

Temporal Variations in Asteroseismic Frequencies of KIC 6106415: Insights into the Solar-Stellar Activity from GOLF and Kepler Observations

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ABSTRACT

The Global Oscillations at Low Frequencies (GOLF) instrument aboard the Solar and Heliospheric Observatory (SOHO) mission has provided over two decades of continuous, high-precision data, enabling detailed measurements of the Sun’s oscillation frequencies. These oscillations, analyzed through Doppler velocity shifts, offer invaluable insights into the Sun’s internal structure and dynamics by applying methods of helioseismology. This methodology has been extended to the study of stars beyond the Sun, using data from various space missions. In particular, NASA’s Kepler mission, in operation from 2009 until 2018, observed over 500,000 stars, analyzing variations in brightness over time and creating a vast database of photometric data to study. This investigation focuses on the solar-type star KIC 6106415, comparing its oscillation frequencies with those derived from the GOLF data. By analyzing frequency patterns and mode lifetimes, we explore similarities and differences in internal structures, stellar evolution, and magnetic activity cycles between KIC 6106415 and the Sun. Our analysis reveals that KIC 6106415 exhibits starspot numbers similar to the Sun, peaking at an estimated 175, consistent with its faster rotation rate. The data suggest that KIC 6106415 may have shorter magnetic activity cycles than the Sun, reinforcing the link between stellar rotation and magnetic field generation in solar-type stars.

1. INTRODUCTION

Although significant progress has been made in observing the external layers of stars, their interior properties remained largely mysterious until the advent of helioseismology in the 1990s (e.g. [Kosovichev 2011](#)). By studying sound waves trapped within the Sun, this revolutionary technique enables the quantification of key stellar parameters, including mass, age, chemical composition, and radius. When applied to stars beyond the Sun, this approach is known as asteroseismology. It serves as an invaluable tool for placing the Sun in a broader stellar context, enhancing our understanding of stellar evolution and dynamics, while also providing insights into the behavior of solar-type stars.

NASA’s Kepler mission, originally designed to detect exoplanets, has provided extensive datasets of light curves, representing the flux of stellar brightness as a function of time ([Borucki et al. 2010](#)). Many of the observed stars are classified as solar-type, with similar mass, radius, and chemical composition to the Sun. Investigating these stars is critical for placing the Sun within a broader astrophysical framework. Preceding the Kepler mission, the Global Oscillations at Low Frequency (GOLF) experiment ([GOLF 2020](#)) aboard the Solar and Heliospheric Observatory (SOHO) was commissioned to study both gravity and acoustic modes on the solar disk using a resonant scattering photometer ([Gabriel et al. 1995](#)). Acoustic modes, in particular, play a central role in probing the internal structure of stars, as they are more sensitive to the outer convective regions and are more easily detectable due to their higher frequency values ([Lopes & Gough 2001](#)).

In the Sun and other similar stars, acoustic modes are stochastically excited by convective motions in the outer regions. Temporal variations in mode frequencies can be observed for different radial orders, n , and angular degrees, ℓ , due to their sensitivity to different stellar layers. Notably, higher-frequency modes in the Sun exhibit larger shifts compared to the smaller shifts seen in lower-frequency oscillations (e.g. [Kosovichev 2011](#)).

In this study, we present an analysis of the solar-type star KIC 6106145, utilizing three years of high-precision photometric observations from the Kepler mission ([Mikulski Archive for Space Telescopes 2023](#)). The light curves of KIC 6106145 reveal evidence of magnetic activity in the form of stellar flares, suggesting a dynamic outer layer resembling

the Sun's. These flares may play a role in the stochastic excitation of oscillation modes, potentially influencing the observed temporal variations in mode frequencies. Our results highlight that higher-frequency oscillation modes in KIC 6106145 exhibit more pronounced temporal variations compared to lower-frequency modes, mirroring behavior observed in the Sun. This finding underscores the connection between surface magnetic activity and stellar oscillations, offering valuable information on the physical processes that occur in the outer layers of solar-type stars (Broomhall et al. 2015).

2. KEPLER LIGHT CURVES

The Kepler mission, renowned for its high-precision photometric observations, provided a wealth of data essential for studying stellar oscillations and magnetic activity. For this study, the Mikulski Archive for Space Telescopes (MAST) database was queried to identify stars with parameters similar to the Sun, such as mass, radius, effective temperature, and metallicity. From this search, three years of pre-conditioned simple aperture photometry (PDCSAP) light curves were downloaded for detailed analysis of KIC6106415, one of which is shown in Figure 1 (Mikulski Archive for Space Telescopes 2023). These light curves differ from the standard SAP flux in that they aim to eliminate planetary signals and other systematic noise in the form of cotrending basis vectors (Reinhold et al. 2013). The data used for this study were obtained at a 1-minute cadence, allowing the identification of oscillation periods comparable to those of the Sun, which are on the order of 5 min. The Python software package, AltaiPony, allowed for identification of flare activity in the time series. Data points in each observation window were compared with a known flare model, with points above a chosen threshold highlighted to indicate possible areas of interest (see Figure 2) (Ilin 2021).

