Exoplanet Reflections: the light from 51 Peg b

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Abstract

The direct detection of reflected light from an exoplanet is, even in the most favourable cases, a herculean task, close to the detection limit of current observing facilities. To surpass this problem, we made used of a technique (Martins et al. 2013, MNRAS, 436, 1215) that uses the power of the Cross Correlation Function to recover the minute reflected signal from 51 Pegasi b with a $3\sigma$ significance. This allowed us to conclude that this prototypical hot-Jupiter is most likely a highly inflated planet with a high albedo. These results were presented in the OHP2015: Twenty years of giant exoplanets conference and published in Martins et al. 2015, A&A, 576, A134.

1 Introduction

Twenty years have passed since the pioneering discovery of the prototypical Hot-Jupiter 51 Peg b (Mayor & Queloz 1995), the first planet to be discovered around a solar-type star other than our Sun. Now over two thousand exoplanets have been confirmed (see http://exoplanet.eu, Schneider et al. 2011), some of them in systems with a level of complexity that challenges our own (e.g. HD10180 with 7 planets, Lovis et al. 2011). An interesting result in this line of research is the correlation between stellar metallicity and the presence of giant planets: stars hosting the giant planets are systematically more metallic than a normal sample of stars (Bond et al. 2008; Sousa et al. 2011). Curiously, this correlation was found not to hold for low-mass rocky planets (Sousa et al. 2011), which are now believed to be abundant and outnumber the higher-mass population characterized up to now (Mayor et al. 2011).

A rarity at first, exoplanets have been found to be ubiquitous around solar-type stars (Howard et al. 2010) and extremely diverse in terms of characteristics (Schneider et al. 2011). Their characterization is one of the greatest challenges in exoplanet science, to the point that it is now possible to determine the bulk composition and planetary structure of several planets, some of which seem to be mostly rocky/iron in nature (e.g. Batalha et al. 2011; Léger et al. 2009). The boundaries of this line of research are being pushed towards the characterization of planetary atmospheres, for which several techniques have been developed.

Transmission spectroscopy (e.g. Charbonneau et al. 2002; Knutson et al. 2014) measures the wavelength dependence of the radius of a planet during transits to infer the atmosphere’s composition. Occultation photometry and spectroscopy techniques measure the wavelength dependency of the depth of the occultation of a transiting planet to infer the planetary thermal (e.g. Snellen et al. 2010) and reflected (e.g. Rodler et al. 2013) signals. The measurement of the flux variation of a planet along its orbit allows to reconstruct the planetary phase variation along its orbit and recover its reflected signal (e.g. Knutson et al. 2009).

Another approach in the study of planetary atmospheres is the measurement of their albedo as it permits to constrain current atmosphere models (Cowan & Agol 2011; Demory 2014) and infer their composition (e.g. the presence of clouds in HD 189733 b, see Barstow et al. 2014). Unfortunately, the measurement of the optical spectroscopic reflected signal from exoplanets has been elusive for many years. The main challenge to this is the low planet-to-star flux ratio in the optical, which is in the most favourable scenarios of the order of $10^{-4}$, at the detection limit of current observing facilities. Consequently, the initial attempts at capturing the reflected signal of
an exoplanet in the optical (e.g. [Collier Cameron et al. 1999] [Charbonneau et al. 1999]) were inconclusive, although of great scientific value as they permitted to place upper limits on the planetary albedo of the targets. More recently, using a technique that makes use of the Cross Correlation Function of high resolution spectra with a binary mask, Martins et al. (2015) were able to detect with a ≳ 3 − σ confidence the reflected signal of 51 Pegasi b, 20 years after its discovery. This detection shows that 51 Pegasi b is most likely a highly inflated Hot-Jupiter with a high albedo. It also permitted to break the degeneracy between the planetary mass its inclination.

In this article we will summarize the method and results presented in the OHP2015: Twenty years of giant exoplanets conference and published in Martins et al. (2013, 2015). We describe the method in Section 2. The results are presented and discussed in Section 3 and we conclude in Section 4.

