A Multi-Year Transit Search of Proxima Centauri

Artist Interpretation: ESO

Dax Feliz

Master's Thesis Defense

August 8th, 2018 Fisk University, Nashville, TN

Outline for Defense

- Motivation
- Observations
- Data Reduction
- Quality Check
- Light Curves Corresponding To Previously Published Ephemerides
- Generalized Transiting Planet search using BLS
- BLS sensitivity and Recovery analysis
- Conclusion
- Current and Future Work

Motivation

- As part of the Global Earth M-dwarf Search Survey (GEMSS), observations of Proxima Centauri began in 2006 and (is further described in Blank et al. 2007).
- As described in Shankland et al. 2006 and Nutzman and Charbonneau 2008, Submeter diameter telescopes with commercial grade CCD cameras can provide sufficient photometric precision to detect transiting terrestrial-type exoplanets around mid- and late- M dwarf stars.

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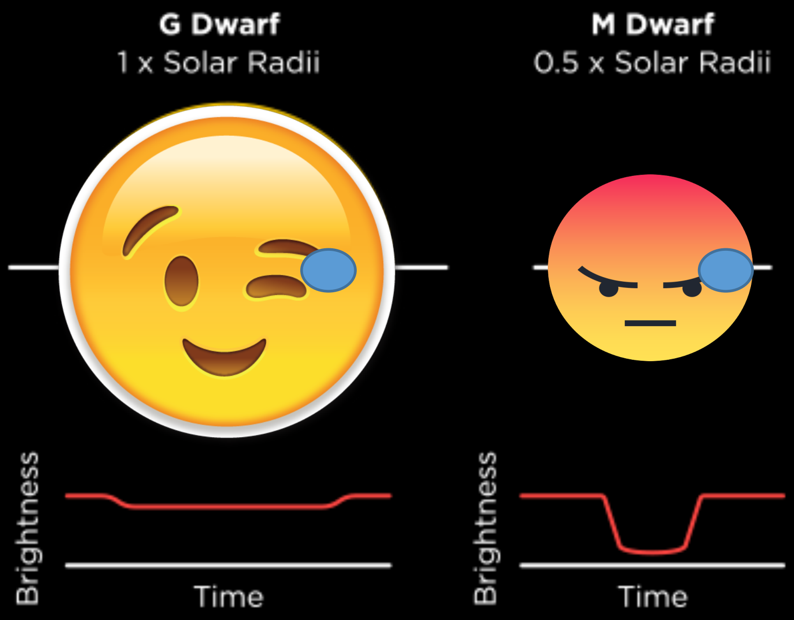

Image: Harvard CFA
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Motivation

- In 2014, David Kipping made an announcement of an upcoming transit survey of Proxima with the Microvariability and Oscillation of Stars (MOST) Telescope. This prompted David Blank to obtain a large amount fo telescope time from the SKYNET robotic telescope network throughout most of 2014 and through 2015-2016.
- During the bridge orientation in August 2016, the announcement of the discovery of Proxima Centauri b via the radial velocity method was published in Nature (Anglada-Escude et al. 2016).
- With this new announcement and a ton of photometric data spanning from 2006 – 2016, there was a ton of work to do in order to conduct this search for transiting exoplanets.

Motivation

- In the Fall of 2016, I began working with Karen Collins and learning how to use AstroImageJ to perform differential photometry on our data set.

- I also took Dennis Consti's AAVSO(**American Association of Variable Star Observers)** course for additional training for AIJ.

- Even with these great hands on training experiences, Proxima Centauri is a pretty tricky star to work with.

Let’s talk about it: Proxima Centauri

- Radius ~ 0.1524 R_{sun} , Mass ~ 0.1221 M_{sun} (Kervella et al. 2017)
- Metallicity [Fe/H] ~ 0.21 (Schlaufman & Laughlin 2010)
- Effective Temperature ~ 3042 K, log(g) ~ 5.20 (Segransan et al. 2003)

- Proxima Centauri is a well known flare star (Shapley 1951, Walker 1981). Davenport et al. 2016 found that Proxima emits low energy flares at an average rate of 63 times per day (every ~20 minutes). More on this finding later.

Summary of Observations

- As part of the GEMSS project, David Blank obtained observations of Proxima using the Real Astronomy Experience (RAE) Robotic Telescope at the Perth Observatory in Bickley, Western Australia from 2006 to 2008.
- Throughout 2013 – 2016, David was also able to get telescope time from Skynet's world-wide network of remotely operated telescopes:
  Cerro Tololo, Chile (Prompt 1, 2, 4, 5, and 8), Sliding Springs, New South Wales, Australia (Prompt SS01, SS02, SS03, and SS04) and Perth, Western Australia (RCOP).
- We also obtained observations from the Kilodegree Extremely Little Telescope Follow-Up Network KELT-FUN based on the Anglada-Escude 2016 RV-based ephemeris throughout the summer of 2017.

Table 2: Summary of Photometric Observations Analyzed in this work

Telescope Name	Aperture (m)	FOV (arcmin^2)	Plate-Scale (arcsec pixel^{-1})	Start Date (UT)	End Date (UT)	Exp. Time (sec)	Filter	# Obs (nights)
RAE	0.35	10.4×10.4	1.2	2006 May 24	2008 Feb 25	20	R	23
RCOP	0.4	24.2×16.3	0.76	2014 Feb 13	2014 Aug 23	16-20	R	30
Prompt 1	0.4	9.64×9.64	0.9	2013 Aug 17	2015 Apr 22	16-20	R	40
Prompt 2	0.4	21×14	0.41	2013 Aug 21	2017 Mar 07	15–20, 65	R,G	50
Prompt 4	0.4	10×10	0.59	2014 Mar 07	2015 May 11	15-20	R	50
Prompt 5	0.4	10.25×10.25	0.59	2014 Mar 16	2016 Mar 29	18-20	R	10
Prompt 8	0.6	22.6×22.6	0.69	2014 Jun 20	2015 Mar 15	16-18	R	3
Prompt SS01	0.42	15.6×15.6	0.9	2014 Feb 23	2015 May 05	15-20	R	46
Prompt SS02	0.42	15.6×15.6	0.9	2014 Feb 23	2014 Jul 30	17-20	R	18
Prompt SS03	0.42	15.6×15.6	0.9	2014 May 08	2014 Aug 14	15-20	R	40
Prompt SS04	0.42	15.6×15.6	0.9	2013 Sep 02	2013 Sep 13	20	R	2
Hazelwood	0.32	18×12	0.73	2017 Mar 18	2017 Jun 16	5-12	Ic	6
Ellinbank	0.32	20.2×13.5	1.12	2017 Jun 16	2017 Jul 30	14-18	R	5
Mt. Kent CDK700	0.7	27.3×27.3	0.40	2017 Jun 20	2017 Jul 25	20-25	I	3
ICO	0.235	16.6×12.3	0.62	2017 Mar 18	2017 May 14	15-30	I	3

Total of 329 Light Curves; Blank et al. 2018

Data Reduction

- Within AstroImageJ, there is a feature which allows the user to best fit a linear trend to the data and then either subtracted or divided from the light curve (depending on user preference).
- Because all of these light curves are ground based observations, we detrended our data for airmass to correct for changes in airmass across the different telescopes.
- To minimize the effects of long term variations due to stellar activity or stellar rotation, we also detrended against Time (converted to Barycentric Julian Date (BJD_{TDB}).

Data Reduction

- Many of the telescopes used in our observations are un-guided and resulted in meridian flips to maintain tracking, we also fitted and realigned the baseline at those points.
- In some cases we also detrended using the sky background, full-width half-maximum of the stellar point spread function, and/or the total number of comparison star net integrated counts along x- and y-centroid locations of the target star if observations had strong correlations.

Quality Checking

- After detrending the data, we noticed that some data sets were still quite noisy. To account for this scatter, and also the low energy flares mentioned earlier, we employed an iterative 3σ cut based on the RMS of each individual light curve. AIJ detrended and normalized the data again, and the process was repeated until no 3σ outlier data points remained.
- Even still, there were some noisy light curves that remained. We decided to create a quality threshold to use as a guideline to vet each light curve.
- After visually inspecting individual light curves that made this cut, we ended up using 262 of our total 329 light curves in our total analysis.

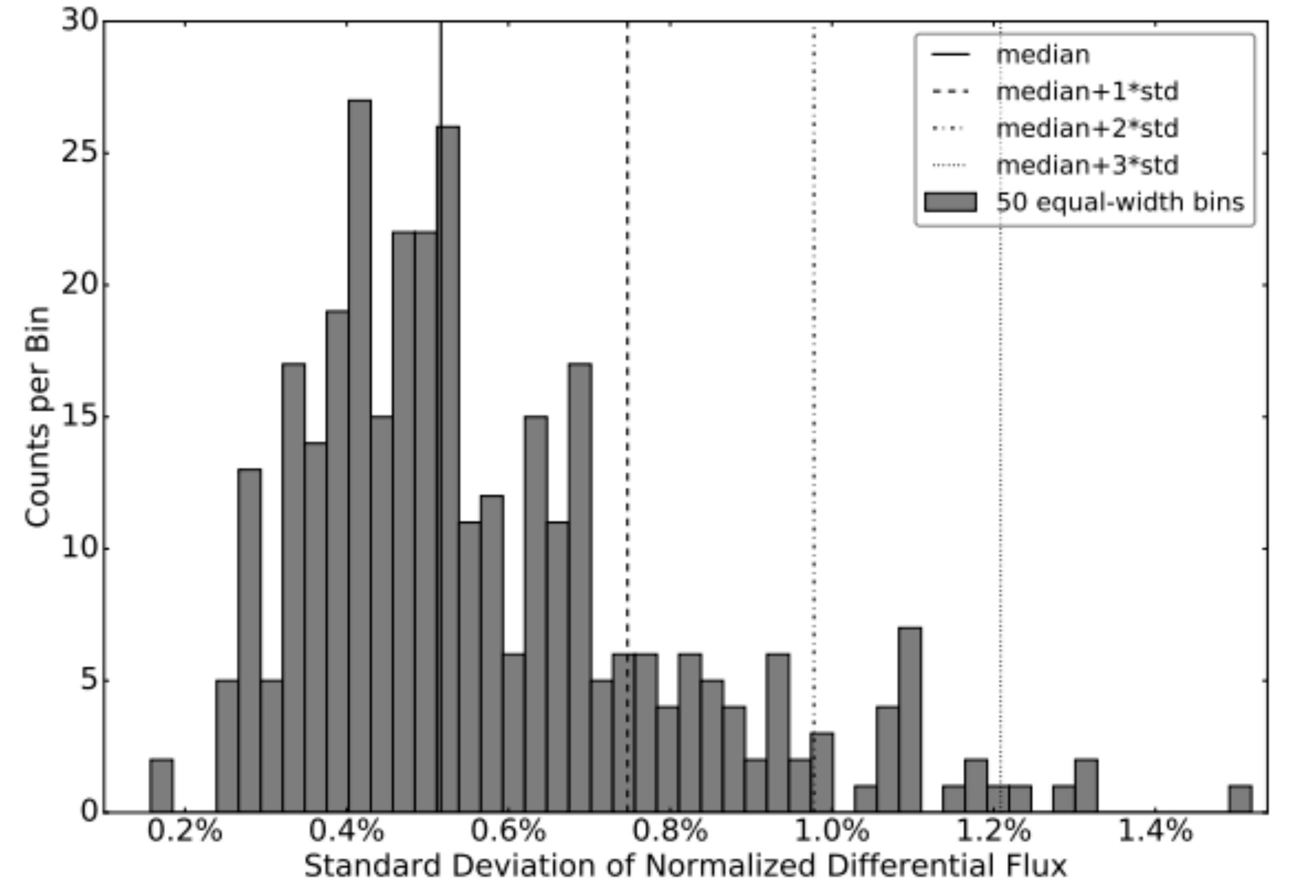

Figure 1: Histogram of the standard deviations of our 329 individual light curves. The solid line marks the median of the distribution at 0.516%. The distribution has a standard deviation of 0.230%. The long-, medium-, and short-dashed lines mark the values of median plus 1, 2, and 3 times the standard deviation, respectively.