To prepare the data for frequency analysis, the light curves were detrended to remove long-term variations caused by instrumental effects or stellar variability unrelated to oscillations. A Savitzky-Golay filter, also implemented through the AltaiPony library, was applied to preserve oscillatory signals while eliminating spurious noise (Ilin 2021). The data were also corrected for outliers and normalized to easily visualize the deviations. To enhance frequency resolution, the light curves were stitched together into 90-day observation periods, comprising each Kepler quarter, with a 45-day overlap between consecutive quarters (Mikulski Archive for Space Telescopes 2023) (see Figure 3). This approach improved the ability to resolve closely spaced frequencies in the subsequent spectral analysis.

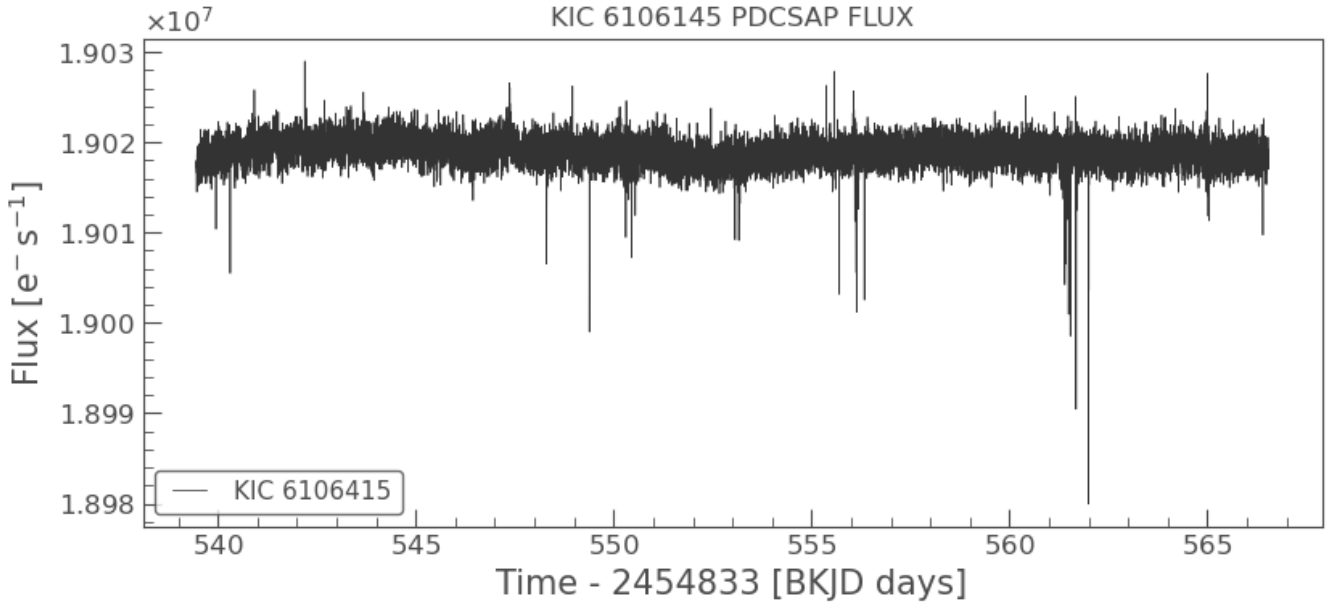


Figure 1. Example of the light curve, before corrections applied, downloaded from MAST database for 30-day observation period.

The processed light curves were then transformed into the frequency domain using the Lomb-Scargle periodogram provided in the Python library, Lightkurve (Lightkurve Collaboration et al. 2018). This method was chosen because of the uneven sampling of the data, and to avoid using interpolation methods to make the time series more consistent

