

Asteroseismology of KIC 7107778

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In this paper I sought to recreate some of the analysis of Li et al.¹ bayesian analysis of the power spectrum of KIC 7107778. In my analysis I fit their same model with semi-informative priors to fit the Gaussian envelope for solar-like oscillations as well as one of the modes of oscillation.

I. INTRODUCTION

In this paper I seek to recreate some of the analysis from Li et al.¹ analysis of binary subgiant KIC 7107778. The purpose of my recreation is purely selfish in my understanding of asteroseismology and bayesian analysis. I will briefly discuss the science of asteroseismology and introduce my data, but I will tend to focus more on my statistical treatment of the data. For more information about the science, reference the original paper¹.

The exigence for studying this binary system is that it provides insight into stellar evolution. Stars that are born together have very similar ages and compositions. This binary system in particular is special because it is unresolved and non-eclipsing. This means that images of it only show one object and that we will not see them cross each other on a scientific timescale. This means that traditional methods of studying binary systems cannot be applied and we have to turn to asteroseismology to get information to study these stars' evolution.

Asteroseismology is the study of how stars' brightness fluctuates. These fluctuations are related to the mechanics and processes that govern the star. There are some stars that have very clear periodicity, often termed as variable stars. The system I am studying is not a variable star, but all stars have some sort of oscillations dependent on interior processes that let us probe stars' interiors.

In order to study these fluctuations astronomers take lots of time series data measuring the flux (energy per area per time). One of the best instruments for taking these is the Kepler space telescope. For this dataset, there exists over 2 years of data sampled about once every minute to analyze and determine the modes of oscillation for this system. This data is then converted into frequency space using Fourier transforms which allows us to see which frequencies are most prevalent in the time-series data, letting us probe the oscillations of the star.

II. DATA ANALYSIS

From the Kepler short cadence data Li et al.¹ have done some preliminary data reduction and have done a Fourier transform of the time-series data. Since the time-series data is not perfectly regular, they have opted to use the Lomb-Scargle method for doing the Fourier

transform. This method is described well in many papers and has been a standard for astronomical time-series manipulation for many years. After the Fourier transform the dataset was also high-pass filtered above 12 μHz and smoothed to 6 μHz . This power spectrum data can be seen in Figure 1.

In order to model this data, we have three major steps

1. Model the Gaussian envelope
2. Analyze the Gaussian envelope
3. Model the modes within the envelope

Once we have the fits of the envelope and the individual modes, the extrapolation of the stellar parameters can be made. I will not be taking this step, but refer to¹ for more information. For all of my modeling I used PyMC3³ which is similar to R's JAGS for probabilistic modeling in python.

A. Gaussian Envelope

The Gaussian envelope model will be taken from Li et al.¹ with the power function

$$\begin{aligned} P(\nu) &= W + R(\nu) \left[\sum_{i=0}^k H_i(\nu) + \frac{H_0^2}{\sigma} \exp \left\{ -\frac{(\nu - \nu_{max}^2)}{2\sigma^2} \right\} \right] \\ R(\nu) &= \text{sinc}^2 \left(\frac{\pi\nu}{2\nu_{Nyq}} \right) \\ H_i(\nu) &= \frac{2\sqrt{2}}{\pi} \frac{a_i^2/b_i}{1 + (\nu/b_i)^4} \end{aligned} \quad (1)$$

W is flat white noise. $R(\nu)$ is the response function which is an artifact of the instrument sampling frequency and the Fourier transform. This modulates all of the expected data from the power spectrum. $H_i(\nu)$ are the Harver power profiles, which are a consequence of granulation on stars' surfaces. Li et al.¹ use three profiles which seems to work well, so I will follow their lead. The last component is the Gaussian envelope. The priors for this model are generally Normal with half-Cauchy for deviation terms². I take the values from Li et al.¹ but leave a higher standard deviation to keep them on target but less informative. Without this I would be afraid of my results overfitting due to both of us using the same data. Here are the priors

$$W \sim N(12, \sigma = 5)$$

$$a_i \sim N([59, 67, 76], \sigma = 20)$$

$$b_i \sim N([5, 150, 400], \sigma = [10, 50, 100])$$

$$H_0 \sim N(17, \sigma = 5)$$

$$\nu_{max} \sim N(568, \sigma = 5)$$

$$\sigma \sim Cauchy(55, 10)$$

The posteriors are listed in Table I and traces are shown in Figure 3.

