

**lightkurve**: an open source Python package for NASA’s *Kepler*, *K2* and *TESS* data analysis

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## ABSTRACT

- We present **lightkurve**, an open source package for analysis of flux time series using Python.
- It is a multipurpose, general tool to make producing time-series photometry from raw pixel data easier and more reproducible between different teams.
- **lightkurve** is designed to interface seamlessly with data from NASA’s *Kepler*, *K2* and *TESS* missions.
- Using these tools it is simple to create corrected time-series photometry from raw pixel data from any of these missions.
- Easy to interact with raw data products and produce fantastic light curves
- Open source, modable
- Supremely reproducible.
- Go from raw data to planet in 5 lines of code.

\*\*\*CLH: What plots do we want? These should be our KILLER selling points. All graphs should be easy to understand as standalone figures. These are what will grab people! But let’s keep it short and sweet.

- Beautiful TPF and masking
- Beautiful flattening?
- Beautiful motion detrending
- Beautiful CBV correction
- Beautiful planet finding

\*\*\*

## 1. INTRODUCTION

What is the background—

- Time series photometry is available for a wide variety of astrophysical purposes and in a wide variety of formats.

- This ranges from 30 year long time series of variable stars? to short time-series of hours for X-Ray objects ?
- In particular, NASA's *Kepler* and *K2* missions have provided some of the most precise, long term monitoring of stars to date ?.
- In the near future the *TESS* mission will be delivering high-precision time series data for 90% of the sky, providing light curves for X millions of objects ?.
- **\*\*\*CLH: What are the challenges we face in time-series astronomy? \*\*\***

*What tools are currently available?—*

- PyKE
- However, no one package provides a simple, open source framework for manipulating time-series data that is general purpose.

*What are we presenting—*

- We present `lightkurve` as a general tool to use almost all time-series photometry, with a particular focus on *Kepler*, *K2* and *TESS*.
- While these missions have powerful pipelines which deliver high-precision light curves for many objects (citation), `lightkurve` allows bespoke analyses tailored for specific science cases.
- These might include custom aperture photometry, PSF photometry in crowded field and studies of long period transient events such as supernovae and AGN.
- We have designed `lightkurve` as a tool process this vast wealth of data easily and intuitively with many features and tools to remove/reduce the overhead in using this data.
- easy reproducibility

*How do you use `lightkurve`?—*

- designed to be flexible
- nuts and bolts
- open source
- easy data fetching
- easy API

*What is the selling point of `lightkurve`?—*

- There are two sides to the `lightkurve` package. Firstly, `lightkurve` can be used as an extraction package for creating time-series photometry from astronomical images such as *Kepler* Target Pixel Files (TPFs) or *TESS* Full Frame Images (FFIs). This includes simple aperture photometry, PSF photometry and centroiding.
- Secondly, `lightkurve` can be used for analysis of time-series photometry. This includes motion detrending, CBV corrections, outlier rejection and period folding.
- Together these two sides can be combined to convert raw data from *Kepler*, *K2* and *TESS* to cleaned light curves of exoplanet candidates, supernovae and extra-galactic objects.

*Future resources?—*

- This is `lightkurve` 1.0
- Anticipate adding new features
- Easily extendable for users to add in new features

*What's in this paper?—*

- In this paper we discuss the basic components of `lightkurve`
- We will show three key components of analysis with `lightkurve`; manipulating lightcurves, creating lightcurves, and removing systematics from lightcurves.
- `lightkurve` has a full compliment of tutorials
- More details can be found in our documentation at link.

## 2. PACKAGE OVERVIEW

**\*\*\*CLH: This needs to VERY clearly show the difference between a TPF, LC and LCF. \*\*\***  
Maybe include a class diagram here, or a table of the modules or classes.

Maybe include a table or graph listing the key functions of the key classes, e.g. Lightcurve: cdpp, fold, stitch, plot TargetPixelFile: tolighcurve, plot

### 2.1. PyKE Tools

- previously there was pyke, don't spend too long on this
- pyke is still available

- `lightkurve` uses only python
- new Python package which makes the custom analysis of target easy. Based on AstroPy (cite Astropy).

### 3. EXAMPLES OF KEY FEATURES

#### 3.1. Working with lightcurves

flatten, fold, finding planets, from archive...

#### 3.2. Making your own lightcurves from target pixel files

explain TPFs, aperture photometry, and PSF photometry

#### 3.3. Removing systematics from lightcurves

We only intend to provide simple tools. Ideally, systematics are removed simultaneously with fitting a model (e.g. Montet and DFM 2015).