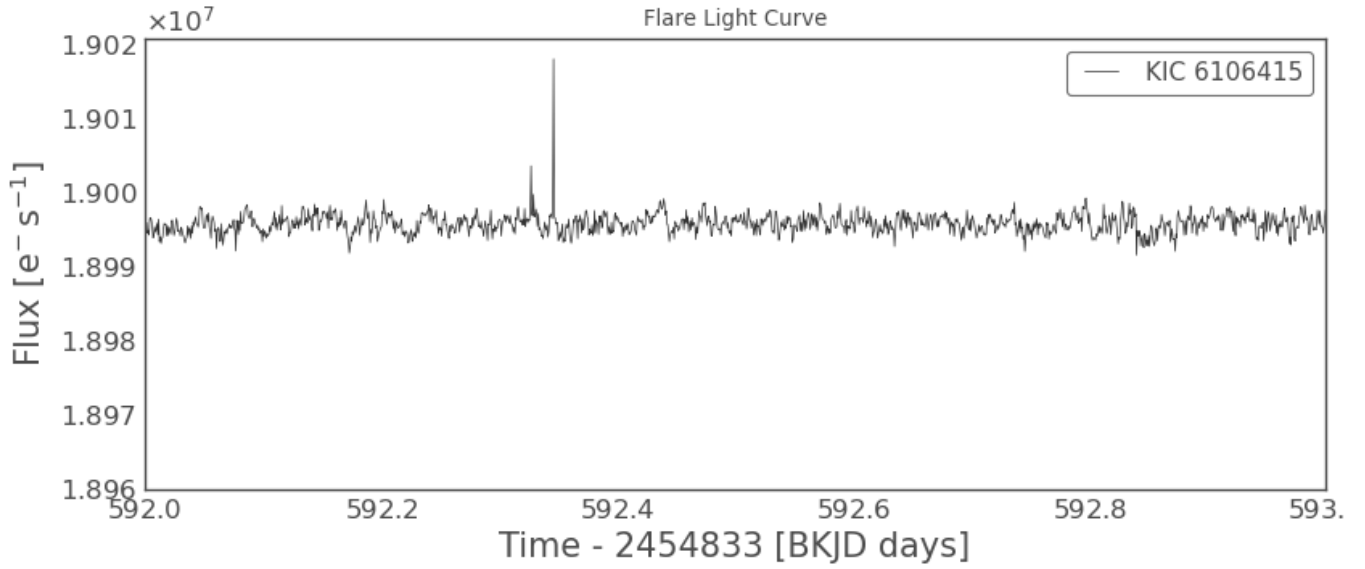


Figure 2. The light curve highlighting the stellar flare activity.

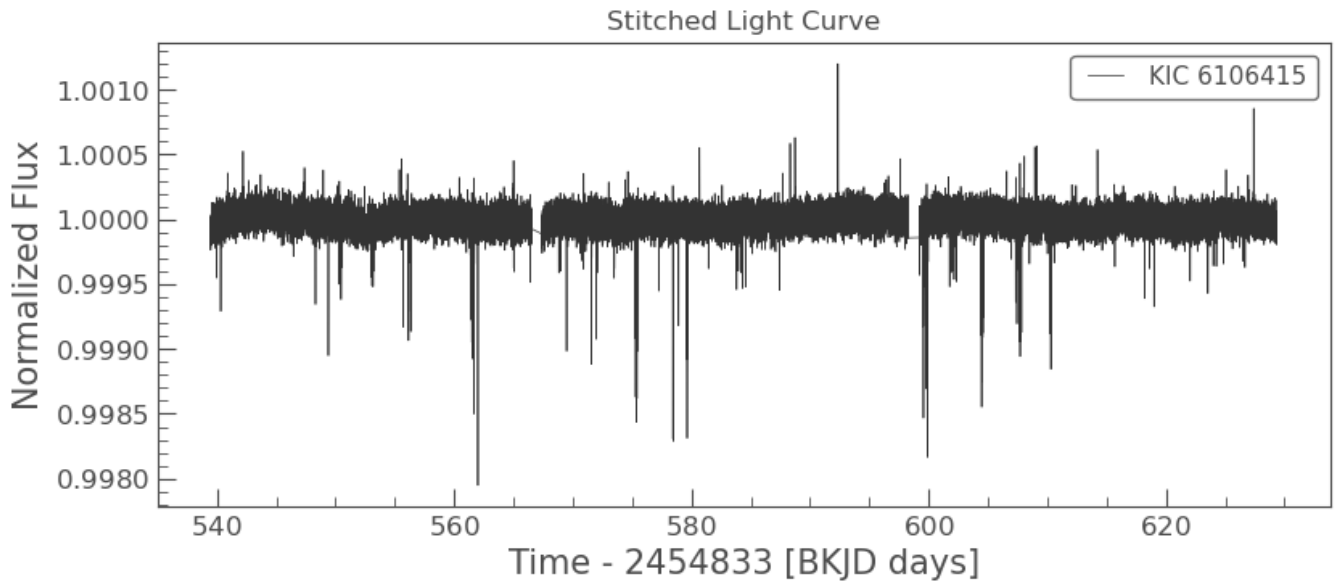


Figure 3. Light curve stitched together in a 90 day observation window. The data have been normalized to better show flux variations away from the mean value.