Once the envelope is fitted, I will manually inspect the data within 2σ of the ν_{max} for modes. I can expect to see “combs” of modes with equal spacing as well as clusters which shows how each stars’ modes are offset slightly from each other.

B. Oscillation Modes

The oscillation modes are modeled as simple Lorentzians modulated by the response function

$$P(\nu) = R(\nu) \left[\frac{A^2/\pi\Gamma}{1 + 4(\nu - \nu_0)^2/\Gamma^2} \right] \quad (2)$$

with Γ being the linewidth and A being the amplitude.¹ I chose 32 frequencies where they wanted to model modes with each mode having 3 degrees of freedom. I could not afford the computational complexity and instead opted to fit only one mode near 477 μ Hz.

$$A \sim N(20, \sigma = 10)$$

$$\nu_0 \sim N(477, \sigma = 2)$$

$$\Gamma \sim \text{half-Cauchy}(2)$$

The posteriors are listed in Table II and the traces shown in Figure 4.

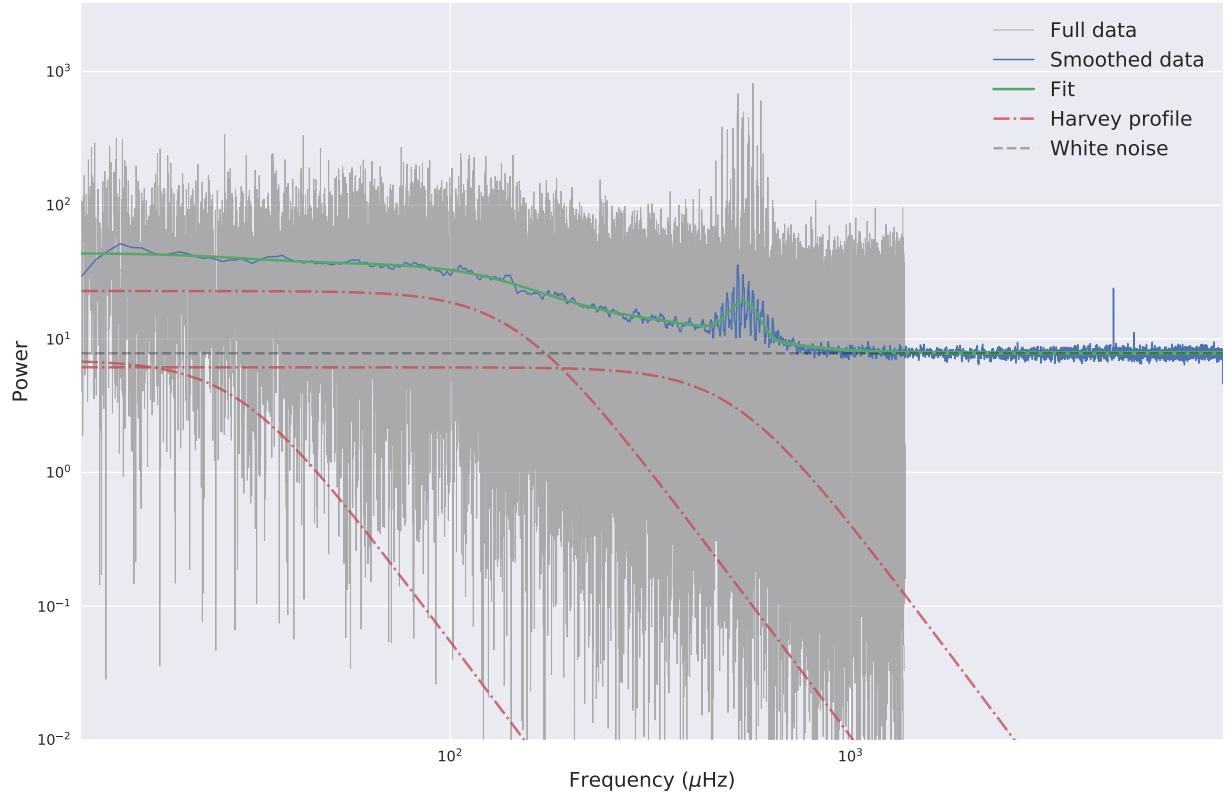


Figure 1. The power spectrum data and fit of KIC 7107778 on a log-log scale. The smoothed data has been smoothed using a $6 \mu\text{Hz}$ Gaussian 1D Kernel and interpolated to a grid with spacing $0.5 \mu\text{Hz}$. The three Harvey profiles account well for the granulation noise. The peaks to the right are the nyquist frequencies of the short cadence data.

