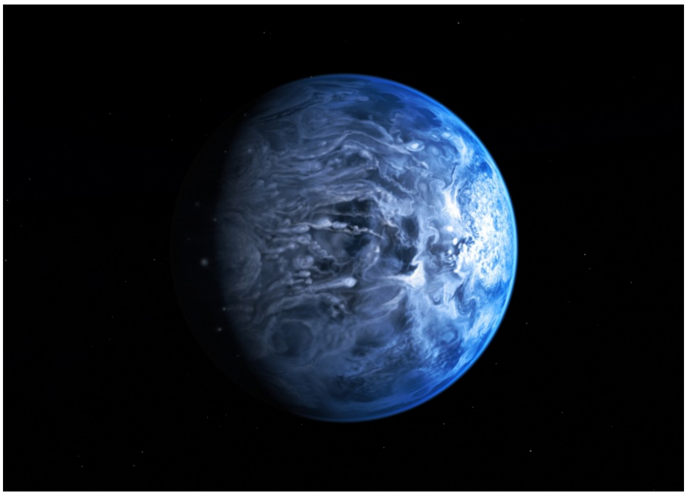
Validation of Exo planet Transit by Differential Photometry



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ABSTRACT

The detection of exoplanets has reached its apotheosis since the first one was detected in 1995. Spatial telescopes, constantly inspecting the Night sky are at the forefront of exoplanet detection. Several optical Techniques combined with advanced signal processing algorithms allow observational astronomers to validate exoplanet transit.
Specifically, differential photometry consists in measuring a star's change in magnitude over time in order to characterize the exoplanet orbiting it.

INTRODUCTION

The distinct method of transits is widely used to detect a subsequent exoplanet. When an exoplanet passes a star, the luminosity received on Earth from this star decreases. Using CCD sensors, the brightness drop can be measured and then, using mathematical formulas and another method called radial velocity method that will not be developed here, some information about the Exoplanet can be deduced such as its radius or distance to its star.

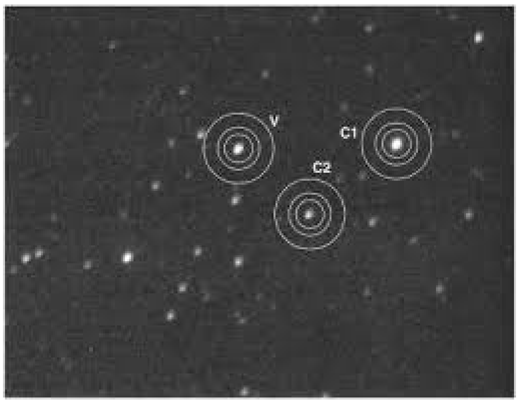
The aim of our PMI was to observe, capture data (with a CCD) and obtain subsequent characteristics of an exoplanet transit. To observe the transit, we would have used the TJMS (Telescope Jean-Marc Salomon) in Buthiers near Fontainebleau, but due to the bad weather conditions we were not able to do so. Because of this we used data obtained from previous observation provided by our PMI tutor Anica Lekic.
Thus, the underneath observations have been done for the following stars:EPIC211089792, TRES-1B and also some examples of data elaboration done for the star WASP-48b.

SUMMARY

1. LITERATURE REVIEW

1.1 Differential Photometry

Differential photometry is the simplest of the calibrations and most useful for time series observations. When using CCD photometry, both the target and comparison objects are observed at the same time, with the same filters, using the same instrument, and viewed through the same optical path. Most of the observational variables drop out and the differential magnitude is simply the difference between the instrument magnitude of the target object and the comparison object (ΔMag = C Mag – T Mag). This is very useful when plotting the change in magnitude over time of a target object, and is usually compiled into a light curve.



The differential photometry technique consists in obtaining measurements on the main target (the expected variable star, V) and one or more reference stars (the comparison stars, Ci). Then, the magnitude differences V-C1, C2-C1, etc., relative to the main comparison star C1, can be determined and the changes in luminosity of V are revealed. The rest of the comparison stars (C2, C3, etc) are used as check stars, to make sure that the variability that we are measuring comes effectively from the main target V, and not from C1.

1.2 The Basic Photometry equation

The following equation shows the basic parameters necessary for measuring a star's flux :

$$\boldsymbol{Mag = Z - 2.5 \times LOG10\,(Flux\,/\,g) - K' \times AirMass + S \times StarColor}$$

Where,

Z= a zero-shift constant, specific to each telescope system and filter (which should remain the same for many months)

Flux= the star's flux (sum of counts associated with the star)

g= exposure time ("g" is an engineering term meaning "gate time")

K'= zenith extinction (units of magnitude)

S= "star colour sensitivity." S is specific to each telescope system (and should remain the same for many months)

Differential photometry is more accurate, able to achieve SE ~ 0.025 to 0.030 magnitudes, for example. As a minimum, this can be done using images with two filters of a star field that includes one star that is calibrated (has known magnitudes for the filter bands in question). Using the calibration star it is possible to determine magnitudes for all other stars in the image. If only one star in the image is calibrated, however, results will be marginal and it will be necessary to employ Differential Photometry Method #1, which in turn assumes that the telescope system has been calibrated using Landolt stars. If, on the other hand, the target star image set includes in the FOV several calibrated stars ("comp" stars), it is possible to perform differential photometry of the target star(s) without having performed Landolt star calibrations of the telescope system. For this case the several calibrated stars can serve to establish approximate values for star colour sensitivities and zero shifts. Accuracy won't be as good, but until the Landolt star calibration is performed it's the only alternative.

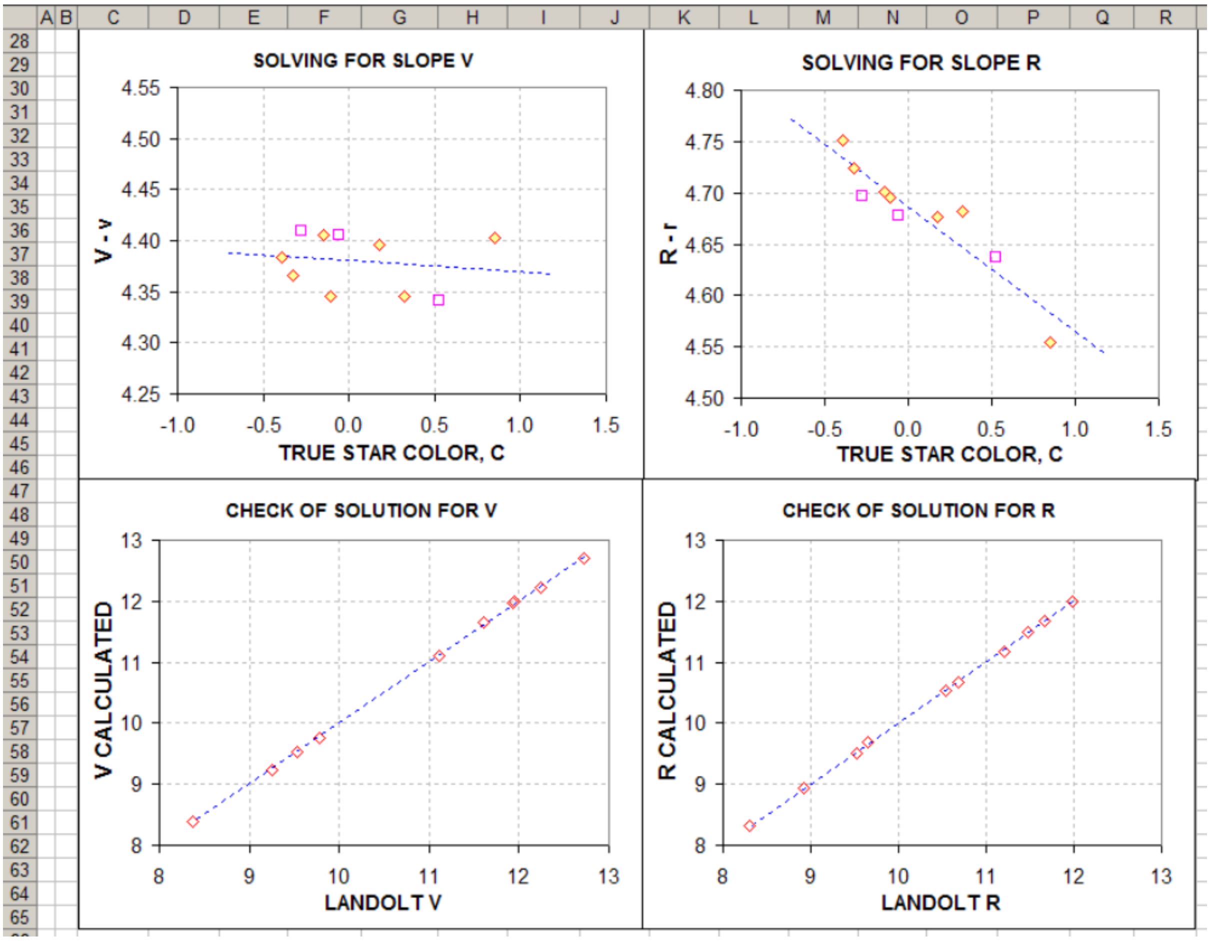
1.3 Calibrating a Telescope System

Typically more than a half dozen stars are required to obtain a useable version of the telecope system's "star color sensitivity parameters" Sv and Sr (or Sb for B-band, Si for I-band and Sc for clear). These are known as S-parameters; they're the only parameters that need to be calibrated ahead of time in order to use this differential photometry method. It is recommended that frequent (at least twice yearly) calibration of the S-parameters is done.

S-parameters can be determined by observing a group of calibrated stars that fit within a FOV, for which the many Landolt star fields are ideal. The calibrated star fluxes are measured and used to produce instrumental magnitudes. Differences between true and instrumental magnitudes for a filter band are plotted, and the slope to that plot corresponds to the S-parameter for that filter. Real observations of two Landolt star fields were used (L0652, for example, is the terminology for Landolt star field at RA = 06:52).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1		This spreadsheet is for determining Sv and Sr from flux readings of Landolt stars																	
2			Enter fluxes in aqua-colored cells																
3			Adjust Zero-shifts (O7 & P7) until average diffs are zero (O8 & P8)																
4			Verify quality by viewing 4 plots & RMS performance (Q23 & R23)																
5			Start with an image set of M67 or Landolt stars & measure their fluxes																
6																Calculated V & R			
7									Instrument mag's							19.381	19.686		
8			Landolt	True V & R			Star fluxes									0.000	0.000	Set manually	
9			Field	V	R	C	V	R	v	r	V-v	R-r	C*v-V	C*r-R	C^2	V'	R'	diff V	diff R
10		1	L0652	8.378	8.307	-0.329	248490	368720	4.012	3.583	4.366	4.724	-1.437	-1.554	0.108	8.396	8.309	0.018	0.002
11		2	L0652	9.539	9.530	-0.391	86669	122553	5.155	4.779	4.384	4.751	-1.714	-1.858	0.153	9.541	9.513	0.002	-0.017
12		3	L0652	11.930	11.207	0.323	9247	24543	7.585	6.525	4.345	4.682	1.403	1.512	0.104	11.962	11.172	0.032	-0.035
13		4	L0652	11.118	10.543	0.175	20478	45018	6.722	5.867	4.396	4.676	0.769	0.818	0.031	11.101	10.531	-0.017	-0.012
14		5	L0652	11.954	11.664	-0.110	9046	16308	7.609	6.969	4.345	4.695	-0.478	-0.516	0.012	11.991	11.668	0.037	0.004
15		6	L0652	12.723	11.469	0.854	4697	17145	8.320	6.915	4.403	4.554	3.760	3.889	0.729	12.692	11.496	-0.031	0.027
16		7	L0652	12.240	11.985	-0.145	7350	12205	7.834	7.284	4.406	4.701	-0.639	-0.682	0.021	12.217	11.987	-0.023	0.002
17		1	L0557	9.260	8.922	-0.062	114340	200660	4.855	4.244	4.405	4.678	-0.273	-0.290	0.004	9.236	8.937	-0.024	0.015
18		2	L0557	9.781	9.657	-0.276	71023	103727	5.372	4.960	4.409	4.697	-1.217	-1.296	0.076	9.756	9.680	-0.025	0.023
19		3	L0557	11.608	10.680	0.528	12399	38261	7.267	6.043	4.341	4.637	2.292	2.448	0.279	11.642	10.665	0.034	-0.015
20																			
21																			
22											y	y	v	r				rms V	rms R
23						x	SlopeV	SlopeR		y-bar	4.380	4.680	0.247	0.247	num1			0.028	0.020
24					x-bar	0.057	-0.011	-0.122					0.2484	0.2653	num2	19.381	19.686		
25					x-bar^2	0.0032	IntrcptV	IntrcptR	x	-0.7	4.3883	4.7718						12.723	11.985
26					avg(x^2)	0.152	4.38072	4.6864	x	0.0	4.3807	4.6864						8.378	8.307
27									x	1.2	4.3677	4.5401							

Sv is calculated by LS fitting a slope to the plot "V-v versus C." Similarly, Sr is the slope of "R-r versus C." This is illustrated by the following plots.



1.4 Differential Photometry method

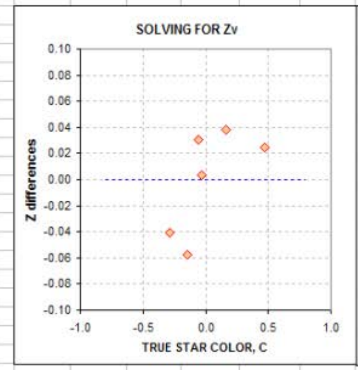
Here, another method is suggested instead of the classical CCD Transformation Equations. Even though this method and the classical one both require prior calibration of your telescope system, this method is easier to use because it is more intuitive, and it is less prone to book-keeping errors. Perhaps a more important advantage of this method is that it does not assume that atmospheric extinction conditions are similar to those when the telescope system was calibrated, which the classical "CCD Transformation Equations" implicitly assume.

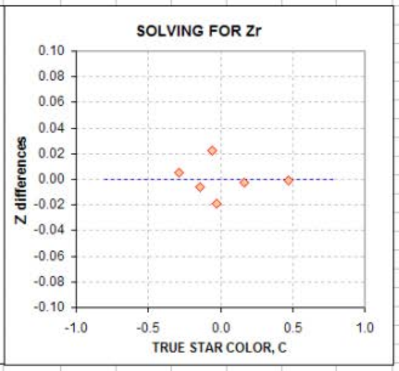
When the telescope system has been calibrated, as described in the earlier section, we have information about S-parameters. Here we know Sv and Sr. This is all we need for performing differential photometry using this Method.
The following is from the same spreadsheet that was used to solve for Sv and Sr, used for illustration in the previous section. It shows flux reading from another landolt star field (on the same night used to solve for S-parameters, but Landolt stars at different air mass). The values for Sv and Sr are entered in cells G76 and J76. Landfolt star V and R magnitudes are entered, as are measurements of star fluxes. The spreadsheet calculates zero shifts that can be used for the same image set (but not any other image sets).

This section is for determining zero-shift for a specific image set that includes target star & several cal stars

It is used only if Sv & Sr are known and when the image set with a target star also includes several calibration stars.
Star with image set of the target star & calibration star; measure cal star fluxes
Enter fluxes in aqua-colored cells
Note that when the target & cal stars are in the same image set they have the same air mass, so the extinction term can be absorbed by the zero-shift term.
Also, the value for exposure time, g, is irrelevant because it also can be absorbed by the sero-shift term
Thus, Mag = Z - 2.5 * LOG (Flux) +S * C, where this Z only applies to this set of images (i.e., this exposure time, air mass and extinction condition)

	Known values for S:				Sv	-0.011			Sr	-0.122		Z suggestions			
	Images of L0355 & L0454											19.615	19.822		
	True V & R			Landolt	Star fluxes				Set to above suggestion:			19.615	19.822		
	V	R	C	Field	V	R	g	v	r	V-v	R-r	Mag V	Mag R	diff V	diff R
1	12.064	11.805	-0.141	L0355	11066	16450	10	7.390	6.960	4.674	4.845	12.007	11.799	-0.057	-0.006
2	10.938	10.064	0.474	L0355	28761	75919	10	6.353	5.299	4.585	4.765	10.963	10.063	0.025	-0.001
3	12.196	11.634	0.162	L0355	8945	18543	10	7.621	6.830	4.575	4.804	12.234	11.632	0.038	-0.002
4	12.927	12.556	-0.029	L0355	4721	8233	10	8.315	7.711	4.612	4.845	12.930	12.537	0.003	-0.019
1	9.652	9.307	-0.055	L0454	94015.2	158377	10	5.067	4.501	4.585	4.806	9.683	9.329	0.031	0.022
2	9.300	9.184	-0.284	L0454	139187	184919	10	4.641	4.333	4.659	4.851	9.259	9.189	-0.041	0.005
														RMS	RMS
											-0.8	0		V	R
											0.8	0		0.040	0.014 Internal scatter (RMS)
	Check quality of solutions (look for outliers to delete)													**0.018**	**0.006** SE on average





The accepted data yield the following solution: Zv = 19.615 +- 0.018
Zr = 19.822 +- 0.006

The zero shifts Zv and Zr are obtained by adjusting the values in cells L78 and M78 to agree with the suggested values (cells L77 and M77). When this is done we have agreement between instrument magnitudes and the Landolt V and R magnitudes. Keep in mind that instrument magnitudes are defined in this spreadsheet according to the general equation: Mag = Z - 2.5 * LOG (Flux/10) + S * C. Extinction is irrelevant here because all stars are from one image set that was made at one air mass. Other stars, such as target stars, will be at the same air mass and will experience the same extinction. That's why we can ignore the extinction term in the magnitude equation. For the next step we simply enter measured fluxes for target stars with the beginning assumption that their star color is zero (i.e, "typical"). This is illustrated in the next picture of a lower section of the same spreadsheet.

This section is for converting target star fluxes to V & R, calculating tentative V & R magnitudes using star color = 0, and iterating target star color based on intermediate results for V &R, thus arriving at a final V & R.

We adopt the Sv & Sr and Zv & Zr parameters values determined from the above sections.

Sv	-0.011	Sr	-0.122	Zv	19.615	Zr	19.822
SE		SE		SE	0.018	SE	0.006

	Target Fluxes				1st iteration		1st it'n	2nd iteration		2nd it'n	3rd iteration		3rd it'n				
	v	r		Landolt	Calc'd	Calc'd	Calc'd	Calc'd	Calc'd	Calc'd	Calc'd	Calc'd	Calc'd	Landolt True			
	Flux	Flux	g	Field	V	R	C	V	R	C	V	R	C	V	R	diff V	diff R
1	17100	51420	10	L0558	11.533	11.740	-0.61	11.539	10.618	0.52	11.527	10.481	0.65	11.525	10.465	0.001	0.015
2	94015	158377	10	L0452	9.682	9.889	-0.61	9.689	9.397	-0.11	9.683	9.336	-0.05	9.683	9.329	0.001	0.007
3	139187	184919	10	L0452	9.256	9.463	-0.61	9.263	9.229	-0.37	9.260	9.199	-0.34	9.260	9.196	0.000	0.003
4	91706	229362	5	L0256	8.956	9.163	-0.61	8.963	8.242	0.32	8.953	8.129	0.42	8.952	8.116	0.001	0.013
5	114287	177346	5	L0256	8.717	8.924	-0.61	8.724	8.521	-0.20	8.720	8.471	-0.15	8.719	8.466	0.001	0.006
6	4516	7178	5	L0256	12.226	12.433	-0.61	12.232	12.003	-0.17	12.227	11.950	-0.12	12.227	11.944	0.001	0.006
																RMS	RMS
																V	R
																0.000	0.005 Internal scatter (RMS)

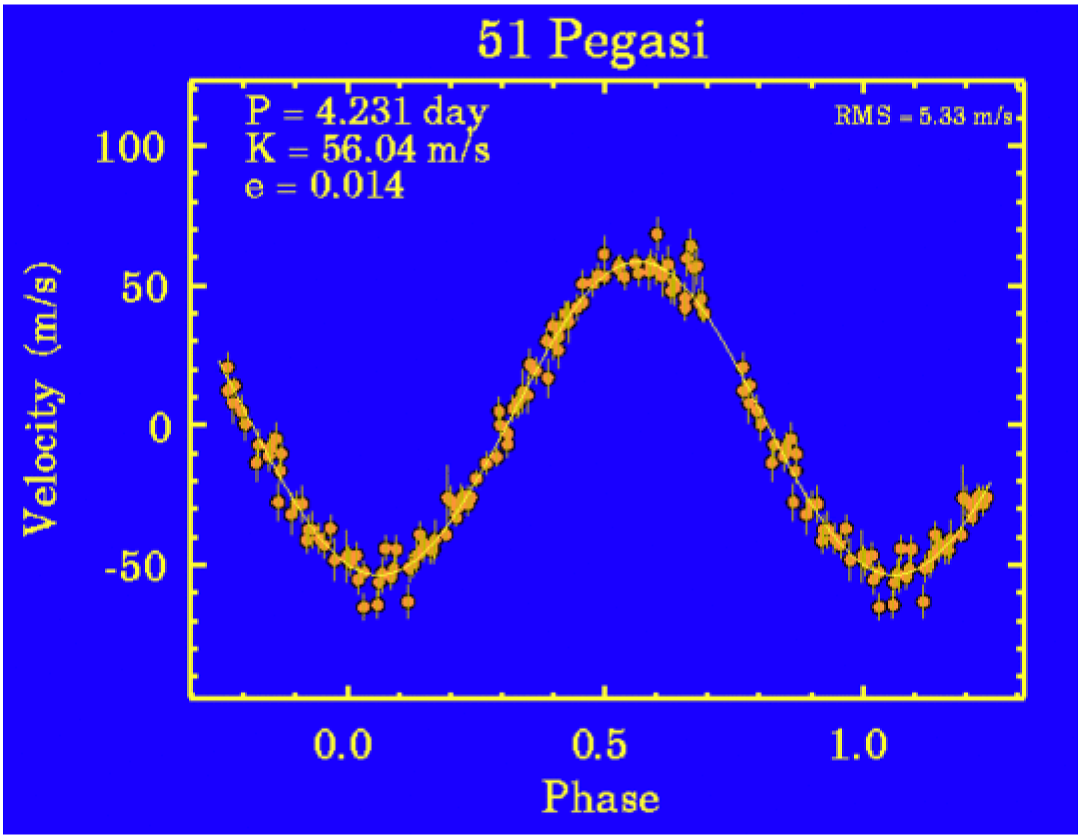
The stars chosen to be target stars in the above spreadsheet section are from different Landolst star fields than were used for deriving S-parameters and Z-parameters, and they are at different air masses. In spite of these differences the iteration achieves acceptable results for RMS differences with the true, Landolt magnitudes.

1.5 Radial velocity method :

The radial velocity method, also known as Doppler spectroscopy, is the most effective method for locating extrasolar planets with existing technology. Though other approaches hold great promise for the future, the vast majority of Exoplanets discovered so far were detected by this method.

The radial velocity method relies on the fact that a star does not remain completely stationary when it is orbited by a planet. It moves, ever so slightly, in a small circle or ellipse, responding to the gravitational tug of its smaller companion. When viewed from a distance, these slight movements affect the star's normal light spectrum, or color signature. If the star is moving towards the observer, then its spectrum would appear slightly shifted towards the blue; if it is moving away, it will be shifted towards the red.

Using highly sensitive spectrographs, planet hunters on Earth can track a star's spectrum, searching for periodic shifts towards the red, blue, and back again. The spectrum appears first slightly blue-shifted, and then slightly red-shifted. If the shifts are regular, repeating themselves at fixed intervals of days, months, or even years, it means that the star is moving ever so slightly back and forth - towards the Earth and then away from it in a regular cycle. This, in turn, is almost certainly caused by a body orbiting the star, and if it is of a low enough mass it is called a planet.



The above picture is THE RADIAL VELOCITY GRAPH OF 51 PEGASI

51 Pegasi was the first exoplanet detected and confirmed. The points on the graph indicate actual measurements taken. The sinusoid is the characteristic shape of the radial velocity graph of a star rocking to the tug of an orbiting planet.

1.6 Radial velocity signal:

Semi-amplitude of radial velocity given by

$$K = \sqrt[3]{\frac{2\pi G}{Porb}} * Mp \frac{sini}{(M * +Mp)^{0.66}} * \frac{1}{\sqrt{(1-e^2)}}$$

Porb: orbital period • M*: mass of star • MP: mass of planet • i: inclination, angle between normal to orbital plane and line of sight • e: eccentricity

For circular orbits with MP << M* in meter/second

$$vobs = 28.4 * \frac{Mpsini}{(\sqrt[3]{Porb}) * M *^{0.66}}$$

MP in Jupiter masses • Porb in years • M* in solar masses

Transit signals

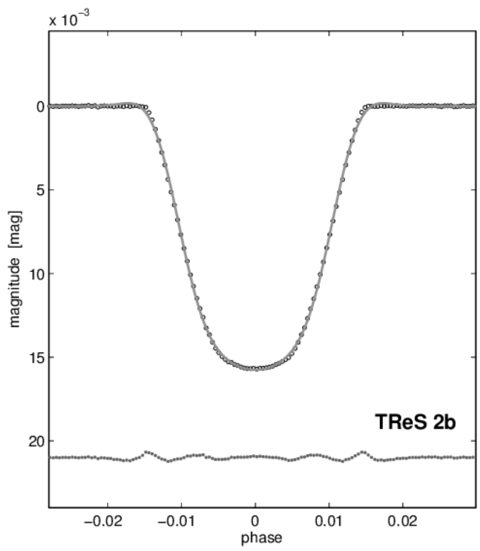
$$\frac{\Delta I}{I} = (\frac{Rp}{R} *)^2$$

R* stellar radius • Rp planet radius

1.7 Light Curve:

In astronomy, a light curve is a graph of light intensity of a celestial object or region, as a function of time. The light is usually in a particular frequency interval or band. Light curves can be periodic, as in the case of eclipsing binaries, Cepheid variables, other periodic variables, and transiting extrasolar planets, or aperiodic, like the light curve of a nova, a cataclysmic variable star, a supernova or a microlensing event. The study of the light curve, together with other observations, can yield considerable information about the physical process that produces it or constrain the physical theories about it.

