International Baccalaureate Extended Essay

Physics

Standard level

Estimating parameters of Kepler-10 using asteroseismology

Research question: How can asteroseismology be used to determine the stellar parameters: Radius, mass and gravitational field strength of the star Kepler-10?

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1. Introduction

This investigation concerns the star Kepler-10 and estimating some of its stellar quantities. Kepler-10 is the host star of three confirmed exoplanets: Kepler 10b, 10c and 10d. Kepler-10 is interesting since it hosts a rocky exoplanet 10b which was one of the first rocky exoplanets discovered by the Kepler telescope. This solar system has great diversity and the study of the host star Kepler-10 can be important to understand other factors within the solar system (Solbu, 2014).

The field of asteroseismology gives tools to study oscillating stars like Kepler-10. The word asteroseismology is derived from astero and seismology. Astero is the word for star in Greek and Seismology is the study of the earth's interior by analyzing mechanical waves from earthquakes. Asteroseismology, however, is the study of a star's stellar interior by analyzing its oscillations which are, according to Mauro "produced by standing waves traveling inside the star which interfere constructively with themselves giving rise to resonant modes." (Mauro, 2016, p.1)
One mode is called the pressure mode, which are acoustic waves. They are called pressure modes, since pressure is the restoring force in the oscillation. Kepler-10 has solar-like oscillations, which is used to describe oscillations in a star's outer convective zone and show p-modes in their frequency spectrum. (Chaplin & Miglio, 2013; Garcia & Ballot 2019, as cited in Mullner et al, 2021).

In this investigation the data was from the Mikulski Archive for Space Telescopes (MAST) . The Kepler telescope generated a lot of time series data of oscillating stars including the star

Kepler-10. The program LightKurve will be used to analyze the data, as it was specifically created to analyze data from the Kepler, K2 and Tess-telescopes.

1.1 Research question

The research question for this extended essay is: How can asteroseismology be used to determine the stellar parameters: Radius, mass and gravitational field strength of the star Kepler-10?

The variables are:

- Independent variable: frequency of oscillation of Kepler-10
- Dependent variable: power output of Kepler-10

This is because it is the frequency vs power spectrum that will be analyzed to locate what is called the p-mode envelope. Here there is a peak in power which has a gaussian-like or bell shape. Therefore this peak is modeled by a gaussian curve, as this can give insight into the star. The curve has a maximum called v_{max}, and an average frequency spacing called Δv. The first part of this investigation will be determining v_{max} and Δv, and the final part will be using scientifically established scaling relations to determine Kepler-10's mass, radius and gravitational field strength.

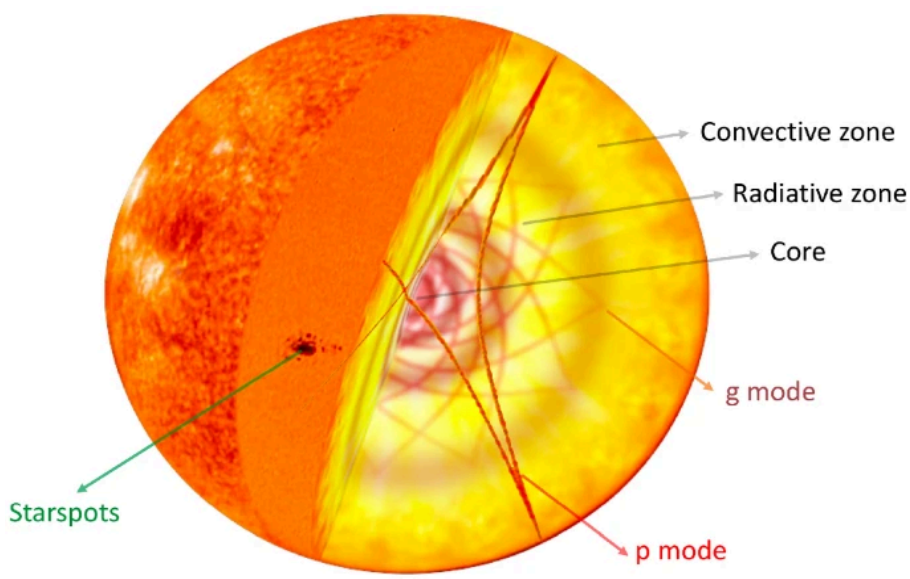
2. Background theory

Asteroseismology studies the "sound" of stars, that is, they study mechanical waves that propagate through the star. The field does not rely on hearing this sound, as sound waves cannot travel through a vacuum. Instead they study what can be seen: The star's oscillations. Chaplin et al describe stellar oscillations as “visible manifestations of standing waves in the stellar interiors" (Chaplin et al., 2011, p.213).

2.1 Solar-like oscillators

Stars are divided into several different classes based on the differences in their oscillations. One of these categories are solar-like oscillators. The term refers to stars that have oscillations which are stable, random and turbulent within the star's convective envelope, shown in **Picture 1.** Kepler-10 is a solar-like oscillator.

Picture 1: In (García, R.A., Ballot, J. 2019, p.4, Fig 2,)



2.2 Modes of oscillations

The waves within the stellar interior are primarily divided into two: p-modes and g-modes. The modes of oscillations of a star is what drives its oscillations. P-mode is abbreviated from pressure-mode as pressure is the main restoring force for the oscillation from equilibrium.

G-modes, short for gravity modes, is when buoyancy is the restoring force of the oscillations (Aerts et al., 2010, p.17). G-modes are illustrated in picture 2, as b.

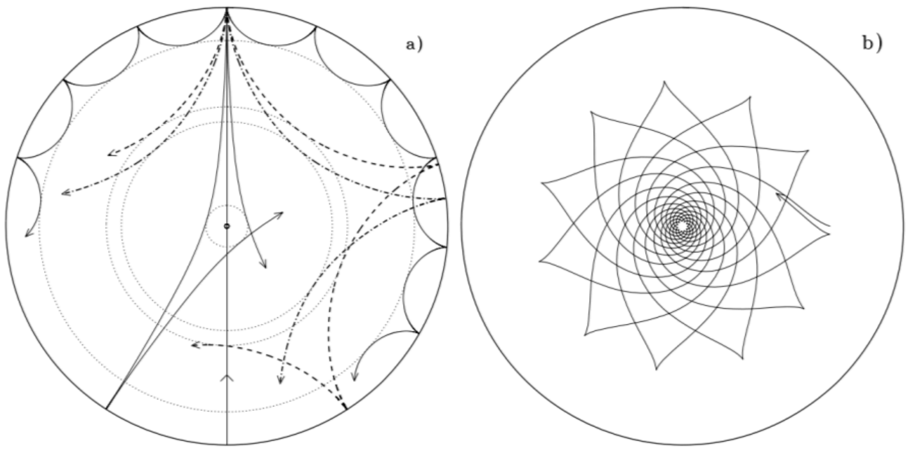
2.2.2 Pressure modes

P-modes, according to Garcia and Ballot, are the most important modes in solar-like star seismology since they are by far the most observed ones."(García, R.A., Ballot, J., 2019, p.13). One reason p-modes give insight into a star is through the knowledge we have regarding sound waves, and the speed of sound waves depends on temperature. The speed of sound in a real gas can be expressed in the equation: $C = \sqrt{ZkRT}$

- C: Speed of sound
- Z: Compressibility factor
- k: adiabatic gas constant
- R: gas constant
- T: temperature in Kelvin

In **Picture 2**, the wave path is bent by the increase in speed, due to increased temperature within the star. The dotted circles in the illustration show a turning point for the wave, where it undergoes total internal refraction. In the convective zone, the waves are reflected as the density of the star decreases rapidly (Aerts et al., 2010, p.18). P-modes occur at the outer part of the star and can therefore be observed. An asymptotic relation exists that states that p-modes have approximately equal spacing in frequency, which is utilized in this investigation.