72 with the traditional Fourier transform (VanderPlas 2018). Interpolation is known to introduce aliasing in the frequency
 73 peaks of the resulting periodogram. An oversample factor of 10 was used in calculating these periodograms to more
 74 accurately resolve closely spaced peaks in the spectrum (VanderPlas 2018). This value was chosen based on the
 75 frequency resolution, calculated from $1/T$, where T represents the total observation time. By dividing this value by
 76 the oversampling factor we attain the grid spacing in the frequencies, which was $0.013 \mu\text{Hz}$ for this data (VanderPlas
 77 2018). Maximum and minimum values were set to highlight the p-mode section of the frequency domain. These
 78 frequency spectra were critical for identifying the oscillation modes of KIC 6106145 and provided insights into the

79 star’s magnetic activity and oscillatory behavior. By leveraging this high-cadence data, we were able to analyze the
 80 stellar oscillations of KIC 6106145, furthering our understanding of solar-type stars.

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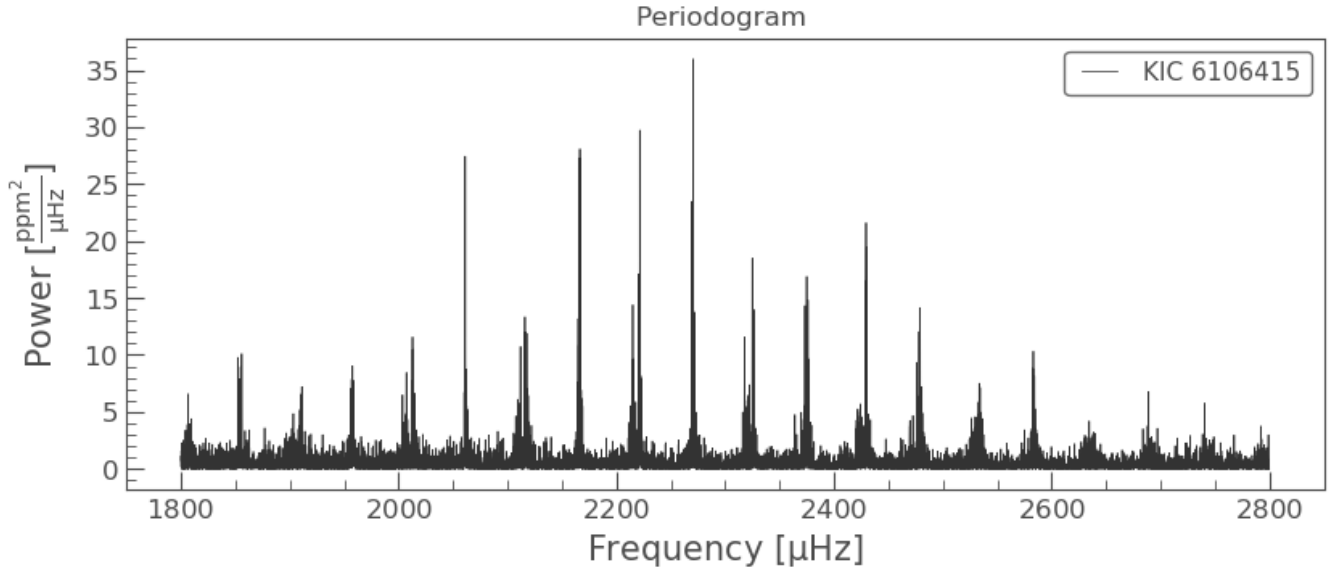


Figure 4. Lomb-Scargle periodogram calculated from the above 90-day observation period. Power has been normalized to relative units.

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3. ANALYSIS OF GOLF DATA

83 The global oscillation frequencies of the p-modes from the solar observations have been recorded for Solar Cycles 22
 84 and 23 (Salabert et al. 2011). The temporal shifts of these frequencies exhibit a strong dependence on magnitude, with
 85 higher frequency modes showing larger variations compared to lower frequencies. This is attributed to the differing
 86 sensitivities of p-modes to various depths below the solar surface, with higher frequency modes probing shallower
 87 layers and lower frequency modes penetrating deeper (Salabert et al. 2015). There is also a strong dependence on ℓ
 88 value, with the low degree modes probing deeper into interior layers of the star (Demarque & Guenther 1999). These
 89 shifts are indicative of structural changes in the sub-surface layers, such as variations in temperature or the size of the
 90 acoustic cavity, and are closely linked to the spatial distribution of the Sun’s magnetic field. It has been known for
 91 some time that the frequencies also depend heavily on the Sun’s 11-year magnetic cycle, with values at a maximum
 92 when the Solar activity also reaches it’s highest point (Broomhall et al. 2015). Salabert et al. (2011) concluded their
 93 analysis midway through Solar Cycle 24, highlighting the weaker activity levels of the cycle and the corresponding
 94 smaller frequency shifts compared to Cycle 23. Our subsequent work extended the analysis to include the complete
 95 Cycles 23 and 24.

