Revisiting stellar parameters of ζ Pegasi using asteroseismology

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Abstract

ζ Pegasi is a slowly pulsating B-type star exhibiting a primary oscillation period of 1.07 days, accompanied by several minor oscillations. Spectroscopic observations suggest that ζ Pegasi is a potential binary system. In this study, we employ asteroseismology to refine the stellar parameters of ζ Pegasi, offering new insights into its physical characteristics. Our analysis yields reasonable estimates for the star's radius and mass, consistent with previously reported values in the literature. However, the derived radius presents discrepancies, indicating the need for further investigation. These findings contribute to a deeper understanding of the internal structure and evolutionary status of ζ Pegasi.

Introduction

Asteroseismology relies significantly on the study of pulsations, which are cyclic variations in the brightness of stars caused by internal processes. These pulsations provide invaluable insights into a star's internal structure, composition, and overall evolution. Asteroseismologists can deduce key information about a star's mass, age, and chemical composition by analysing the frequency, amplitude, and duration of pulsations. Slow pulsating B-type (SPB) stars play an important role in the field of asteroseismology. These stars of spectral type B2 to B9 exhibit radial and non-radial pulsations with periods ranging between approximately half a day and five days. The SPBs are situated in the main sequence, just below the β Cep stars in the H-R diagram. Like for the β Cep stars, the κ-mechanism has to be invoked to explain the instabilities [1]. SPB stars usually show pulsations in high-order gravity(g) modes [2], allowing us to probe deeper into the stellar structure, reaching down to the boundary of the convective core [3]. The variability is present in both their light curves and in their spectral line profiles. The variations in magnitude may reach 0.1 magnitudes, but in general are smaller[4].

Target characterization

ζ Pegasi is a B-type main-sequence star located in the constellation Pegasus. With an apparent magnitude of +3.4, it is visible to the naked eye and lies approximately 62.7 parsecs from the Sun. ζ Pegasi is characterized by a rapid rotation and a periodic brightness variation with a cycle of 22.95 hours. The star has an estimated age of 120 million years, a radius approximately four times that of the Sun, and an effective temperature of 11,190 K.

TESS photometry

The Transiting Exoplanet Survey Satellite (TESS), a NASA space telescope designed for discovering exoplanets through the transit method, offers high-precision photometry [5] which we can use to look for pulsations. In 2022, TESS performed observations in 56th sector over 22 days with an exposure time of 2 minutes. The data was downloaded via package Lightkurve [6]. It was automatically processed and detrended with SPOC pipeline [7] and contains 20079 datapoints. The light curve obtained from TESS is displayed of Figure 1.