Blank et al. 2018

Quality Checking:
Example of high scatter data we vetted to include

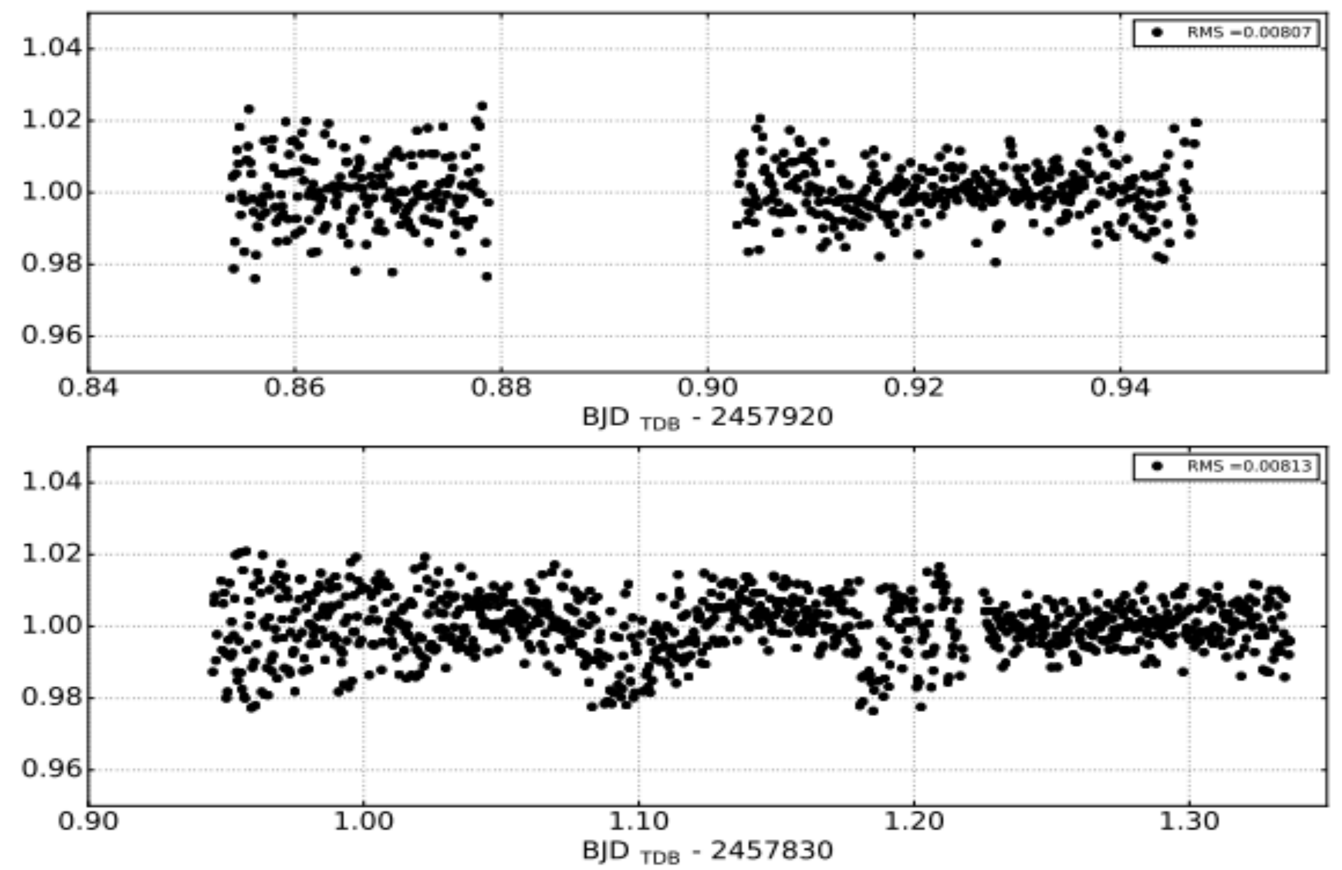

Figure 2: Examples of light curves retained in our data set, despite having standard deviation above our threshold. (Top Panel) The KELT-FUN Hazelwood Observatory light curve from UT 2017 June 16 is relatively flat but has scatter above our threshold. (Bottom Panel) The KELT-FUN ICO light curve from UT 2017 March 18 has a transit-like feature that contributes to the high scatter.

Blank et al. 2018

Light Curves Corresponding To Previously Published Ephemerides

- As previously mentioned, Anglada-Escude et al. 2016 discovered Proxima Centauri b via the radial velocity method using the High Accuracy Radial velocity Planet Searcher (HARPS) installation on 3.6m ESO telescope in La Silla observatory, Chile. They detected a signal corresponding to an orbital period ~11.186 days for a minimum planet mass ~1.27 M_{earth}
- Damasso and Del Sordo 2017 provided a re-analysis of the Anglada-Escude RV data using a Gaussian Processes framework to mitigate the stellar correlated noise in the RV time-series and produced similar results: Period ~11.1855 days, minimum Mass ~ 1.21 M_{Earth}
- Of our 262 light curves, 96 coincide with the predicted times of transit from previously published claims in Liu et al. 2017 and Kipping et al. 2017. (Proxima Centauri is a very popular subject of study 2016-2018!)

Light Curves Corresponding To Previously Published Ephemerides: Kipping et al. 2017

- In 2014, Kipping et al. obtained ~42 observations of Proxima Centauri in 2014 and 2015 from the MOST telescope in addition to observations by the ground based HATSouth telescope network spanning from June 14th, 2012 and September 20th, 2014.
- a Gaussian Processes (GP) + transit model with an "uninformative prior" on transit phase (model M1): Orbital Period ~11. 185 days, planet radius ~ 1.38 R_{Earth}
- a GP + transit model with an "informative prior" on transit phase (model M2): Orbital Period ~11. 187 days, planet radius ~ 1.23 R_{Earth}
- In addition to new photometric observations, Kipping et al. also provided a re-analysis of the Anglada-Escude et al. 2016 ephemeris and orbital period:
  Orbital Period ~11. 1856 days, transit depth ~ 0.48%
- In total, 85 of our light curves contribute data within 2σ of the Kipping RV-based ephemeris.

Light Curves Corresponding To Previously Published Ephemerides: Kipping et al. 2017: RV ephemeris and orbital period

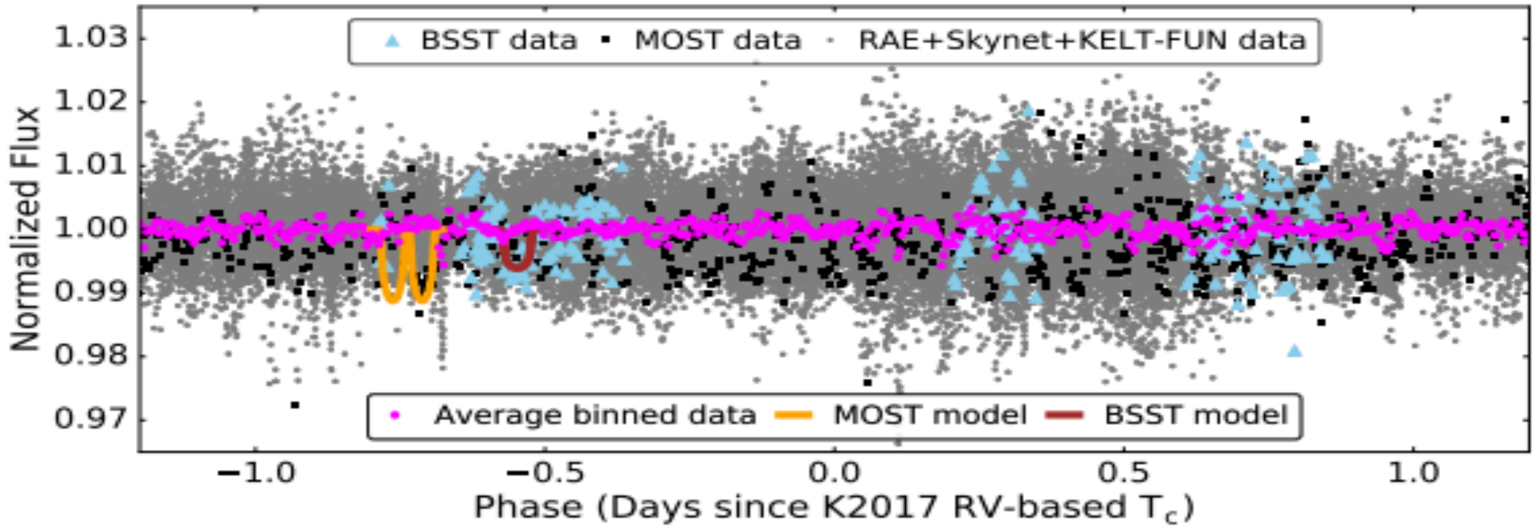

Figure 4: All light curve observations, including those from the literature and those newly obtained by us, folded on the K2017 RV-based ephemeris. The data from this work are displayed as grey dots, and after combining and binning at five minute intervals, as magenta dots. The K2017 MOST data are also displayed as black squares, and the L2017 BSST data are shown as light blue triangles. The K2017 Signal C transit models are displayed as orange solid lines. The L2017 BSST transit model is displayed as a brown solid line. There are no obvious periodic transit signals, at the depth of the plotted models, evident within the noise of the binned data.

