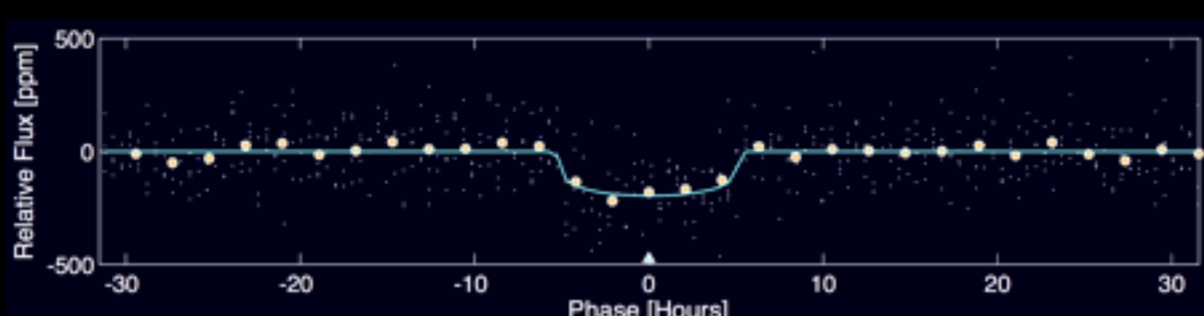
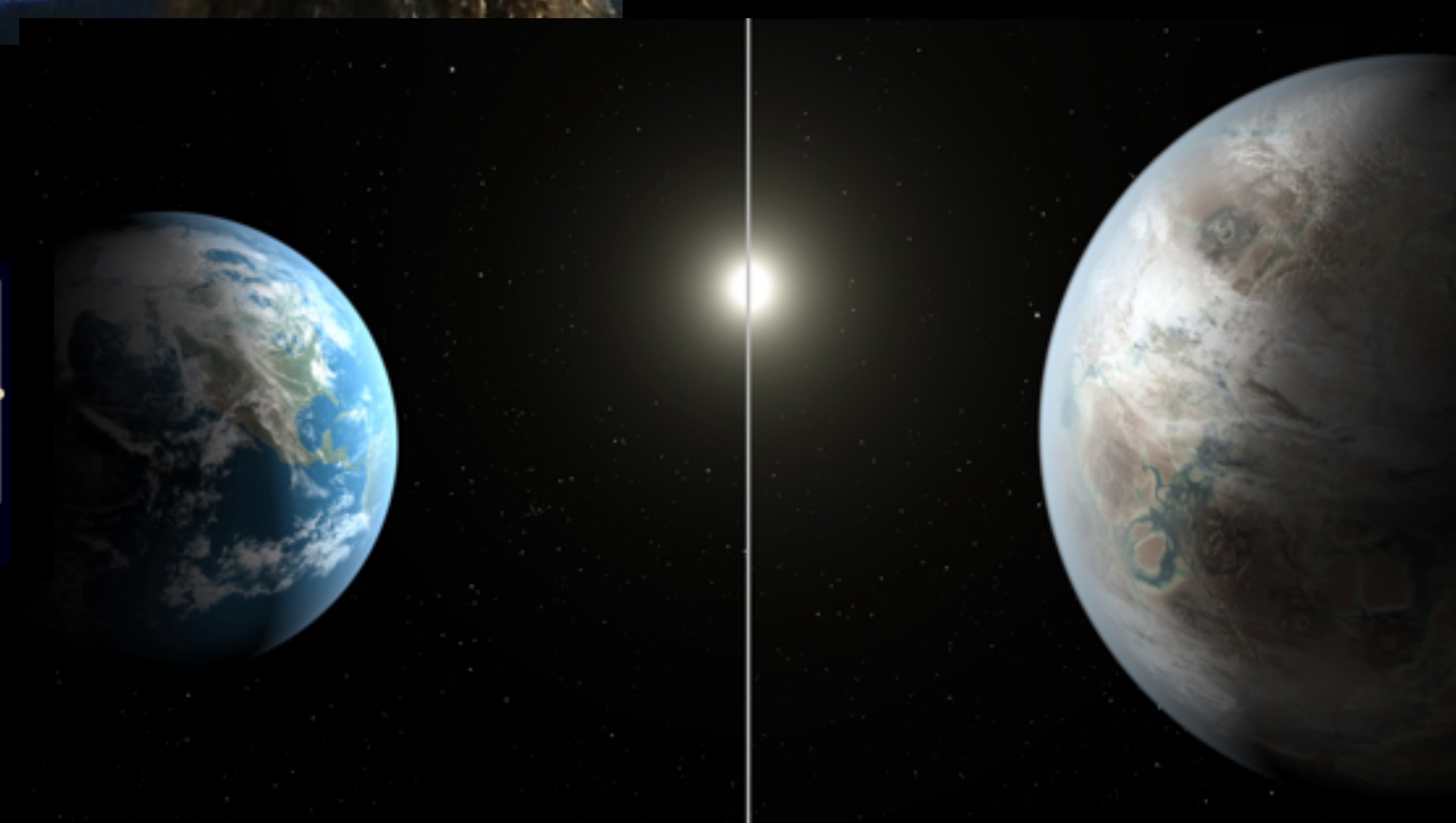
Earth 2.0?