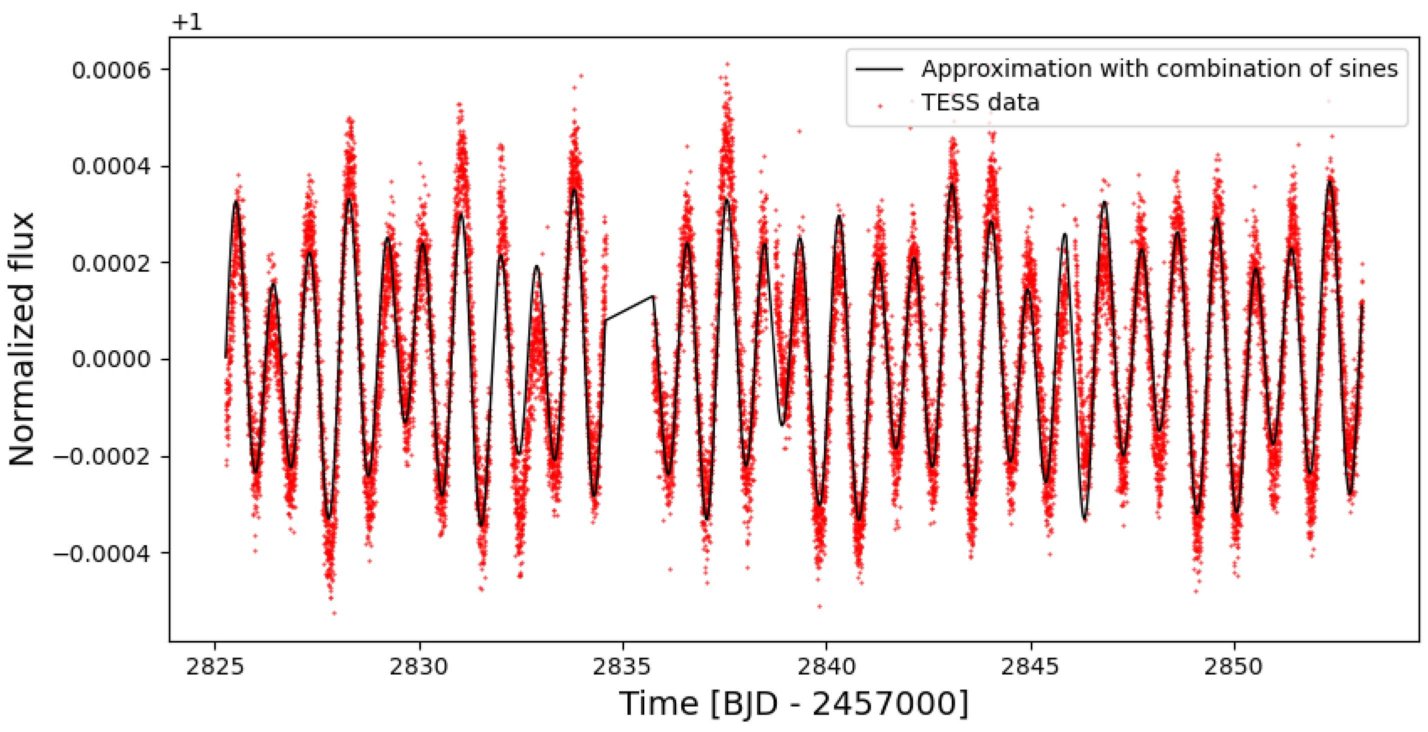

Figure 1. TESS lightcurve (black) with our model (red).

We employed the Lomb-Scargle periodogram technique to identify periodicities within our TESS dataset. Figure 1 displays our periodogram, revealing at least two distinct peaks at 1.070 cycles per day and 0.750 cycles per day. We also approximated the light curve with combination of 2 harmonic oscillations with obtained frequencies(Figure 2). This fit is good but not perfect, leaving root mean square residual of 6×10^{-5}.

