Detecting Exoplanet Signals from Direct Imaging through K-L Transformation and High-pass Filtering

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***Abstract*—Computer vision is becoming more and more widely used in fields of astrophysics, especially in the field of exoplanet, which has recently become a popular issue. Inner exoplanets are often difficult to be directly imaged because of their proximity to very bright stars. Knowledge and algorithms from computer vision can help us achieve high resolution astronomical image processing and analysis, so we hope that through the principal component analysis (PCA) method such as reproducing the Karhunen-Loève eigen-image and the method of special filtering of the image, we are able to extract faint signals of the exoplanets from the bright background. The data set comes from images taken by the European Southern Observatory Gemini Telescope and the Hubble Space Telescope (HST).**

I. Introduction

Image data is one of the main outputs and important research media of modern astronomical observation. With the continuous development of image processing methods and the interdisciplinary interaction, the application of computer vision in astronomy and astrophysics is becoming more and more extensive. For example, Hirsch et al.[1] proposed the use of the deconvolution method to reduce the effect of atmospheric turbulence on image quality and enable real-time and efficient data quality improvement of terrestrial telescope observations; Lang et al. [2] proposed an automatic extraction and recognition of images (stars, galaxies), and the algorithms and software have been widely recognized and applied in the field; Huertas-Company et al.[3] applied deep convolution neural network (CNN) on CANDELS (Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey) to conduct visual-like automatic classification on galaxies faraway.

In the field of extraplanent exploration, the existing detection methods include the transit method, line-of-sight velocity method, micro-gravitational lensing and direct imaging. Direct imaging enables the detection of extrasolar planets by direct imaging of the neighborhood of distant stars by means of a ground-based or space telescope. This method can help us to detect young (<300 Myr), large mass (>2 Jupiter masses), distant from the mother star (>5 astronomical units) planets, and other methods such as transit method, velocity method would detect older exoplanet closer to the mother star, which can form a complementary method for the follow-up study, such as extrasolar planetary statistical properties of the sample by adding completeness.

However, the direct imaging method is very challenging, and it faces various problems: on the one hand, the radiant intensity of the exoplanet is extremely weak compared with the radiation intensity of the stars, and the difference is about ten orders of magnitude; on the other hand, significant diffraction effects occur within the instrument to produce speckle noise similar to planetary signals, and for ground-based telescopes there are atmospheric turbulence disturbances.

Over the past five years, thanks to the significant improvement of observation technology and the introduction of a variety of computer image processing algorithms, direct imaging methods have made a great deal of progress. The current research approach is to observe with the use of adaptive optics (AO) technology and coronation mirror (Coronagraph) equipment to eliminate atmospheric jitter and effect that the star signal is too strong, and then with the introduction of follow-up image processing methods to extract exoplanet signals. Some methods of image processing proposed in recent years include the PCA method proposed by Sommer et al.[4] based on Karhunen-Love transformation [5][6]; Marois et al.[7] proposed an image rotation differential (ADI); Crepp et al.[8] proposed the high-pass filter method and local image weighted overlay(LOCI) method and so on.

This project attempts to extract the weak exoplanet signals from the image of star by Karhunen-Love transform (hereinafter referred to as K-L transform) and high-pass filtering. The experimental data were obtained from the Gemini Planet Imager project (Gemini Planet Imager) and the Hubble Space Telescope (HST).

II. Method

A. *K-L transformation*

The K-L transformation method was proposed by Sommer et al.[4] in 2012. The basic principle is to use a series of reference library to estimate and reconstruct the point spread function (PSF) of the central star by subtracting the target image to extract extrasolar planetary signals, which is based on the PCA method. The reference image library is modeled by simulation or observed and contains different types of stars that may be generated with various specific instruments. Since all the reference images in the constructed image library do not exist exoplanets, that is, the signal components are orthogonal to them, so that the signals from the extrasolar planets are preserved in the subtraction result.