III. RESULTS

The fits of the Gaussian envelope are shown in Figure 1 and the single oscillation mode fit is shown in Figure 2. For both fits I took 2000 samples after a 1000 sample burn in. The summary statistics for each posterior are shown in Table I and Table II. One of the parameters of interest for the stellar modeling is ν_{max} , although I am not able to report it because I do not have it split between the two stars effectively.

IV. DISCUSSION

The results of the fitting are not too different from the results of Li et al.¹. I cannot conclude any differences because they do not describe their priors at all and I had to interpolate

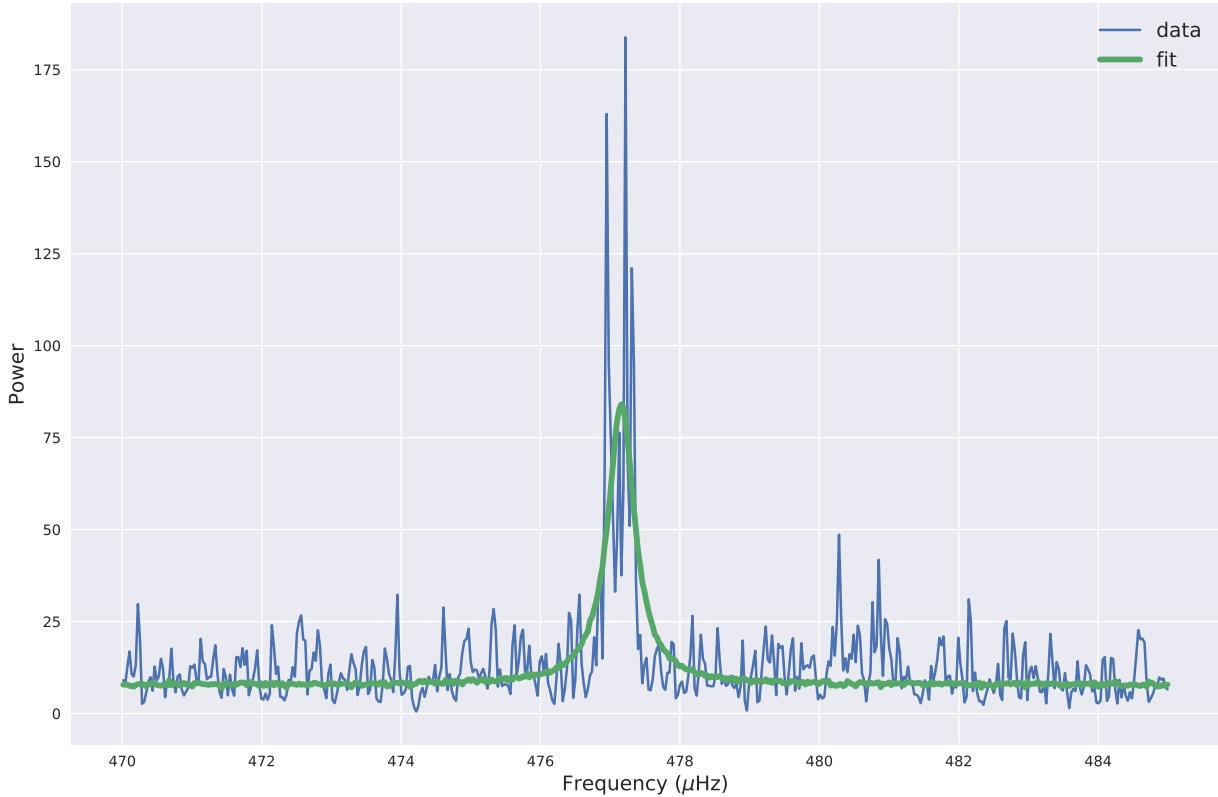


Figure 2. The fit of the Lorentzian to a single mode near 477 μHz

my data. I also cannot comment on the results they receive for the average spacing of modes because I only fit one mode. With that being said, I am very happy with the fact that I was able to fit this model at all given the high dimensionality and modality. The original authors use a completely different package to achieve their samples and I have recreated most of it in python.

I wish I could have better computing power or have the time to learn the DIAMONDS package they use for sampling to recreate their analysis. I would say that the authors models effectively work with the data, though.