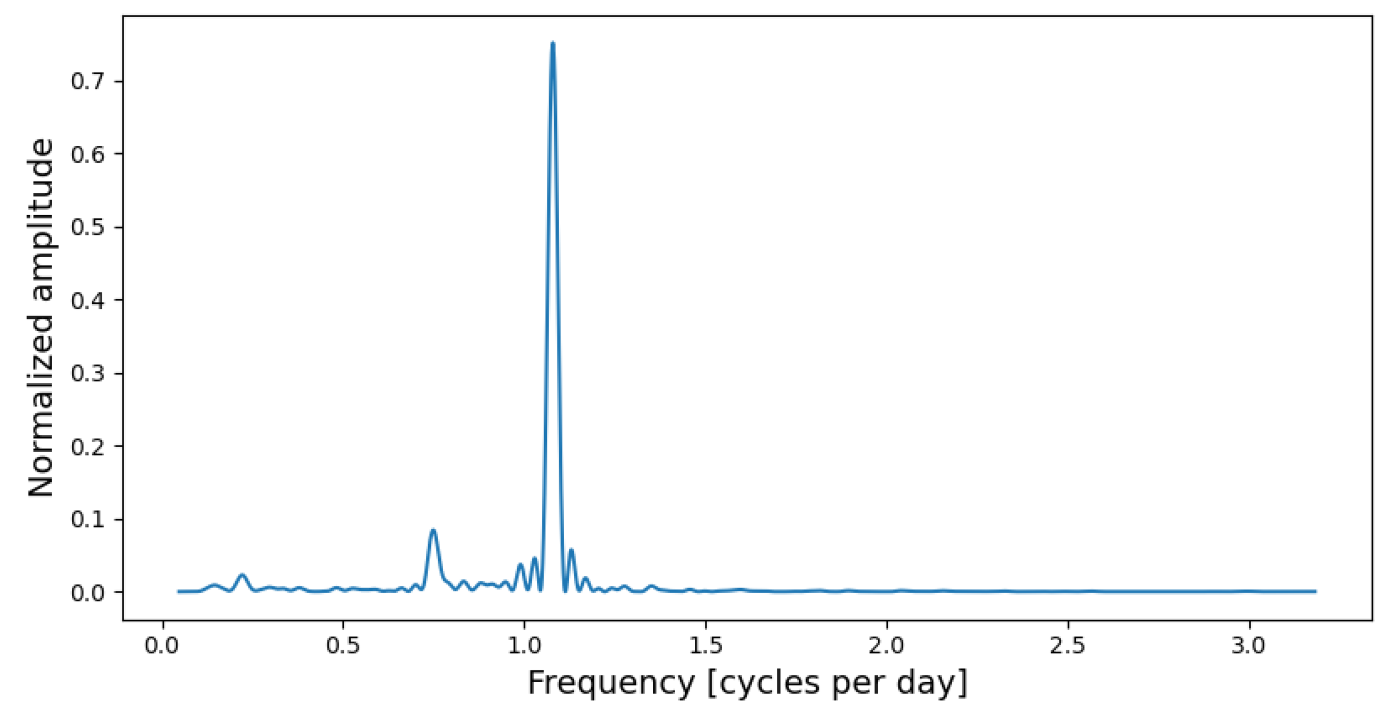

Figure 2. Lomb-Scargle periodogram based on TESS data.

FAMIAS

The next step in our analysis involves employing the FAMIAS (Frequency Analysis and Mode Identification for Asteroseismology) code. FAMIAS is a package of state-of-the art software tools for the analysis of photometric and spectroscopic time-series data [8]. FAMIAS allows to carry out a mode identification for the detected pulsation frequencies to determine their pulsational quantum numbers, the harmonic degree, l, and the azimuthal order, m. However, since TESS does not provide the multi-wavelength photometry required for the photometry module, our focus is on the spectroscopy modules. In the analysis of spectroscopic time series for pulsating stars, two primary methods are commonly used: (i) the moment method ([9]; [10]), and (ii) the pixel-by-pixel method ([11]; [12]; [13]). The moment method involves numerically integrating the statistical moments of an observed spectral line, describing the line profile variations in terms of the equivalent width (0th moment); centroid velocity (1st moment); profile width (2nd moment); and profile skewness (3rd moment). This method is particularly effective for slowly rotating stars (i.e. v sin $i < 50$ km s^{-1}), where the rotation period is significantly longer than the pulsation period, making pulsations the dominant line-broadening mechanism rather than rotation.On the other hand, the pixel-by-pixel method is more suitable for moderately and rapidly rotating stars. Both the moment and pixel-by-pixel methods are available in the FAMIAS software package. Given that ζ Pegasi is a fast rotator with v sin $i > 140$ km s^{-1}[14], we opted for the Fourier Parameter Fit (FPF) method to estimate the stellar parameters. For slowly pulsating B-type stars, the Si II 4130 Å doublet is ideal for such analyses[15]. Our calculations yielded a stellar mass $M = 3.25 M_{\odot}$ and a stellar radius $R = 4.9 R_{\odot}$. The value of mass aligns closely with those reported in the literature, where $M = 3.22 M_{\odot}$[16], although the value of radius appears to be slightly overestimated: $R = 4.03 R_{\odot}$[17].

Analysis of ζ Pegasi Binary Status

To investigate whether ζ Pegasi is a binary star, we analyzed 241 spectra of the star, constructing a broadening function [18] from the data. The broadening function reveals three stationary peaks, which might suggest the presence of multiple components(Figure 3).

