# SPECTRAL RECONSTRUCTION METHOD FOR EXOPLANETS

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A method to reconstruct spectra of exoplanets is presented. The image and objective spectrum of a star-planet system are simultaneously observed. Starlight is destructively interfered to detect faint planetary signal. By referring to the image of the star-planet system the pseudo objective spectra are computationally synthesized by using the stellar spectrum. Thus the synthesized pseudospectra consist of only the stellar spectrum. The difference between the pseudo and the observed spectra reveals the features of the planetary spectrum.

## Introduction

Spectroscopic observations of exoplanets are needed to characterize them. However, it is not an easy task to image directly exoplanets. Extremely high intensity ratio of a star to its planet, say more than $10^6$ in IR region, hampers their direct detection. A method to mitigate this high contrast problem is the nulling technique, where bright starlight is destructively interfered and then faint exoplanets located near their parent star become detectable [1]. Unfortunately it is very difficult to achieve perfect nulling of starlight in practice. The images of exoplanets are embedded in speckle noise. Therefore, spectroscopy for exoplanets will be more difficult than imaging. Such a situation is similar to speckle spectroscopy [2].

When the planetary light is considered to be the reflected and scattered light of its parent star, then the planetary light is expected to be partially poralized. In such a case a polarization differential method is useful for retrieving the objective spectrum [3,4,5]. However, the degree of polarization depends on the phase angle of the planet, its atmosphere, observational wavelength, and so on [6,7]. In thermal IR region the polarization differential method would not be very effective.

In this paper we demonstrate a method to obtain the spectrum of an exoplanet without relying on the polarization nature of planetary light. The planetary light is expected to exhibit absorption and/or emission features in its spectrum because of the planetary atmosphere. Therefore, these spectroscopic features are different from the stellar spectrum. Our method utilizes the spectral difference to extract the planetary spectrum. We show the usefulness of our method through an optical simulation experiment. The spectral reconstruction result is also shown.

## Method

Light from an exoplanet is so faint that high or medium resolution spectroscopy would not be effective for exoplanets. Objective spectroscopy is a low-resolution spectroscopic method and it would be useful for exoplanet characterization.

The objective spectrum is obtained without a slit and formed around the location of the image. Therefore, the objective spectrum of an exoplanet is contaminated with noisy objective spectra of its parent star even after starlight suppression with a nulling coronagraphic scheme [8,9,10,11,12].

In our method it is supposed to employ an imaging spectroscopic setup. The image and objective spectra are simultaneously detected after passing through a nulling stellar coronagraph. We synthesize the pseudo objective spectra by using the detected image data and the stellar spectrum that can be obtained by observing the star itself or a reference star with the same spectral type as the target star. These pseudospectra consist of only the stellar spectrum. Then, the difference between the observed and the pseudo spectra reveals the spectral features of the exoplanet.

The critical matter in our method is how to synthesize the pseudospectra. In the experimental setup the image and the objective spectra of a star-planet system are simultaneously obtained. When the optical system can be assumed to be a space invariant system, the pseudospectra would be synthesized by convolving the image with the stellar spectrum. In nulling stellar coronagraph with a phase mask, however, the spectral response can become space variant. Then, a simple convolution technique cannot be applied to synthesize the pseudospectra. It is necessary to use a method that can handle space-variant system. We apply the CLEAN algorithm [13,14], which has been developed in radio astronomy, to synthesize the pseudospectra.

In the CLEAN algorithm the brightness distribution of the image is broken into point-source responses. Our procedure to synthesize pseudospectra based on the CLEAN algorithm is the followings:

i) Find the highest brightness point on the image (I-image), which is the observed image at the first iteration, and subtract the reference image (R-image) of the star centered on that position. Here, the reference image is chosen according to the peak position relative to the phase mask of the nulling coronagraph. The peak intensity of the subtracted R-image is equal to $\gamma$ (< 1) times the corresponding I-image intensity, where $\gamma$ is called loop gain in the CLEAN algorithm.

$$I^{ij} = I^{ij} - \gamma \cdot R^{(i+shift\_i)(j+shift\_j)}, \qquad (1)$$

where $I^{ij}$ is the intensity of the image at the *(i,j)* pixel, $R^{(i+shift\_i)(j+shift\_j)}$ the intensity of the reference image at the *(i+shift_i, j+shift_j)* pixel. The *shift_i* and *shift_j* represent the displacement values in pixels between the locations of the searched maximum of the image and the maximum of the reference one. It should be noted that shifts have to be calculated at every subtraction, because the reference image at every subtraction has to be centered on the maximum of the image.

