Analysis of the Gravity Mode of a Pulsating Doradus-type Star

F. Davoudi, D. Jassur

JOURNAL OF OCCULTATION AND ECLIPSE (JOE)
ISSN 2522-7955
No. 6, 2019

Analysis of the Gravity Mode of a Pulsating Gamma Doradus-type Star

F. Davoudi[1], D M. Jassur[1]
[1]Department of Theoretical Physics and Astrophysics, Tabriz University, Tabriz 51664, Iran

Abstract
In recent decades, asteroseismology has become a powerful tool in checking models for the structure and evolution of stars. From the perspective of asteroseismology, pulsating stars are invaluable. For this type of star, γ Doradus-type stars have a special feature. Since the atmosphere of such stars is in the transition phase from radiant state to convection state, gravity mode oscillations are visible in these stars. Since gravity modes are originated from central stellar regions, detecting them provides valuable information about these regions.

In this study, photometric data of KIC11826272 provided by the Kepler satellite has been analyzed. The gravity mode's pattern and the average period have been determined. Deviation from the uniform ΔP in the form of a pattern is due to the mean rotation of the star. The rotational frequency splitting effect has increased the gravity mode's frequency. A decaying deviation found in the pattern represents prograde modes that are moving in the direction of rotation of the star. Finally, the degree of gravity mode has been determined.

Keywords: Asteroseismology, Gravity modes

Introduction

Uncertainties happen for the theoretical modeling of structure and evolution of stars near the intersection of the red edge of the classical instability strip and the main sequence in the Hertzsprung-Russell diagram. Theoretical modeling of the evolution of stars depends on the chemical composition of stars and their interfacial processes (Miglio et al. 2008). This applies to those main sequence stars with an intermediate mass ($1M_\odot < M_* < 2M_\odot$). This is the transition range from low mass stars with a radiative core and a convective envelope to high mass stars with a convective core and a radiative envelope (Van Reeth et al. 2015). A good way to calibrate and improve upon the existing stellar structure and evolution theories in this mass range is to conduct a detailed seismological study of γ Dor pulsators. Such stars are slightly more massive (1.4–2.5 $M_\odot$) and more luminous than the Sun and exhibit non-radial gravity mode pulsations (Kaye et al. 1999). The pulsations, which have a typical period between 0.3 and 3 days and are excited by the convective flux blocking mechanism at the bottom of the convective envelope, probe the internal stellar structure of the stars up to the edge of the convective core (Guzik et al. 2000).

In this study we looked at a star of this type named KIC11826272. We used the four-year high-precision Kepler photometry; the details of photometry are mentioned in Data Sets section below. In the Method section we described the basis of the study and the methodology. In the Data Analysis section we summarized the analysis of the star. Finally, in the Conclusion section the degree of gravity mode has been determined and the realized decaying deviation in the pattern represents prograde modes that are moving in the direction of rotation of the star.

Data Sets

KIC11826272 (also known as BD + 493115) is one of the stars that has been observed by the Kepler mission. Kepler light curves for this star are long cadence, i.e., with an integration time of 29.4 minutes. Data has been collected over a time interval of 1470.46248 days and marked for 18 quarters from Q_0 to Q_{17}. Each light curve contains a set of 429 frames. The time that the camera remained open to collect flux from a target sample is 6.02 seconds for this star. The time it takes for each data set to be logged is 0.52 seconds with a frequency equivalent to the time of sampling of the landing flux $f_{nyq} \approx 283\ \mu\mathrm{Hz}$ and power of frequency separation $f_{res} = 0.00068\ d^{-1}$.

Method

In this project we used the traditional signal-to-noise ratio (SNR) method with code written on the target pixel file of the star. The file contains approximately 90,000 data points and was obtained based on the observed time and relative magnitude. Then, the possible oscillating frequencies from 90,000 frequencies have been found by the "prewhitening method". The prewhitening method is based on the Lomb-Scargle periodogram method; the details were provided by Timothy Van Reeth and his colleagues in 2015 (Van Reeth et al. 2015). The result has been the introduction of 511 possible oscillatory frequencies (Ershadi et al. 2015). After determining the frequencies, the next step was to interpret them which will then lead to finding the oscillating modes of the star.