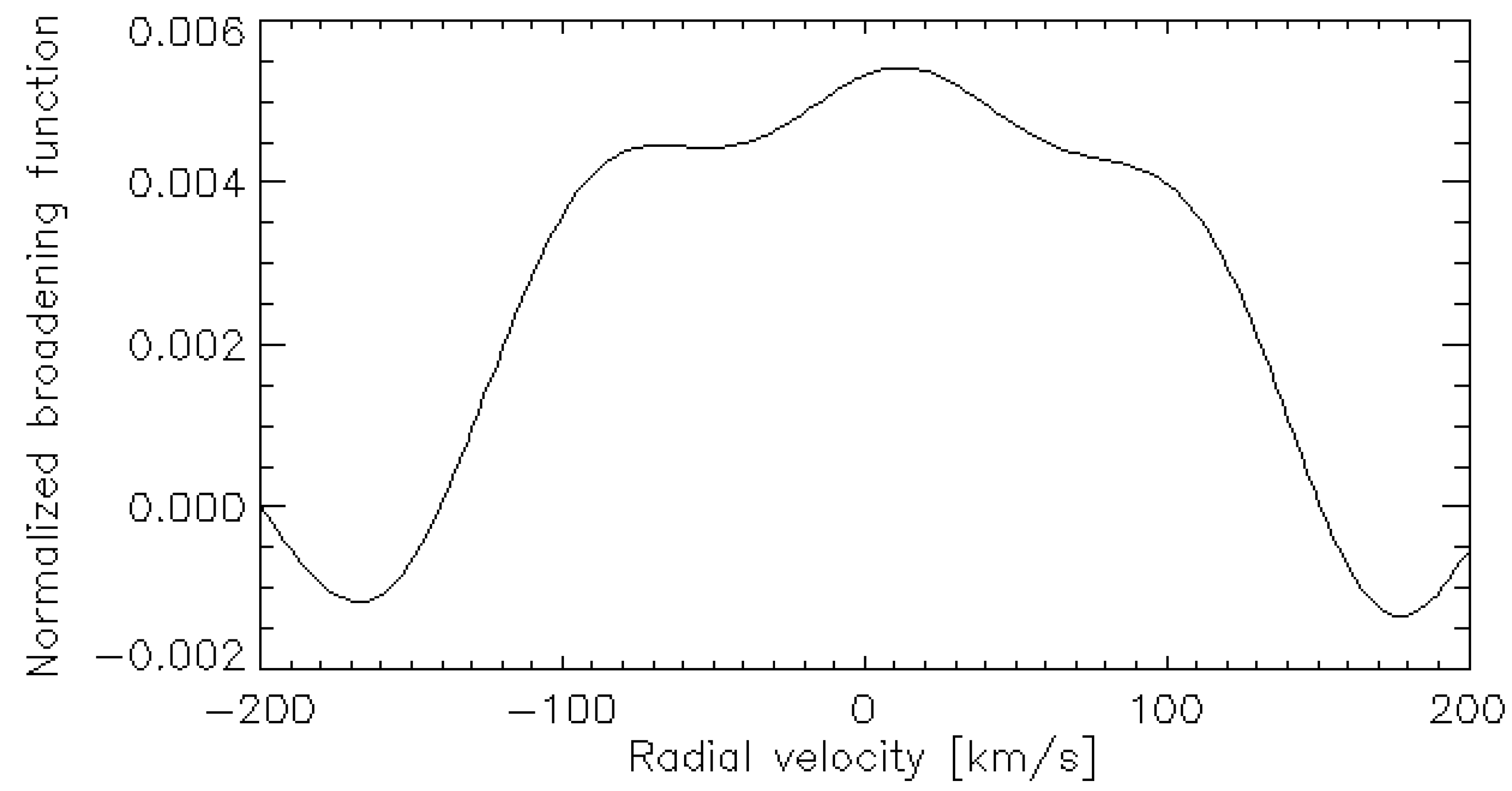

Figure 3. Broadening function based on data FEROS obtained on MJD = 53156.40338696

However, when plotting the maximum of radial velocity as a function of observation date, no periodicity was detected(Figure 4). This lack of periodic variation in radial velocity implies that if ζ Pegasi is a binary system, it is either in a configuration that does not produce detectable radial velocity shifts or the components are not in a short-period orbit. Further investigation is required to confirm the nature of these components.

