REPORT

CI 421C

VALIDATION OF TRANSITING EXOPLANETS

Numerical processing of light curves from Muniwin

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Part I

Title of the first part

1 Introduction

An exoplanet also called extrasolar planet is a planet that revolves around a star other than the Sun. Considering the number of stars, there are chances they have planets around them. But planets are small compared to the size of stars, and they do not generate light. Therefore, it is more difficult to detect them. But on October 6th 1995 Michel Mayor and Didier Queloz were the first to detect an exoplanet: 51 Pegasi b. Located in the Pegasi constellation, 51 Pegasi b is approximatively 50 light-years away from us. Michel Mayor and Didier Queloz used radial velocity method to discover the exoplanet and also to determine some characteristics of 51 Pegasi b. But now, we have a lot of different methods to detect an exoplanet. Below, you can see a graphic made by Michael Perryman.

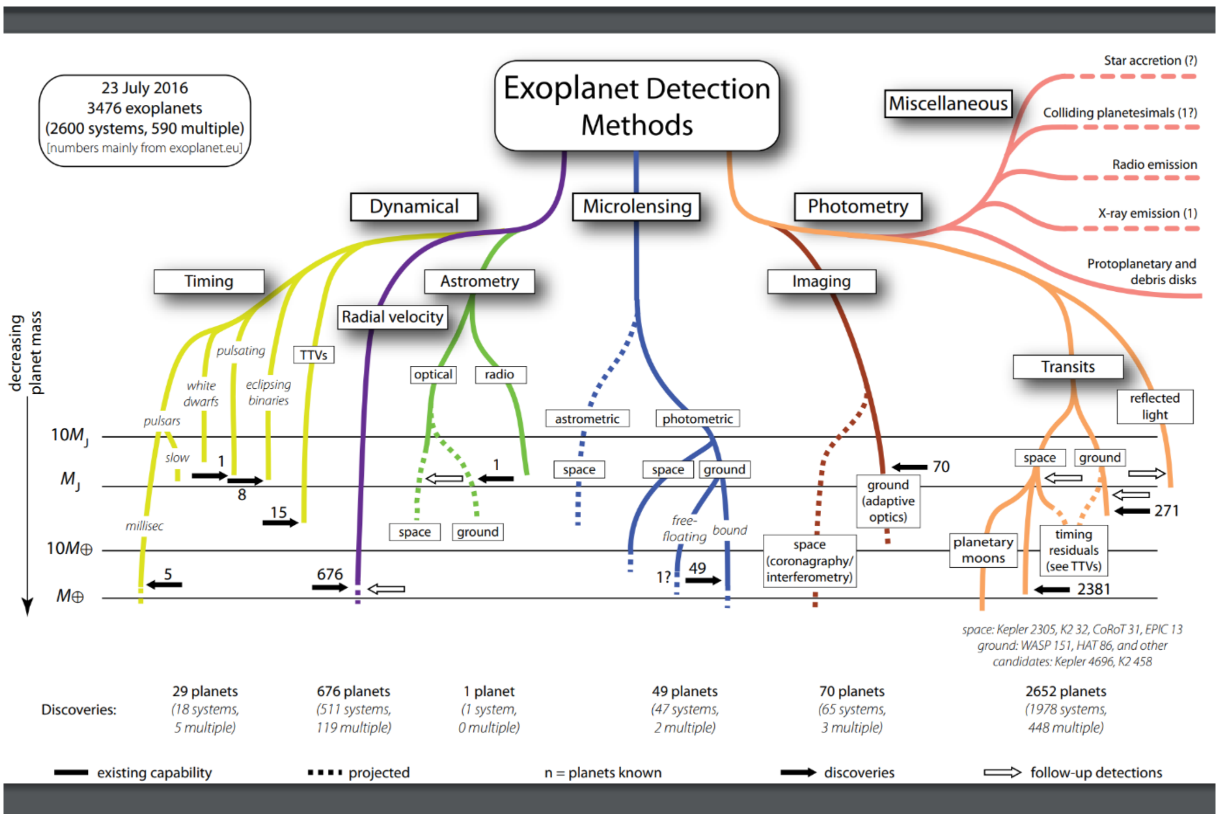


Figure 1: Exoplanet detection Methods

Each one of them have their own advantages and disadvantages. And among them, transits method is easy to do. You can practice this method with tools from Earth. Using a protocol, you can be sure around 100 percent if you discover a real exoplanet.

2 Found exoplanets using transit

2.1 Transit

2.1.1 Transit versus eclipse

Firstly, what is a transit? It's, in astronomy, the passage of a celestial object between the observer and another object. In our case an exoplanet in front of a star. The celestial object (exoplanet) need to have an angle diameter largely smaller than the other celestial object (star). Otherwise it's an eclipse.

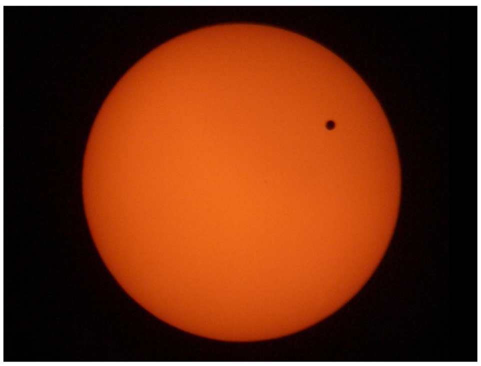


Figure 2: Transit of Venus - A photograph taken at 15:39 Hong Kong time (07:39 UTC) from Tuen Mun, New Territories, Hong Kong.(2004)

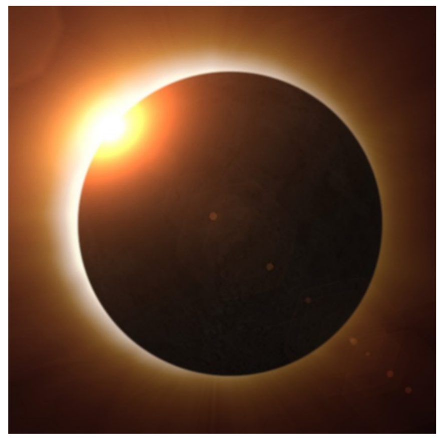


Figure 3: Solar eclipse - credit: NASA/GSFC/CI Lab

2.1.2 Transit to discover exoplanet

Transit is a phenomenon occur when three celestial objects are perfectly aligned. In general case there are a star, an object which is passing in front of the star, and finally Earth where we see a transit.

