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Results of the Light Curve Analysis of TIC 372275195

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We present the results of our analysis of the light curves of the star TIC 372275195 based on observations from the TESS mission. Our frequency analysis has revealed the fundamental frequency, f_0, and the subharmonic frequency, f_1, while f_2 and f_3 correspond to higher harmonics. The star TIC 372275195 pulsates in the radial p-mode at the fundamental frequency $f_0 = 7.614$ day^{-1}, corresponding to the period $P_0 = 0\overset{\text{d}}{.}1313$, and is located on the main sequence of the Hertzsprung–Russell diagram. The star exhibits a relatively low metallicity index and belongs to the δ Scuti type. The light curve of TIC 372275195 has an asymmetric shape. Using the value of the pulsation constant, a physical model of the star was constructed. The pulsation constant was found to be $Q \approx 0\overset{\text{d}}{.}087$, which is larger than the characteristic values of the pulsation constant for typical δ Scuti stars.

1 Introduction

Variable stars of the δ Scuti type belong to spectral types ranging from A0 to F5 and are located on the main sequence of the Hertzsprung–Russell diagram or in its immediate vicinity, as well as within the classical instability strip. The stellar masses of this type are approximately in the range of $1.4 - 2.5\,M_\odot$ (Netzel & Smolec 2022). In particular, Delta Scuti stars have attracted considerable attention in the recent years due to their large number of radial and non-radial pulsation modes, driven primarily by the κ mechanism, which operates in the He II ionization zone (Wang et al. 2024). These pulsations provide valuable information about the internal structure of δ Scuti stars, especially concerning the processes of energy transport in the transition region between the radiative core and the convective envelope (Aerts et al. 2010). Luminosities of δ Scuti stars cover a broad range, typically between 2 and 50 $L_\odot$ (Kurtz 2022). They belong to short-period variable stars, with oscillation periods from about $0\overset{\text{d}}{.}02$ to $0\overset{\text{d}}{.}25$. Variability amplitudes range from 3 millimagnitudes up to 0.9 magnitudes (Qian et al. 2018).

2 Cross-identification and Observational Data

Within the framework of the Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2015), the star with Gaia DR3 (Gaia Collaboration 2022) coordinates $\alpha_{2000} = 03^{\text{h}}19^{\text{m}}24\overset{\text{s}}{.}928$, $\delta_{2000} = +56^\circ44'25\overset{''}{.}79$ is listed under the designation TIC 372275195 (TIC is the TESS Input Catalog). In the APASS catalog (AAVSO Photometric All-Sky Survey), it is identified as APASS 57229944; in the Two Micron All Sky Survey, it is registered as 2MASS 03192491+5644257; in the Gaia mission, as Gaia DR3 448018797543294464; in the UCAC catalog (U.S. Naval Observatory CCD Astrograph Catalog), as UCAC 734-029884; and in the AllWISE catalog (All Wide-field Infrared Survey Explorer), as AllWISE J031924.90+564425.8. The star TIC 372275195 was identified as a rotational variable star with a period of 377.960394 days in the study by Qiao et al. (2024) and was included in the LAMOST DR9 catalog under the number 537603216 (Qiao et al. 2024). Figure 1 presents a chart of TIC 372275195.

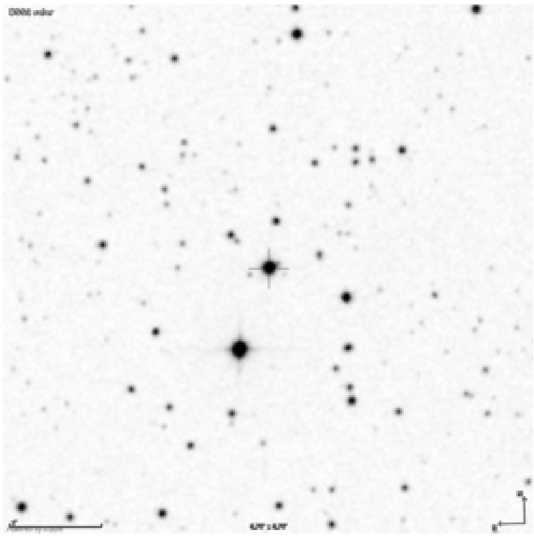

Figure 1.
The field ($5\overset{\prime}{.}78 \times 5\overset{\prime}{.}78$) around TIC 372275195 (in the center). North is up, and east is to the left. The visualization was generated using Aladin v12.0.