A Fourier transform was applied in the interval 0-3 days for the period and in the interval of $0 - 3\left(\frac{1}{days}\right)$ for the frequency are shown in Figure 1 and Figure 2; that includes 90,000 frequencies in the background (blue lines) and 511 frequencies selected on it (black lines). The vertical axis is the amplitude (Amp) and the horizontal axis is the frequency or period.

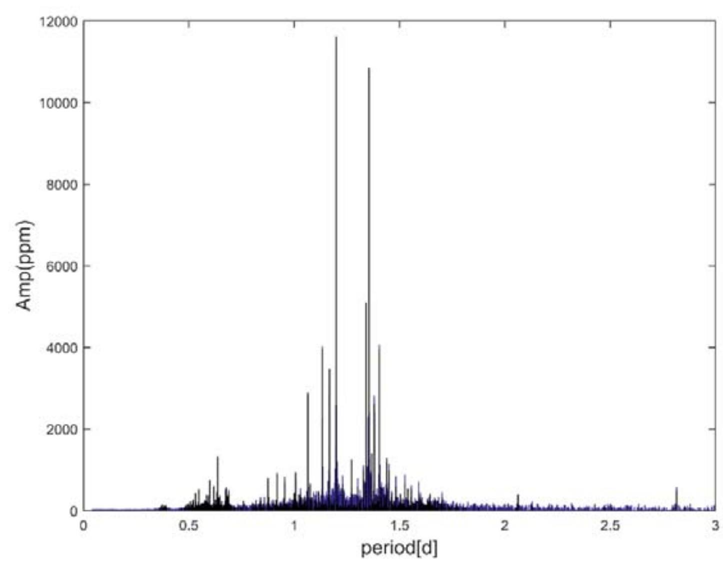

Figure 1. Period spectrum of KIC 11826272. Fourier transform applied in the interval $0 - 3\ days$.

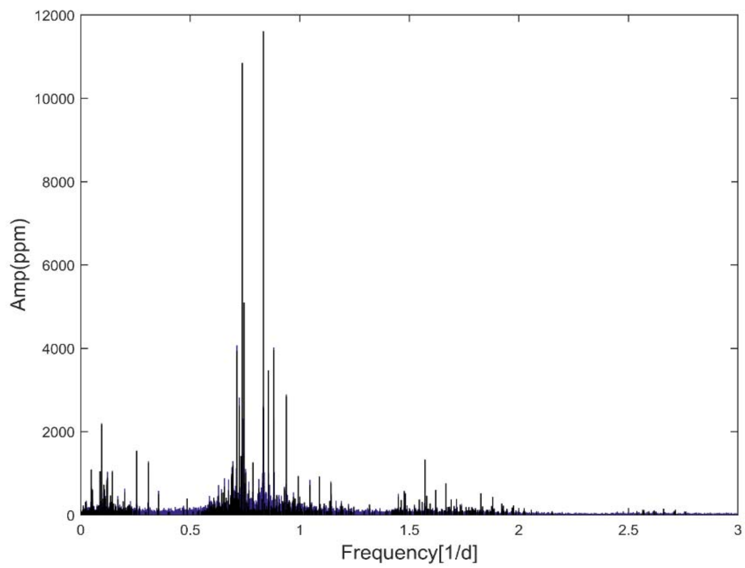

Figure 2. Frequency spectrum of KIC11826272; Fourier transform applied in the interval $\mathbf{0-3}\ \left(\frac{1}{d}\right)$.

Data Analysis

Since these stars are at the lowest part of the unstable strip they can be observed in both pressure mode and gravity mode (Aerts et al .2010). In our case, the target star has only significant frequency changes in the low-frequency region, gravity mode. High-frequency areas were also investigated and no significant peak exceeding 100 ppm was observed. In addition, to ensure that the other peaks observed are not related to pressure mode they can be examined if they are other than synthetic frequencies. Below we showed that no oscillation frequency occurred in the region exceeding 1.7 days. So again we conclude that there are only gravity modes.