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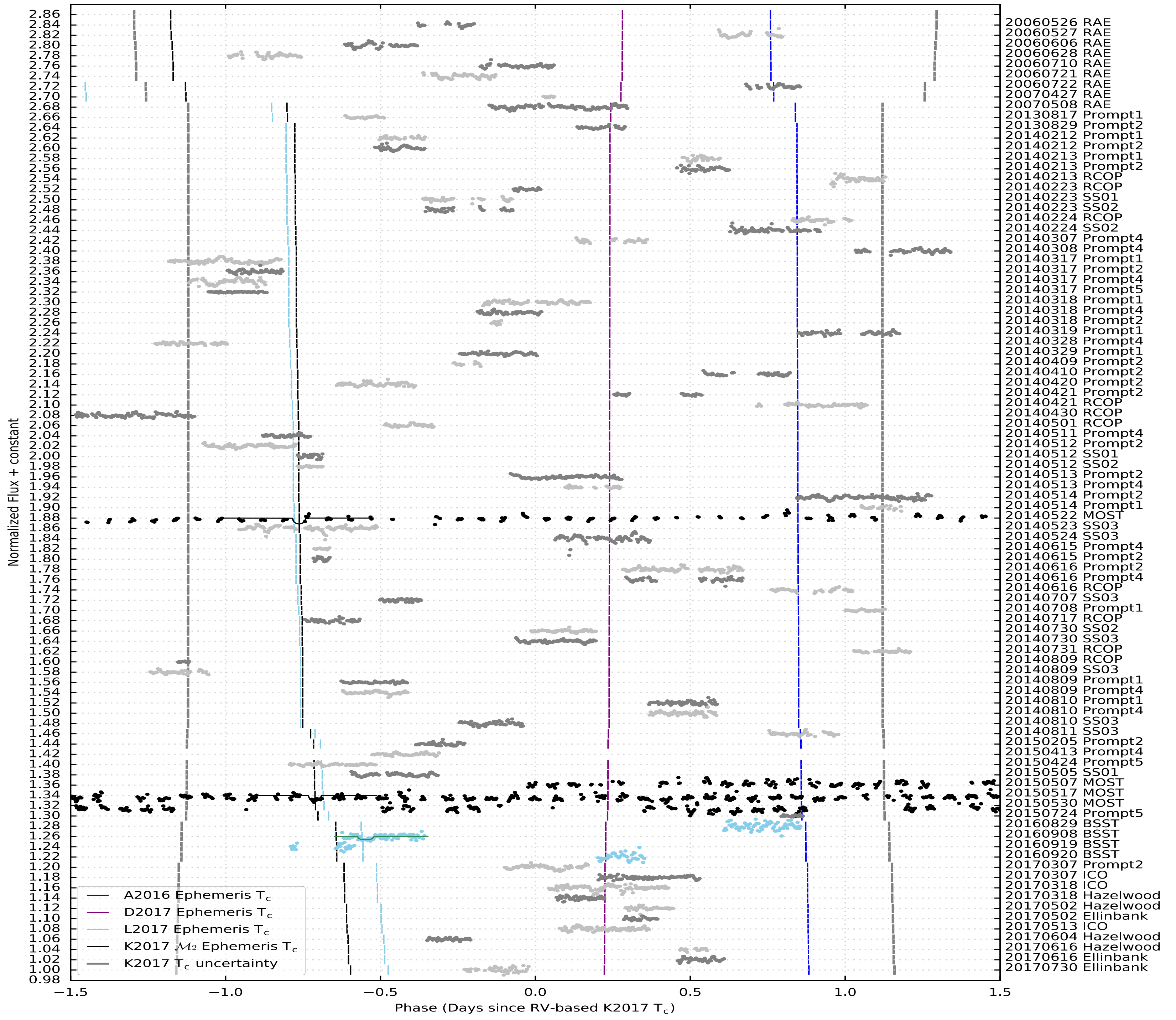
Light Curves Corresponding To Previously Published Ephemerides: Kipping et al. 2017: RV ephemeris and orbital period



Light Curves Corresponding To Previously Published Ephemerides: Kipping et al. 2017: M1 ephemeris and orbital period

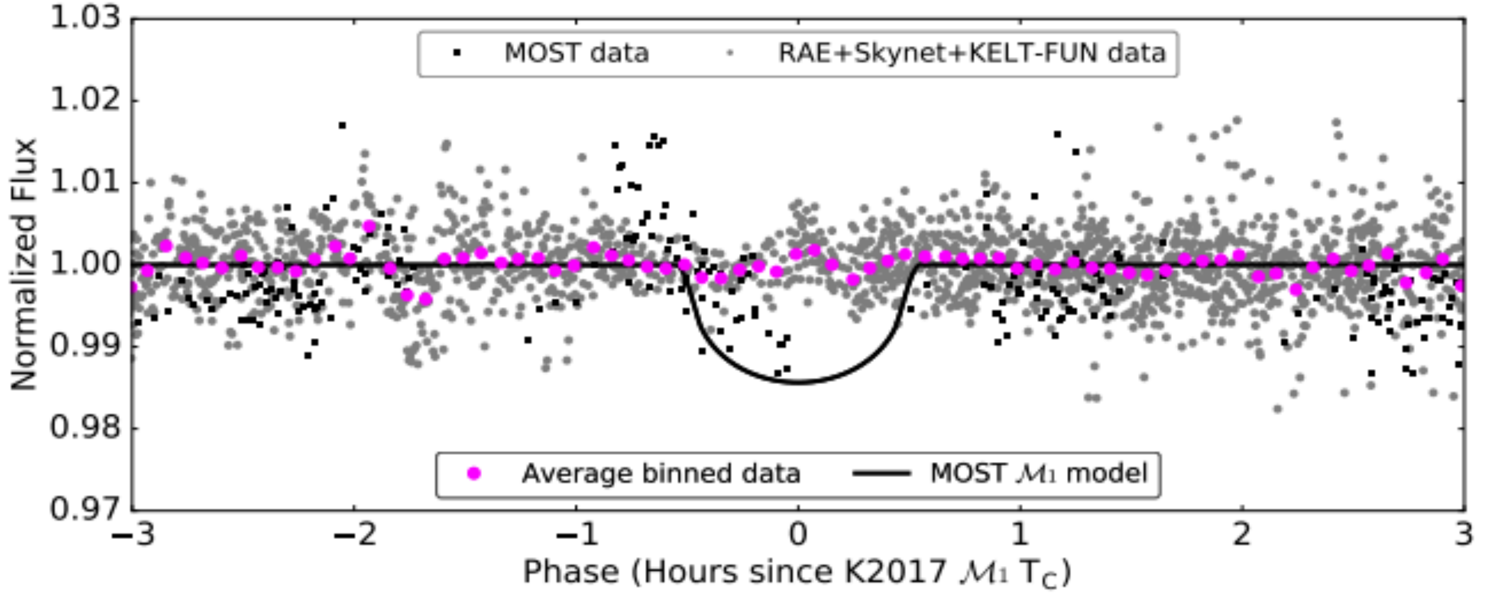
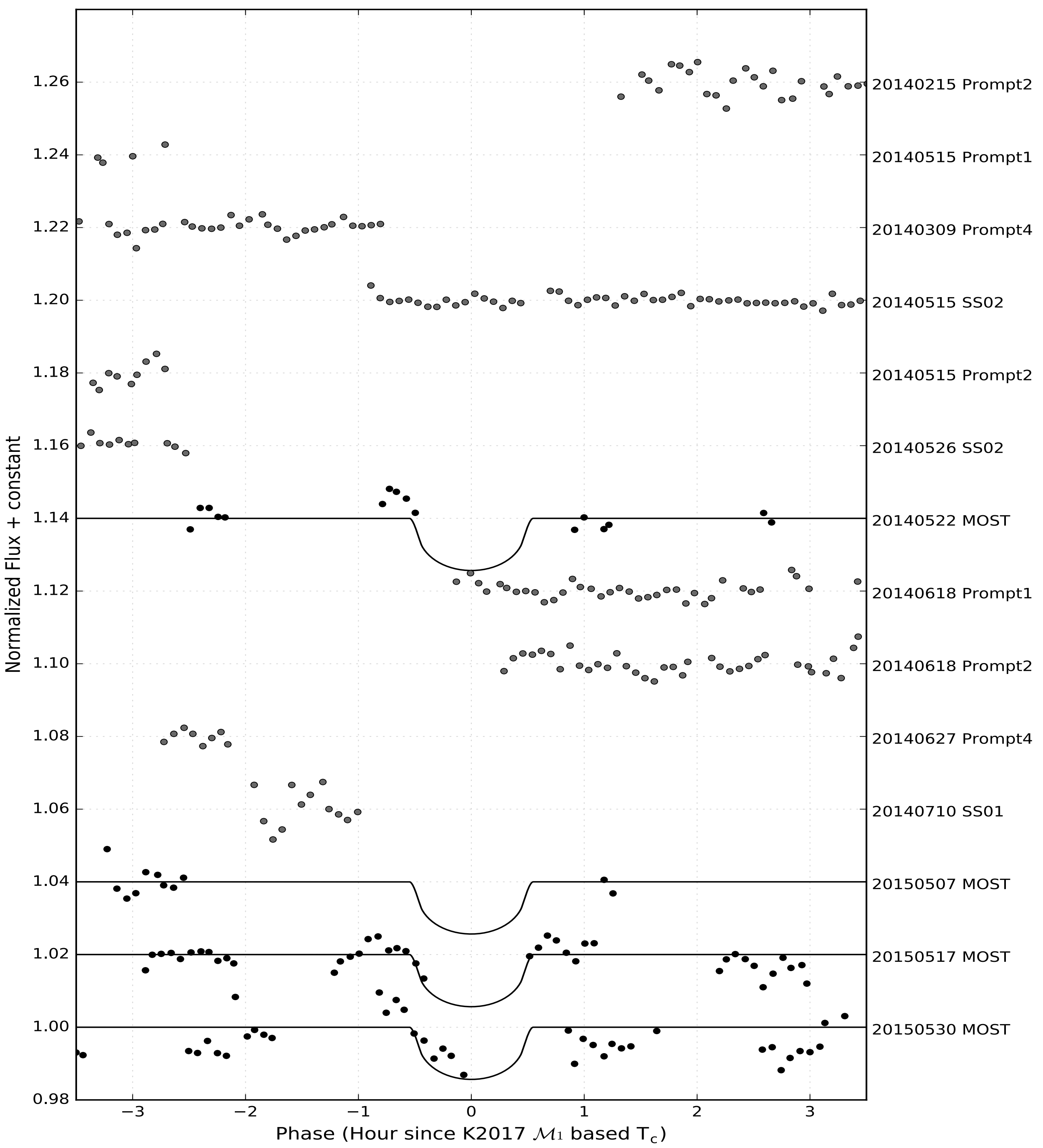


Figure 6: All light curve observations, including those from the literature and those newly obtained by us, folded on the K2017 Model $\mathcal{M}_1$ ephemeris. The phase range displayed is ± 3 hours from the Model $\mathcal{M}_1$ transit center time. Light curves from this work are displayed as grey dots, and after combining and binning at five minute intervals, as magenta dots. The MOST data are shown as black squares and the $\mathcal{M}_1$ transit model is displayed as a black solid line. No BSST data contribute to the displayed phase range.

Light Curves Corresponding To Previously Published Ephemerides: Kipping et al. 2017: M1 ephemeris and orbital period



Light Curves Corresponding To Previously Published Ephemerides: Kipping et al. 2017: M2 ephemeris and orbital period

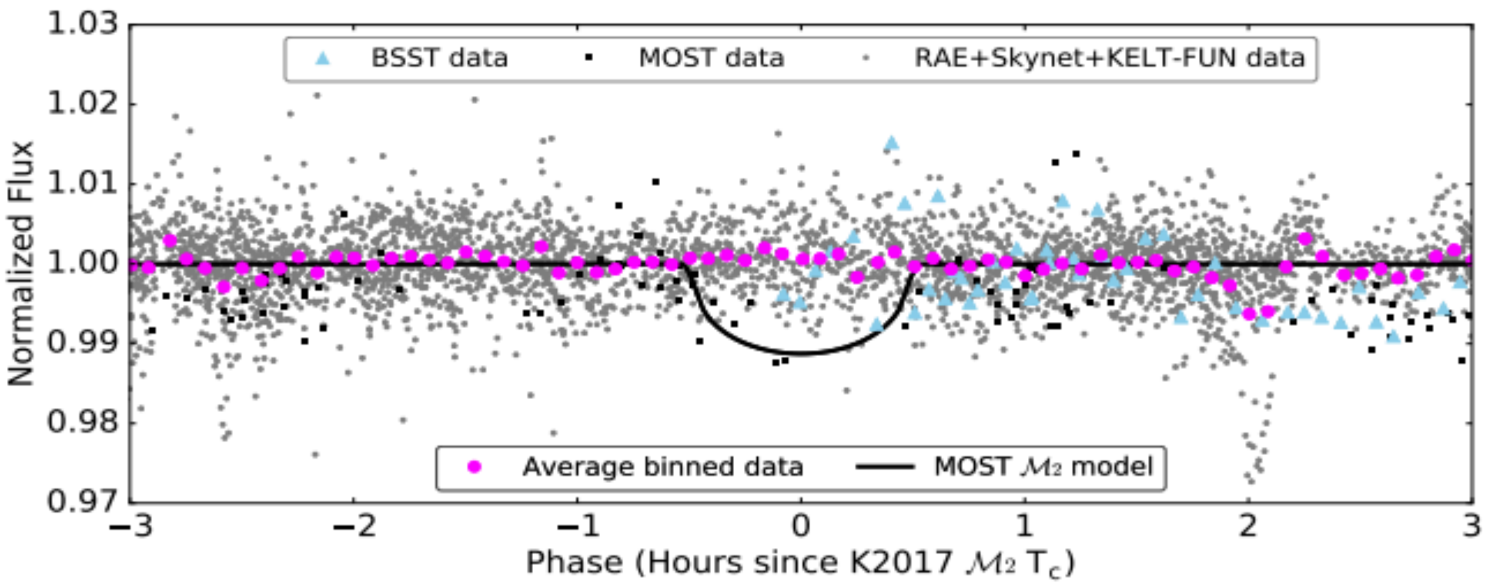


Figure 5: All light curve observations, including those from the literature and those newly obtained by us, folded on the K2017 Model $\mathcal{M}_2$ ephemeris. The phase range displayed is ± 3 hours from the Model $\mathcal{M}_2$ transit center time. Light curves from this work are displayed as grey dots, and after combining and binning at five minute intervals, as magenta dots. The MOST data are shown as black squares and the BSST data are displayed as light blue triangles. The K2017 $\mathcal{M}_2$ transit model is displayed as a black solid line.