Photometric data for TIC 372275195 were obtained by the TESS mission in Sectors 18, 19, 58, 59, and 86. For the present study, we used photometric data from the preliminary Quick-Look Pipeline (QLP, Huang et al. 2020), which were retrieved from the Mikulski Archive for Space Telescopes (MAST)[1]. The physical parameters of TIC 372275195 are summarized in Table 1. The data are from the TESS Input Catalog v8.2 (Paegert et al. 2021) and from the Gaia DR3 catalog (Gaia Collaboration 2022).

The overall light curve of TIC 372275195, showing DET_FLUX (Detection Flux) in Sector 59 versus BJD/TIME (Barycentric Julian Date), is presented in Fig. 2.

[1]https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

Table 1. Stellar Parameters of TIC 372275195

Parameter	Value	Error
TESS Input Catalog v8.2		
B (mag)	13.545	0.039
V (mag)	12.786	0.092
TESS (mag)	12.020	0.006
$T_{\rm eff}$ (K)	6538	202.18
$\log g$ (cm/s^2)	4.239	0.096
Mass ($M_\odot$)	1.349	0.229
Radius ($R_\odot$)	1.459	0.066
Contam. Ratio	0.2600947	–
Gaia DR3		
RUWE	0.952	–
Plx (mas)	2.1187	0.011
[Fe/H]	–0.328	–
RV (km/s)	15.66	1.2

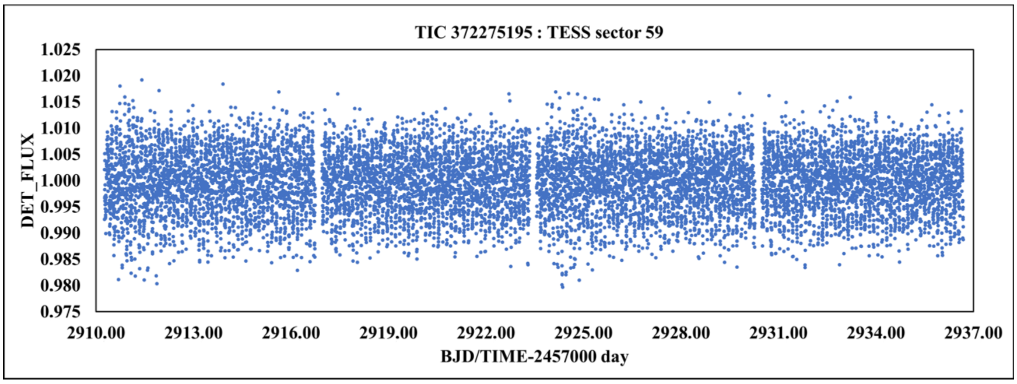

Figure 2.
The overall light curve of TIC 372275195 from observations in TESS sector 59.

3 Frequency Analysis

To identify pulsation or oscillation frequencies of TIC 372275195 based on its brightness variations, a frequency analysis was performed using the Period04 software (Lenz & Breger 2005). To improve the signal-to-noise ratio (SNR) in the TESS observations, data sequences with 1800-second exposures from Sectors 18 and 19 were combined, including the parameters BJD/TIME and KSPSAP_FLUX (Kepler Spline Simple Aperture Photometry), together with the corresponding uncertainties KSPSAP_FLUX_ERR (Vanderburg & Johnson 2014). A similar procedure was applied to the datasets with 200-second exposures from Sectors 58, 59, and 86. The amplitude spectrum of TIC 372275195 was constructed using BJD/TIME, DET_FLUX, and DET_FLUX_ERR from TESS Sector 59 (Fig. 3).

Using the Period04 software, the pulsation (oscillation) frequencies, amplitudes, phases, their uncertainties, as well as the signal-to-noise ratios (SNRs), were calculated for the star (Table 2).

