Pt5m: Monitoring Binary Pulsar systems

Rahul Avula

Overview

Using a pipeline to fit light curves to FITS images of pulsars taken using pt5m.

The creation of this pipeline will allow for

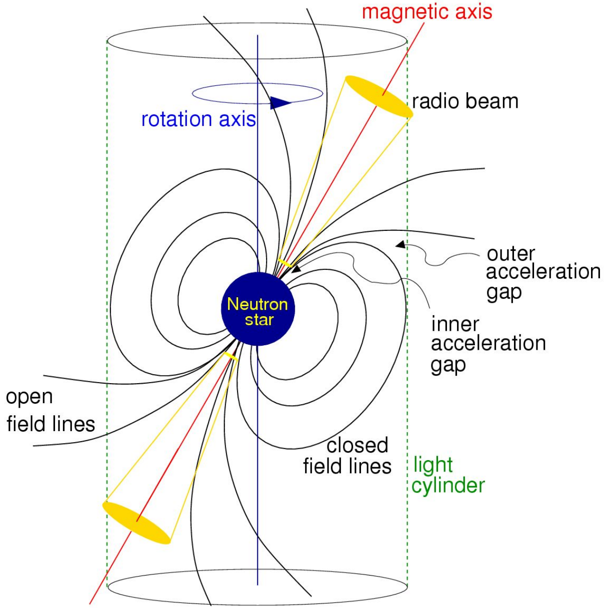
- Determination of parameters in a pulsar system

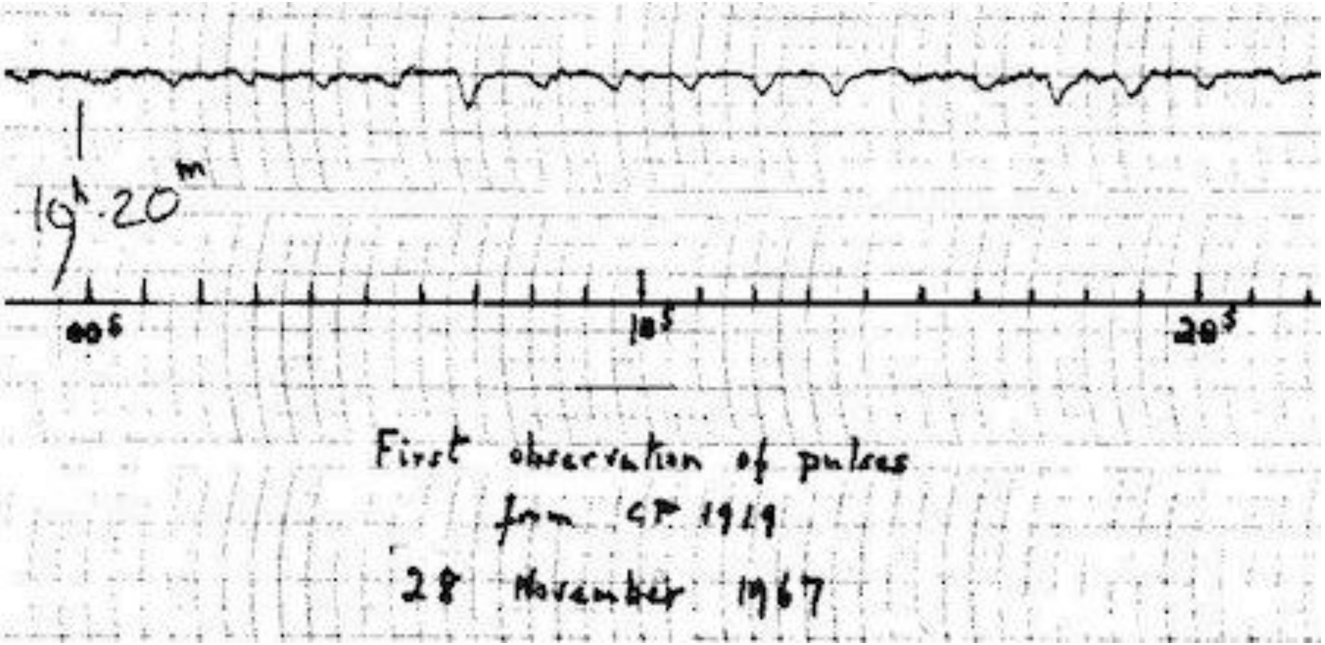
The final aim

To find changes in a transitional millisecond pulsar system.

What are pulsars?

- Pulsars:
  - Rotating neutron stars
  - Supernovae remnants
  - Mass < 1.4 solar masses
  - Pulsing signal
  - Charged particles + rapid rotation = magnetic fields
  - Collimated beam