96 SOHO data was utilized from 1996 until 2022 and, using a similar methodology to Salabert et al. (2011), we identified
 97 that higher angular degree modes ($\ell = 2$) exhibited greater temporal variations compared to lower-degree modes.
 98 Figures 5, 6 and 7 show the frequency variations, averaged over all observed n values, for $\ell = 1, 2, 3$ respectively. $\ell = 0$
 99 modes were averaged over $n = 14 - 24$, $\ell = 1$ modes were average over $n = 13 - 24$, and $\ell = 2$ modes were average
 100 over $n = 14 - 23$. The range of frequencies for the $\ell = 2$ modes indicated values between -0.0002 mHz and 0.0002
 101 mHz, corresponding to a 0.0004 mHz fluctuation. This range represents a greater overall variation when compared to
 102 the 0.0002 mHz fluctuation for $\ell = 0$ and the approximately 0.00025 mHz change for $\ell = 1$. Again, since higher degree
 103 ℓ modes are more sensitive to the outer layers of the sun, this finding is consistent with the expectation that they will
 104 exhibit greater temporal variations than the lower-degree mode frequencies.

105 This result underscores the potential for more detailed studies of mode dependence variations to further elucidate
 106 the effects of magnetic and structural changes in the Sun’s sub-surface layers. By including the full duration of

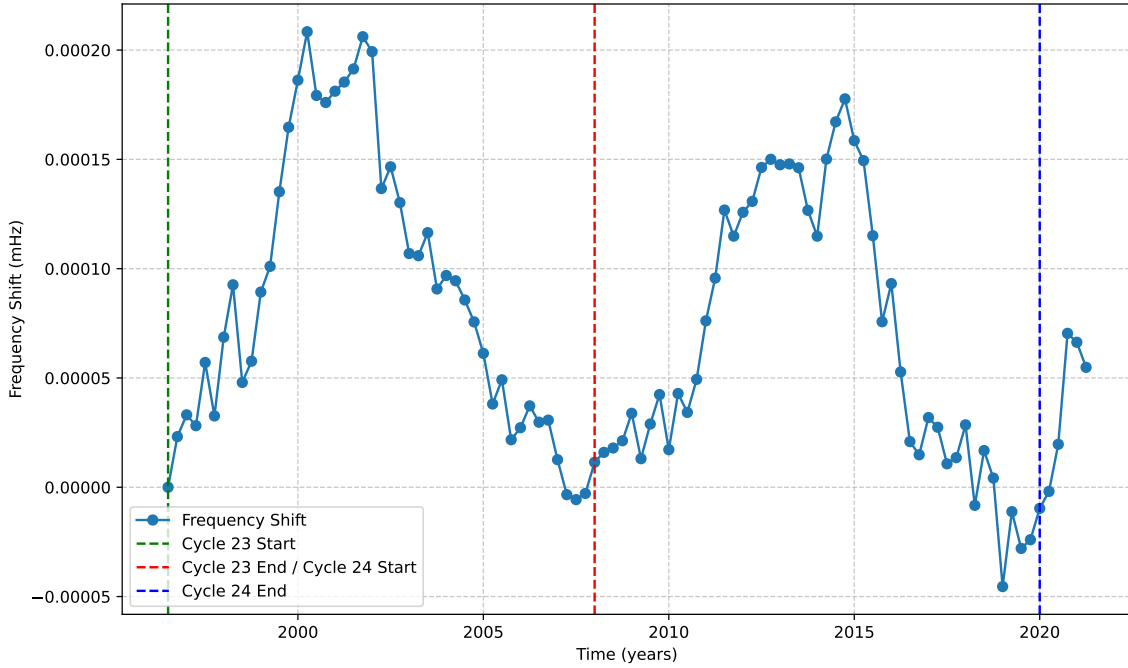


Figure 5. $\ell = 0$ frequency shifts averaged over all n values.

107 Cycles 23 and 24, our work captures the contrasting activity levels between cycles. The consistent methodological
 108 framework applied here enables strong comparisons across cycles, ensuring that observed variations are intrinsic
 109 to the Sun and not artifacts of data reduction or analysis techniques. In addition to expanding our understanding of
 110 solar oscillations, these results have broader implications for stellar astrophysics. The sensitivity of p-mode frequencies
 111 to surface magnetic fields provides a powerful diagnostic tool for studying magnetic activity in solar analogs. This