Picture 2: (Aerts et al., 2010, p.18)



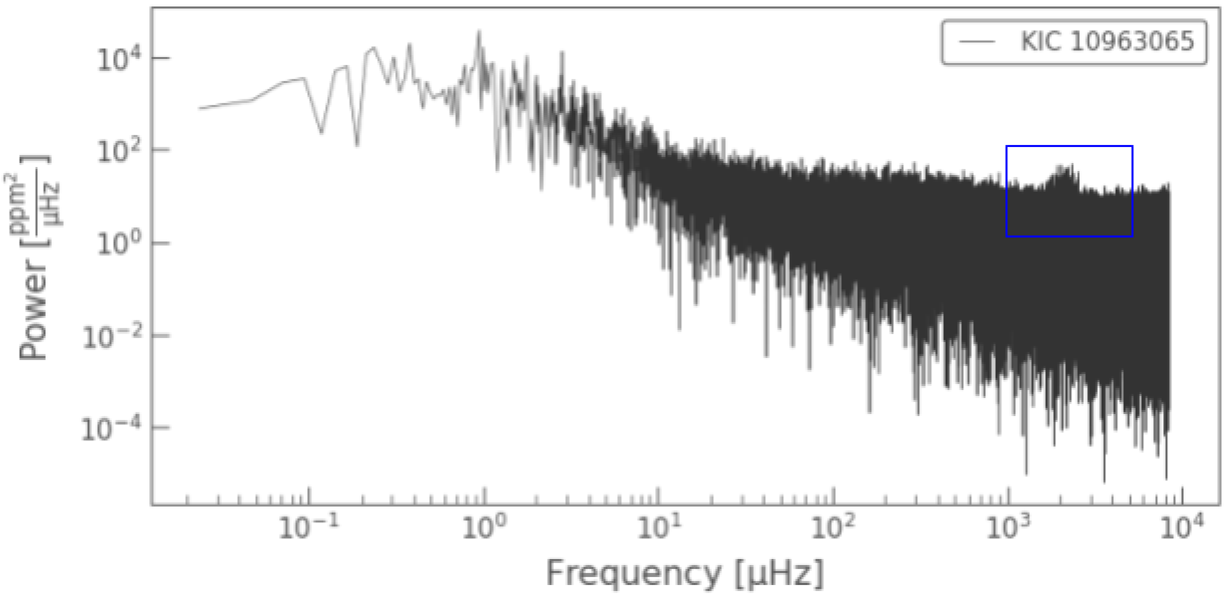
2.3 The periodogram

A periodogram is often "used to identify the dominant periods (or frequencies) of a time series"(*6.1 the Periodogram | STAT 510*, n.d.). The dominant frequency is where the p-mode envelope of a frequency vs power periodogram is. This is utilized to gain information about Kepler-10, namely Δv, and $v_{\max}$. The periodogram that will be constructed later takes data from the Kepler telescope showing the power on the y-axis and the frequency of oscillations on the x-axis. Since the telescope has gained data by looking at the star Kepler-10 various times this data will essentially be glued together forming a single periodogram.

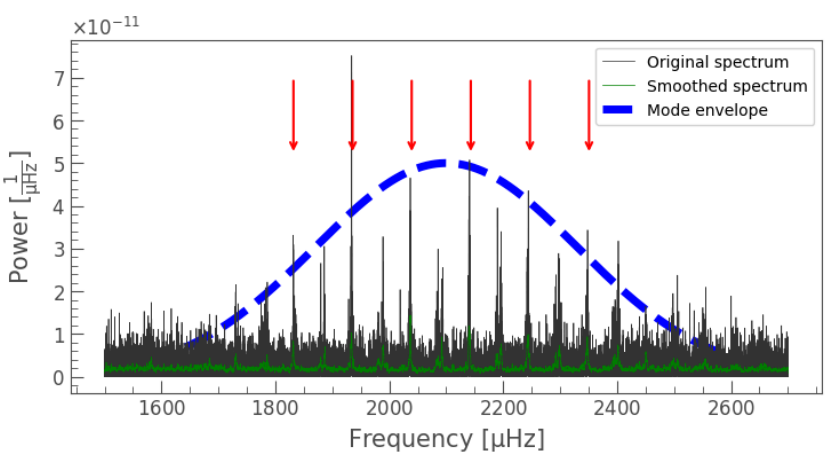
2.3.1 Identifying mode envelope within a periodogram

An example of identifying the p-mode envelope of the star Ruby can be found in the Lightkurve tutorial: (Hall & Barentsen, 2020b). In **Picture 3** a power excess with some periodic signals within it is spotted. Therefore it is determined to be the p-mode envelope. P-modes tend to occur at frequencies around 1000 μHz and above, seen in illustration of page 18 (Aerts et al, 2010, p.18). This area of the periodogram is therefore zoomed in on, seen in picture 4.

Picture 3: Periodogram of star Ruby (Hall & Barentsen, 2020b)



Picture 4: p-mode envelope of star Ruby, (Hall & Barentsen, 2020a)



A gaussian curve is then nicely fitter over the power excess, and Δv can be seen as the red arrows in picture 4. Δv is determined to be $= \ 103.11 \mu Hz$, and the maximum, $v_{\max}$ $= \ 2145.00 \mu Hz$.

2.4 Scaling relations

There are scientifically established scaling relations for solar-like oscillators (Hall & Barentsen, 2020a). These relate Δv and $v_{\max}$ to the values of the mass, radius and gravitational field of a star. The symbol: ⊙ means the sun. Values for the sun appear in the scaling relations as much more is known about the sun due to its proximity to earth.

$$\frac{M}{M_{\odot}} \simeq \left(\frac{v_{max}}{v_{max,\odot}}\right)^{3} \left(\frac{\Delta v}{\Delta v_{\odot}}\right)^{-4} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{\frac{3}{2}}$$ Scaling relation (1)

$$\frac{R}{R_{\odot}} \simeq \left(\frac{v_{max}}{v_{max,\odot}}\right) \left(\frac{\Delta v}{\Delta v_{\odot}}\right)^{-2} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{\frac{1}{2}}$$ Scaling relation (2)

$$\frac{g}{g_{\odot}} \simeq \left(\frac{v_{max}}{v_{max,\odot}}\right) \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{\frac{1}{2}}$$ Scaling relation (3)

2.5 Database selection and data retrieval

The secondary data that is being used to create the periodogram in Lightkurve is from the Mikulski Archive for Space Telescopes. The program Lightkurve is made for some of the telescopes in the archive and uses the archives's data. The Kepler telescope was rotated by 90 degrees every ninety days. It sampled data at two cadences: long cadence (30 minutes), and short cadence (1 minutes). The data from this telescope may have limitations, however the scientists that have constructed Kepler with precision in mind, and knowledge way beyond this investigation. There is, however, a limitation in studying stars that are far away in of itself. A specific way this can be seen is when it comes to signal to noise ratio. Data from stars further away are more contaminated with noise data, and will yield less precise results. The data from MAST (MAST, n.d.) was chosen because there is available data of Kepler-10.

3. Methodology

The research question for this investigation is: How can asteroseismology be used to determine the stellar parameters: Radius, mass and gravitational field strength of the star Kepler-10? To answer this question the program Lightkurve was chosen to obtain $\Delta\nu$ and ν_{max}. With these values one can estimate mass, radius and gravitational field strength. The primary reason for the use of Lightkurve was that it had all of the functions needed to determine $\Delta\nu$ and ν_{max} for Kepler-10 as it was specifically created for Kepler, K2 and Tess data.

3.1 Data analysis of Kepler-10 data using Lightkurve

The code used in this investigation is collected from two Lightkurve tutorials:

- How to estimate a star's mass and radius using asteroseismology (Hall & Barentsen, 2020a)
- How to understand and manipulate the peridogram of an oscillating star (Hall & Barentsen, 2020b)

The code is modified to study the star Kepler-10, opposed to the star Ruby in the tutorials. All code cells can be viewed in the appendix. The Lightkurve program is used (Lightkurve collaboration, 2018). The package Astropy which is an astronomy package for python was utilized (Astropy collaboration, 2022). Asteroquery, which is a package that provides tools to collect data from databases (astroquery, 2019).