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Light Curves Corresponding To Previously Published Ephemerides: Liu et al. 2017:

- Liu et al. report photometric observations from the Bright Star Survey Telescope (BSST) located at the Chinese Antarctic Zhongshan Station. Ten nights of observations were obtained from August 29th to September 21st in 2016.
- They detected a transit-like event ~ 1σ from the Kipping et al. 2017 and ~ 2σ from the Damasso & Del Sordo 2017 RV predicted ephemerides with a 2.5σ confidence.
- This event occurs 138 min later than predicted by the Kipping et al. 2017 model M2 ephemeris possibly due to Transit Timing Variations induced by an outer planet in this system.

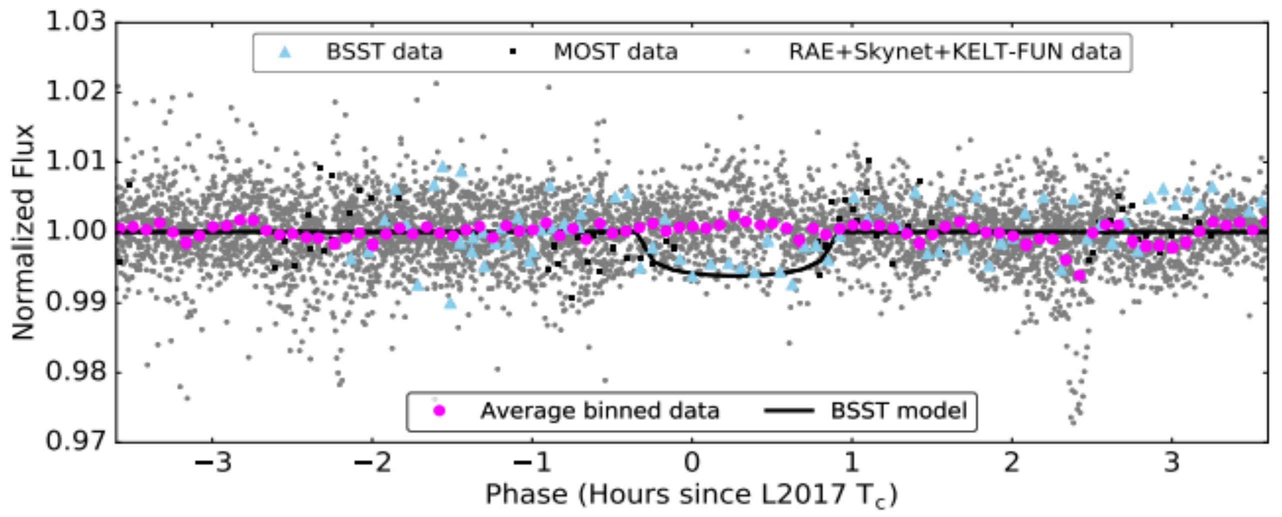

Figure 7: All light curve observations, including those from the literature and those newly obtained by us, folded on the L2017 ephemeris. The phase range displayed is ±3 hours from the L2017 transit center time. The data are displayed as described for Figure 5, except that the L2017 transit model is displayed as a black solid line.

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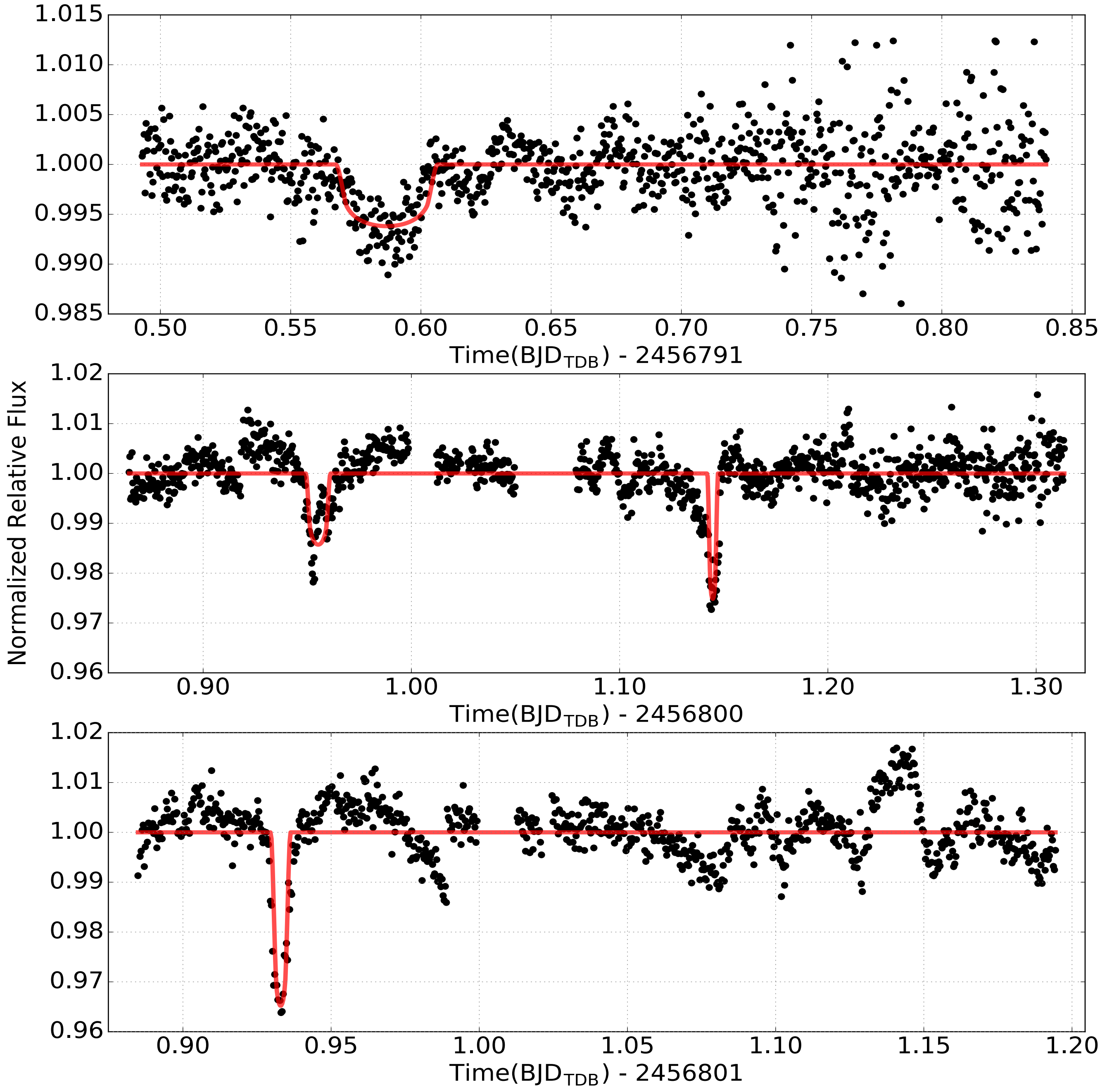
Examples of Transit-like events in our data:

Top, Prompt2 5/14/2014:

- Has some post-egress variation which suggests this event may not have been caused by a transiting planet.

Middle, PromptSS03 5/23/2014 &
Bottom, PromptSS03 5/24/2014:

- These short, asymmetric events are unlikely to have been caused by Proxima Centauri b. We have light curves from PromptSS01 on the same nights at the similar times that do not show these features.



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That pretty much sums up work done for Paper 1

- After many years in the making we were able to publish our work in The Astrophysical journal!

THE ASTRONOMICAL JOURNAL, 155:228 (15pp), 2018 June https://doi.org/10.3847/1538-3881/aabded

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A Multi-year Search for Transits of Proxima Centauri. I. Light Curves Corresponding to Published Ephemerides

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Abstract

Proxima Centauri has become the subject of intense study since the radial-velocity (RV) discovery by Anglada-Escudé et al. of a planet orbiting this nearby M dwarf every ~11.2 days. If Proxima Centauri b transits its host star, independent confirmation of its existence is possible, and its mass and radius can be measured in units of the stellar host mass and radius. To date, there have been three independent claims of possible transit-like event detections in light curve observations obtained by the *MOST* satellite (in 2014–15), the Bright Star Survey Telescope telescope in Antarctica (in 2016), and the Las Campanas Observatory (in 2016). The claimed possible detections are tentative, due in part to the variability intrinsic to the host star, and in the case of the ground-based observations, also due to the limited duration of the light curve observations. Here, we present preliminary results from an extensive photometric monitoring campaign of Proxima Centauri, using telescopes around the globe and spanning from 2006 to 2017, comprising a total of 329 observations. Considering our data that coincide directly and/or phased with the previously published tentative transit detections, we are unable to independently verify those claims. We do, however, verify the previously reported ubiquitous and complex variability of the host star. We discuss possible interpretations of the data in light of the previous claims, and we discuss future analyses of these data that could more definitively verify or refute the presence of transits associated with the RV-discovered planet.

Key words: planetary systems – stars: individual (Proxima Centauri) – techniques: photometric

In this work, we presented 96 of our 262 light curves.

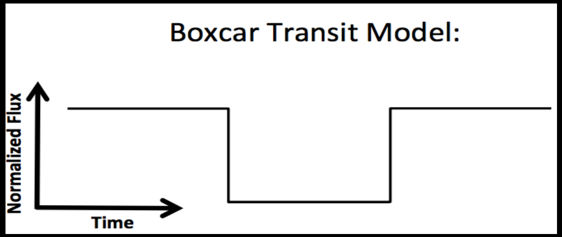
In a follow up paper, we intend to publish the full data set.

On to Paper 2!

- Our strategy to finding transits of Proxima Centauri has three main components:
- 1) Use the Box-fitting Least Squares (BLS) period finding algorithm to search for transit events in our data.
- 2) We also determine the statistical significance of peaks within the BLS periodogram.
- 3) Additionally, we simulate fake transits to see what our detection limits are and whether or not we would be able to detect Proxima Centauri b.

Box-fitting Least Squares Period Finding Algorithm

- Kovacs et al. 2002 introduced the algorithm by creating a model that assumes two discrete values: High and Low, forming a “box” that can be fit to a transit model:



Eric Agol, Sagan Workshop 2012

- The time spent in “Low” is approximately equal to the fractional transit length times the orbital period: L ~ qP
- Hartman et al. 2016 has a modified version of BLS within their software package called VARTOOLS.