ii) Return to i) and repeat the procedure iteratively until all significant structure has been removed from the I-image.

iii) Add the corresponding reference objective spectra to the calculated spectra to synthesize the pseudo objective spectra;

$$PS^{ij} = \sum_n \gamma_n \cdot RS^{(i+shift\_i_n)(j+shift\_j_n)}, \qquad (2)$$

where $RS^{(i+shift\_i_n)(j+shift\_j_n)}$ is the intensity of the reference spectrum at the $(i+shift\_i_n, j+shift\_j_n)$ pixel, and $\gamma_n$ is the same coefficient used at the *n*th image subtraction (Eq. (1)) and usually taken as 0.3-0.5. For the calculation of the pseudospectra we choose the reference image and spectrum in accordance with the location of the found maximum in the observed image. Thus we can accommodate to space variant system.

## Experiment

We conducted an optical simulation experiment to show the effectiveness of our method. The experimental setup is shown in Fig. 1. Xe lamps are used for star and planet models. An artificial absorption line is introduced for planetary light by using an interference filter ($\lambda$=633 nm, $\Delta\lambda$=10 nm) as a reflection mirror. The light from the star-planet system is led to a nulling stellar coronagraph.

A four-quadrant polarization mask (FQPoM) [10] is employed to cause the destructive interference for starlight incident on the center of the FQPoM that is made up of ferroelectric liquid-crystal. Each quadrant works as a half-wave plate and its optic axis is shown in the inset of Fig. 1. The incident light to the FQPoM is first made linearly polarized at $\theta$=0° with a linear polarizer. The light after passing through each quadrant of the FQPoM are linearly polarized at $\theta$=45° for the first and third quadrants and at $\theta$=-45° for the second and fourth ones. When the light pass through the second polarizer ($\theta$=90°) the phase difference of the beams between the adjacent mask zones becomes $\pi$ and destructive interference occurs. Thus, the FQPoM coronagraph works for achromatic light because the nulling is based on polarization interference. The achromatic performance is needed to achieve spectroscopy in a wide wavelength region. The diameter of the Lyot stop is set to 80% of that of the entrance-pupil image. After passing through the nulling coronagraph the light is led to imaging and spectroscopic channels. A blazed holographic grating (600 *l*/mm) is used to form the image in the 0th order and the objective spectra in the 1st order. The image and objective spectra are simultaneously detected with two EM(electron-multiplier)-CCD cameras. The spectral region is firstly limited by a long-pass filter ($\lambda$>540 nm) and a short-pass filter ($\lambda$<800 nm) as shown in Fig. 1 and then effectively restricted within the lateral size of the CCD detector.

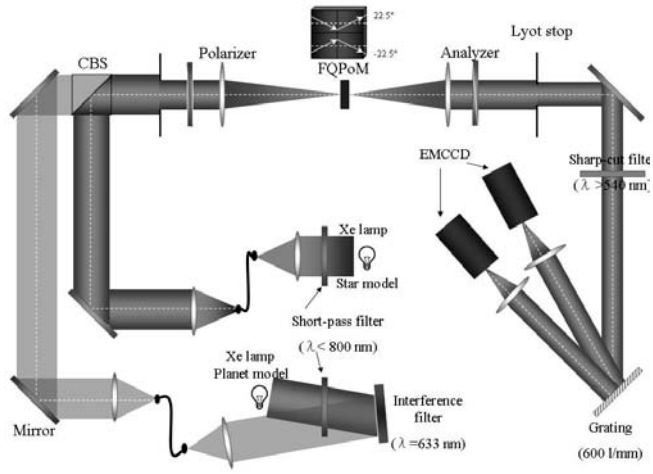


Fig. 1 Experimental setup for optical simulation

The observed image and objective spectra are shown in Fig. 2. The spectral range shown is about 160 nm centered on 630 nm. A contrast of the planet to the star is $5\times10^{-5}$ and the angular separation is 4.9 $\lambda$/D. Neither image nor objective spectrum of the planet can be recognizable in Fig. 2. The absorption feature of the planetary spectrum is obscured by noisy stellar spectra.

Fig. 2 Image (left) and objective spectra (right)

As shown in Fig. 3 we took four reference images and objective spectra for four quadrants of the FQPoM, where destructive interference does not occur. In the experiment we cut the planetary light to take the reference data, but the light of the star-planet system would be employable in practical observations because of the extreme intensity difference between them, where the planetary light is too faint to be detected without destructive interference of starlight. The reference data are used to synthesize the pseudo objective spectra that consist of only the stellar spectrum. The four reference spectra are found to be very similar, but the transmittance of the first and third quadrants

differs a little from that of the second and fourth quadrants.