### 4. FUTURE WORK

Explain PSF photometry needs users and data-driven model capability.

We do not intend to implement transit fitting, more advanced detrending, etc. Instead, `lightkurve` intends to provide the building blocks needed to build or interact with such packages.

We intend to add many tutorials.

Explain how people can contribute.

### 5. CONCLUSIONS

we will discuss =; we have discussed

## 6. LIGHTCURVE BASICS

### 6.1. The `LightCurve` and `KeplerLightCurve` classes

The `LightCurve` class is a simple container to store numpy arrays (hereafter, arrays) related to flux time-domain measurements.

The `LightCurve` object provides methods to store, process, and convert lightcurves. Table 1 contains a description of a subset of the methods.

A `LightCurve` object can be instantiated by passing a `time` array, a `flux` array, and, optionally, a `flux_err` array which accounts for uncertainties in the flux measurements, i.e.,

```
>>> from lightkurve import LightCurve
>>> lc = LightCurve(time, flux)
```

The `KeplerLightCurve` class extends `LightCurve` by adding attributes to store metadata information such as channel number, quality flags, campaign or quarter number, kepler id, etc.

Additionally, `KeplerLightCurve` can be corrected for motion-dependent correlated noise using the `correct` method which will be discussed in Section 8.3.

**Table 1.** A subset of methods provided by the `LightCurve` class

Method	Short description
<code>stitch</code>	appends the attributes <code>flux</code> , <code>time</code> , and <code>flux_err</code> of other given <code>LightCurve</code> objects.
<code>flatten</code>	applies a Savitzky-Golay filter to capture low frequency flux variations which can be then removed in order to aid transit detection algorithms.
<code>fold</code>	folds a lightcurve at a given period and phase.
<code>bin</code>	bins a lightcurve using a block mean or median.
<code>cdpp</code>	computes the Combined Differential Photometric Precision (CDPP) metric, which is a proxy for the amount of scatter in the lightcurve signal.
<code>plot</code>	displays a lightcurve.

### 6.2. The `KeplerLightCurveFile` class

The `KeplerLightCurveFile` class defines a structure to deal with lightcurve files from both NASA's Kepler and K2 missions.

To instantiate a `KeplerLightCurveFile` object, it is necessary to pass a path which represents the address (url or local path) of a lightcurve file in the fits (or compressed) format, and a `quality_bitmask` string which specifies quality flags of cadences that should be ignored.

One crucial method of the `KeplerLightCurveFile` class is `get_lightcurve` which returns a `KeplerLightCurve` object with the metadata provided by the corresponding `KeplerLightCurveFile`.

Therefore, one can, for example, perform the following series of operations in order to fold a lightcurve from the MAST archive

```
>>> lc_file = KeplerLightCurveFile("kplr011904151-200935")
>>> klc = lc_file.PDCSAP_FLUX.fold(period=0.837495)
>>> klc.plot()
```

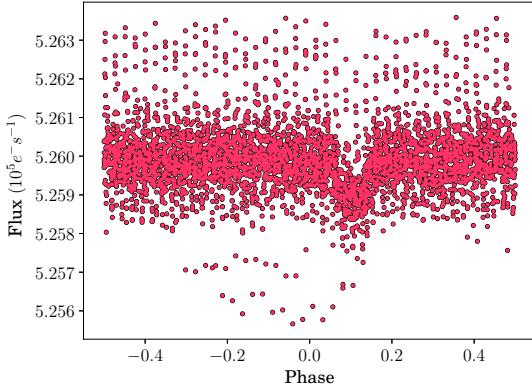
## 7. TARGET PIXEL FILE BASICS

### 7.1. The `KeplerTargetPixelFile` class

A `KeplerTargetPixelFile` object can be instantiated by passing a path (URL or local) of a target pixel file. Optionally, the user can elect to throw away frames that contain a specific flag by using the `quality_bitmask` argument.