The shapes of variable star light curves give valuable information about the underlying physical processes producing the brightness changes. For eclipsing variables, the shape of the light curve indicates the degree of totality, the relative sizes of the stars, and their relative surface brightness. It may also show the eccentricity of the orbit and distortions in the shape of the two stars. For pulsating stars, the amplitude or period of the pulsations can be related to the luminosity of the star, and the light curve shape can be an indicator of the pulsation mode.

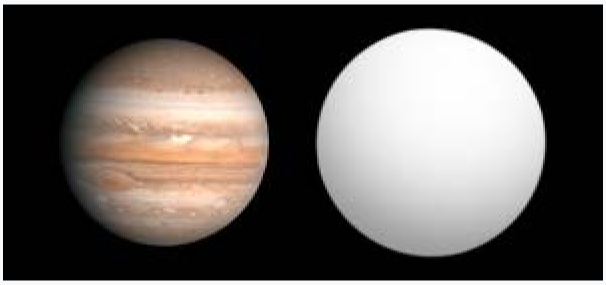


- Example of a light curve

1.8 TrES-1b

TrES-1b is an extra solar planet approximately 512 light-years away in the constellation of Lyra (the Lyre). The planet's mass and radius indicate that it is a Jovian planet with a similar bulk composition to Jupiter. Unlike Jupiter, but similar to many other planets detected around other stars, TrES-1 is located very close to its star, and belongs to the class of planets known as hot Jupiters.

TrES-1b



Size comparison of TrES-1 with Jupiter.

Parent star		
Star		GSC 02652-01324
Constellation		Lyra
Right ascension	(α)	$19^h\ 04^m\ 09^s$
Declination	(δ)	+36° 37′ 57″
Distance		512 ± 20 ly (157 ± 6 pc)
Spectral type		K0V
Orbital elements		
Semi-major axis	(a)	$0.03926^{+0.00058}_{-0.00060}$ [1] AU
Eccentricity	(e)	<0.012[1]

Orbital period	(*P*)	3.03006973±0.00000018[2] d
Inclination	(*i*)	88.2 ± 1°
Semi-amplitude	(*K*)	$106.7^{+2.9}_{-2.8}$[1] m/s
Physical characteristics		
Mass	(*m*)	$0.697^{+0.028}_{-0.027}$[1] M_J
Radius	(*r*)	$1.081^{+0.18}_{-0.04}$ R_J
Density	(*ρ*)	642 kg m^{-3}
Surface gravity	(*g*)	0.52 *g*
Temperature	(*T*)	1,060 ± 50
Discovery information		
Discovery date		24 August 2004
Discoverer(s)		Alonso *et al.*
Discovery method		Transit, Radial velocity, and Infrared light
Discovery site		TrES Spain United States
Discovery status		Published[3]

1.9 EPIC211089792 b

EPIC211089792 b, was first detected by the Super-WASP observatory and then by the K2 space mission during its campaign 4. The planet has a period of 3.25d, a mass of 0.73 +/- 0.04 Mjup, and a radius of 1.19 +/- 0.02 Rjup. The host star is a relatively bright (V=12.5) G7 dwarf with a nearby K5V companion. Based on stellar rotation and the abundance of Lithium, we find that the system might be as young as about 450 Myr. The observation of the Rossiter-McLaughlin effect shows the planet is aligned with respect to the stellar spin. Given the deep transit (20mmag), the magnitude of the star and the presence of a nearby stellar companion, the planet is a good target for both space- and ground-based transmission spectroscopy, in particular in the near-infrared where the both stars are relatively bright.

Star name	EPIC 211089792
Alternate name	"K2-29 , WASP-152"
Star Distance (LY/pc)	0.0000
Stellar Radius (Rsun)	0.0000
Stellar Mass (Msun)	0.0000
Spectral type	G7V
Metalicity	0.0000
Absolute Magnitude	25.00
Apparent magnitude	22.00
Right Ascension (RA)	62.67083
Declination(DEC)	24.40194

- (Rsun, measured) = 0.8518
- (Msun/ observed) = 0.9420
- The star EPIC 211089792 has apparent magnitude of 22.0, with absolute magnitude of 25.0.
- Number of Extrasolar Planets : 1
- Name of the 1 Planet K2-29 b radius 1.190000 mass 0.730000 orbital distance 0.042170
- The Star EPIC 211089792 's habitable zone is located at the following distance:
    1. Inner Boundary (the orbital distance at Venus's Equivalent Radiation) : 0.560 AU (83808643.8 km)
    2. Earth Boundary (the orbital distance at Earth's Equivalent Radiation) : 0.774 AU (115845447.5 km)
    3. Outer Boundary (the orbital distance at Mars's Equivalent Radiation) : 1.180 AU (176522825.4 km)
    4. Snow Line (the orbital distance at Snow Line Equivalent Radiation) : 1.736 AU (259761070.6 km)

1.10 Sky Survey

Sky surveys represent a fundamental data basis for astronomy. We use them to map in a systematic way the universe and its constituents, and to discover new types of objects or phenomena. We review the subject, with an emphasis on the wide-field, imaging surveys, placing them in a broader scientific and historical context. Surveys are now the largest data generators in astronomy, propelled by the advances in information and computation technology, and have transformed the ways in which astronomy is done

1.11 The Kepler field of View

In order to facilitate the selection of targets, the Kepler Field was observed using The All Sky Automated Survey - North (ASAS - North) instruments for over a year. Then a detailed search for variability was performed, which resulted in detection of almost 1000 variable stars that are presented in this catalogue

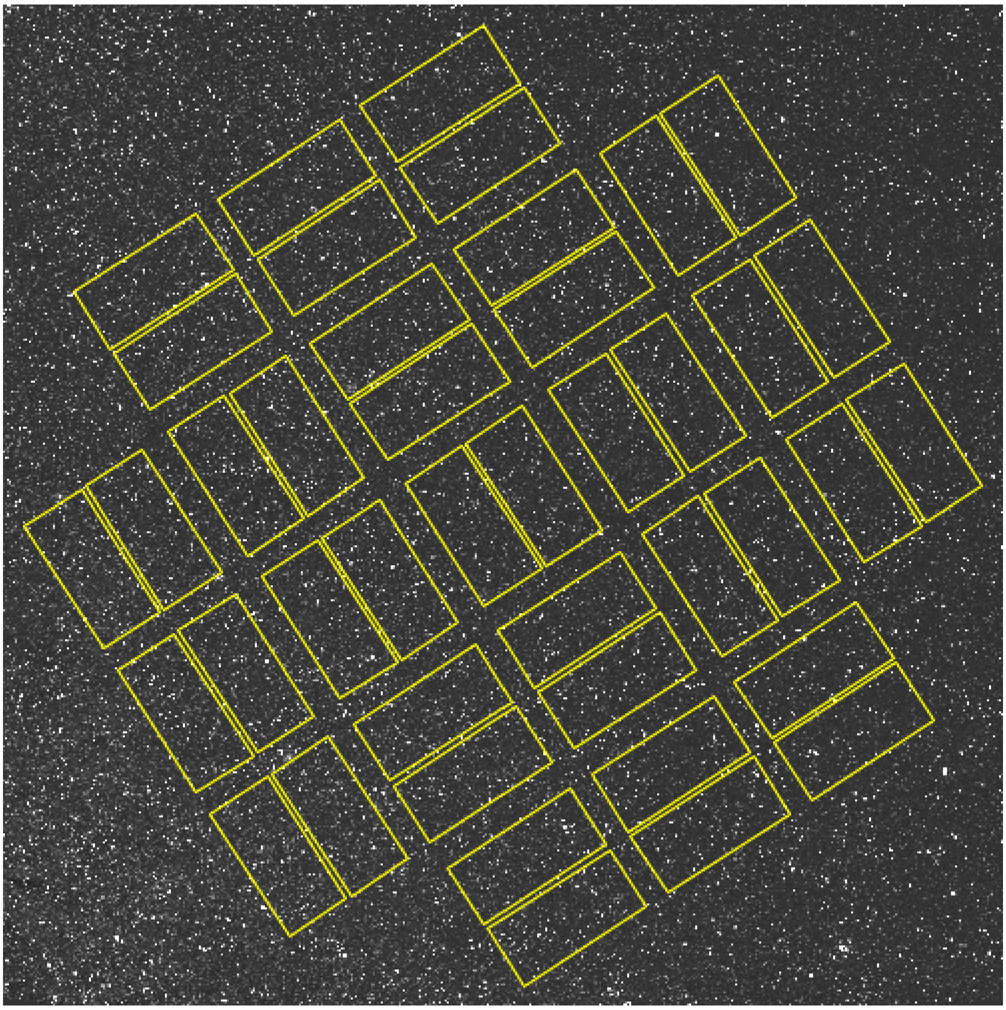
The data analyzed here were obtained in the ASAS3-North station located at Haleakala (Maui, Hawaii Islands) using two wide-field instruments, equipped with Nikkor 200mm f/2.0 lenses and Apogee AP-10, 2048x2048 CCD cameras, collecting data in two filters (V and I). The data cover roughly 500 days between July 2006 and December 2007. The resolution of ASAS images amounts to almost 15 arcsec/pixel.

The variability search was carried out using the data in the intermediate aperture (diameter of 4 pixels) by means of Fourier amplitude periodogram calculated in the range between 0 and 30 d-1. All light curves and periodograms were inspected visually. The variability type was assigned taking into account the period, amplitude and/or the shape of the light curve. In total, 947 stars were selected as variable among about 250,000 searched for variability. ONLY stars that will be covered by the CCD chips of Kepler satellite were considered. The catalog does not contain variable stars that are located in the gaps between chips.

The list of variables in the Kepler field is given below:

No.	ID	RAd	DEC	V	I	V-I	J	J-H	H-K	Type	Period
	-	[deg]	[deg]	[mag]	[mag]	[mag]	[mag]	[mag]	[mag]	-	[days]
1	183952+4323.1	279.96787	43.38568	12.847	12.417	0.430	12.163	0.173	0.094	EW	0.474549
2	184321+4734.7	280.83771	47.57899	12.768	12.388	0.380	12.069	0.137	0.021	EA	0.73455
3	184347+4732.0	280.94540	47.53245	11.900	9.461	2.439	7.999	0.908	0.232	APER	-
4	184356+4715.0	280.98364	47.25142	14.000	13.075	0.925	12.328	0.561	0.090	PER	0.293484
5	184408+4426.8	281.03385	44.44747	10.415	9.764	0.651	9.378	0.216	0.079	PER	0.295512
6	184510+4338.1	281.29237	43.63546	13.095	7.962	5.133	4.432	1.321	0.894	MIRA	502

- **List of variables in Kepler field**

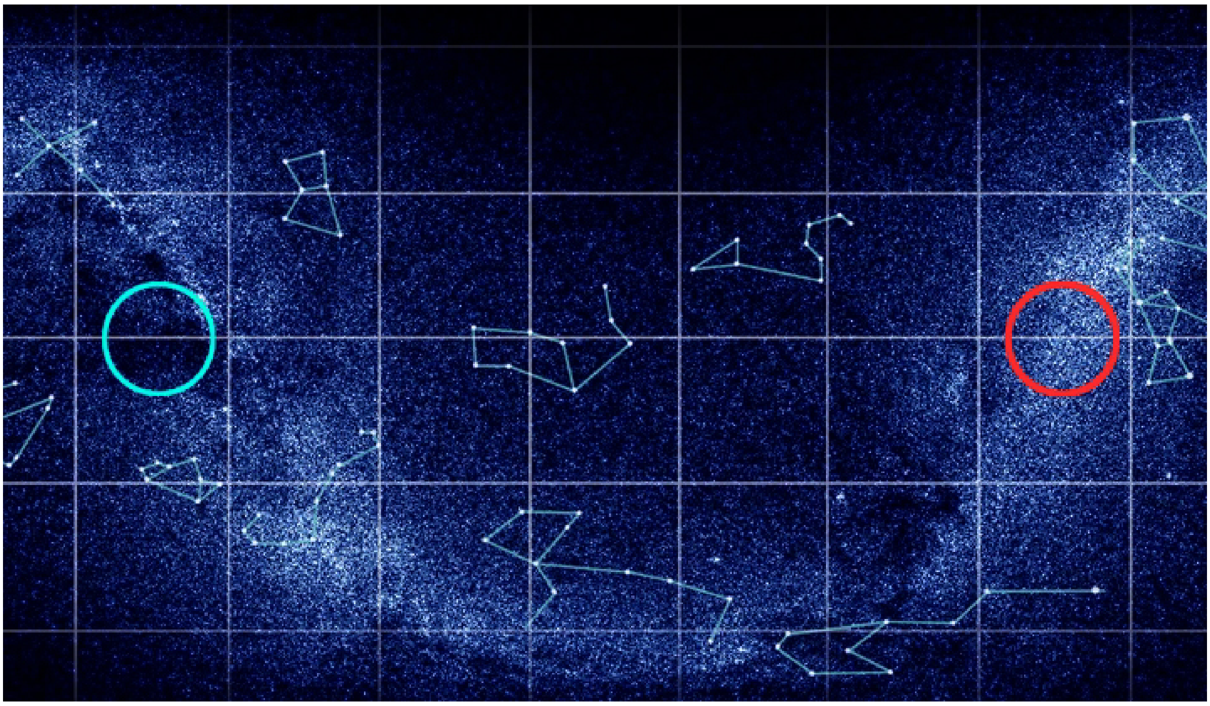


- **The Kepler F.o.V**

1.12 COROT

CoRoT (French: COnvection ROtation et Transits planétaires; English: COnvection ROtation and planetary Transits) was a space observatory mission which operated from 2006 to 2012. The mission's two objectives were to search for extra solar planets with short orbital periods, particularly those of large terrestrial size, and to perform astro seismology by measuring solar-like oscillations in stars.[2] The mission was led by the French Space Agency (CNES) in conjunction with the European Space Agency (ESA) and other international partners.

Among the notable discoveries was COROT-7b, discovered in 2009 which became the first exo planet shown to have a rock or metal-dominated composition.



- *Position of the CoRoT eyes in the sky. The blue/green and red circles represent the center and anti-center.*

Constrained by the satellite orbit and the need to restrict scattered light from the Earth, the CoRoT satellite is restricted to fields of regard on the sky located near the galactic centre and anti center - often referred to as the "CoRoT eyes". The CoRoT eyes are 10° in diameter and are centred at &alpha=18h50m & delta=0° for the centre field and at &alpha=6h50m & delta=0° for the anti-centre field. Within the 15.7 square degree fields of regard, the satellite can observe approximately 8 square degrees at one time corresponding to the focal plane arrangement. The satellite spends approximately 6 months per year observing in the centre direction and 6 months per year observing in the anti-centre direction.

1.13 References:

https://exoplanetarchive.ipac.caltech.edu/docs/datasethelp/ETSS_CoRoT.html

https://arxiv.org/ftp/arxiv/papers/1203/1203.5111.pdf

http://brucegary.net/DifferentialPhotometry/dp.htm

http://www.planetary.org/explore/space-topics/exoplanets/radial-velocity.html

http://home.strw.leidenuniv.nl/~keller/Teaching/ADA_2011/ADA_2011_L06_Exoplanets.pdf

https://arxiv.org/abs/1601.07680

http://www.exoplanetkyoto.org/exohtml/EPIC_211089792.html

http://www.astrouw.edu.pl/asas/?page=kepler

2. DATA PROCESSING

The process to achieve the brightness curve of our star has two phases. First of all, we have to prepare our night of observation in order to be in the best conditions to recover the data of the sensors CDD.
Then we will have to process our data, by first going through a PRISM preprocessing phase and then a Muniwin processing phase. You will find below the tutorial that we have mentioned chronologically with some initial information about flat dark and bias frames aka offsets frames.

2.1 Light Frames

The Light Frames are the images that contain the real information: images of galaxies, nebula.This is what you want to stack.

2.2 Dark Frames and Dark Flat Frames

The Dark Frames are used to remove the dark signal from the light frames (or the flat frames for the Dark Flat frames).With DSLRs and CCD Camera, the CMOS or CCD is generating a dark signal depending of the exposure time, temperature and ISO speed (DSLR only).The best way to create the dark frames is to shoot pictures in the dark by covering the lens.
The dark frames must be created with the exposure time, temperature and ISO speed of the light frames (resp. flat frames).Since the temperature is important try to shoot dark frames at the end or during your imaging session.

2.3 Bias Frames (aka Offset Frames)

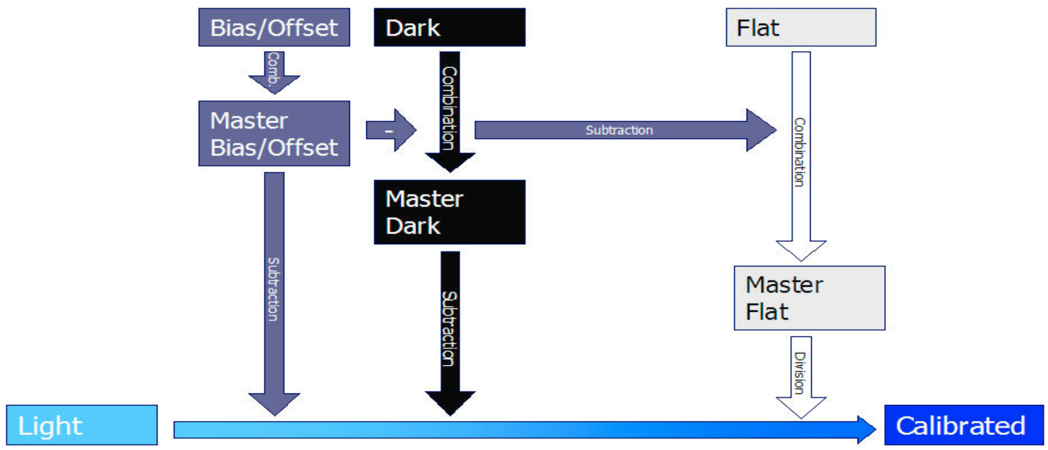
The Bias/Offset Frames are used to remove the CCD or CMOS chip readout signal from the light frames.Each CCD or CMOS chip is generating a readout signal which is a signal created by the electronic just by reading the content of the chip.

It's very easy to create bias/offset frames: just take the shortest possible exposure (it may be 1/4000s or 1/8000s depending on your camera) in the dark by covering the lens.

2.4 Flat Frames

The Flat Frames are used to correct the vignette and uneven field illumination created by dust or smudges in your optical train.To create good flat frames it is very important to not remove your camera from your telescope before taking them (including not changing the focus)

2.5 Calibration: how to use dark, flat and bias frames
The calibration is the process consisting in subtracting the bias and dark signals and dividing by the flat signal.
Our goal is not to take perfect flat dark and bias images but to have a better understanding how these can be used in calibration process in order to produce a image with reduction in subsequent noise.



According the square root rule of photometry you will have much cleaner masters if you use a lot of frames to create them.For example, when you subtract the master dark from each light frame you are adding the noise of the master dark to the noise of the light frame. The smaller the noise of the master dark, the less noise you will add to the light frame. This is also true for the master bias and the master flat.

In fact by using only a very small number of frames for the creation of the masters you can easily triple the noise of the calibrated light frame (bias and dark subtracted and flat divided) compared to the noise of the light frame before calibration.

2.5 PROCESSING FILES USING PRISM AND MUNWIN

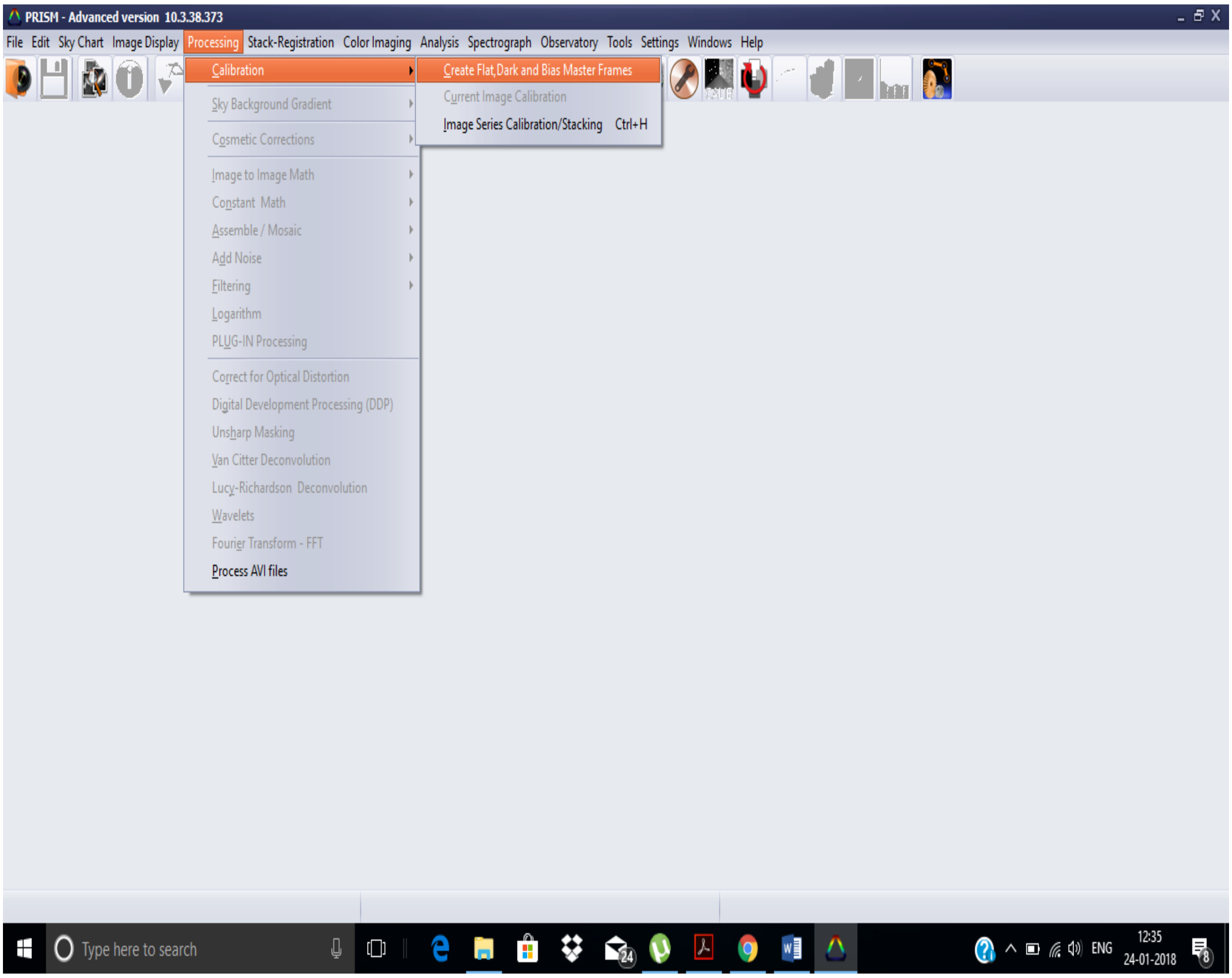
Once the observation at the night is done, We recovered three different types of files which further enhanced for the calibration process for the images that we will obtain for the studying the relevant stars as these file or bias includes-

- Offset
- Dark
- Flat

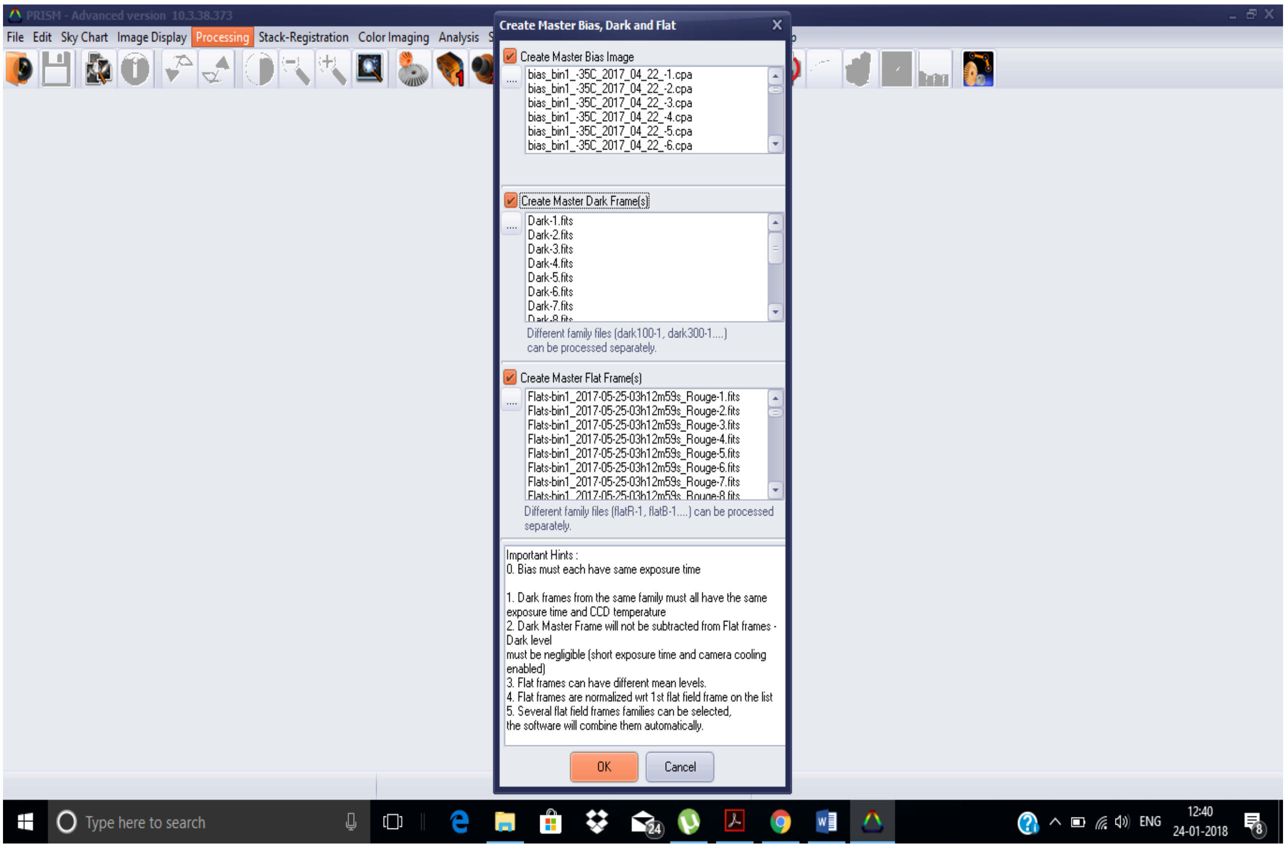
We also retrieved number of images of the sky and for the relevant star, as all these images and image data will bear the name of the star that we are studying. Lastly our main is to process the ample number of images of the sky with the relevant calibration files that have been mentioned above in order to reduce the noise and varying pixels of the images.