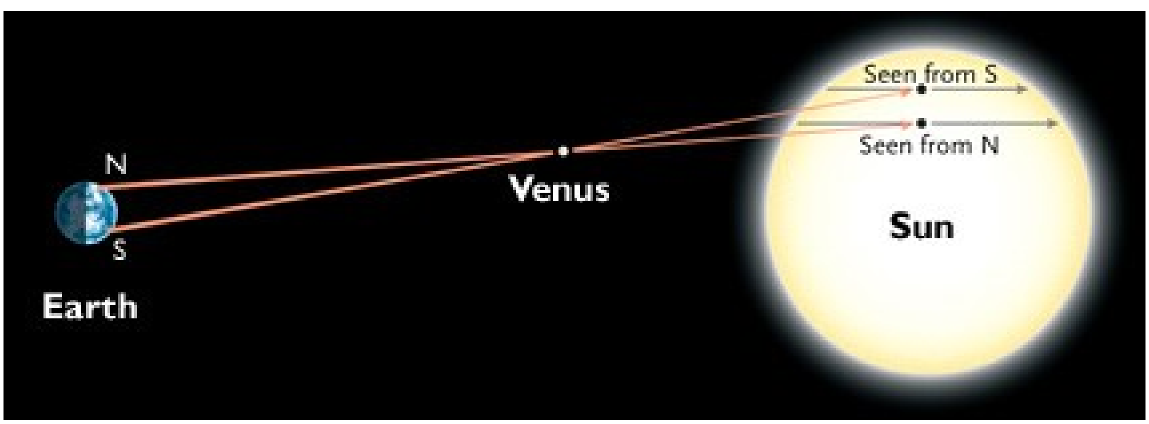


Figure 4: Transit of Venus – Credit: Sky & Telescope illustration

There are four steps during a transition. The first one is when the planet (or exoplanet) beginning to go inside the disc formed by the star. The second is when the planet (or exoplanet) is completely inside the disc formed by the star. The third is when the planet (or exoplanet) beginning to leave the disc formed by the star. The fourth and last step is when the planet (or exoplanet) is totally outside the disc formed by the star. Just below, an example for transit of Venus.

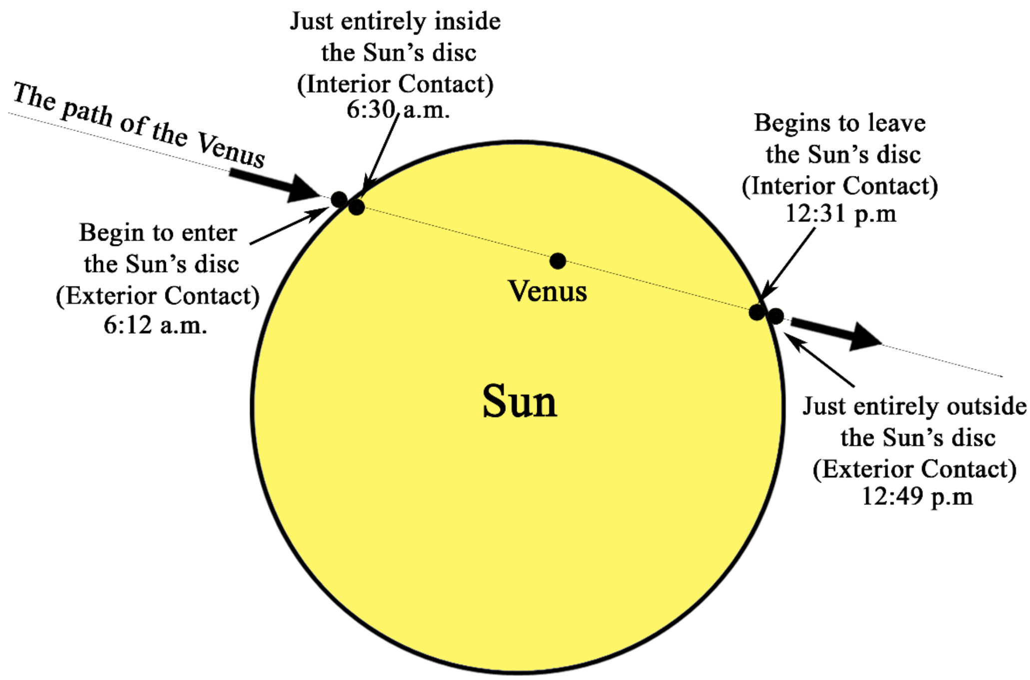


Figure 5: Transit of Venus – Hong Kong Observatory

The main part of a transit regarding to the time is between the step 2 and step 3. Nevertheless, there are a lot of things to do with the beginning end the end of a transit. With this method we can just detect exoplanet who they pass exactly in the angular diameter of the star.

Transit in our solar system can occur only for Venus and Mercury. But how this method can help us to detect some exoplanets? There are a lot of stars in the sky and some of them have exoplanets who sometime are perfectly between his star and us, Earth. From Earth or telescopes around the Earth we can detect when it occurs. But we can't see it like for Venus transit or Mercury transit. Nevertheless, we can detect a variation in the level of intensity of light(energy) coming from the star. We just record flux of light during the transit and we can deduce lots of things with this. Transit is a photometry method. Photons is light particles and they have some energy. There are a difference of energy coming from the star when a planet hides a (small) part of the star and stop the light before it comes to us. We can plot a curve we called "transit light curve".

