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To be determined

Master Thesis

Exoplanets and Habitability
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Abstract

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1 Introduction

2 Aperture Photometry

In order to determine the flux of different objects in astrophysics, like stars and planets, aperture photometry can be used. This method sums the counts of the pixels inside a certain aperture around the star. In our case this aperture is usually a circle. In order to account for the background noise an annulus around the aperture is taken and the mean of the summed up pixels inside the annulus is subtracted from the apertures pixels. The flux of this aperture is then given by [2]

$$F_{ap} = F_{tot} - n_{px} \langle F_{bg} \rangle, \quad (1)$$

where F_{tot} is the total flux inside the aperture (sum up the pixel values inside the aperture), n_{px} is the number of pixels inside the aperture and $\langle F_{bg} \rangle$ is the mean background per pixel. This mean background per pixel is defined through the annulus and calculated from

$$\langle F_{bg} \rangle = \frac{1}{m} \sum_{i=1}^m c_i, \quad (2)$$

where m is the number of pixels in the annulus and c_i the respective pixel value. Figure 1 shows an example for a possible aperture and an annulus around a star, which can be used to do an aperture photometry.

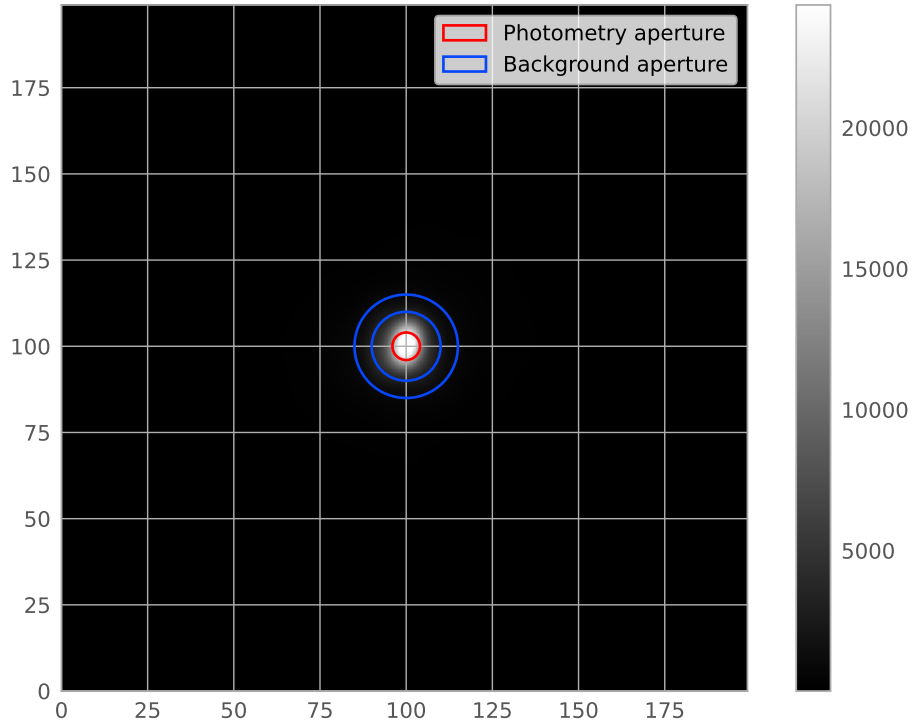


Figure 1: An aperture photometry for the star in the center, where the red circle indicates the aperture used and the two blue circles define the annulus used for the background subtraction.

From the figure you can see that we chose the annulus not directly after the aperture, but this is just one way to do it. One could also choose the annulus directly after the aperture or choose a different distance between the annulus and the aperture. However the annulus should give a good

approximation for the background inside the aperture and therefore it should not be too far away from the aperture. We chose a small distance between the aperture and the annulus of 4 pixels, because we wanted that as little starlight (in this case) as possible is included in the annulus. If we plot the counts per pixels which are included in a certain radius around the star, as it is done in figure 2 we see that after around 10 pixels the increase is decreasing rapidly. That is where there is only little starlight left. This is also why we choose the annulus to go from a radius of 10 to 15 pixels.



Figure 2: The total flux of the star is calculated for different radii and plotted. This shows that after a radius of 10 pixels the contribution from the star is almost gone.

Additionally we choose the radius of the aperture to be 6 pixels.

2.1 Aperture photometry and ghosts

In order to detect exoplanets one can use aperture photometry. In this subsection we are going to do these steps for the two ghosts which we have in our data from the circumstellar disk HD142527, in order to demonstrate how this could be done for an exoplanet and to learn more about ghosts. A ghost is a copy of the star, which is created by the back-reflection of the star on optical components of the telescope. Figure 3 is an image of HD142527, where the two ghosts are indicated. We see that the ghost on the top right (we will call this ghost 1) is brighter than the ghost on the bottom left (ghost 2).



Figure 3: An image of the circumstellar disk HD142527, where the two ghosts are indicated.

If we want to confirm the signal from our ghost or also from other objects like exoplanets, which usually can not be seen by eye, we use the signal to noise ratio S/N . This means we do aperture photometry for several points around the star which are at the same separation from our star as the ghost (or exoplanet etc.), as in figure 4. From this we can calculate the standard deviation σ from the mean of all aperture fluxes and the signal to noise ratio. If the signal to noise ratio is larger than the standard deviation, this means that we have a source (ghost, exoplanet) at this position.