The principles and basic steps of the experiment are as follows:

1) subtracting the mean and normalizing the target image so that the mean is 0 and has the same standard deviation as the reference image

2) The reference image library is the KL transformed principal component calculated from the eigenvector of its

covariance matrix and is arranged in order from large to small (representing the observed parameters such as time, wavelength, angle, stellar type):

$$Z_K^{KL}(n) = \frac{1}{\sqrt{\Lambda_K}} \sum e_K(\Phi_p) R_p(n) \tag{1}$$

The data provided by the HST has contained the intrinsic image already;

3) The first M principal components are taken as the base vectors, the target image is projected onto the M basis vectors, and the eigenvector is weighted by the projection coefficient to obtain the best estimate of the stellar PSF:

$$I_{\tilde{\Phi}_0}(n) = \sum < T, Z_K^{KL} > Z_K^{KL}(n) \tag{2}$$

4) Subtract the reconstructed stellar PSF from the target image, that is, the processed image result:

$$F(n) = T(n) - I_{\tilde{\Phi}_0}(n) \tag{3}$$

5) Finally, the image results are superimposed by different observation times and taken the median to improve the signal-to-noise ratio (SNR).

B. High-pass Filtering

The high-pass filtering method is based on the following principles:

1) The peripheral halo of the star is continuously distributed in the image, which corresponds to the low frequency component in the spectrum, and the point source and the diffraction mark occupy the high frequency component in the image;

2) According to the diffraction theory in optics, the diffraction speckle will move outward as the observed wavelength changes.

Therefore, we can use high-pass filtering method to remove the residual pattern in the image, and by checking whether the signal changes with the observed wavelength in the apparent radial displacement to exclude the diffraction markings left.

The basic steps of the experiment are as follows:

1) Read the GPI raw data as a four-dimensional data volume (time wavelength image length image width)

2) For each observation time, each image of each observation band high-pass filtering would be used include: Fourier window filter, Fourier continuous filtering (primary, secondary, Gaussian), Laplace operator, Sobel operator etc.

3) Superimposing images at different times and take the median value to improve the SNR.

4) On this basis try to do a first erosion of the image after the expansion (i.e. open operation) to eliminate small noise, smooth boundary. Because of the fact that exoplanets have their own PSF, this step theoretically would not erase their signals.

5) Compare the image results of two different bands to check whether the signal is displaced: if so, it indicates that the signal is excluded from the diffraction pattern of the instrument; if not, it indicates that the signal came from the extrasolar planets.

C. Forward Modeling

After searching for signals from extrasolar planets, we can further maximize the SNR by the Forward Modeling method proposed by Sommer[4] and Ruffio[9]. If the noise is independent isotropic distribution, it is possible to simulate the noise by cross-correlating the template. In the actual exoplanet images, the noise is related and anisotropic, which requires the estimation of the disturbance of the noise. In Ruffio et al (2017), the planetary signal of the matched filter is the PSF of the planets obtained by perturbation of the two-dimensional Gaussian function, the contrast of the extracted signal relative to the background of the star, and the final signal and overall SNR can be enhanced, effectively reducing the background fluctuations.

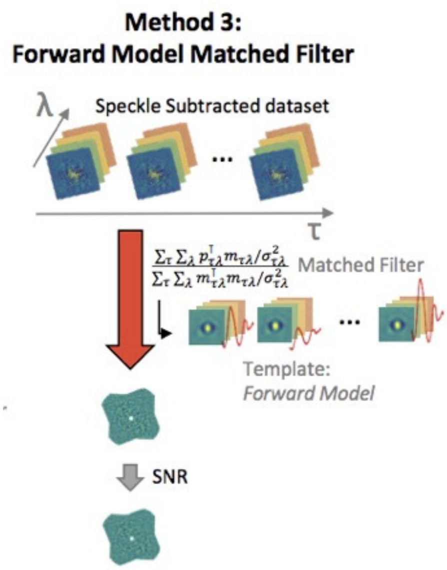

Fig. 1. Principle of Matched-Filter Forward Modeling

We calculate each feature picture according to the first order estimate of the disturbance of the K-L eigenvector in Pueyo et al. (2016):

$$\frac{\Delta Z_K}{\epsilon} = -(\frac{v_K^T C_{AR} v_K}{2\mu_k}) + \sum (\sqrt{\frac{\mu_j}{\mu_k}} \frac{v_K^T C_{AR} v_K}{\mu_k - \mu_j}) z_j + \frac{1}{\sqrt{\mu_K}} A^T v_K \tag{4}$$