2.1.3 How naming an exoplanet?

An exoplanet is named in function of his star and the number of exoplanets already discovered around this star. A star is the first thing we plot in the name. The name of the star is considering to be "name of the star "a"". So, exoplanet begins at "b" for the first planet discovered, after it's a "c" etc. For example, Kepler 4 is the star and b is because it's the first exoplanet detected (Name of the exoplanet: Kepler 4b).
The nomenclature is a system using to name a body or a part of a body to easily know some information about the body only reading the name of the body. The international union of astronomy created in 1919 uniformed the nomenclature

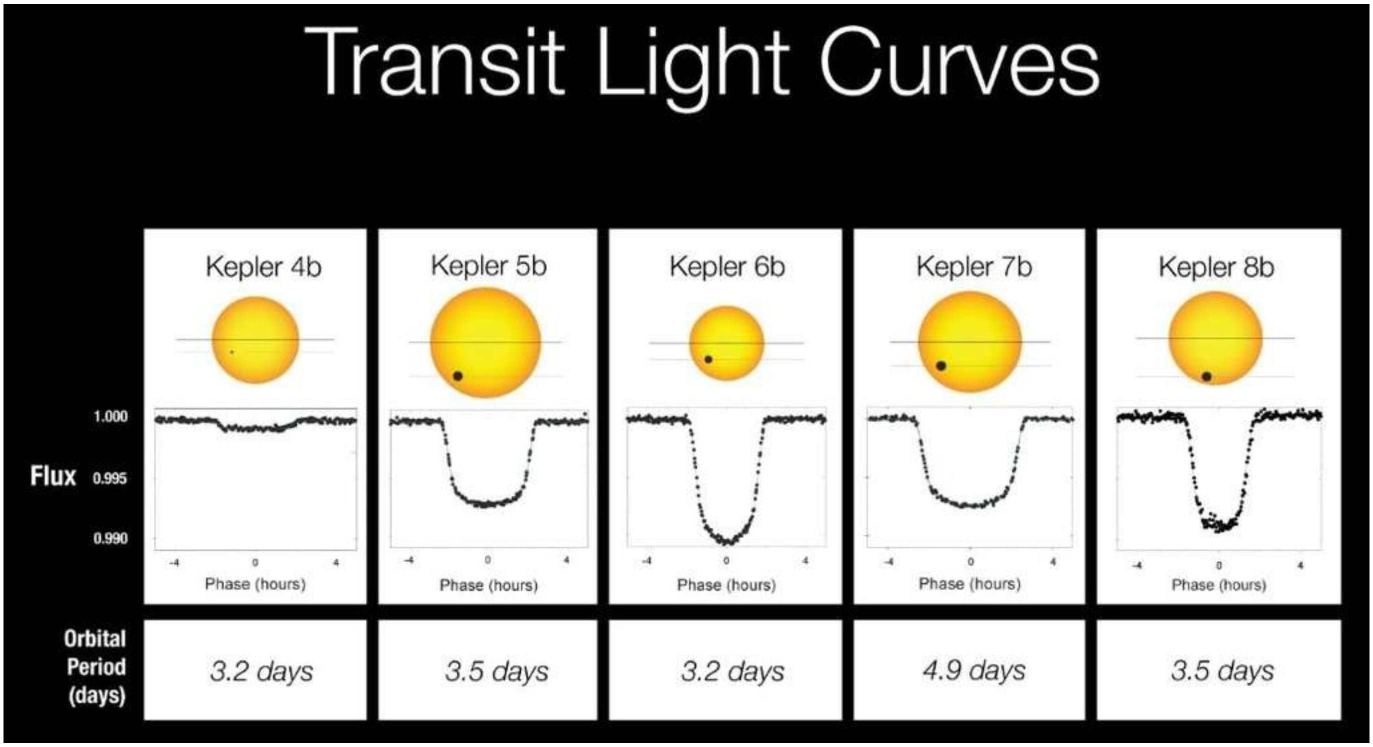


Figure 6: Different transit light curves for different stars by the telescope Kepler. Credit: Nasa

of celestial body.

2.1.4 Transit light curve

To determine if an exoplanet is passing in front of the star, if there are a transit, we record the variation in the flux of the light coming from the star to us. We use the photometry to measure the intensity of the flux of light. We use for this a CCD camera to record the transit and plot the transit light curve. A CCD camera is a photodetector who is converting photon to electron. More photons come to the CCD camera, more the current is high in the detector. Therefore, variation of light is converting in variation of current. We plot this variation in function of the time, and we get the transit light curve. That is the theory. But variations of the light are very small, around 0,02 magnitude. (Magnitude is a scale to measure the light of a star. The Vega star have a magnitude of 0, Neptune have +8, the Sun have -26 magnitude. More the magnitude is high, less light is coming to your eyes.)

So, the variation of magnitude is also very small. Therefore, there are frequently much noise in the recorded data. There are lots of parameters who modify the possible noise during the transit. There are some things to know and consider to choose a good condition transit to record a workable data.

2.2 Observation conditions

To beginning, the most important thing to have a beautiful light curve is to have a light curve. So, if there have some clouds in the sky, it's finish. We cannot see the star so we cannot study it. Weather is the first thing to look at. The magnitude variation is very small, so we need to be precise. A transit duration is around 2-3 hours. Therefor we need to consider the rotation of the Earth during this time. If the star is under the treetops that's very disappointing. We must consider the Light coming from the Sun and the Moon. If the Sun is near our star during the transit (sunset for example) we should have a lot of noise. Is the same for the Moon. If the Moon is bright near our start or if it's a full

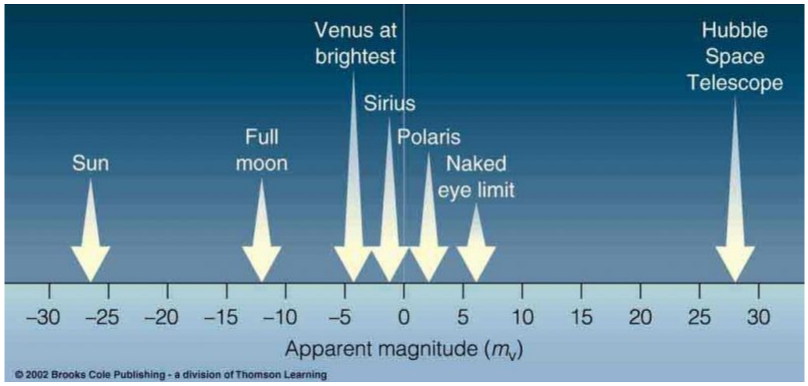


Figure 7: Apparent magnitude scale - EarthSky.org

Moon, the light from the Sun who coming to the Moon who coming in our CCD will generate some noise. Globally, all unwanted light we want to reduce. Like light pollution from cities. To keep far from this light, we need to keep a great incline from the horizon. The light form cities is on the ground so if we look up it could be good. The light pollution is less concentrated. Also, we need to know the transit duration for the same reason as the treetop but for the cities light. We need to consider the thickness of the atmosphere who is not the same at each point of the Earth, and it depend of the incline we have. And this incline changing during the transit due to the rotation of the Earth. Longer is the transit duration, higher is the variation of magnitude due to atmosphere thickness. Therefore, once we choose our location, we choose the star in the transit database and we choose a star who is not near the horizon during it's transit, we look if the Moon is not near our star, same for the Sun regarding to the time of the transit (close to the sunset or early in the morning). If these parameters are good, we just hope to not have some clouds during the transit. Or, have a telescope in the space.