2.6 **PROCESSING FILES USING PRISM-**

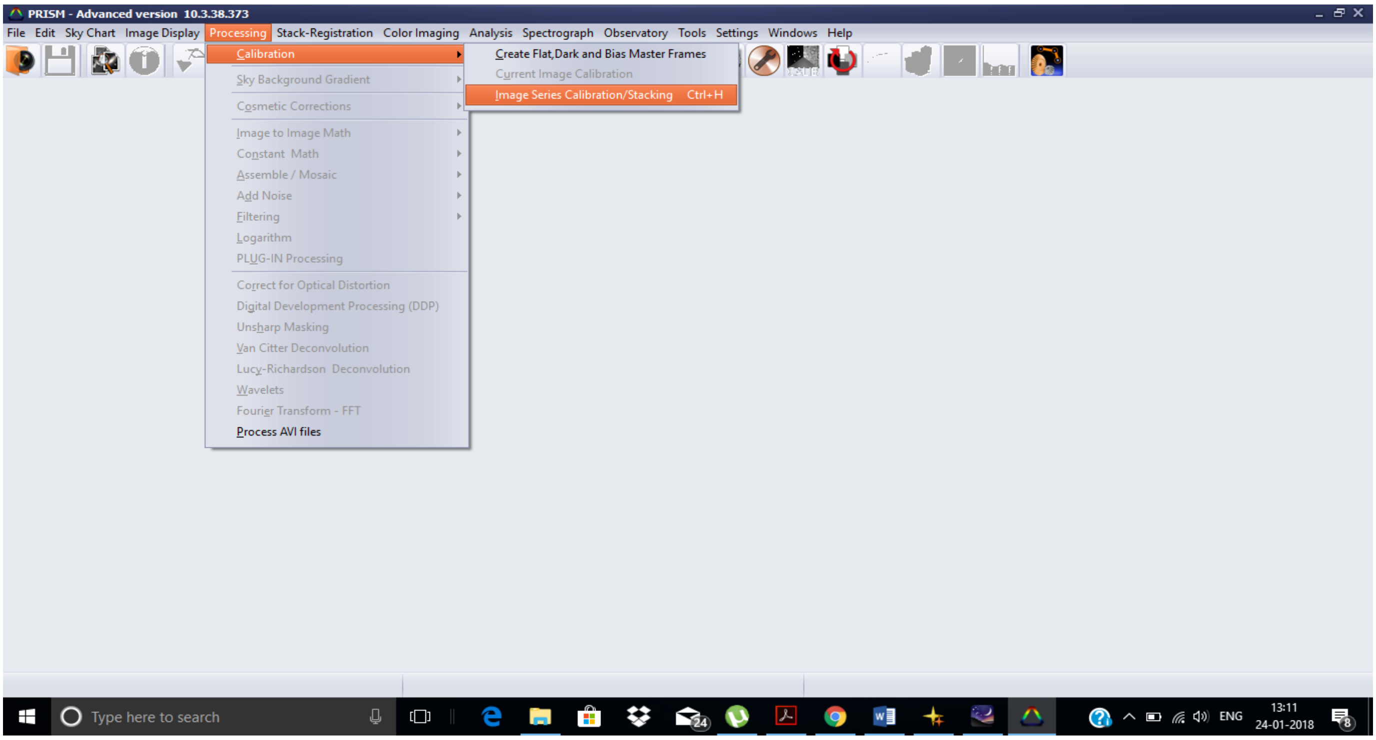
- Open PRISM
- Go to PROCESSING → Calibration → Create Flat Dark and Master bias of the frame



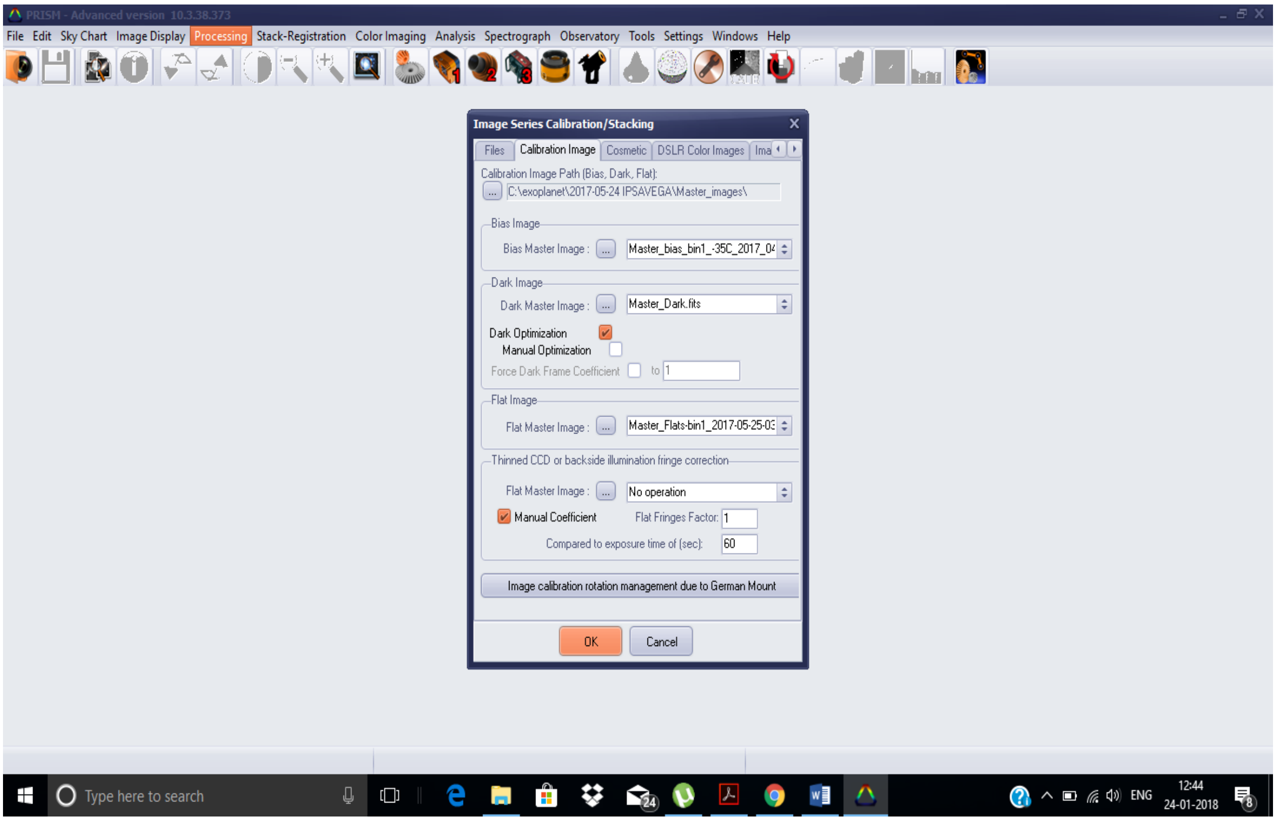
- Check "create reference master offset images", "create reference darks image" and "create reference flats images". Then select about fifteen bias, about fifteen darks and about fifteen flats from your calibration files. Click Ok. Ensure master offset bias will be in .cpa format. All other would be in .fits only with their respective names.



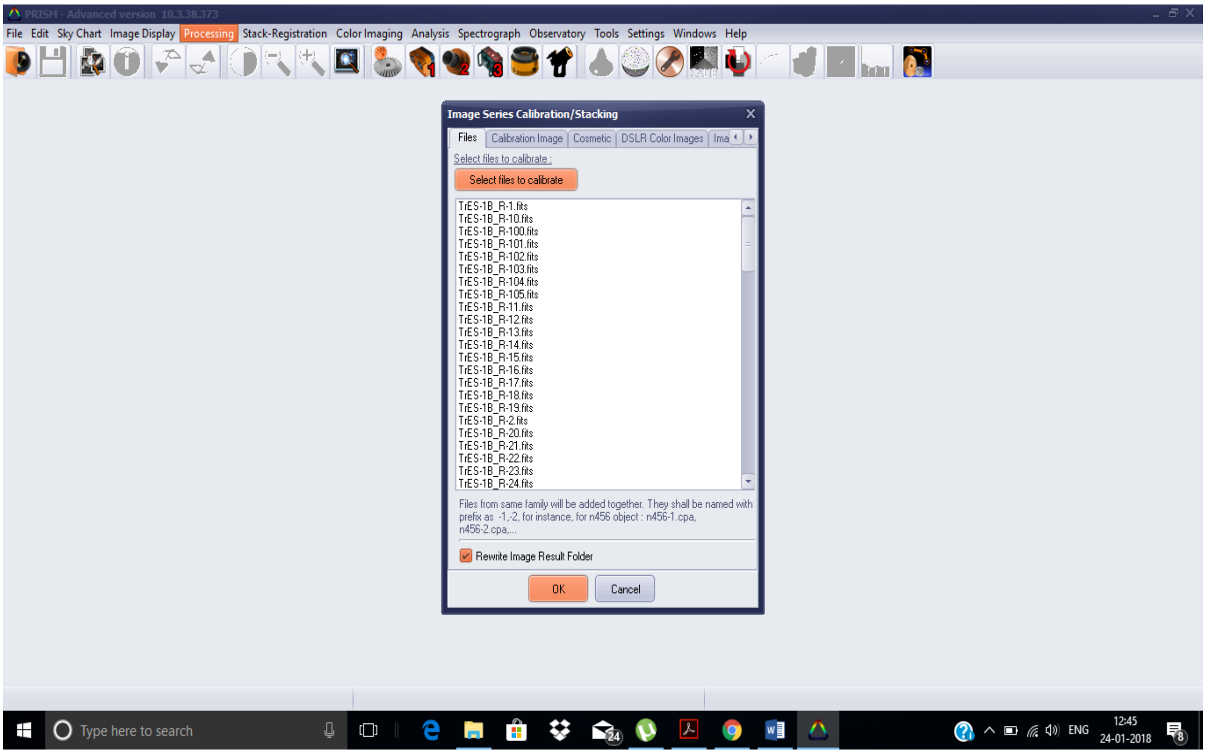
- Then further go to Processing> Calibration>Image series calibration/stacking for processing your images with respective calibration files.



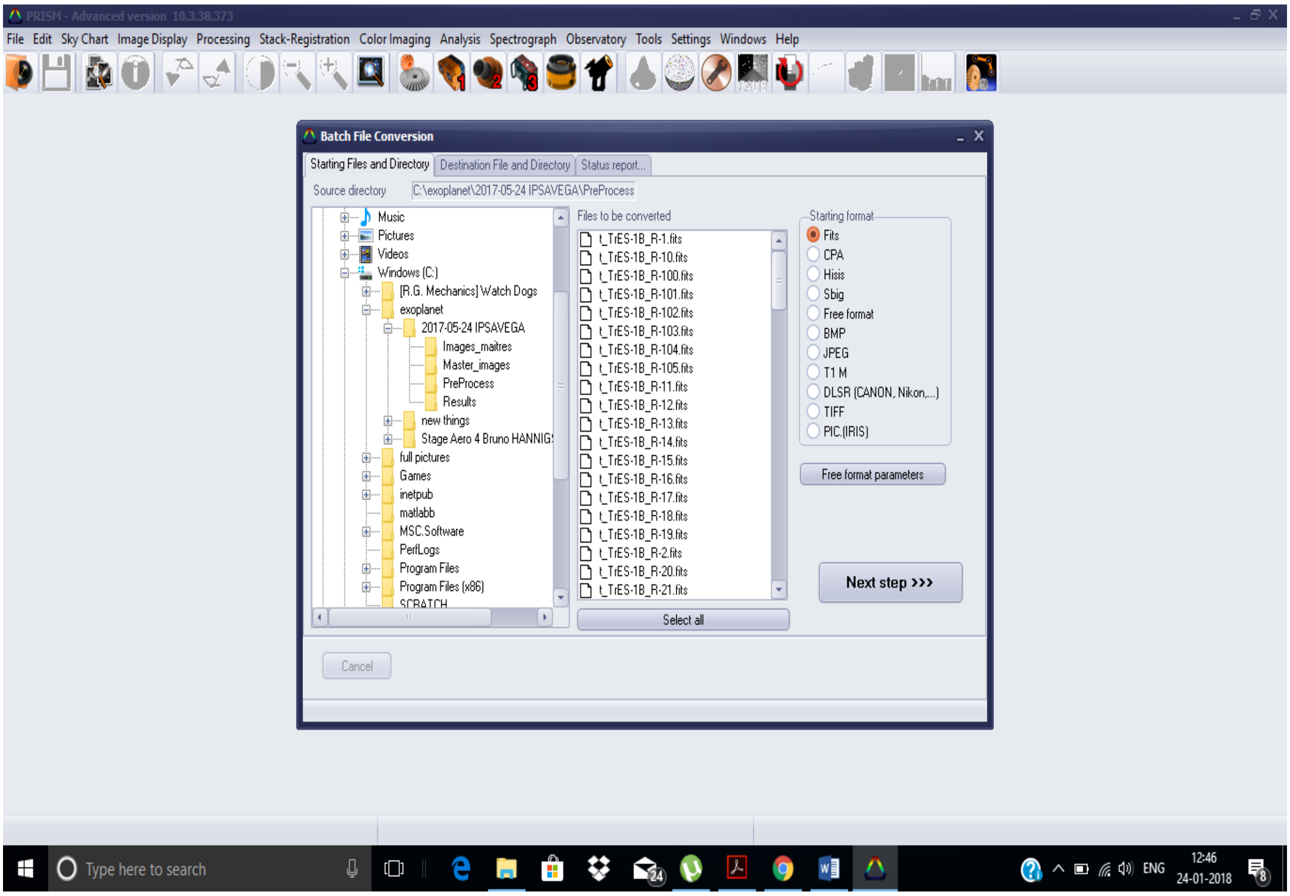
- In the "Calibration Images" tab, select the master files created previously in your respective folder.

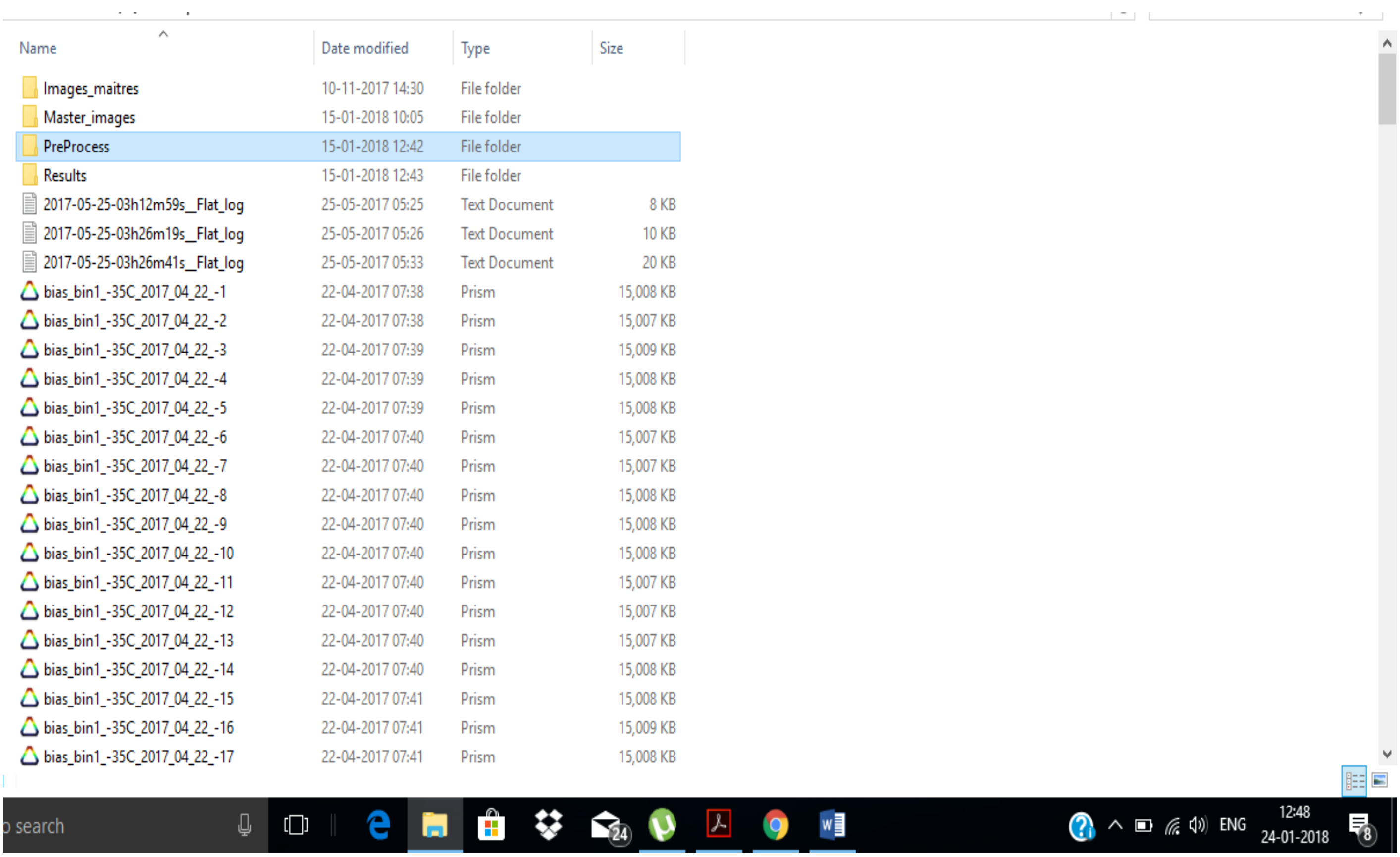


- In the file tab, select those only files which are having the name of your star and lastly Click OK.



- The newly created files will all be automatically placed in a new folder named "PreProcess". If You are having a file in .cpa format you have to convert them to .fits format so that Muniwin can process them. For this, Files> Batch file format conversion. Select previously created files then check CPA, and NEXT STEP. Then check Fits and OK.