3.1.1 Data selection

Kepler did not observe and collect data of Kepler-10 for the entirety of its mission. It was therefore important to download the correct data when Kepler-10 was observed. This was done by finding the quarters the Kepler telescope looked at Kepler-10, seen in code cell 3.

To construct a periodogram of a solar-like oscillator the correct time series data had to be used. The Kepler telescope collected data in two cadences, 1-minute and 30-minutes. According to Gilliland et al., solar-like oscillations oscillate in short time spans of 3-10 minutes, and can therefore not be studied by long cadence data (Gilliland et al., 2010, p.1). Using a cadence of 30 minutes could make it difficult to see the oscillations of the star in a periodogram. This is why only short cadence data of Kepler-10 was downloaded in **Code cell 3.**

In code cell 3 it can be seen that the telescope collected data of Kepler-10 in 34 different quarters, from 2009 to 2013.

Code cell 3

```
search_result = lk.search_lightcurve('KIC 11904151', author='Kepler', cadence="short
search_result
```

SearchResult containing 34 data products.

#	mission	year	author	exptime s	target_name	distance arcsec
0	Kepler Quarter 02	2009	Kepler	60	kplr011904151	0.0
1	Kepler Quarter 03	2009	Kepler	60	kplr011904151	0.0
2	Kepler Quarter 03	2009	Kepler	60	kplr011904151	0.0
3	Kepler Quarter 03	2009	Kepler	60	kplr011904151	0.0
4	Kepler Quarter 07	2010	Kepler	60	kplr011904151	0.0
5	Kepler Quarter 07	2010	Kepler	60	kplr011904151	0.0
6	Kepler Quarter 07	2010	Kepler	60	kplr011904151	0.0
7	Kepler Quarter 06	2010	Kepler	60	kplr011904151	0.0
8	Kepler Quarter 06	2010	Kepler	60	kplr011904151	0.0
9	Kepler Quarter 06	2010	Kepler	60	kplr011904151	0.0
...	...	...	...	...	...	...
24	Kepler Quarter 13	2012	Kepler	60	kplr011904151	0.0
25	Kepler Quarter 13	2012	Kepler	60	kplr011904151	0.0
26	Kepler Quarter 14	2012	Kepler	60	kplr011904151	0.0
27	Kepler Quarter 14	2012	Kepler	60	kplr011904151	0.0
28	Kepler Quarter 14	2012	Kepler	60	kplr011904151	0.0
29	Kepler Quarter 15	2012	Kepler	60	kplr011904151	0.0
30	Kepler Quarter 15	2012	Kepler	60	kplr011904151	0.0
31	Kepler Quarter 17	2013	Kepler	60	kplr011904151	0.0
32	Kepler Quarter 15	2013	Kepler	60	kplr011904151	0.0
33	Kepler Quarter 17	2013	Kepler	60	kplr011904151	0.0

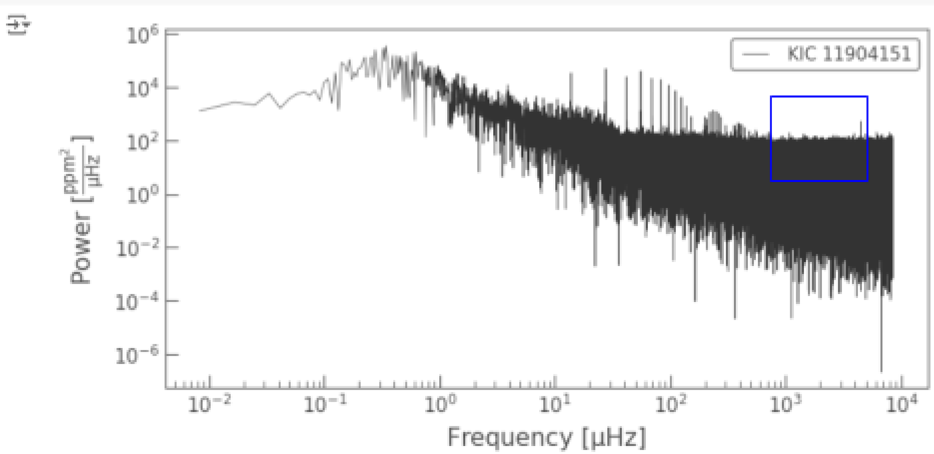
Length = 34 rows

Then the power vs frequency periodogram of Kepler-10 was constructed as shown in **Code cell 4.** In this code all of the 34 search results are downloaded and stitched together into one periodogram.

The 34 data products were downloaded to minimize random errors and retain the highest certainty in results, as choosing only a few could lead to missing significant signals.

Code cell 4

```
[ ] search_result = lk.search_lightcurve('KIC 11904151',
                                        mission='Kepler',
                                        cadence='short')
    lc = search_result[0:34].download_all().stitch()
    pg = lc.normalize(unit='ppm').to_periodogram(normalization='psd')
    pg.plot(scale='log');
```



3.1.1 Obtaining the correct p-mode envelope

Now the p-mode envelope of Kepler-10 could be identified. Estimate.numax, and estimate.deltanu are methods that are built into Lightkurve. These use something called an autocorrelation function. A limitation of the autocorrelation function is that it has “significant risk of false detection”(Balona, 2020, p.1). It is therefore important to inspect and evaluate the result.

This method was applied resulting in **Code cell 8**.

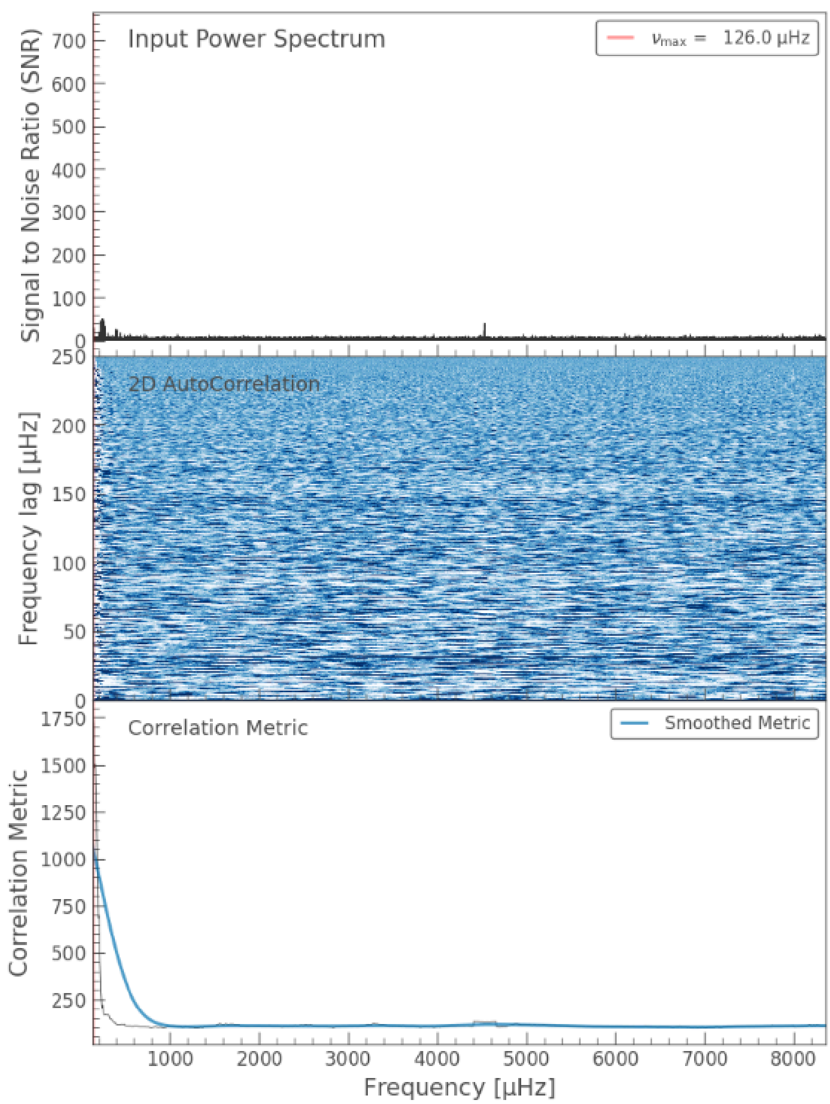
Code cell 8:

```
[ ]  seismology.estimate_numax()
```

```
numax: $126.00$ $\mathrm{\mu Hz}$ (method: ACF2D)
```