2.3 Protocol

To be able to record data and use them we need to follow a precise protocol to affirm if we recorded an exoplanet transit. To do it, firstly we look for an exoplanet transit in ETD (Exoplanet Transit Database) to find a transit who occurs with good condition for us. Once we chosen an exoplanet transit, we record the transit with telescope. Now, we need to compute data. Using MUNIWIN and the protocol, we can affirm if yes or not the transit we recorded is a transit of exoplanet or if is not acceptable.

3 Wasp-43b

WASP-43 b is a transiting planet in orbit around the star WASP-43. This star is a young and low-mass star in the constellation SEXTANS. This exoplanet is a Hot Jupiter with the orbit closest to its star. Its mass is twice than Jupiter's mass.

It was the SuperWASP program that determined that WASP-43 was a candidate for the detection of exoplanets by the transit method. This star was first observed by WASP-South at the South African Astronomical Observatory in 2009. Then, observations by the two programs WASP-South and WASP-North led to the collection of 13768 data points in 2010, then to the use of CORALIE at the observatory of La Silla, in Chile. CORALIE is a scale spectrograph installed in April 1998 on the Leonhard-Euler Swiss telescope and intended mainly for the search for exoplanets using the radial velocity method. The radial velocity method confirmed that WASP-43b was a planet, also revealing its mass.

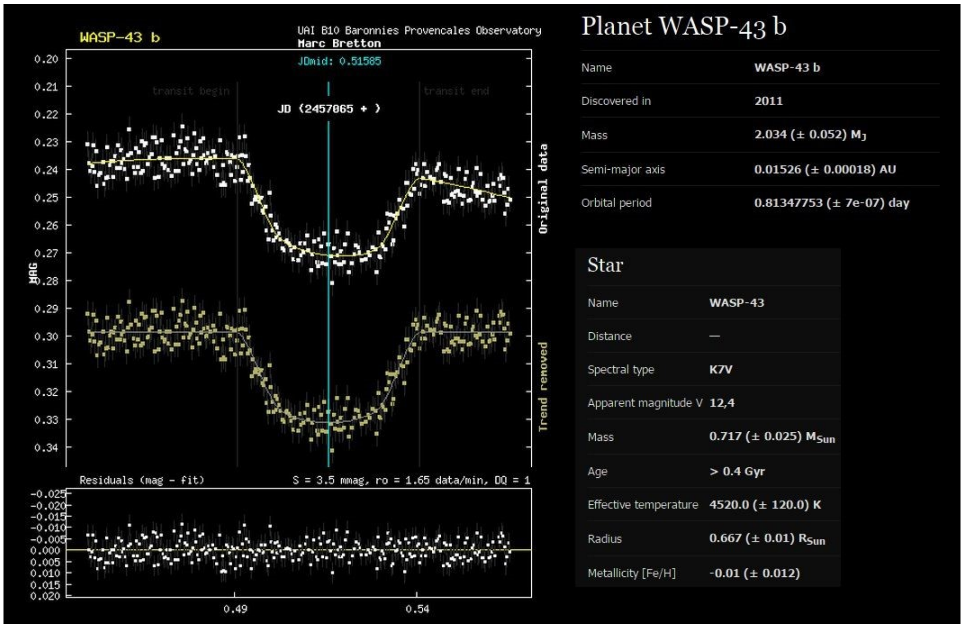


Figure 8: The transit light curves of WASP-43 b

4 About Exoplanet

4.1 TOI 700d

NASA announced that its satellite TESS had made it possible to discover a new planet the size of Earth and at a distance neither too close nor too far from its star for liquid water to be present maybe. TOI 700 d was the first exoplanet discovered by TESS. The planet is close to us: a hundred light years away TESS or “Transiting Exoplanet Survey Satellite” is a small space telescope dedicated to the search for exoplanets launched on April 18, 2018. The system was nearly missed by TESS, but several amateur astronomers and a high school student Alton Spencer, discovered an initial classification error. The discovery was finally confirmed by the Spitzer space telescope. TESS fixes a part of the sky to detect if celestial objects pass in front of stars. This passage causes a temporary decrease in brightness of the star which allows TESS to infer the presence of a planet. The TOI 700 star is small. TESS discovered three planets around this star, named TOI 700 b, c, and d. Only the "d" is in the habitable zone. It is almost the size of the Earth and orbits its star in 37 days. It receives 86To predict the composition of the atmosphere and the surface temperature, the researchers generated models based on the size and type of the star. One of the models is an ocean planet with "a dense atmosphere dominated by carbon dioxide, similar to what Mars looked like when it was young, according to scientists” assumptions". A face of this planet always faces its star, a phenomenon called synchronous rotation. According to this model, this face would be constantly covered with clouds.

4.2 Trappist 1

NASA announced that of an extrasolar system made up of a red dwarf, Trappist-1a, and seven potentially rocky planets. This system is located 39 light years from home. Three of them meet optimal living conditions that is why this system is one of the most promising leads in the search for extra-terrestrial life. The first three planets (b, c and d) were detected around the star 2MASS J23062928-0502285 in the constellation Aquarius in 2015. This first discovery was made by the planetary transit method. This method makes it possible to determine the size of the exoplanets studied, their orbital period and their density. In 2016, the other four planets (e, f, g and h) were discovered, by the same telescope. T The telescope which allowed the discovery of planets is called Trappist, for Transiting planets and planetesimals small telescope. For this reason, the system was named Trappist-1, and its star renamed Trappist-1a.

