SIMULATION OF IMAGING EXTRASOLAR PLANETS NEARBY STAR

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Abstract

Two-dimensional computer simulations are carried out to demonstrate the essential features of observing extrasolar planet nearby star. It has been shown that the wings of the point spread function of the optical telescope play an important rule in suppressing the features that related to the planet. The planet lies beneath these wings and the final image that recorded by an optical telescope looks like a star. Quantitative assessment of observing planet nearby star at different relative brightness and separation are demonstrated in this study.

Key words:Coronography, Adaptive optics,Fourier transform,Image formation.

محاكاة لتصوير الكواكب الخارجية قرب نجم

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الخلاصة

محاكاة حاسوبية ذات بعدين اجريت لبيان الصفات الجوهرية لمشاهدة كوكب يقع قرب نجم . اوضحت الدراسة ان اطراف دالة الانتشار النقطية تكون المسؤولة الاولى عن هذه المشاهدة حيث تأثيرها يكون كبيراً وذلك لتوهينها المعلومات العائدة للكوكب. الصورة النهائية لهذا الكوكب والنجم المرصودة بواسطة التلسكوب البصري ستكون على شكل نجم احادي. الدراسة بينت ايضاً التقييم الكمي لمشاهدة الكوكب بالقرب من النجم عند قيم مختلفة من تباين النورانية والمسافة.

Introduction:

The fundamental problem in direct imaging of Extrasolar planets refers to the ratio of the reflected photons from a planet to the received photons from a star and this ratio is extremely small. We know that the brightness of the star is greater than 10^9 of that of the planet. Many methods have been utilized to discover extrasolar planets since 1995, such as (Radial velocity, Astrometry, Microlensing, ..., ect.) [1]. These methods are considered to be indirect imaging, but direct imaging using ground based optical telescope is not yet discovered Earth-like planet [2].

In order to make the optical telescope to observe an extrasolar planet, we could control its aperture to suppress or reduce the brightness of the star relative to the reflected brightness of the planet [3]. In the past few years, many astronomers were starting to solve this problem using 8-10 m ground based optical telescope [4].

However, finding planet like our Earth around a nearby star like our Sun is extremely difficult.
Different shapes of the telescope aperture were used heavily in optical imaging such as circular, square, rectangular, …., ect. The shape of the aperture determines the diffraction pattern of an imaging system. An optimal diffraction pattern created from a circular aperture is a series of concentric rings surrounding a central bright spot and this is known as an Airy disk or point spread function (psf) [5].
The psf is the intensity distribution of the image of a point source (star) that taken by an optical telescope. The limited size of the circular aperture of the ground based optical telescope makes the stellar wavefront to be diffracted as an Airy disk pattern and the planet nearby star buried in the psf of the optical telescope [6].
The pupil function is given by:

$$P(\zeta,\gamma) = \begin{cases} 1 & \text{if } \rho \leq R \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where R is the radius of the telescope and ρ is given by:

$$\rho = ((\zeta-\zeta_c)^2+(\gamma-\gamma_c)^2)^{1/2} \quad (2)$$

(ζ_c, γ_c) is the center of a 2-dimensional array. When a light beam strikes the aperture, the wavefront takes a certain function depending upon the shape and size of the aperture of the optical telescope [7].
Many attempts have been made to reveal the information that belongs to the planet. This involving reshaping the aperture of the optical telescope, the process called apodization [8]. Apodization typically refers to any modification of the aperture to alter the psf [9]. Apodization is used to smooth the attenuations that would happen to the diffraction limited psf of the optical telescope in use [10]. This also involves the reduction of the intensity of the diffraction rings owing to reveal the faint features of the planet [11]. In this paper we are demonstrating the mathematical model of the essential features of the problem that associated with imaging extrasolar planet nearby star.