Code cell 9:

```
[ ]  seismology.diagnose_numax();
```

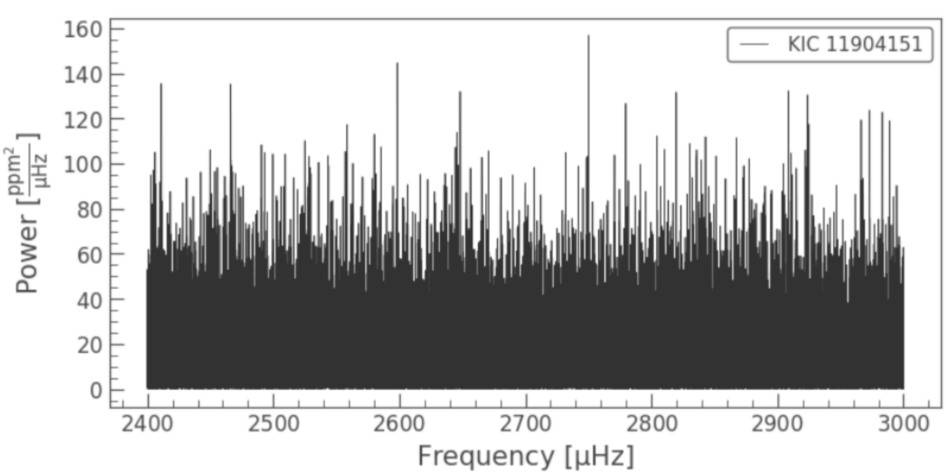


The value for ν_{max} given to be $126.00\mu Hz$, which is not in the range p-modes usually are, which is about 1000 and above. By using a diagnosing tool, there is also no significant correlation shown, suggesting that this may be a false detection of the ν_{max}.

A characteristic that p-modes oscillations have that can be used to identify its mode envelope is that p-mode envelopes have approximately equally spaced frequencies, Δv, and a v_{max} at higher frequencies. The periodogram in **Code cell 4** was visually analyzed to determine where periodic excesses of power could be seen, focusing on higher frequencies. The region of 2400-3000μHz was zoomed in on due to a seemingly periodic, but small power excess.

Code cell 5

```
[ ] zoom_pg = lc.normalize(unit='ppm').to_periodogram(normalization='psd',
                                                     minimum_frequency=2400,
                                                     maximum_frequency=3000)
    zoom_pg.plot();
```



In **Code cell 5** there seems to be the p-mode characteristic of equally spaced frequencies and a power max where a gaussian curve could shape it. Therefore this was determined to be the p-mode envelope in this investigation.

As the p-mode envelope had been found Δv and v_{max} could be estimated. The v_{max} is determined to be approximately $2740\mu Hz$. The uncertainty in Δv and v_{max} is ½ of the separations on the x-axis, thus uncertainty is $\pm 10\mu Hz$.

There are many frequency separations in this periodogram and it is therefore difficult to determine Δv by looking at the periodogram. To make this easier an established relation that gives an approximation to Δv in a solar like oscillator by knowing v_{max} is used.

This relation is from the paper Stello et al and is:

$$\Delta v \simeq (0.263 \pm 0.009) \times v_{max}^{0.772\pm 0.005}$$

(Stello et al., 2009, p.1)

$$\Delta v \simeq (0.263 \pm 0.009) \times (2740\pm 10)^{0.772\pm 0.005}$$

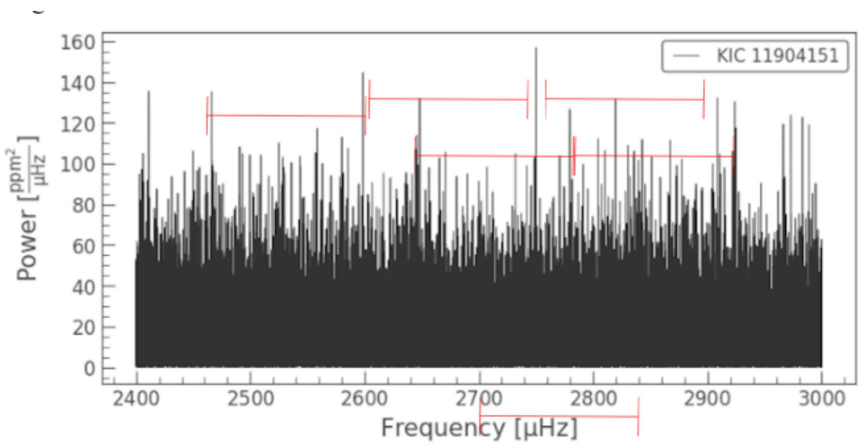
$$\Delta v \simeq 0.263 \times 2740^{0.772}$$

$$\Delta v \simeq 118.5493516$$

$$\Delta v \simeq 119\, microhertz$$

This is an estimation used to guide in the analysis of the periodogram to more accurately estimate the actual Δv. A measuring stick was created and scaled to 119 over the periodogram:

Periodogram from code cell 5:



As seen in the periodogram from **code cell 5** this value corresponds to the frequency separations in the periodogram and was therefore chosen as the final estimation of Δv. There is still a large uncertainty that can be seen since the red lines do not perfectly match, however 119 μHz was chosen as the final value as it seems accurate.

Table 1:obtained values for Δv and v_{max}

Δv and v_{max}	Value
Frequency max, v_{max} (μHz)	2740 ± 10
Average frequency spacing, Δv (μHz)	119 ±10

Uncertainties in analysis of the periodogram

The uncertainties for Δv and v_{max} in this investigation has been determined to be ±10μHz. It is likely that these uncertainties are larger than ½ of the separations on the x-axis, as there are various uncertainties in the method that remains unknown such as: the uncertainty in the data itself collected from the telescope, the program Lightkurve, the visual inspection of the periodogram to find the mode envelope. This can intuitively be deduced as the paper Davies et al determined v_{max}= 2730 ± 280 and Δv = 118.2 ± 0.20. (Davies et al., 2021, p. 2185) with more complicated methods than that of this investigation. This illustrates that the uncertainties calculated above are misleading as they are too small.

3.2 Calculation of Stellar parameters: Radius, Mass, and Gravitational Field Strength

For the calculations of the stellar parameters of Kepler-10, the scaling relations will be used. Other parameters of the sun and also of the star have to be known, and have therefore been taken from secondary sources, presented in **Table 2**.

