Discovery of extrasolar planets by examining the light emission from their respective stars

**Abstract**

Characterizing objects within far remote solar system is beyond the reach of telescopic methods. However, examining properties of the light emitted from the star can give information of orbiting planets. I have here examined variation in the wavelength of the H-alpha spectral line of five stars to determine existence of orbiting planets and further characterize their properties. Changes in wavelength caused by the doppler effect was used to estimate radial velocity of the star ~~with respect to its centre of gravity~~. Potential eclipsing planets was determined by change in flux. These data were further used to estimate the mass of planets and to create models of the planet’s radial velocities. The model was obtained by fitting a sine function to the data using the least squared method. I discovered orbiting planets around four of the stars. Two showed eclipse, which enabled estimates of the mass and radial velocity. Star 1 had mass of.. and mass of … . star 3 … In the two non-eclipsing stars only a lower bound of the mass and velocity can be estimated. These were… I also examined the eclipse data with the goal of revealing the planets radius, however, the time resolution was too low. Hence, the density of the planets could not be estimated.

Noise???

**Introduction**

The vast amount of astrophysical research suggests high prevalence of stars with orbiting planets [Hansen]. There are two main strategies for discovering planets. Direct imaging by telescoping and indirect methods based on changes in the light pattern of stars orbited by planets. Telescopic imaging is limited by their angular resolutions, which means that distance between objects, as a star and a planet, and the distance between observation point and objects determines the detection potential (Hansen). These are both highly relevant parameters in the universe were extreme distances is a prominent factor. Thus, telescoping is limited to nearby solar systems (ref). The Kepler telescope had by 2016 verified 1284 new planets (ref).

To gain information from more remote solar systems indirect methods have been fruitful. Here, I have used the radial velocity method and the transit method to explore five solar system with the goal of finding orbital planets and further characterize the planets velocity, mass, radius and density. To surmount the noise in the data I have generated a simple model of the radial velocity of the star orbit through a least square fit to a sine function.

An attractive question is if there exist life external to earth. The life type we know is dependent on liquid water. Thus, as the data provided by these methods can be used to verify the presence of liquid water on other planets, they can help in reveling this question.

HOW?

Two bodies of relevance

As of 3 September 2020, there are 4,330 confirmed exoplanets in 3,200 systems, with 708 systems having more than one planet [3].

Liquid water could pool on the surface and support life. Earth size planets in the habitable zone surrounding a star.

On May 10, 2016, NASA announced that the Kepler mission has verified 1,284 new planets.[[18]](https://en.wikipedia.org/wiki/List_of_exoplanets_discovered_using_the_Kepler_space_telescope" \l "cite_note-haul_2016-18)

Can I use <http://kelpler.nasa.gov/> as ref?

Some exoplanets have been [imaged directly](https://en.wikipedia.org/wiki/Direct_imaging" \o "Direct imaging) by telescopes, but the vast majority have been detected through indirect methods, such as the [transit method](https://en.wikipedia.org/wiki/Transit_method" \o "Transit method) and the [radial-velocity method](https://en.wikipedia.org/wiki/Doppler_spectroscopy" \o "Doppler spectroscopy). As of 3 September 2020, there are 4,330 confirmed [exoplanets](https://en.wikipedia.org/wiki/Exoplanet" \o "Exoplanet) in 3,200 [systems](https://en.wikipedia.org/wiki/Planetary_system" \o "Planetary system), with 708 systems [having more than one planet](https://en.wikipedia.org/wiki/List_of_multiplanetary_systems" \o "List of multiplanetary systems).[[3]](https://en.wikipedia.org/wiki/Discoveries_of_exoplanets" \l "cite_note-Exoplanet_Catalog_(epc)-3) .

**Methods**

**The radial velocity method**

In this method, the stars velocity relative to an observation point in our solar systems is determined. The velocity is termed radial velocity because it is the velocity component oriented in radial direction from the observer.

In a solar system containing a planet that have a relatively large mass compared to the star the center of mass of the solar system will be localized distal to the star. The star will orbit this center of mass (ref TWO stars??). This center of mass has a near constant velocity with respect to the center of mass of our solar system (ref). This particular velocity is called the peculiar velocity. If there exist a large enough planet in a solar system, the velocity of the star will change relative to us as it orbits the mass center. If there is no planet in the solar system or if the masses of the planets are small compared to the star the center of mass will be in the center of the star. Consequently, such a radial velocity change will not exist.

There are two challenges with the method. Firstly, the earth as an observation point is not in the center of our solar system causing a relative change in velocity of the observation point too. However, this velocity is well characterized and can be adjusted for. Secondly, a more vital challenge is the orbital angel of the star relative to the direction of observation (fig). The orbit of the star forms a plane. The angel of the normal vector to this plane and the line of sight is called the inclination (i). If the inclination is 90 degree the radial velocity measured half way between the stars nearest and most distance point relative to us will represent the orbiting velocity of the star (peculiar velocity must be subtracted). However, if the inclination angle is 0 degree no change in radial velocity can be observed.

The doppler effect can be used to measure the relative velocity of the star as it circulates its mass center (fig). The doppler effect is a phenomenon occurring when two objects are moving relatively to each other. In this situation, light emitted from one object will be observed with a different wavelength at the other object (ref). The observed wavelengths will be shortened if the objects are closing in on each other and prolonged with increasing distance (Hansen 2020). This relation between wavelengths and velocities is given by the doppler formula

Doppler formula

Where v is the radial velocity (relative velocity between the two objects), lamda0 is emitted wavelength and lambda is observed wavelength (Hansen 2020). As lambda0 I have used the H-alpha spectral line with a wavelength of 656.28 nm, which is emitted from the stars (Hansen 2020. MÅ jeg forklare hvorfor??). As c I have used the speed of light in vacuum (ref: tool box 2020).