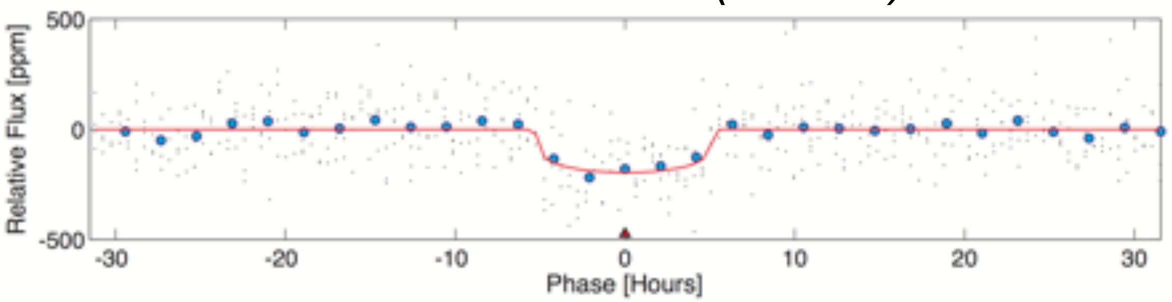


Quick bit of background...

In 2015, Kepler announced the discovery an Earth-like transiting planet

Discovery and Validation of Kepler-452b: A 1.6-$R_\oplus$ Super Earth Exoplanet in the Habitable Zone of a G2 Star

Jenkins et al. (2015)



The New York Times

NASA Says Data Reveals an Earth-Like Planet, Kepler 452b

By DENNIS OVERBYE JULY 23, 2015

people got excited...

SPACE.com

NEWS TECH SPACEFLIGHT SCIENCE & ASTRONOMY

Space.com › Science & Astronomy

Kepler-452b: What It Would Be Like to Live On Earth's 'Cousin'

By Mike Wall, Space.com Senior Writer | July 24, 2015 06:00am ET

2848 219 170 301 86 MORE

Artist's concept of the surface of the newfound exoplanet Kepler-452b, which is about 60 percent wider and five times more massive than Earth. This illustration imagines that a runaway greenhouse effect has begun to take hold on Kepler-452b, driving off much of the planet's surface water.

Credit: SETI Institute/Danielle Futselaar

Kepler-452b may be Earth's close cousin, but living on the newfound world would still be an alien experience.

A group of pioneers magically transported to the surface of Kepler-452b — which is the closest thing to an "Earth twin" yet discovered, researchers announced yesterday (July 23) — would instantly realize they weren't on their home planet anymore. (And magic, or some sort of warp drive, must be invoked for such a journey, since Kepler-452b lies 1,400 light-years away.)