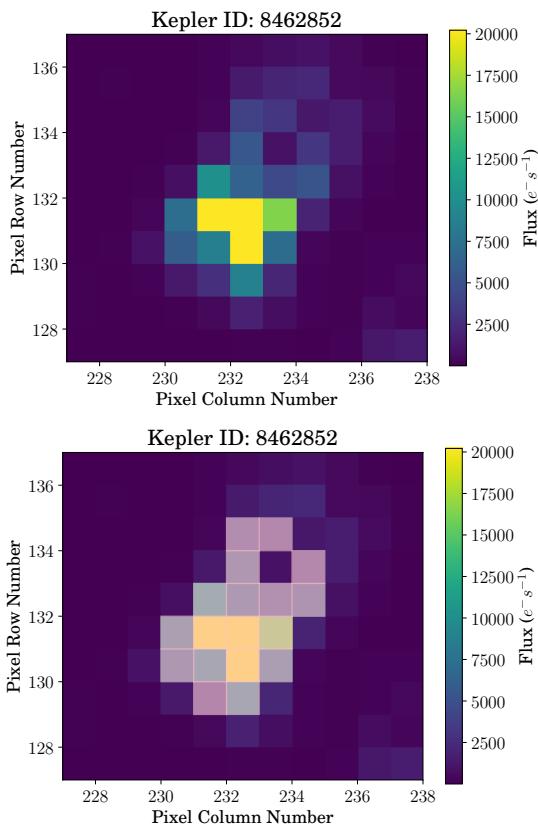
`KeplerTargetPixelFile` offers a number of methods that range from getting raw aperture photometry lightcurves to data visualization.

For instance, the method `plot` can be used to visualize a given frame, which are depicted in Fig. 2.



**Figure 1.** Folded lightcurve of target KIC011904151 quarter 3, showing the transit signal of Kepler-10b.

```
>>> import numpy as np
>>> from lightkurve import KeplerTargetPixelFile
>>> tpf = KeplerTargetPixelFile("kplr008462852-2011073133259-1pd-targ.fits")
>>> tpf.plot()
>>> tpf.plot(aperture_mask=tpf.flux[0] > np.nanmean(tpf.flux[0]))
```



**Figure 2.** Displaying a given frame of a TPF using `plot`. Optionally, an `aperture_mask` can be passed which is highlighted on the right hand side.

In an image with  $n$  pixels, where the flux and the center positions of the  $i$ -th pixel are denoted as  $f_i$  and  $(x_i, y_i)$ , respectively, the centroids may be expressed as

$$x^* = \frac{\sum_{i=1}^n f_i x_i}{\sum_{i=1}^n f_i}, \quad y^* = \frac{\sum_{i=1}^n f_i y_i}{\sum_{i=1}^n f_i}. \quad (1)$$

In `lightkurve`, the centroids in every cadence can be computed as

```
>>> from lightkurve import KeplerTargetPixelFile
>>> tpf = KeplerTargetPixelFile('ktwo246199087-c12_1pd-targ.fits')
>>> x_star, y_star = tpf.get_centroids()
```

## 8. TOOLS

### 8.1. Cotrending basis vectors

Cotrending basis vectors (CBVs) can remove global correlated systematics present in a given channel [Smith et al. \(2012\)](#).

Given a set of  $n$  CBVs, one is interested in finding a vector of  $n$  coefficients  $\boldsymbol{\theta} = (\theta_1, \theta_2, \dots, \theta_n)$  which minimizes some cost function between the SAP flux and the set of CBVs. The mathematical structure of the cost function is a direct consequence of the statistical assumptions made for data.

For instance, if one assumes that the data comes from an independent and identically distributed (iid) multivariate Gaussian distribution with mean  $\sum_{j=1}^n \theta_j v_j(t)$  and known variance  $\sigma^2$ , then the cost function can be expressed as follows

$$\mathcal{C}(\boldsymbol{\theta}, f_{SAP}) = \sum_t \left( f_{SAP}(t) - \sum_{j=1}^n \theta_j v_j(t) \right)^2, \quad (2)$$

in which  $f_{SAP}$  is the SAP flux and  $v_j$  is the  $j$ -th CBV.

The maximum likelihood estimator for  $\boldsymbol{\theta}$ ,  $\boldsymbol{\theta}^*$  can be expressed as

$$\boldsymbol{\theta}^* = \arg \min_{\boldsymbol{\theta} \in \Theta} \mathcal{C}(\boldsymbol{\theta}, f_{SAP}). \quad (3)$$

However, Equation (2) is sensitive to outliers [Ivezic et al. \(2014\)](#), therefore, as a default behaviour in `lightkurve`, we use the following cost function

$$\mathcal{C}(\boldsymbol{\theta}, f_{SAP}) = \sum_t \left| f_{SAP}(t) - \sum_{j=1}^n \theta_j v_j(t) \right|. \quad (4)$$