WASP-43b	
star	WASP-43
mass	3,38*10^27 kg
mean radius	66488 km
semi-major axis	0,0142 ua
orbital period	19,5 hours
eccentricity	0,0298
inclination	82,33

	WASP-43	SUN
Type	K	G
Distance	261 al	1 ua
Temperature	4 400 K	5 778 K
Mass	1,154*10^30 kg	1,989*10^30 kg
Radius	647596,2 km	696340 km
Age	598 MM ans	4,603 MMM ans
Magnitude	12,4	4,74

Figure 9: some figures of the planet, its star and the Sun

This star is a red dwarf. This kind of stars are not very bright and not very massive, so difficult to find. Thus, Trappist-1a represents only 8

Because of their distance close to their star, the researchers observe that these planets make a turn on themselves in a single orbit, thus always showing the same face to their star: synchronous rotation. We also observe that the planets Trappist-1e, f and g orbit the habitable zone of their system. It is possible that these three planets shelter water in a liquid state. These exoplanets encounter a problem: their red star bombards them with solar radiation powerful, which is a hindrance to the onset of life. Trappist-1a is young for its planets to harbor intelligent life. This star is only 500 million years old. Maybe, a primitive life form may already exist on the planets of Trappist-1.

Part II

Python Implementation

5 Introduction

The work present in this report is the continuation of the work made by Abhishek MAURYA, Marco INCHINGOLO and Sharon Xavier in 2018 for their PMI. Their work consist in analysing data of WASP-48b from Muniwin to get information about the planet such as semi-major axis, inclination, impact parameter etc. To achieve it, they designed a Matlab program witch only work for specific data.
The next step explicited here is to rewrite the code in python to make the code more accessible, and to work with any data set. To achieved the program the library used are:

- matplotlib
- PyQt5
- scipy
- datetime
- numpy
- pyvo
- sympy

They need to be installed just like python3 to make the program work. Another way to use the algorithm is to launch the application **.exe** (solution only available for windows). The program read **.txt** files obtain from **Muniwin**. The data-set in this files is the magnitude of the star, reference stars and errors.

The software take data enter by the user and compute it to calculate:

- Planet radius
- Planet mass
- Star density
- Star mass
- Depth of the transit
- Total duration of the transit
- Full duration
- Impact parameter b
- Semi major axis a
- Inclination

For the proper functioning of the program, the transit data must be complete, with points before and after the beginning of the transit.
The program can be find here: `https://github.com/pwnorbitals/TrAS`.

6 Data optimisation

The data composing the light curve can be diffuse, noisy. One of the possibilities to smooth the curve is the moving average. however it is not used here. The implementation of a 1D gaussian filter was made through the numpy function **gaussian_filter1d**.
The propose of it is to smooth data but modifying the input signal by a convolution with a Gaussian function characterized by a standard deviation which can be modify by the user.

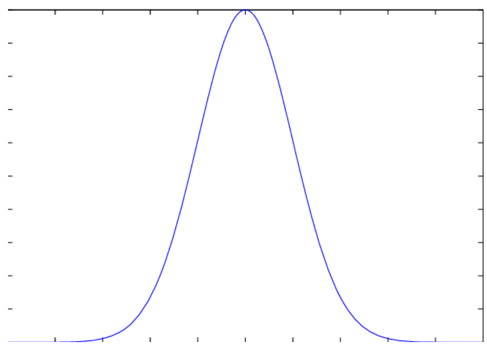


Figure 10: Impulse response of a typical Gaussian filter

The result is a smoothed curve, and therefore more easily usable.

7 Fitting

Once the data is optimised, the objective is to approximate the light curve as the basic analytic light curve shown in figure 12. The standard error is calculated depending on the number of data points and can be changed by the user. Finding peaks in the standard error allows to considered the curve between two peaks as a linear function $y = ax + b$. We added a constraint to link each linear approximation to the previous one.

Figure 11: Fitting example

For each part, the time data is subtracted by the first time value in order to have a time series beginning by 0. Considering $Y_c = ax + b_c$, we set a constraint on the b_c for the linear regression (b_c is equal to the previous intensity).
This constraint forces the linear regression to adopt an appropriate a value. Then, the linear function has to be moved to its real time interval. This is done by computing a new $b_r = b_c - a * t$.
So now, the appropriate linear function is $Y = a * t + b_r$ which gives the representation on the left.

8 Calculation

8.1 Parameter deduced from the curves

Once the fitting is done, we want to calculate an approximation of basic parameters from the system (the star and its planet). As we have the light curve, we can compute the depth of magnitude, the set of transit's time (see the figure below).

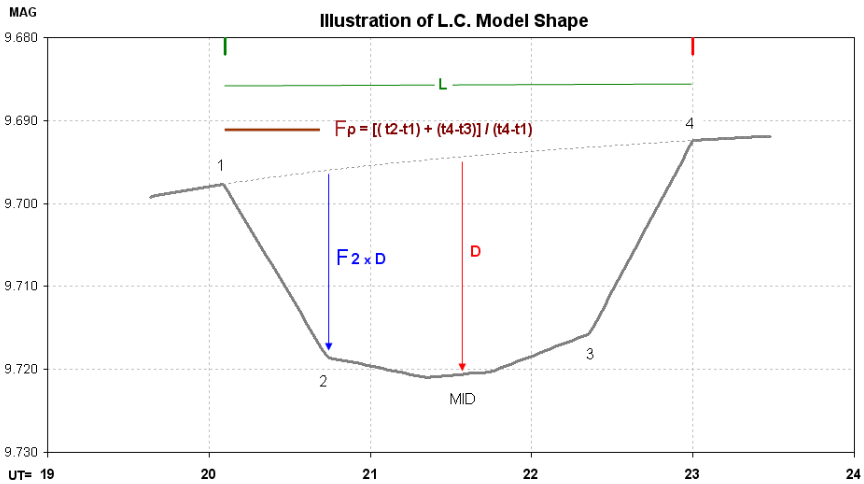


Figure 12: Transit light curve data

The graph we computed is composed of multiple segments, theirs ends are not linked between each others. We can compute the depth and the four times nodes by using functions that we explain in the next section.
As our predecessors, we will need the Star's radius (in kilometers) and the orbit's period (in seconds). First of all, we need the depth Then we use the formulas below.
The planet's radius is obtain by :

$$R_p = \frac{\sqrt{Depth}}{R_*}; \tag{1}$$

The impact parameter b and the semi-major axis are given by :

$$b = \left\{ \frac{(1-\sqrt{Depth})^2 - \frac{sin(t_F\pi/P)^2}{sin(t_T\pi/P)^2}(1+\sqrt{Depth})^2}{1-[sin(t_F\pi/P)^2/sin(t_T\pi/P)^2]} \right\}^{1/2} \tag{2}$$

$$a = R_* \left\{ \frac{(1+\sqrt{Depth})^2 - b^2[1-sin(t_T\pi/P)^2]}{sin(t_T\pi/P)^2} \right\}^{1/2} \tag{3}$$