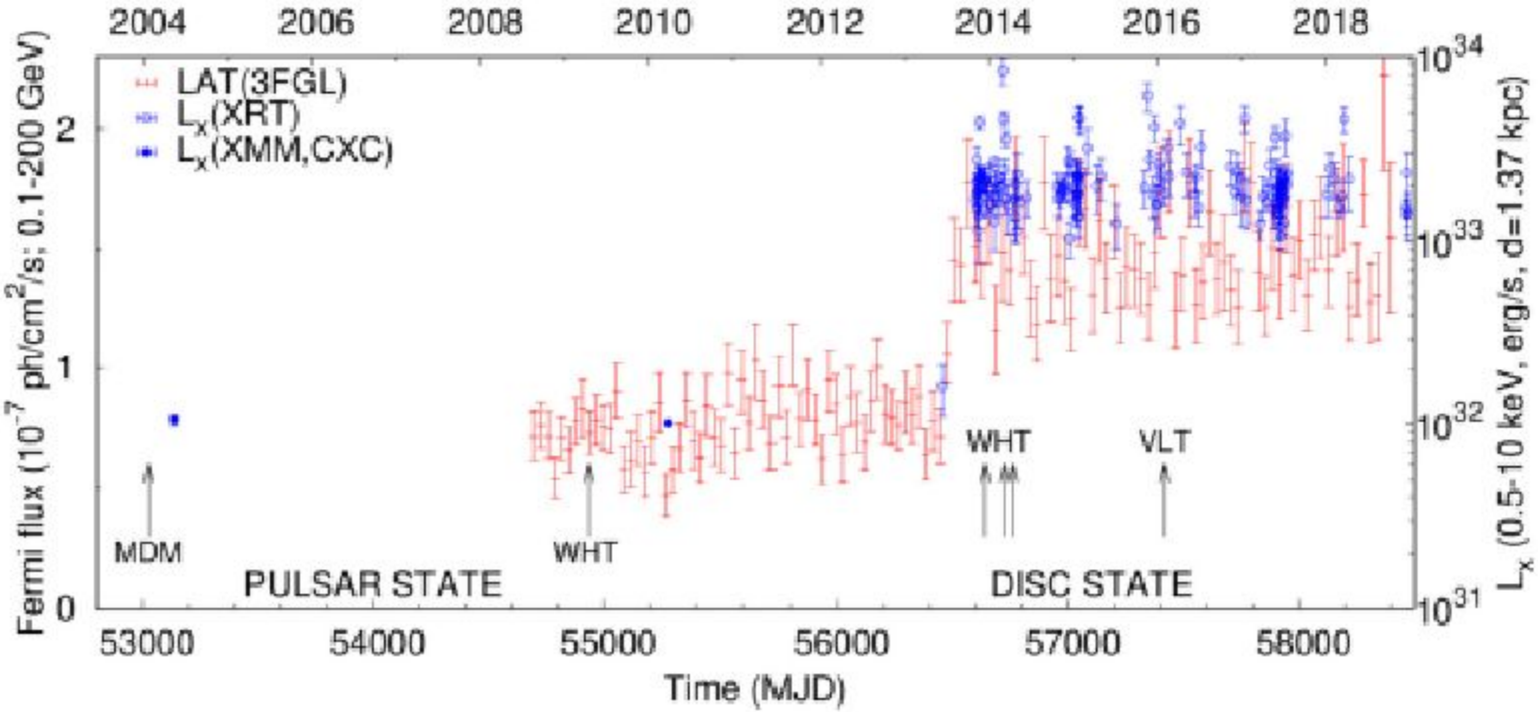



19h 20m
00s
10s
20s
First observation of pulses
from CP 1919
28 November 1967

Type of pulsars

- Millisecond pulsars - typically found in binary
- Spider pulsars: Redback (M > 0.1 Ms) and black widow (M > 0.01 Ms)
- Transitional millisecond pulsars; accreting and high-energy emitting X-ray binary system as well as a radio powered rotation state.
- Human timescales transitions:months/years
- Transient bursts turn on the radio-powered rotation mode
- Magnitude differences in luminosity between states

First transition directly observed

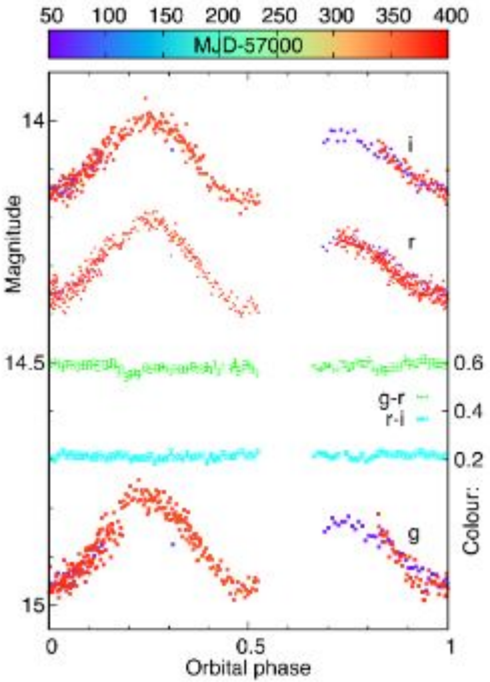


Pt5m

- Optical observation taken with science camera QSI 53 and a Cousins R filter
- Images taken of field
- Calibrated fields
- Pt5m is normally used in the measurement of pulsating stars
- 2048 by 2048 pixel image output

The pipeline
(Example 3FGL J0212+5320)