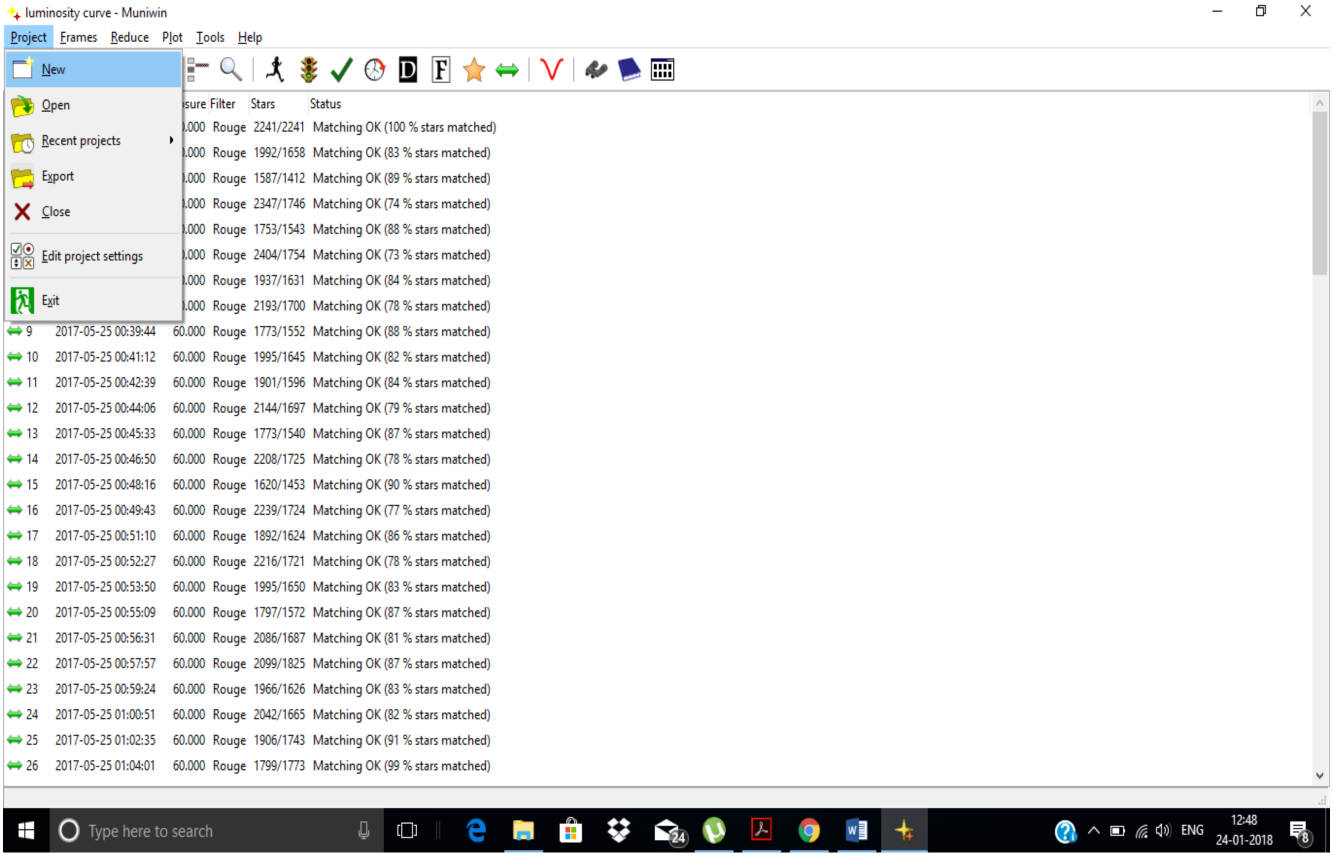


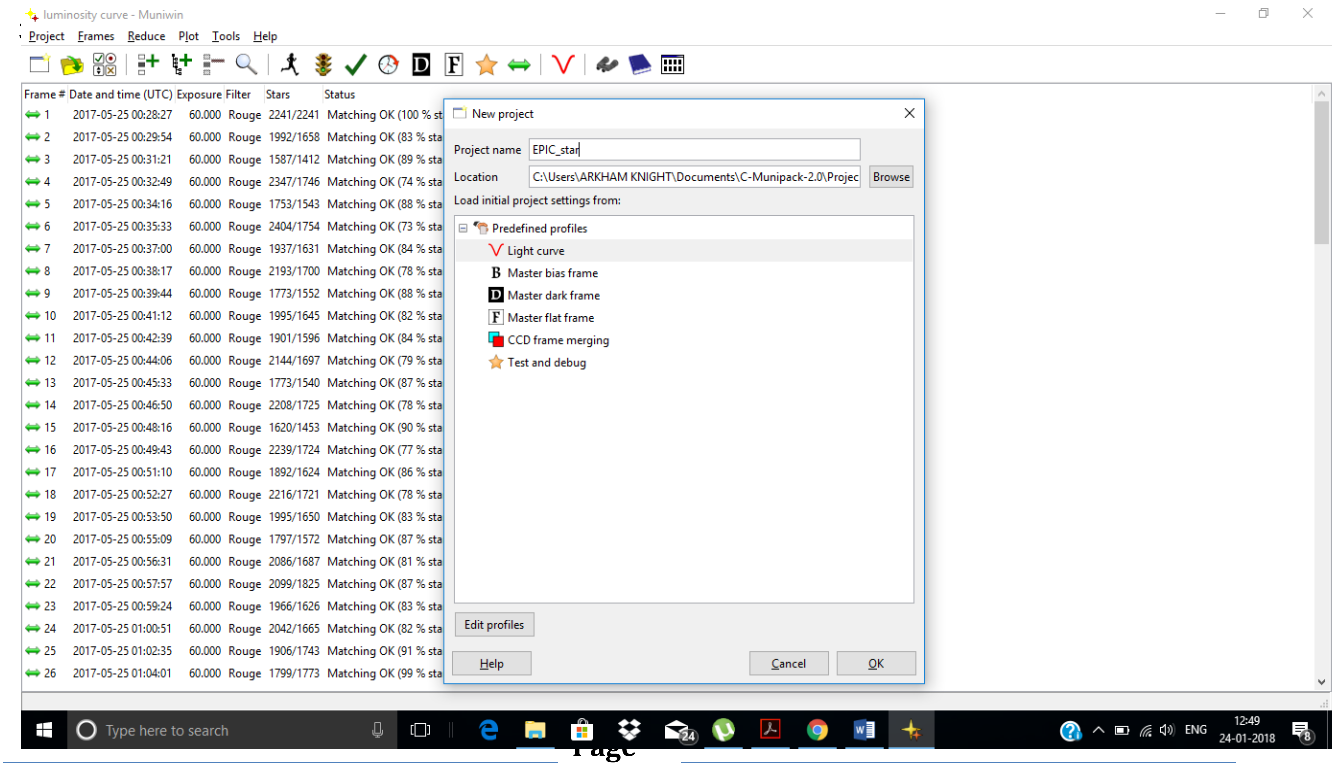


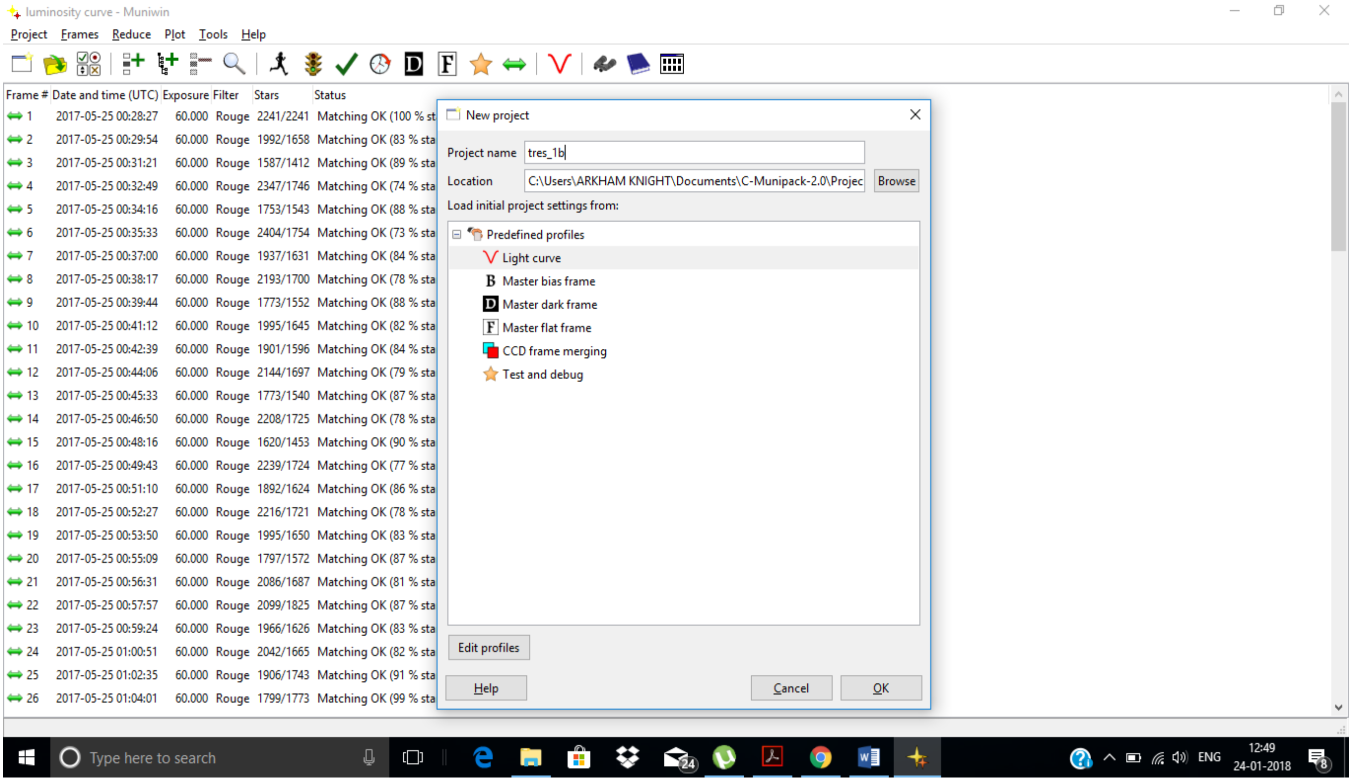
Now our objective is that, it will be necessary to select reference stars, which are stars with a magnitude and a near colour index. There are two methods to obtain these brightness curves: the classic method of selecting a single reference star, and the so-called virtual star method of selecting several reference stars at the same time, and creating from these one single star of reference, the virtual star, which is the average of the real stars.

2.7 Open Munwin

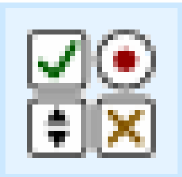
- Project → NEW



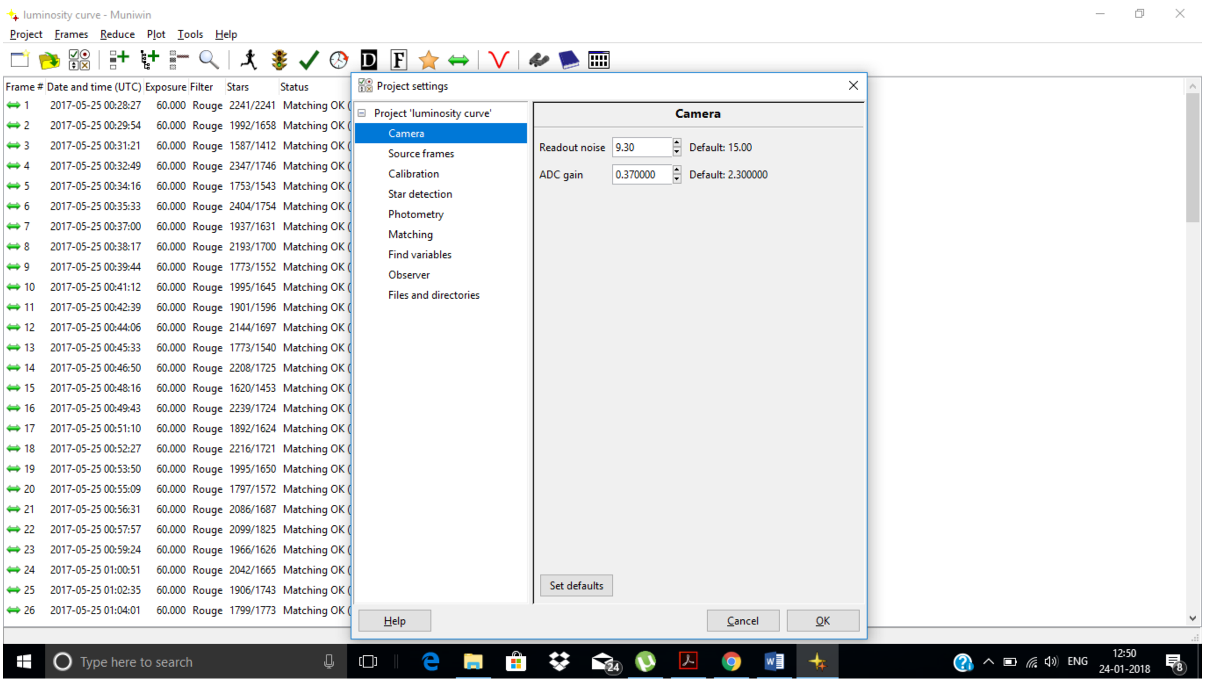




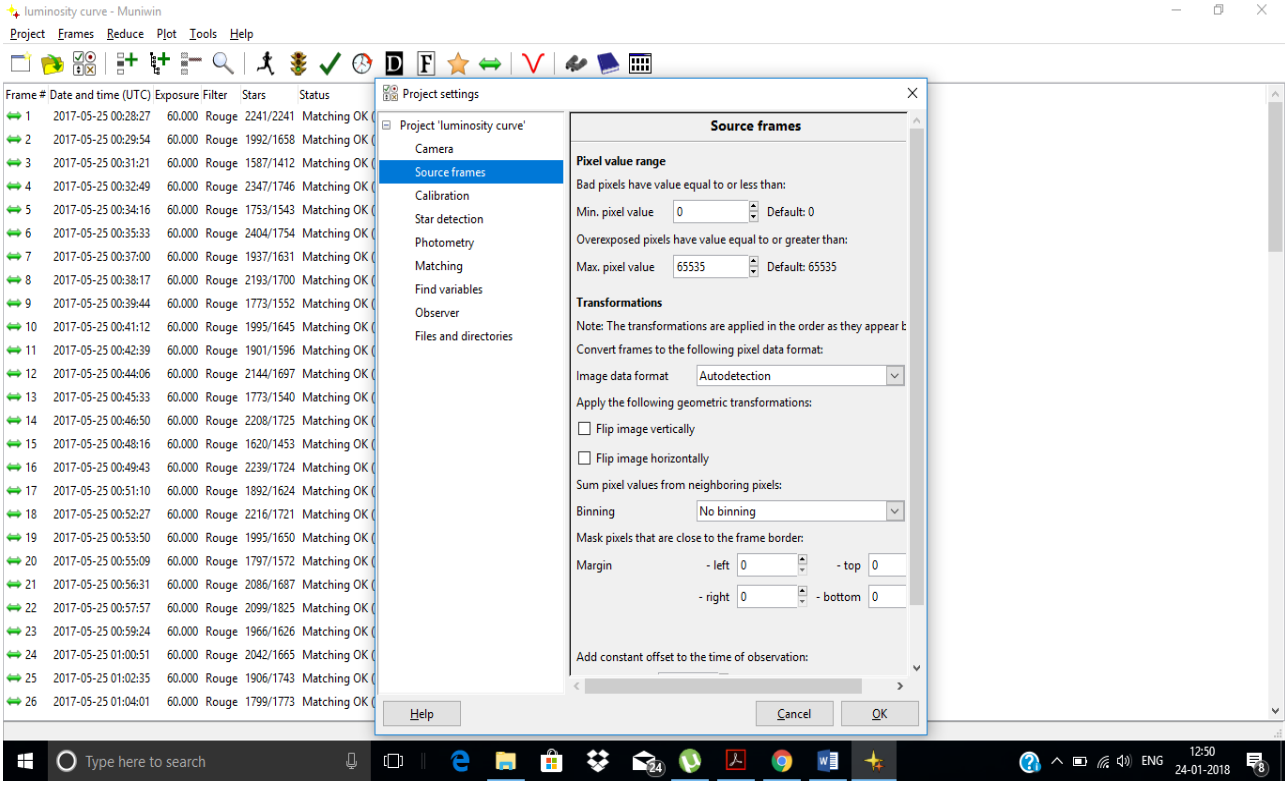
- Click on the "Edit Project Setting" icon



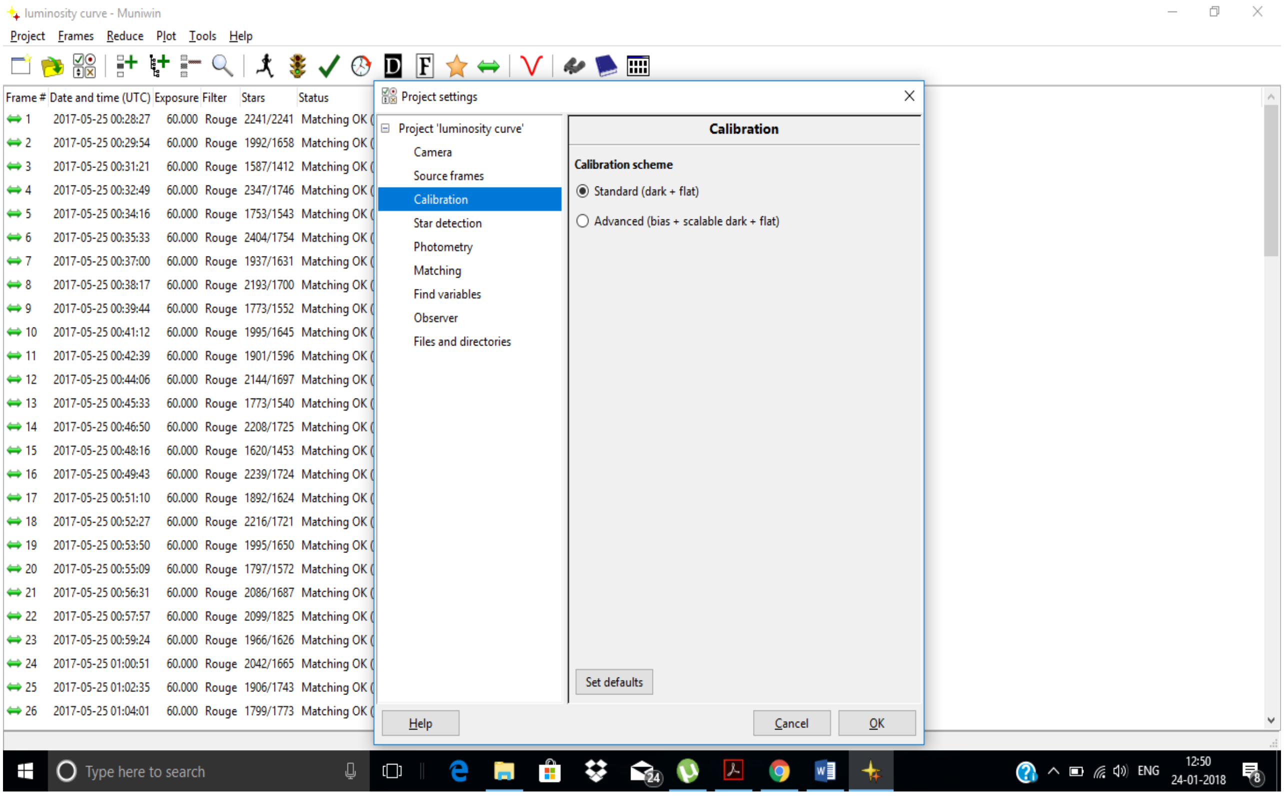
- Enter the following parameters under subsequent option which are the following: CAMERA



