Author: Grace Chiodo

Title: Measuring Stellar Heartbeats: An Asteroseismic Analysis of KIC7431665

Research Summary:

This paper demonstrates the results of an asteroseismic analysis of the heartbeat red giant star KIC7431665. This research utilized photometric data from Kepler from 2009 to 2013. The Lightkurve package was used to create a power density spectrum from these data. A Gaussian fit was applied to a region of excess power, which approximates the envelope that contains the oscillation modes of the star. A triangular filter was applied to the power density spectrum to remove noise. The peak oscillation frequency was obtained by using 2D autocorrelation. Δυ was also calculated by examining one FWHM window on either side of the peak frequency. The mass, radius, and luminosity were determined from scaling relations. Log(g) was also determined. Bootstrapping was used to determine the uncertainties in υ_{max} and Δυ. Lastly, an Echelle diagram was created to examine the oscillation modes, and the diagram confirms the value of Δυ. The results are all within 2% error or less of the values determined by previous papers. Future studies will incorporate binary analysis to further confirm the stellar parameters.

Recommendation: Accept with minor revision

The methodology and contribution to science this paper presents are excellent. The paper only needs a few minor tweaks based on formatting and structure. Also, there are a few places where further explanations are needed.

Concerns:

Major points:

- All in-text citations should be parenthetical and in the proper AAS format: (Name year) rather than (Name (year)).
- The Kepler mission and Lightkurve should both be cited with papers when they are first mentioned.
- More emphasis should be placed on the importance of this study as it contributes to science, especially since the values found are all extremely close to those found in previous literature. What does this study present that others have not, and what does it contribute?

Minor points:

- The author uses “we” and “us” (plural) when there is only one author on the paper.
- Table captions should be above the table, not below, and should be more descriptive rather than just giving the references cited.

Abstract:

- “Their light curves exhibit two forms of variability…otherwise be unobservable” should be stated in the introduction and does not need to be mentioned in the abstract.

- The author states “detailed asteroseismic analysis” but more details should be given on this analysis in the abstract.

Introduction:

- υ_{max} and $\Delta\upsilon$ should be defined and explained in the introduction.

Observations:

- The time over which data were taken should be more specific. The exact dates should be given, rather than the year (“2009 to 2013”).

Stellar Parameters:

- What is winsorization? This should be explained.
- The Lomb-Scargle method needs a citation.
- “The triangular method applies a boxcar filter to another boxcar.” This needs more explanation.
- The definitions of the scaling relations and the definition of g_* should have equation numbers.
- The scaling relations show up at the top of the next page, not after the paragraph where they are referenced.
- The result of log(g) should be given after the method of finding log(g) is explained (at the end of the same paragraph).

Uncertainty Determination:

- This section can be combined with the Stellar Parameters section, and the uncertainty methods can be explained after the determination of υ_{max} and $\Delta\upsilon$ is explained.

Echelle Diagram:

- The process of how the Echelle diagram is made (e.g., did the author specify 5.47 uHz to make the diagram or did Lightkurve determine this?) and what it means should be explained a bit more.

Discussion:

- The percent differences should also be placed in new columns in Table 2 to facilitate comparisons.
- “A unique feature of heartbeat red giants is that they exhibit two forms of variability…” This sentence should be in the introduction, not the discussion.

Evaluation of Criteria:

Is the length appropriate?

Yes, the length is appropriate.

Are the title and abstract sufficiently informative?

The title is sufficiently informative. The abstract could use more specifics on the analysis performed.

Is the contribution to science significant?

The contribution to science is significant. The use of recent Kepler data provides important updates to the stellar parameters of the target star. However, more emphasis should be placed on this importance on the paper.

Is level of English adequate?

The level of English is adequate.

Is the literature properly cited?

The author should cite the missions and packages referenced in the paper (Kepler and Lightkurve).

Are the results clearly and accurately presented?

The results are clearly and accurately presented.

Is the topic appropriate for the journal?

The topic is appropriate for the journal.

Data Management Plan:

The data and packages used are all available online, and the results are available in the paper and in a table. Therefore, the results are reproducible.

Additional Comment: The author did an excellent job with this paper!