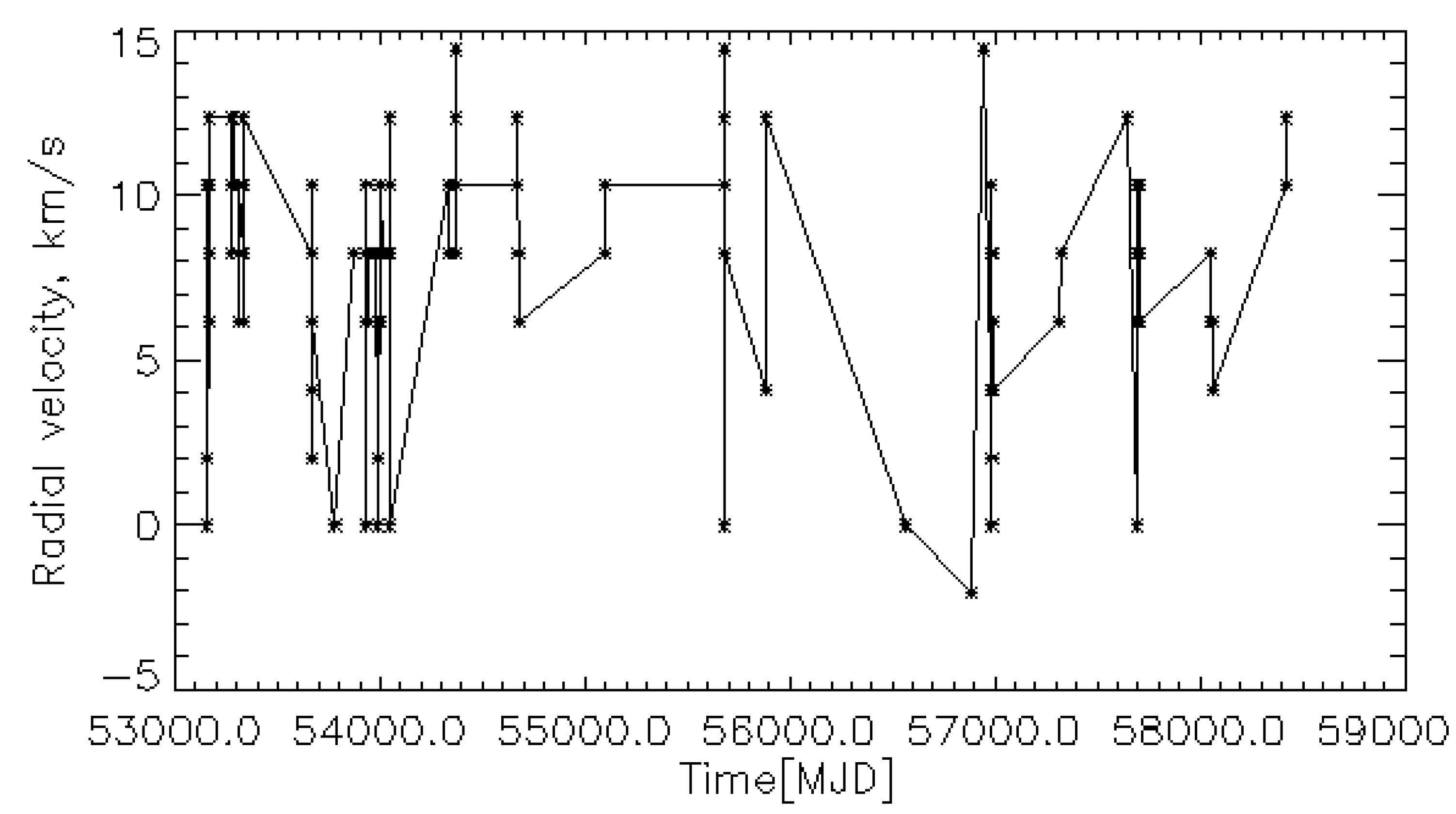

Figure 4. Variations of radial velocity of ζ Pegasi

Conclusions

Our asteroseismic analysis of ζ Pegasi has provided significant insights into the star's physical characteristics, reinforcing its classification as a rapidly rotating, slowly pulsating B-type star. The identification of a primary oscillation period of 1.07 days, coupled with additional minor oscillations, aligns with its known variability. The refinement of stellar mass and radius parameters contribute to the broader understanding of its internal structure. However, the observed discrepancies in the star's radius suggest that further investigations are warranted. The presence of second component in the system is still under question.