Mathematical Model:

In order to observe an extrasolar planet, we assume the aperture of the optical telescope is a circle and the following issues must be taking into account:
1.The psf is computed as follows [12]:

$$psf(x,y) = |FT(P(\zeta,\gamma))|^2 \quad (3)$$

where FT denotes Fourier transform operator and $|\ |$ is absolute value.
2.The simulations must be based on the fact that the wings of the psf is in some how covering the information that belong to the planet.
3.Star and planet are generating according to the following equation [13]:

$$str\_pl(x,y) = A * e^{-((x-x_c)^2+(y-y_c+d)^2/(2*\sigma_1^2))} + e^{-((x-x_c)^2+(y-y_c-d)^2/(2*\sigma_2^2))} \quad (4)$$

where A is the brightness of the star. σ_1, σ_2 are the standard deviations of the star and the planet respectively, and d is the distance between the star and the planet. It should be pointed here that the brightness of the planet kept constant at a value of one.
4.The result that obtained from implementing step 3 is convolved with the psf of the telescope in use:

$$str\_pl\_t(x,y) = \iint_{-\infty}^{\infty} str\_pl(x',y')\,psf(x-x',y-y')\,dx'dy' \quad (5)$$

The above equation may be written as

$$str\_pl\_t(x,y) = str\_pl(x,y) \otimes psf(x,y) \quad (6)$$

where $\otimes$ denotes convolution.
This equation demonstrates the observation of star and planet via an optical telescope in the absence of atmospheric turbulence and any geometrical aberrations that contributed from the optical telescope.
5.The Fourier transform of equation (5) is given by:

$$STR\_PL\_T(u,v) = STR\_PL(u,v) \cdot PSF(u,v) \quad (7)$$

where capital letters denotes Fourier transformations [14]. The above equation will be examined in the next section by changing the relative contrast (Rc) (i.e. changing the value of A). Rc is defined as the ratio of the maximum brightness of the planet to maximum brightness of the star (Rc=1/A).
6. To reduce the dynamic range of the images, the following equation is used:

$$str\_pl\_t\_l(x,y) = Log(str\_pl\_t(x,y)) \quad (8)$$

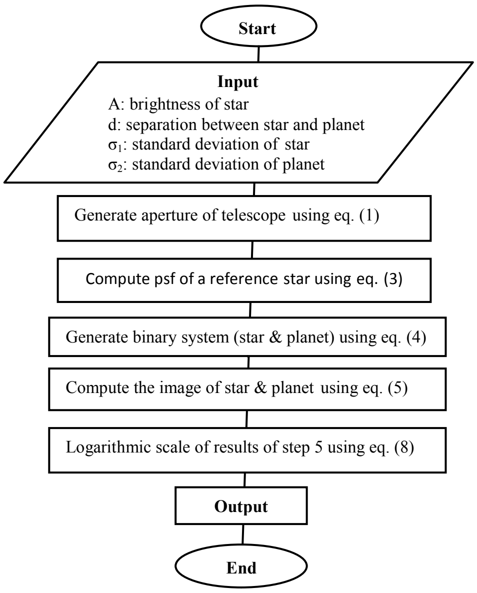
Simulations and Results:

The block diagram of the mathematical model that presented in section (2) is demonstrated in (Figure-1). Two-dimensional computer simulations are carried out to investigate the relationship between observing planet nearby star and the value of A and d. The aperture of the optical telescope is generated in an array of size 256 by 256 pixels using R=60 pixels following eq.(1). The array is then Fourier transformed and the absolute square is performed as given in eq.(3).

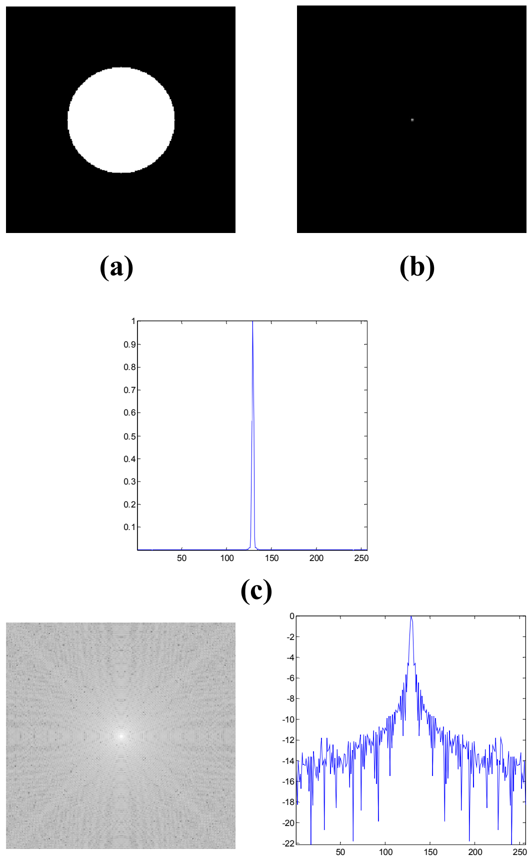
The result is an image of a reference star via optical telescope or psf as shown in (Figure-2).