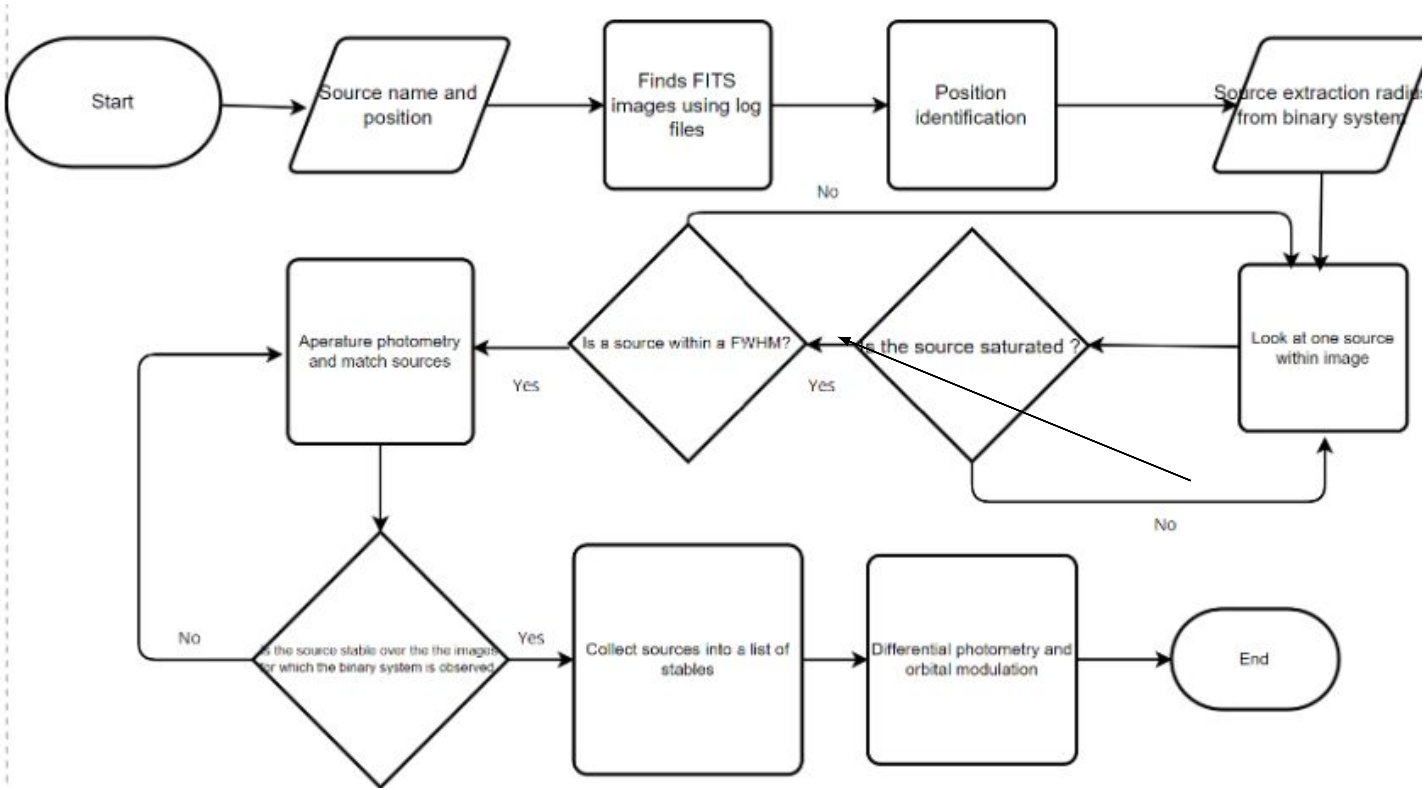
Previous research



3FGL J0212+5320		
Parameters	Value	Reference
Pulsar mass (M_{NS})	1.3-1.6$M_\odot$	Linares et al. (2017)
Companion mass (M_c)	0.34 0.42$M_\odot$	Linares et al. (2017)
Orbital period (P_{orb})	0.86955 d	Li et al. (2016)
Roche lobe filling factor	0.64>	Li et al. (2016)
Mass ratio (q)	$0.26^{+0.02}_{-0.03}$	Linares et al. (2017)
Inclination angle (i)	90	Linares et al. (2017)

- Average magnitude suggest that the its one of the brightest binary systems
- Companion uniformly irradiated suggest higher mass ratio than calculated
- No evidence of heating
- Mass lighter leading to a higher calculation of luminosity than normal
- System transition to accretion state suggested
- High interaction
- Asymmetric light curve - off-centre heating due to binary shock
- Constant shape across colours

Pipeline method



FITS info

- Three different time periods: 2018-07-04 to 2019-02-07, 2019-06-26 to 2020-02-07 and 2020-08-19 to 2021-02-23
- R band filter
- FOV = 10.1 x 6.83 arcmins
- Exposure time = 60s
- Pulsar coords = (454,498)

Pt5m data structure

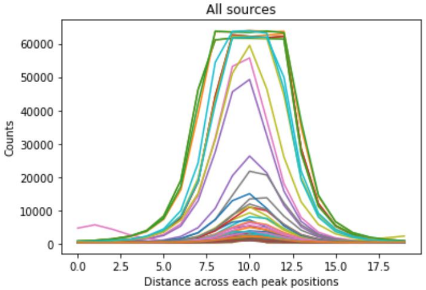
- Log files contain information about each night's observations.
- Actual data .fits files that include dark and bias
- The pipeline starts by parsing the log files to get all information from a particular source on a set timeframe