BLS Input Parameters

- Orbital Period, P_{max} , P_{min} : set by user.

- Fractional Transit Length, q_{max} , q_{min}

$$q \sim \frac{1}{\pi} \sin^{-1} \left[\frac{R_{star}}{a} \frac{\sqrt{(1+k)^2 - b^2}}{\sin i} \right] \sim \frac{T_{transit\ duration}}{P_{planet}}$$

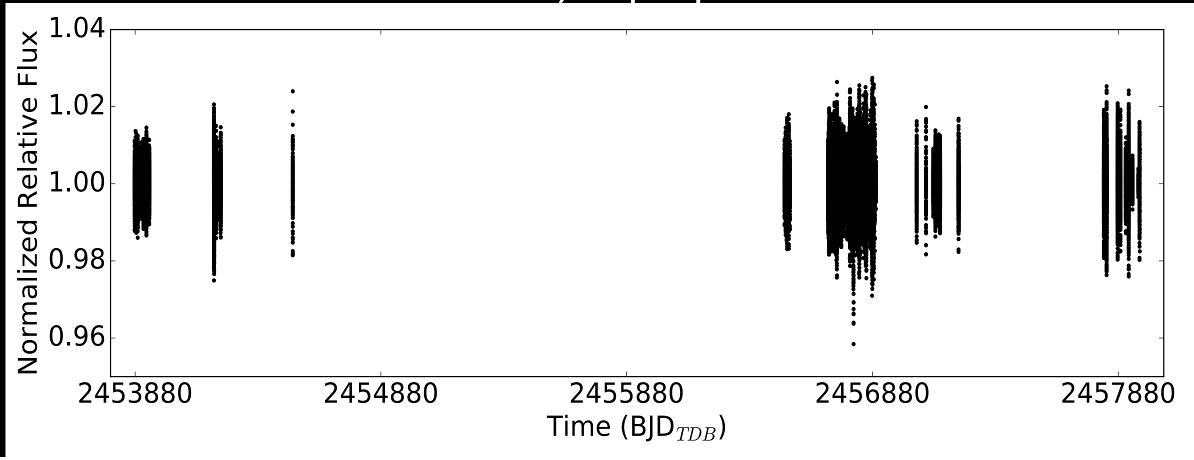
(where $k = R_{planet}/R_{star}$)

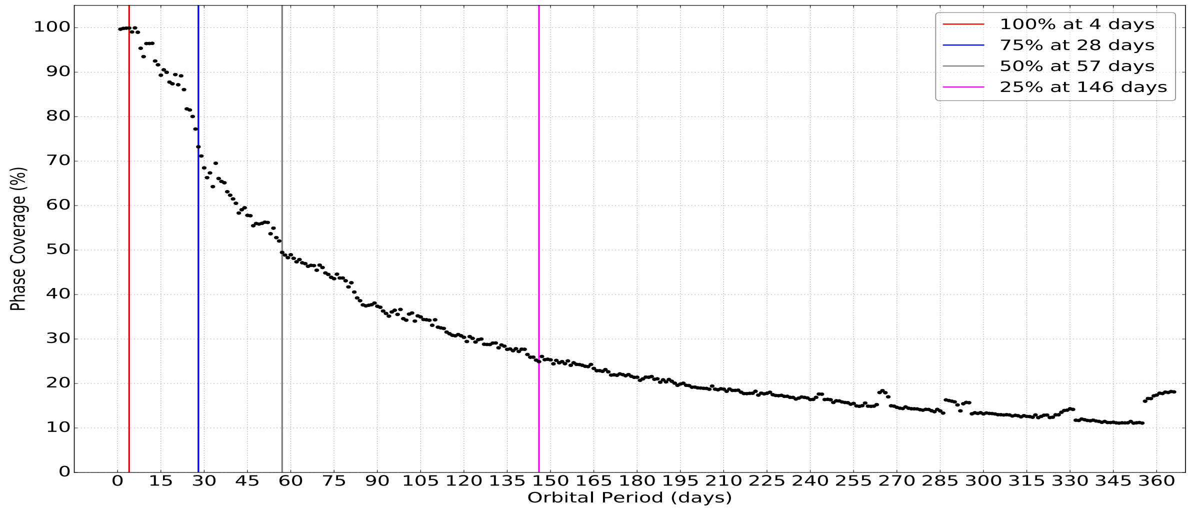
- Number of Phase bins, $\mathrm{N_{bin}} \leq {}^{2}/_{q_{min}}$

- Number of Frequencies $\mathrm{N_{freq}} = 4\mathrm{T}_{duration} \frac{\left({}^{1}/_{Pmin} - {}^{1}/_{Pmax}\right)}{q_{min}}$

What BLS parameter values to use? Min/Max Orbital Period

D.L. Feliz et al. 2018, in prep.





- Initially, we chose the min/max periods to be 1 – 30 days. To try and justify the upper limit of orbital period search parameter out to around 30 days, I calculated the phase coverage our data set covers over the period range of 1 – 365 days.

- We chose a lower limit of orbital period to be 1.01 days to avoid potential fractional/multiple aliases in periodogram

$$Phase = \left(\left(time - time[0] + \frac{Period[x]}{2}\right) \% \, Period[x]\right) - \frac{Period[x]}{2})$$

What BLS parameter values to use? q_{max}, q_{min}, N_{bins} and N_{freq}

- Using a the minimum orbital period of 1.01 days, we wanted to allow for transit events with durations of at least 25 minutes:
  q_{min} = 25 minutes / 1.01 days ~ 0.017, q_{max} = 3 day/ 30.5 days ~ 0.1

- With q_{min}~0.017 ; N_{bins} ~ 120 and N_{freq} ~ 920,500

What does BLS outputs look like?

- The basic statistic computed by the BLS algorithm is the Signal Residue (SR) as function of trial transit frequency as defined by Kovacs et al. 2002.
  (where φ = phase, r = sum of weighted pts in "Low")

$$\mathrm{SR}(f) = \max_{\phi_0,q}\left\{\left[\frac{s^2(\phi_0,q,f)}{r(\phi_0,q,f)(1-r(\phi_0,q,f))}\right]\right\} \qquad (10)$$

where

$$s^2(\phi_0,q,f) = \sum_{\mathrm{transit}} \bar{w}_i \bar{x}_i \qquad (11)$$

Hartman and Bakos, 2016

$$\mathrm{SDE} = \frac{\mathrm{SR_{peak}} - \bar{\mathrm{SR}}}{\sigma_{\mathrm{SR}}}$$

$$\mathrm{S/N}(f) = \frac{\mathrm{SR}(f) - \bar{\bar{\mathrm{SR}}}(\mathrm{f})}{\sigma_{\bar{\mathrm{SR}}}}$$

False Alarm Probability (FAP) Thresholds

- To determine the statistical significance of peaks in the BLS periodogram, we define the False Alarm Probability (FAP) to be the likelihood of a peak having equal strength by random chance or due to the cadence of our sampling.

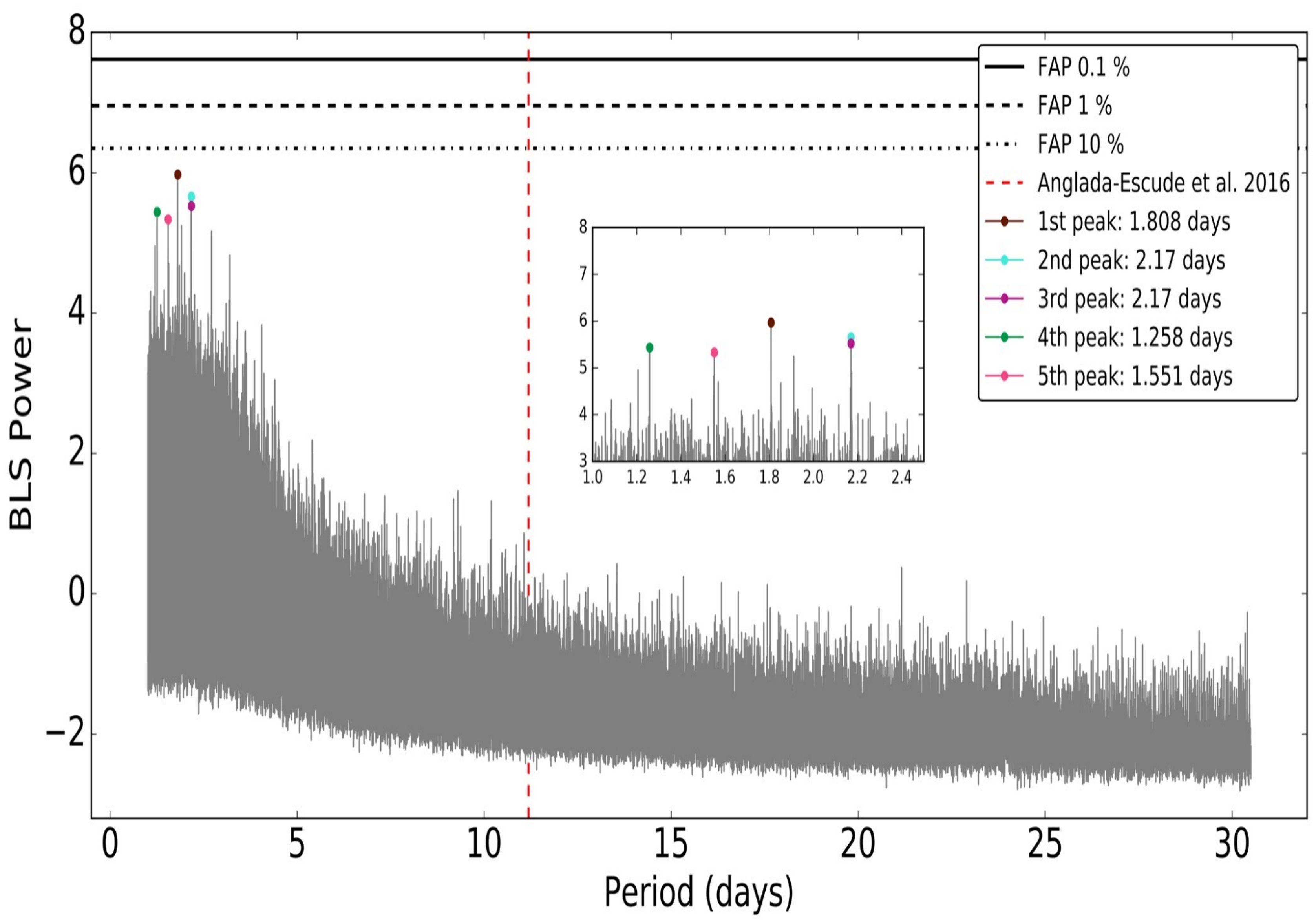
  1)

T[0] M[0] E[0]		T[5094] M[0] E[1]
T[1] M[1] E[1]	shuffle	T[45] M[1] E[1]
…	=====>	...
T[N-1] M[N-1] E[N-1]	data	T[120521] M[N-1] E[N-1]
T[N] M[N] E[N]		T[12] M[N] E[N]

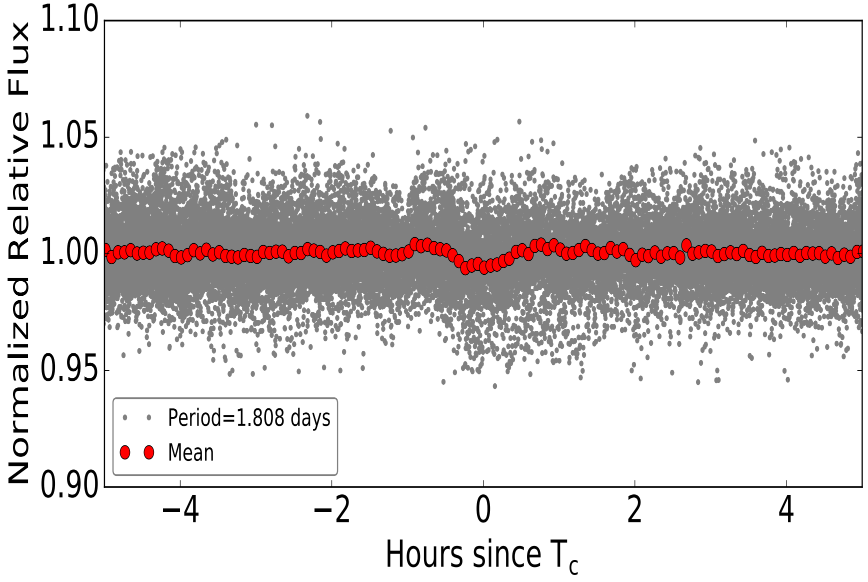
  2) Apply BLS and grab maximum peak of periodogram
  3) Re-shuffle and repeat 1,000 times

- 0.1 % FAP = 999/1000th highest maximum
- 1% FAP = 990/1000th highest maximum
- 10 % FAP = 900/1000th highest maximum

BLS Periodogram



Phase Folded Light Curve of maximum BLS peak



D.L. Feliz et al. 2018, in prep.