Then the slope can be deduced :

$$i = cos^{-1}(R_* b/a) \tag{4}$$

Those are the main parameters that transit's light curve allows to compute with relative precision. The following parameters are less precise, we added them in the program though the order of magnitude is often 10^{-2} from the real magnitude.

$$\rho_* = (\frac{4\pi^2}{P^2G}) \left\{ \frac{(1+\sqrt{Depth})^2 - b^2[1-sin(t_T\pi/P)^2]}{sin(t_T\pi/P)^2} \right\}^{3/2} \tag{5}$$

$$M_* = \frac{4}{3}\pi R_*^3 \rho_* \tag{6}$$

$$M_p = \frac{4\pi^2 a^3}{P^2 G} - M_* \tag{7}$$

8.2 Function

Now that we have the formulas, we need to find a relatively accurate method to find the nodes and the depth of magnitude. Those will be critical in the calculation of the parameters. Our program makes a mobile mean of the data, then slices it (depending on the resolution and the custom-able parameter K) into multiple segments. From there we take all the extremities of each segment.

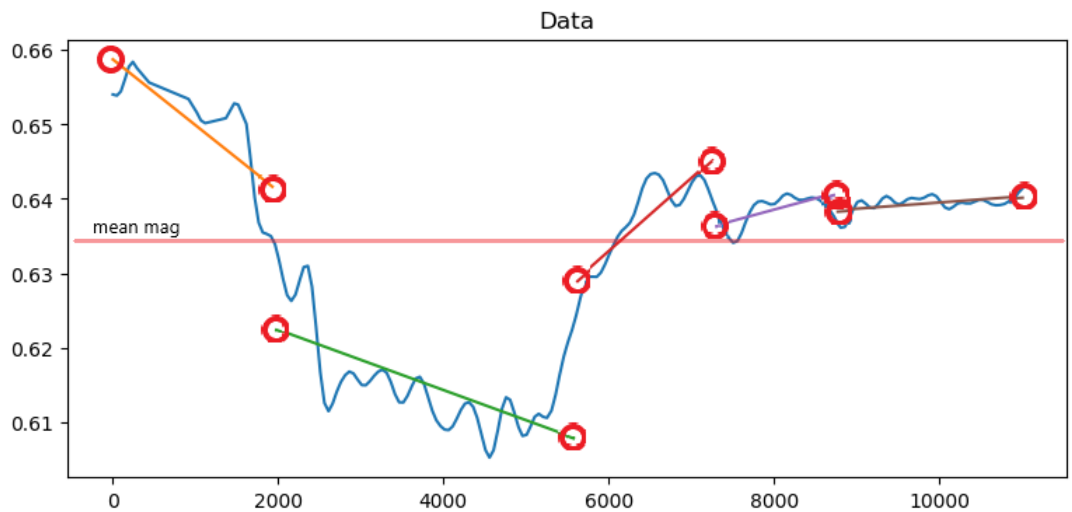


Figure 13: Segmentation of the light curve:
This figure is from an old version where the linear functions weren't constrained. Though, the presented algorithm works the same

Considering a simple mean of the Y-value (magnitude), we can separate the data points in two side: above and below the mean magnitude. Then we can compute :

- t_1 corresponds to the last point before the curve goes below the mean;
- t_2 corresponds to the first point when the curve is below the mean;
- t_3 corresponds to the last point when the curve is below the mean;
- t_4 corresponds to the first point before the curve goes again above the mean;

Then the depth of magnitude is derive from a second mean calculate with the magnitude points above the global mean, subtracted to the minimum magnitude below the global mean.

9 Getting started with the software

The graphical interface without any import data look like:

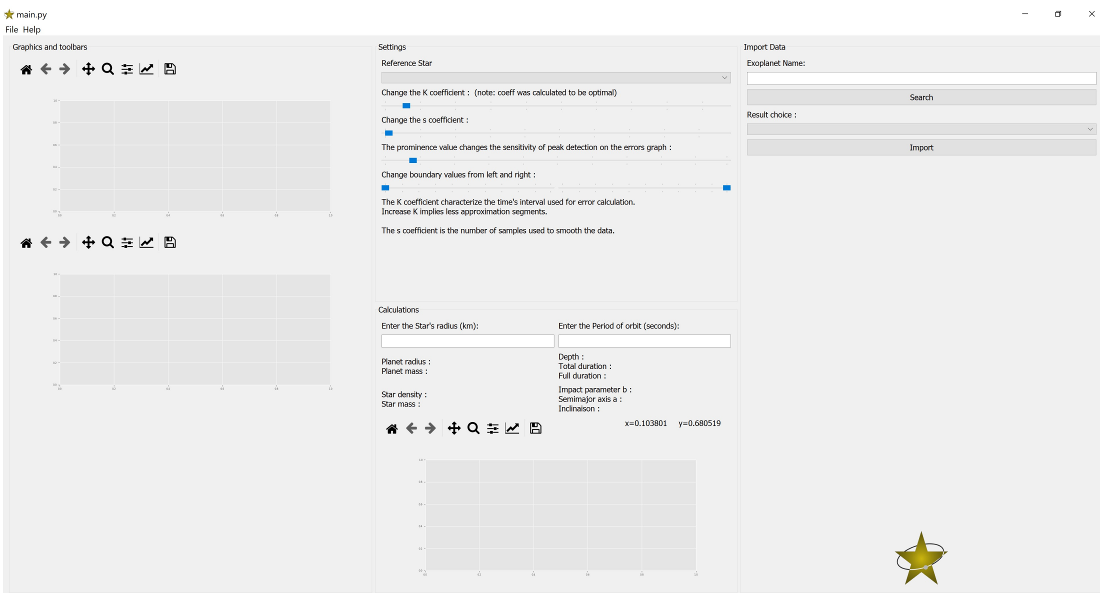


Figure 14: Program without data

On the left there are the **Graphics and toolbars** section of the software, the light curve and other information will be shown here. Each graphic has its own toolbars witch allow the modification of the display without the modification of the data, the usage will be explain later. The first graphic shows the data computation and the second one standard errors.

