Draft version December 9, 2021
Typeset using LaTeX default style in AASTeX631

Detecting Exoplanets Using Transits

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(Dated: December 2021)

ABSTRACT

In this letter we present an analysis of the Kepler 8b, an exoplanet orbiting Kepler 8 (a star in the constellation of Lyra which is comparable to the sun in mass and radius but is slightly larger in both aspects). We determine the radius of the Kepler 8b to be R = $(1.19 \pm 0.12)\, R_J$ with a semi-major axis of $a = 0.04532\, AU$, a density of $\rho = (0.31653 \pm 0.00083)\, g\, cm^{-3}$ and an orbital inclination of 88.366^o relative to the stellar disk. The exoplanet is found to have a orbital period of 3.25 days and a transit duration of 0.1 days.

Keywords: Exoplanets — Planetary Transit — History of astronomy(1868) — Interdisciplinary astronomy(804) — Kepler Mission

1. INTRODUCTION

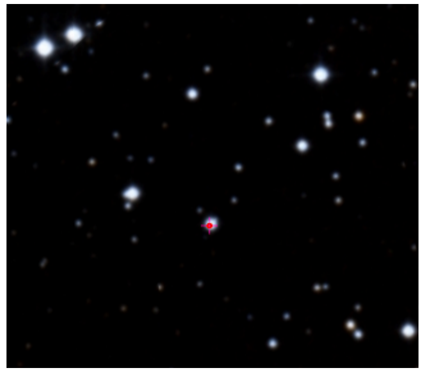
For as long as humanity has been making records, our curiosity has always wondered beyond our atmosphere and the possibilities that exist there. When Copernicus first presented his model of a heliocentric universe, it opened the doors to the never before explored ideas of multiple replicas of the solar system, each with a possible planetary system moving around its parent star, such planets would later become known as exoplanets.

In October 1995, Micheal Mayor and Didier Queloz of the Geneva Observatory made public what is today regarded as the first discovery of an exoplanet around a solar type star Mayor & Queloz (1995). To date, more than 4000 exoplanets [1] have been discovered and are considered confirmed. However exoplanets do more than just feed our curiosity, they have become very useful tools to probe into the processes that are involved in planet formations and the different characteristics that planets may have. Due to the nature of the solar system it was largely accepted that planets came in two distinct classes, the terrestrial and Jovian planets. However study of exoplanets has revealed at least six other classes, many of which are still not very well understood. One of the most commonly studied type are the Hot Jupiters (planets with sizes comparable to Juipter but have formed extremely close to the parent star). By the data provided by the Kepler mission researchers are now leaning towards naming mini Neptunes as another dominate class of exoplanets [2].

However it is important to note the bias that the study of exoplanets intrinsically has due to availability of data. To observe exoplanets takes a large amount of effort and computation and in most cases advance telescope systems, this can largely be attributed to the fact that the planet will be significantly smaller and dimmer than its parent star, making direct observations close to impossible. In response to this problem over the years astronomers have developed indirect methods of inferring or observing exoplanets. In this letter we investigate the transit method. This essential is a method whereby the existence of an exoplanet around a star is inferred by the periodically dipping in the light curve of the star. The periodically dipping is interpreted as the light being blocked out from our line of sight as the exoplanet eclipses the star.

[1] https://exoplanets.nasa.gov/faq/6/how-many-exoplanets-are-there/

[2] https://www.universetoday.com/107816/the-most-common-exoplanets-might-be-mini-neptunes/


[a]

[a] https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

Figure 1. Astronomical Imaging of Kepler 8b extracted from MAST catalogue

2. DATA AND OBSERVATIONS

For the purposes of this letter we will be using data from the Kepler telescopes. The Kepler telescope is carrying out a mission by NASA to find Earth-size planets orbiting other stars that are considered to be similar to the sun Kipping & Bakos (2011). The data is made available on the MAST catalogues [3]. Our focus in this letter is KIC 6922244 otherwise known as Kepler 8b.

The Kepler telescope captures data using a 0.95m aperture Schmidt telescope. These photons are then passed to an CCD detector array of 94.6 million pixels. This array consists of both Science and Fine Guidance Sensor (FGS) CCDs.The FGS CCD comes in four modules that are mounted on the corners of the Science array, this was done in order to minimize thermo-mechanical drift between the altitude control system and the science CCDs in order to maintain the required 0.009 arcsec 3 single-axis pointing stability on 15 min time scales.

Every three months, Kepler rolls about its optical axis by 90 degrees to keep the Sun on the solar panels and the radiator, which cools the focal plane, pointed to deep space. The same area of the sky is observed for the entire mission, but a given star will wind up in four different parts of the focal plane, depending on the season. The data that was used in this letter is based on quarter 4 from the launch of the mission Van Cleve & Caldwell (2016).

2.1. *Properties of Kepler 8*

In order to conduct in an in depth analysis of an exoplanet some information on the parent star is necessary. We used the stellar parameters provided in Jenkins et al. (2010) in order to carry out our analysis. The stellar radius was determined to be $R_\star = 1.46^{+0.053}_{-0.062} R_\odot$ and the stellar mass was given as $M_\star = 1.213^{+0.067}_{-0.063} M_\odot$. It was also derived in this paper that the impact parameter is $b = 0.724 \pm 0.020$.

[3] https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

3. METHOD

As stated in the Introduction the focus of this letter is the transit method and the information on which we can extract from this method. The transit method is based on the eclipsing of a parent star's light along our line of sight as a planet moves along it's orbit as shown in the figure below.