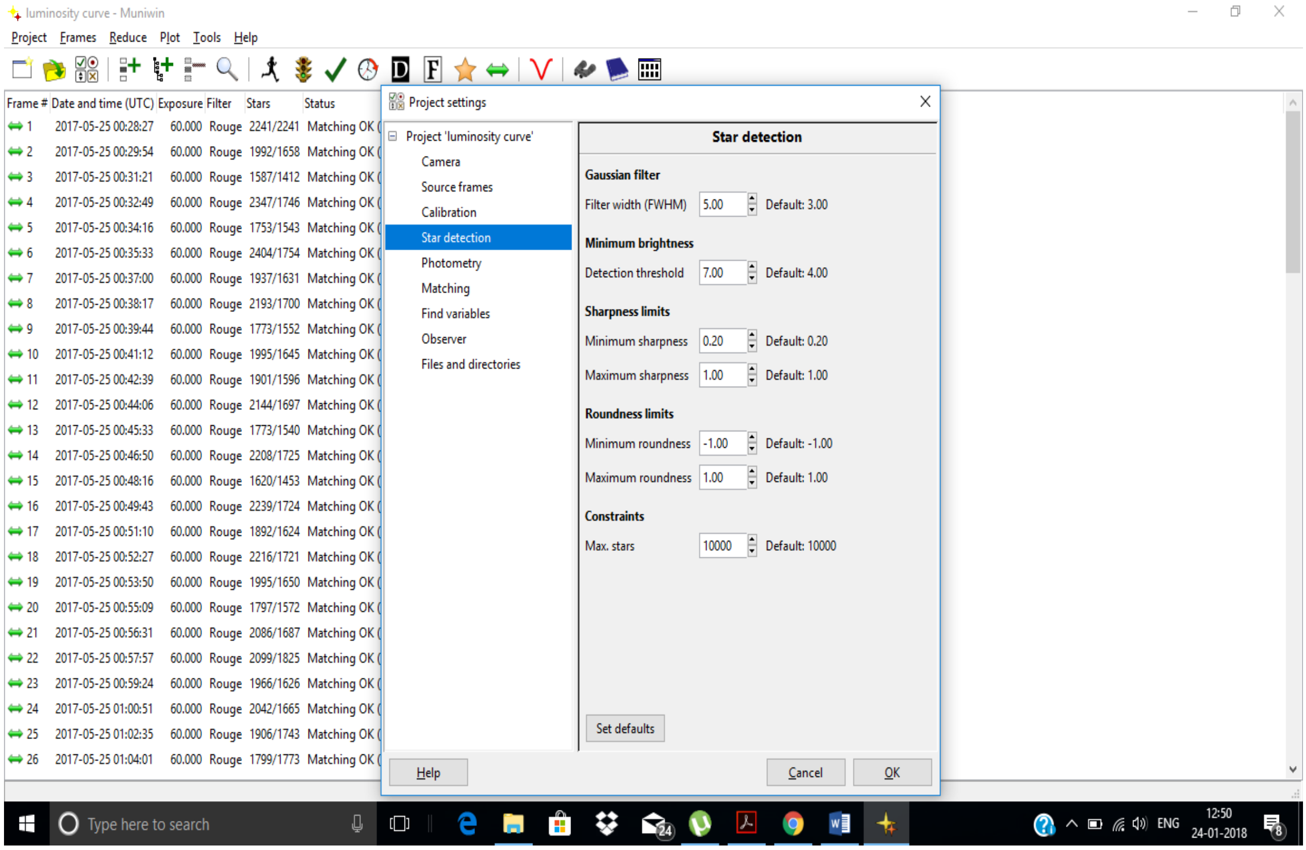
SOURCE FRAMES



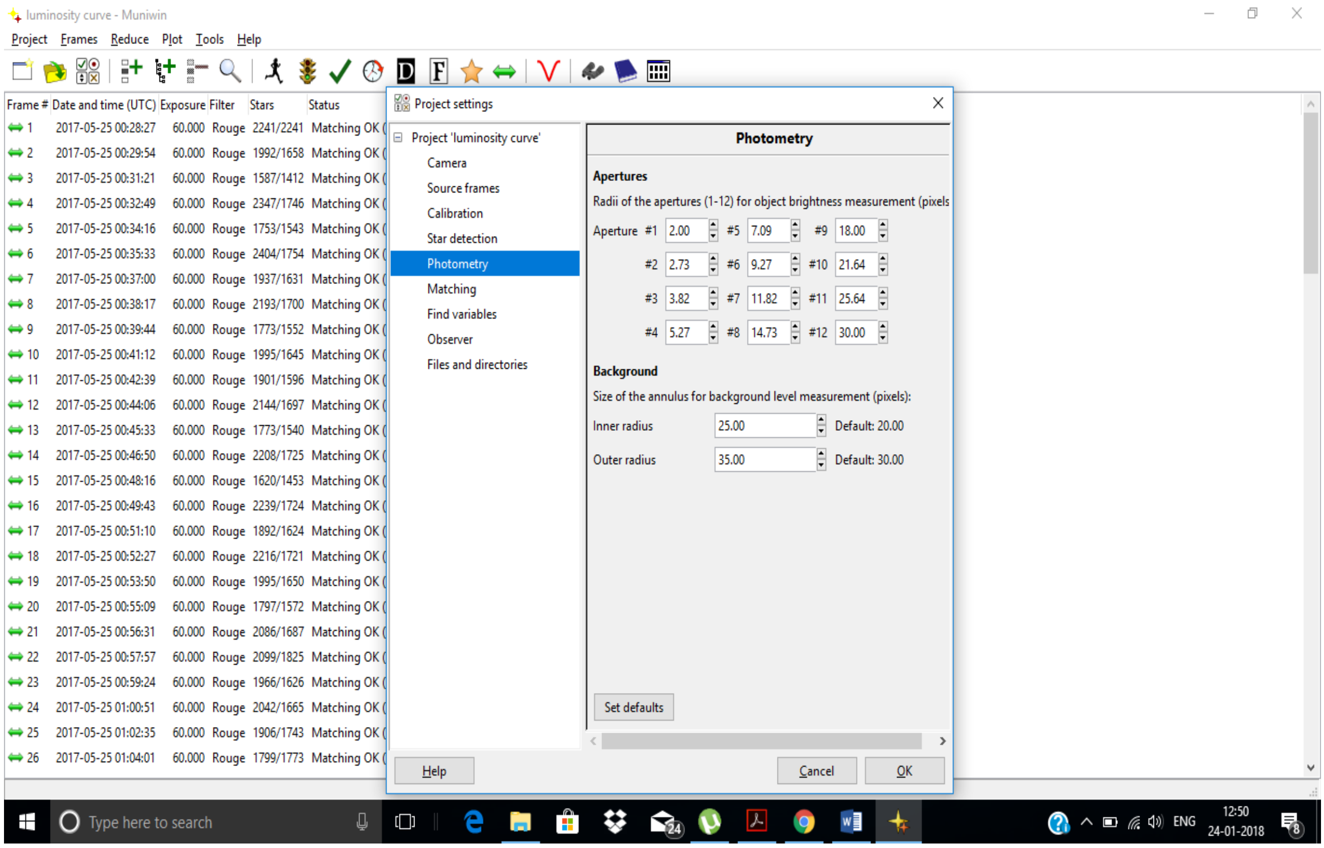
2.8 CALIBRATION



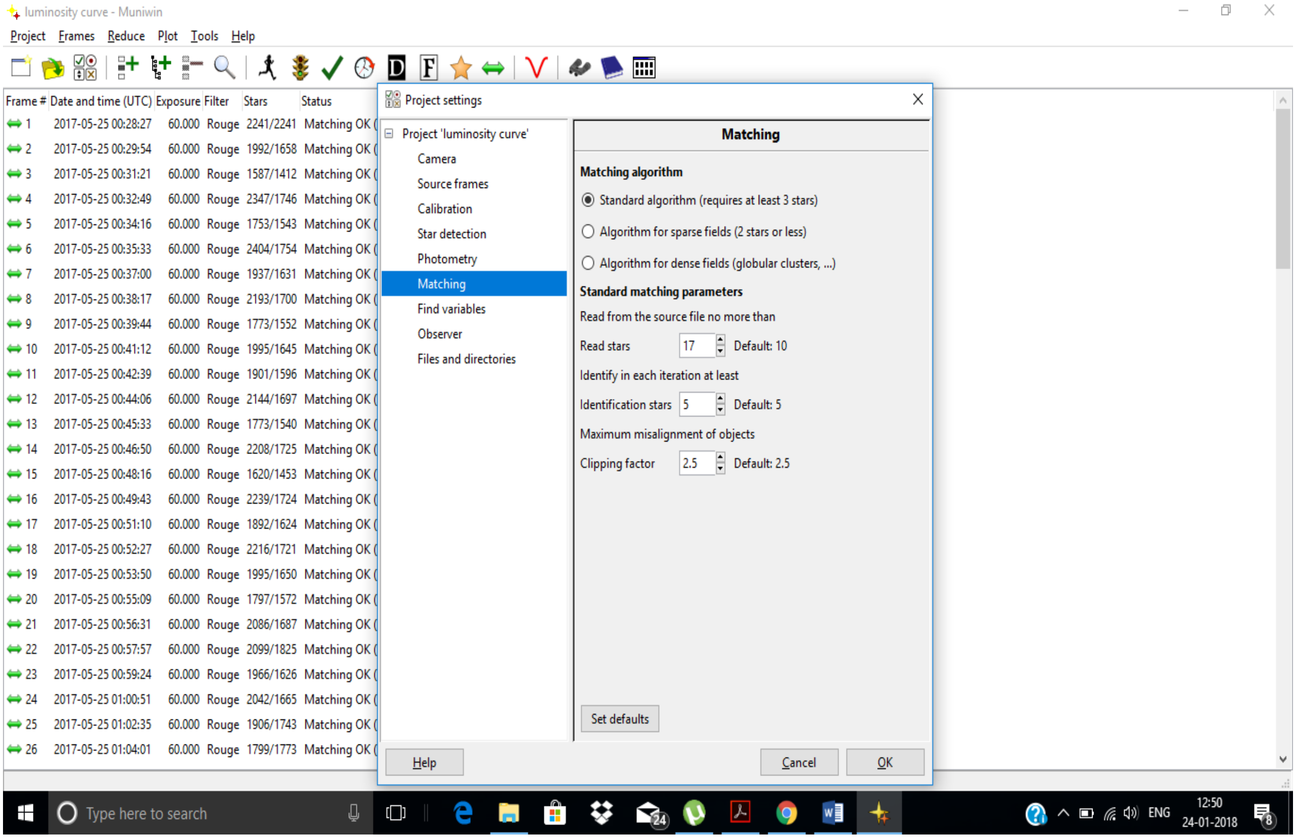
STAR DEFINITION



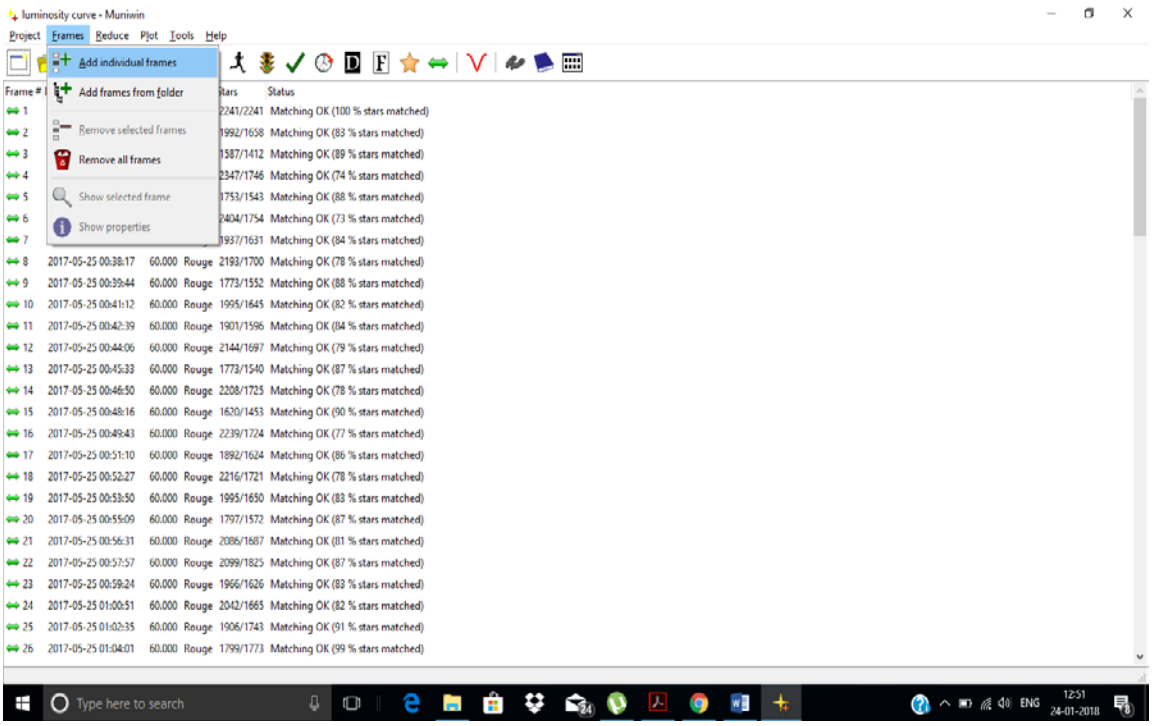
PHOTOMETRY



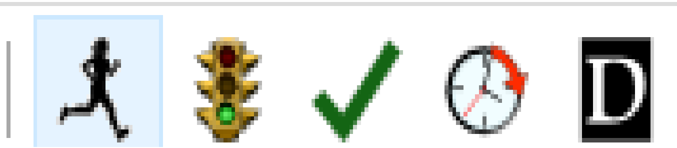
MATCHING

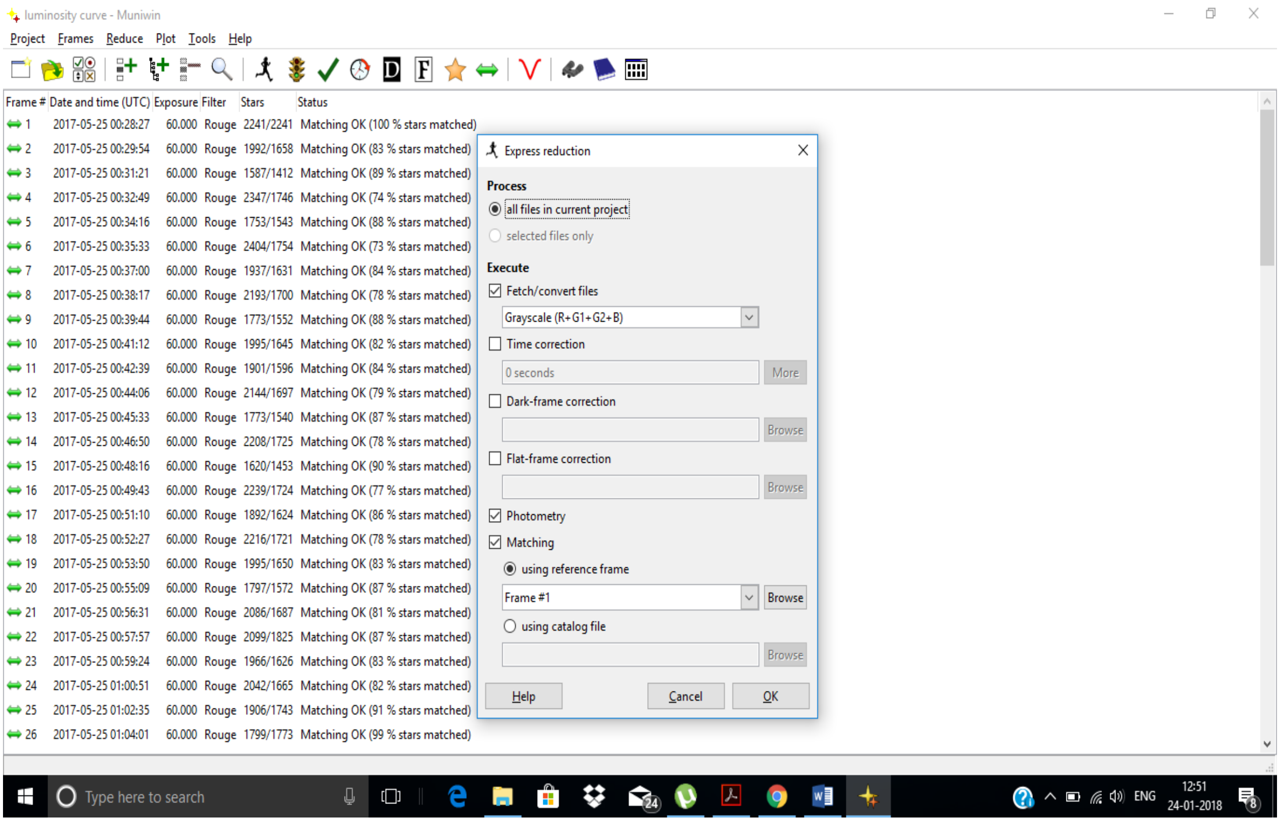


- Frames> Add individual frames. Select only the files with the fits extension in the pre process folder.



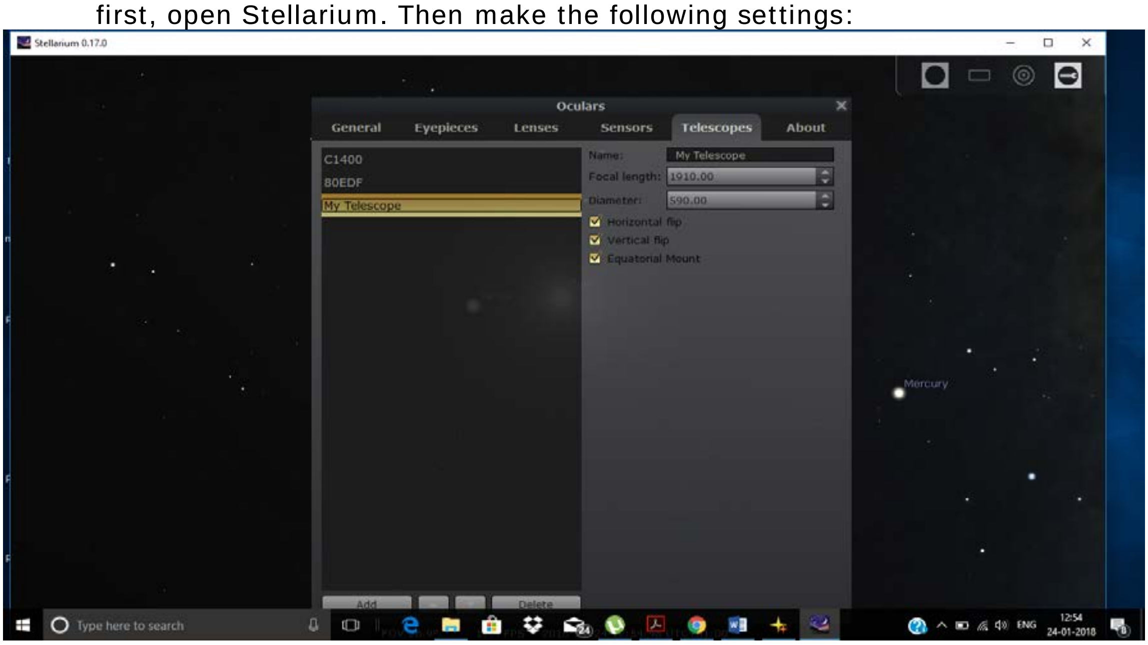
- Click on Express Reduction

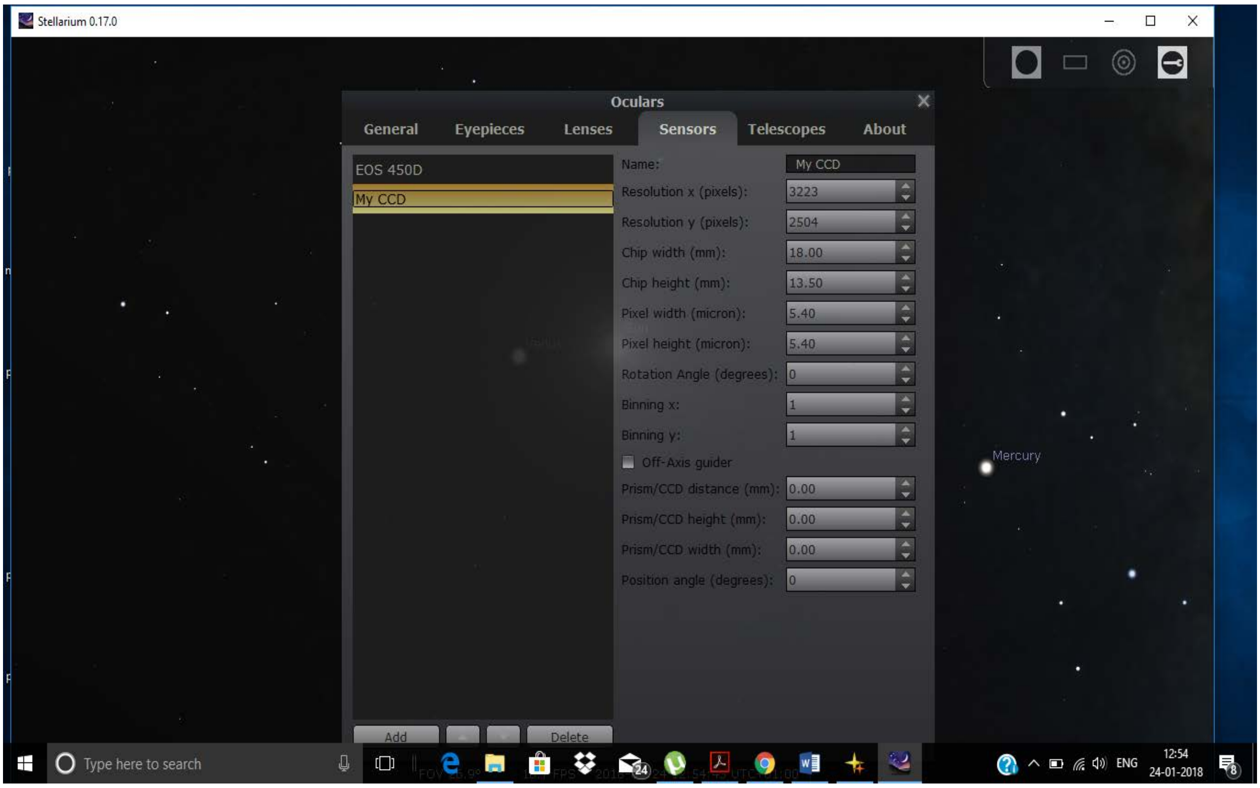




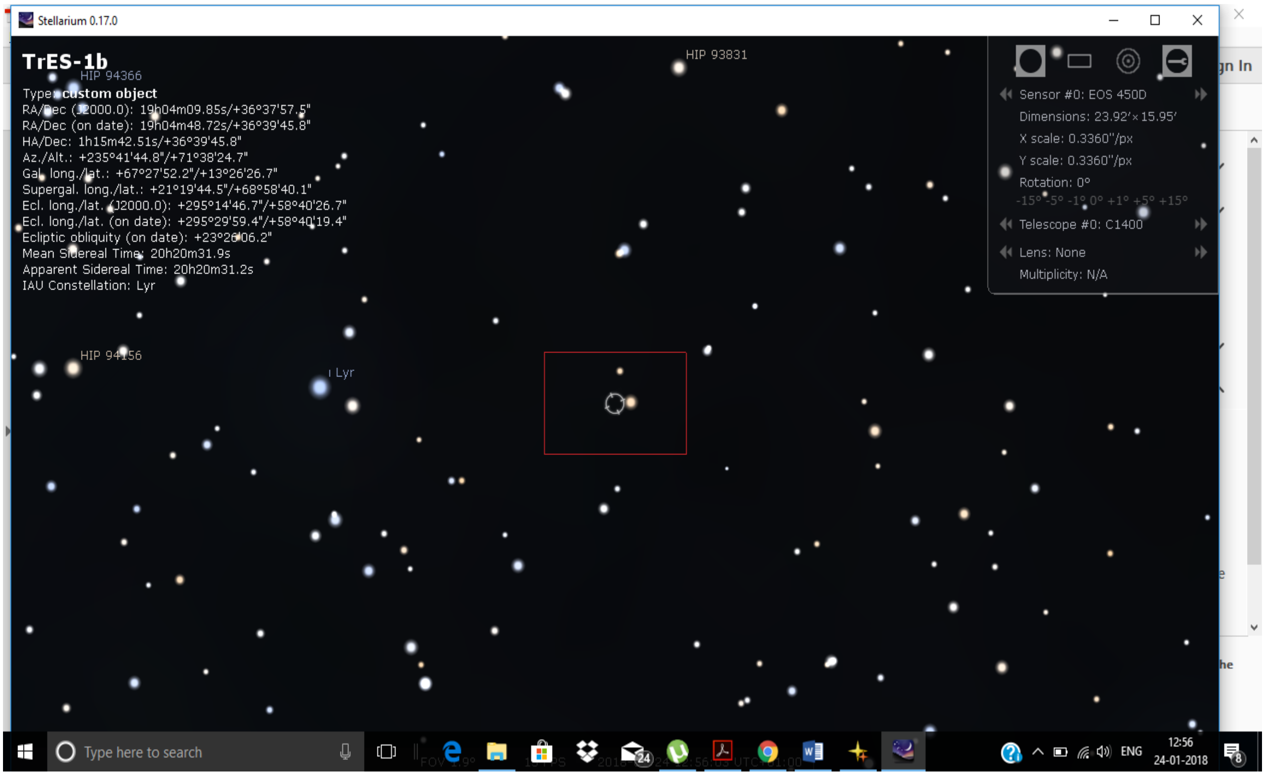
USING STELLARIUM FOR DETERMINING THE REFRENCE STARS-

- We will have to define reference stars to obtain our photometric curve. For that first, open Stellarium. Then make the following settings:

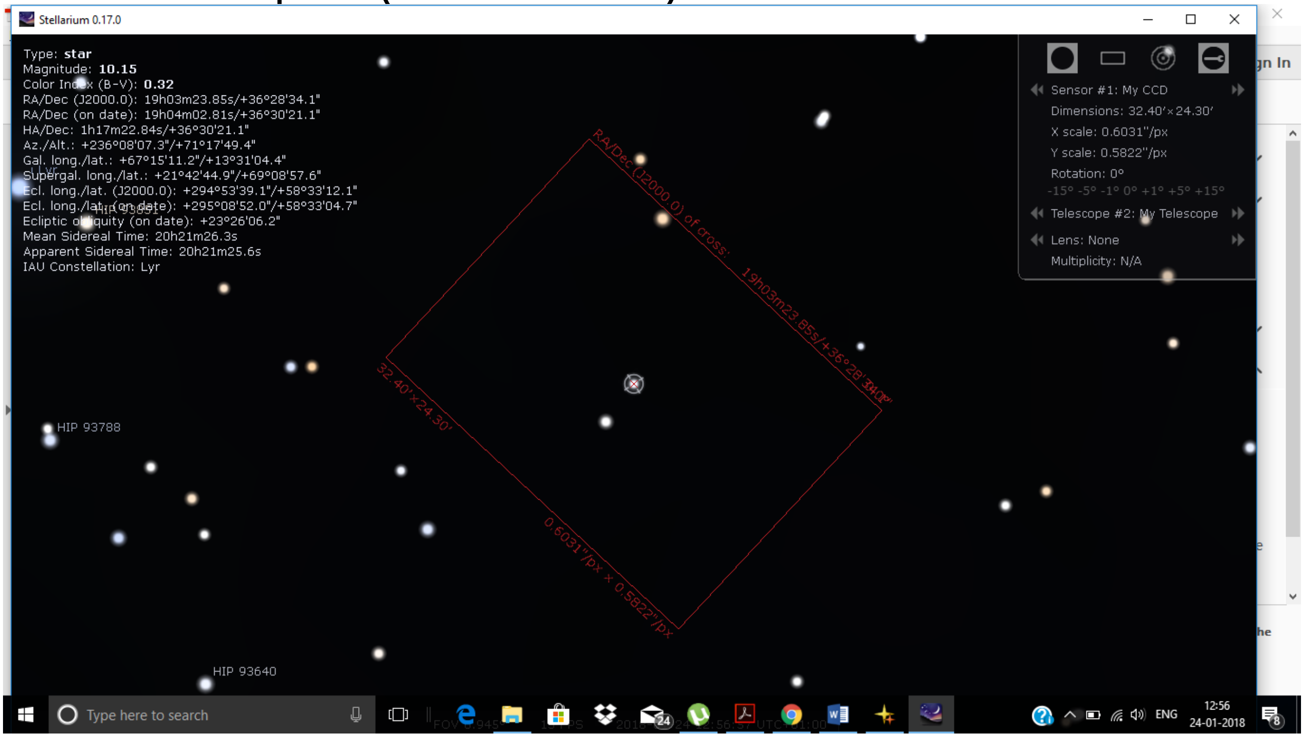




Then, still in Stellarium, type the name of your star in the search bar. The reference stars must be in the red rectangle.
Then read in the top left the magnitude and color index of your star. Then by clicking on the other stars in the red rectangle, find 3 or 4 with a similar magnitude and color index. These will be your reference stars. For example for the star TrES-1, we have as magnitude 11.40 and a color index 0.92.

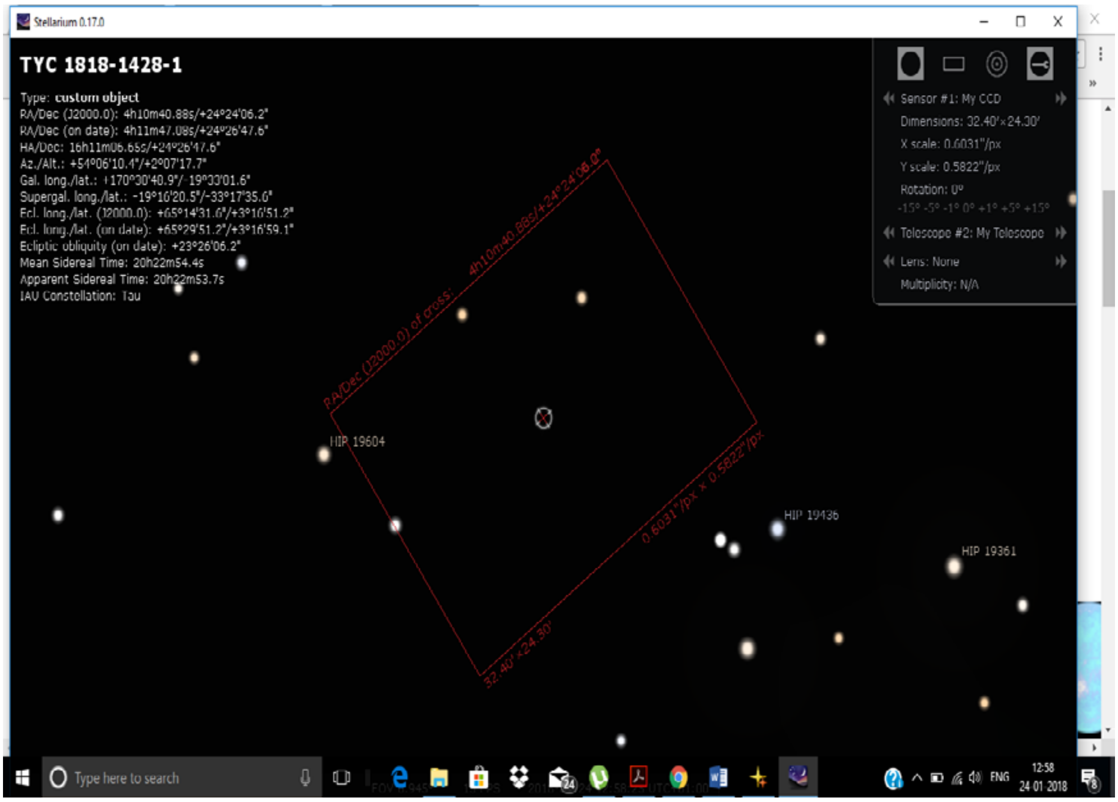


Star of Tres1b exoplanet (GSC 02652-01324)

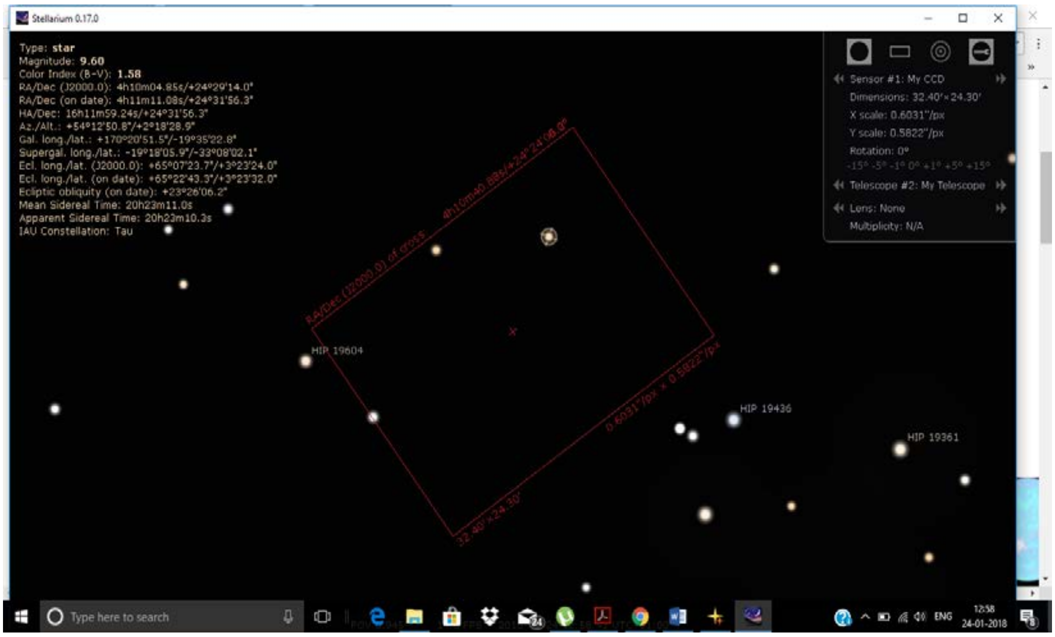


Reference stars of Tres 1b exoplanet

2-EPIC 211089792(Star)