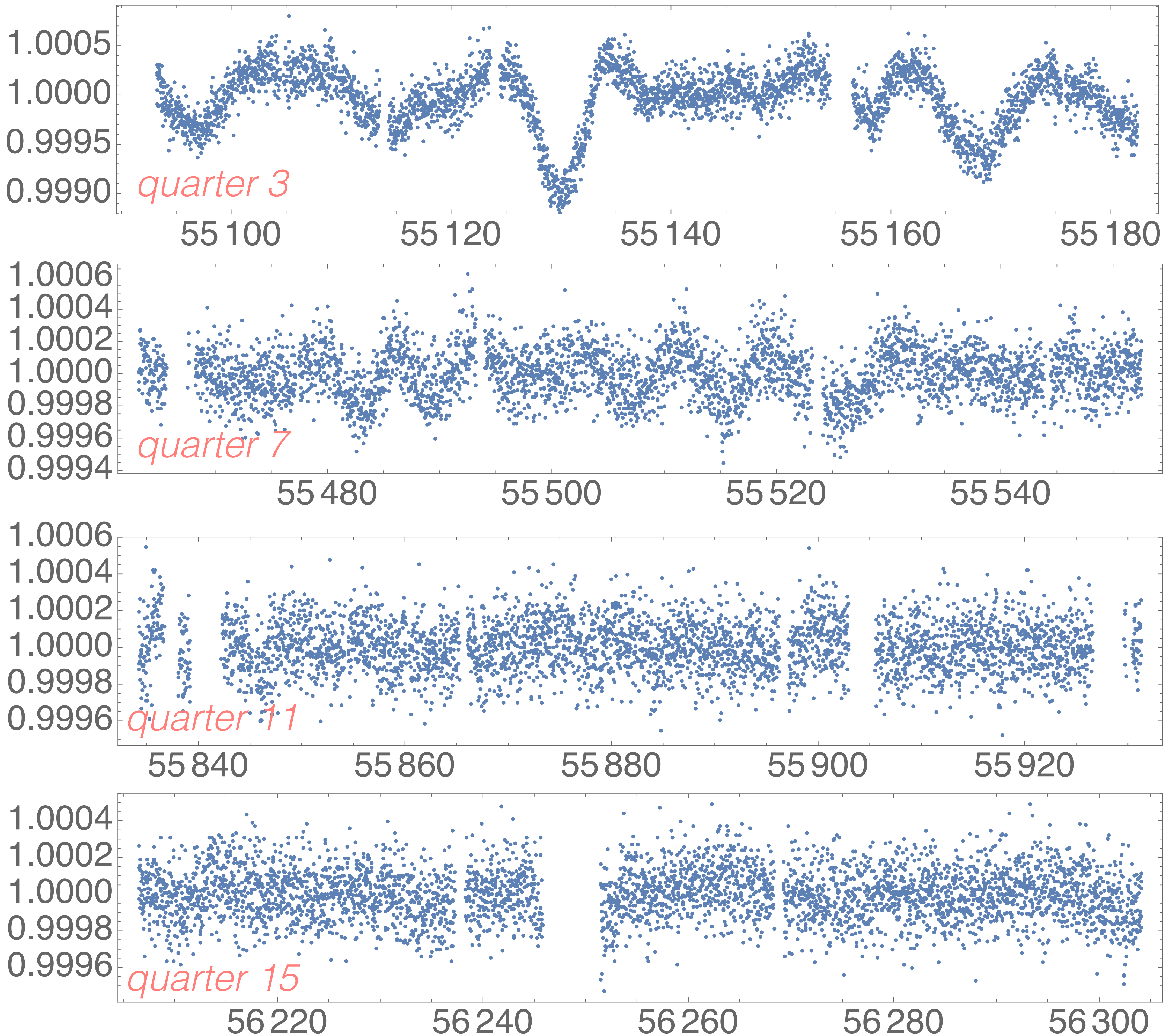
Let’s test that for ourselves!

science question: What is the probability this is a rocky and HZ planet?

Let’s test that for ourselves!

1] import the raw data...

(I have removed bad data flags, normalized by quarter median, parsed the data for you and trimmed irrelevant quarters)



quarter 3
1.0005
1.0000
0.9995
0.9990
55 100
55 120
55 140
55 160
55 180
quarter 7
1.0006
1.0004
1.0002
1.0000
0.9998
0.9996
0.9994
55 480
55 500
55 520
55 540
quarter 11
1.0006
1.0004
1.0002
1.0000
0.9998
0.9996
55 840
55 860
55 880
55 900
55 920
quarter 15
1.0004
1.0002
1.0000
0.9998
0.9996
56 220
56 240
56 260
56 280
56 300

2] remove outliers and apply detrending (as necessary)

```
In [1]: import numpy as np
        import matplotlib.pyplot as plt
        import batman
```

```
In [2]: # Define some things we know
        P_literature = 384.843
        tau_literature = 54833 + 314.98
        T_literature = 10.63/24.0       # literature reported transit duration
```