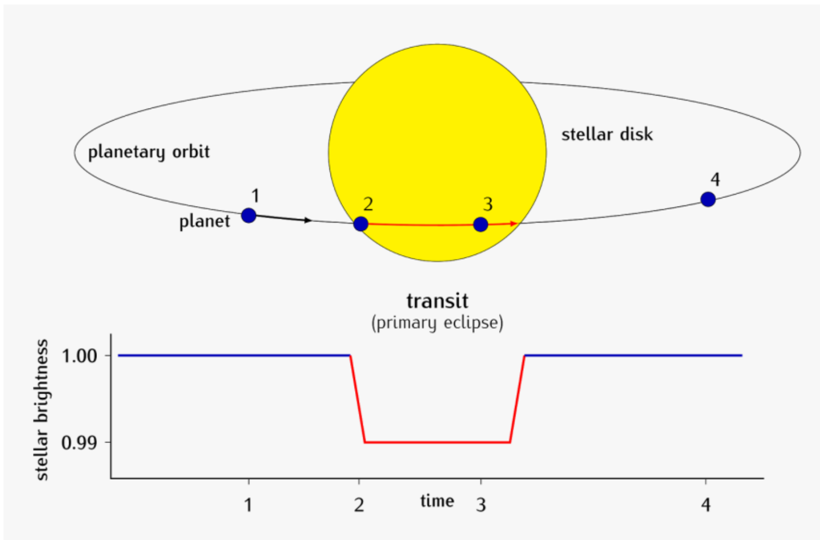


Figure 2. Exoplanet Transit Schema

We made use of the python library lightkurve [4] to process the 3 month data. The Kepler telescope design is such that there are no filters, dispersive elements or integration parameters for an user to tweak, once the photometer is calibrated and long-term operating parameters are set, they are fixed during the commission of the telescope.
From the MAST catalogues we pull the pixel file of Kepler 8b that is stored as 5X5 pixel arrangement,that is focused on the target as shown in the figure below. Using lightkurve, the pixel file is then converted to a light curve in order to observe the nature of the flux from Kepler8 as seen from the space based telescope.

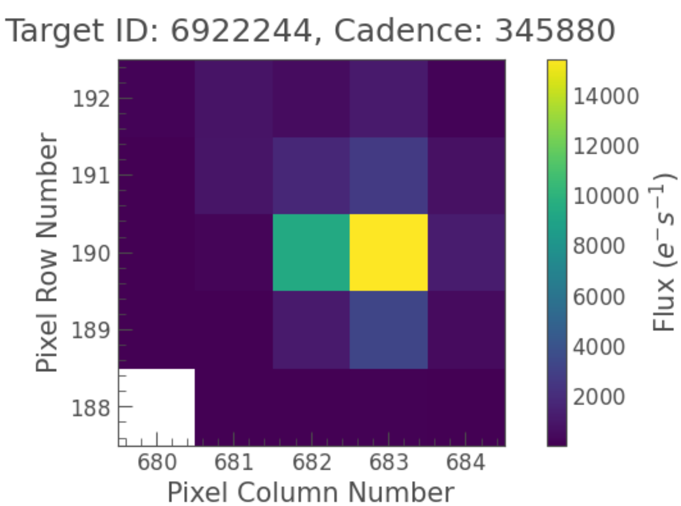


Figure 3. The pixel detection of Kepler 8b by the Kepler telescope

[4] https://docs.lightkurve.org/

4. ANALYSIS

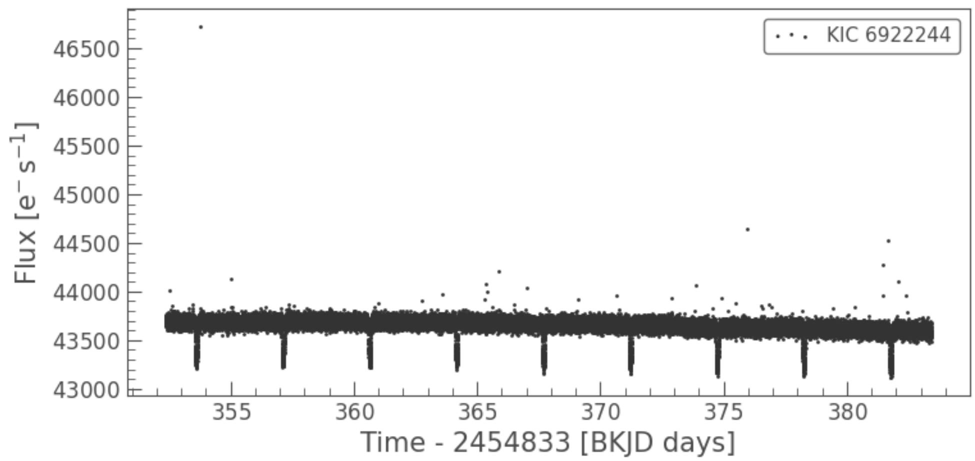


Figure 4. Kepler 8b Light Curve

Using the pixel array we can we produce a light curve of Kepler 8b, we observe that that there is indeed a periodic behaviour in the dips of light that we receive from the host star, this is the first indication of a planet orbiting the star. The next step was finding the period of the planet. In order to achieve this we employed the periodogram function of the lightkurve module. This function converts a light curve to a periodogram power spectrum object that shows the frequency of periods. Conveniently we can also extract the transit duration from with a built in function of periodogram.

From the periodogram plot in conjunction with the available functions we can extract the period of the planet's orbit, this is the period that has the highest Box Least Squares (BLS) Power. From this analysis we get that P = 3.52 days.

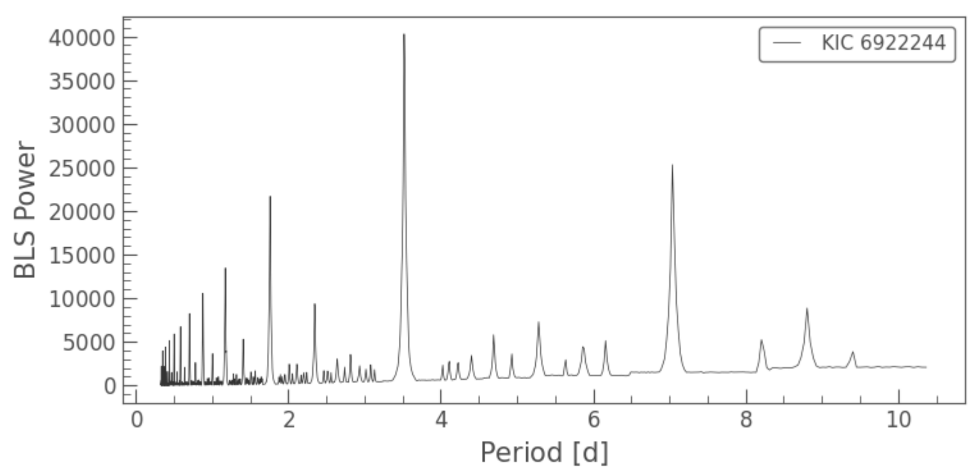


Figure 5. BLS Periodogram of Kepler 8b

Equipped with the period of the planet we can now begin to construct a visual representation of the curve that is easier to work, a folded light curve. This light curve is essentially taking the repetitive nature of the eclipsing of light as the planets moves around its host star and stacks them in order to produce a singular dip that is more representative of the light eclipsing.