Nonlinear pulsation effects can manifest themselves in the Fourier spectrum as combination frequencies and harmonics of a few parent frequencies. There is a formula for hybrid frequencies where n and m are small integers, f_i and f_j are the parent frequencies, and f_k the combination frequency (Schmid et al. 2015):

$$nf_i + mf_j = f_k \qquad n + m \leq 2 \qquad (1)$$

$$\left(nf_i + mf_j\right) - f_k < f_{res} \qquad (2)$$

To find hybrid frequencies, we selected frequencies with $SNR > 3.8$ and amplitudes above 800 ppm as the source frequencies. We applied relation (1) by applying the condition of relation (2) where k and j are members of the source frequencies, while i can be the residual member of the frequencies. We found 394 hybrid frequencies, which we illustrate as their equivalent periods in Figure 3. The vertical axis is the amplitude and the horizontal axis is the period.

The Fourier transform, which is the basis for the prewhitening method, generates harmonic frequencies that are multiples of the basic pulse frequencies. These multiples can be from two to four times the original frequency according to relation (1); eight harmonic frequencies are shown in Figure 4. The vertical axis is the amplitude (Amp) and the horizontal axis is the frequency.

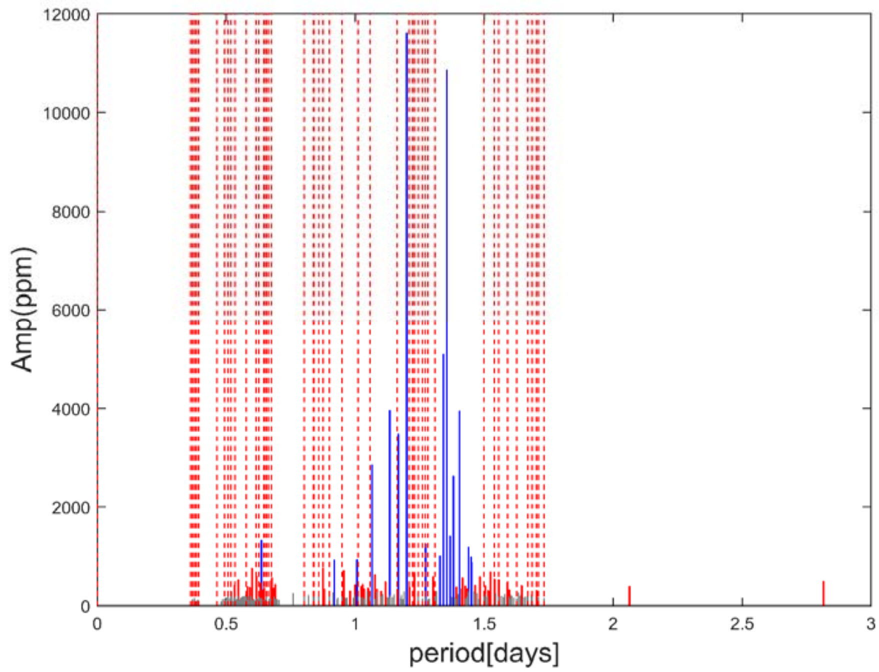

Figure 3. Hybrid frequencies of KIC11826272.