The psf is then threshold to a certain value in order to boost up or enhance its wings as shown in (Figure-3). It is clear that as the brightness of the star increases, the wings of the psf become dominant and it will cover the information that related to the planet. This will tend to suppress the features of the planet and prevent them to be seen by an optical telescope.

Now, the star and the planet are simulated using eq.(4). Rc is taken to be 1:10, 1:10^2, 1:10^3, and 1:10^6. This binary system at different Rc is then convolved with the psf of the optical telescope. The results are demonstrated in (Figure-4). It is clear that the planet is hardly to be seen at Rc =1:100. The logarithmic results of (Figure-4) are presented in (Figure-5). Now,the planet is clearly visible at Rc=1:1000.Surface and contour plots after implementing eq. (8) are shown in (Figures-6and7) respectively.The results revealing some of the features that belong the planet even withRc=1:1000 (the planet is clearly visible).The Fourier fringes of the binary system is also computed and the results are displayed in (Figure-8). The fringes is clearly visible at Rc=1:10 and hardly notecibale at Rc=1:100.Since we know the location of the planet, it is important to study the height of the planet to the height of the star of the observed image. This relative height (RH) gives the quantitative assesmant of detecting information related to the planet at different Rc.The results are shown in (Figure-9) .It should be indicated here that Rc values are in logarthimic scale.

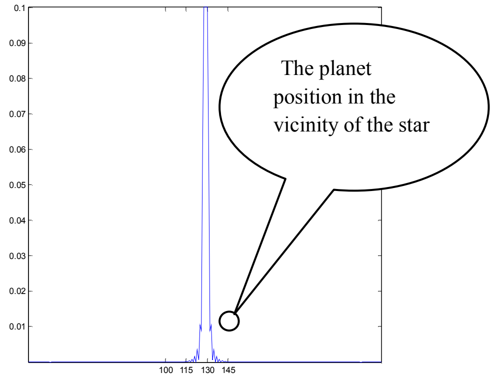


(Figure-1): Block diagram of the principle of imaging of extrasolar planet nearby star.

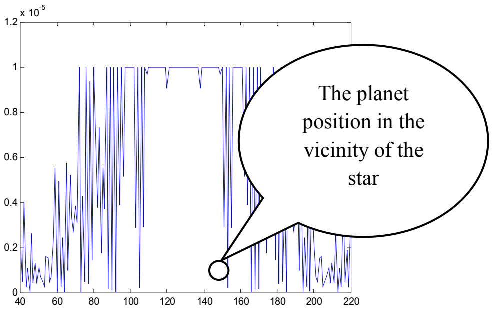


(d) **(e)**

(Figure-2): a- Aperture of the optical telescope, b –Image of a star or psf, c - Central plot through(b), d - Log (b), and e- Central plot through (d).

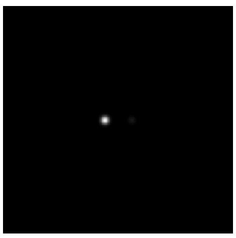


Rc=1:10

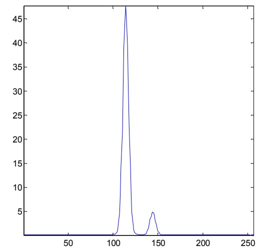


Rc=1:100000

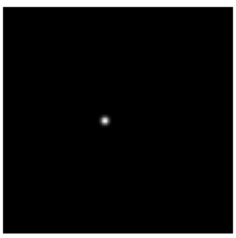
(Figure-3): the planet location in the vicinity of an image of star at different Rc