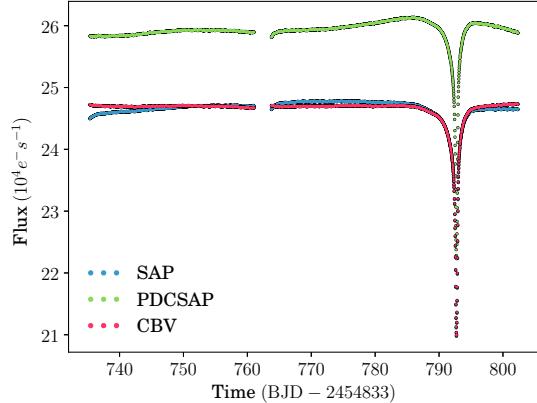
Then, the CBV-corrected flux can be computed as

$$f_{CBV} = f_{SAP} - \sum_{j=1}^n \theta_j^* v_j(t). \quad (5)$$

An example of SAP flux correction for target KOI 8462852 (Tabby's star) can be written as follows

```
>>> from lightkurve.lightcurve import KeplerCBVCorrector
>>> cbv = KeplerCBVCorrector("kplr008462852-2011073133259")
>>> cbv_lc = cbv.correct(cbvs=[1,2])
```

Fig 3 illustrates the correction. The pink line has a shift from the green line because in `lightkurve` we do not account the flux lost outside of the aperture mask.



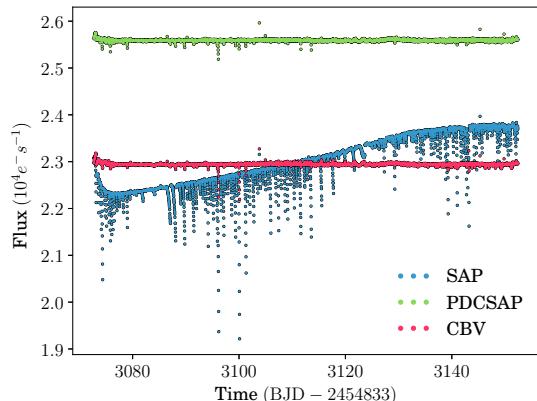
**Figure 3.** CBV correction applied on KOI 8462852

Improperly tuning the number of CBVs can cause over-/under-fitting. One way to identify a reasonable number of CBVs is to perform a grid search as shown in Fig (6).

In the same fashion, we can apply cotrending basis vector correction to *K2* lightcurves.

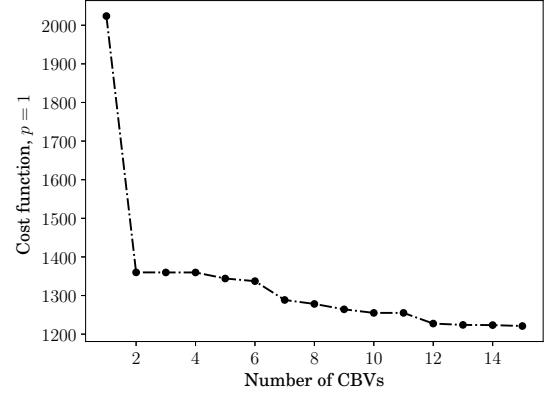
Fig. 4 shows the detrended lightcurve after estimating the first nine coefficients for CBV correction on *K2* target EPIC 201543306. The selection of the number of CBVs is set by inspecting the grid search curve can be set through model comparison heuristics like AIC, BIC, or cross-validation Ivezić et al. (2014).

#### 8.1.1. Number of CBVs



**Figure 4.** CBV correction applied on EPIC 201543306.

The number of CBVs will directly contribute to overfitting. One effective way to identify a reasonable number of CBVs is to perform a grid search as suggested in Fig (6), which shows the cost function as a function of the number of CBVs. Usually, as the number of CBVs increases, the value of the cost function decreases. And therefore, the user should empirically choose a number of CBVs which does not remove the astrophysical signal of interest [add reference].



**Figure 5.** Grid search on the number of CBVs

An objective way of selecting the number of CBVs is to use Bayes' factors [add reference]. In the Bayes' factor setting, the selected number of CBVs is the one that provide the least gain in posterior probability, i.e., for all ordered pairs of CBVs, the Bayes factor selects  $n^*$  number of CBVs as follows

$$n^* = \arg \min_n \frac{p_{n+1}}{p_n}, \quad (6)$$

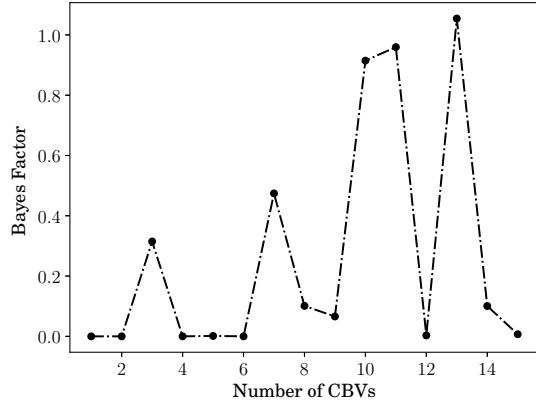
in which  $p_n$  is the posterior probability evaluated at the Maximum A Posteriori Estimator (MAP) obtained using  $n$  CBVs.