Peer review report

Title: Measuring Stellar Heartbeats: an Asteroseismic Analysis of KIC 7431665

Author: Grace E. Chiodo

Summary

The study focuses on determining the fundamental parameters (mass, luminosity, and log(g)) of the heartbeat binary KIC 7431165 by employing asteroseismic analysis with Kepler data. The author uses *LIGHTKURVE* package as a main code for the study. After reducing flux variations that are unrelated to the solar-like oscillations, the Kepler data was put into the Lomb-Scargle method to return a periodogram. The author utilizes the autocorrelation function to determine the frequency with the highest correlation power - $\nu_{max} = 54.5 \pm 0.4\,\mu Hz$. From this value, the *LIGHTKURVE* package determines $\Delta\nu$ to be $5.47 \pm 0.01\,\mu Hz$ by evaluating one full-width-half-max window on either side of ν_{max} in the power spectrum. Using ν_{max} and $\Delta\nu$, the author calculates the radius, the mass, the luminosity, and log(g) of KIC 7431165. The uncertainties of these parameters are determined by a bootstrapping resampling process. Moreover, the author generates an Échelle diagram and confirm the value of $\Delta\nu$, thus further verifying the accuracy of other parameters. Lastly, the computed parameters are compared with the literature. The percent differences between this work and two others are smaller than 2% for all calculated values.

Recommendation: accepted with minor revisions.

Justification

a. Major points

- Introduction:
  - *"Beck et al. (2014) conducted an asteroseismic study … The sample included the heartbeat binary KIC 7431665."*: the author should discusses more clearly what are the differences between her method and Beck et al.'s method because they both study the same object by using asteroseismology.

- Uncertainty Determination:
  - *"The error propagation calculations for the scaling relations sum the squares of the propagation of errors for each variable from this study that contains error…"*: the exact equations should be included. Also, the scaling relations are not a linear function of ν_{max} and $\Delta\nu$, thus I think the error of the scaling relations should not be calculated the way the author point out. The author can refer to the "Simplification" section in this link https://en.wikipedia.org/wiki/Propagation_of_uncertainty for the relationship between errors. If this is not what the author means, the author should explains it clearer.

b. Minor points

- Abstract:
  - *"… we conducted a detailed asteroseismic analysis of KIC 7431665 …"*: the author should add the term "heartbeat binary" before "KIC 7431665" to emphasize the type of the object.
  - The author should state by words what all mathematical notations are (for example, Radius R, mass M, etc.)
  - *"We hope future studies will conduct a … oscillation mode."*: I think this should not be in the abstract. The abstract should focuses on the analysis and the result of the work, rather than suggestion/ expectation for further studies.

- Introduction
  - *"… from the discovery of red giant heartbeat stars."*: need citation for the discovery.
  - *"Convection in the envelope generates solar-like oscillations via the …"*: the author should briefly explains what a solar-like oscillation is or what is its mechanism.
  - *"In the case of red giants ... largest amplitudes in the core."*: need citation.
  - *"... derive from various scaling relations."*: the author should briefly explain what scaling relations mean.
  - *"The scaling relations for stellar mass … from the power spectrum."*: need citation.

- Observation
  - *"The effective temperature applied in this study is 4580K …"* : the author should explain why and how the effective temperature is applied to this study (i.e what do we need it for?).

- Stellar Parameters
  - *"We combine the individual light curve … all observation windows"*: the author should refer to her Figure 1 after this sentence.
  - *"We remove these eclipses by winsorization …"*: the term "winsorization" should be explained clearer. Also, I think the author should include two light curves before and after the winsorization reduction so we can see what the winsorization's effect on the light curve is.
  - *"The LIGHTKURVE packages…"*: need citation for the package.
  - *"... the Lomb-Scargle method…"*: need citation for the method.
  - *"We remove this noise by flattening the power spectrum with a triangular filter…"*: the author should show a flattened power spectrum in the paper.
  - *"… for KIC 7431665 with the following scaling relations: …"*: the equations should be listed right after the colon (instead of on the next page) – format problem.

- Uncertainty Determination
  - *"… and the generate a random sample from that data."*: the author should explain clearer what she means "generating a random sample from that data". For example,

what distribution that random sample follows, or what parameters of the sample are taken from the data.