Acknowledgements

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REVISITING STELLAR PARAMETERS OF Z PEGASI USING ASTEROSEISMOLOGY

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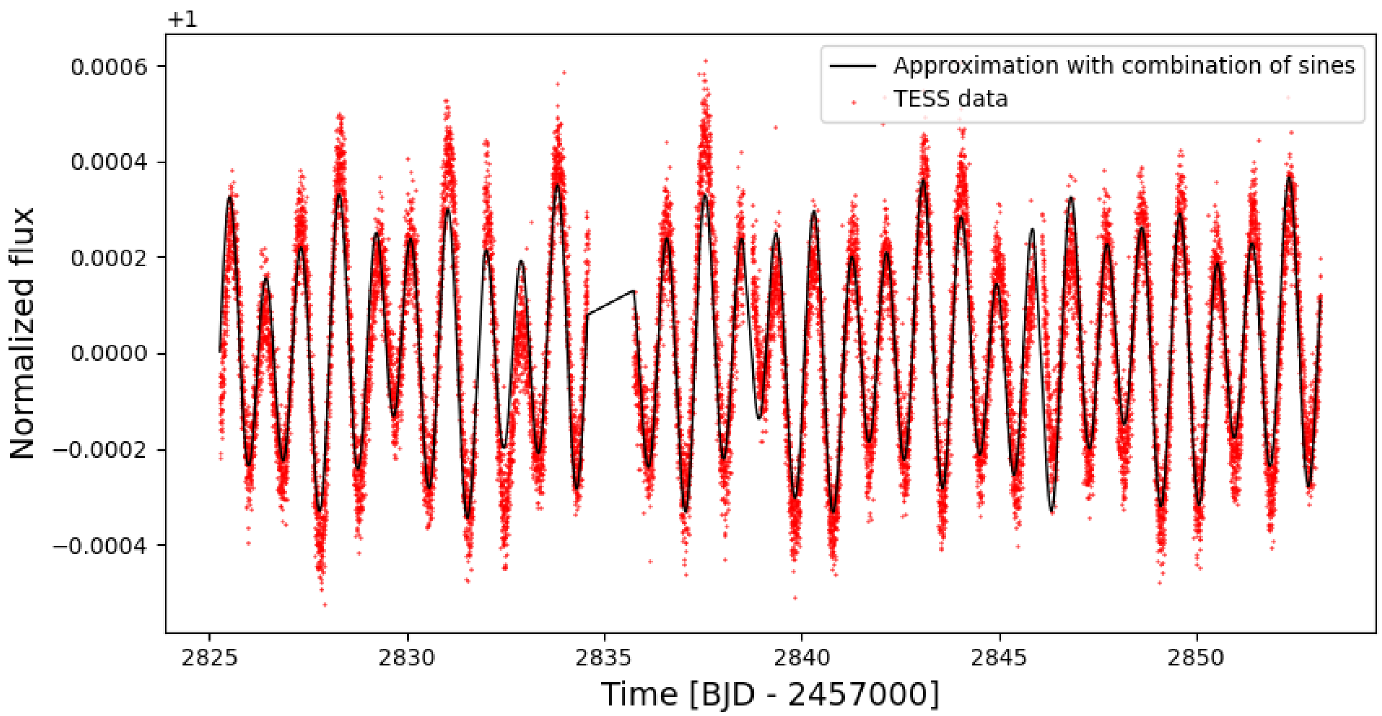