2 Detecting the reflected signal from an exoplanet

The detection of optical reflected light from an exoplanet is a difficult technical challenge at best due to the low planet-to-star flux ratio. This ratio can be estimated from

\[
\frac{F_{\text{Planet}}}{F_{\text{Star}}} = A_g(\alpha) \left( \frac{R_{\text{Planet}}}{a} \right)^2
\]

where \(A_g\) represents the planetary geometrical albedo (several albedo definitions exist (e.g. Marley et al. 1999; Collier Cameron et al. 2002; Seager 2010), but we will here only consider the geometric albedo \(A_g\), defined as the ratio of a planet’s flux measured at opposition (\(\alpha = 0\)) by the flux of a Lambertian disk at the same distance and with the same radius as the planet), \(g(\alpha)\) the phase function, \(R_{\text{Planet}}\) the planetary radius and \(a\) the orbital semi-amplitude (see Seager 2010 for more details). Thus, even in the best case scenarios, the planet-to-star flux ratio will be of the order of \(10^{-4}\), requiring a final signal-to-noise above \(10^4\), way beyond the capability of current observing facilities.

To surpass this problem we propose the technique portrayed in figure 1 and described in detail in Martins et al. (2013). This technique makes use of the Cross Correlation Function (hereafter CCF) of high resolution spectra with a binary mask (as described in e.g. Baranne et al. 1996) to enhance the minute planetary signal and make it surface above the noise level. In a good approach the CCF stacks together all identified from the mask identified in the spectra into a single average spectral line, with a S/N increase proportional to the number of lines. Typically a few thousands of lines can be identified in high resolution spectra of solar-type stars, boosting the S/N by 60-70 times.

The reflected planetary signal is basically a copy of the stellar one, but scaled down by a factor given by equation 1. Thus, two superimposed signals are expected on the CCF - one for the star and one for the planet - but shifted in radial velocity. A correct removal of the stellar signal is critical and towards that project we use a stellar template constructed from the observations themselves by stacking them together after correction from the stellar radial velocity. This will increase the S/N of the star, but since the planetary signal will show up at different radial velocities, it will be diluted amidst the noise. This template will then be used to normalise every star+planet CCF in order to remove the stellar signal. Please note that this correction is not perfect, in particular close to the centre of the stellar CCF where noisy artefacts are left. Thus, we discard observations where the planetary and stellar signals are spectroscopically blended (or close to) in the radial velocity domain. The remaining normalised CCFs are co-added, after correction of the expected planet radial velocity to further enhance the planetary signal, yielding an increase in the S/N proportional to the square root of used spectra. A detailed explanation of the process can be found on Martins et al. (2013, 2015).

3 Results and Discussion

Our choice of target fell over the prototypical hot-Jupiter 51 Pegasi b, as we required a planet with an expected large radius in a close in orbit of a bright star. Our data was collected over 7 nights with the HARPS spectrograph at ESO’s 3.6-m Telescope at La Silla-Paranal Observatory, as part of ESO programme 091.C-0271. We collected a

Figure 1: Schema of method to detect the optical reflected signature from exoplanets as described in Martins et al. (2013).
total of 91 spectra with a S/N on the 50th order (∼5560 Å) that varies between 122 and 388. The spectra cover the wavelengths range from roughly 3781 Å to 6910 Å.

Applying the aforementioned technique to the collected data, we were able to recover the planetary signal with a $\geq 3 - \sigma$ significance. Table 1 shows the fitted Gaussian parameters of both the stellar and planetary CCFs (from Martins et al. 2015). For the star signal, we present the median value of the amplitude and FWHM of its CCF for all observations. For the planet CCF we present the values of the amplitude and FWHM of its Gaussian fit, as well its detection significance. Please note that in both cases, the level of the CCF continuum flux has been set to one.

The recovered signal parameters suggest that 51 Pegasi b is most likely an inflated hot-Jupiter with a high albedo, i.e., assuming a geometric albedo of $0.5 R_{\text{Planet}} \approx 1.9 R_{\text{Jup}}$ (note that from Equation 1 we can see that the albedo and planetary radius will be degenerated). Although these values might seem high, planets with similar values for the radii and albedo have already been detected (e.g. the case of Kepler-7b [Muñoz & Isaak 2015]).