- Échelle Diagram:
  - A brief explanation of the purpose of Échelle diagram should be given. Also, the author should explain what each axis in the Échelle diagram represents.
  - *"The diagram indicates oscillation modes of l = 1,2, and 0 corresponding …"*: what is the oscillation mode l? The author should explain it along with the explanation of oscillation modes p and g in the introduction.

- Discussion:
  - *"For the comparison to Beck et al (2014) … For the comparison to Manuel & Hambleton (2018) …"*: the author should briefly mention the methods of Beck et al (2014) and Manuel & Hambleton (2018) to understand why the results are slightly different.
  - *"An interesting binary analysis would …"*: I don't think "interesting" is a good word to use in this sentence.

- Conclusion:
  - *"The uncertainty ranges result from the standard error and error propagation."*: the author should also briefly remind the readers that bootstrapping resampling process is the method to calculate the standard error.

Evaluation

The length of the paper is appropriate and the topic is appropriate for the journal. The title and the abstract convey the content of the study. The contribution to science is significant. The English in the paper is easy to follow, however, some citations are missing in the paper. The author should also pay attention to the citation format. It should be (author year) rather than (author (year)). The result is well stated, especially with Table 2. Regarding the Data Management plan, the author uses the data from Kepler, which is already publicly accessible.

All my comments are constructive reviews and sometimes they can come from personal preference or personal experience. Please understand if I misunderstand the author in some points. Also, please send my congratulation on the author's work and I enjoy reading the paper.

Author: Grace Chiodo

Title: Measuring Stellar Heartbeats: an Asteroseismic Analysis of KIC 7431665

Summary:

This study conducts an asteroseismic analysis of the red giant heartbeat binary KIC 7431665. Photometric observations were obtained from the Kepler spacecraft. First, the binary system exhibits large brightness variations due to binary motion. These variations were removed to study just the pulsations. Using Lightkurve, a power spectrum was created, and the region of excess power was studied. Through autocorrelation methods, the values of $\Delta\nu$ and ν_{max} were determined, and system parameters were calculated using various scaling methods. Uncertainties for $\Delta\nu$ and ν_{max} were determined using bootstrapping and error propagation was conducted to obtain error ranges on the stellar parameters. Lastly, for the analysis, an Echelle Diagram was created to analyze the pulsation modes for KIC 7431665.

Rating: Accept with Major Revision

Minor Revisions:

- Throughout the text, there are instances where in text citations are not placed in parenthesis when they should be
- There are many technical details in the introduction that are mentioned with no explanation. Why do p modes dominate solar like oscillations in the convective envelope while g modes have large amplitudes in the core for red giants? How does temperature determine the oscillation mechanism of a star? There are many statements in the

introduction that should be explained further. This happens again in Section 3 with certain details or features that are mentioned but not explained. For example, what is winsorization and the region of excess power?

- Equation 1 is not placed in the correct location. There seems to be a break in section 3 where the equation would go but then the equation is displayed on the next page. Also, the solar symbol, $\odot$, should be placed in the subscript, not the superscript.
- The Echelle diagram needs to be better explained. It is hard to understand what is actually being plotted and what this plot demonstrates.
- In the Discussion, there is a comparison to the results of Manuel & Hambleton (2018). Did they also study KIC 7431665, are there values for $\Delta\nu$ and ν_{max} determined for KIC 7431665?

Major Revisions:

- There needs to be a larger, in-depth discussion of Heartbeat red giant stars. There is very little stated on these stars even though the project is an asteroseismic analysis of heartbeat binaries. There needs to be more stated about the theory of these objects and a better literature review on the physics of Heartbeat stars.
- There are many citations missing. There needs to be a citation for Kepler and KIC and also all the programs used, including Lighkurve, Lomb-Scargle, bootstrapping etc.
- There is not much to distinguish this paper from the previous studies conducted on KIC 7431665. There seems to have already been two in depth asteroseismic studies on the target that already used Kepler data. This study seems to have just repeated their analyses. The results seem to confirm this as all the determined values are very similar to

the values in the literature. There needs to be something else added to separate this study from what has already been done. Perhaps a discussion/analysis of internal structure or the oscillation modes. I also wonder if there are any other sources of new observations (perhaps TESS). It seems like asteroseismology has already been conducted on this star with the Kepler observations, a study with new measurements would be interesting to reconfirm the literature parameters or analyze any changes. As of now, it is unclear why another asteroseismic study on the Kepler data is needed.