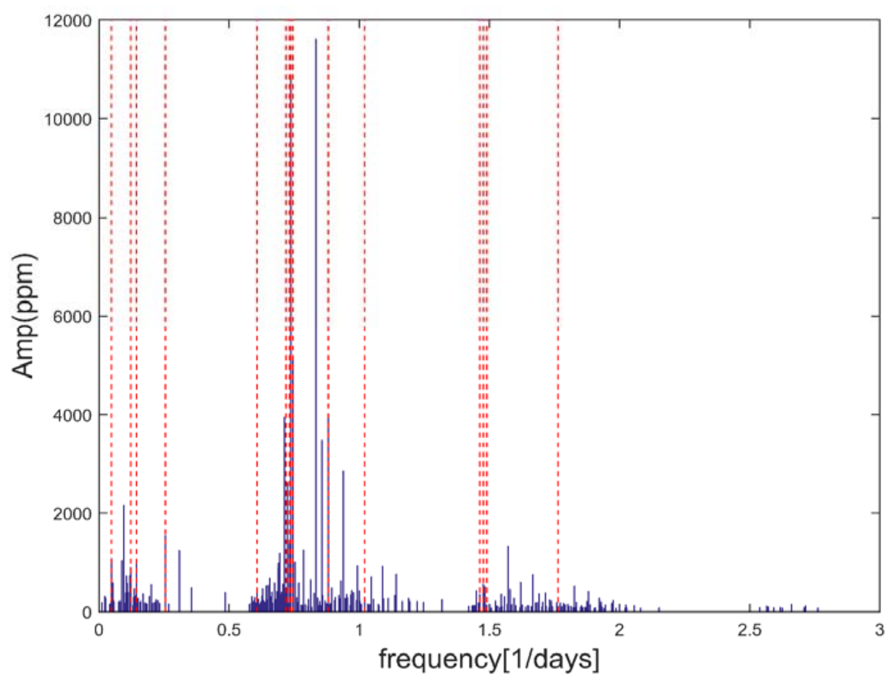

Figure 4. Harmonic frequencies of KIC11826272.

In the first-order asymptotic approximation of a non-rotating star the periods of high order ($n \gg l$) gravity modes in stars with a convective core and a radiative envelope (Tassoul 1980) are defined as

$$P = \frac{2\pi^2}{\sqrt{l(l+1)}\int_{r_1}^{r_2}\frac{N}{r}dr}\left(n + \alpha_{l,g}\right), \quad (3)$$

Here $\alpha_{l,g}$ depends on the boundaries of the trapping region, P is the oscillation period, r the distance from the stellar center, and N the Brunt-Väisälä frequency. Following this relation modes with the same degree l, but consecutive orders n, are equidistantly spaced in the period. Their spacing value ΔP is then given by

$$\Delta P = P_{n+1} - P_n = \frac{2\pi^2}{\sqrt{l(l+1)}\int_{r_1}^{r_2}\frac{N}{r}dr} \quad (4)$$

As a result, the expected period spacings for different l -values will have fixed ratios.

For this work we found periods with $SNR > 3.8$ which had distinct intervals from their next period and then we looked for a regular iterative pattern. This procedure is performed by examining each period and is repeatedly tested to confirm or reject the obtained ΔP. The relationship between the found l is proportional to the ΔP ratio of spherical degrees 1 and 3. On the other hand, according to the same theory, the ratio of smaller degree modes to larger degree modes should be greater than one, so smaller degree modes have a larger ΔP. Two patterns are evident for the star's gravity mode, which are shown in Figure 5, with separate intervals.

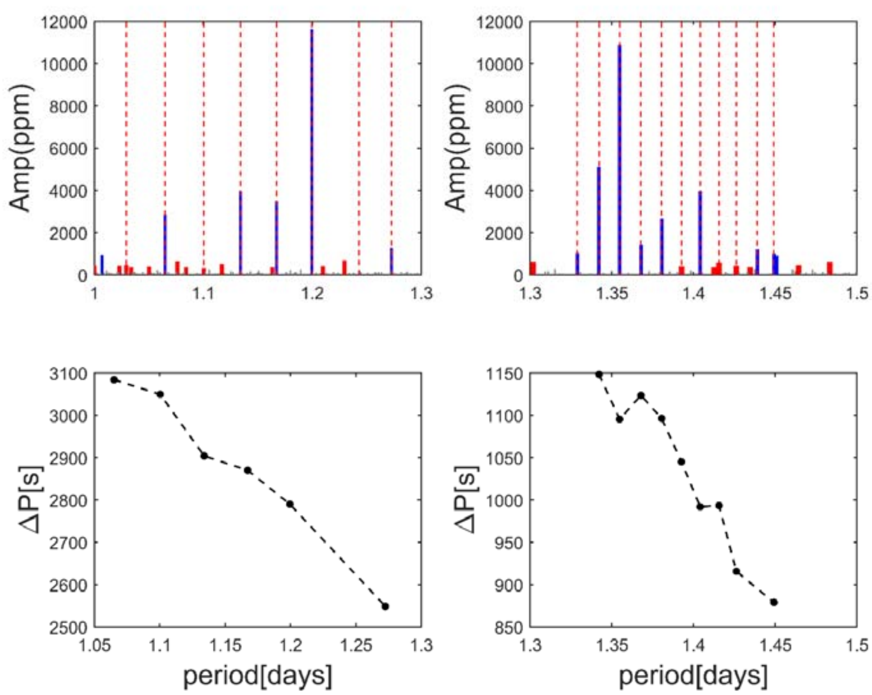

Fig 5. The prograde period spacing patterns of KIC11826272.