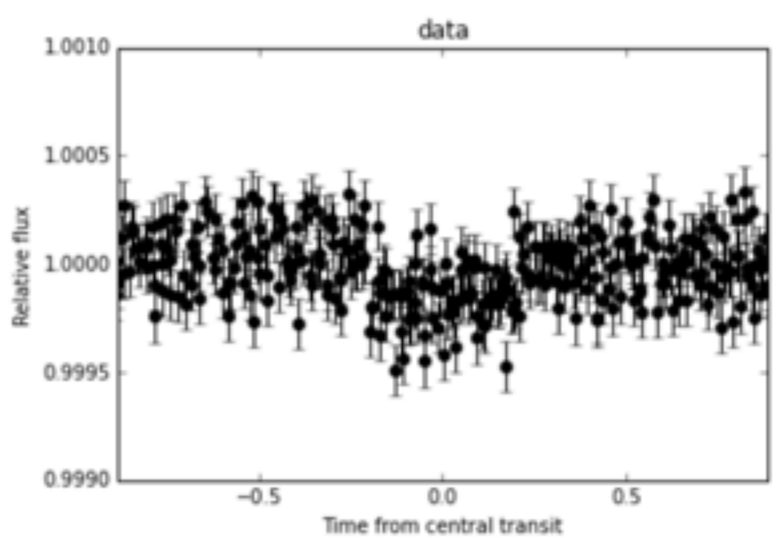
```
In [3]: # Define a set of test parameters
        theta=np.empty([5])
        theta[0] = 0.0128           # Rp/Rstar
        theta[1] = 3.306            # log(rho* [kg/m3])
        theta[2] = 0.69             # b impact parameter
        theta[3] = P_literature     # orbital period
        theta[4] = tau_literature   # transit mid-point
```

```
In [20]: # Define a set of test times
         #t = np.linspace(theta[0]-2.0*T_literature, theta[0]+2.0*T_literature, 1000)

         data = np.genfromtxt("lightcurve.dat", dtype=None)
         tobs=data[:,0]     # times of observations
         fobs=data[:,1]     # relative fluxes
         sigfobs=data[:,2] # errors on fluxes
         tobsfolded=np.empty([len(tobs)])
         for i in range(len(tobs)):
             tobsfolded[i]=tobs[i]-tau_literature-P_literature*np.round((tobs[i]-tau_literature)/P_literature)

         %matplotlib inline

         plt.figure()
         plt.errorbar(tobsfolded, fobs, yerr=sigfobs,fmt='ko')
         plt.title("data")
         plt.xlabel('Time from central transit')
         plt.ylabel('Relative flux')
         plt.xlim(-2*T_literature,+2*T_literature)
         plt.ylim(0.999,1.001)
         plt.show()
```



3] I'll give you a starter notebook to plot the data...

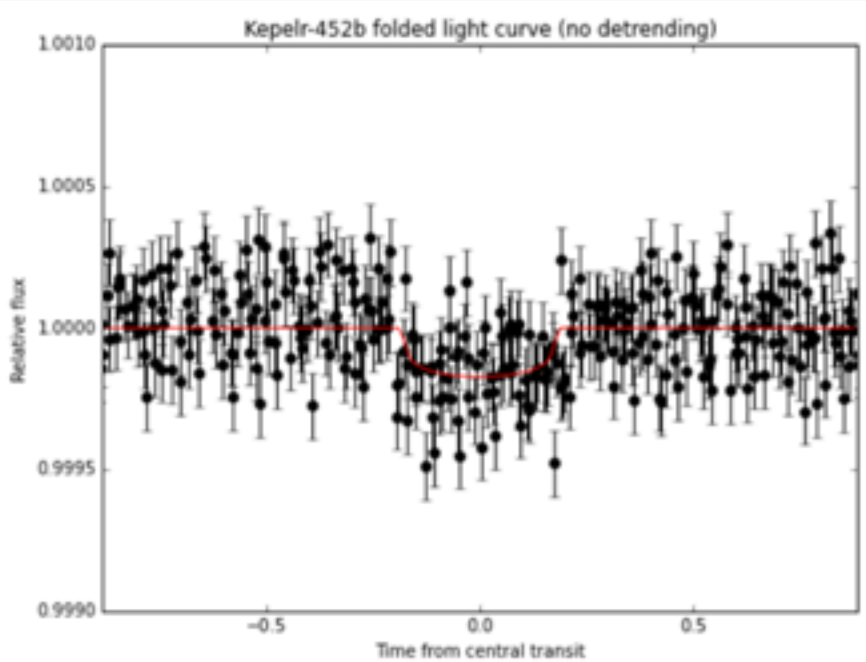
(no data cleaning shown here, that's raw data!)