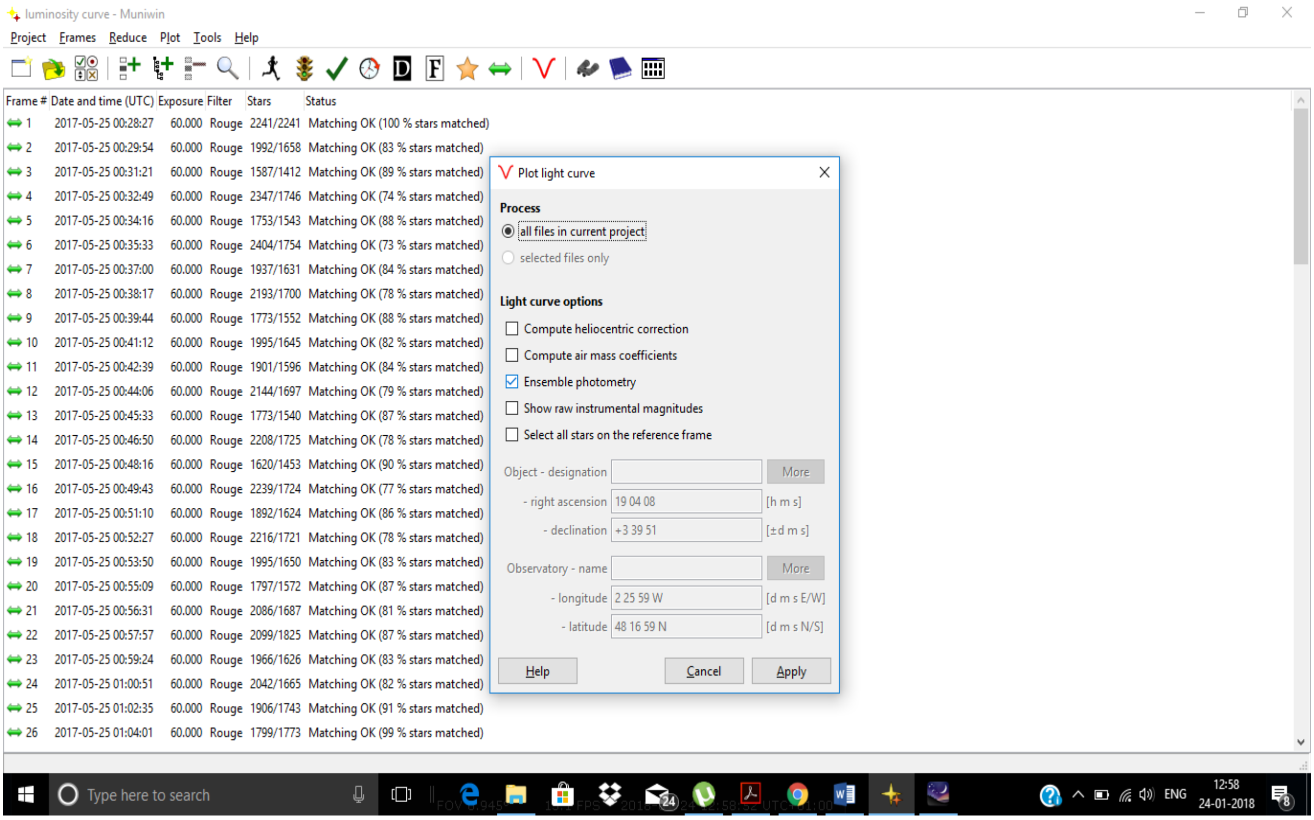


Epic reference stars-



The reference stars for both tres1 and epic is shown above

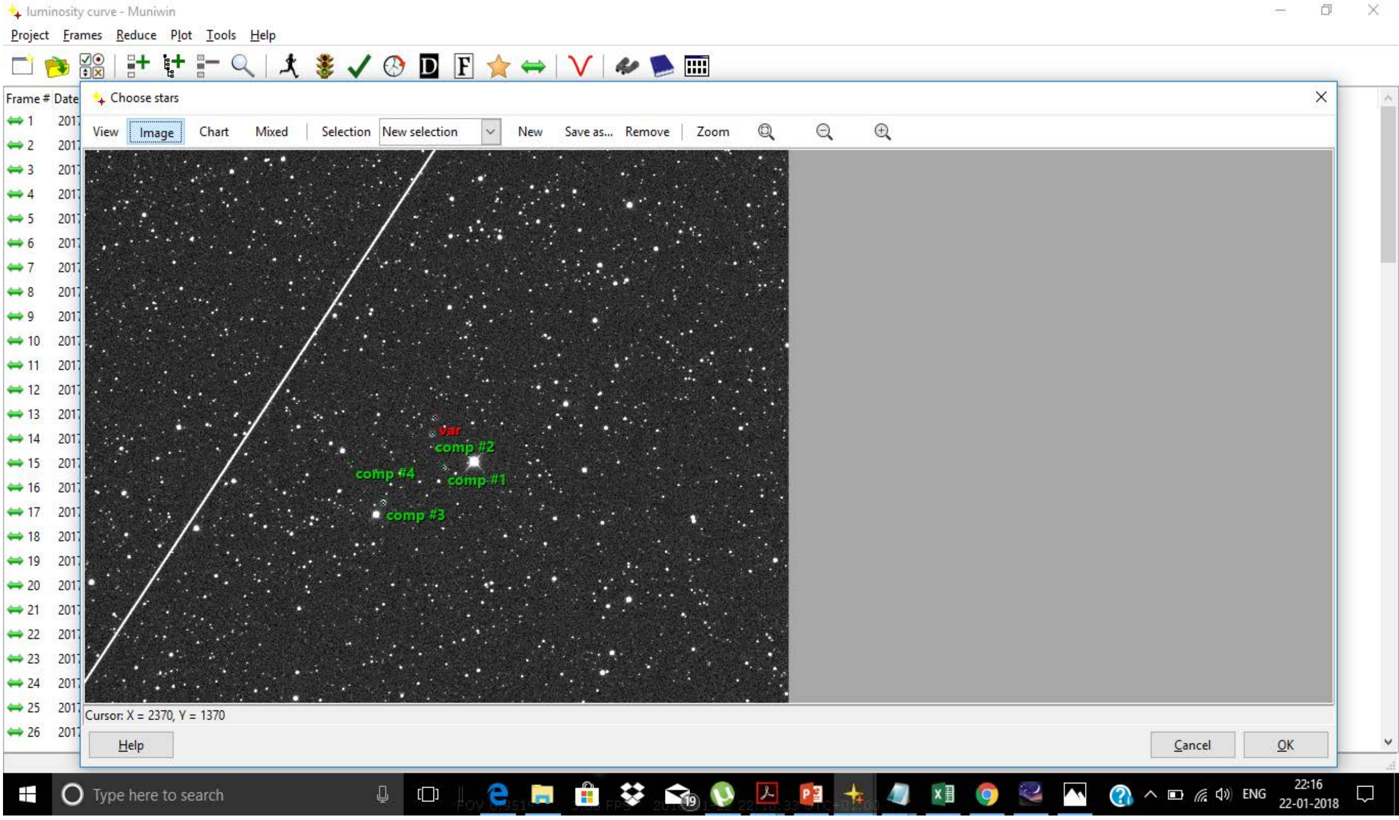
- NOW OnMuniwin, click on Plot Light Curve



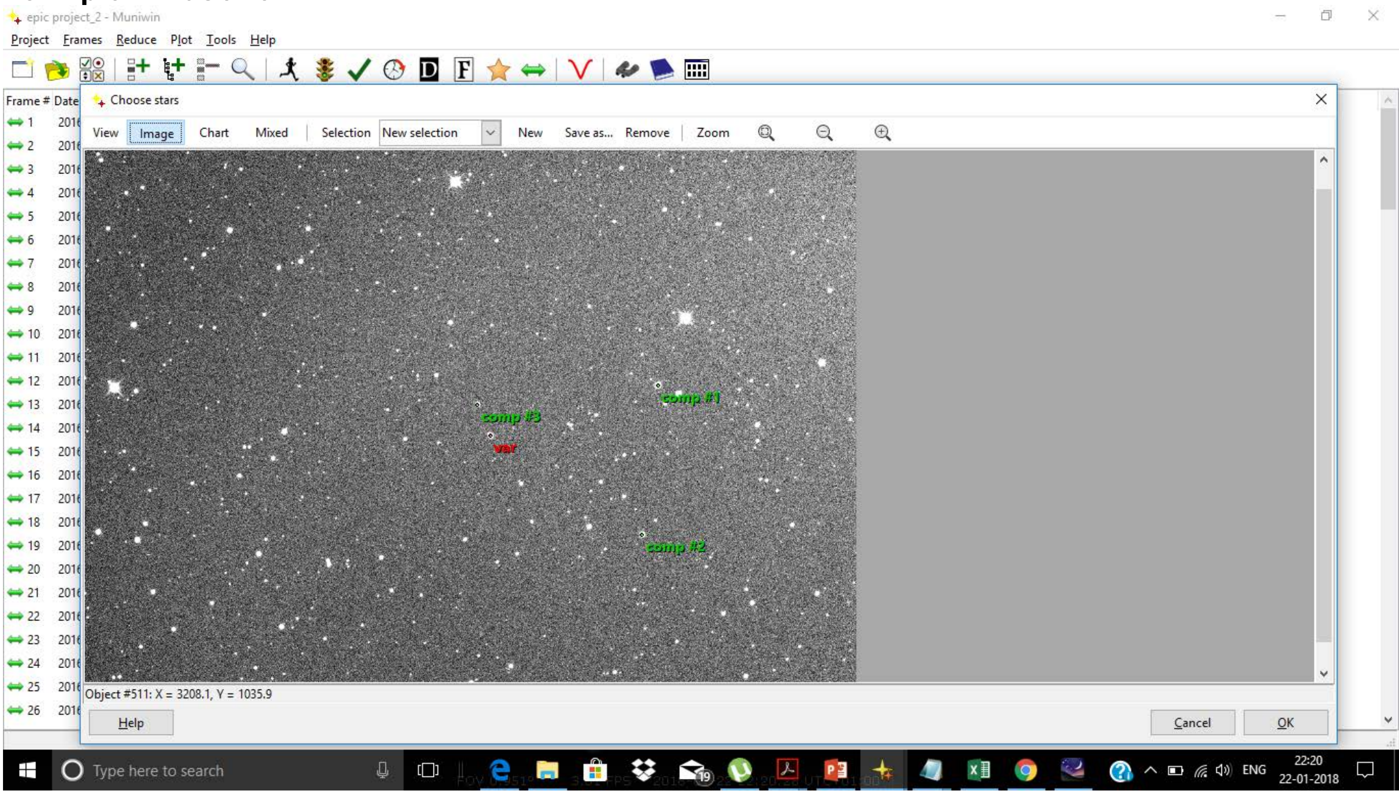
Check only Photometry set if you want to apply the variable star method, or uncheck this box if you want the classic method with a single reference star. Then Apply.

- On the image of the sky presented further, it is necessary to locate your star and the stars of reference. Be careful, it is difficult to be precise and to be sure of having to choose the right star (s). Right click on the one you think is your star and choose variable. Then right click on your reference stars and select comparison. You only have to choose one if you use the classic method, and many if you use the virtual star method.

For tres1b

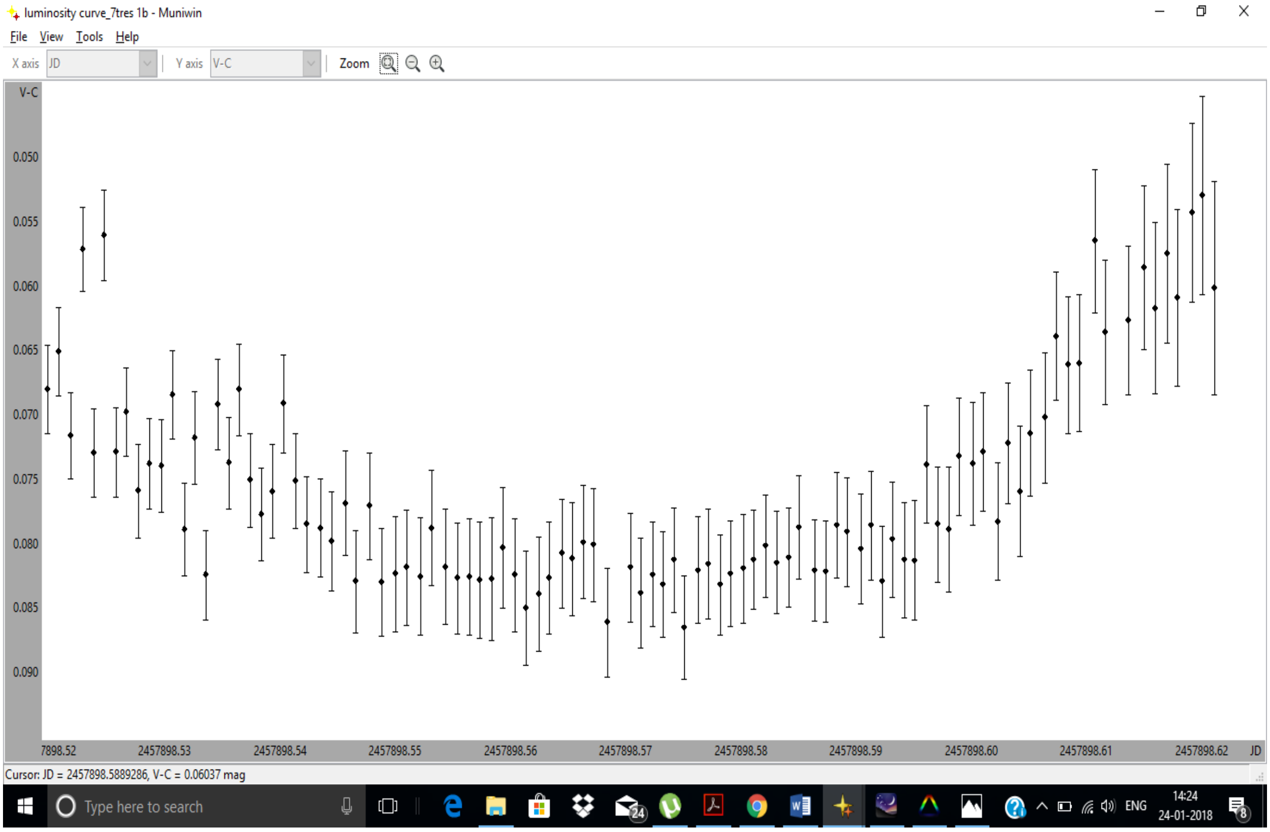


For Epic211089792

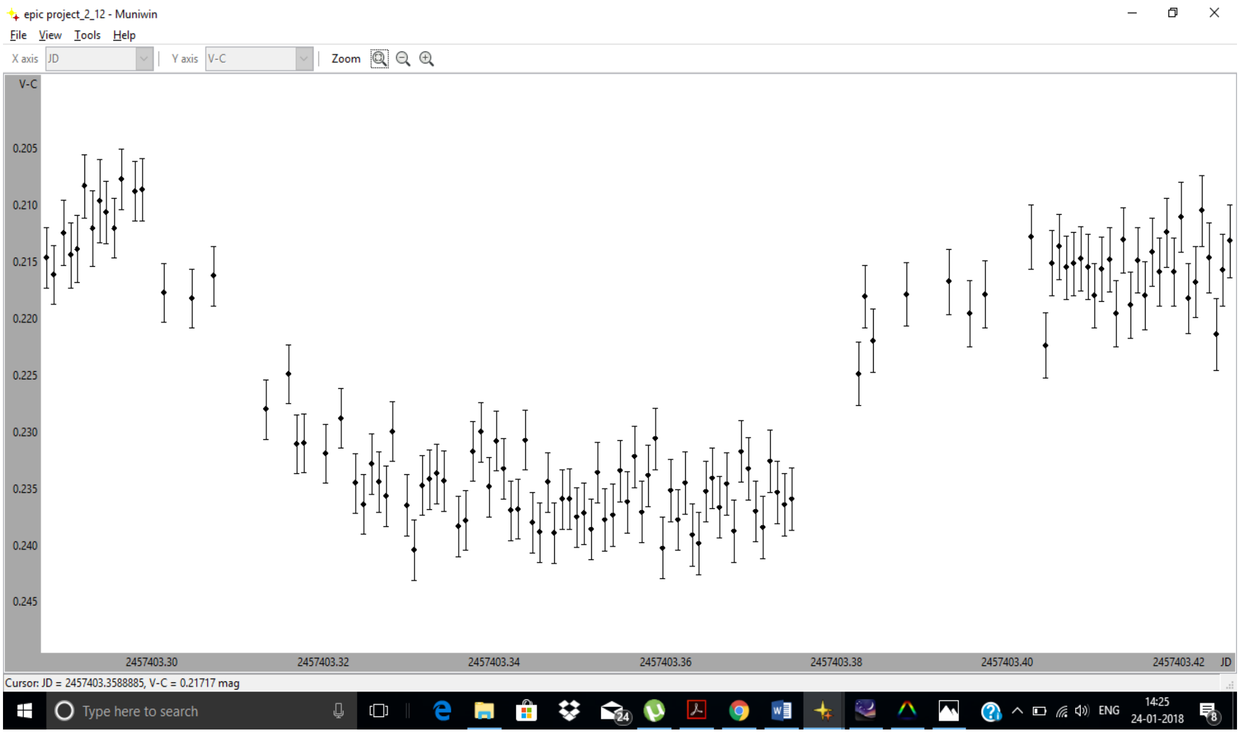


Then validate. And here is our beautiful and sterling curve!

For Tres1b-



For EPIC211089792



- save your curve by clicking on File> Save and enter the name of your file in .txt format.

We realized all of its steps from the data retrieved by the Observatory. Our team has managed to find out the consistent curve of the two above mentioned exoplanets i.e Tres-1b and EPIC211089792.

REFERENCES:

- Exoplanet transit Database: http://var2.astro.cz/ETD/
- Nasa SkyView: https://skyview.gsfc.nasa.gov/current/cgi/titlepage.pl
- Stellarium: http://stellarium.org/it/
- Muniwin manual: https://www.as.up.krakow.pl/rzeczy/cmpack-1.1-doc-en.pdf

3. MATLAB PROGRAM

After having obtained the magnitude data from Muniwin, it would be interesting to try to analyse those data and get information about the planet, such as: semimajor axis, inclination, impact parameter etc.

3.1 DATA IMPORT

To do that we designed a Matlab program that takes as input the .txt file obtained from Muniwin and the principle parameters that can be obtained from online databases.

Thus, the required parameter for the analysis are:

- Name of the muniwin .txt file, Ex. `'WASP-48b.txt'`
- Orbital period of the planet
- Radius of the star
- Limb-darkening coefficients of the star

The .txt file should be formatted as a table in the following format: Julian Day, Magnitude, error.

Ex.

```
JD V-C s1
Aperture: 4, Filter: Rouge, JD: geocentric
2457898.5197668 -2.67014 0.00365
2457898.5207691 -2.66991 0.00358
….
```

To run the program properly, the first 2 rows of the file must be deleted.
The orbital period of the planet must be expressed in days, the radius of the star in km. Those parameters
can be easily found online, for example at http://exoplanet.eu/catalog/.
For what concerning the Limb effect coefficients of the star, it's a little bit more complicated to find them, indeed the scientific literature should be used, a possible process is also illustrated in the following paragraph. In this program the 2-values for the quadratic limb darkening coefficients are needed as vector of 2 elements, otherwise if not available you can just use [0 0].
After that, the program will automatically import the data into the Mag, D and err vector.

3.2 DATA OPTIMIZATION

Before starting with the data analysis, would be better to improve our data so that they follow a better behaviour.

First, the removal of outlier is necessary. This can simply be done by using the Matlab function:

```
TF = isoutlier(Mag,'movmedian',0.01,'SamplePoints',D);
```

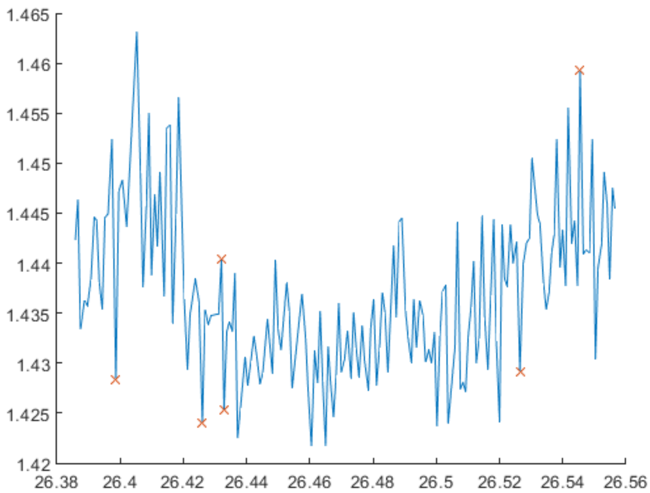
Where Mag, is the Magnitude vector and D is the day vector. This function computes the local average and finds the values to far from it. In this example 0.01 express the interval in which the local average is calculated; As a result, a vector containing zeros and one is returned, the positions of the ones are the position of the outliers, so that they can be simply removed with the command:

```
D(TF) = [];
M(TF) = [];
```

We can see how our outlier values are distributed with:

```
plot(D,Mag,D(TF),Mag(TF),'x')
```

obtaining the following graph:



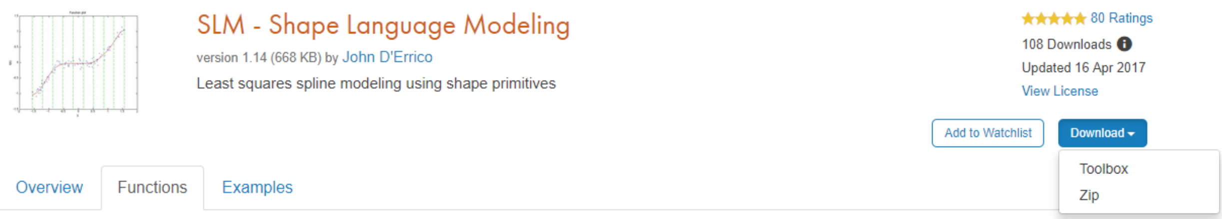
Another possible optimization, if a lot of data are available, is to divide them into x subarrays of n elements and calculate the average for each group. The new average values will have a lower dispersion so that the fitting process will be more accurate.

3.3 LINEAR FITTING

The first thing that must be calculated to further proceed in the analysis, are the transit times.

First of all we need to obtain the time for which the transit begins and ends. To do this we use Slmengine.

To use this library, we have to download it from [Mathworks] as a zip, unzip it and then put it in the working directory of Matlab.



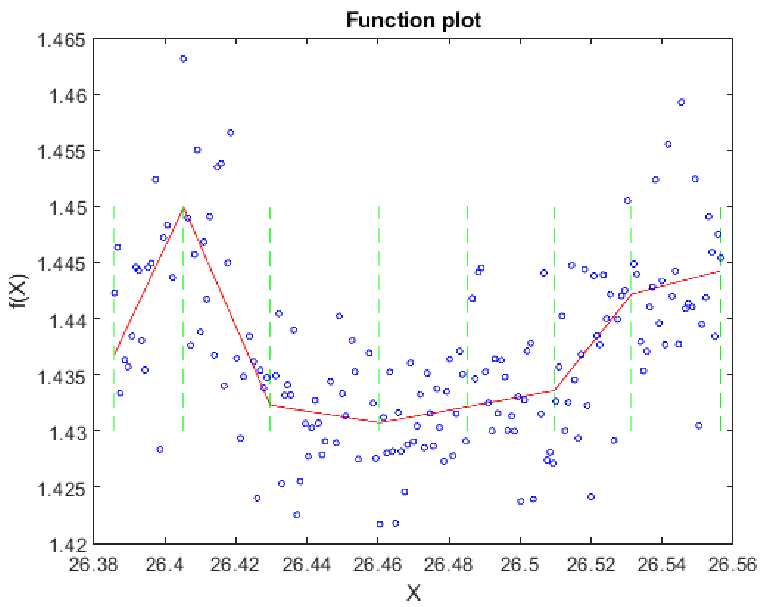
Slmengine is a very powerful tool that helps you fitting curves in the best way possible and in a very simple manner. For more information and a list of the possible parameters, you can open the slm_tutorial.html file in *SLMtools/html/slm_tutorial.html.*

After that we can begin to use it.

We want to obtain a 7-segment linear fitting of our data (exoplanetarchive), in such a way that is easy to find the interesting times, we also want to ensure that our curve is always concave up in the relevant part of the transit, those two things are very easy to do with slmengine:

```
Kn = 8;%to obtain 7 segment we need 8 knots
slmengine(D,Mag,'degree',1,'knots',Kn, 'interiorknots','free','plot','on','ConcaveUp',[26.42 26.52]);
```

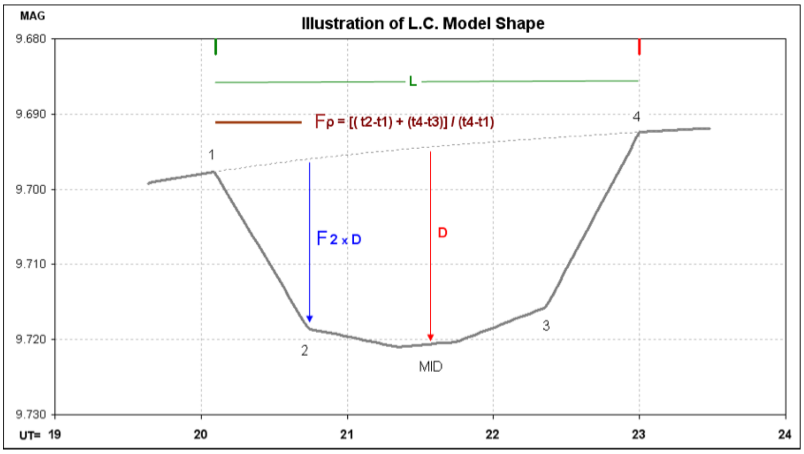
A similar plot should be obtained:



If the curve doesn't look as expected we can do additional manipulation of the data, for example removing uninteresting ones such as the one outside of the transit.
We can see that the relevant times of the transit are already shown with the vertical green lines, those represent the knots of the linear fitting.