ACKNOWLEDGMENTS

I would like to thank Dr. Steve Kawaler¹ for his help in understanding the astronomy behind this problem and for his help in accessing the Kepler data I used in the analysis. I

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Table I. Posterior parameters for the Gaussian envelope fit with 95% HPD interval

	Unit	mean	sd	2.5	97.5
a_0	[ppm]	15.15	0.4591	14.28	16.07
a_1	[ppm]	60.96	0.3549	60.29	61.66
a_2	[ppm]	59.23	0.4772	58.32	60.17
b_0	[μHz]	29.76	1.641	26.61	33.00
b_1	[μHz]	146.6	1.345	144.0	149.2
b_2	[μHz]	514.7	9.656	495.9	533.8
σ	[μHz]	42.57	0.9466	40.69	44.40
W	[$ppm^2/\mu Hz$]	7.808	0.01144	7.786	7.831
H_0	[$ppm/\mu Hz$]	29.82	0.3629	29.10	30.53
ν_{max}	[μHz]	542.2	0.8259	540.5	543.8

Table II. Posterior parameters for the Lorenztian mode fit with 95% HPD interval

	Unit	mean	sd	2.5	97.5
A	[$ppm/\mu Hz$]	7.480	0.2237	7.057	7.938
ν_0	[μHz]	477.2	0.01817	477.1	477.2
Γ	[μHz]	0.2320	0.01872	0.1948	0.2684

would also like to thank Dr. Alicia Carriquiry²for her instruction in the ways of Bayesian analysis and Nicholas Berry² for his instruction and help with debugging my computational models.

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Appendix: Trace Results

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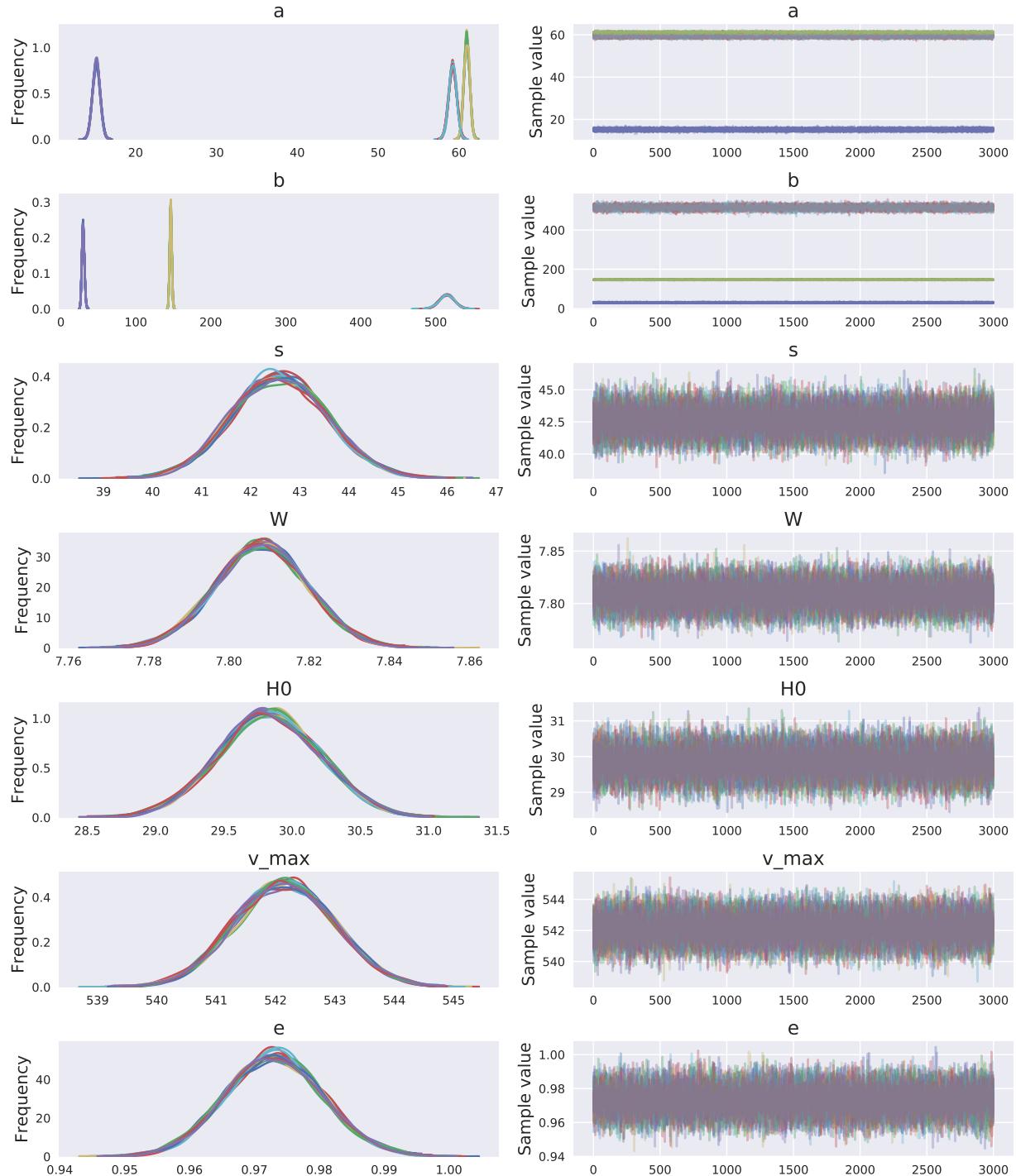