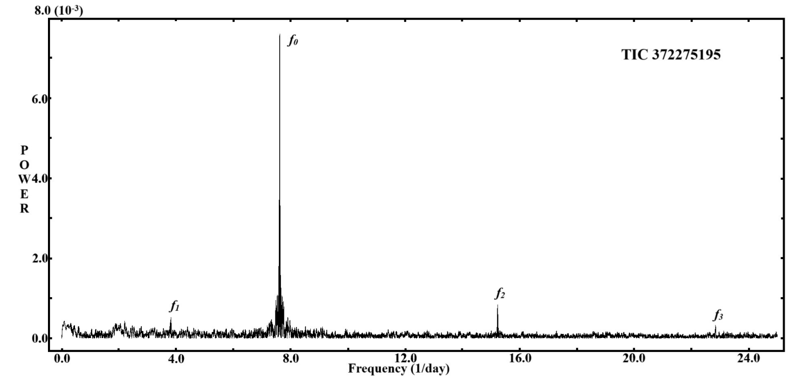

Figure 3.
Oscillation frequencies of TIC 372275195.

Table 2. Frequencies, amplitudes, phases, and SNRs of TIC 372275195 from TESS observations

TESS Observation			
Frequency (day^{-1})	Amplitude (mmag)	Phase (rad)	SNR
Sectors 18, 19			
$f_0 = 7.61469 \pm 0.00008$	7.19 ± 0.05	0.021 ± 0.001	25.4
$f_1 = f_0/2 = 3.8053 \pm 0.0004$	1.29 ± 0.05	0.572 ± 0.007	13.1
$f_2 = 2f_0 = 15.227 \pm 0.001$	0.62 ± 0.05	0.27 ± 0.01	8.4
Sectors 58, 59, 86			
$f_0 = 7.614350 \pm 0.000004$	7.63 ± 0.04	0.7418 ± 0.0009	27.3
$f_1 = f_0/2 = 3.81467 \pm 0.00006$	0.48 ± 0.04	0.857 ± 0.014	4.4
$f_2 = 2f_0 = 15.23008 \pm 0.00003$	0.83 ± 0.04	0.707 ± 0.008	11.5
$f_3 = 3f_0 = 22.84311 \pm 0.00008$	0.35 ± 0.04	0.55 ± 0.02	5.5

For our program star TIC 372275195, the frequency f_0 is identified as the fundamental mode: it exhibits the highest stability as well as the largest amplitude and signal-to-noise ratio compared to the other detected frequencies (Table 2). The fundamental frequency determines the key properties and characteristics of the star. The fundamental frequency is $f_0 = 7.614$ day^{-1}, which corresponds to the period $P_0 = 1/f_0 = 0.^{\mathrm{d}}1313$.

3.1 Characteristics of oscillation modes

In order to investigate the pulsational properties of TIC 372275195, we employed the period ratio method introduced by Petersen (1973). This diagnostic tool enables us to assess whether the star exhibits radial or non-radial oscillations in the fundamental mode and to identify the presence of possible overtones. The method has proven to be particularly valuable for a wide range of pulsating variable stars, including δ Scuti (DSCT), γ Doradus (GDOR), RR Lyrae, SX Phoenicis (SXPHE), and Cepheid-type variables, as it provides a means to discern the fundamental mode, its overtones, and the interrelations among different pulsation modes (Poretti & Beltrame 2004; Smolec & Śniegowska 2016). The primary purpose of applying this method is to determine the pulsation regime of the star and to assess its consistency with theoretical stellar models. According to the Petersen method, the fundamental and overtone frequencies exhibit well-defined ratios. For typical pulsating stars, the first-overtone to fundamental-mode ratio is $P_1/P_0 = 0.71-0.79$, while the second-overtone to fundamental-mode ratio is $P_2/P_0 = 0.58 - 0.63$ (Rathour et al. 2021; Popielski et al. 2000). Transforming the frequencies f_1, f_2, f_3 from Table 2 into periods, we calculated the ratios P_i/P_0 to examine whether they correspond to overtones or other pulsation modes:

$P_1/P_0 = f_0/f_1 \approx 2$ allows us to interpret f_1 as a subharmonic of the fundamental frequency or a possible g-mode;

$P_2/P_0 = f_0/f_2 \approx 0.5$ indicates that f_2 may represent the second harmonic of the fundamental frequency, characteristic of a high-frequency radial mode;

$P_3/P_0 = f_0/f_3 \approx 0.33$ suggests that f_3 is close to the third harmonic of the fundamental frequency.