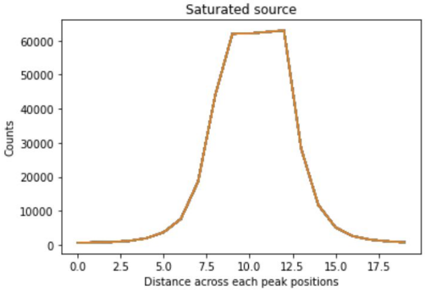
run	object	type	ra (j2000)	dec (j2000)	UT start	exp (s)	filt	airm	track	guide	rot	foc	CCD temp (degC)	wind (m/s)	cloud (oktas)	bin	id	user
r0504881	BIAS	BIAS	23:10:20.96	60:00:00.0	2018-10-30 17:52:15.2	0.030	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.5	2x2	manual	None
r0504882	BIAS	BIAS	23:10:20.96	60:00:00.0	2018-10-30 17:52:20.5	0.030	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.5	3x3	manual	None
r0504883	BIAS	BIAS	23:10:20.96	60:00:00.0	2018-10-30 17:52:25.9	0.030	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.5	3x3	manual	None
r0504884	BIAS	BIAS	23:10:20.96	60:00:00.0	2018-10-30 17:52:30.1	0.030	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.5	3x3	manual	None
r0504885	BIAS	BIAS	23:10:20.96	60:00:00.0	2018-10-30 17:52:34.6	0.030	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.5	3x3	manual	None
r0504886	BIAS	BIAS	23:10:20.96	60:00:00.0	2018-10-30 17:52:38.8	0.030	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.5	3x3	manual	None
r0504887	DARK	DARK	23:10:20.96	60:00:00.0	2018-10-30 17:52:43.1	60.000	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.4	1x1	manual	None
r0504888	DARK	DARK	23:10:20.96	60:00:00.0	2018-10-30 17:53:52.1	60.000	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.4	1x1	manual	None
r0504889	DARK	DARK	23:10:20.96	60:00:00.0	2018-10-30 17:55:01.0	60.000	H	2.14	0	0	n/a	202.49	-20.0	9.5	7.4	1x1	manual	None
r0504890	DARK	DARK	23:10:20.96	60:00:00.0	2018-10-30 17:56:10.0	60.000	H	2.14	0	0	n/a	202.49	-20.0	7.4	7.4	1x1	manual	None
r0504891	DARK	DARK	23:10:20.96	60:00:00.0	2018-10-30 17:57:19.3	60.000	H	2.14	0	0	n/a	202.49	-20.0	7.4	7.3	1x1	manual	None
r0504892	DARK	DARK	23:10:20.96	60:00:00.0	2018-10-30 17:58:28.2	60.000	H	2.14	0	0	n/a	202.49	-20.0	7.4	7.5	2x2	manual	None
r0504926	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:02.6	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504927	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:08.7	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504928	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:14.9	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504929	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:21.1	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504930	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:27.3	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504931	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:33.6	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504932	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:39.7	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504933	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:45.9	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504934	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:52.2	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504935	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:56:58.3	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504936	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:57:04.5	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504937	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:57:10.7	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504938	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:57:16.9	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab
r0504939	Uranus	SCIENCE	1:52:28.99	10:57:06.1	2018-10-31 02:57:23.1	1.000	V	1.29	1	0	n/a	202.49	-20.0	6.2	0.0	2x2	59876	astrolab

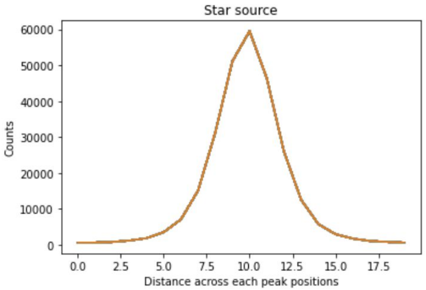
Fig 2: example log file

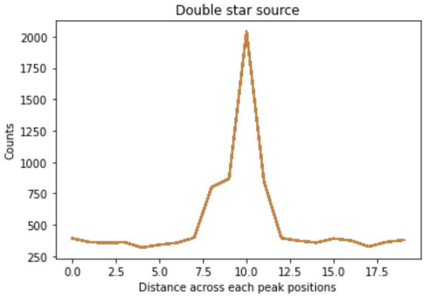
Saturation points

- Overflow of electrons
- False matches, inaccurate peaks
- By modelling the sources psf as a gaussian, it's possible to determine the saturation points as the tops will be flat.









Coordinate transformation

- Reference image is chosen
- Astrometry.net api is used to calibrate it to wcs
- Astroalign is then used to obtain transformation matrices for all images
- Sources chosen nearby sources