In [5]:
```python
# Set a definition for the model
def model(theta,times):
    Grv = 6.67408e-11
    impact = theta[2]
    logrho = theta[1]
    rhostar = np.power(10.0,logrho)
    aR = np.power( ( Grv*(theta[3]*86400.0)**2*rhostar )/( 3.0*np.pi ), 0.33333333 )
    incdeg = (180.0/np.pi)*np.arccos(impact/aR)
    # Initialize the Batman code
    params = batman.TransitParams()
    # Set the model parameters
    params.rp = theta[0]                  #R_planet/R_star
    params.a = aR                         #a/R_star
    params.inc = incdeg                   #orbital inclination (degrees)
    params.per = theta[3]                 #orbital period (days)
    params.t0 = theta[4]                  #transit midpoint time (days)
    # These parameters are just kept fixed
    params.ecc = 0.0                      #eccentricity
    params.w = 90.                        #longitude of periastron (degrees)
    params.limb_dark = "nonlinear"        #limb darkening model--other choices include quadratic, etc.
    # Coefficients for a nonlinear limb darkening law.
    params.u = [0.1570656, 0.9361135, -0.4313317, 0.0572520]
    # Call the Batman code
    m = batman.TransitModel(params, times, supersample_factor=30, exp_time=0.020434)
    flux = m.light_curve(params) #calculate the flux
    return flux
```

In [19]:
```python
%matplotlib inline

theta[4]=0.0 # since I have folded the lightcurve, purely for the sake of visualization,
             # i am going to set tau=0 to give a nice plot
# since i'm going to do a continuous line for my model, i need to sort the times first
fmod = model(theta,np.sort(tobsfolded))

fig = plt.figure(figsize=(8,6))
plt.errorbar(tobsfolded, fobs, yerr=sigfobs,fmt='ko')
plt.plot(np.sort(tobsfolded), fmod, c='r')
plt.title('Kepelr-452b folded light curve (no detrending)')
plt.xlabel('Time from central transit')
plt.ylabel('Relative flux')
plt.xlim(-2*T_literature,+2*T_literature)
plt.ylim(0.999,1.001)
plt.show()
```