Based on these ratios, we conclude that f_1, f_2, f_3 are not overtones of the fundamental frequency f_0, but rather harmonics. This in turn may indicate the presence of subharmonic frequencies caused by nonlinear non-radial pulsation modes or by the influence of another component in the system. If $f_1 \approx f_0/2$, this is a clear signature of a strongly nonlinear subharmonic resonance rather than a g-mode. The frequencies f_2 and f_3 are harmonics, integer multiples of the fundamental frequency f_0, and may represent the physical manifestation of modulated emission. The presence of high-frequency modes, particularly f_3, could be related to stellar rotation or to resonance phenomena. As shown in Table 2, the following pattern is observed: $f_1 \approx f_0/2$, $f_2 \approx 2f_0$, $f_3 \approx 3f_0$. If no overtones are observed in the stellar pulsations and only the fundamental mode is detected, it can be concluded that the pulsations are active exclusively in this single mode. In such a case, no radial nodes arise, and the star contracts and expands spherically symmetrically throughout its volume, it pulsates in the radial mode (Percy 2007). In the case of TIC 372275195, in addition to the fundamental mode, subharmonic and high-frequency harmonic modes are also present. The observed pulsation modes of this star exhibit dominant characteristics of p-modes, which is typical of δ Scuti-type stars.

3.2 Light Curve

The mathematical model of brightness variations for TIC 372275195 was constructed based on temporal evolution using a harmonic sinusoidal equation, derived from the frequencies, amplitudes, and phases presented in Table 2:

$$y(t) = b + \sum_{n=0}^{3} A_n sin(2\pi f_n t + \phi_n), \tag{1}$$

where b is a constant bringing the mathematical model in agreement with the observed flux variations; A is amplitude; f is frequency; ϕ is phase; and t is time. In our case, since the variation in stellar magnitudes is normalized to the light flux relative to unity, we adopt $b = 1$, while the values of A, f, and ϕ are taken from Table 2. The parameter t is the observation time BJD/Time for each sector. TESS observations of the star TIC 372275195 within the time interval of Sector 59 (from BJD/Time 2912.2 to 2912.8) were used to construct the light curve based on the DET_FLUX values. A comparative plot of the observed light curve and the mathematical model obtained from equation (1) is presented in Fig. 4.

The star TIC 372275195 pulsates in the fundamental radial mode; however, this pulsation is nonlinear in its nature. The presence of harmonic frequencies $2f_0$ and $3f_0$ indicates that the pulsations exhibit slightly asymmetric shapes, which is typical of this type of stars. In the case of TIC 372275195, the observed variability is not due to multiperiodicity but rather to a nonlinear fundamental pulsation.

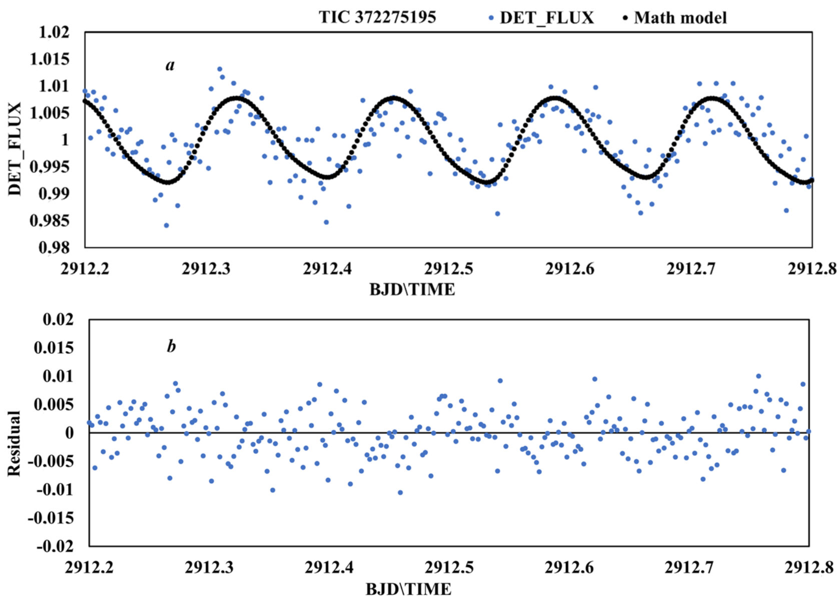

Figure 4.
The light curve of TIC 372275195 modelled from TESS observations; observing data are blue points; the asymmetric mathematical model is shown with black points (a); panel (b) displays the residuals (noise).