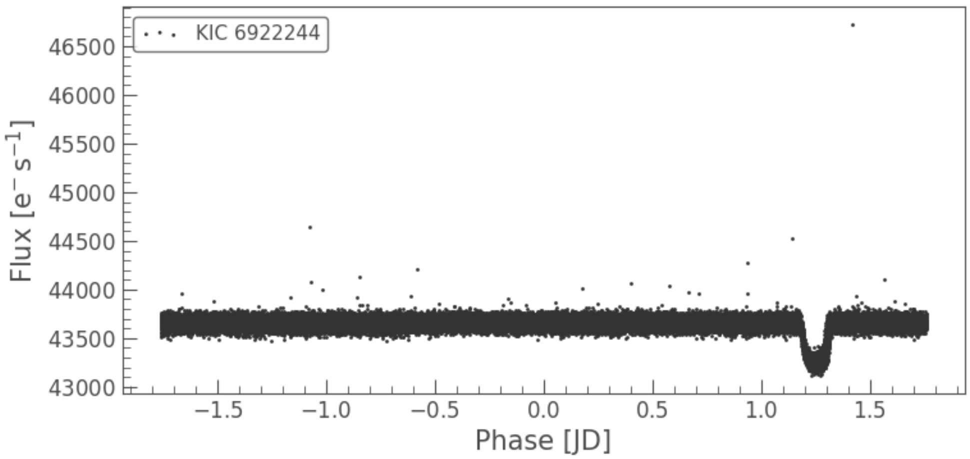


Figure 6. Folded Light curve of Kepler 8b

We further normalized the folded light curve and set the epoch time of the transit to be the first transit that is experienced in Figure 4. We then computed a transit model that estimates the behaviour of the light this curve and plotted them on the same axis.

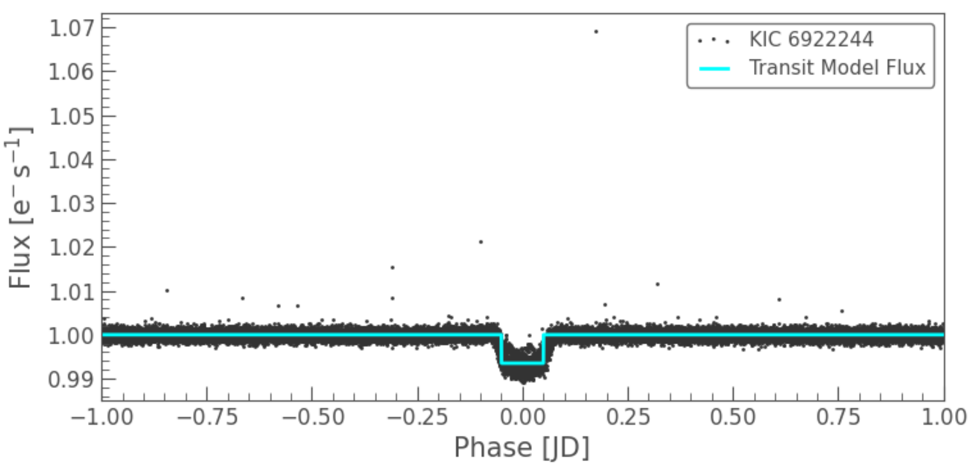


Figure 7. Normalized Folded Light curve of Kepler 8b with the Transit Model

5. RESULT

Equipped with the orbital period we then use Newton's version of Kepler's third law of planetary motion in order to find the semi-major axis or the planet's orbit. This law an be represented as

$$P^2 = \frac{a^3}{M_\star + M_p}$$

where P is the period expressed in Earth years, $M_\star + M_p$ expressed in solar masses where $M_\star$ is the stellar mass and M_p is the planetary mass and a is the semi-major axis expressed in units of AU. We make the assumption that $M_\star >>> M_p$ which simplifies Kepler's law to

$$P^2 = \frac{a^3}{M_\star}$$

This yields the result

$$a = 0.05497AU$$

The radius of the planet can be extracted from the equation

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_\star^2}$$

where

$$\Delta = F_{notransit} - F_{transitdepth}$$

which simplifies to

$$\sqrt{\frac{\Delta F}{F}} R_\star = R_p$$

If we consider the data, the following deductions can be made:

$$\sqrt{\frac{\Delta F}{F}} R_\star = 0.15415 R_\odot = R_p$$

which can be expressed in terms of Jupiter's radius, then $R_p = 1.53407 R_J$.

And looking at the transit model we find that

$$\sqrt{\frac{\Delta F}{F}} R_\star = 0.19130 R_\odot = R_p$$

which can be expressed in term of Jupiter's radius then $R_p = 1.19130 R_J$.

To consolidate the transit model and transit data we take the average of the two as the best estimate. Then $R_p = 1.36269 R_J$.

From the data acquired it was not possible to acquire the mass of Kepler 8b, However the classification of a planet involves knowing it density. To carry out this analysis we use the mass presented by Jenkins et al. (2010), this value is $M = 0.603^{+0.13}_{-0.19} M_J$.

The volume of Kepler 8b is therefore given by

$$V = \frac{4}{3}\pi R^3 = 3.62341\ cm^{-3}$$

We can then find the density of the exoplanet using the usual density expression

$$\rho = \frac{M}{V} = 0.31653\, g\, cm^{-3}$$

From the periodogram produced earlier from the python lightkurve module, we can also extract the duration of the duration of the transit which comes out to be $\tau = 0.1$ days $= 2.4$ hrs. This is consistent with the folded light curve produced in Figure 6.
We are now in position to find the inclination of the planets orbits around it host, assuming a circular orbit the impact parameters is given by

$$b = \frac{acosi}{R_\star}$$

which can be expressed as

$$cos^{-1}(\frac{bR_\star}{a}) = i$$

which yields $i = 88.366^o$

6. ERRORS AND UNCERTAINTIES

The data as received from the MAST catalogue has already been processed and errors have already been accounted for, in this section will highlight some of these corrections.