A Laplacian prior with zero mean and variance 16 is the default prior density over the CBVs coefficients.

#### 8.2. Point spread function photometry

Point Spread Function (PSF) photometry is the de facto technique to process crowded-field images Stetson (1987); Heasley (1999). In context of Kepler and *K2* missions, Libralato et al Libralato et al. (2016) have shown...

The underlying principle of PSF photometry consists in modelling a given crowded image as a linear combination of individual PSFs and possibly a background model. On the PSF model itself, it is commonly assumed that the flux at an arbitrary pixel position increases linearly with the integrated flux Stetson (1987); Heasley (1999).



**Figure 6.** Bayes factors as a function of the number of CBVs for EPIC 201543306

`lightkurve` contains routines to perform PSF photometry in TPFs which are implemented in the `psf` module.

Briefly, the PSF photometry problem that `lightkurve` solves can be formulated as follows. Given an image  $\mathbf{y}$ , with  $n$  pixels and  $m$  stars, and a PSF model  $\lambda(\boldsymbol{\theta}) = \sum_{j=1}^m \lambda_j(\boldsymbol{\theta}_j)$ , find the best parameter vector (which encodes fluxes and center positions for  $m$  stars)  $\boldsymbol{\theta}^* = (\theta_1^*, \theta_2^*, \dots, \theta_m^*)$  that minimizes some cost (or loss) function  $R(\lambda(\boldsymbol{\theta}), \mathbf{y})$  of assigning  $\boldsymbol{\theta} = \boldsymbol{\theta}^*$ .

From a probabilistic point of view, one is often interested in minimizing the expected cost with respect to some probability distribution assigned to the data  $\mathbf{y}$  and to the parameter vector  $\boldsymbol{\theta}$ , from which the cost function  $R$  naturally arises. The default assumption, made in `lightkurve`, on the data is that it follows a Poisson probability distribution, whereas the probability distribution on the parameter vector has to be assigned by the user using the `prior` argument. Using a uniform prior for  $\boldsymbol{\theta}$ , the MAP estimator can be written as

$$\boldsymbol{\theta}^*(\mathbf{y}) = \arg \min_{\boldsymbol{\theta} \in \Lambda} \sum_{i=1}^n \left( \sum_{j=1}^m \lambda_i(\boldsymbol{\theta}_j) - y_i \log \sum_{j=1}^m \lambda_i(\boldsymbol{\theta}_j) \right), \quad (7)$$

in which  $\Lambda$  is the support of  $\boldsymbol{\theta}$ .

The example below illustrates PSF photometry on the target EPIC 246199087 (Trappist-1):

```
>>> from lightkurve import KeplerTargetPixelFile
>>> from lightkurve.psf import PRFPhotometry, SceneModel
>>> from oktopus import UniformPrior
>>> tpf = KeplerTargetPixelFile("ktwo246199087-c12_1pd-t")
>>> prf = tpf.get_psf_model()
>>> prior = UniformPrior(lb=[4e3, 990, 25, 1], ub=[2e4,
>>> scene = SceneModel(prf=[prfs])
>>> phot = PRFPhotometry(scene_model=scene, prior=prior)
>>> results = phot.fit(tpf.flux + tpf.flux_bkg)
```

The photometric results are stored in a  $c \times 4$  matrix, where  $c$  is the number of frames (cadences).

Another important aspect is the PSF model...

### 3.3. Motion-dependent Correlated Noise

Spacecraft-induced correlated noise remains one of the greatest hurdles to analyzing K2 lightcurves. Many algorithms have been developed to mitigate motion-dependent artifacts Vanderburg & Johnson (2014)[CITE K2SC and EVEREST]. In `lightkurve`, we implement an algorithm based off of the self-flat-field (SFF) presented in Vanderburg & Johnson (2014).

Basically, SFF works by decorrelating the simple aperture flux against the information on the spacecraft motion, obtained by computing the arclength using the centroids of the target.

```
from lightkurve import KeplerTargetPixelFile
tpf = KeplerTargetPixelFile("ktwo248667471-c14_1pd-targ")
lc = tpf.to_lightcurve()
centroids = tpf.get_centroids()
lcc = lc.correct(centroids[0], centroids[1])
```

We would like to express our gratitude...

*Facilities:* Kepler

*Software:* astropy

## APPENDIX

### A. APPENDIX INFORMATION

## REFERENCES

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