- In the beginning of section 4, one of the results of this project is that it "demonstrates the necessity for single-star studies in refining the results of pipeline projects …". I feel that this result is not met by this study. As stated before, this study conducted asteroseismology using the same data as other studies, and therefore there were minimal changes in the parameters determined. Since the determined parameters are so close to the previous values, this claim does not hold.

Evaluation of Criteria:

Is the length appropriate?

- Additional analysis or discussion would be beneficial to add

Are the title and abstract sufficiently informative?

- Yes, the title is catchy and informative, and the goals and results are stated in the abstract

Is the contribution to science significant?

- While the analysis is in depth and scientifically minded, this paper does not seem to contribute new knowledge. It conducted a similar analysis on the same dataset as two

previous studies. Something should be added to improve the scientific merit of this paper. Potential suggestions are listed above

Is the level of English adequate?

- Yes

Is the literature properly cited?

- The background given in the introduction on asteroseismology is rooted in literature. As stated before, there needs to be citations given for the programs used in this study. There also needs to be a better literature review of the theory and physics of heartbeat binaries

Are the results clearly and accurately presented?

- Yes, the numerical results are clearly listed in a table

Is the topic appropriate for this journal?

- Yes

Data Management Plan

- The results and numerical data produced in this study are accurately displayed within tables

Additional Comments:

- This study was very interesting and in-depth. I would like to thank the author for all their hard work in producing this paper.

Note to the Editor – Grace

To the Editor-

I stand by my review of this paper, the editor is free to disclose my identity to the author, should it be requested. I did not find any truly significant issues with this paper. The research itself is easy to follow and the author makes a point at confirming why this research is important in larger significance. There were a few minor points where I would have appreciated clarification of certain terms or concepts, but otherwise, I found no fault with it. I would certainly recommend the publication of this paper due to its importance in the study of stellar astrophysics. The implications of this research have the potential of being very significant in future stellar modelling and analysis programs.

Best regards,

Danielle Mortensen

Grace Review

Summary:

The author conducts a study of the stellar heartbeat binary KIC7431665. They use *Kepler* data to generate lightcurves and from here analyze the power spectrum. From the power spectrum, the author can determine the modes of oscillation, and from here the program *Lightkurve* is used to determine a value for v_max, the peak frequency of the excess of oscillation power. The value of v_max is then used to calculate delta v, and between the two values, estimations of the red giant mass, radius, luminosity, and surface gravity can be made. The values for these are R ~ 9.58 solar radii, M ~ 1.43 solar masses, L ~ 36.2 stellar luminosities, and log(g) ~ 2.63 dex. Uncertainties on these values are calculated using bootstrapping, and an Echelle diagram confirms the stellar oscillation modes, l = 1, 2, and 0.

Recommendation:

I would recommend that this paper be **accepted with minor modifications**.

Justification:

- *Major Points:* None.
- *Minor Points:*
    - Introduction: "…red giant dominates the observational properties of a heartbeat binary unless the companion star is of high density, such as a white dwarf."
        - It may be helpful to characterize or just mention the companion star in this binary system. I was left wondering what type of star the companion was and if/how it affected the system as a whole.
        - Do we not know much about it? Can we infer anything about it by studying the red giant?
    - Observations:
        - A question of little concern, but is there a reason why the author did not consider more recent *TESS* data over *Kepler* data?
    - Seismic Analysis: "…provides the normalized flux with corresponding BKJD days…"
        - "BKJD" is never defined here. Assuming it's a certain type of Julian Date?
    - Seismic Analysis: "We remove these eclipses by winsorization of all normalized…."
        - "Winsorization" is also not a commonly used term and may be beneficial to define.
    - Seismic Analysis: "…shifts windows of 25 μHz along the data to evaluate the correlation of the data with itself."
        - Is there a reason the shift is by 25 μHz? Is this just a small enough frequency shift to find the correlation?