In the main, errors and uncertainties come about from the instrumental noise and defects since Kepler is a space based telescope. The Kepler Instrument Manual also accounts for Ground Based Test. we have extracted the following text from the manual 'Ground-based tests supply calibration and performance data which are not available on-orbit, either because of the lack of a shutter, the presence of cosmic rays, the lack of a uniform illumination calibration source, or the cost in science data not taken. Table 2 shows the most important of these tests. Each test has an alphanumeric BATC test ID used to unambiguously identify the test, since test descriptions and labels can vary over time as the test concept is developed'Van Cleve & Caldwell (2016)

We then consider the primary mirror, a Schmidt Corrector is placed on the primary mirror, this corrector is coated with an anti-reflection coating to deal with chromatic aberrations.
The Schmidt Corrector is useful with dealing the spherical aberration,the corrector breaks the symmetry of the telescope.

No confidence interval could be determined for the period as it was computed from a lightkurve function that doesn't offer an error handling method. This in turn means we cannot find a confidence interval for the semi-major axis, since it is derived from the period. We also note that limb darkening affects were not taken to account when analyzing the transit of Kepler 8b.

To find the confidence interval for the radius we employ a statistical approach and use the standard deviation divided by the square-root of the number of results, N = 2,(obtained from the model and the actual data)

$$\sigma_R = \frac{\sigma}{\sqrt{N}} = 0.12$$

The remaining uncertainties are treated as Type B evaluations. We use the following equations to account for the propagation of uncertainties through calculations:

Form of equation from which result R is calculated	Formula for calculating the standard uncertainty $u(R)$
$R = aA \pm bB + c$	$\{u(R)\}^2 = \{a\,u(A)\}^2 + \{b\,u(B)\}^2$ or $u(R) = \sqrt{\{a\,u(A)\}^2 + \{b\,u(B)\}^2}$
$R = cA^a B^b$	$\left\{\frac{u(R)}{R}\right\}^2 = \left\{a\frac{u(A)}{A}\right\}^2 + \left\{b\frac{u(B)}{B}\right\}^2$ or $u(R) = R\sqrt{\left\{a\frac{u(A)}{A}\right\}^2 + \left\{b\frac{u(B)}{B}\right\}^2}$

[a]

[a] http://www.phy.uct.ac.za/sites/default/files/imagetool/images/281/courses/phylab1/MeasurementmanualUCTPhysics.pdf

Figure 8. Equations for the propagation of uncertainties through calculations

Then from the equation of density, the uncertainty can be expressed as

$$u(\rho) = \rho\sqrt{(-3\frac{u(R)}{R})^2} = 0.00083$$

7. CONCLUSION

Figures 5 and 6 exhibit the transits of Kepler 8b across the Kepler 8 with Figure 6 showing the transit period to be 0.1 days. From the periodogram we deducted the planets period to be 3.52 days. A semi-major axis of a = 0.04532 AU was calculated using Kepler's third Law of motion. From the ratio of the transit depth and the transit flux we deduced Kepler 8b to have a radius of R = $(1.19 \pm 0.12)\,R_J$. This leads to the density of $\rho = (0.31653 \pm 0.00083)\,g\,cm^{-3}$, finally with the assumption of a circular orbit we found the inclination of planet to stellar disk during transit to be 88.366^o. We can then conclude that Kepler 8b is a Hot Jupiter orbiting Kepler because of its low density and small semi-major axis.

REFERENCES

Jenkins, J. M., Borucki, W. J., Koch, D. G., et al. 2010,

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doi: 10.1088/0004-637x/724/2/1108

Kipping, D., & Bakos, G. 2011, The Astrophysical Journal, 730, 50, doi: 10.1088/0004-637x/730/1/50

Mayor, M., & Queloz, D. 1995, Nature, 378, 355

Van Cleve, J. E., & Caldwell, D. A. 2016, Kepler Instrument Handbook, Kepler Science Document KSCI-19033-002

In [37]:

```
import lightkurve as lk
import matplotlib.pyplot as plt
from matplotlib.widgets import Cursor
import numpy as np
%matplotlib inline
```

In [38]:

```
from lightkurve import search_targetpixelfile
```

In [39]:

```
pixelFile=search_targetpixelfile('KIC 6922244', quarter=4).download()
```

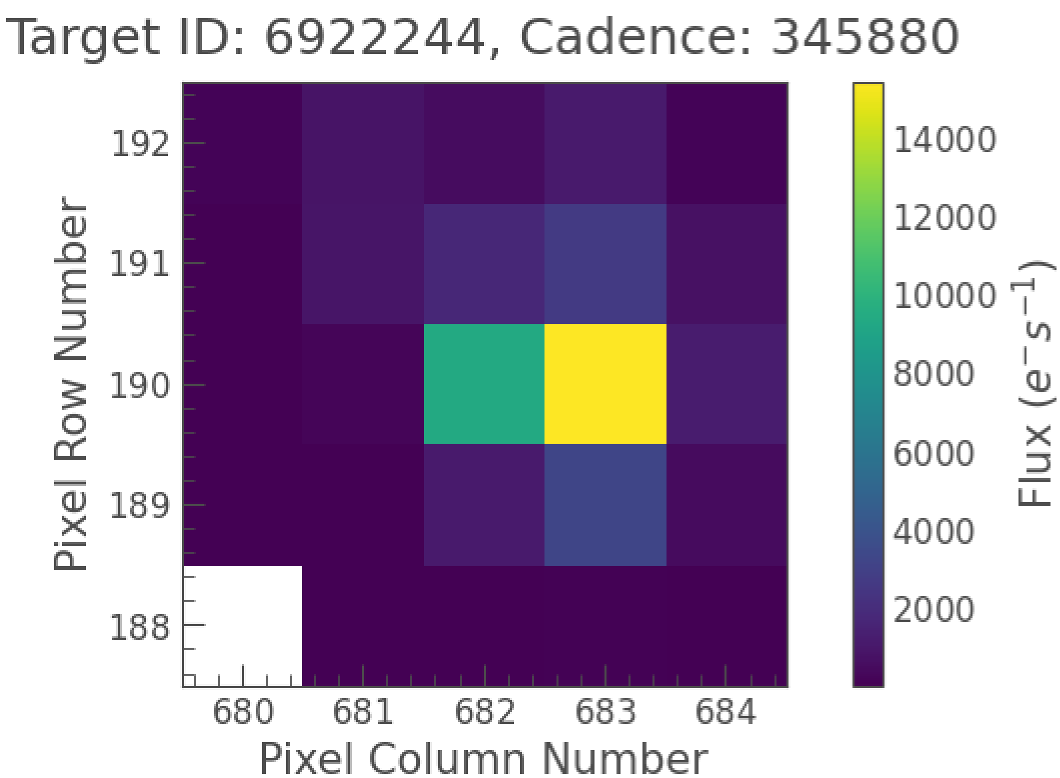
```
/home/catalyst/.local/lib/python3.8/site-packages/lightkurve/search.py:346: LightkurveWa
rning: Warning: 4 files available to download. Only the first file has been downloaded.
Please use `download_all()` or specify additional criteria (e.g. quarter, campaign, or s
ector) to limit your search.
  warnings.warn(
```