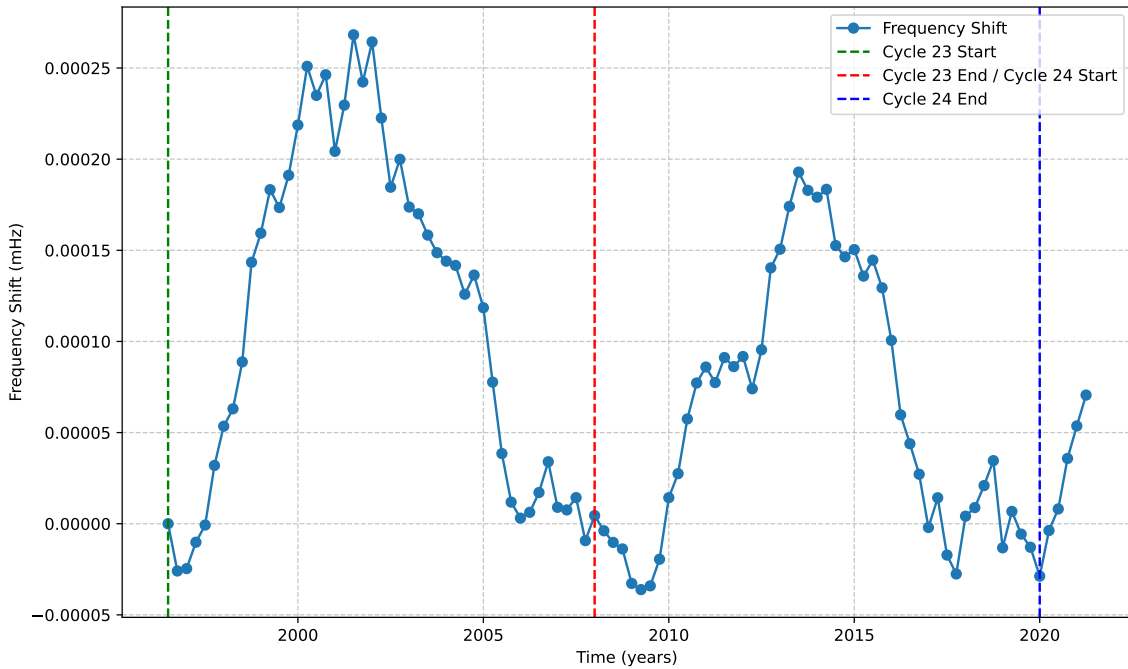


Figure 6. $\ell = 1$ frequency shifts averaged over all n values.

112 cross-disciplinary approach promises to deepen our understanding of the underlying physics driving stellar variability
 113 and evolution.

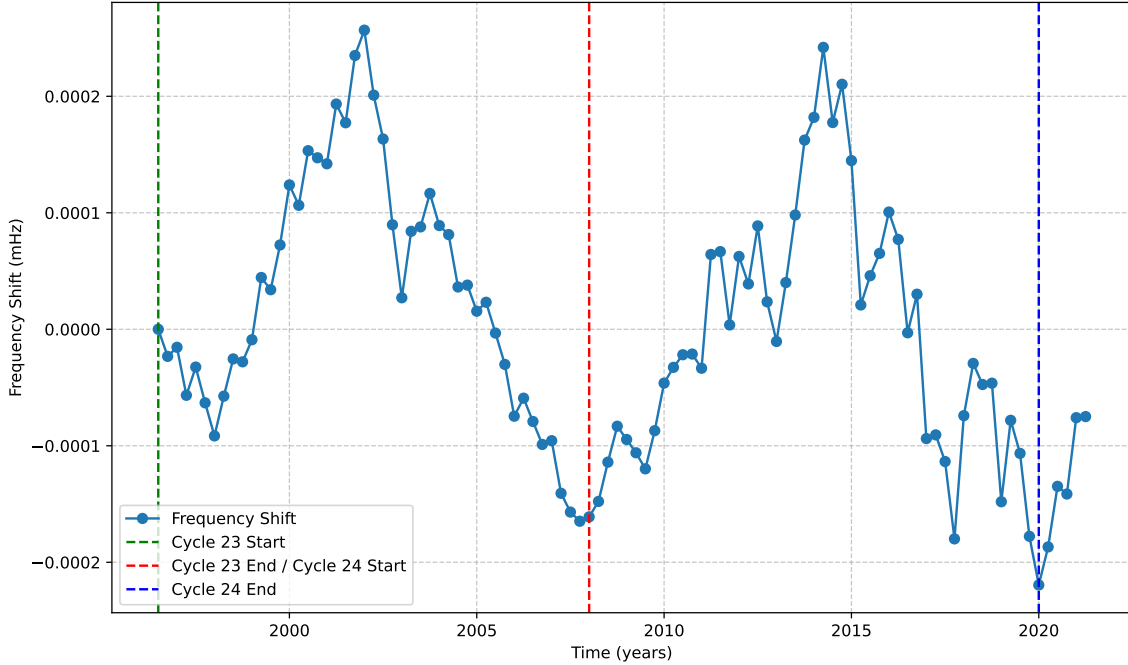


Figure 7. $\ell = 2$ frequency shifts averaged over all n values.

114 4. MODE FITTING FOR KIC 6106415

115 The oscillation modes of KIC 6106415 were analyzed using the Apollinaire package, a Python-based tool specifically
 116 designed for Bayesian peakbagging in asteroseismology (Breton et al. 2022). Apollinaire employs a Markov Chain
 117 Monte Carlo (MCMC) technique to accurately fit the oscillation modes by exploring the parameter space and deter-
 118 mining the most probable values for frequency, amplitude, and width. This approach provides a robust statistical
 119 framework for quantifying uncertainties in the fitted mode parameters, ensuring reliable results (for more info see
 120 Breton et al. (2022)). The Bayesian framework further enables the incorporation of prior knowledge about mode
 121 properties, enhancing the precision of the fits and reducing the risk of overfitting.