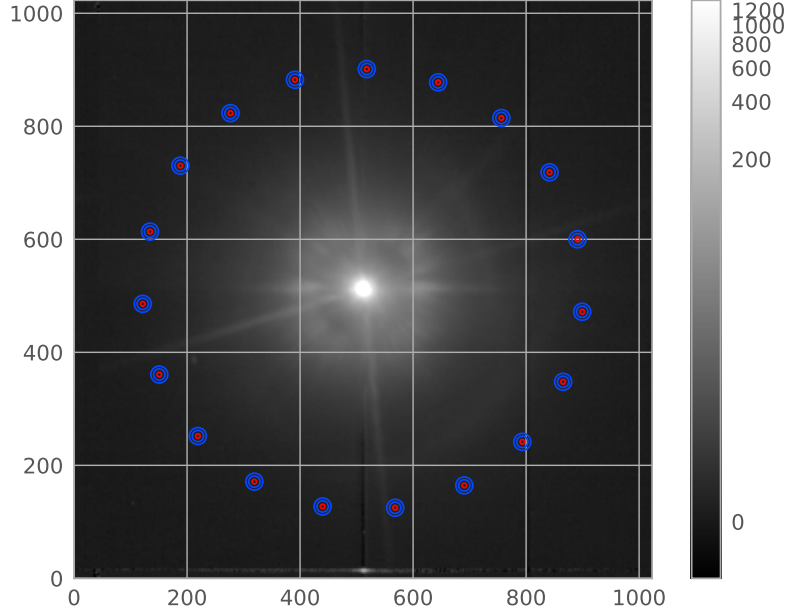


Figure 4: In order to confirm the signal from the ghost, we do aperture photometry for several points around the star which are at the same distance from the star as the ghost. We then calculate the standard deviation of all the aperture fluxes and from there find the signal to noise of the ghost's aperture. If the signal to noise is larger than the standard deviation, the position of the ghost is confirmed.

The standard deviation is calculated by

$$\sigma = \sqrt{\frac{1}{k-2} \sum_{ap=2}^k (F_{ap} - F_{mean})^2}, \quad (3)$$

where the aperture of the ghost is at $ap = 1$, k is the number of apertures and F_{mean} is the mean flux of the apertures (without the aperture of the ghost) given by

$$F_{mean} = \frac{\sum_{ap=2}^k F_{ap}}{k-1}. \quad (4)$$

From this we can find the signal to noise ratio as

$$S/N = \frac{F_1 - F_{mean}}{\sigma}. \quad (5)$$

The results we get from our data about the ghosts are shown in table 1. It confirms that both ghosts are where we expected them to be, since for both the signal to noise is larger than the standard deviation.

We also want to compare the intensity of the ghosts to the intensity of the star. For this we calculate the ratio between the aperture flux of the ghost and the star. We find that the ghosts are about 10^{-4} times less bright than the star.

	Ghost 1	Ghost 2
S/N	33.9	16.5
σ	7.9	9.8
Ratio	$1.1 \cdot 10^{-4}$	$7 \cdot 10^{-5}$

Table 1: Signal to Noise of the ghosts and their brightness with respect to the sun.

3 Transformation to the r-phi plane

We have now seen that the ghosts are about 10^{-4} times less bright then their star, but potential exoplanets are even less bright. A Jupiter like exoplanet would be 10^{-9} less bright (reflecting light) and an Earth like even only $2 \cdot 10^{-10}$. Therefore the data must be really sensitive, with a high contrast and a high spatial resolution. As we can see in figure 3 the star produces strong spiders and speckles which have similar brightness as the ghosts or are even brighter. Therefore exoplanets which are situated in this regimes cannot be detected, unless we are able to take out the signals of the spiders and speckles without taking away other signals, like the ones from exoplanets.

If we take a closer look at figure 3 we observe that the structure of the spiders and the speckles are radially oriented around the star. In order to get rid of this effects it might be a good idea to transform the image into the r-phi plane, where we define the star to be at radius zero. After the transformation the spiders and speckles are distributed along the phi axis and they become weaker along the r axis.

Lets have a look at how one can transform the image into the r-phi plane. This kind of transformation is called image warping in image processing. In our case the image warping is based on a specific transformation, namely the transformation from cartesian to polar coordinates and is therefore also called polar-cartesian distortion.

In general an image warping is based on a transformation $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$, such that

$$\vec{x} \mapsto \vec{u} = \begin{pmatrix} T_u(x, y) \\ T_v(x, y) \end{pmatrix}, \quad (6)$$

where $\vec{x} = \begin{pmatrix} x \\ y \end{pmatrix}$ and $\vec{u} = \begin{pmatrix} u \\ v \end{pmatrix}$. When we want to warp an image f into an image g we do the following calculation

$$g(\vec{u}) = g(T(\vec{x})) = f(\vec{x}). \quad (7)$$

This means that at pixel \vec{u} the computed image g has the same intensity as the original image f at pixel \vec{x} . [1]

Next:

- Keep in mind: not bilinear and Before we can do the distortion we have to define our coordinate systems.
- how I did it (insert a little code fragment of the warping to r-phi) - what about warping back? (no code fragment) - data examples - circle -> to explain chosen length of this - was the aperture preserved?

4 Acknowledgments

A

References

- [1] Christian Bauckhage. Numpy / scipy recipes for image processing: General image warping. 01 2019.
- [2] Gisin Dominique. HR 8799 imaged in the long I band. 2021.