In [40]:

```
pixelFile.plot()
```

Out[40]:

```
<AxesSubplot:title={'center':'Target ID: 6922244, Cadence: 345880'}, xlabel='Pixel Colum
n Number', ylabel='Pixel Row Number'>
```



In [41]:

```
lc =pixelFile.to_lightcurve(aperture_mask=pixelFile.pipeline_mask)
```

In [42]:

```
lc = lc.remove_nans()
```

In [43]:

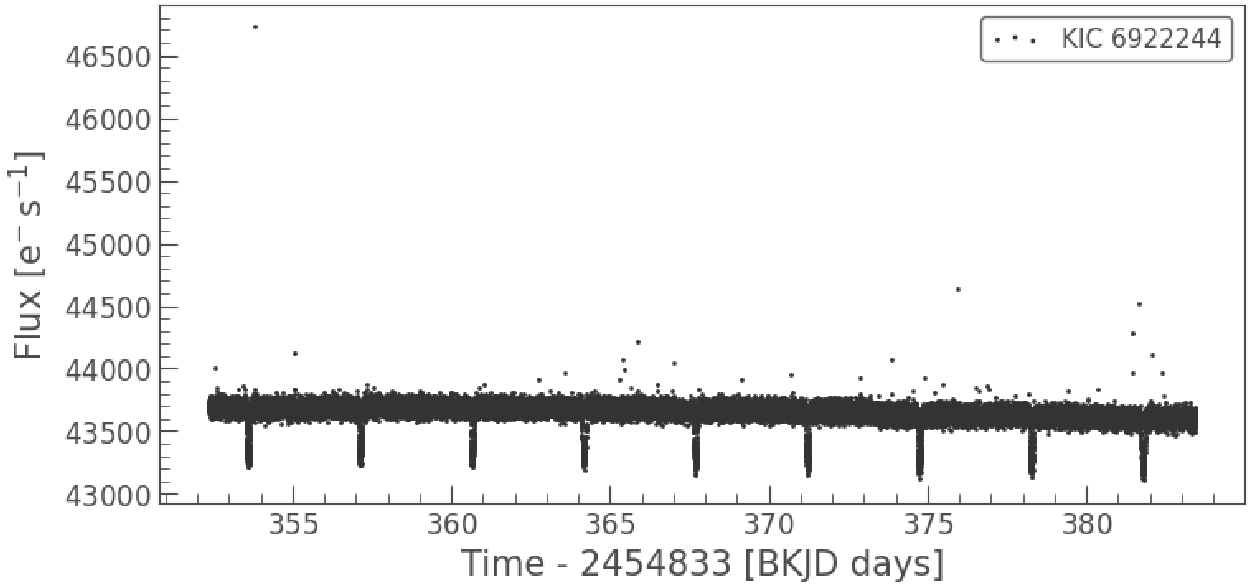
```
flux_depth = lc.flux.mean() - min(lc.flux)
```

```
flux_depth
```

Out[43]: $538.72266\ \frac{\mathrm{e^{-}}}{\mathrm{s}}$

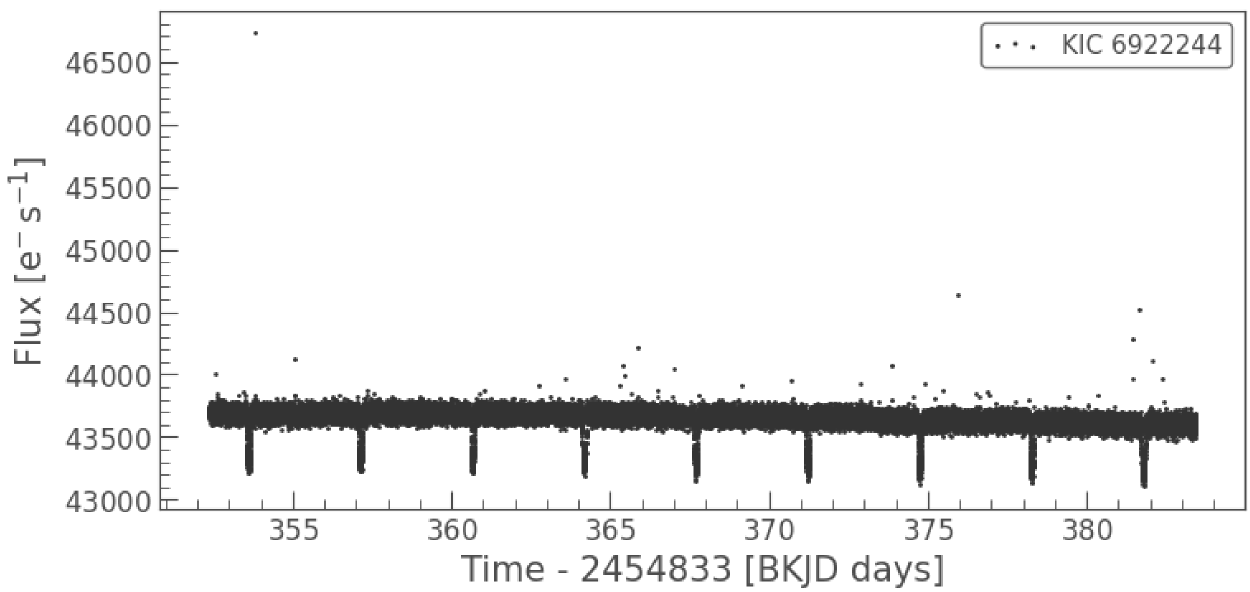
In [44]:

```
ax = lc.scatter()
cursor = Cursor(ax, useblit=True, color='red', linewidth=2)
```