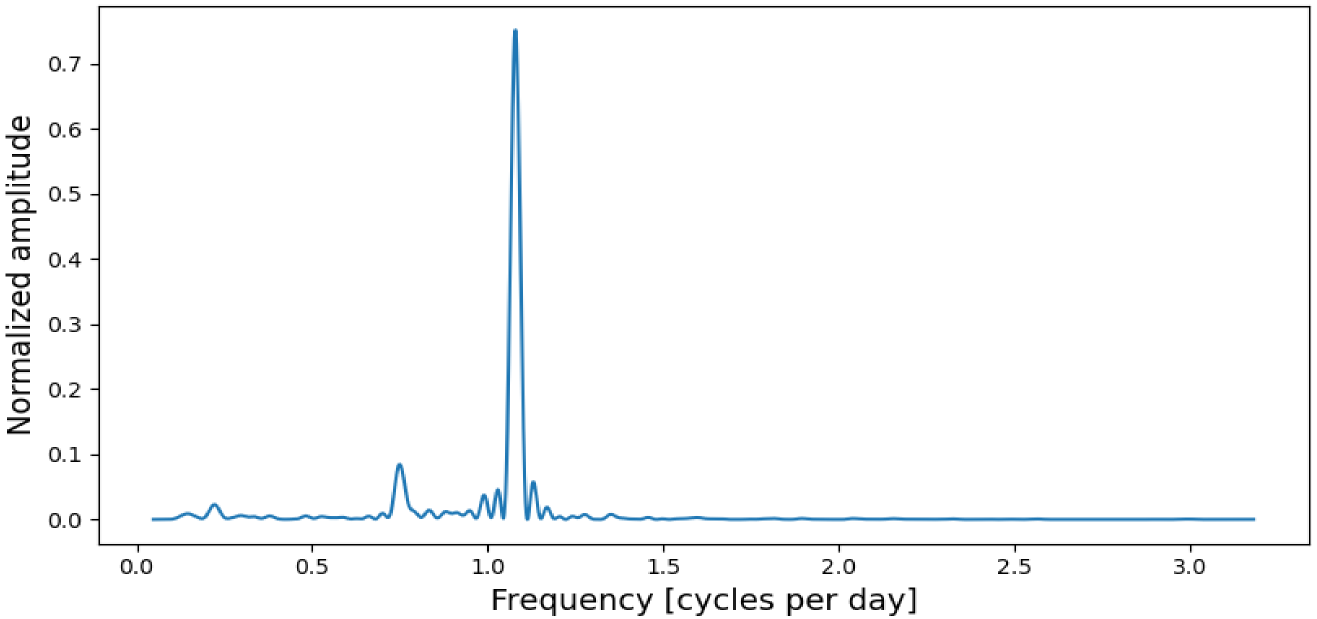

	Literature	FAMIAS
$M[M_{SUN}]$	3.22(Challouf, 2014)	3.25
$R[R_{SUN}]$	4.03(Fitzpatrick, 2005)	4.9