Transit Injection analysis to determine sensitivity of BLS algorithm

- We use a Mandel & Agol Transit model to simulate planets using the PyTransit python package which accepts the following parameters:
  - Time
  - Transit Depth
  - Limb Darkening coefficients (determined by EXOFAST) ~ [0.425,0.298]
  - Midpoint
  - Orbital Period
  - Scaled Semi-major axis, $a_s = \frac{(G(m_p + ms)P^2)^{1/3}}{4\pi^2 R_s}$
  - Inclination (assumed $\pi/2$), and consequently, $b = \frac{a \cos i}{R_s} = 0$
  - Eccentricity (assumed 0)
  - Argument of periastron (assumed $\pi/2$)
- After creating and injecting the transit model into our data, we then run BLS to see if we successfully recover the injected signal.

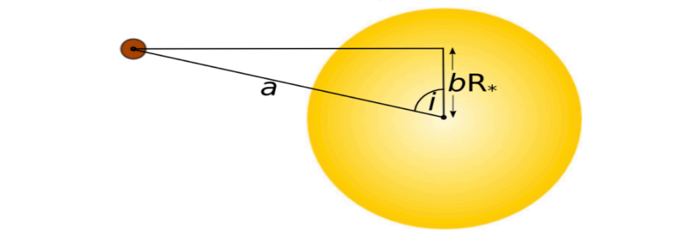
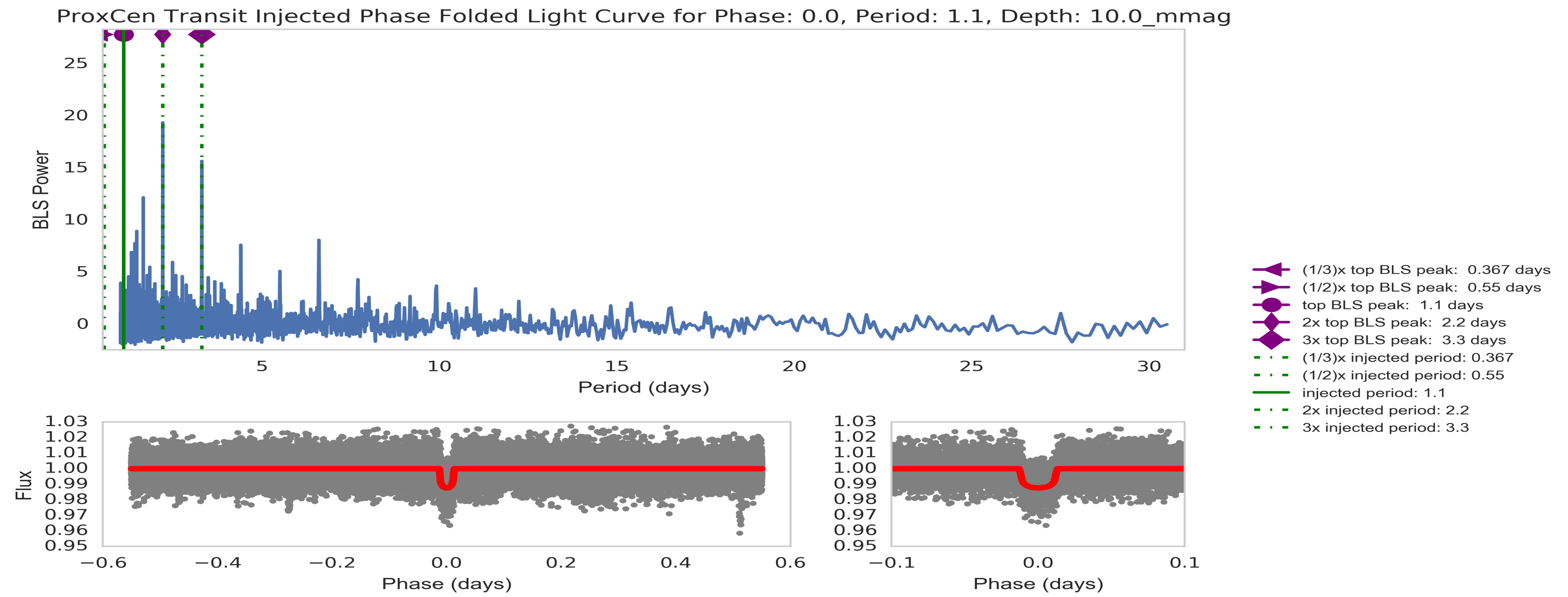


Fig. 1: The impact parameter b varies from $b = 0$ centre of stellar disk with $b = 1$ being on the cusp of the disc.

Paul Wilson

An example of BLS Recovery: Real Combined Light Curves

As a proof of concept, here is a transit injected data set:



Detection Criteria

- In our analysis, we are currently defining a successfully recovered signal with the follow criteria:

  1) The BLS recovered signal is within 1% of the injected signal (also accounting for 1/3x, 1/2x, 2x and 3x aliases)

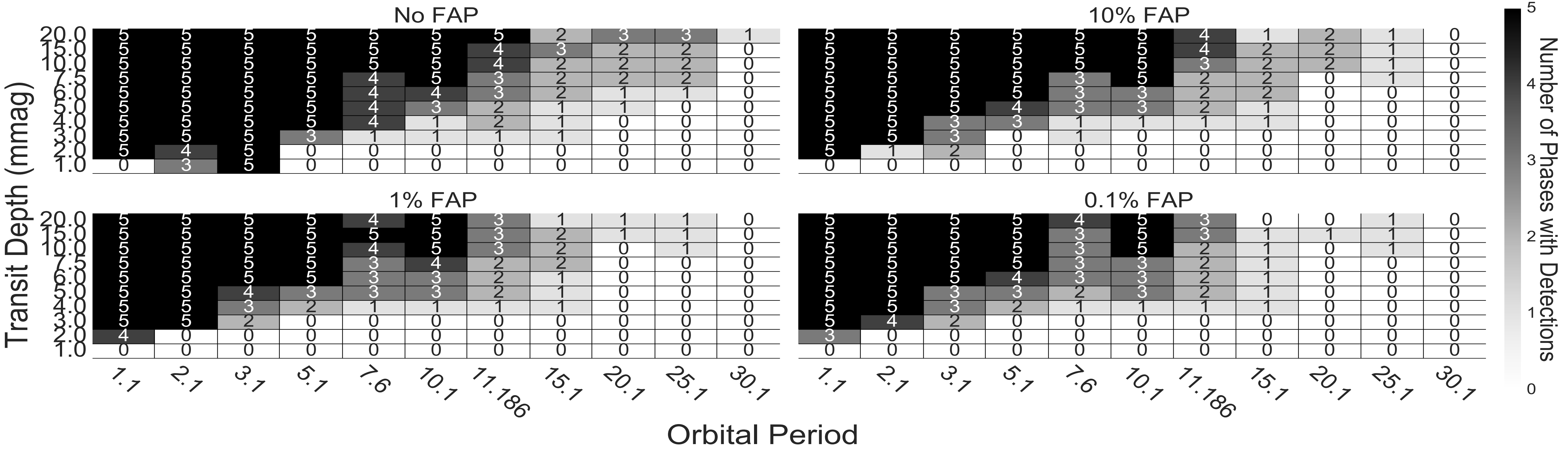
  2) The BLS Power of the recovered signal is above the 0.1%, 1% or 10% False Alarm Probability thresholds.

Injection Parameter Grid and Preliminary Results

- Transit Depth (mmag) = 1, 2, 3, 4, 5, 6, 7.5, 10, 15.0, 20
- Orbital Period (days) = 1.1, 2.1, 3.1, 5.1, 7.6, 10.1, 11.186, 15.1, 20.1, 25.1, 30.1
- Orbital Phase = -0.4, -0.2, 0.0, 0.2, 0.4

Injection Parameter Grid and Preliminary Results

- Transit Depth (mmag) = 1, 2, 3, 4, 5, 6, 7.5, 10, 15.0, 20
- Orbital Period (days) = 1.1, 2.1, 3.1, 5.1, 7.6, 10.1, 11.186, 15.1, 20.1, 25.1, 30.1
- Orbital Phase = -0.4, -0.2, 0.0, 0.2, 0.4



Conclusions

- We were unable to verify any of the claimed detections from previously published works and find no compelling evidence for the existence of Proxima Centauri b.
- The low energy flares occur on the time scale of the predicted Proxima b transit duration, which could contribute to the variations seen in our data. Also, it is possible that starspots forming or changing significantly on ~ hour timescales could produce photometric dips similar to the transit-like events and other variations detected in this work and by other authors.
- Our Transit Injection analysis tells us the data is sensitive enough to detect a significant amount of signals up until a transit depth of 5 mmag and an orbital period ~ 10 days.

Current and Future Work

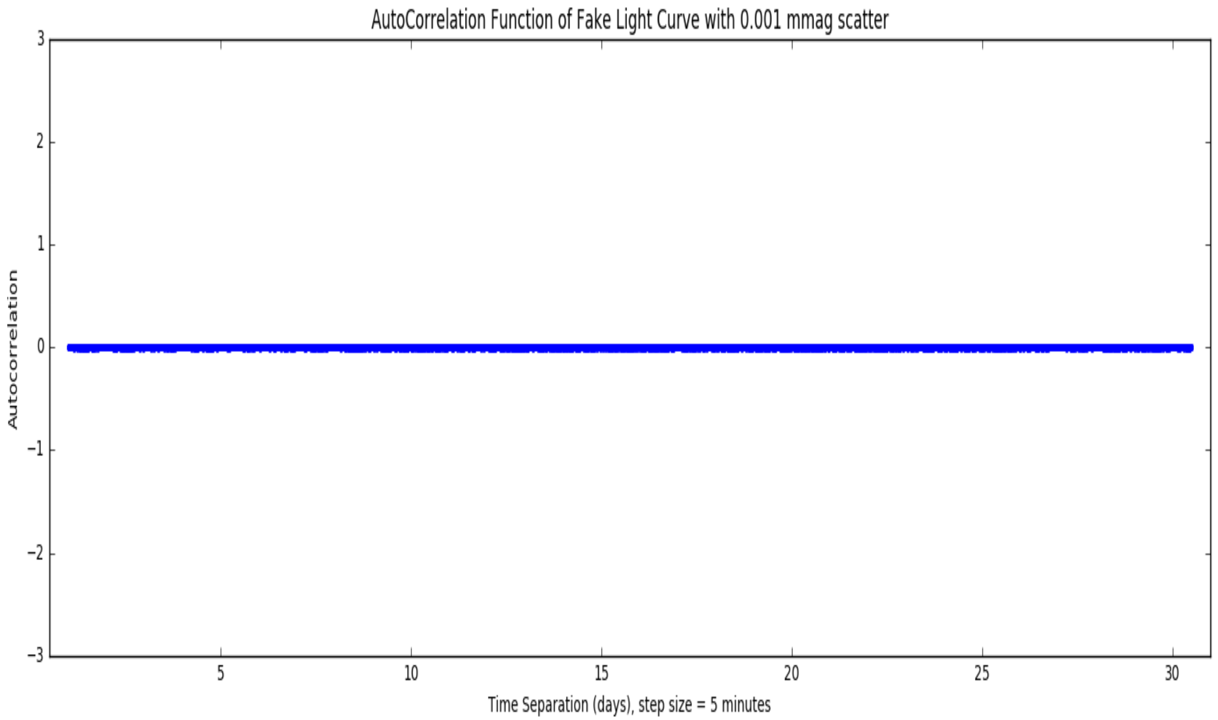
- Anglada-Escude et al. provide some upper limits to the eccentricity of Proxima Centauri b, $e < 0.35$. For the preliminary results shown today, we assumed $e = 0$.