Table 2: Parameters collected from the internet

Parameter	Value	Taken from
Effective temperature of Kepler-10 (T_{eff})	$5708 \pm 28\ Kelvin$	(Bonomo et al., p.4, 2023)
Effective temperature of the sun ($T_{eff\odot}$)	$5772.0\ \pm\ 0.8\ Kelvin$	(Prša et al., 2016, p.3)
Mass of the sun ($M_\odot$)	$(1.988400\ \pm\ 0.000092)\ \times 10^{30} kg$	(Prša et al., 2016, p.6)
Radius of the sun ($R_\odot$)	$695\,700\ \times 10^{3} m$	(Williams, 2022)
Gravitational field strength of the sun ($g_\odot$)	$274.0\ ms^{-2}$	(Williams, 2022)
Average frequency spacing of the sun ($\Delta \nu_\odot$)	$135.1 \mu Hz$	(Hall & Barentsen, 2020a)
Frequency max of the sun ($\nu_{max,\odot}$)	$3090 \mu Hz$	(Hall & Barentsen, 2020a)

3.2.1 Calculations

$$\frac{M}{M_{\odot}} \simeq \left(\frac{v_{max}}{v_{max,\odot}}\right)^{3} \left(\frac{\Delta v}{\Delta v_{\odot}}\right)^{-4} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{\frac{3}{2}}$$

$$\frac{M}{1988400\times10^{24}kg} \simeq \left(\frac{2740\mu Hz}{3090\mu Hz}\right)^{3} \left(\frac{119\mu Hz}{135.1\mu Hz}\right)^{-4} \left(\frac{5708}{5772}\right)^{\frac{3}{2}} = 2.264 \times 10^{30}kg = 2.26 \times 10^{30}kg$$

$$\frac{R}{R_{\odot}} \simeq \left(\frac{v_{max}}{v_{max,\odot}}\right) \left(\frac{\Delta v}{\Delta v_{\odot}}\right)^{-2} \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{\frac{1}{2}}$$

$$\frac{R}{695\,700\times10^{3}m} \simeq \left(\frac{2740\mu Hz}{3090\mu Hz}\right) \left(\frac{119\mu Hz}{135.1\mu Hz}\right)^{-2} \left(\frac{5708}{5772}\right)^{\frac{1}{2}} = 790696257.2 = 7.91 \times 10^{8} m$$

$$\frac{g}{g_{\odot}} \simeq \left(\frac{v_{max}}{v_{max,\odot}}\right) \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{\frac{1}{2}}$$

$$\frac{g}{274.0\ Nkg^{-1}} \simeq \left(\frac{2740\mu Hz}{3090\mu Hz}\right) \left(\frac{5708}{5772}\right)^{\frac{1}{2}} = 119.1314022\ ms^{-2} = 1.19 \times 10^{2}$$

4. Results

Table 1:obtained values for Δv and v_{max}

Δv and v_{max}	Value
Frequency max, v_{max} (μHz)	2740 ± 10
Average frequency spacing, Δv (μHz)	119 ± 10

Table 3: Calculated values for mass, radius and gravitational field strength of Kepler-10

Stellar parameter	Value
Mass (kg)	2.26×10^{30}
Radius (m)	7.91×10^{8}
Gravitational field strength (ms^{-2})	1.19×10^{2}

4.1 Calculating uncertainties

The uncertainty in the deduced parameters can be calculated by using the uncertainties in Δv and v_{max} as well as the uncertainties in the parameters from other sources. And adding them together in the scaling relations.

$$\frac{M}{(1.988475\pm0.000092)\times10^{30}} \simeq (\frac{2740\pm10}{3090})^{3}(\frac{119\pm10}{135.1})^{-4}(\frac{5708\pm28}{5772\pm0.8})^{\frac{3}{2}} = 2.264 \times 10^{30}$$

The individual uncertainties that were available for the parameters are listed in **Table 2.** Some uncertainties were difficult to find and were not listed in the sources the parameters are taken from, hence they have not been included. This means that in reality the uncertainties for: M, R and g will be greater than what is calculated.

First the percentage uncertainty was calculated:

$$percentage\ uncertainty = \frac{uncertainty\ of\ individual\ parameter}{individual\ parameter} \times 100$$

$$percentage\ uncertainty\ in\ v_{max} = \frac{10}{2740} \times 100 = 0.365\%$$

Since the v_{max} is raised to the power of three the percentage uncertainty is multiplied by three:

$$Percentage\ uncertainty\ in\ v^{3}_{max} = 0.365\% \times 3 = 1.095\%$$

This procedure is repeated with Δv:

$percentage\ uncertainty = \frac{uncertainty\ of\ individual\ parameter}{individual\ parameter} \times 100$

$percentage\ uncertainty\ \Delta v = \frac{10}{119} \times 100 = 8.403\%$

$percentage\ uncertainty\ \Delta v^{-4} = 8.403\% \times 4 = \pm\ 33.612\%$

The negative is ignored since it will be $\pm$

T_{eff}

$T_{eff}\ Kepler\ uncertainty = \frac{28}{5708} = 0.491\%$

$T_{eff\odot}\ uncertainty = \frac{0.8}{5772} = 0.014\%$

$0.491\% + 0.014\% = 0.505\%$

$0.505\% \times \frac{3}{2} = 0.7575\%$

Mass of sun:

$M_{\odot} uncertainty = \frac{0.000092}{1.988475} \times 100 = 0.00463$

Since the scaling relation involves multiplication the uncertainty is added together:

$1.095\% + 33.612\% + 0.7575\% + 0.00462\% = 35.46912\%$

The absolute uncertainty was obtained by

$absolute\ uncertainty = \frac{percentage\ uncertainty \times parameter}{100\%}$

$absolute\ uncertainty\ of\ Mass = \frac{35.47\% \times 2.26 \times 10^{30}}{100\%} = 8.03 \times 10^{29}$

These processes were repeated for the remaining two scaling relations and uncertainty can be viewed in **Table 4.**

Table 4: Mass, radius and gravitational field strength of Kepler-10, along with their percentage and absolute uncertainties.

Parameter	Value	% Uncertainty	Absolute uncertainty
Mass (kg)	2.26×10^{30}	$\pm\ 35.47\%$	$\pm\ 8.03 \times 10^{29}$
Radius (m)	7.91×10^{8}	$\pm\ 17.42\%$	$\pm\ 1.38 \times 10^{8}$
Gravitational field strength (ms^{-2})	1.19×10^{2}	$\pm\ 0.62\%$	$\pm\ 0.74 \times 10^{0}$

Table 5: Scientifically established values of mass, radius and gravitational field strength of Kepler-10 (X. Dumusque et al., 2014, p.4)

Parameter	Value in asteroseismology unit	Value on the form (kg, m, or ms^{-2})	% Uncertainty	Absolute uncertainty
Mass	0.910 ± 0.021	1.810×10^{30} kg	$\pm 11.057\%$	$\pm 2.001\times10^{0}$
Radius	1.065 ± 0.009	7.409×10^{8}m	$\pm 0.845\%$	$\pm 6.261\times10^{6}$
Gravitational field strength	$log\ (g) = 4.344 \pm 0.004$	2.208×10^{2} ms^{-2}	$\pm 1.842 \times 10^{-4}$	$\pm 4.067\times10^{0}$

**Calculations of uncertainties and conversion of values on the asteroseismological form from (X. Dumusque et al., 2014, p.4) can be found in appendix i.*

5. Conclusion

The research question for this investigation was: How can asteroseismology be used to estimate the stellar parameters: Radius, Mass and Gravitational Field Strength of the star Kepler-10? The methods utilized in this investigation were the tools the field of asteroseismology provided. Such as finding the p-mode envelope of the star Kepler-10 through the analysis of its frequency vs power periodogram. By visually analyzing the periodic peak in power, Δv and v_{max} were determined to be: 2740 ± 10μHz and 119 ± 10μHz, respectively. The parameters: Radius, mass and gravitational field strength, were possible to estimate through the use of the scaling relations the field asteroseismology has provided. The parameters were estimated to be:

$M = 2.26 \times 10^{30} \pm 8.03 \times 10^{29} kg,\ R = 7.91 \times 10^{5} \pm 1.38 \times 10^{5} m$,

$g = 1.19 \times 10^{2} \pm 0.74\, ms^{-2}$. The scientifically established values are:

$M = 1.810 \times 10^{30} \pm 2.001\, kg, R = 7.409 \times 10^{8} \pm 6.261 \times 10^{6} m$,

$g = 220.80 \pm 0.74 ms^{-2}$. This further illustrates that the uncertainties calculated above are artificially low as the values in this investigation are somewhat different from the scientifically established ones.