In the center, in the subsection **Settings** are present:

- Reference star choice: allow user to select one of the reference star present in the data file.
- K slide bar, K characterize the time's interval used for error calculation.
- S slide bar, s: the number of samples used to smooth the data.
- Slide bar to change the sensitivity of peak detection on the error graphic (bottom one).
- boundary slider, to changes the boundary values.

In the subsection **Calculations** we can find:

- Two inputs fields witch allow data entry needed for further calculations.
- Text field that display the results of the calculations.
- Graph where will be show the analytical light curve.

The last subsection of the software is **Import Data**. It's permit to automatically find needed data: the star radius and the period of the orbit. The data is imported from: `http://voparis-tap-planeto.obspm.fr/tap`

9.1 Import Data

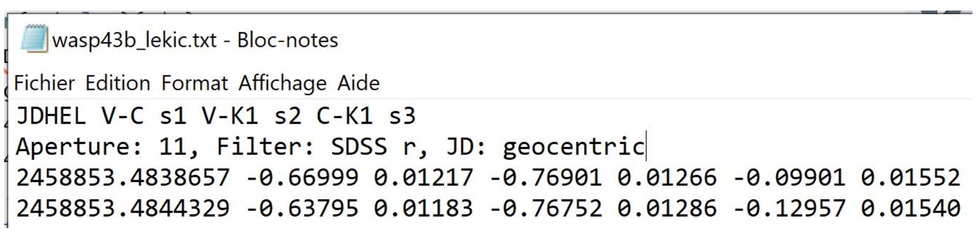
This part shows the importation function of the software. The software data feeding is based on the file format from Muniwin.

JDHEL	V-C	s1	...
Aperture:	11,	Filter:	...

Therefore, the program takes into account the headers. The second line is not taken in account, though the first line arguments are used as an index (JDHEL and V-C) to get times and magnitudes. To summarize, the file needs to be a .txt, the first line must have the arguments "JDHEL" and "V-C", a second line without data as time or magnitude, then the rest is the data.

JDHEL	V-C
Ignored	line
2458853.4838657	-0.66999
2458853.4844329	-0.63795
....	....

So, make sure your file header looks like that:




```
JDHEL V-C s1 V-K1 s2 C-K1 s3
Aperture: 11, Filter: SDSS r, JD: geocentric
2458853.4838657 -0.66999 0.01217 -0.76901 0.01266 -0.09901 0.01552
2458853.4844329 -0.63795 0.01183 -0.76752 0.01286 -0.12957 0.01540
```

Figure 15: Header file

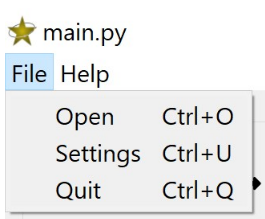


Figure 16: Menu bar

To import your data into the software you have to go to **File>Open** or use the shortcut **Crtl+O**.
Make sure to open file generate by Muniwin with **.txt** extension. We can also notice the option "Quit" which can also be used with the shortcut **Ctrl+Q**.

With open data, the window look like the representation in the figure bellow:

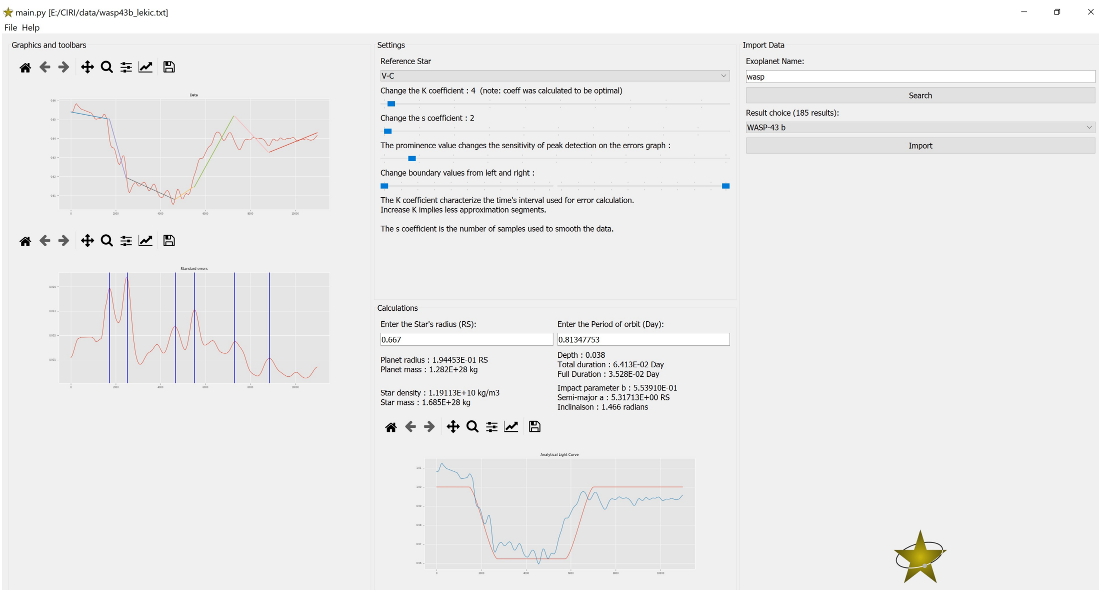


Figure 17: Open data

The path to your data appears on the top next to the software name. The first graphic show the smooth data with the fitting curves. the second one show the standard error.