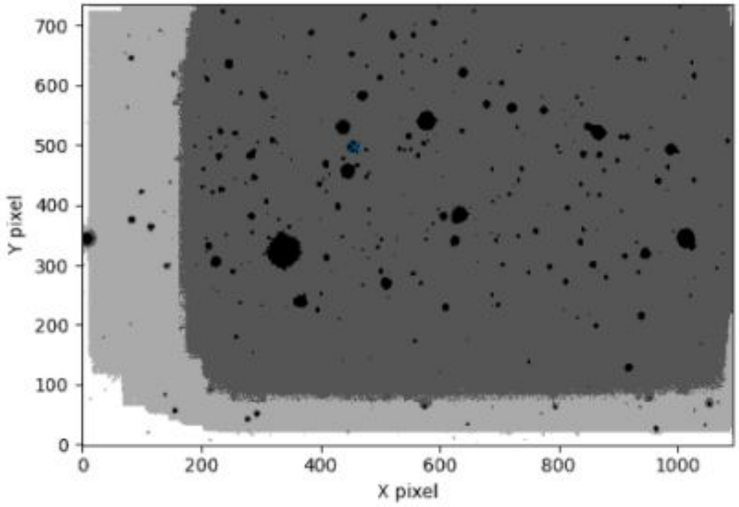
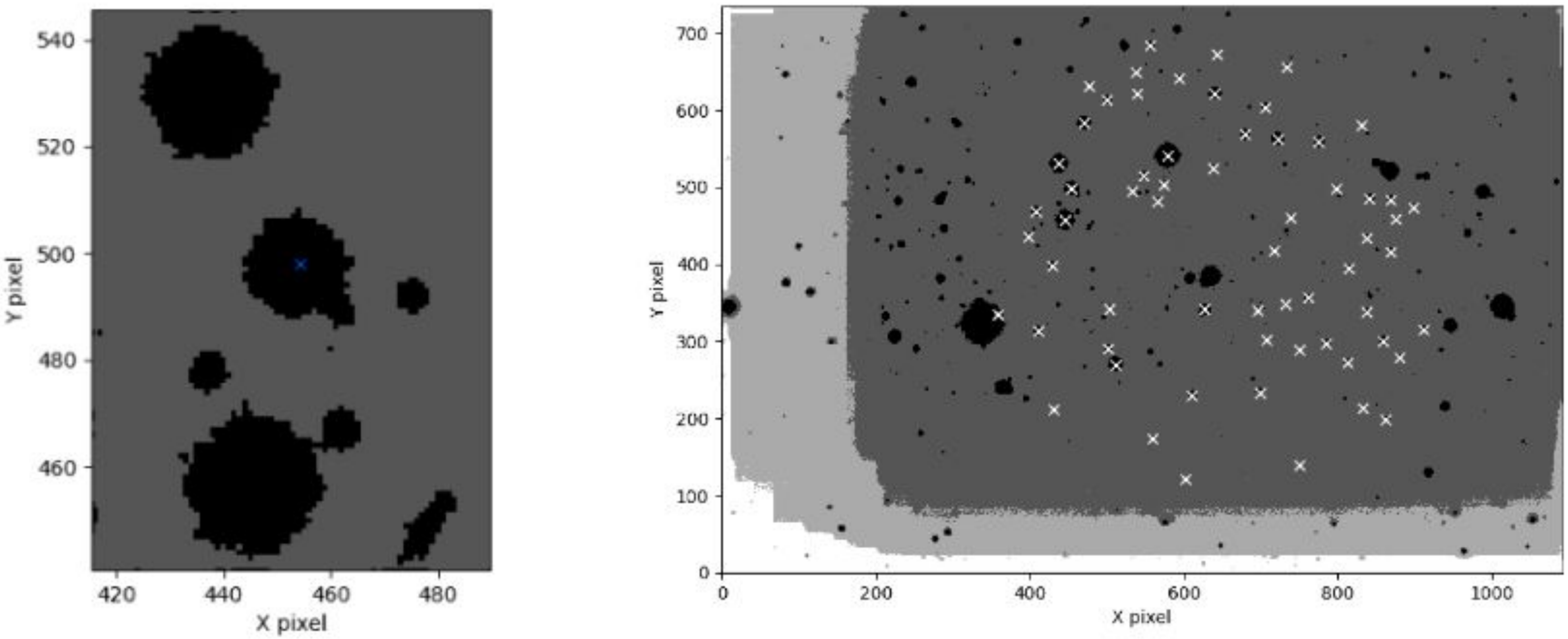


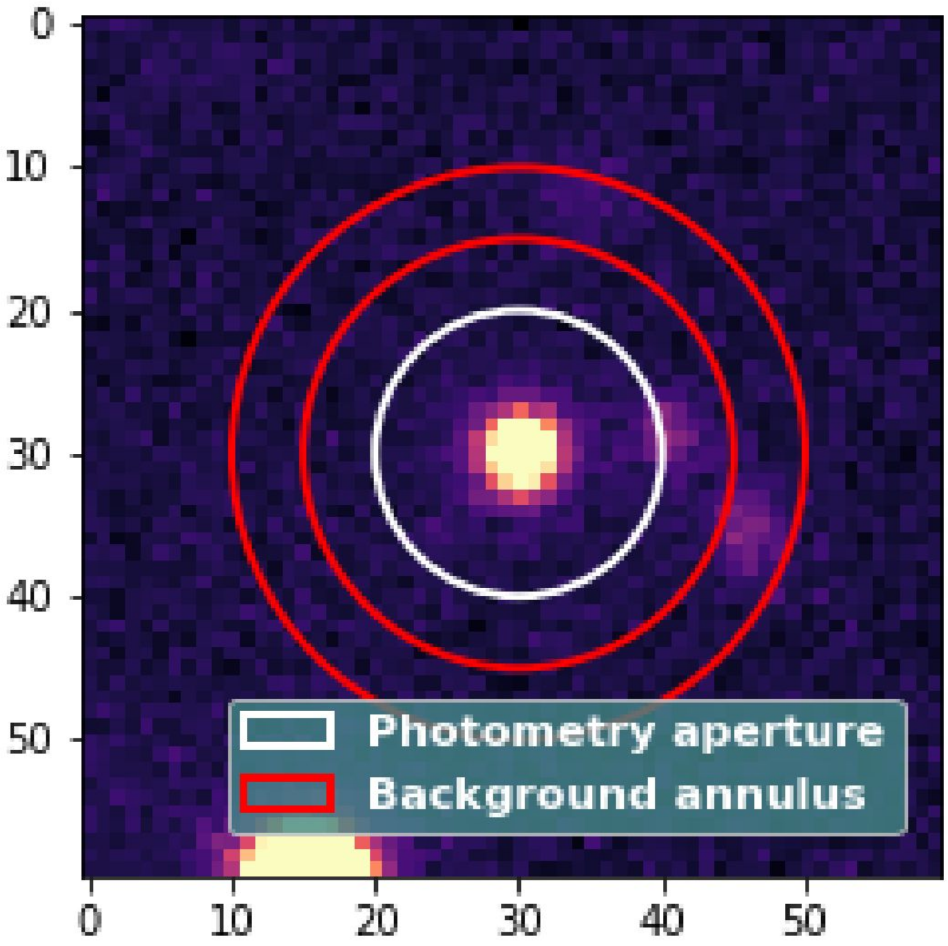
Fig 3: Stacked image of transformed set of images