122 For this analysis, frequency tables were generated for different radial orders, n and angular degrees, ℓ , over each ob-
 123 servational period. These frequency tables allowed for detailed tracking of temporal variations in the oscillation modes,
 124 revealing the impact of magnetic activity and structural changes on the stellar interior. Individual mode frequencies
 125 were plotted to visualize their behavior over time, highlighting both short-term fluctuations driven by transient activity
 126 and long-term trends associated with stellar magnetic cycles. This approach provided a comprehensive view of how
 127 the oscillation modes evolved during the observation period.

128 Figures 8, 9, and 10 display examples of these frequency plots for chosen n values, with error bars to showcase
 129 uncertainties in the calculations. To capture a broader overview, the mode frequencies were averaged across all n and
 130 ℓ values for each observation, and these averages were plotted to assess the overall temporal evolution of the star's
 131 oscillatory properties. This averaging process provided insights into global changes in the star's acoustic cavity and its
 132 magnetic environment, particularly during periods of heightened stellar activity. To investigate potential frequency-
 133 dependent trends, the frequencies were divided into two regimes: high frequency and low frequency. This division
 134 was based on a threshold, approximately halfway between the minimum and maximum observed values, ensuring a
 135 balanced analysis across the frequency spectrum. By separating the data into these two regimes, distinct trends in
 136 frequency shifts were analyzed, offering a detailed perspective on how the different layers of KIC 6106415's interior
 137 respond to magnetic activity, temperature variations, and other stellar dynamics.

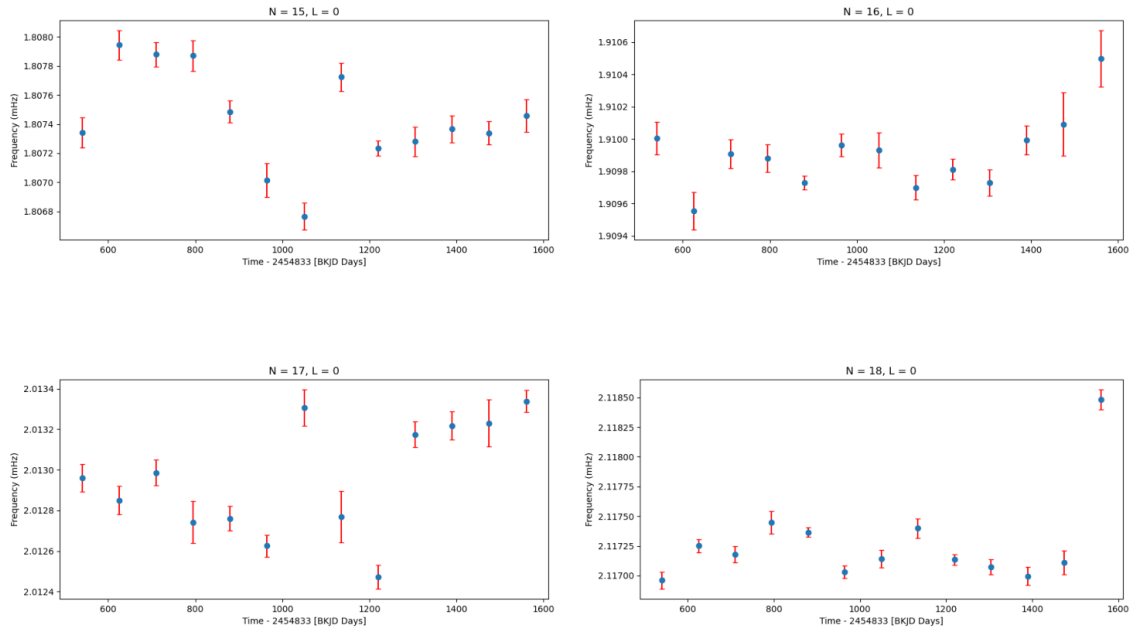


Figure 8. Temporal Variations for $\ell = 0$ modes for $n = 16, 17, 18, 19$.