6. Evaluation

Even though the values of the parameters of Kepler-10 that were found were relatively close to scientifically established values, there are some considerable limitations to this investigation. One of these limitations were that the mathematical or data program way did not work, as it gave unlikely values for $\Delta\nu$ and $\nu_{\max}$. The method of visually analyzing the periodogram was therefore applied, which can be a less precise methodology.

However this method is heavily covered in asteroseismological literature, and whilst the results are impacted by many uncertainties, they gave quite accurate results for a star that is extremely far away, which is a strength in this investigation.

There could also be significant errors within this investigation. A systematic error that could potentially exist is exemplified by the low signal to noise ratio in the periodogram. According to Jenkins & Dunnuck "There are instrumental effects and noise even in the space environment" (Jenkins & Dunnuck, 2011, p.2). This could also lead to the systematic error of obtaining the wrong p-mode envelope. Random errors of this type of investigation could be random stellar phenomena which may be difficult to account for. To account for random errors all Kepler quarters where the telescope observed the star Kepler-10 were obtained and used to construct the periodogram.

Many of the limitations stated are impossible for an investigation of this level to account for. Possible extensions are therefore limited. One extension could be to find other data programs to see if the answers regarding $\Delta\nu$ and $\nu_{\max}$ would be different. Another extension could be analyzing the same star with data from a different telescope if that is made available.

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8. Appendix

Appendix i: Calculations of uncertainties and conversion of values on the asteroseismological form from (X. Dumusque et al., 2014, p.4)

Table: 5

Parameter	Value in asteroseismology unit	Value on the form (kg, m, or ms^{-2})	% Uncertainty	Absolute uncertainty
Mass	0.910 ± 0.021	1.810×10^{30} kg	$\pm$11.057%	$\pm 2.001\times10^{0}$
Radius	1.065 ± 0.009	7.409×10^{8}m	$\pm$0.845%	$\pm 6.261\times10^{6}$
Gravitational field strength	$log\ (g) = 4.344 \pm 0.004$	$2.208\times10^{2}\ ms^{-2}$	$\pm 1.842 \times 10^{-4}$	$\pm 4.067\times10^{0}$

Mass:

$\frac{0.021}{0.910} \times 100 = 11.0526\%$

Mass of kepler: 0.910 ± 0.021, is relative to the mass of the sun. $0.910 \pm 0.021 \times (1.988400 \pm 0.000092) \times 10^{30} kg = 1.80951225 \times 10^{30} kg$

Since multiplication the uncertainties are added together:

$11.0526\% + 0.00463\% = 11.05726\%$.

$Absolute\ uncertainty = \frac{11.05726 \times 1.810 \times 10^{30}}{100} = \pm\ 2.001 \times 10^{30}$

Radius:

$\frac{0.009}{1.065} \times 100 = 0.845\%$

Since the uncertainty for the radius of the sun was unavailable, this remains the total percentage uncertainty.

$absolute\ uncertainty = \frac{0.845 \times 7.049 \times 10^{8}}{100} = 6260605 = 6.261 \times 10^{6}$

Gravitational field strength:

$logg = 4.344 \pm 0.004$

Upper and lower bound method is used:

$absolute\ uncertainty\ =\ 10^{4.344}-10^{4.34}=406.735$ Is divided by 100 because of unit cm→m

$\frac{406.735}{100}=4.067$

$Percentage\ uncertainty\ =\frac{4.067}{10^{4.344}}=1.842\times10^{-4}$

Appendix ii: Code cells in google colab

Code cell 1:

```
[ ] pip install lightkurve #installs the program lightkurve, as well as all other necessary packages.

Requirement already satisfied: lightkurve in /usr/local/lib/python3.10/dist-packages (2.4.2)
Requirement already satisfied: astropy>=5.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (5.3.4)
Requirement already satisfied: astroquery>=0.3.10 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (0.4.7)
Requirement already satisfied: beautifulsoup4>=4.6.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (4.12.3)
Requirement already satisfied: bokeh>=2.0.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (3.3.4)
Requirement already satisfied: fbpca>=1.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (1.0)
Requirement already satisfied: matplotlib>=3.1 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (3.7.1)
Requirement already satisfied: memoization>=0.3.1 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (0.4.0)
Requirement already satisfied: numpy>=1.18 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (1.25.2)
Requirement already satisfied: oktopus>=0.1.2 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (0.1.2)
Requirement already satisfied: pandas>=1.1.4 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (2.0.3)
Requirement already satisfied: patsy>=0.5.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (0.5.6)
Requirement already satisfied: requests>=2.22.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (2.31.0)
Requirement already satisfied: scikit-learn>=0.24.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (1.2.2)
Requirement already satisfied: scipy>=1.7 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (1.11.4)
Requirement already satisfied: tqdm>=4.25.0 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (4.66.4)
Requirement already satisfied: uncertainties>=3.1.4 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (3.2.1)
Requirement already satisfied: urllib3>=1.23 in /usr/local/lib/python3.10/dist-packages (from lightkurve) (2.0.7)
Requirement already satisfied: pyerfa>=2.0 in /usr/local/lib/python3.10/dist-packages (from astropy>=5.0->lightkurve) (2.0.1.4)
Requirement already satisfied: PyYAML>=3.13 in /usr/local/lib/python3.10/dist-packages (from astropy>=5.0->lightkurve) (6.0.1)
Requirement already satisfied: packaging>=19.0 in /usr/local/lib/python3.10/dist-packages (from astropy>=5.0->lightkurve) (24.0)
Requirement already satisfied: html5lib>=0.999 in /usr/local/lib/python3.10/dist-packages (from astroquery>=0.3.10->lightkurve) (1.1)
Requirement already satisfied: keyring>=15.0 in /usr/lib/python3/dist-packages (from astroquery>=0.3.10->lightkurve) (23.5.0)
Requirement already satisfied: pyvo>=1.1 in /usr/local/lib/python3.10/dist-packages (from astroquery>=0.3.10->lightkurve) (1.5.2)
Requirement already satisfied: soupsieve>1.2 in /usr/local/lib/python3.10/dist-packages (from beautifulsoup4>=4.6.0->lightkurve) (2.5)
Requirement already satisfied: Jinja2>=2.9 in /usr/local/lib/python3.10/dist-packages (from bokeh>=2.0.0->lightkurve) (3.1.4)
Requirement already satisfied: contourpy>=1 in /usr/local/lib/python3.10/dist-packages (from bokeh>=2.0.0->lightkurve) (1.2.1)
Requirement already satisfied: pillow>=7.1.0 in /usr/local/lib/python3.10/dist-packages (from bokeh>=2.0.0->lightkurve) (9.4.0)
Requirement already satisfied: tornado>=5.1 in /usr/local/lib/python3.10/dist-packages (from bokeh>=2.0.0->lightkurve) (6.3.3)
Requirement already satisfied: xyzservices>=2021.09.1 in /usr/local/lib/python3.10/dist-packages (from bokeh>=2.0.0->lightkurve) (2024.4.0)
Requirement already satisfied: cycler>=0.10 in /usr/local/lib/python3.10/dist-packages (from matplotlib>=3.1->lightkurve) (0.12.1)
Requirement already satisfied: fonttools>=4.22.0 in /usr/local/lib/python3.10/dist-packages (from matplotlib>=3.1->lightkurve) (4.53.0)
Requirement already satisfied: kiwisolver>=1.0.1 in /usr/local/lib/python3.10/dist-packages (from matplotlib>=3.1->lightkurve) (1.4.5)
Requirement already satisfied: pyparsing>=2.3.1 in /usr/local/lib/python3.10/dist-packages (from matplotlib>=3.1->lightkurve) (3.1.2)
Requirement already satisfied: python-dateutil>=2.7 in /usr/local/lib/python3.10/dist-packages (from matplotlib>=3.1->lightkurve) (2.8.2)
Requirement already satisfied: autograd in /usr/local/lib/python3.10/dist-packages (from oktopus>=0.1.2->lightkurve) (1.6.2)
Requirement already satisfied: pytz>=2020.1 in /usr/local/lib/python3.10/dist-packages (from pandas>=1.1.4->lightkurve) (2023.4)
Requirement already satisfied: tzdata>=2022.1 in /usr/local/lib/python3.10/dist-packages (from pandas>=1.1.4->lightkurve) (2024.1)
Requirement already satisfied: six in /usr/local/lib/python3.10/dist-packages (from patsy>=0.5.0->lightkurve) (1.16.0)
Requirement already satisfied: charset-normalizer<4,>=2 in /usr/local/lib/python3.10/dist-packages (from requests>=2.22.0->lightkurve) (3.3.2)
Requirement already satisfied: idna<4,>=2.5 in /usr/local/lib/python3.10/dist-packages (from requests>=2.22.0->lightkurve) (3.7)
Requirement already satisfied: certifi>=2017.4.17 in /usr/local/lib/python3.10/dist-packages (from requests>=2.22.0->lightkurve) (2024.6.2)
Requirement already satisfied: joblib>=1.1.1 in /usr/local/lib/python3.10/dist-packages (from scikit-learn>=0.24.0->lightkurve) (1.4.2)
Requirement already satisfied: threadpoolctl>=2.0.0 in /usr/local/lib/python3.10/dist-packages (from scikit-learn>=0.24.0->lightkurve) (3.5.0)
Requirement already satisfied: webencodings in /usr/local/lib/python3.10/dist-packages (from html5lib>=0.999->astroquery>=0.3.10->lightkurve) (0.5.1)
Requirement already satisfied: MarkupSafe>=2.0 in /usr/local/lib/python3.10/dist-packages (from Jinja2>=2.9->bokeh>=2.0.0->lightkurve) (2.1.5)
Requirement already satisfied: future>=0.15.2 in /usr/local/lib/python3.10/dist-packages (from autograd->oktopus>=0.1.2->lightkurve) (0.18.3)
```