540
520
500
480
460
Y pixel
420
440
460
480
X pixel
700
600
500
400
300
200
100
0
Y pixel
0
200
400
600
800
1000
X pixel

Photometry

- Photometry extraction of Light from image
- Differential photometry : Comparison relatively stable stars against the average. The difference is then used against the actual values of comparison stars to find flux of variable sources
- Top 25% of pixel values removed from sky annulus

$$M_{star}(t) = (M_s(t) - M_{pul}(t)) + M_{gaia}$$

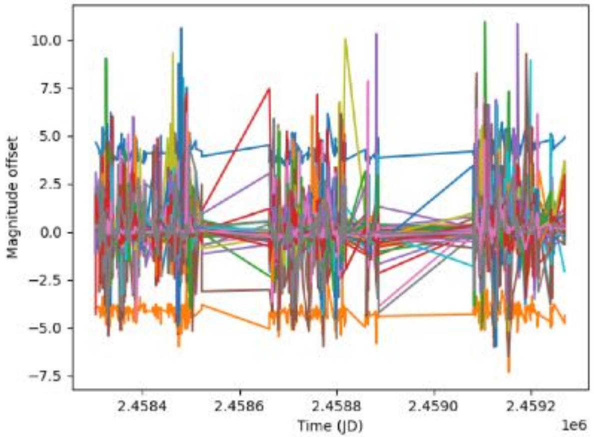


0
10
20
30
40
50
0
10
20
30
40
50
Photometry aperture
Background annulus

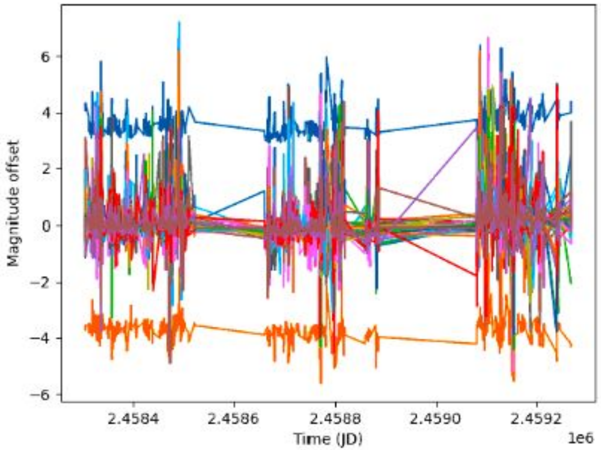
Stable sources

A reliable set of comparison sources to compare against our variable sources:

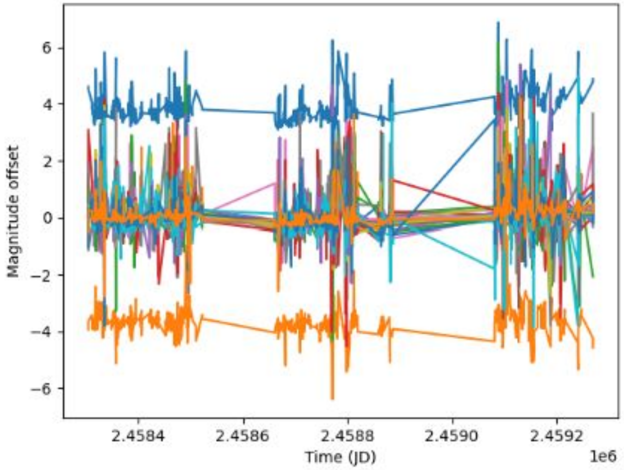
- Residuals
- sigma clipping - upper bound and lower bound limits for stability
- In the following slide, its shown that the limits for stability was 3 standard deviations
- Using higher limits is a lot more necessary for the flux since fluctuations are always possible but big changes in magnitude require large changes in flux.