In [45]:

```
ax = lc.scatter()
ax.figure.savefig('lightcurve')
```



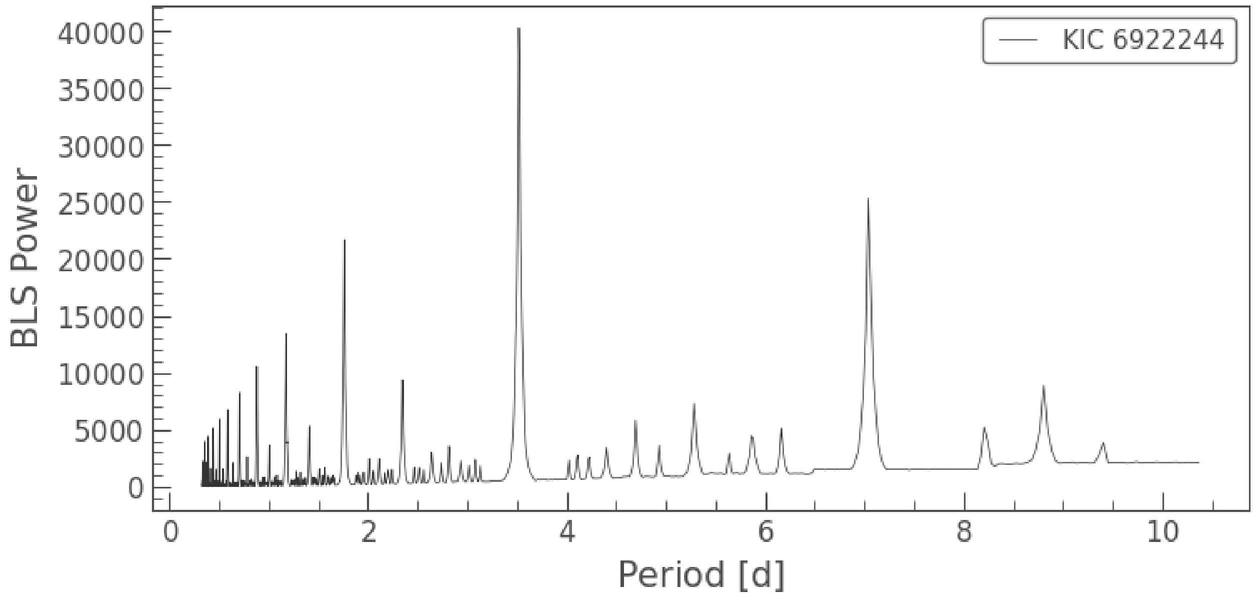
In [46]:

```
flat_lc = lc.flatten(window_length = 401)
min(flat_lc.flux)
```

Out[46]: $0.98904704\ \frac{\mathrm{e^{-}}}{\mathrm{s}}$

In [47]:

```
periodogram = flat_lc.to_periodogram(method='bls')
ax = periodogram.plot()
ax.figure.savefig('periodogram')
```



In [83]:

```
(periodogram.period).var()
```

Out[83]: 2.0508868 d^2

In [75]:

```
kepler8b_period =periodogram.period_at_max_power
kepler8b_t0 = periodogram.transit_time_at_max_power
kepler8b_dur = periodogram.duration_at_max_power


kepler8b_period
#kepler8b_t0
#print(f'The period of KIC 6922244 is {kepler8b_period:.3f}')
#print(f'The transit time of KIC 6922244 is {kepler8b_t0.value:.3f}')
# print(f'The transit duration of KIC 6922244 is {kepler8b_t0:.3f}')
#kepler8b_dur
```

Out[75]: 3.5200513 d

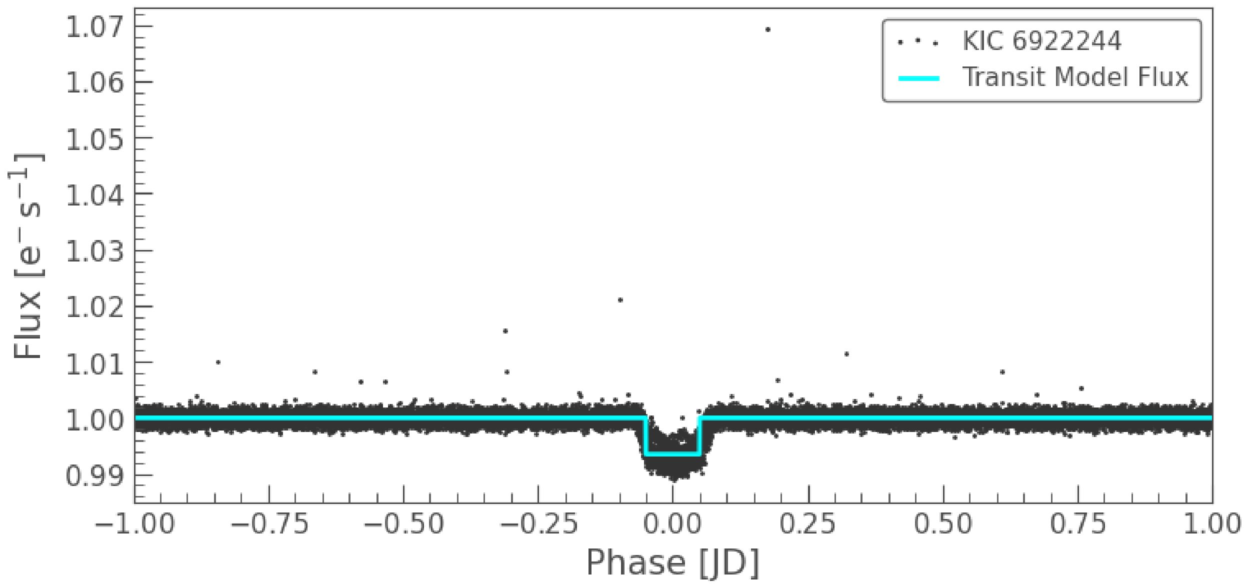
In [33]:

```
kepler8b_transit_model = periodogram.get_transit_model(period=kepler8b_period,
                                                       transit_time=kepler8b_t0,
                                                       duration=kepler8b_dur)
```