Figure 2 shows the recovered signal, as well as the detection significance as a function of the planetary orbital semi-amplitude $k_{\text{planet}}$ (right panel). On figure 3 it can be seen that, as expected, the detection significance increases as $k_{\text{planet}}$ gets closer to the real value for the orbit as in this case the planetary signals on each individual CCF are aligned in the radial velocity domain. When an incorrect $k_{\text{planet}}$ is used to compute the radial velocity of the planet on each CCF, the planetary signals on each individual CCF are co-added misaligned, diluting the signal amidst the noise and decreasing the detection significance. The best fit semi-amplitude of the orbital motion of the planet is $k_{\text{planet}} = 132^{+14}_{-10}$ km s$^{-1}$, yielding a real mass for 51 Peg b of $0.46^{+0.01}_{-0.00}$ $M_{\text{Jup}}$ and an inclination of $80^{+10}_{-6}$ degrees. More details can be found in [Martins et al. 2015].

Although these results show that the detection of the optical reflected signal from exoplanets is already possible with current telescopes and instrumentation, the technique presented in [Martins et al. 2013, 2015] will be most useful with next generation of observing facilities. The next generation of high-resolution spectrographs to be mounted in the 8-m class facilities (e.g. ESPRESSO@VLT) and on the E-ELT (e.g. HIRES) will permit the direct detection of reflected light from increasingly smaller planets with larger period orbits or a close-in planets on a much higher signal-to-noise domain. figures 4 and 5 show a simulation of the 51 Peg b of $0.46^{+0.01}_{-0.00}$ $M_{\text{Jup}}$ and an inclination of $80^{+10}_{-6}$ degrees.

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4 Conclusions

The detection of optical reflected light is even in the best case scenario a difficult task. Applying a technique that makes use of the Cross Correlation Function to high resolution HARPS spectra of 51 Pegasi b the results presented in [Martins et al. 2015] suggest that we were able to successfully detect the reflected signature of 51 Pegasi on its planetary companion. The signal was detected at a planetary orbital semi-amplitude of $k_{\text{planet}} = 132^{+14}_{-10}$ km s$^{-1}$, from which a real mass for 51 Peg b of $0.46^{+0.01}_{-0.00}$ $M_{\text{Jup}}$ and an inclination of $80^{+10}_{-6}$ degrees can be inferred. The results also suggest that 51 Pegasi b is most likely an inflated hot-Jupiter with a high albedo.

Although only a 3-$\sigma$ detection significance was achieved, the results show promising as proof of concept, showing that the technique presented in [Martins et al. 2013] can be used successfully to recover the optical spectral

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Star</th>
<th>Planet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>$0.48 \pm 0.2$</td>
<td>$6.0 \pm 0.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>Significance $[\sigma_{\text{noise}}]$</td>
<td>$3.7 \pm 0.2$</td>
<td>$-$</td>
</tr>
<tr>
<td>FWHM [km s$^{-1}$]</td>
<td>$7.43 \pm 0.2$</td>
<td>$22.6 \pm 3.6$</td>
</tr>
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Table 1: Comparison of the stellar and planet CCF parameters.
signature of a star reflected on its companion planet. Furthermore, simulations show an extremely promising future for this technique when applied to next generation of observing facilities (e.g. ESPRESSO@VLT or ESO’s E-ELT). These should allow to not only probe into smaller planets at increased distances from their host stars, but also characterize in more detail the atmosphere close-in hot-Jupiter planets.

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Figure 2: Detected planetary signal for maximum detection significance and fitted Gaussian curve.
Figure 3: Evolution of the detection significance of the signal with the orbital planetary semi-amplitude ($k_2$).
Figure 4: Simulated E-ELT observations of an inflated hot-Jupiter planet (13 $R_{Jupiter}$) on a two day orbit (from Martins et al. 2013) - CCFs of the E-ELT observations after removal of the star, where the signal of the planet is clearly evident on each CCF as a dark path, as well as the phase variation (the central white stripe corresponds to the position of the star in the radial velocity domain).
Figure 5: Simulated E-ELT observations of an inflated hot-Jupiter planet (13 $R_{\text{Jupiter}}$) on a two day orbit (from Martins et al. 2013): Top: Same as figure 4, but centred on the planet radial velocity for each observation; Bottom: recovered planet CCF by stacking the CCFs in the top panel.