Here where v_j is the eigenvalue of $C = RR^T$ (R is the matrix of the reference image $N_R \times N_x \times N_y$), and μ_j is x eigenvector of $C = RR^T$.

Thus the signal of the model exoplanet can be expressed as:

$$m = a - Z_K^T Z_K a - (Z_K^T \Delta Z_K + (Z_K^T \Delta Z_K)^T) \frac{i}{\epsilon} \tag{5}$$

For the final result we need, calculate the $Z_K' = Z_K + \Delta Z_K$, and then use the K-L processing steps to get the final image after the Forward Modeling.

III. Results

A. K-L Transformation

The target object of the experiment is the star HR8799 (Figure 2) taken by the Hubble Space Telescope (HST). As shown in Figure 2, the center of the star is very bright, the candidate exoplanets are located near the orange cross in the figure, so seeing the exoplanets directly from this image is a task that is almost impossible to accomplish. Coronagraph technology, by limiting the most central part of the star is used to reduce the contrast.

Fig. 2. Star HR8799, image from HST, the NICMOS data field is only a small part of its center.

The original image data captured by the NICMOS coronagraph is shown in Fig. 3 (a). Although the corona mirror substantially attenuates the radiation from the stars, there is still significant residual from the diffraction effect in the image, dropping the signal of the exoplanets.

After processing steps described in 2.1, the processing results are shown in Figure 3, and (b) (c) and (d) correspond to the results of 30/50/90 principal components, respectively. It can be seen that the PSF of the stellar diffraction is greatly suppressed, and a clearly visible dot-like signal (in the red circle in Figure 3) appears in the middle of the star in the result image, which is a possible exoplanet candidate. As the number of principal components gradually increases the signal gradually becomes more obvious, but the principal component should not be too much to avoid the appearance of over-fitting. In addition, given that there is still a flux surplus near the star(i.e., the cross in Figure 3(a)), the point source closer to the star and the speckle may be a false-positive and should be inspected and the point source signal is at a distance from the star / speckle, so it is one that can plausible.

B. high-pass filter

The experimental object is the the star Beta Pic shot by the Gemini telescope GPI project (see Figure 4). The Beta pic original data consist of 37 bands, 19 observation time with a total of 703 images, at each time in each band corresponds to a matrix of 281 * 281, and the original data is occluded.

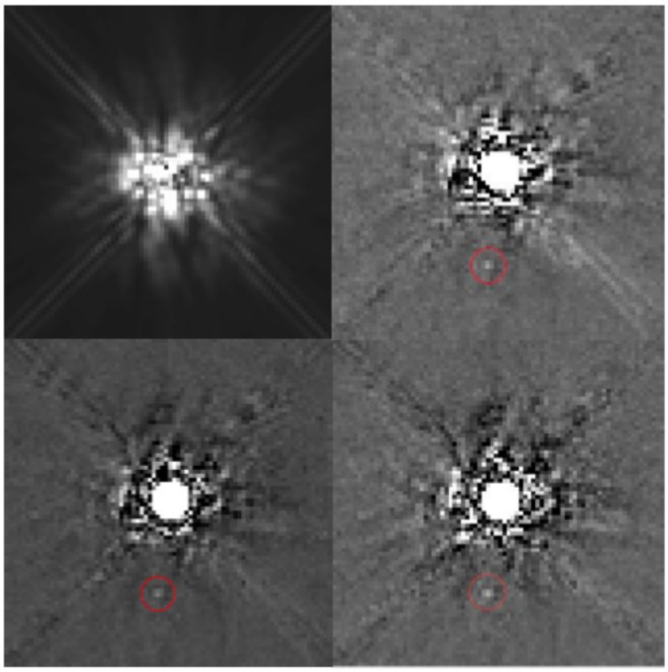

Fig. 3. (a) HR8799 HST-NICMOS raw image; (b)(c)(d) HR8799 after K-L algorithm, corresponding to the number of principal components using K = 30/50/90 results, respectively.