Transit flux model

In [69]:

```
ax = flat_lc.fold(kepler8b_period, kepler8b_t0).scatter()
kepler8b_transit_model.fold(kepler8b_period, kepler8b_t0).plot(ax=ax, c='cyan', lw=2)
ax.set_xlim(-1, 1);
ax.figure.savefig('transit_model')
```



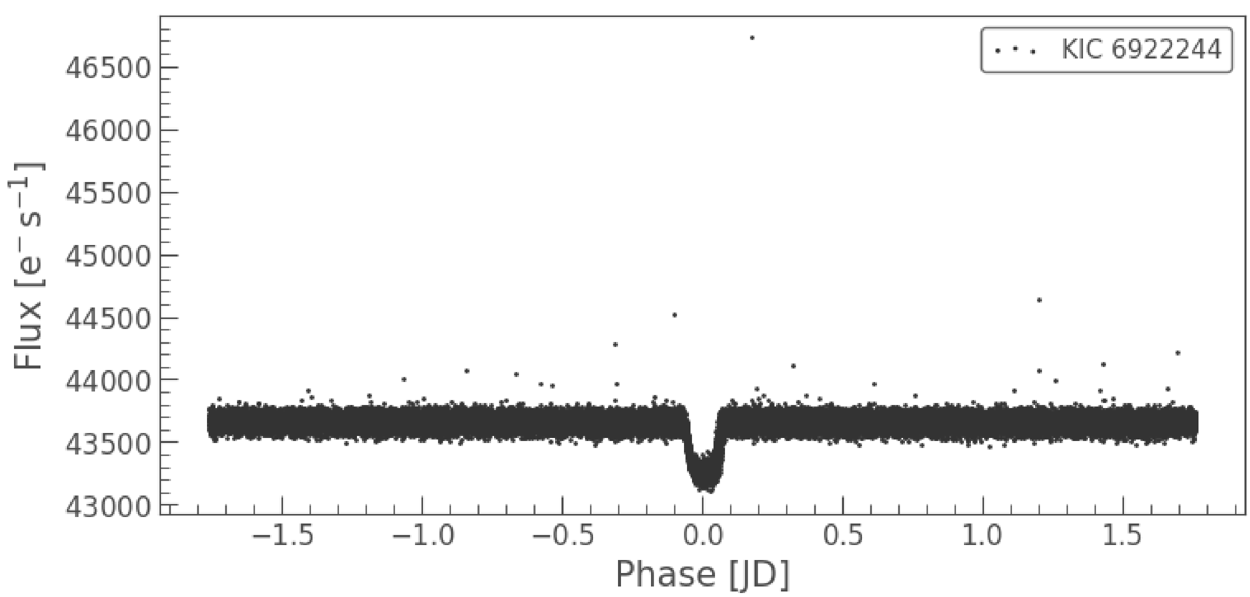
In [62]:

```
print(f'The transit model min flux is {min(kepler8b_transit_model.flux)} and the max is

print('*********************************************************************')

print(f'The transit model min flux is {min(flat_lc.flux)} and the max is {(flat_lc.flux
```

```
the transit model min flux is 0.9935045602999173 electron / s and the max is 0.999989993
6703666 electron / s  making the depth 0.006485433370449267 electron / s
**********************************************************************
the transit model min flux is 0.9890470429300836 electron / s and the max is 0.999802465
9308924 electron / s  making the depth 0.010755423000808784 electron / s
```

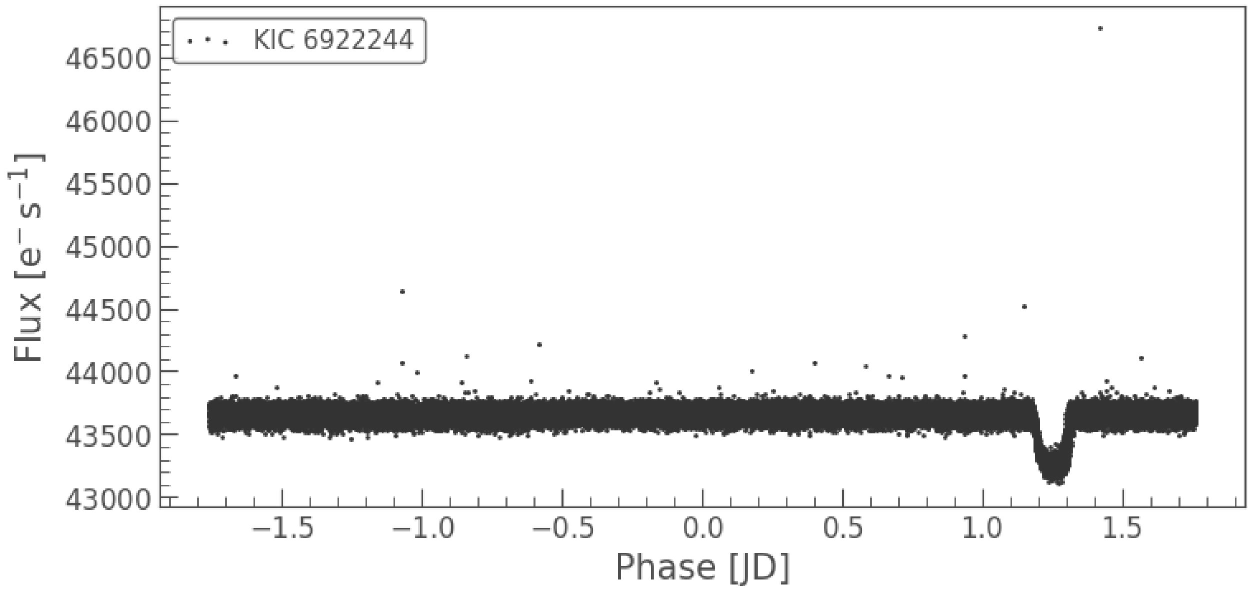
In [72]:

```
fold_lc = lc.fold(period=kepler8b_period, epoch_time=kepler8b_t0)
ax = fold_lc.scatter()
ax.figure.savefig('folded_not_norm')
```



In [74]:

```
fold_lc = lc.fold(period=kepler8b_period)
ax = fold_lc.scatter()
ax.figure.savefig('lc_fold')
```