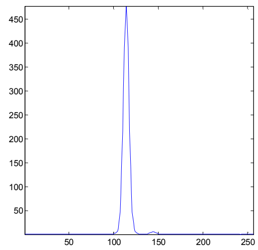
(a)



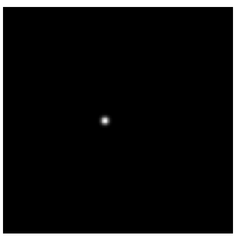
(b)



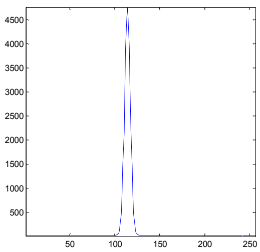
(c)



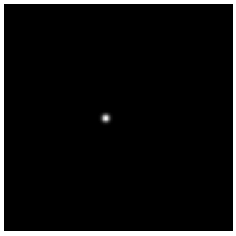
(d)



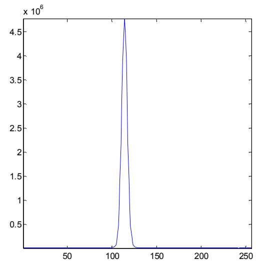
(e)



(f)

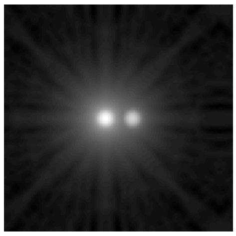


(g)

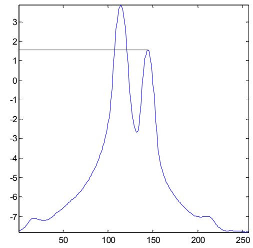


(h)

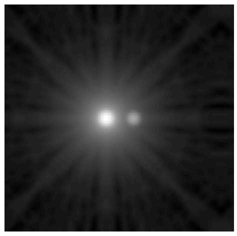
(Figure-4): The brightness of the planet nearby star at different Rc, a- Rc =1:10, b- Central plot through (a), c- Rc =1:100, d- Central plot through (c), e- Rc =1:1000, f- Central plot through (e), g-Rc =1:1000000, and h- Central plot through (g).



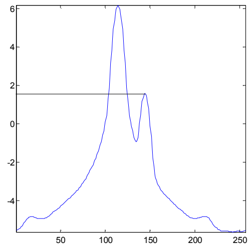
(a)



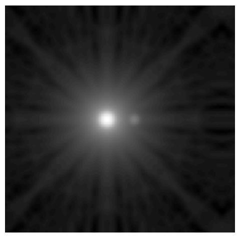
(b)



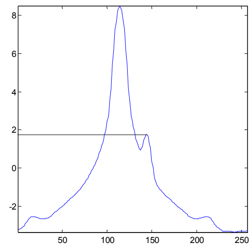
(c)



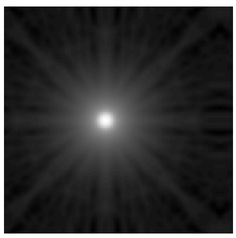
(d)



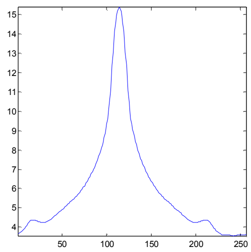
(e)



(f)

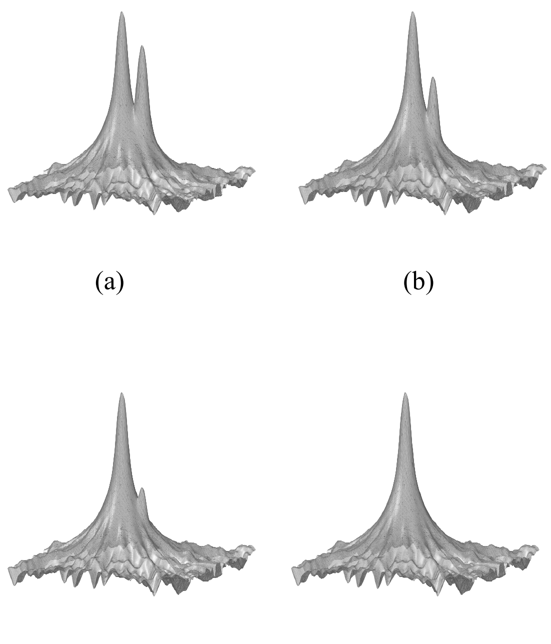


(g)