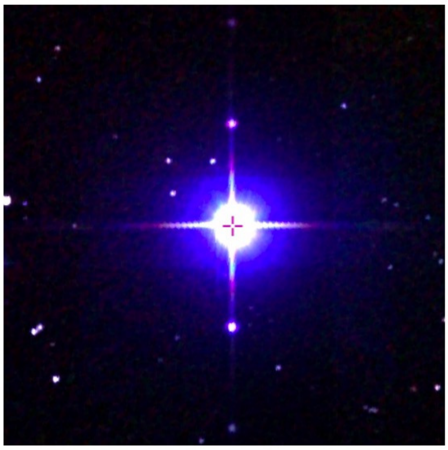

Fig. 4. Star Beta pic, image from 2MASS, the data field is only a small part of its center.

As shown in Fig. 5(a), the effect of Fourier filtering is superior to other filters, and the effect of the quadratic response curve is better than that of Gaussian and primary curve, and Fourier window filtering can cause the image to appear corrugated artifact. The filtering results show that the continuous part of the outer peripheral halo of the star has been well deducted, but it still retains some noise; the single noise is removed after the erosion operation, and the signal from the exoplanets remains; and after an expansion operation, although distortion, the signal can be strengthened so that it can reach the level to be seen by naked eye (in green circle in Figure 5). Figure 5(b)(c)(d) shows the results of Fourier high-frequency second-order filtering, filtering after erosion and filtering after opening. The selected band is the Methane Band that exoplanet signals are strong. Checking the results of different bands leads to the conclusion that due to the presence of significant migration, some signals from the periphery of the star are from the residual diffraction markings (blue circle in the figure).

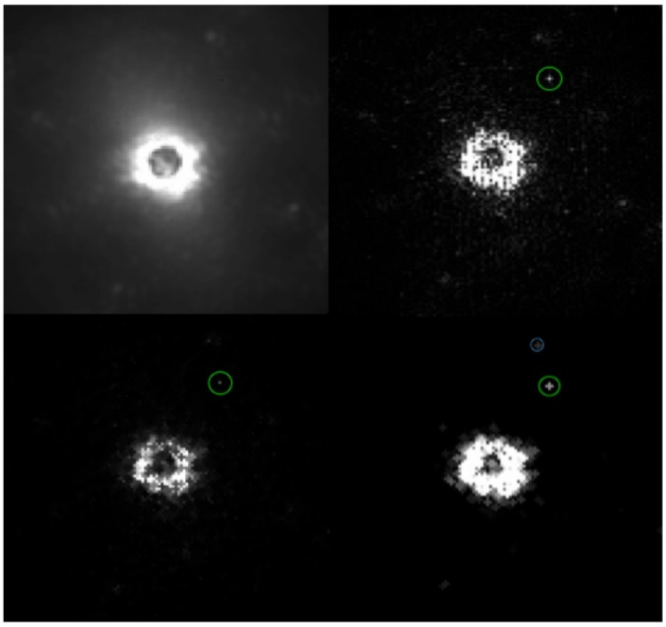

Fig. 5. (a) GPI original image; (b) image after secondary Fourier high-pass filtering; (c)image with erosion operation after filtering; (d) image with open operation after filtering.

C. Forward modeling

Forward modeling has constructive effects on the judgment of exoplanet signal because the selection of the model depends on the property of the image including the contrast to the star, the nature of the reaction image space (,), and whether the description of the relationship between the noise and the signal in the image space is complete. To extract the target signal, noise depression should have a good performance.