- Installs the program lightkurve, as well as other necessary packages

Code cell 2:

```
import lightkurve as lk #Lightkurve is imported into the colab notebook, and denoted as 1k, so it can easily be used further down
import numpy as np #numpy is imported into colab notebook, and denoted as np
%matplotlib inline #matplotlib is a program that visualizes data for python, inline ensures that the visulalizations are directly plotted in the colab notebook
```

- Lightkurve is imported into the notebook, and denoted as 1k, so it can be more easily used further down in the code
- Numpy is imported into the colab notebook, and denoted as np
- Mathplotlib is a program that visualizes data for python, by writing inline it ensures that the visualizations are directly plotted in the colab notebook.

Code cell 3

```
search_result = lk.search_lightcurve('KIC 11904151', author='Kepler', cadence="short")
search_result
```

SearchResult containing 34 data products.

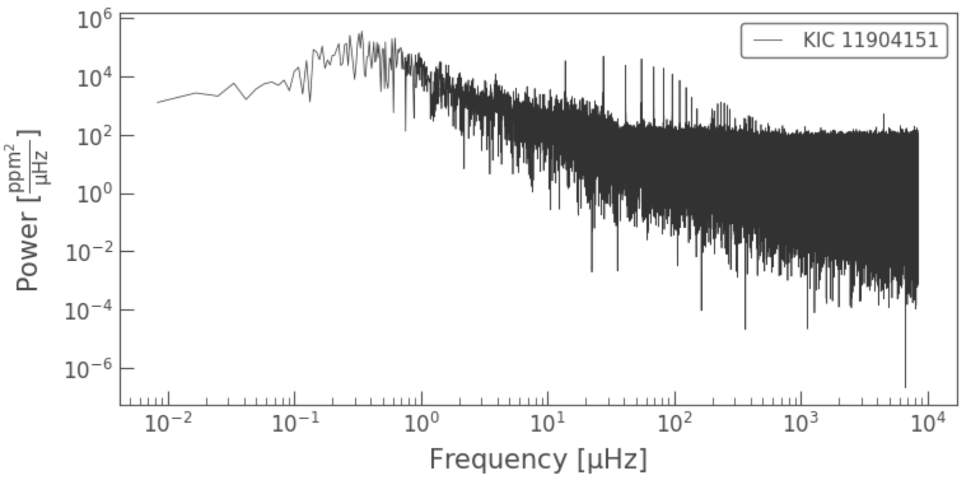
#	mission	year	author	exptime s	target_name	distance arcsec
0	Kepler Quarter 02	2009	Kepler	60	kplr011904151	0.0
1	Kepler Quarter 03	2009	Kepler	60	kplr011904151	0.0
2	Kepler Quarter 03	2009	Kepler	60	kplr011904151	0.0
3	Kepler Quarter 03	2009	Kepler	60	kplr011904151	0.0
4	Kepler Quarter 07	2010	Kepler	60	kplr011904151	0.0
5	Kepler Quarter 07	2010	Kepler	60	kplr011904151	0.0
6	Kepler Quarter 07	2010	Kepler	60	kplr011904151	0.0
7	Kepler Quarter 06	2010	Kepler	60	kplr011904151	0.0
8	Kepler Quarter 06	2010	Kepler	60	kplr011904151	0.0
9	Kepler Quarter 06	2010	Kepler	60	kplr011904151	0.0
...	...	...	...	...	...	...
24	Kepler Quarter 13	2012	Kepler	60	kplr011904151	0.0
25	Kepler Quarter 13	2012	Kepler	60	kplr011904151	0.0
26	Kepler Quarter 14	2012	Kepler	60	kplr011904151	0.0
27	Kepler Quarter 14	2012	Kepler	60	kplr011904151	0.0
28	Kepler Quarter 14	2012	Kepler	60	kplr011904151	0.0
29	Kepler Quarter 15	2012	Kepler	60	kplr011904151	0.0
30	Kepler Quarter 15	2012	Kepler	60	kplr011904151	0.0
31	Kepler Quarter 17	2013	Kepler	60	kplr011904151	0.0
32	Kepler Quarter 15	2013	Kepler	60	kplr011904151	0.0
33	Kepler Quarter 17	2013	Kepler	60	kplr011904151	0.0

Length = 34 rows

- Lighkurve is searched for short cadence data regarding Kepler-10 which has the KIC-id of 11904151. Lightkurve is compatible with the data portal that MAST has and the data is collected and imported from there.

Code cell 4

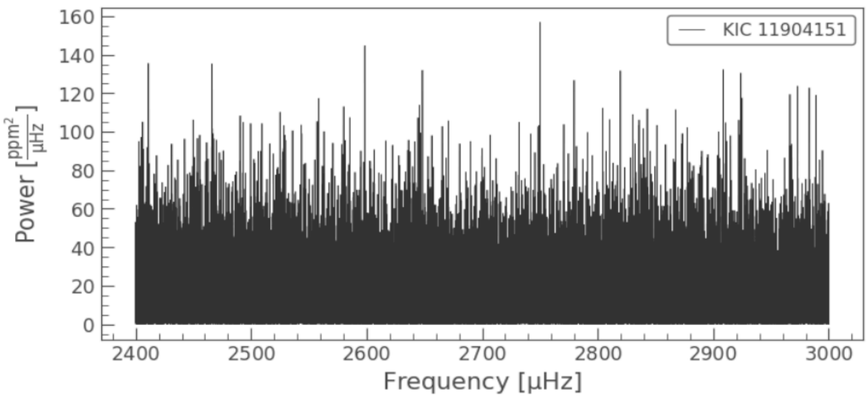
```
search_result = lk.search_lightcurve('KIC 11904151',
                                     mission='Kepler',
                                     cadence='short')
lc = search_result[0:34].download_all().stitch()  #All 34 rows of data for code cell 3 is downloaded
pg = lc.normalize(unit='ppm').to_periodogram(normalization='psd') #the data is normalized, and the p
pg.plot(scale='log'); #periodogram, pg, is plotted in a logarithmic scale
```



- Line 1-3: The search results from Code cell 3 are defined as search-result.
- Line 4: All 34 rows of data from Code cell 3 are downloaded and "stitched together" to form one periodogram of all the data collected. This is denoted as 1c to simplify further down.
- Line 5: The data is normalized, and the power fluctuations (y-axis) are converted to the units ppm: parts per million. Data object is then converted into a periodogram.