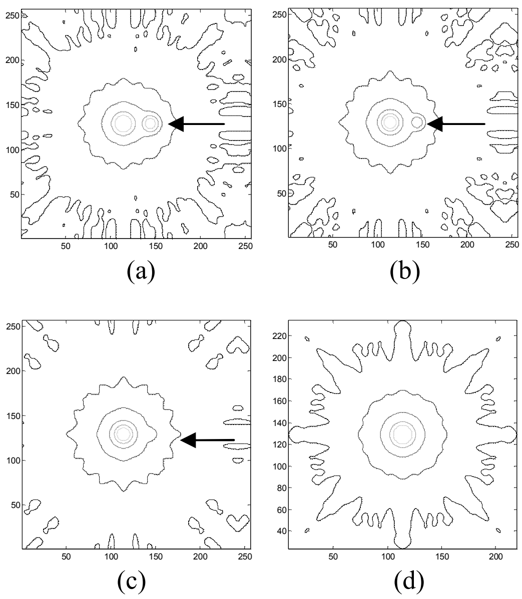


(h)

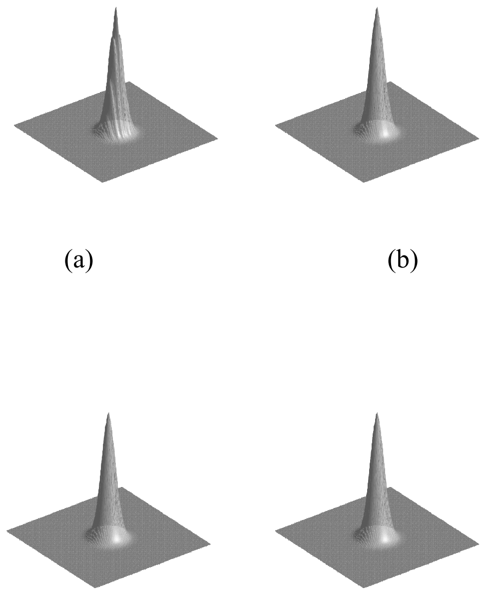
(Figure-5): Logarithmic images of (Figure-4) respectively.



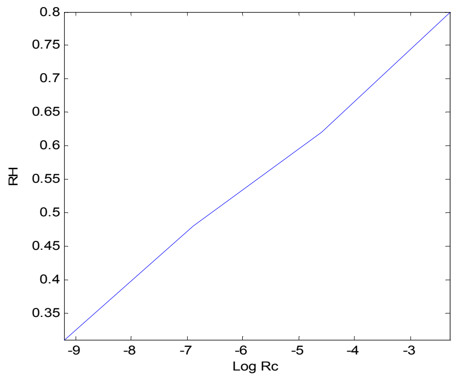
(Figure-6): Surface plots of the planet nearby star at different Rc, a- Rc =1:10, b- Rc =1:100, c- Rc =1:1000, and d- Rc=1:1000000.



(Figure-7): Contour plots of (Figure-6) respectively. Note:← indicating the existence of the planet.



(Figure-8): Fringes of (Figure.-6) respectively.



(Figure-9): The relationship between RH and Log Rc.

Conclusions:

Several important points could be concluded from the results of this study:

1.The distance between the star and the planet is considered to be an important parameter in determining the possibilities of observing planet nearby star.

2.The relative contrast (Rc) is another vital parameter in observing planet nearby star because as Rc decreases, the planet becomes totally covered by the wings of the psf of the optical telescope in use.

3.The smoothness of the fringes for binary system (star & planet) is directly proportional to the relative contrast Rc.

4.RH is exponentially related to Rc or linearly related to log Rc.

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