- Seismic Analysis: "The diagram indicates oscillation modes of l=1, 2, and 0 corresponding to the ridges from left to right."
  - I wish the author would have described what "ridges" mean in reference to this diagram. Are they at the points when the SNR is highest?
  - In addition, what is the significance of these oscillation modes? What do the numbers 1, 2, and 0 mean?
- Seismic Analysis: "…verifies that we can confidently perform calculations dependent on…"
  - Why is the author confident of performing actions on delta v from the observation of these ridges?

Evaluation:

- *Is the paper length appropriate?*
  - Yes. The paper seemed to explain everything in depth but also maintained concise wording.
- *Are the title and abstract sufficiently informative?*
  - Yes. The title was very informative of what the study is about, and the abstract accurately explains the premise of the problem and the findings of the research.
- *Is the contribution to science significant?*
  - Yes. I was hesitant to say that the findings were quite significant in nature, however the author explains in their Discussion section that this will help to refine results of pipeline projects which frequently generalize astrophysics to include most of the stars analyzed in their programs. After understanding this significance, the research seems much more suggestive than previously thought!
- *Is the level of English adequate?*
  - Yes. Quite easy to read and understand.
- *Is the work properly grounded in literature?*
  - Yes. Particularly the work done in the introduction while explaining stellar heartbeat stars and then further throughout the paper the literature on KIC7431665 are more than adequate.
- *Are the results clearly and accurately presented?*
  - Yes. The results are clearly laid out in the abstract, the analysis, and the conclusion sections.
- *Is the topic appropriate for the Journal?*
  - Yes. The author's research is a clear fit for this Journal being on the topic of stellar analysis.
- *Is the data management plan good?*
  - The author does not really address a data management plan, however they do explain where all of the data came from (Kepler Input Catalog) and what primary software was used to do the analysis (Lightkurve). From this, it would seem that the research is perfectly repeatable in nature.

Final Comments:

This is a fantastic paper on a very special target! I was excited to hear about all of the future applications of this research. The author makes the process sound simple and intelligible, and argues a good point for using asteroseismology on future projects. I hope these comments are accepted as constructive criticisms and the author finds them helpful. My best wishes in their success!

Summary:

This paper details an asteroseismic analysis of the heartbeat binary KIC7431665. Observations from the *Kepler* spacecraft covering Q0-Q17 from 2009 to 2013 were used to create a light curve spanning all observations. The eclipses present in the light curve were removed and the resulting curve was converted to a power spectrum. The LIGHTKURVE package was used to construct a periodogram from the light curve data. The power spectrum was renormalized, and the region of excess power focused on. Background noise was removed using a triangular boxcar filter application. The flattened power spectrum was run through an autocorrelation function to measure the correlation of the data with itself. The frequency with the highest correlation power is the maximum frequency v_{max} and is used as the center point to calculate Δv. These parameters were used to calculate the mass, radius, log(g), and luminosity of KIC7431665. Error bars were provided by bootstrapping analysis. An Échelle diagram was generated to determine oscillation modes of l=1,2, and 0. Percent differences for the values of v_{max} and Δv were compared to values from literature. The author describes how future studies could yield more accurate and detailed information about the target.

Recommendation:

Accept with minor revision

Points of Consideration:

Major:

None

Minor:

Tables could use descriptions

A brief description of the LIGHTKURVE package might aid in understanding. Is it standalone software or part of some other program

Plot size can be increased for better clarity and detail

Unclear how the Échelle diagram indicates modes of l=1,2, and 0

Paper would benefit from an additional proofread

Evaluation:

Length:

Length is appropriate

Title and Abstract Sufficiency:

Both title and abstract sufficiently describe the research conducted

Contribution to Science:

The paper not only provides an additional analysis on a *Kepler* object, it also provides a detailed case on the validity of this method of analysis

Level of English:

Paper is easy to read, and language used is understandable

Literary Citations:

All credit is given where due. Introduction and values used are all properly cited

Clarity and Accuracy of Presentation:

Results and process are clearly worked out step by step with all determined properties clearly listed and labeled

Topic Appropriate for Journal:

The topic of this paper is appropriate for this Journal

Data Management Plan:

All data is publicly accessible as well as software used. Process is repeatable

Additional Comments:

This paper is very well constructed. The presentation of necessary background information as well as the process by which the analysis was carried out is clearly described. In the hope that the author accepts these comments, I accept the author's work and compliment them on their hard work and results. My strongest compliments to the author.