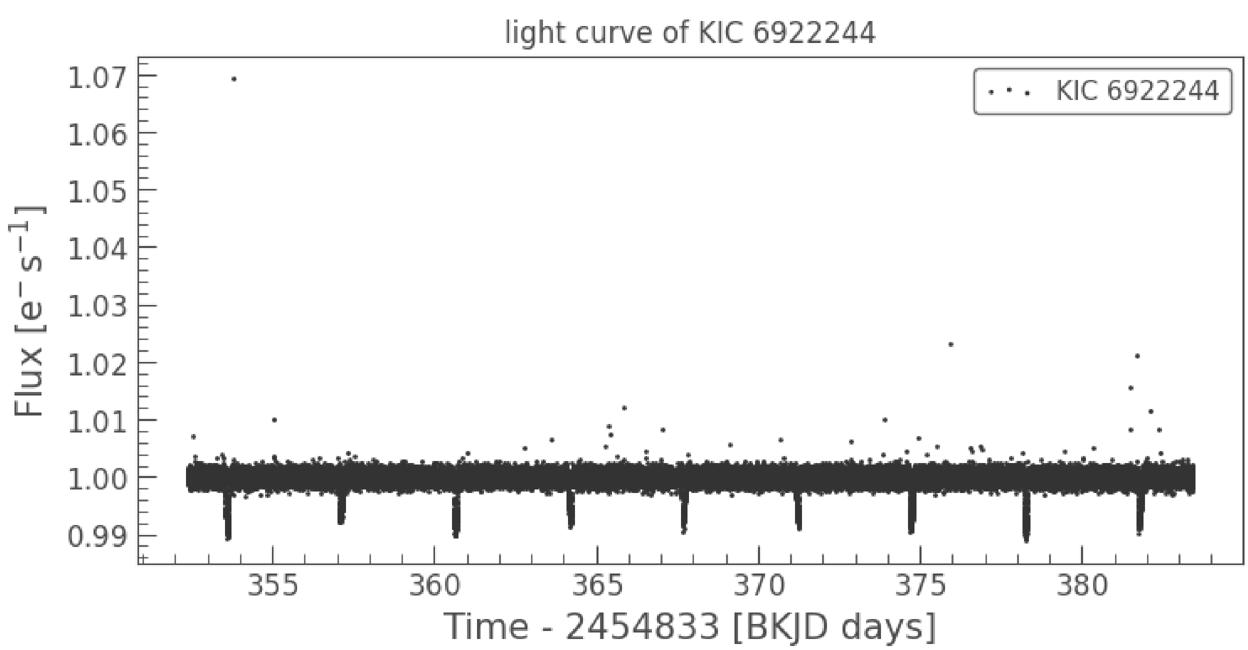
In [68]:
```
print(f'The transit model min flux is {min(fold_lc.flux)} and the max is {(fold_lc.flux
```

```
The transit model min flux is 43112.65234375 electron / s and the max is 43651.375 elect
ron / s  making the depth 538.72265625 electron / s
```

In [17]:
```
planet_b_model = periodogram.get_transit_model(period=kepler8b_period,
                                               transit_time=kepler8b_t0,
                                               duration=kepler8b_dur)
```

In [18]:
```
ax = flat_lc.scatter()
ax.set_title("light curve of KIC 6922244")
```

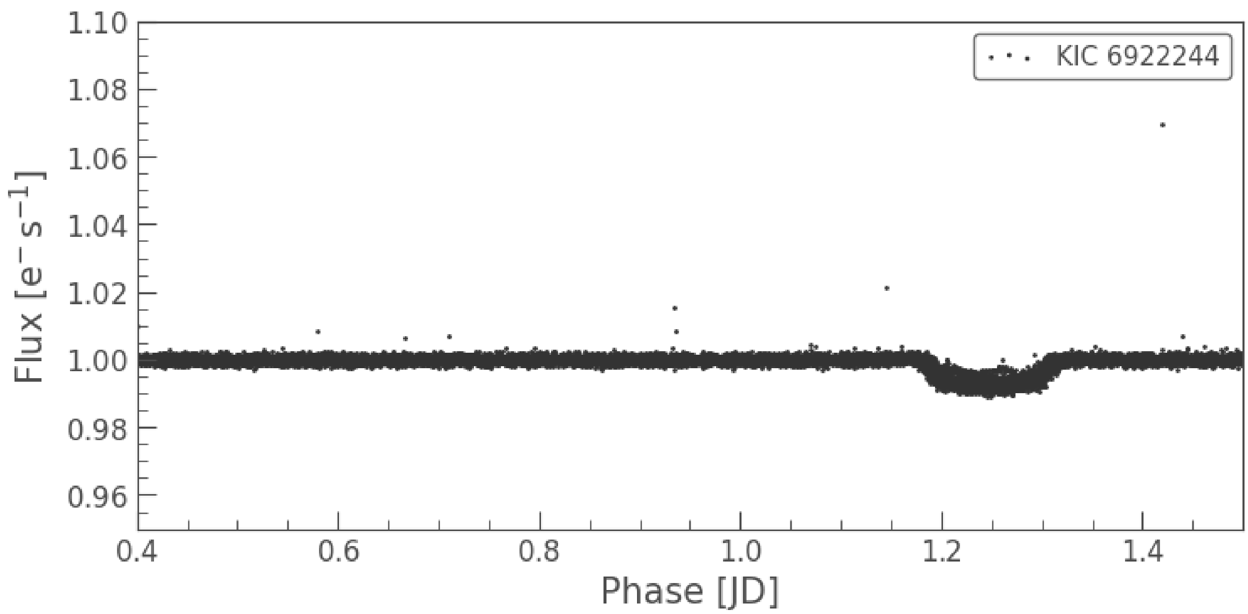
Out[18]:
```
Text(0.5, 1.0, 'light curve of KIC 6922244')
```



In [19]:
```
ax.figure.savefig('demo-lightcurve.png')
```

```
In [39]: folded_lc = flat_lc.fold(period=kepler8b_period)
         ax = folded_lc.scatter()

         ax.axis(ymin=0.95,ymax=1.1)
         ax.axis(xmin=0.4,xmax=1.5)
```

Out[39]: (0.4, 1.5, 0.95, 1.1)




```
In [21]: min(folded_lc .flux)
```

Out[21]: $0.98904704\ \frac{e^{-}}{s}$