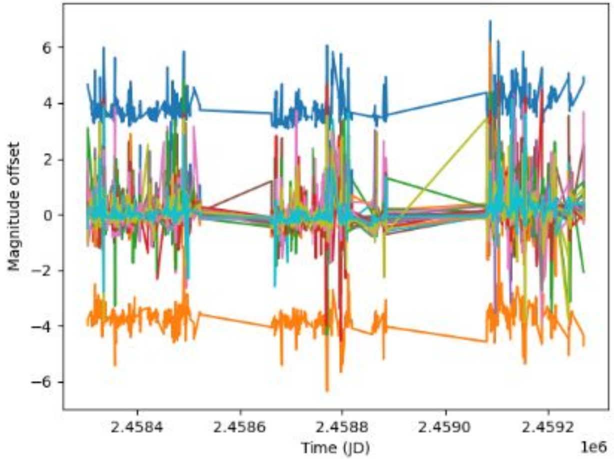
Magnitude offset
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
2.4584
2.4586
2.4588
2.4590
2.4592
1e6
Time (JD)



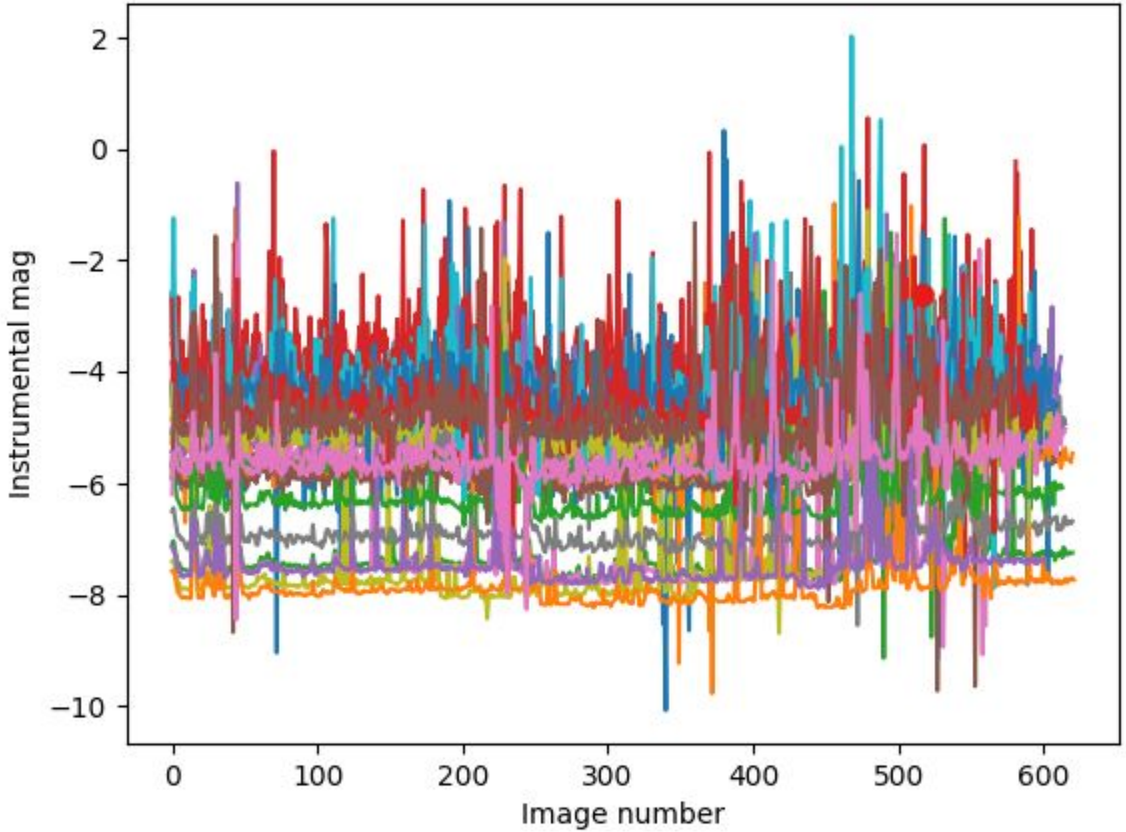
Magnitude offset
6
4
2
0
−2
−4
−6
2.4584
2.4586
2.4588
2.4590
2.4592
1e6
Time (JD)



Magnitude offset
6
4
2
0
−2
−4
−6
2.4584
2.4586
2.4588
2.4590
2.4592
1e6
Time (JD)



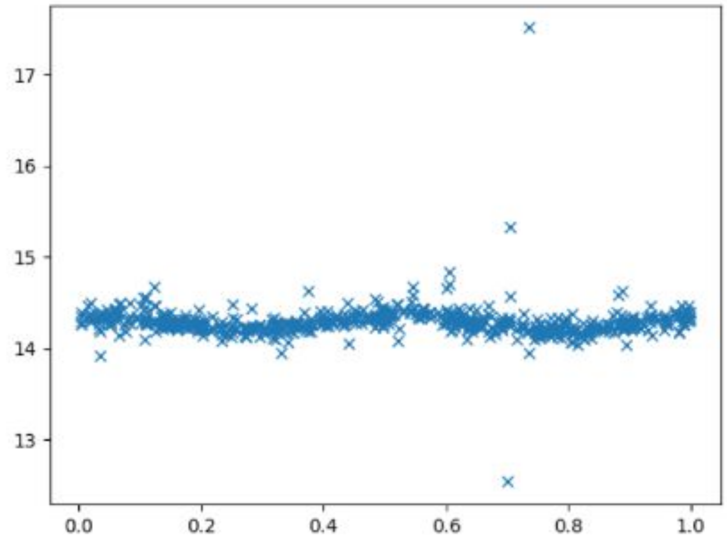
Magnitude offset
6
4
2
0
−2
−4
−6
2.4584
2.4586
2.4588
2.4590
2.4592
1e6
Time (JD)