4 Discussion

The construction of a model for the pulsating star TIC 372275195 was carried out on the basis of its fundamental frequency $f_0 = 7.614$ day^{-1} ($P_0 = 0^{\mathrm{d}}.1313$). For this purpose, the fundamental physical parameters of the star were employed, such as the effective temperature, mass, radius, surface gravity, and metallicity index, as listed in Table 1. In asteroseismology, a well-established empirical relation exists between the pulsation period of a star and its mean density (Christensen-Dalsgaard 1993):

$$P_0 \propto \frac{1}{\sqrt{\bar{\rho}}}, \tag{2}$$

where P_0 is the fundamental pulsation period of the star, and $\bar{\rho}$ is its mean density. It follows from equation (2) that, as the density decreases, the pulsation period increases; in other words, stars with larger radii pulsate slower. Equation (2) can be expressed in a more precise form as follows:

$$P_0 = Q\sqrt{\frac{\rho_\odot}{\bar{\rho}}}, \tag{3}$$

where $\rho_\odot$ is the mean density of the Sun, $\bar{\rho}$ is the mean density of the star, and Q is the pulsation constant, which depends on the internal structure of the star. This quantity reflects the physical state of the pulsations, the pulsation mode, and the internal stellar structure. The parameter Q carries information about the type of pulsation regime and is widely used as a diagnostic of pulsational properties (Handler & Shobbrook 2002). It should be emphasized that the value of Q is specific to each class of pulsating stars. Q can be expressed in terms of the pulsation period of the star, its mass, and radius by the following relation:

$$Q = P_0 \cdot \left(\frac{R_\odot}{R}\right)^{3/2} \cdot \left(\frac{M}{M_\odot}\right)^{1/2}. \qquad (4)$$

For the star TIC 372275195, the pulsation constant Q, calculated using equation (4), is:

$$Q = 0.1313 \cdot 1.459^{-1.5} \cdot 1.349^{0.5} = 0.0866. \qquad (5)$$

Thus, the pulsation constant calculated for the star TIC 372275195 is $Q \approx 0\overset{d}{.}087$. We can compare the values of the pulsation constant Q, calculated using equation (4) for TIC 372275195 and for typical δ Scuti stars: δ Sct and V784 Cas. The pulsation period for δ Sct (TIC 162499828) is $P_0 = 0\overset{d}{.}1937697$, $M = 1.53M\odot$, $R = 4.2R\odot$, $Q = 0\overset{d}{.}0278$; for V784 Cas (TIC 12221925), $P_0 = 0\overset{d}{.}10921$, $M = 1.54M\odot$, $R = 2.8R\odot$, $Q = 0\overset{d}{.}029$. The periods were taken from the GCVS 5.1[2] (Samus et al. 2017), while the masses and radii were taken from the TESS Input Catalog v8.2.

The mass, effective temperature, $\log g$, and pulsation period of TIC 372275195 correspond to typical parameters of δ Scuti-type stars. However, for representative members of this class, the value of the pulsation constant Q is usually within the range $0\overset{d}{.}015 - 0\overset{d}{.}033$ (Breger 1990). This naturally raises the question: if TIC 372275195 indeed belongs to the δ Scuti type, why does its pulsation constant significantly exceed the expected range?

To address this question, we perform a theoretical estimate of the fundamental radial pulsation frequency of TIC 372275195. Using the stellar parameters provided in Table 1, we obtain a mean density of $\bar{\rho}/\rho_\odot = 0.435$. Assuming the theoretical value of the pulsation constant $Q_{\text{theor}} = 0.033$, we then calculate the pulsation period according to equation (3): $P_{\text{theor}} = Q_{\text{theor}}\sqrt{\rho_\odot/\bar{\rho}} \approx 0\overset{d}{.}05$, this corresponds to the theoretical fundamental frequency $f_{\text{theor}} = 20$ day^{-1}. Thus, the theoretical value of the fundamental frequency f_{theor} is significantly higher than the observed fundamental frequency f_0 of TIC 372275195. From this, two possible conclusions can be drawn. The first interpretation is that TIC 372275195 does not pulsate in the fundamental radial mode, but rather in a high-order radial p-mode. The second solution is that, when calculating the pulsation constant in this study, we used values for the star's physical characteristics taken from the TESS catalog. These were not measured directly, but rather calculated using various data sources (GAIA measurements in combination with theoretical models of stellar evolution and various empirical relationships). Their accuracy, therefore, can vary depending on the measurements used and the type of star (Stassun et al. 2019). The average density of the star in our case could have been underestimated, meaning that its radius was overestimated and its mass, underestimated. Consequently, if we assume that the mass of TIC 372275195 is lower and its radius is higher than the initial estimates, its parameters could be consistent with those of RR Lyrae stars. However, the observed pulsation period would still differ from the typical values for RR Lyrae variables.

