000$
K-band, $\Lambda = 100\,000$