3.4 DATA ANALYSIS

Once obtained the wanted curve is possible to obtain the times as in the figure below:



- t1: Beginning of ingress
- t2: End of ingress
- t3: Beginning of egress
- t4: End of egress
- L: length of transit from t1 to t4
- MD: mid-point of transit

- D: Transit depth at transit midpoint
- Fp: Partial transit fraction;
- F2: Fractional transit depth at t2

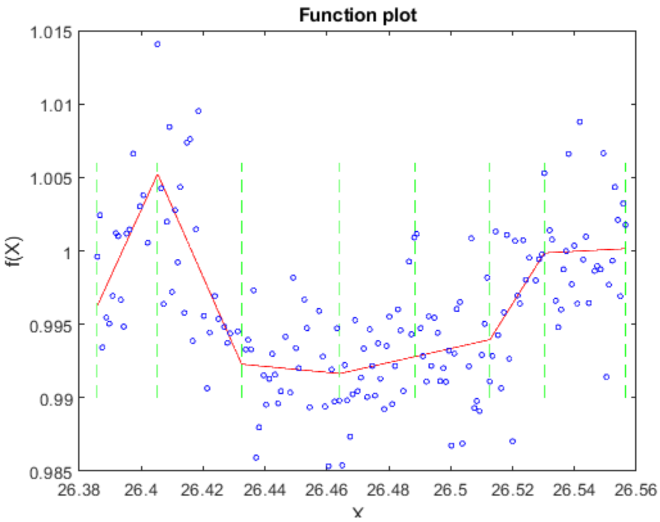
The values of the x knot of the segmented fitted curve can be obtained using t = slm.knots(x).
Thus, the times are obtained with:

```
t1 = slm.knots(2);
t2 = slm.knots(3);
t3 = slm.knots(end-2);
t4 = slm.knots(end-1);
tmiddle = (t3+t2)/2;
tt = t4-t1
tf = t3-t2
```

Where tt is the total duration of the transit, and tf is the full duration.
Next step is to obtain the transit Depth, from which is possible to get the Radius of the planet knowing the one of the star.
Before doing this is necessary to normalize our magnitude. This can be done by obtaining the average magnitude before or after the transit and then dividing all the magnitude data by it:

```
averageMag = (slmeval(slm.knots(end),slm)+slmeval(slm.knots(end-1),slm))/2
Mnorm = M/averageMag;
```

In this example the end part of the data are used to calculate the average, because they seem to be less noisy.
After plotting the new Magnitude the following graph should be obtained:



as we can see in this case the minimum magnitude is given by the 4th node, the minimum of the fitting curve can be obtained with slmengine like this:

```
[MinMag,MinTime] = slmpar(slm2,'minfun')
```

And the depth:

```
Depth = 1-MinMag
```

The depth of the transit is also equal to:

$$Depth = \Delta F = \left(\frac{R_p}{R_{star}}\right)^2$$

Thus, knowing the radius of the star the one of the planet can be obtained.

Starting from this, a lot of other parameters can be defined, we begin by getting the impact parameter b:

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

And the semimajor axis of the planet's orbit:

$$a = R_\star \left\{\frac{(1+\sqrt{\Delta F})^2 - b^2[1-sin^2(t_T\pi/P)]}{sin^2(t_T\pi/P)}\right\}^{1/2}$$

Using the definition of $b = \frac{a}{R_\star}\cos(i)$, is possible to calculate the inclination:

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

Other formulas are available to also calculate the density of the star, and the masses of star and planet, but the results obtained are far less precise then the one of the other parameters, also them will be included in the Matlab program for completeness:

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

Where G is the gravitational constant and P is the period of the orbit in SI (seconds).

Thus, using the volume of the sphere, the mass of the star will be:

$$M_\star = \frac{4}{3}\pi {R_\star}^3 \rho_\star$$

And from the newton gravitational law, we can get the mass of the planet as:

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

An example of those calculations done for Wasp-48p, is implemented in 2 Matlab files: light_curve_ls.mlx and light_curve_fit.m.

Those two are basically the same, but the mlx file is a live script, a kind of Matlab script easier to read, with the possibility to add plain text and images, and a better subdivision of paragraph. This kind of file can be read with Matlab 6 or later. The second file is instead a transposition of live script into a normal script, so it is lighter and faster, I suggest trying firstly the live script to better understand how it works, and then the normal one for actually using it.

3.5 THEORETICAL LIGHT CURVES

To further confirm the correctness of our calculations, could be useful to check if they light curve that they produce approximately fits our data. To do this, is necessary to build a mathematical model that matches experimental data. This has been thone for the first time by Mandel & Agol in 2002 and successively, more clearly, by Andras Pal in 2008.

Based on the work of Andras Pal we built a Matlab program capable of plotting any light curve, included the consideration of a quadratic limb effect.

The surface brightness of a star as a function of the normalized distance 0 ≤ r ≤ 1 assuming quadratic limb darkening is given by:

$$I(r) = 1 - \sum\nolimits_{m=1,2} \gamma_m \left(1 - \sqrt{1 - r^2}\right)$$

Where the constants γ_1,γ_2 quantify the limb darkening.

The total flux of the star during the transit can be instead described by the relationship:

$$f = 1 - \Delta f$$

Where the flux decrease can be obtained by:

$$\Delta f = W_0 F_0 + W_2 F_2 + W_1 [F_1 + F_k K(k) + F_E E(k) + F_\Pi \Pi(n,k)]$$

Where K(k), E(k) and $\Pi(n,k)$ are the complete elliptic integrals of the first second and third order. Those three functions can be calculated with Matlab using the functions: $ellipke(k_m)$, and$ellipticPi(n,k_m)$, where $k_m = k^2$.

Instead the variable W_n with n= 0,1,2 are only dependent with the limb darkening coefficients, as follows:

$$W_0 = \frac{6 - 6\gamma_1 - 12\gamma_2}{W}$$

$$W_1 = \frac{6\gamma_1 + 12\gamma_2}{W}$$

$$W_2 = \frac{6\gamma_2}{W}$$

$$W = 6 - 2\gamma_1 - \gamma_2$$

Last thing to calculate are the F_n functions, they're laws change depending on the position of the planet relative to the star, is in fact possible to identify 12 cases as described in the table below.

Step	Relation	Case
1	$z = 0 \,\&\, p < 1$	A
2	$z \leq p - 1$	A_G
3	$z < p \,\&\, z < 1 - p$	B
4	$z < p \,\&\, z = 1 - p$	B_T
5	$z < p$	B_G
6	$z = p \,\&\, z < 1 - p$	C
7	$z = p = 1/2$	C_T
8	$z = p$	C_G
9	$z < 1 - p$	D
10	$z = 1 - p$	E
11	$z < 1 + p$	F
12	–	G

In those 12 different cases the values of F_n functions, k and n are:

Step	Case	F_0	F_1	F_K	F_E	F_Π	F_2	k	n
1	A	p^2	$\frac{2}{3}(1-(p')^3)$	0	0	0	$\frac{1}{2}p^4$	–	–
2	A_G	1	$\frac{2}{3}$	0	0	0	$\frac{1}{2}$	–	–
3	B	p^2	$\frac{2}{3}$	$C_I C_{IK}$	$C_I C_{IE}$	$C_I C_{I\Pi}$	$\frac{1}{2}p^2(p^2+2z^2)$	$\sqrt{\frac{4pz}{1-a}}$	$-\frac{4pz}{a}$
4	B_T	p^2	T_I	0	0	0	$\frac{1}{2}p^2(p^2+2z^2)$	–	–
5	B_G	G_0	$\frac{2}{3}$	$C_G C_{GK}$	$C_G C_{GE}$	$C_G C_{G\Pi}$	G_2	$\sqrt{\frac{1-a}{4pz}}$	$\frac{a-1}{a}$
6	C	p^2	$\frac{1}{3}$	$\frac{2}{9\pi}(1-4p^2)$	$\frac{8}{9\pi}(2p^2-1)$	0	$\frac{3}{2}p^4$	$2p$	–
7	C_T	$\frac{1}{4}$	$\frac{1}{3} - \frac{4}{9\pi}$	0	0	0	$\frac{3}{32}$	–	–
8	C_G	G_0	$\frac{1}{3}$	$-\frac{1}{9\pi p}(1-4p^2)(3-8p^2)$	$\frac{1}{9\pi}16p(2p^2-1)$	0	G_2	$\frac{1}{2p}$	–
9	D	p^2	0	$C_I C_{IK}$	$C_I C_{IE}$	$C_I C_{I\Pi}$	$\frac{1}{2}p^2(p^2+2z^2)$	$\sqrt{\frac{4pz}{1-a}}$	$-\frac{4pz}{a}$
10	E	p^2	T_I	0	0	0	$\frac{1}{2}p^2(p^2+2z^2)$	–	–
11	F	G_0	0	$C_G C_{GK}$	$C_G C_{GE}$	$C_G C_{G\Pi}$	G_2	$\sqrt{\frac{1-a}{4pz}}$	$\frac{a-1}{a}$
12	G	0	0	0	0	0	0	–	–

Where all the missing parameters are:

$$a = (p-z)^2 \quad b = (p+z)^2 \quad t^2 = p^2 + z^2 \qquad \hat{p} = \sqrt{p(1-p)} \quad p' = \sqrt{1-p^2}$$

$$C_I = \frac{2}{9\pi\sqrt{1-a}} \quad C_{IK} = 1 - 5z^2 + p^2 + ab \qquad C_{IE} = (z^2 + 7p^2 - 4)(1-a) \quad C_{I\Pi} = -3\frac{p+z}{p-z}$$

$$C_G = \frac{1}{9\pi\sqrt{pz}} \quad C_{GK} = 3 - 6(1-p^2)^2 - 2pz(z^2 + 7p^2 - 4 + 5pz) \qquad C_{GE} = 4pz(z^2 + 7p^2 - 4) \quad C_{G\Pi} = -3\frac{p+z}{p-z}$$

$$T_I = \frac{2}{3\pi}\arccos(1-2p) - \frac{4}{9\pi}(3 + 2p - 8p^2)\hat{p} \qquad k_0 = \arccos\left(\frac{p^2+z^2-1}{2pz}\right) \quad k_1 = \arccos\left(\frac{z^2+1-p^2}{2z}\right)$$

$$G_0 = \frac{p^2 k_0 + k_1 - \sqrt{z^2 - \frac{1}{4}(1+z^2-p^2)^2}}{\pi} \qquad G_2 = \frac{k_1 + p^2(p^2+2z^2)k_0 - \frac{1}{4}(1+5p^2+z^2)\sqrt{(1-a)(b-1)}}{2\pi}$$

We can see that all those functions are only depending on p and z. Where z is the distance between the centre of the stellar and planetary disk, and p is the relative radius of the planet, $p = \frac{R_p}{R_\star}$. So, the problem can be completely solved. The only thing missing is the time dependent equation of z:

$$z^2(t) = (a/R_\star)^2 sin^2[n(t-E)] + b^2 cos^2[n(t-E)]$$

Where this time a is the semimajor axis of the planet orbit; $n = \frac{2\pi}{P}$, with P period of the orbit; b is the impact parameter; and E is the time for which the planet has completed half of the transit.

All of those equations are thus implemented in a Matlab function called:

```
theoretical_light_curve_Pal(Rplanet,Rstar,limbcoefficients,TIn,Tend,tE,Period,a,inclination)
```

with the obvious meaning of his parameters.

The equivalent function has been also written with the Mandel & Agol model:

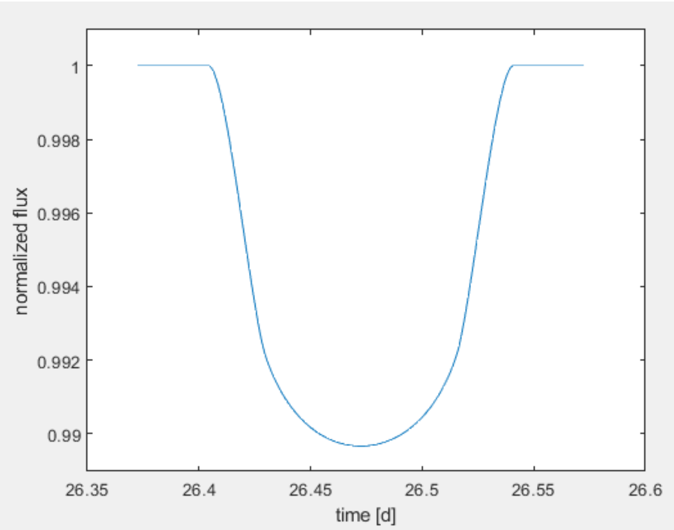
```
theoretical_light_curve_mandel(Rplanet,Rstar,limbcoefficients,TIn,Tend,tE,Period,a,inclination
)
```

obtaining the same results.

Those functions return `[flux, time]`so that it is very easy to plot the results with:

```
plot(time,flux);
```

Once plotted something similar should be obtained:



3.6 OBTAIN LIMB DARKENING COEFFICIENTS

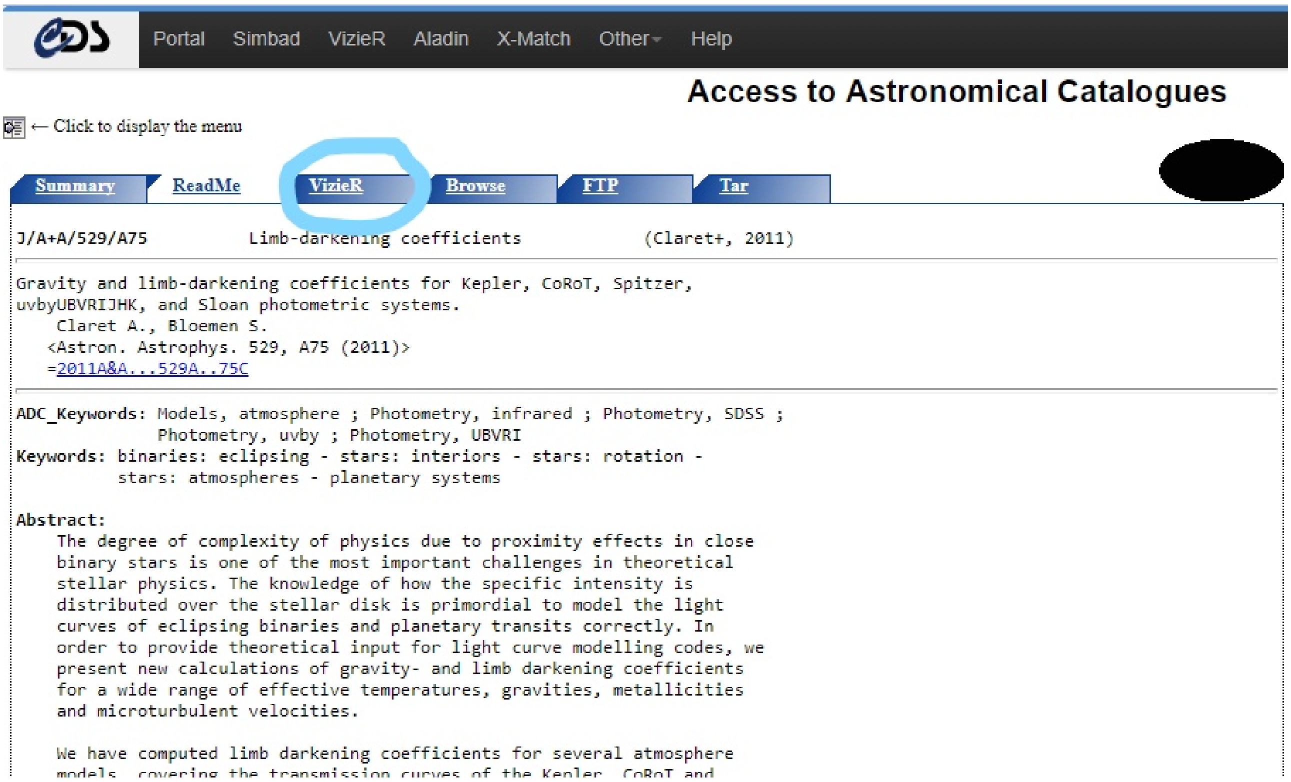
During next paragraphs limb-darkening coefficients are required to obtain the theoretical light curves.

A possible way to get them is using the online tool available at:http://cdsarc.u-strasbg.fr/viz-bin/Cat?cat=J%2FA%2BA%2F529%2FA75&target=readme&

Essentially, it's a table where is possible to query the coefficients, based on some available parameter of the subject star, such as its effective temperature and surface gravity acceleration.

In this paragraph is explained how to get the coefficients for quadratic limb darkening.

First of all, visit the website, then click on the tab "VizieR", as indicated in the following image:


Portal Simbad VizieR Aladin X-Match Other Help

Access to Astronomical Catalogues

← Click to display the menu

Summary ReadMe VizieR Browse FTP Tar [redacted]

J/A+A/529/A75 Limb-darkening coefficients (Claret+, 2011)

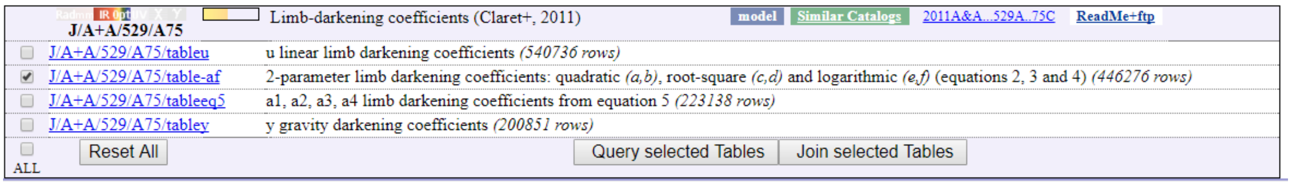
Gravity and limb-darkening coefficients for Kepler, CoRoT, Spitzer,
uvbyUBVRIJHK, and Sloan photometric systems.
Claret A., Bloemen S.
<Astron. Astrophys. 529, A75 (2011)>
=2011A&A...529A..75C

ADC_Keywords: Models, atmosphere ; Photometry, infrared ; Photometry, SDSS ;
Photometry, uvby ; Photometry, UBVRI
Keywords: binaries: eclipsing - stars: interiors - stars: rotation -
stars: atmospheres - planetary systems

Abstract:
The degree of complexity of physics due to proximity effects in close binary stars is one of the most important challenges in theoretical stellar physics. The knowledge of how the specific intensity is distributed over the stellar disk is primordial to model the light curves of eclipsing binaries and planetary transits correctly. In order to provide theoretical input for light curve modelling codes, we present new calculations of gravity- and limb darkening coefficients for a wide range of effective temperatures, gravities, metallicities and microturbulent velocities.

We have computed limb darkening coefficients for several atmosphere
models, covering the transmission curves of the Kepler, CoRoT and

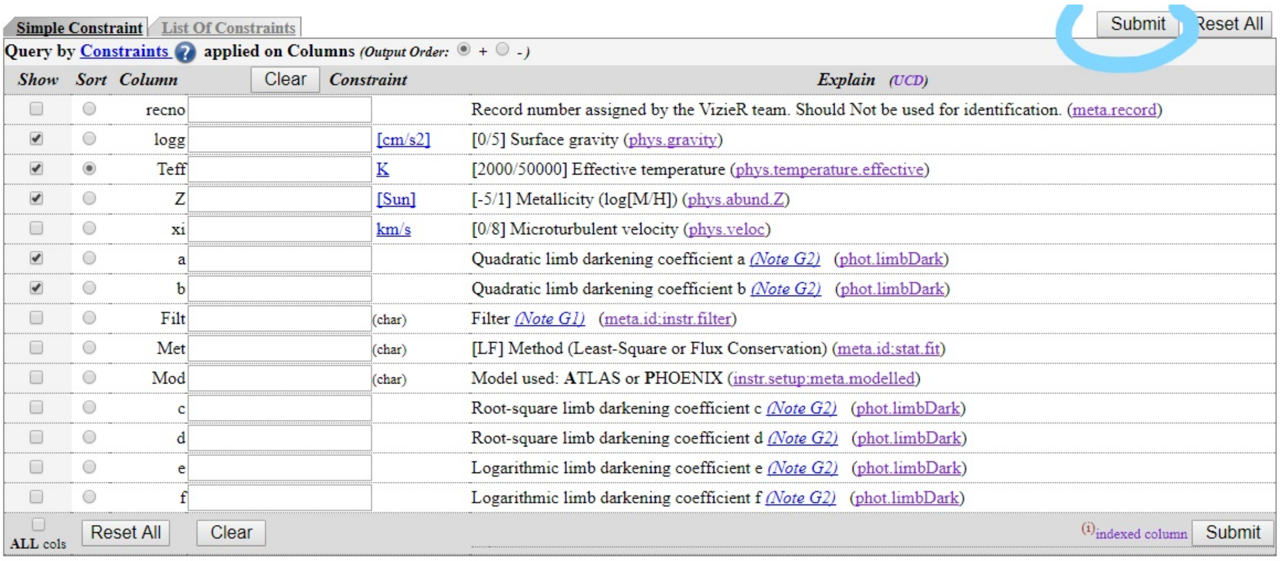
The following page will be presented:



J/A+A/529/A75	Limb-darkening coefficients (Claret+, 2011) model Similar Catalogs 2011A&A...529A..75C ReadMe+ftp
☐ J/A+A/529/A75/tableu	u linear limb darkening coefficients *(540736 rows)*
☑ J/A+A/529/A75/table-af	2-parameter limb darkening coefficients: quadratic *(a,b)*, root-square *(c,d)* and logarithmic *(e,f)* (equations 2, 3 and 4) *(446276 rows)*
☐ J/A+A/529/A75/tableeq5	a1, a2, a3, a4 limb darkening coefficients from equation 5 *(223138 rows)*
☐ J/A+A/529/A75/tabley	y gravity darkening coefficients *(200851 rows)*
☐ ALL Reset All	Query selected Tables Join selected Tables

Select the row relevant to the quadratic limb darkening and click on "Query selected Tables".

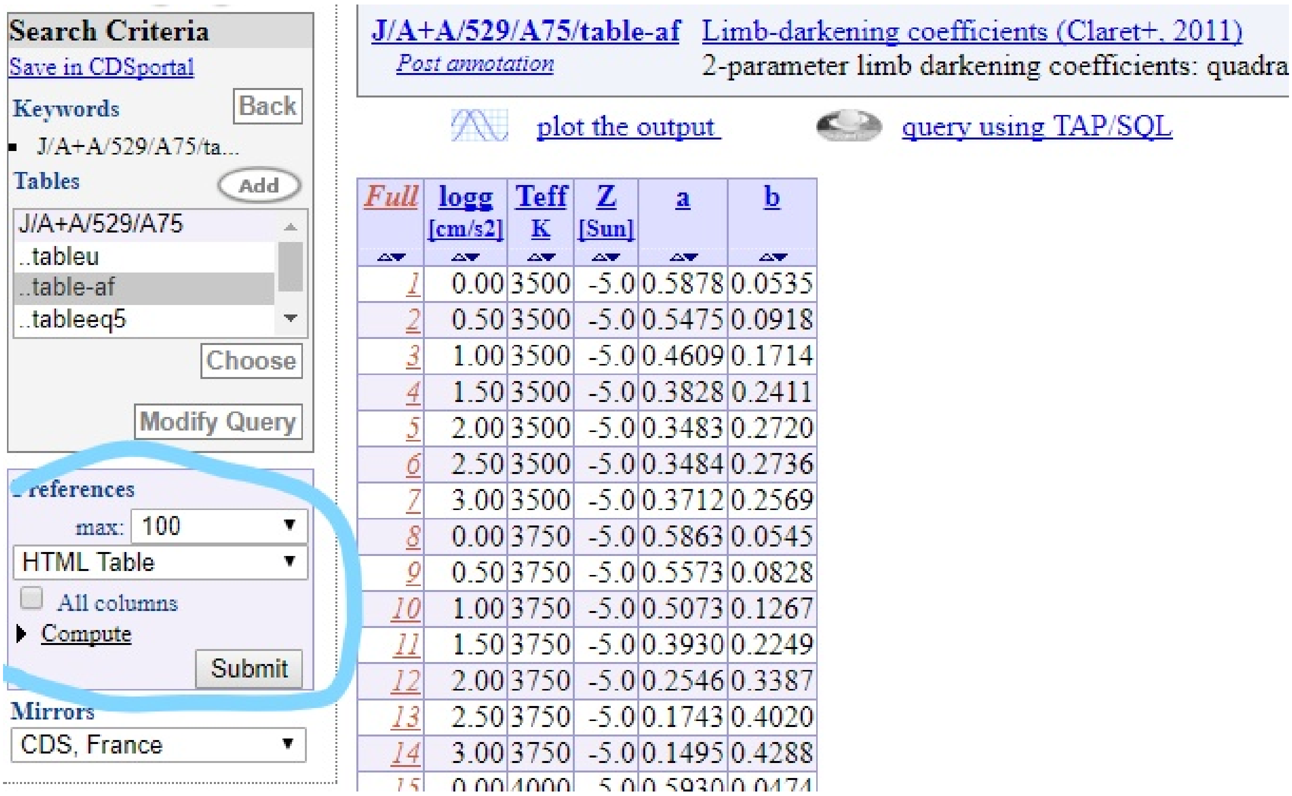
After that select only the parameters you are interested in and click "Submit".



Now you'll be presented with a table, with a list of parameters. You can find yours by simply looking at the corresponding Temperature and surface gravity, the limb darkening parameters will be "a" and "b".