Figure 3. The traces of the envelope fitting.

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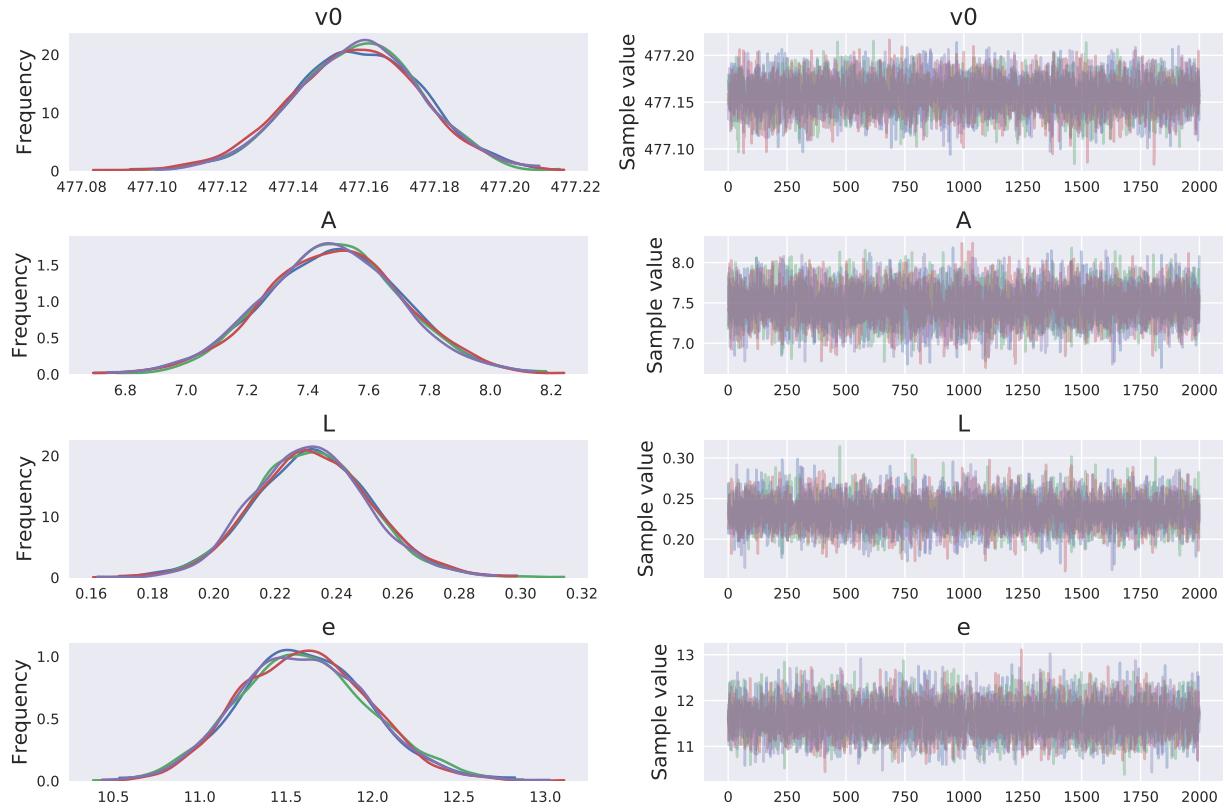


Figure 4. The traces of the mode fitting.