Conclusion

The combination of frequencies was determined by two degrees of mode $l = 1$ and $l = 3$ for star pulsations. For $l = 1$, eight gravity mode frequencies are involved in the pattern whose ΔP is 2870. For $l = 3$, eleven gravity mode frequencies are involved in the pattern whose ΔP is 1032.

The deviation from the constant ΔP is due to the star's rotation or different layouts of star's density. If the star's rotation speed is too low and the star layering is almost uniform in the structure the gravity modes of the star do not frequency shift. But if this deflection is affected by the medium to fast rotation of the star or the star layering does not have a uniform structure, the gravity modes of the star do frequency shift. Consequently, the deviation from the constant ΔP intensifies and the pattern will appear in ascending or descending form (Van Reeth et al. 2015). The descending pattern of our star (prograde mode) is due to placing the mode in the lower frequencies.

Acknowledgments

This research was supported by Department of Theoretical Physics and Astrophysics, Tabriz University, Tabriz, Iran. We would also like to show our deep gratitude to Timothy Van Reeth (Institute of Astronomy, KU Leuven) for the permission he has given us to use the relevant Python code for this project. Furthermore, thanks Atila Poro (The President of IOTA/ME) for his guidance and assistance to publish this paper.

References

Miglio, A., Montalbán, J., Noels, A. and Eggenberger, P., 2008. Probing the properties of convective cores through g modes: high-order g modes in SPB and γ Doradus stars. *Monthly Notices of the Royal Astronomical Society*, *386*(3), pp.1487-1502.

Van Reeth, T., Tkachenko, A., Aerts, C., Pápics, P.I., Triana, S.A., Zwintz, K., Degroote, P., Debosscher, J., Bloemen, S., Schmid, V.S. and De Smedt, K., 2015. Gravity-mode Period Spacings as a Seismic Diagnostic for a Sample of γ Doradus Stars from Kepler Space Photometry and High-resolution Ground-based Spectroscopy. *The Astrophysical Journal Supplement Series*, *218*(2), p.27

Kaye, A.B., Handler, G., Krisciunas, K., Poretti, E. and Zerbi, F.M., 1999. γ Doradus stars: defining a new class of pulsating variables. *Publications of the Astronomical Society of the Pacific*, *111*(761), p.840.

Guzik, J.A., Kaye, A.B., Bradley, P.A., Cox, A.N. and Neuforge, C., 2000. Driving the gravity-mode pulsations in γ Doradus variables. *The Astrophysical Journal Letters*, *542*(1), p.L57.

Ershadi, A., Jassur, D.M,.2015. Thesis: Studying the pulsations of KIC 11826272, a γ Dor star of the Kepler Space Telescope, Department of Theoretical Physics and Astrophysics, Tabriz University of Iran.

Aerts, C., Christensen-Dalsgaard, J., Kurtz, D. W.(2010*). Asteroseismology*. Astronomy and Astrophysics Library.Springer.

Schmid, V.S., Tkachenko, A., Aerts, C., Degroote, P., Bloemen, S., Murphy, S.J., Van Reeth, T., Pápics, P.I., Bedding, T.R., Keen, M.A. and Prša, A., 2015. KIC 10080943: An eccentric binary system containing two pressure-and gravity-mode hybrid pulsators. *Astronomy & Astrophysics*, *584*, p.A35.

Tassoul, M., 1980. Asymptotic approximations for stellar nonradial pulsations. *The Astrophysical Journal Supplement Series*, *43*, pp.469-490.

Van Reeth, T., Tkachenko, A., Aerts, C., Pápics, P.I., Degroote, P., Debosscher, J., Zwintz, K., Bloemen, S., De Smedt, K., Hrudkova, M. and Raskin, G., 2015. Detecting non-uniform period spacings in the Kepler photometry of γ Doradus stars: methodology and case studies. *Astronomy & Astrophysics*, *574*, p.A17.