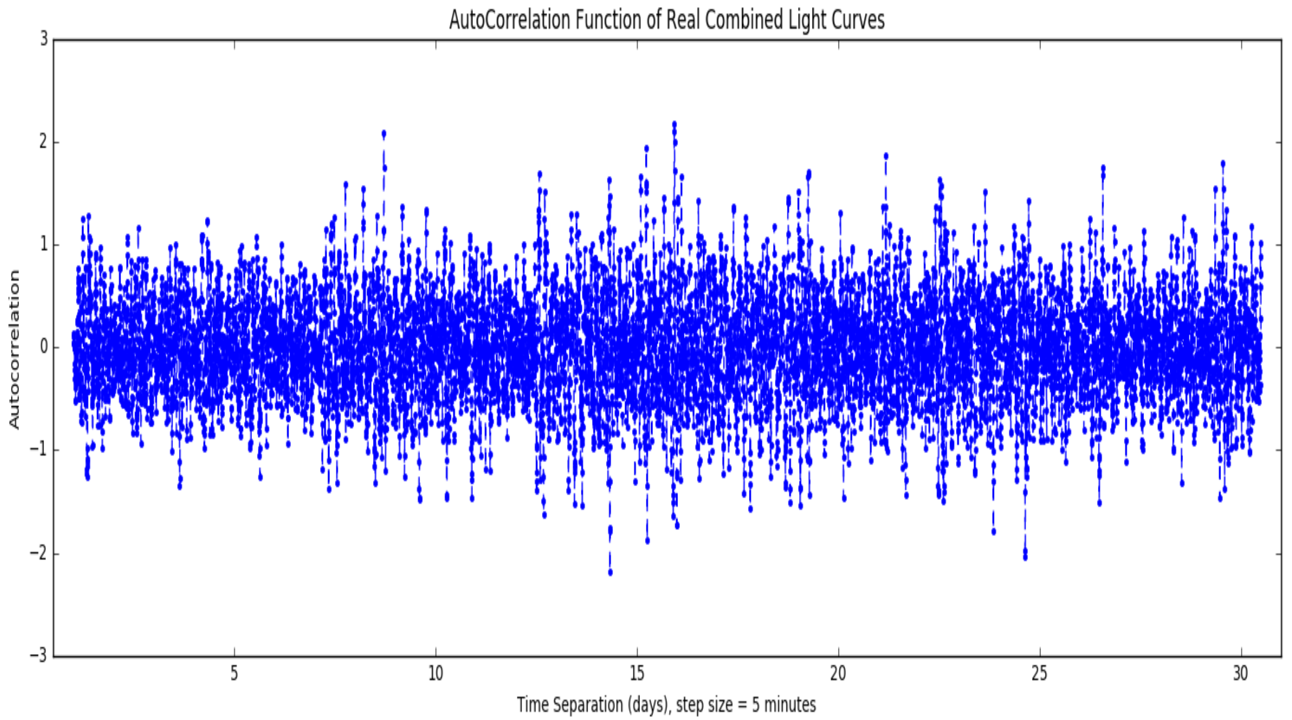
  I intend to conduct the full transit injection analysis with this change to see how it affects our recoverability. (I suspect it will go down)

- We still have some vetting to do but we may end up removing the 5/23/2014 and 5/24/2014 PromptSS03 light curves and repeating the analysis if we find they contribute to numerous signals in phase folded light curves.

Correlated Noise in our data is a problem

- Vartools has also has a discrete autocorrelation function to measure correlations between data points of a time-series. Here I compare a fake light curve created with the real time stamps of our data set but with a small and random scatter.
- Vartools' autocorrelation functions accepts only 3 parameters: start, stop and stepsize





How to re-approach detrending: Regression Analysis (Gaussian Processes)

- Modelling the correlated noise due to systematics
- Because the meridian flips due not occur at identical times throughout observations (some have 1 or 2, some as high as 3-4), these must still be manually detrended either before/after GP.

How to re-approach accounting for Flares

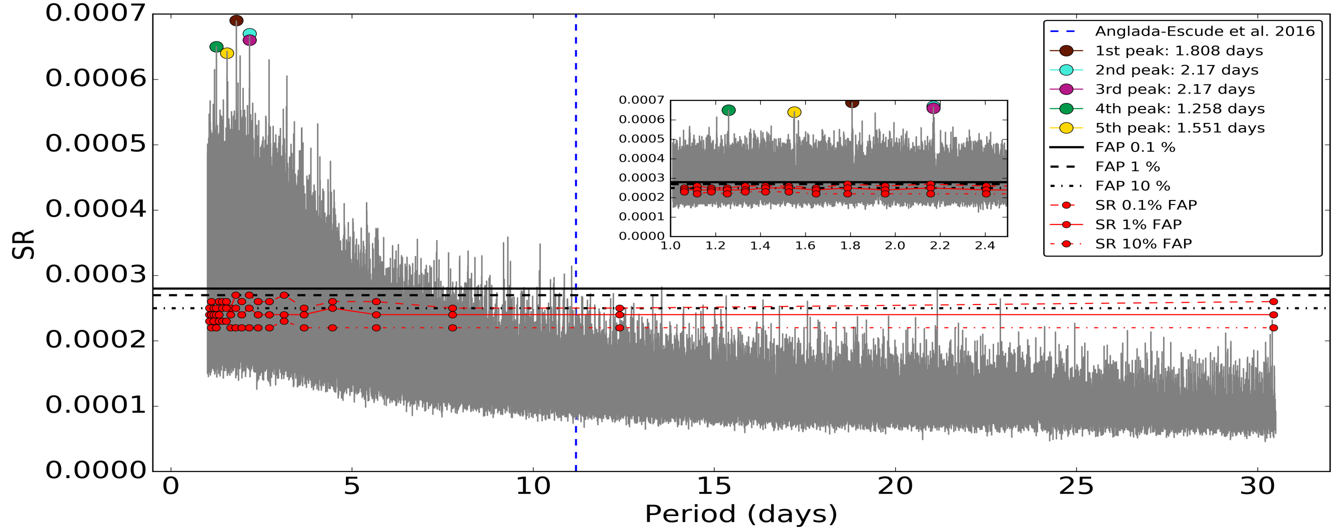
- Currently, Graeme White et al. is leading an initiative to quantify Proxima Centauri's flare rate from our data set while also attempting to model the flare events. Depending on this success, we may be able to remove the flares better than a 3$\boldsymbol{\sigma}$ cut.
- Possibly, some kind of Power Law fit may be of use (not yet attempted)

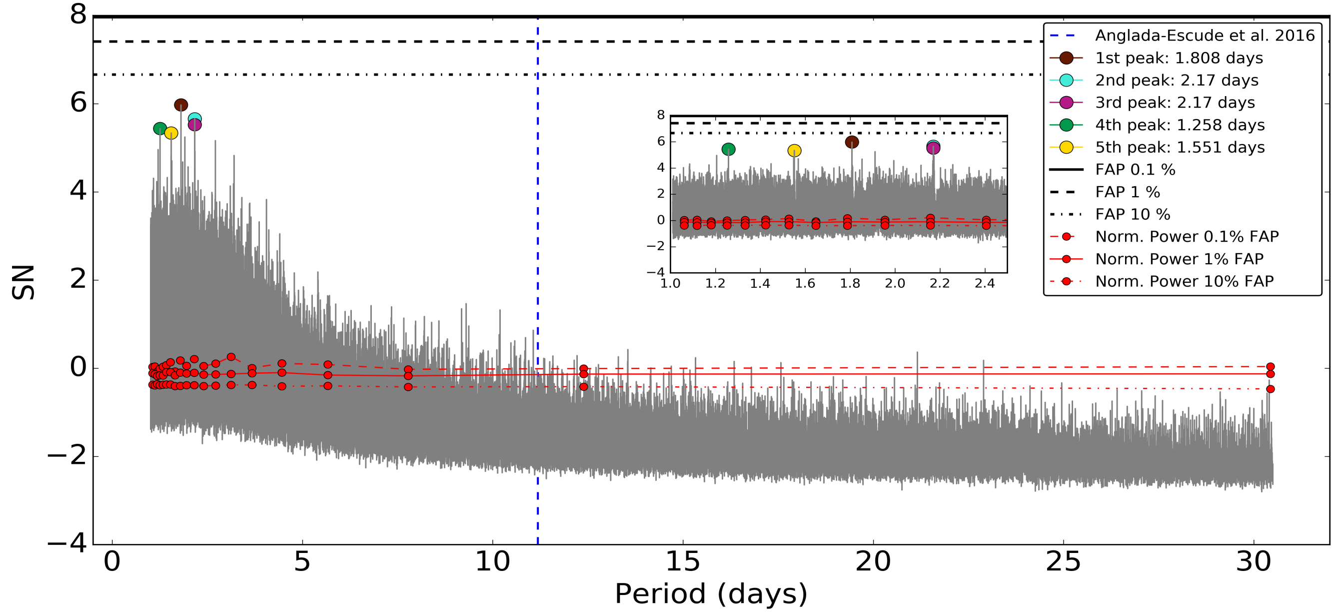
How to re-approach False Alarm Probability: FAP as a function of Period