9.2 Data manipulation

Once the data is imported, you can use the multiple sliders to modify the different value involved in the computation. To rightfully set up the sliders, the graph with the analytical light curve can be used to get feedback on the modified data.

- The box allows you to choose which reference star (column of intensity values) to compute;
- The K slider is use for the cutting of the data. It will determine the number of peak you want to find;
- The s slider is about the mobile mean of the raw data (determine the number of point to consider for the mean);
- The prominence slider changes the sensitivity of the program to find peak. In other terms, this can change the number of peaks;
- The interval of data used can be reduce by using the two last sliders;

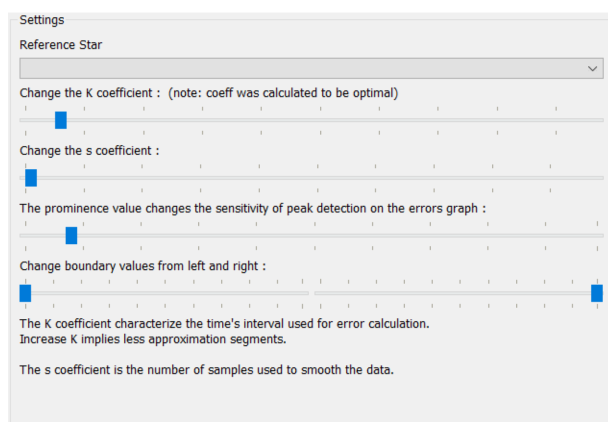


Figure 18: Sliders

9.3 Calculation

To allow the calculation of:

- Planet radius
- Planet mass
- Impact parameter b
- Semi-major a
- Inclination
- Star density
- Star mass

The star radius in kilometers and the orbit period must be entered. the default value is 1. To set them up we have two possibilities:

- Enter them manually thanks to entry fields in the subsection **Calculations**
- Use the subsection **Import data**

The changes in the sliders influence the results of parameters itemize above. Make sure to memorise the K coefficient calculated by the software if you planed to change it.

A new feature has been added in the last version of the software. You can now choose which units to use for the characteristics of the system (star's radius, period, inclination, etc). You can click on **File** or use the keyboard shortcut **Ctrl+U**.
One have to keep in mind the importation of data presented earlier while automatically change the units of length and time to Solar Radius and Days.

9.4 Graphics

Above the graphical representation of the data, there are toolbar from the matplotlib library. The functions present inside allow to manipulate the graphics without modify variables present in the right part of the window.

Figure 19: Matplotlib toolbar

- House icon: Come back to the first representation/position.
- Right and left arrow: undo option, use to navigate between your changes.
- Four arrow cross: displace the graphic.
- Magnifying glass: zoom, you have to draw a rectangle to zoom.
- Setting icon: modify borders and spacing.
- Graphic arrow icon: modify the curve rendering options such as color, size or line type.
- Save icon: Export data to image.

9.5 Unit change

The modification of the unit for the result display by the program is very easy. Select wanted unit next to the the result thought the scrolling menu.

10 Possible improvements of the algorithm

10.1 Automatically download needed data (already implemented)

Since catalogs are organized data structure, a possible improvement will be to automatically download needed data. The internet connection have to be take in account. In fact, it's still have to remain possible to input data manually, the user doesn't necessary have internet connection. Therefore two possibilities have to be present:

- download data: induce the input of the name of the star
- set up the data manually

Error handling must be implemented. An error can occur due to internet connection or the wrong star name.

10.2 Noise reduction

Currently the noise reduction is achieve through 1D Gaussian filter. However **Muniwin** generates date error which can be used to reduce noise. Yet, the software Muniwin can be assimilate to an black box, so we can't really know what is inside or how the error data is calculate.

10.3 Code structure

For a better reading of the code it would be wise to create a UML diagram in order to reorganize the functions in class. (Already started)

10.4 Model of analytical light curve

The program already plot an analytical light curve based on the Mandel & Agol model. However, some of its where proven wrong in recent article [12]. Even if this errors are not significant in our case, there is other models which could be implemented as the models in this two articles:

- N. Winn, 2014 September 24.
  Transits and Occultations
- Giménez, 2005 December 29, Astronomy & Astrophysics, 450, 1231-1237.
  Equations for the analysis of the light curves of extra-solar planetary transits

Also, using another model might reduce the computation time.

10.5 Use of thread to avoid slow down

One of the most time consuming part of the software is the calculation of the analytical light curve as it involves calculation of elliptic integral. For now on, the program makes all the calculation (data optimisation, peaks finding, parameters, analytical light curve) when one slider is changed or a value is entered by the user.
Using thread to compute in parallel the analytical light curve or separate this part of the software from the first analysis are possible improvement.

Part III
Data Comparison

In this part we will present our results. For tres-1b, comparison to the real parameters and the previous work of our predecessor.

	Theoretical Values	Previous Values	Obtained Values	Last Version
Depth	0.0170	0.0181		0.017
Impact parameter b	0.229	0.8611	0.18722	0.765
Semi-major axis	5879196	5191022	5997140	2363919
Inclination	88.5	84.37	88.94	76.92
Planet's radius	77211	79721	122123	91781
Planet's mass	1.4236e+27	3.85e+30	5.936e+27	3.347e+27
Star's mass	1.7499e30	5.05e+30	7.798e+27	4.397e+27

The result with data of wasp-43b is present bellow. Results are obtain without any change in the slider, but an better approximation can be obtain with the manipulation of some parameters (Theoretical values from expolanet.eu):

	Theoretical Values	Obtained Values V1	Obtained values last version
Impact parameter b	none	0.437883	0.55391
Semi-major axis	2 289 000	4.13343e+6	3 702 530
Inclination	82.33	85.773	83.9956
Planet's radius	72 427	156 570	135 405
Planet's mass	1.4236e+27	1.784e+28	1.282e+28
Star's mass	1.42606e+30	2.344e+28	1.685e+38

The program work properly only with complete data curve. The calculations present a lot of variation on certain values. The differences can be due to the approximations and errors that the algorithm have to compose with. Better approximation can be obtain with the use of sliders, but the implemented solution is not precise. However, the real value we have to obtain are the transit time and time at the beginning and at the and of the transit, which are reliable.

Part IV

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