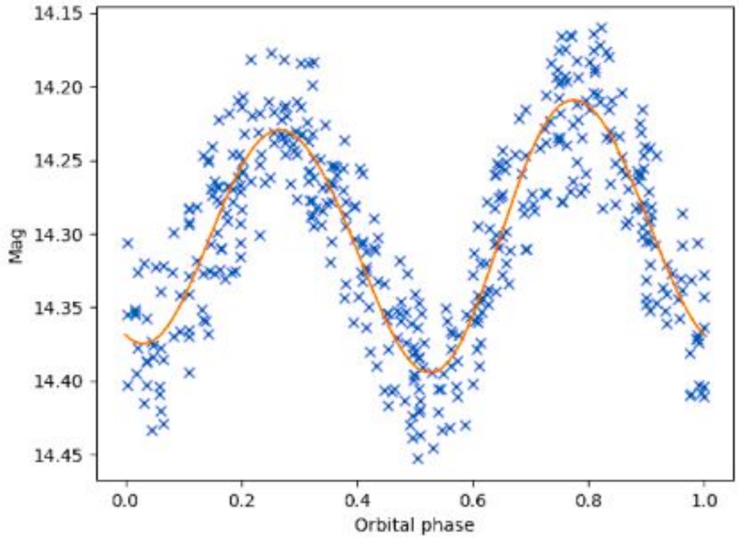

Instrumental mag
Image number
2
0
−2
−4
-6
−8
−10
0
100
200
300
400
500
600

Ensemble photometry

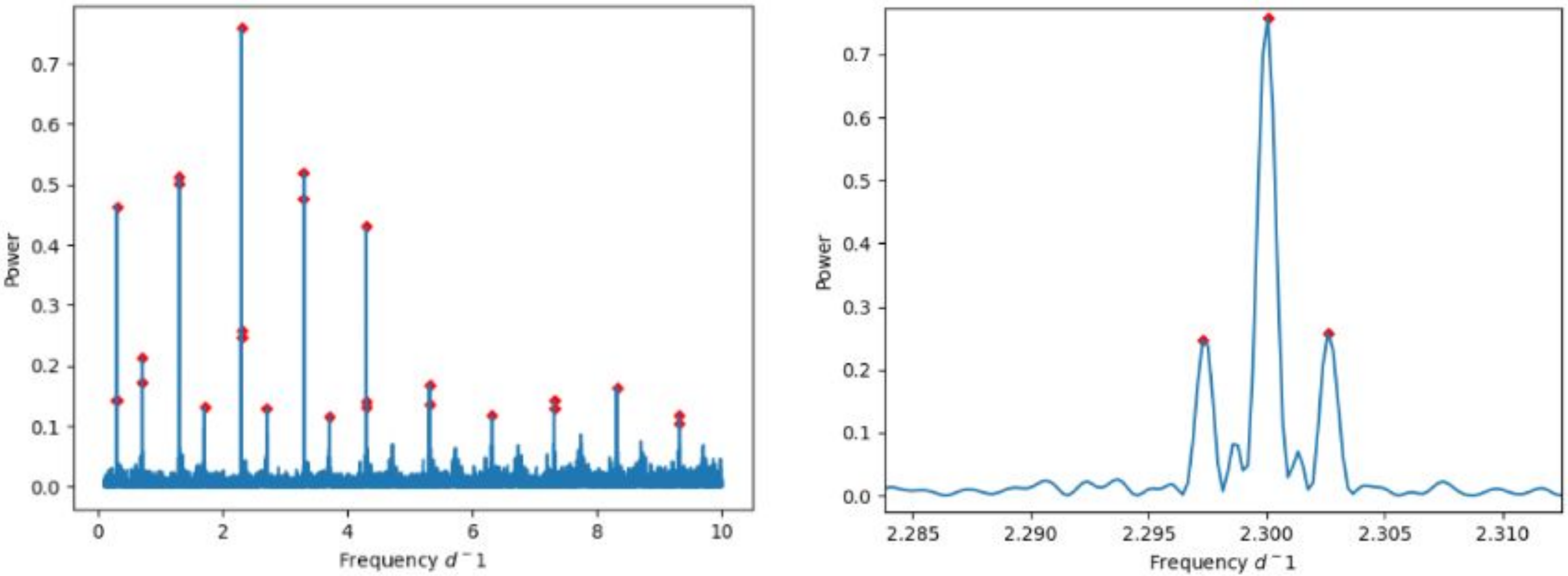
- Using gaia query function, the centre coordinates determined by wcs function set as center of image with a source detection radius of 0.4 degrees
- Gaia query : real magnitude of sources
- Using instrumental difference, accurate conversion to real.

Final light curve





- Folded at points at orbital period and divided by orbital period 0.86955d
-



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Power
0
2
4
6
8
10
Frequency d^-1
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Power
2.285
2.290
2.295
2.300
2.305
2.310
Frequency d^-1

$$F(\phi) = a_0 + \sum_{i}^{4} a_i(\cos 2\pi i\phi + \sin 2\pi i\phi)$$

$$A_2 \cos\phi_2 = f_{EV} \frac{M_2}{M_1} \left(\frac{R_1}{a}\right)^3 \sin^2 i,$$

$$r_L = \frac{0.49q^{\frac{2}{3}}}{0.6q^{2/3} + \ln 1 + q^{1/3}}.$$