Full	logg [cm/s2]	Teff K	Z [Sun]	a	b
1	0.00	3500	-5.0	0.5878	0.0535
2	0.50	3500	-5.0	0.5475	0.0918
3	1.00	3500	-5.0	0.4609	0.1714
4	1.50	3500	-5.0	0.3828	0.2411
5	2.00	3500	-5.0	0.3483	0.2720
6	2.50	3500	-5.0	0.3484	0.2736
7	3.00	3500	-5.0	0.3712	0.2569
8	0.00	3750	-5.0	0.5863	0.0545
9	0.50	3750	-5.0	0.5573	0.0828
10	1.00	3750	-5.0	0.5073	0.1267
11	1.50	3750	-5.0	0.3930	0.2249
12	2.00	3750	-5.0	0.2546	0.3387
13	2.50	3750	-5.0	0.1743	0.4020
14	3.00	3750	-5.0	0.1495	0.4288
15	0.00	4000	-5.0	0.5930	0.0474
16	0.50	4000	-5.0	0.5534	0.0855

If the one you want is not displayed, you can extend the research by including more rows, to do that you can simply change the number of rows displayed with the tool on the left, and then click submit:



Full	logg [cm/s2]	Teff K	Z [Sun]	a	b
1	0.00	3500	-5.0	0.5878	0.0535
2	0.50	3500	-5.0	0.5475	0.0918
3	1.00	3500	-5.0	0.4609	0.1714
4	1.50	3500	-5.0	0.3828	0.2411
5	2.00	3500	-5.0	0.3483	0.2720
6	2.50	3500	-5.0	0.3484	0.2736
7	3.00	3500	-5.0	0.3712	0.2569
8	0.00	3750	-5.0	0.5863	0.0545
9	0.50	3750	-5.0	0.5573	0.0828
10	1.00	3750	-5.0	0.5073	0.1267
11	1.50	3750	-5.0	0.3930	0.2249
12	2.00	3750	-5.0	0.2546	0.3387
13	2.50	3750	-5.0	0.1743	0.4020
14	3.00	3750	-5.0	0.1495	0.4288
15	0.00	4000	-5.0	0.5930	0.0474

3.7 MATLAB ANALYSIS

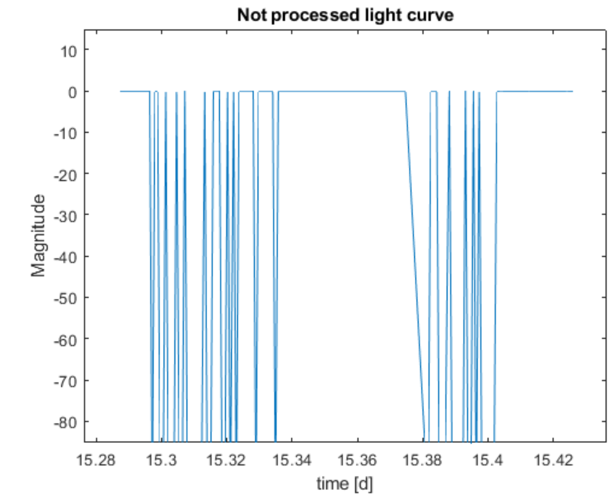
The analysis of data relative to the transit of the planets Epic211089792b and Tres-1b, has been done in a way similar to the one explained before, with some differences. In the following paragraphs are explained the most important differences in the process and the results of the study.

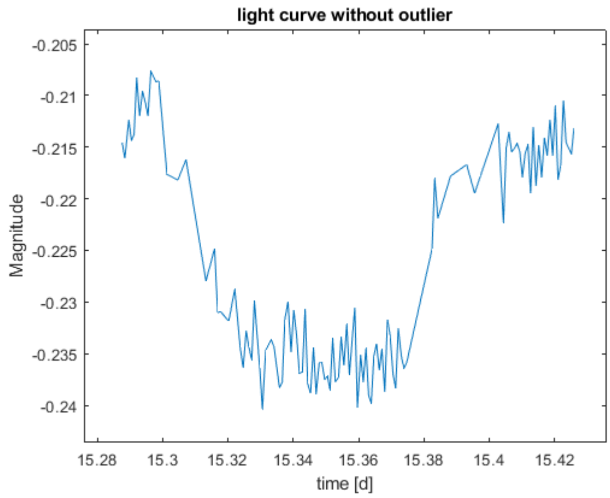
3.7.1 MATLAB ANALYSIS FOR EPIC211089792 B

The planet Epic211089792b, also known as K2-29b, is a giant planet. Those kinds of planets are still studied a lot because they're formation is not completely understood, and they represent the best target for atmospheric characterization.

In this paragraph we firstly obtain a representation of the light curve produced by the transit, and then using the equations seen before, we try to obtain the principal characteristics of the planet.

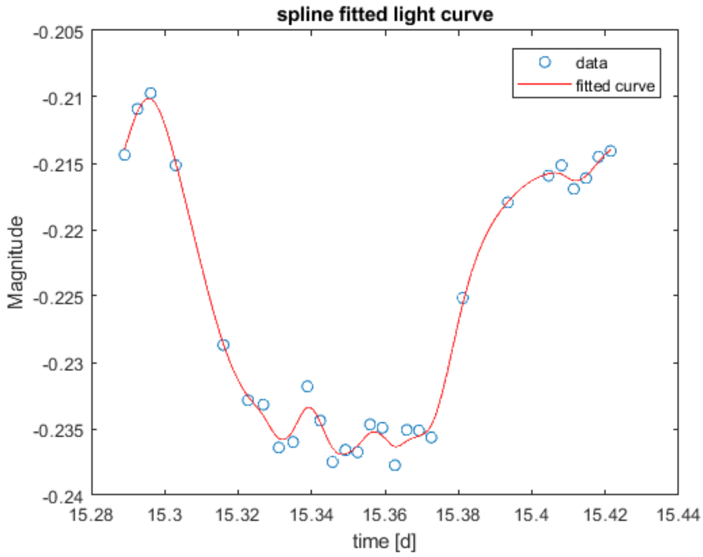
The first thing that has been done, after importing the file into Matlab, is to remove the outlier data. In fact, in this case after the elaboration of the images with Muniwin, was clear that a lot of them produced outlier represented by the presence of magnitude of 99.99 in certain rows in the .txt file.



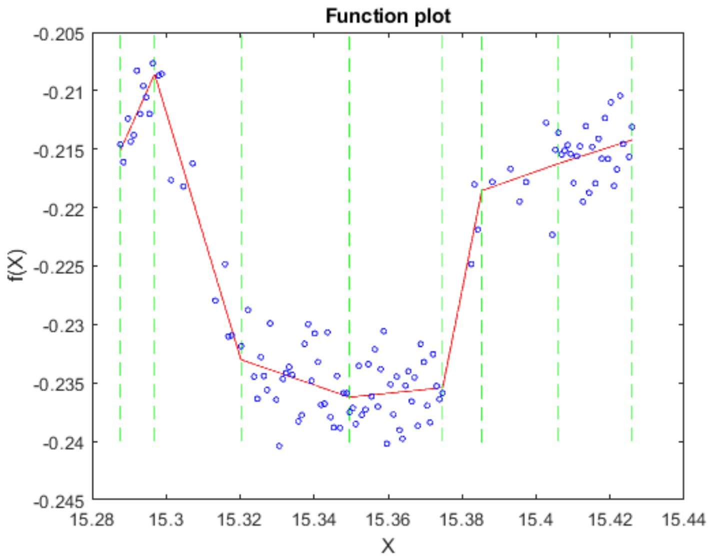


An example of the plot obtained with and without removing the outlier is shown in the following images:

After having removed the outlier and divided the data by groups of 4 elements, is possible to calculate the average of each of them. This will let us obtain a better visualization of the light curve:



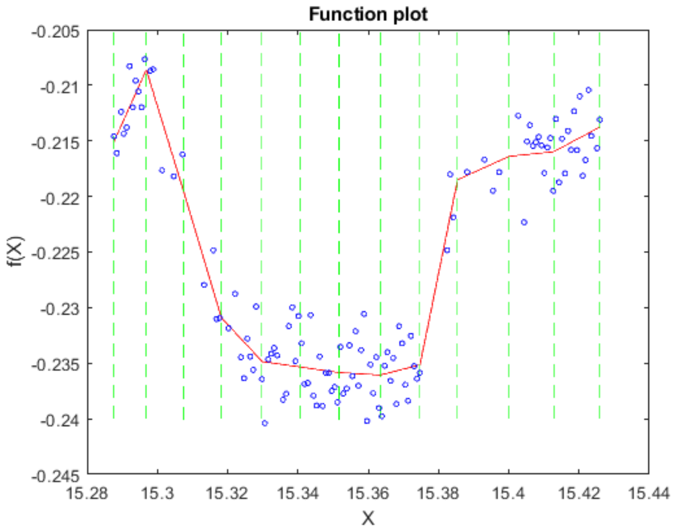
As explained before, to obtain some measurements from the data, the first thing to do is get the characteristic times of the transit. To this in a better way, we need to define a segmented light curve. This is possible with Slmengine.



As is visible in the plot, if only 8 knots were used (like explained in the precedent paragraph) not all the relevant points of the light curve are identified. In fact, the start of the transit is not represented by the second knot but by the small group of 3 point just under it.

The higher group of points is in fact probably just a measurement error, being the level of the normal magnitude clearly visible on the right side.

So, to better express the starting point, we found that 13 points was the best compromise:



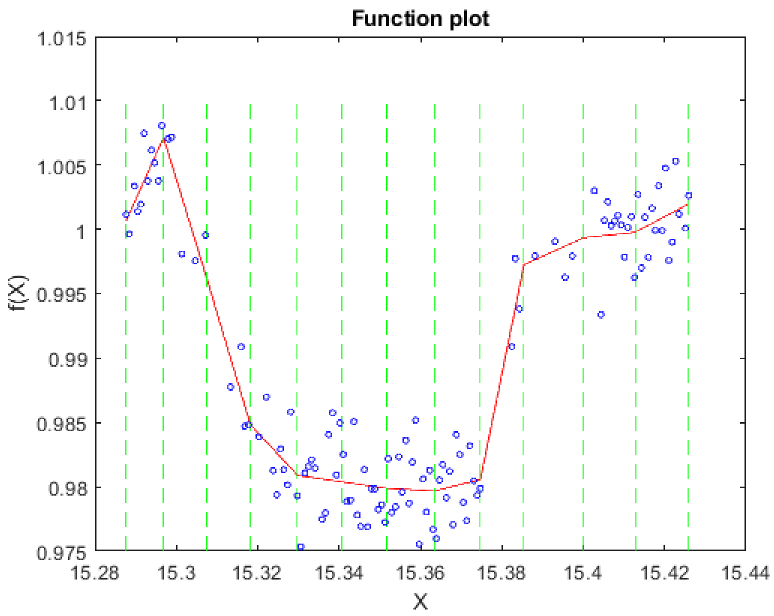
The next step to do would be a normalization of the magnitude, by dividing all the magnitude data by the average magnitude of the star without any planet transiting.

In this case and also for tres-1b the results obtained doing this, for some reasons, are not consistent. Instead all of the parameters become almost identical to the rea one if the normalization is not done. So Is possible to suppose that some kind of normalization is already performed by Muniwin. Because of not enough time to further investigate the origin of this behaviour, we just continued by simply translating the curve in such a way that the average magnitude corresponds to 1.

This is done by:

```
Mag = Mag-averageMag+1;
```

The resultwill be:



After that we can proceed with extrapolation of the information.

Initially the times has been calculated, obtaining:

$$tt = 0.07793\ days$$

$$tf = 0.04495\ days$$

Where tt is the total time and tf is the full time.

The obtained depth is instead:

$$Depth = 0.0203$$

Knowing the radius of the star and the Period of the planet's orbit, is possible to obtain all the other parameters.

The star radius, and all the other real parameters presented later, can be found on the paper"EPIC211089792 b: an aligned and inflated hot Jupiter in a young visual binary".
Thus, the radius is:

$$R_\star = 0.86 * R_{sun}$$

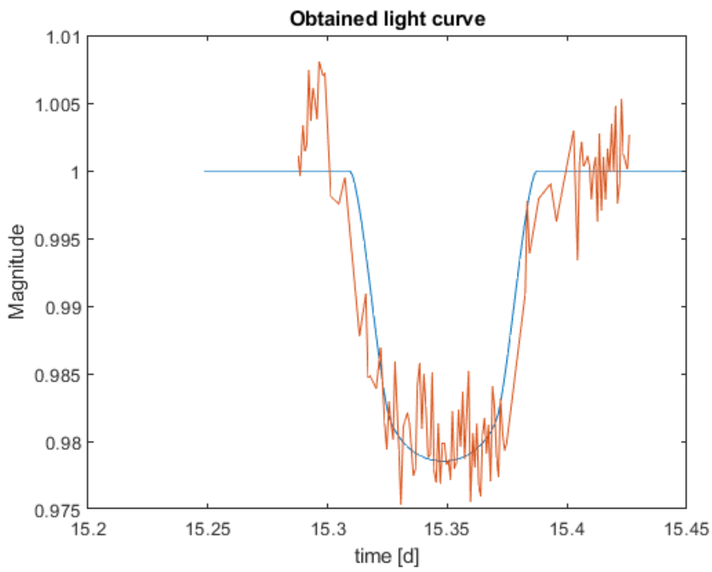
And the period:

$$P = \ 3.2588321\ days$$

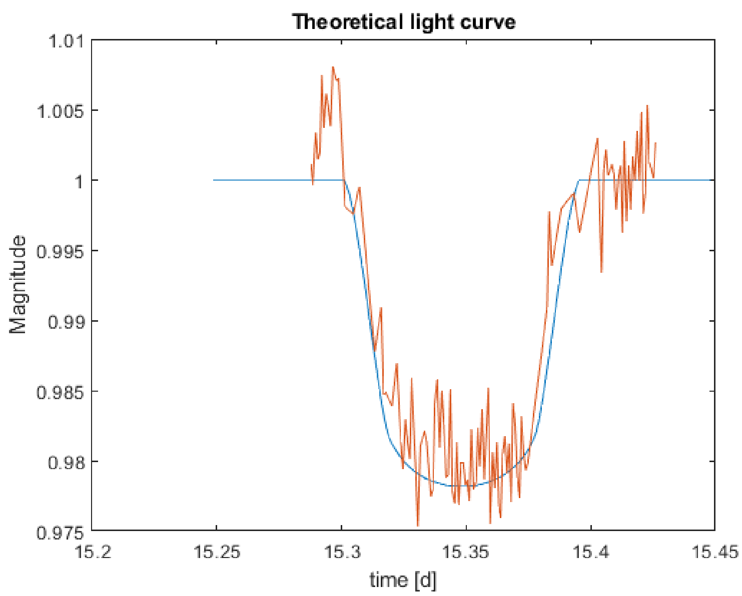
In the following table we can see the results:

	OBTAINED VALUES	THEORETICAL VALUES
Depth	0.020328	0.020219
Radius of the planet [km]	85303	85075
Impact parameter b	0.67094	0.71980
Semimajor axis [km]	7382955	6308542
Inclination [°]	86.88	86.656
Planet mass [kg]	-9.57e30	1.38e+27
Star mass [kg]	1.257e31	1.869e+30
Effective Temperature [K]		5358
Surface gravity log(g) [g.cm-2]		4.54

Apart from the value of the masses (the error was probably amplified after every formula) the result seems pretty satisficing.
With those data is possible to plot the theoretical light curves, with the functions presented in the previous paragraph:



And using the theoretical parameters from the table:



Those two functions have been plotted using the following limb-darkening coefficient:

$\gamma_1 = 0.2451$ $\gamma_2 = 0.3552$

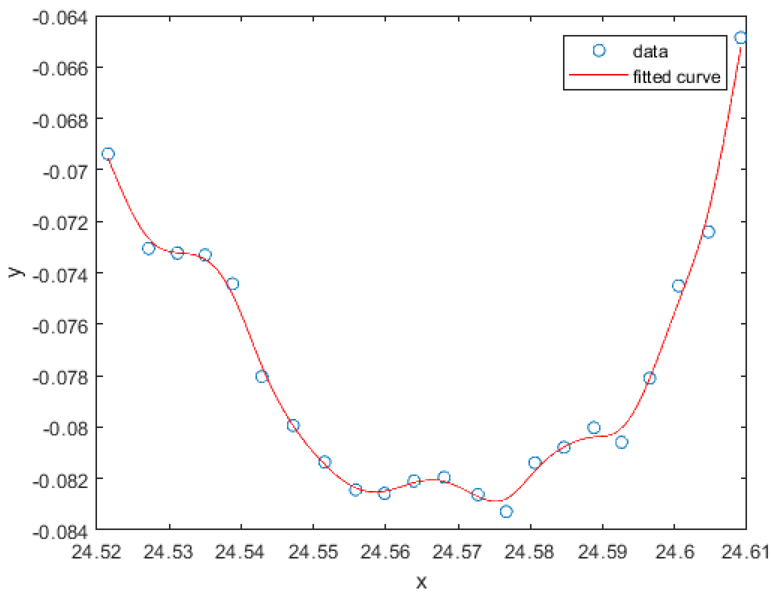
Obtained as explained in the previous chapter, with a star effective temperature of 5500K and log(g) of 4.5, those in fact are the values most near to the theoretical ones.

3.7.2 MATLAB ANALYSIS FOR TRES-1b

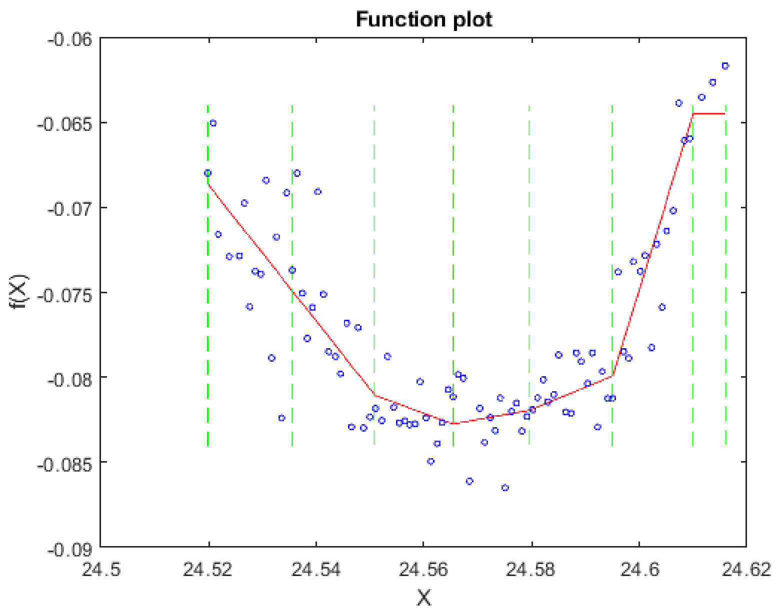
The procedure used for evaluating the parameters for Tres-1b is similar to the one of Epic. The major difference is in the quality of the data. In fact, the starting point of the transit is not included because of technical errors during the telescope observations. Instead in the ending points is not clear which is the normal magnitude of the star after the transit, because of clouds that forced the interruption of the observations.

With those constraint we tried to obtain some consistent data making some assumptions.

The data optimization happen in the same way as epic, by first removing the outlier and then plotting the first spline-light-curve:



Then with an 8-knots linear interpolation, we try to obtain our first data:



In this image we can see the presence of a little horizontal line in the ending part. This is because We forced the ending part to be constant, so that is possible to consider it as the average magnitude after the transit (This is an assumption). This can be done with slmengine using the parameter 'constantregion' and specifying the wanted interval, the tool will choose the best fit for the constant value.

After encountering the same normalization problem of Epic the curve has been translated to an average of 1. And then the times have been evaluated:

$$tt = \ 0.08169 \, days \qquad\qquad tf = \ 0.00918 \, days$$

Since the first part of the light curve is missing, those times has been found by using only the second half of the transit, by assuming it to be symmetrical.

To do that the minimum of the magnitude is considered to be the centre of the transit and then the last but two knot the end of the full duration, the end of the total duration is considered to be the penultimate knot. In such a way that the times can be calculated has follows:

```
tt = (t4-tmiddle)*2;% total duration [days]
tf = (t3-tmiddle)*2; % full duration [days]
```

Then we proceeded by calculating the depth of the transit:

$$Depth = \ 0.0181$$

By having found that on the paper http://iopscience.iop.org/article/10.1086/425256/pdf, that the period of the planet and the radius of the star are:

$$P = 3.030065 \, days \qquad\qquad R_{\star} = 0.85 \, R_{sun}$$

We found the followings:

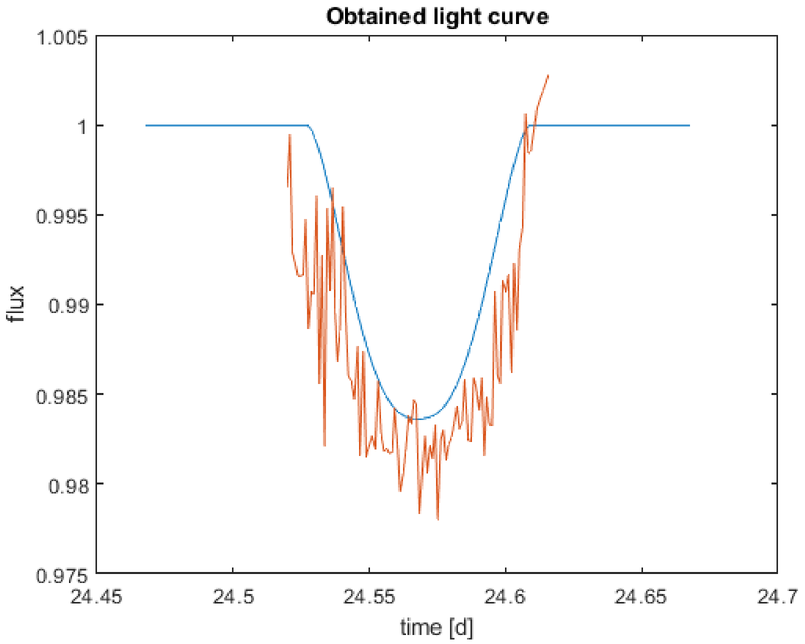
	OBTAINED VALUES	THEORETICAL VALUES
Depth	0.0181	0.0170
Radius of the planet [km]	79721	77211
Impact parameter b	0.8611	0.229
Semimajor axis [km]	5191022	5879196
Inclination [°]	84.37	88.5
Planet mass [kg]	-3.85e+30	1.4236e+27
Star mass [kg]	5.05e+30	1.7499e+30
Effective Temperature [K]		5250
Surface gravity log(g) [g.cm-2]		4.5

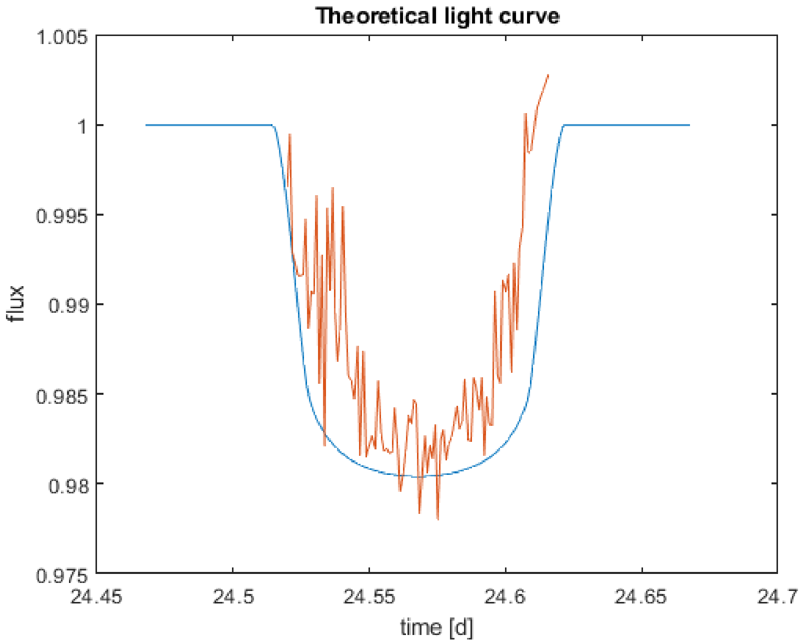
We can see that due to all of the assumptions that we've done, the error was much greater then the one of epic, especially for the impact parameter and the inclination.

The limb darkening coefficients obtained for those values of effective temperature and surface gravity are:

$\gamma_1 = 0.2279$ and $\gamma_2 = 0.3712$.

The errors induced by the calculation created a light curve quite different from the expected one:





3.8 POSSIBLE FUTURE IMPROVEMENTS

A lot can still be done to improve those calculations. For example, would be preferable to calculate the error for each value obtained, so that those results could have a scientific meaning.

Also, we have to consider that in the procedure that here is presented, the limb darkening effect has not been considered while calculating the parameters (in particular for the Depth of the transit), but only after having obtained them. This will certainly produce an error in the calculations, could be interesting to find a way to consider it.

Certainly, another thing to optimize is the automation of the process; in fact a lot of things now must be adjusted to take into accounts the difference in the presentation of the data, such as the number of knots ecc.

Another improvement could be to automatize the importation of the theoretical data found in papers. A possible solution to this problem could be to use some API available online and query the data with Matlab, for example, APIs are available here https://github.com/openexoplanetcatalogue/open_exoplanet_catalogue/ .

Concluding, there certainly needs to be further

investigated the problem relative to the normalization of the magnitude.

REFERENCES:

- A Practical Guide to Exoplanet Observing: Dennis M. Conti 2017
- Exoplanet observing for amateurs: Bruce L. Gary 2009
- The exoplanet Handbook: Michael Perryman 2011
- Properties of analytic transit light-curve models: Andras Pal 2008
- Analytic Light Curves For Planetary Transit Searches: Mandel 2002
- Rapport de stage Aero 4: Bruno HANNIGSBERG 2017
- Gravity and limb-darkening coefficients for the Kepler, CoRoT, Spitzer, uvby, UBVRIJHK, and Sloan photometric systems: Claret 2011
- Tres-1: THE TRANSITING PLANET OF A BRIGHT K0 V STAR: Alonso 2004
- Epic211089792 B: An Aligned And Inflated Hot Jupiter In A Young Visual Binary: Santerne 2016
- WASP-35b, WASP-48b, AND HAT-P-30b/WASP-51b: TWO NEW PLANETS AND AN INDEPENDENT DISCOVERY OF A HOT PLANET: Enoch 2011

CONCLUSION

Hence, the project was successfully completed by doing the literature review, data processing and the plotting of the light curve using PRISM-Muniwin and MATLAB respectively. As a result, we obtained the light curves similar to the theoretical light curves for TrES 1b and EPIC.