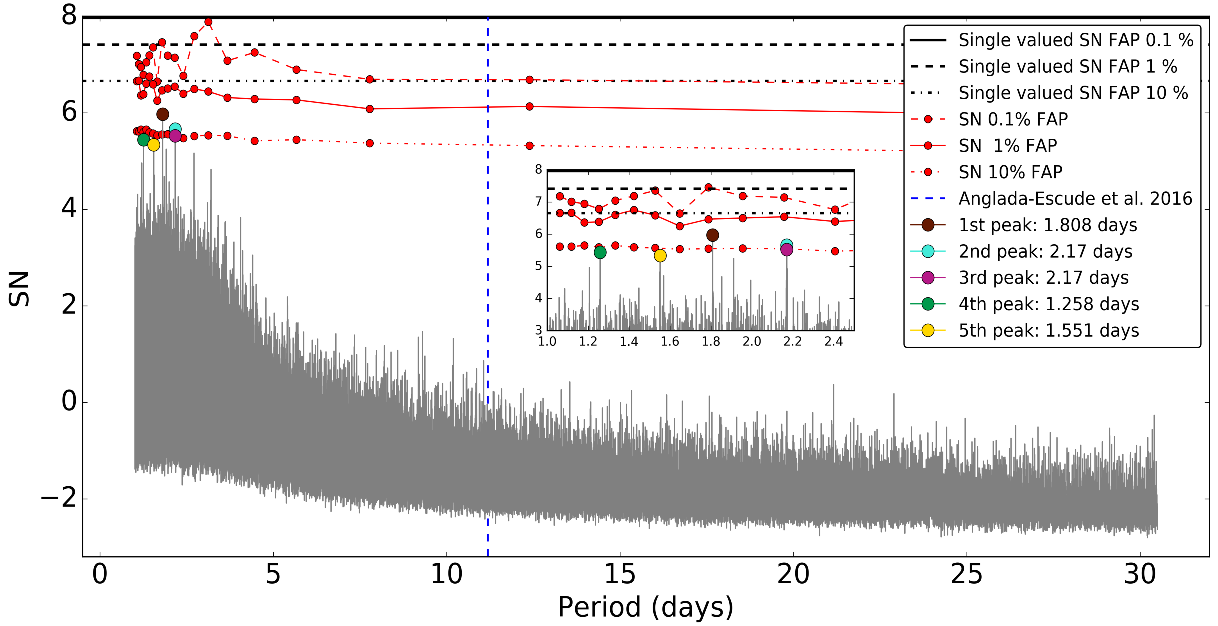
- To attempt to better sample the periodogram in localized regions of period, we separated the periodogram into 20 period ranges with an equal amount of data points in each range.
- We then calculate the FAP thresholds within each period range
- We are currently testing two methods of FAP as a function of Period:
  - Using Vartool’s S/N output (aka “BLS Power”)
  - Defining our own definition of “Normalized Power” which mimics the SDE

$$Normalized\ Power = \frac{SR(f)_{random} - \overline{SR}}{\boldsymbol{\sigma}_{SR}}$$

How to re-approach False Alarm Probability: FAP as a function of Period

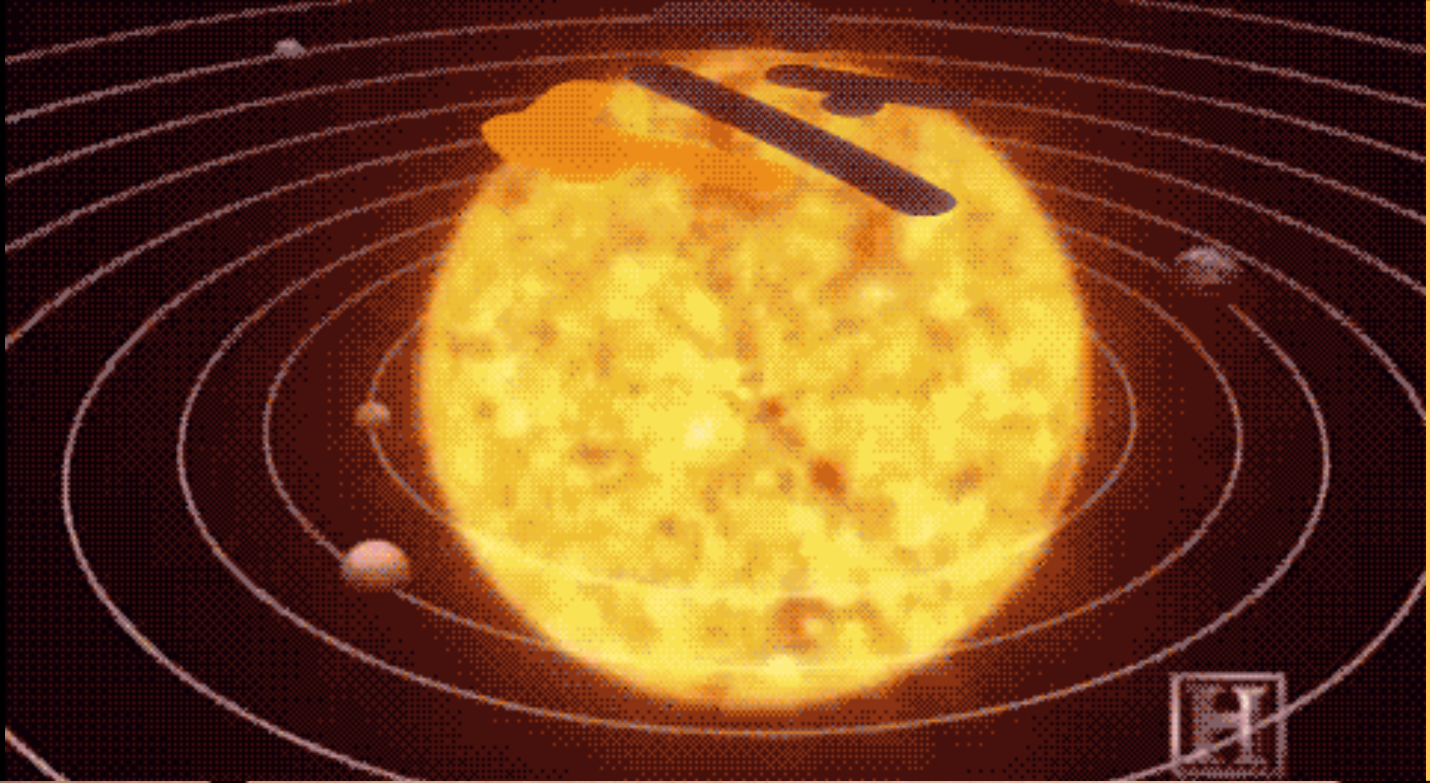


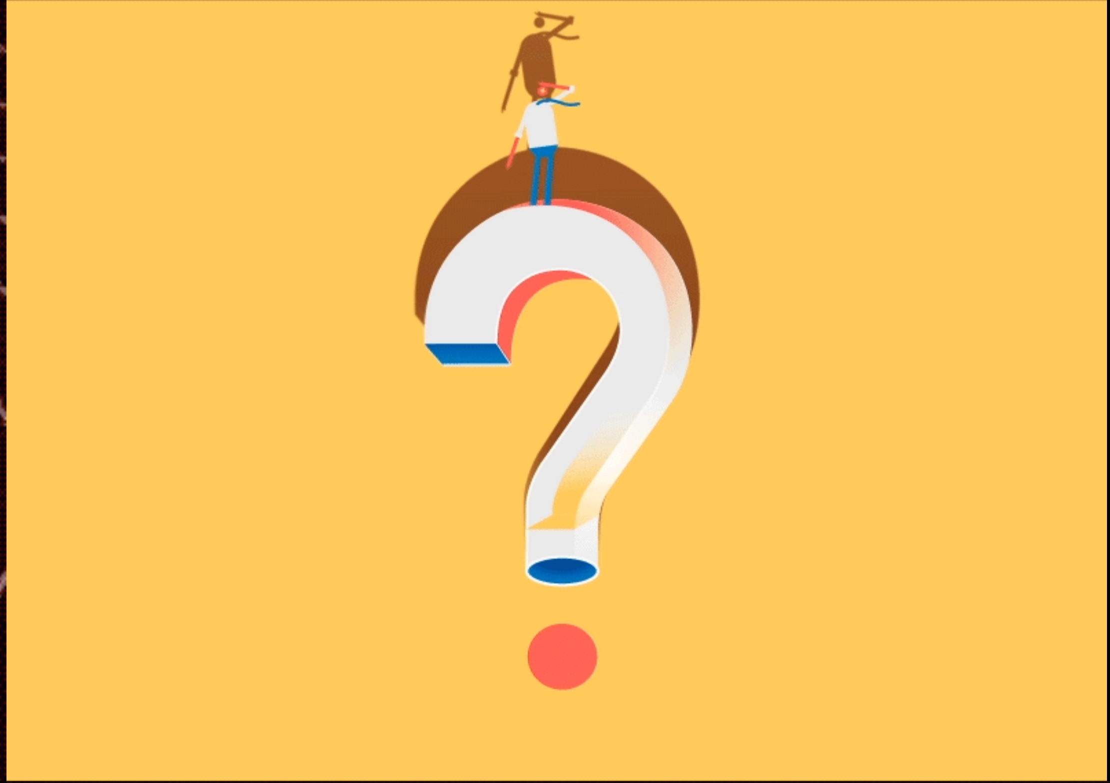


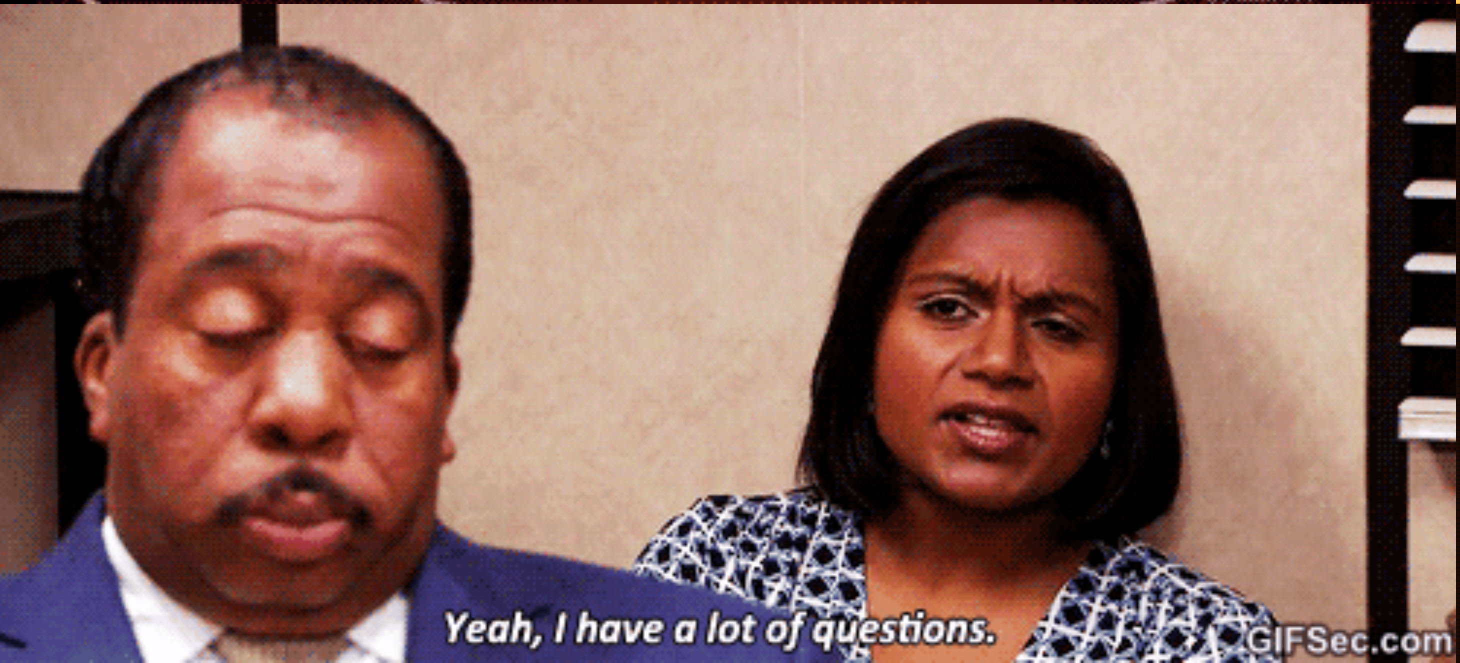


How to re-approach False Alarm Probability: possibly Bayesian Inference?

- BLS assumes white noise (Gaussian), clearly we have some correlated noise in our data.
- The methodology of False Alarm Probability could also be affected by correlated noise (maybe???).






Yeah, I have a lot of questions.
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