Summary

The author first describes what heartbeat stars are and how they provide astronomers with an opportunity to perform asteroseismic analyses. She then goes into detail about the science behind stellar oscillations and how we are able to obtain more extensive measurements of binary characteristics. Then the author describes the modes of oscillation and says how they are important in learning about the internal processes of stars. After, she mentions a preliminary study of heartbeat stars that include the star system in question. In the analysis, she first obtained light curves and eliminated flux variations unrelated to the oscillations. She then converted the light curve to a power spectrum to look at the signatures of solar-like oscillation modes and obtained the frequency of excess oscillation power through autocorrelation. She uses specific scaling relations to then reveal the radius, mass, and luminosity of the star and performs an error analysis. Finally, she creates an Echelle diagram (I am not really sure what this is based on the explanations in the paper). In the Discussion, she explains that the calculation of these parameters are a good first step in future research projects about this heartbeat system.

Recommendation

Accept with minor revision.

Justification of Recommendation

Major points:

1. The only major point I have is that there are many things that very much need additional explanation. Even though this is meant for experts in the field, there are numerous points which I did not at all understand and need clarification, which I will list here.
    a. The author mentions multiple times an “asteroseismic analysis.” What does this entail? Is it a general method of analysis with specific steps to follow or does it differ for each scientist?
    b. What are scaling relations?
    c. In Seismic Analysis, what are BKJD days?
    d. The author states that “the triangular method applies a boxcar filter to another boxcar.” What is the triangular method? What is a boxcar filter and what does she mean she is applying it to another boxcar?
    e. I do not really understand the entire explanation of autocorrelation. What it is and the point of it I think should be explained more clearly.
    f. What is $\Delta\nu$? I do not think it was defined or explained until the very end of the paper.
    g. Regarding the Echelle diagram, I am not sure if this is because I am not an expert in this field, but I am not completely clear on what it is based on the explanation the author provides. More specifically, what is the point of it and what is it supposed to be showing that is relevant to the project?

Minor points:

1. In the abstract, the author lists the results of the study; however, I am not sure about what some of the variables / units mean.

2. There are some instances of incorrect grammar and odd wording, so the author should proofread again.
3. In Table 1 and Table 2, the only thing in the caption is the references. I would like to see more information about what the tables themselves are showing rather than just the references.
4. In the introduction, there is very little background information about the star system itself that is being studied, aside from a few parameters pulled from another paper. It would be beneficial to the reader if the author described the system a little bit more so I have more context about what is being done.
5. I think there should be more information about the data reduction and processing done on this data, if it is available somewhere.
6. The software used should be specified. I know that it is Python, but it is still important to state in case someone does not.
7. All the equations could be formatted a little bit better and actually labeled as equations.
8. Two big studies are mentioned that the author compares her results to. However, I do not know what these studies did. In order to trust that the results can actually be compared, there should be more information about the studies so I know more about the data used, methods, etc.

Evaluation

1. Paper length
    a. The paper is an appropriate length, besides a few things mentioned in the major points that need some additional explanation.
2. Title & abstract
    a. The title and abstract are both very representative of the paper. The abstract explains very well what the paper aims to do and the results.
3. Contribution to science
    a. This project definitely provides a major contribution to science, and will be even more complete once the future studies mentioned in the paper are carried out.
4. Level of English
    a. The level of English is adequate for the most part. I do understand what the author wants to say, but some places could be a little bit clearer.
5. Literature
    a. There is extensive literature used and cited throughout this entire work.
6. Presentation of results
    a. The results are clearly presented in the tables with errors, and they are a direct representation of the methodology described.
7. Topic appropriateness
    a. The topic is appropriate for the journal.

Data Management

The results are reusable for future analyses. I am not sure if the pipeline she wrote for analysis would be available so that the methods used could be corroborated by others or reused in any way.

Additional Comments

This was clearly a complicated study done in a very short amount of time, so congratulations to the author for completing it and coming out with solid results.