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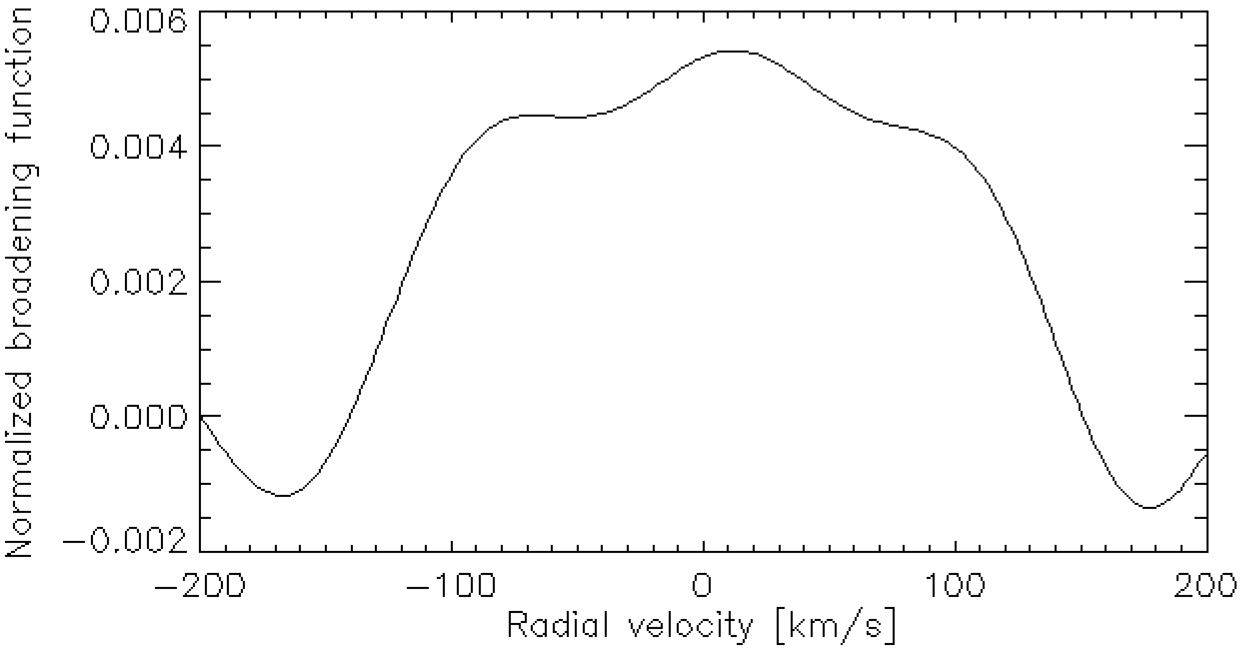
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0.002
0.000
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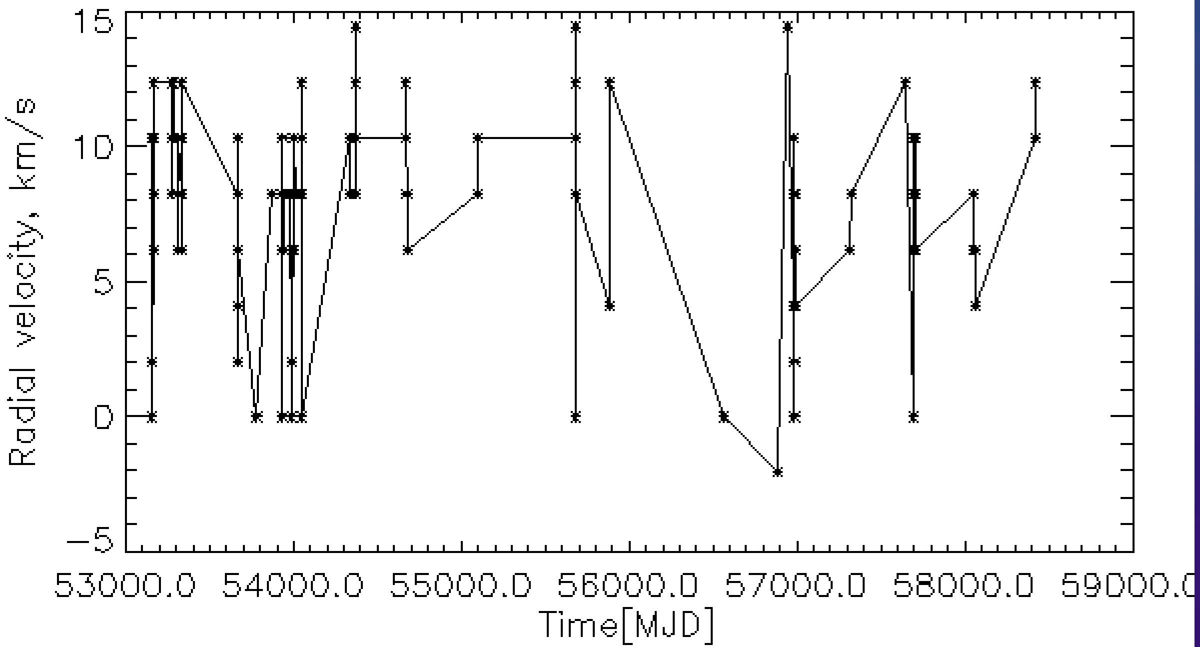
−200
−100
0
100
200
Radial velocity [km/s]


Radial velocity, km/s
15
10
5
0
−5
53000.0
54000.0
55000.0
56000.0
57000.0
58000.0
59000.0
Time[MJD]