Code cell 5

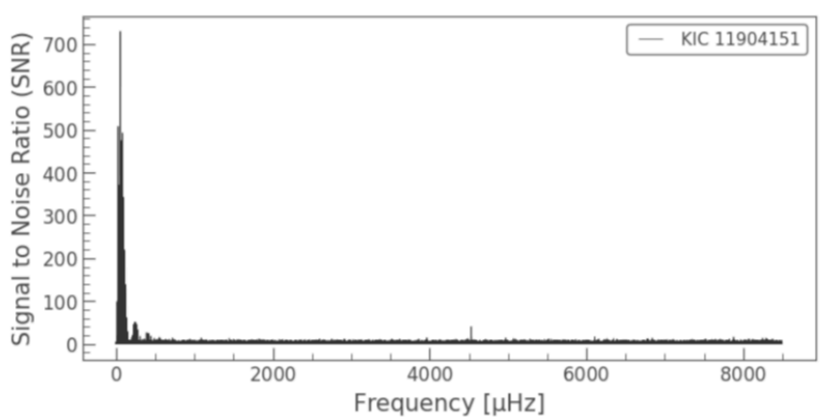
```
[ ] zoom_pg == lc.normalize(unit='ppm').to_periodogram(normalization='psd',  #the periodogram is zoomed in on
                                                       minimum_frequency=2400,
                                                       maximum_frequency=3000)
    zoom_pg.plot(); #zoomed in periodogram is then plotted
```



- Line 1: The periodogram is zoomed in on from a frequency of 2400-3000 microhertz. Everything else remains the same.

Code cell 6:

```
snr = pg.flatten()
ax = snr.plot();
```



- The periodogram called pg, are converted to the units of signal to noise ratio (SNR) on the y-axis.
- It is then plotted.

Code cell 7:

```
[ ] seismology = snr.to_seismology()
```

- The new periodogram is defined as a seismology object in the notebook so it can be called upon later.

Code cell 8:

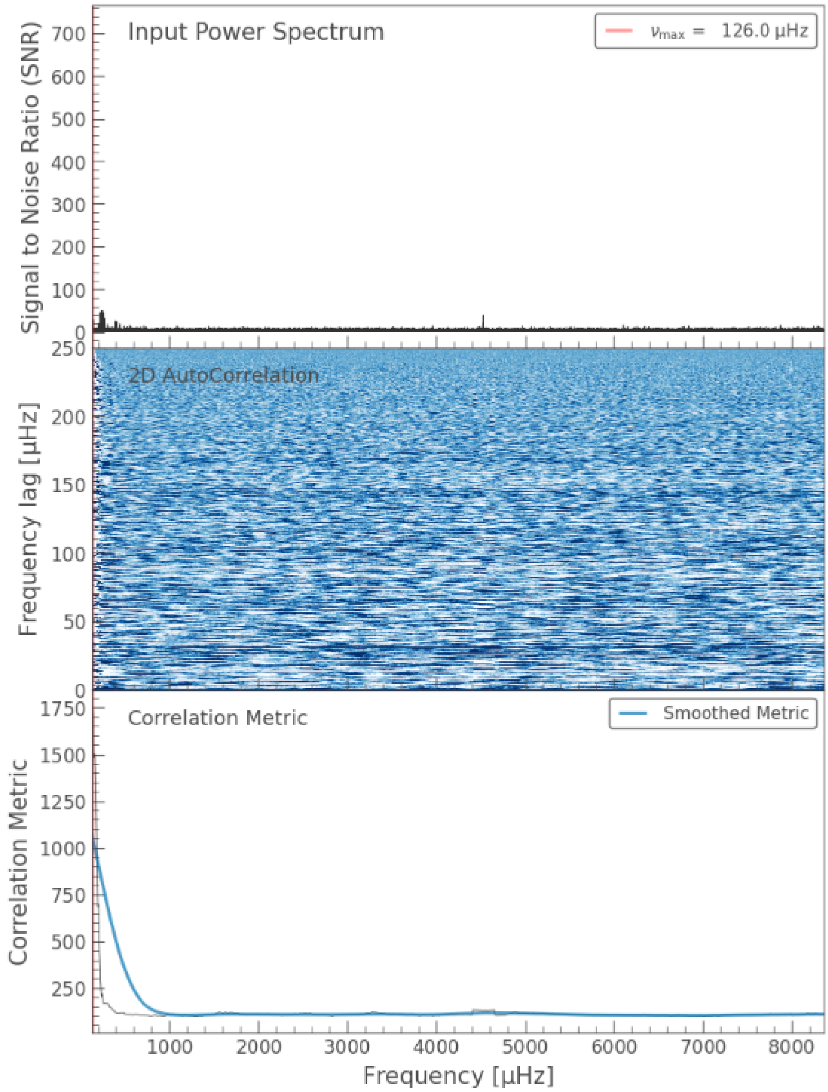
```
[ ] seismology.estimate_numax()
```

```
numax: $126.00$ $\mathrm{\mu Hz}$ (method: ACF2D)
```

- Lightkurve's estimation function is used, which is a 2d autocorrelation. Its estimate for v_{max} is then shown.

Code cell 9:

```
[ ] seismology.diagnose_numax();
```



- Lightkurve's diagnostic method is used to establish whether or not there is a correlation between

Code cell 10:

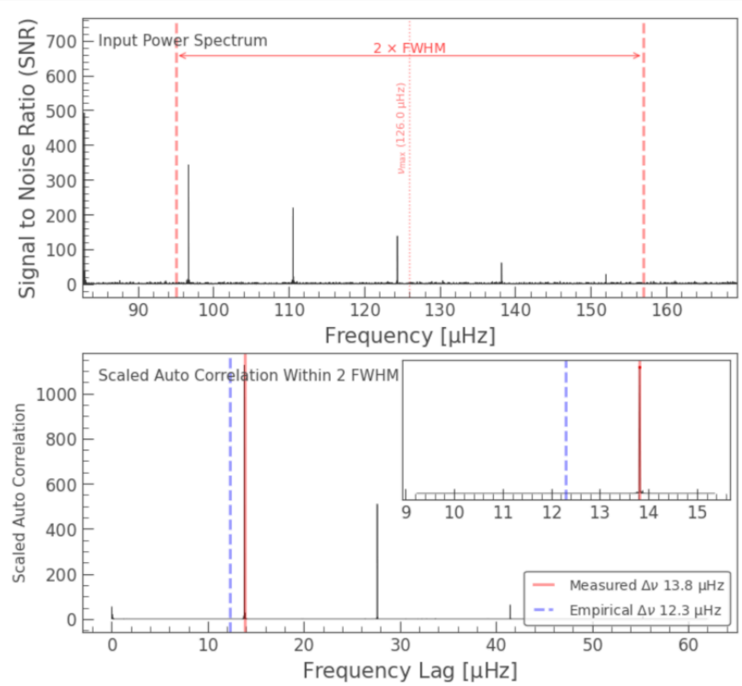
```
[ ] seismology.estimate_deltanu()
```

```
deltanu: $13.82$ $\mathrm{\mu Hz}$ (method: ACF2D)
```

- Lightkurve's estimation function is used, which is a 2d autocorrelation. Its estimate for Δv is then shown.

Code cell 11:

```
seismology.diagnose_deltanu();
```



- Δv is diagnosed, however visually it can be seen that this is not the p-mode envelope.