Our work has completed the construction and code writing of the Forward Modeling algorithm (KLFM.py). However, due to the need to construct a large number of reference images (each target image requires approximately 300 images to be processed), the new data needs to be stored with a lot of memory space, while high-dimensional matrix computing slow the processing speed down. Basically personal computer is difficult to assume a relatively complete calculation, the need for parallel computing or the introduction of large servers. For example, in the literature [9] 38 different time exposure of the image processing requires 32 2.3GHz, 20GB RAM computer to complete the operation.

Unfortunately, we lack sufficient computing resources and computing time, and thus can make a complete test and improvement on the algorithm. In the future at the graduate stage if there is opportunity to continue in related areas of scientific research, we might be able to make further attempts.

IV. CONCLUSION

The project tries to extract and identify the faint exoplanets through K-L transformation and high-pass filtering. Our results show that the proper image processing algorithm can suppress and subtract the residual components of the stellar signal to a certain extent so that the signal of exoplanet that is distant from the star and bright can be extracted well and reach the visible level. We also compare the results with the extrapolated exoplanet candidate location information in the existing research results, and the signals we have obtained are consistent with the existing results and hence are indeed possible candidates.In addition, the implementation of all the code and algorithm construction are from the first-hand scientific literature, rather than existing codes.

The shortcomings of this project are: 1) It is difficult to extract and identify extrasolar planets that are closer to stars. This deficiency is caused by the defect of the direct imaging method itself, and the candidate signal near the center of the star has a great deal of uncertainty, and the situation is more complicated and difficult to specify. 2) In the high-pass filter part, when distinguishing exoplanets and residual diffraction markings, human eyes are used to see whether there is a shift to the migration. This approach lacks a certain degree of automation and intelligence. In addition to the HR8799 image filtering results do the operation will leave the image occupied by the basic unit "+" , making the amount of information reduced and causing image distortion.

3) There are still some problems in Forward Modeling:

- Algorithm: On the basis of K-L processing, it is necessary to measure the contrast relation of each point in space. Because of the complex relationship between the signal and noise of the actual picture and the deviation of the signal from the point source, the first-order approximation of the calculation process is deviated.
- Data reliability: Due to the calculation of eigenvalues and eigenvectors of a large number of reference pictures, there is singularity in the calculation, requiring a higher order approximation for non-singularity of matrix operations.
- Data Redundancy and Computing Resources: As mentioned earlier, this method will consume a lot of memory space and computing resources, it is difficult to run on a personal computer.

In the future this work may be improved as follows:

1) to improve the Forward Modeling method, such as Bayesian Forward Modeling method to accelerate the algorithm, or the use of dynamic storage, redundant storage and other methods to reduce the memory requirements.

2) to use the same filtering method and the corresponding parameters of the treatment of different bands of the results are also different. It may be considered that it would be better to use different filtering parameters for all bands and finally to superimpose the band with stronger partial bands.

3) to minimize artificial impacts, to distinguish between false positive signals, for example, to compare the two different wavelengths of the image after the overall zoom after subtraction. The scaling criterion is that the scaled stars are equal in size, and the more operational approach is to scale

according to the ratio of the wavelengths corresponding to the image. Crepp et al.[6] pointed out that the ideal scaling ratio is essentially the wavelength ratio. Ideally, after stretching, the target signal will appear one by one dark and two spots. The original data adjacent to the smaller wavelength interval, after stretching the target signal position close to or even coincidence, after filtering the subtraction may be the target signal minus, so the choice should be selected when the wavelength difference between the two signals. However, for two images with large wavelength differences, the selection of the filter parameters may not be consistent, which may lead to the final outcome may be deviated from the ideal situation, such as after subtracting the target signal leaves one bright and one dark spot. In summary, in real operation we should also consider the above two factors.

4) Another consideration is the introduction of automatic weighted method, but it should be noted that this method also requires a lot of computing resources, actually in Crepp at al. (2011) the use of Bluedot Super-computing Cluster provided by NASA to implement the automatic weighted method.

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