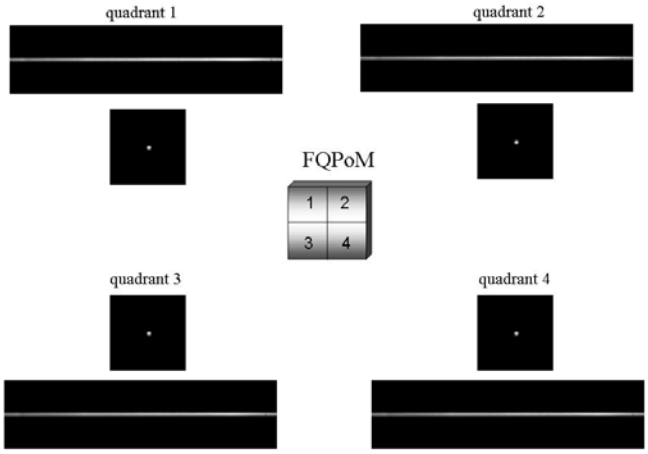


Fig. 3 Reference images and spectra measured for each mask's zone.

The pseudospectra are synthesized with the procedure described in the previous section. Fig. 4 shows the differential spectra between the observed and the pseudospectra. Here the central bright part (± 4.2 λ/D) was discarded, since the residual star-image intensity is too high to process the data and the spectral characteristics on the central part differ from the reference spectrum because of nulling interference with FQPoM. The spectral feature of the planet, namely the absorption line around λ=633 nm is revealed in Fig. 4. To show the absorption feature clearly an enlarged part is also shown in the bottom of Fig. 4.

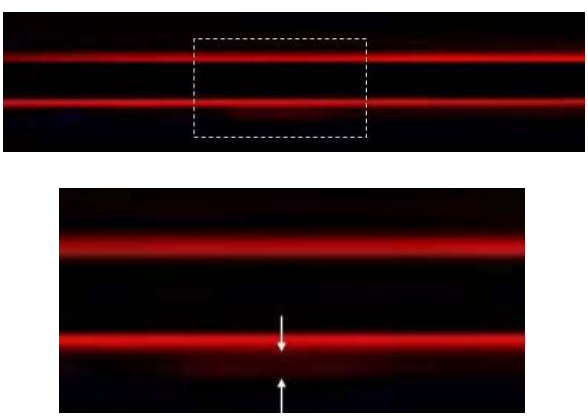

Fig. 4 Differential objective spectra between observed and pseudo spectra. A part of the spectra is enlarged (bottom).

We can reconstruct the planetary spectrum by subtracting the planetary portion of the obtained differential spectrum from the reference spectrum;

$$S^{ij}_{planet} = RS^{ij} - S^{ij}_{differential}, \qquad \textbf{(3)}$$

where $RS^{ij}$ and $S^{ij}_{differential}$ are the intensities of the reference and differential spectra, respectively, at the *(i.j)* pixel. Fig. 5 shows the reconstructed spectrum of the planet (in blue) and the spectrum without the starlight (in green). As can be seen not only the absorption lines but also overall spectral features are well reconstructed. In our method the difference between the stellar and planetary spectra is first found out, and then the difference is used to reconstruct the planetary spectrum from the reference stellar one.

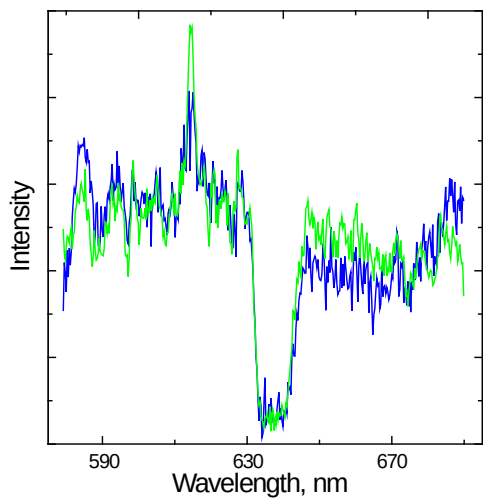


Fig. 5 Reconstructed (blue) and original (green) spectra

## Conclusion

We have shown that objective spectral reconstruction of exoplanets is feasible by using image-spectroscopic data. The method based on the CLEAN algorithm will work effectively in IR region. It will be also useful to detect exoplanets with the spectral difference between an exoplanet and its parent star.

The use of the method described in this paper is not limited to the FQPoM coronagraph employed here. One of advantages in our method is adaptability to space-variant optical system. Therefore, our method will be effective to various kind of nulling coronagraphs equipped with an imaging spectrometer.

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