According to the first interpretation, the frequencies f_2 and f_3, observed in the pulsations of TIC 372275195, represent harmonics of the fundamental frequency f_0. The frequency f_3 is close to the theoretically calculated f_{theor}; however, it was detected only in TESS Sectors 58, 59, and 86, and its occurrence was unstable and of relatively low amplitude. Therefore, f_3 cannot be considered the fundamental pulsation frequency of TIC 372275195.

According to the second interpretation, the mass of δ Scuti-type stars lies within the range of $1.2 - 2.5M\odot$ (Uytterhoeven et al. 2011), the effective surface temperature is from 6300 to 8500 K, the surface gravity ranges between 3.2 and 4.3 (Kırmızıtaş et al.

[2]http://www.sai.msu.su/gcvs/gcvs/

2022). Based on these parameters, the radius of δ Scuti stars may vary from 1.3 to $6.3R_\odot$. If the radius of TIC 372275195 is estimated within the interval of $2.7 - 4.5R_\odot$, the resulting value of the pulsation constant would be consistent with the characteristics of δ Scuti-type stars. The frequency and light curve analysis of TIC 372275195 confirms that the frequency $f_0 = 7.614$ day^{-1} represents its fundamental mode. According to the values of mass, $\log g$, and effective temperature presented in Table 1, TIC 372275195 is located on the main sequence of the Hertzsprung–Russell diagram. Taking into account its metallicity, it can be concluded that the star has not yet evolved into the subgigant phase and is not at the terminal stage of stellar evolution.

5 Conclusion

Based on the TESS observations of TIC 372275195, the period ratios of its pulsations were analyzed to investigate the relationships between different pulsation modes, revealing that the star possessed a complex pulsation structure. The frequency $f_0 = 7.614$ day^{-1} represents the fundamental mode and determines the main pulsation characteristics of this star. TIC 372275195 is classified as a δ Scuti star with a low metallicity index (see Table 1); it pulsates in a radial mode at the frequency f_0. In addition, the subharmonic f_1, as well as the second- and third-order harmonics f_2 and f_3, are detected. The light curve of the star shows a certain asymmetry, which is characteristic of RR Lyrae stars and indicates sensitivity of the stellar interior to the boundaries of the convective zone. The observed combination of pulsation modes points to the dominance of the p-mode, which is typical of δ Scuti stars.

However, it should be noted that, for low-amplitude δ Scuti stars, a rich spectrum of closely spaced frequencies is usually observed, associated with excitation of non-radial p-modes, which may be driven by various internal or external conditions. Also, the frequency spectrum often contains combination frequencies superimposed on the intrinsic modes. The presence of such a spectrum, together with existing asteroseismological techniques, makes it possible to infer information on the rotation, internal structure, and evolutionary stage of the star. In the case of TIC 372275195, however, despite the use of TESS data, we were able to identify only a single fundamental oscillation frequency, which is a rather rare occurrence for this type of stars.

From the observed fundamental frequency $f_0 = 7.614$ day^{-1} obtained from TESS data, the pulsation constant of the star was calculated as $Q \approx 0.087$. The theoretical pulsation constant for typical δ Scuti stars is $Q_{\text{theor}} = 0.033$, corresponding to the theoretically predicted fundamental frequency of $f_{\text{theor}} = 20$ day^{-1}. The significant discrepancy between the experimental and theoretical values of the pulsation constant is most likely related to uncertainties in the estimates of stellar mass and radius. Nevertheless, the frequency analysis and the mathematical model constructed from the light curve confirm that f_0 is indeed the fundamental mode of TIC 372275195.

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