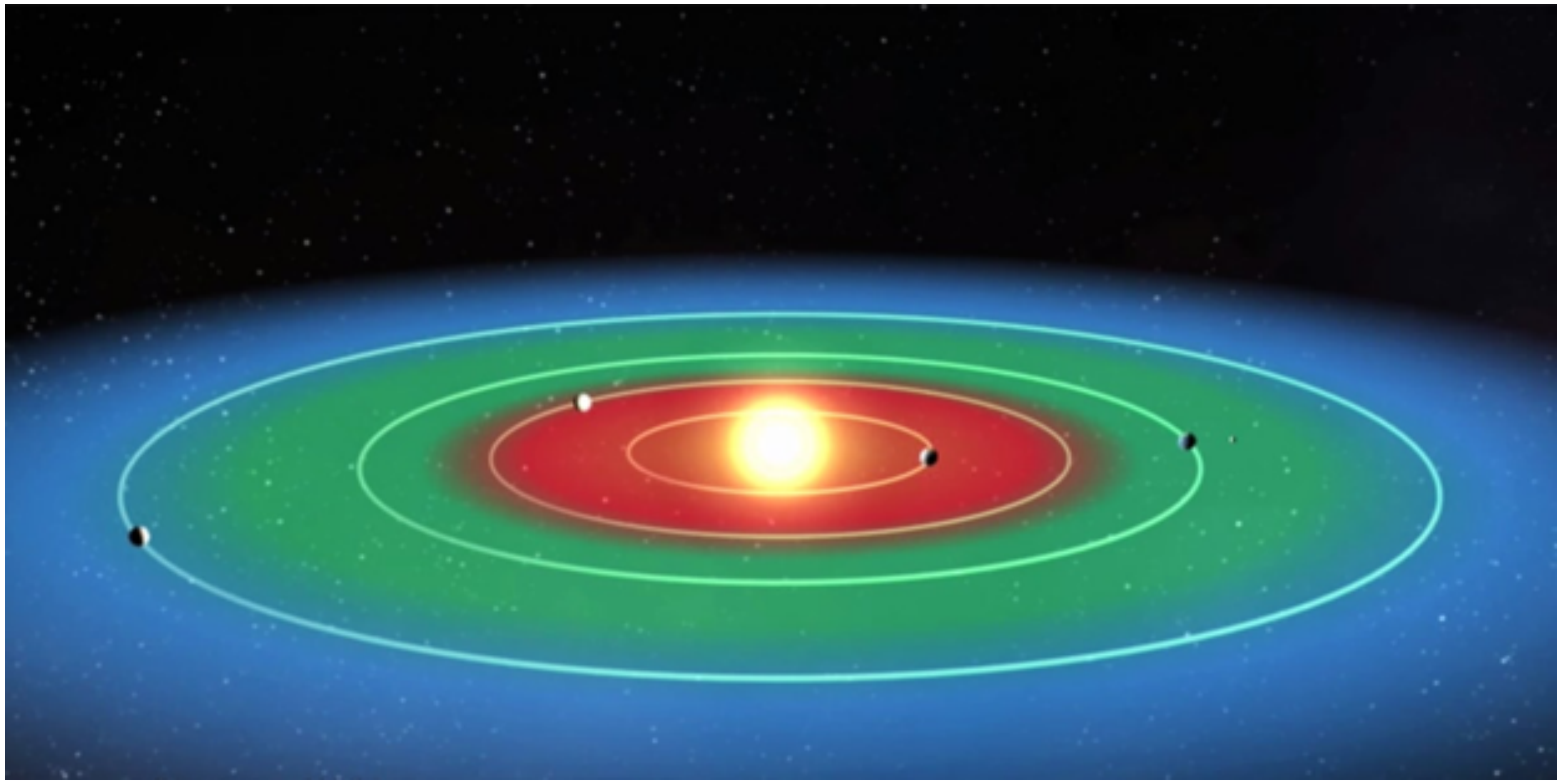
3] ...and how to generate a transit model for some choice of Rp/R*, b (and logrho*)

4] Fit the parameters Rp/R, b (and rho*) with an MCMC*

5] I'll give you a set of posterior sample for Teff, R* and logrho*

...use it to calculate the temperature of the planet (see Wikipedia page on Stefan-Boltzmann law for eqn) and the radius of the planet

6] what fraction of your samples (i.e. what is the probability) fall within the HZ ($207.5K<Tp<320.4K$) and fall below rocky-gas divide (1.23 Earth radii)?



Suggested path forward...

1] Import the data! Get familiar with it, plot it, make sense of it

2] Remove outliers and apply detrending

3] Use starter notebook to plot a guess model through the cleaned data

4] Run an MCMC fitting for b and Rp/R* (+ logrho* for extra credit)

5] Use posterior samples of star's Teff and R* to calculate joint posterior for Rp and Tp => what fraction of trials are HZ and rocky?

6] Can you go further and take your logrho* posterior and compare to independent measurement to emin via...

$$e_{min} = \frac{|1-(\rho_{obs}/\rho_{tru})^{2/3}|}{1+(\rho_{obs}/\rho_{tru})^{2/3}}$$

7] Can you go further and use github/forecaster to predict probability planet is rocky using mass-radius models?

8] Prepare your summary slides and talk!

Suggested path forward...

1] Import the data! Get familiar with it, plot it, make sense of it

2] Remove outliers and apply detrending

3] Use starter notebook to plot a guess model through the cleaned data

4] Run an MCMC fitting for b and Rp/R* (+ logrho* for extra credit)

make sure you quote your final Rp and Tp!

5] Use posterior samples of star's Teff and R* to calculate joint posterior for Rp and Tp => what fraction of trials are HZ and rocky?

covariance -> go through samples

6] Can you go further and take your logrho* posterior and compare to independent measurement to e_{min} via...

$$e_{min} = \frac{|1-(\rho_{obs}/\rho_{tru})^{2/3}|}{1+(\rho_{obs}/\rho_{tru})^{2/3}}$$

7] Can you go further and use github/forecaster to predict probability planet is rocky using mass-radius models?

8] Prepare your summary slides and talk!