Diagram

Description automatically generated

**The transit method**

In this method the amount of flux from the star is recorded over time. If a planet during orbit passes between the star and the point of observation the observed flux can be reduced. From the flux change during the transit, the radius of the planet can be estimated (Hansen 2020, maybe fig with expenation). The method depends on knowledge about the radial velocity of the planets orbit. This can be achieved from the masses of the star (m) and the planets (m) and the radial velocity of the star with this equation

Equation v = v m/m

(Hansen 2020). The mass of the star is often known from spectroscopic measurements (Hansen 2020). The mass of the planets can be estimated with

Big equation

Where ….., and the planet orbit is assumed to be circular. Furthermore, the inclination angle is estimated to 90 degree based on the presence of eclipse. Thus, by taking the time it takes from the start of the eclipse to the planets disc is just fully enveloped by the star disk and multiply by the velocity of the planet with respects to star, the following equation reveals the radius

.

(se figure ).

explain more in fig text

From the radius the the volum acan be caculated, and in combination with the mass the density of the planets can be estimated with:

(Hansen 2020).

Additionally, the transits of a planet in front of its parent star's disk relative to observation line, then the flux reduced ,

depending on the relative sizes of the star and the planet.[7]

**Mathematical model of the radial velocity**

If the inclination angle of the star orbit is near 90 degree and circular orbit is assumed the radial velocity follows a sine function (Hansen 2020) as

Function,

where …

To estimate the parameters for the model I used the least square method to make a best fit of the sine function to the data.

In this method the quadratic sum of the distance between the data points and sine function is calculated for numerous combinations of the parameters. The parameters that leads to the lowest value is selected.

Equation

I used the variant of the least square sum based on constant noise over time. The

The method needs a test ranges for the three parameters. This are provided by a computerized algorithm that first select timepoint where the velocity changes sign. Based on this location along the timeline approximate period, P, t0 and maximum velocity is determined. Ranges around P and t0 is +/- 20% of these values. The velocity range is between the max value minus 150% to minus 50% of the average noise level. The necessary number of values in each range was determine by visual comparison of the data with the model fit. The worst area…

**Results**

Peculiar velocity

The peculiar velocity of the five star is calculated by equation XX and the respective data is presented tin table 1. Star 1 and 2 is coming closer to us while the two others appear to move away from our solarsystem.

Table 1. peculiar velocity of the five stars

Km/s or m/s

Qualitative evaluation of the solar systems

In order to build a first impression of solar systems of the five stars I visually inspected a graphical representation the respective velocity of the stars around their centers of mases (subtracted the peculiar velocity), and further the changes in flux over time (big figure). The star 0,1,2,4 show clear periodic changes in the velocity with curve chapes resembling sine functions. This suggest that the center of mas of their solar systems is remote to the star, which further suggest the presence of other objects in their solar systems. As the curves appear to be sinusoidal it is suggestive of a system composed of two objects: one star and one planet of (two body system). The planet also need to be of a size relatively big compare two the star (se equation XX). I can not observe any changes in the velocity of star 3, thus potential other object in its solar system likely have less mass than object of the other star. Velocities in range substance lower than the recording noise, long or very short orbiting times would prevent detection by pure visual inspection.

The noise in the systems seems of approximately same size for all measurements and similar along the recording periods.

Regarding the flux measurements star XX and XX had clear dip in the flux level at two time points with periods similar to their velocity curves ( big fig). The time of the dip is at the location where the stars are in the orbit furthest away from us. These strongly suggest that planets are eclipsing the stars during the orbit. For the stars not showing this dip in flux there are to my knowledge three potential explanations. Either the star has no orbiting planets, planets are not eclipsing, or the planets disc is to small compared to the disc of the star to absorb enough light that we can extract from out of the noise of the data.

Flux data can be used to estimate radius of a planet by the transit method. This method needs time information about the start of the eclipse and when full disc eclipse. A closer look at the flux data of star 0, 1 and 4 show only one data point representing the eclipse time. Therefore, the resolution is limiting the use of this method.

The mas of an orbiting planet can be estimated by equation 5. However, this require information about the inclination angle, which is not easily available. Nevertheless, a system with an eclipsing planet suggest and inclination angle of near 90 degree. A lesser angle will lead to an overestimate of the mass. Thus, using a visual estimation of the radial velocity (the component seen from us) and the periods in combination with knowledge of star mass, we can estimate a lower bound of the planet mass and in the eclipsing planet the estimate might be close to the real mass. See table xx for estimated values and calculation of lower mass limit for the planets.

Tabell XX:

Star 1 and 2 is the eclipsing (comments in table: table II are displayed in table III. The displayed masses of the planets orbiting star 0 and star 1 are estimates of the exact mass3w of the planetw, while the mass displayed for star 4 is only an estimate for the lower bound of the planet’s mass since we don’t know the exact velocity of the star.).

Curve fitting of star velocity

The least square method is used to fit a sine function to the velocity data of star 0, 1,2, 4 (fig..). The resulting parameters of the sine function is presented in table 2. Figure XX display combined data of the recorded velocity and the model.

Quality of the models was evaluated by visual inspection and testing of various N (fig). And if noise is stable along the measurements. Else time dependent noise waited curve fitting would be recommendable.

Mas of planets based on curve fitting meddles are presented in table XX.

This least square method I have used assumes identical noise distribution over time (ref). This can be evaluated base on a visual inspection of the

**Discussion**

Normal distributed data. Central limiting theorem