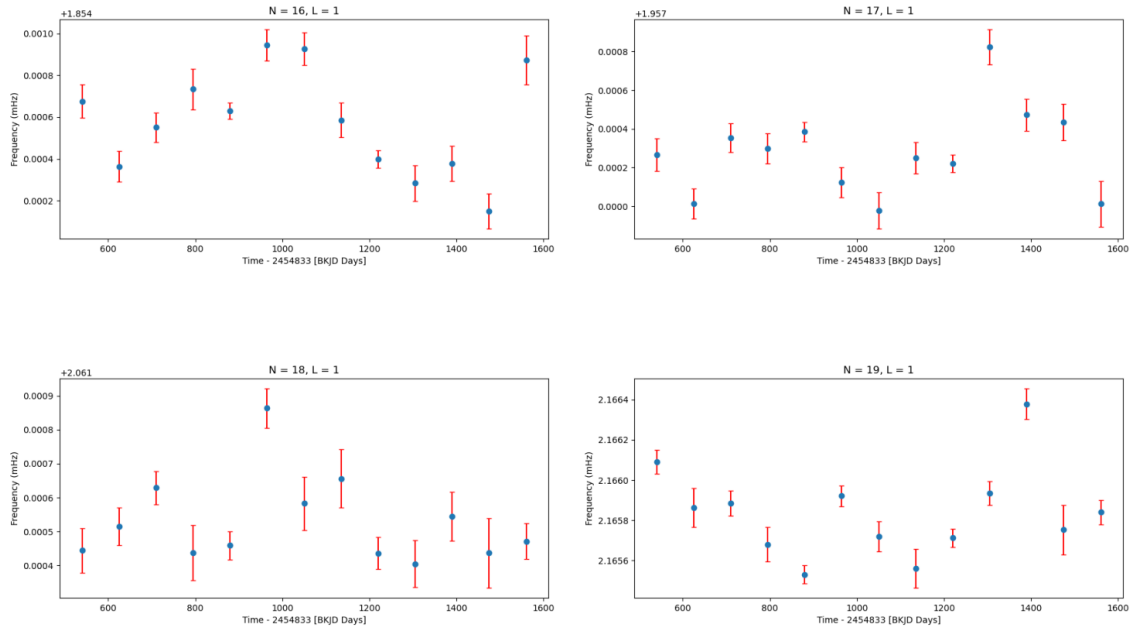


Figure 9. Temporal Variations for $\ell = 1$ modes for $n = 15, 16, 17, 18$.

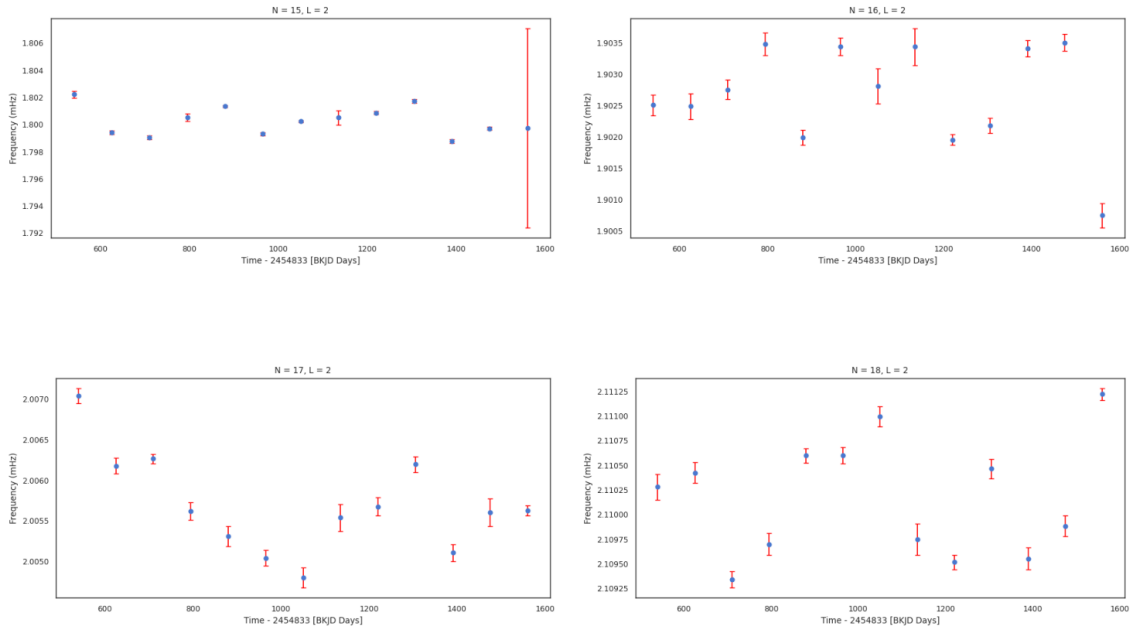


Figure 10. Temporal Variations for $\ell = 2$ modes for $n = 15, 16, 17, 18$.

5. COMPARISON OF TEMPORAL VARIATIONS OF OSCILLATION FREQUENCIES

The Sun’s oscillation frequencies, as measured by GOLF, exhibit well-documented temporal variations closely tied to solar magnetic activity (GOLF 2020). During periods of high solar activity, such as solar maximum, higher-frequency modes display larger frequency shifts due to their sensitivity to near-surface magnetic field perturbations and temperature variations. Lower-frequency modes, which probe deeper into the solar interior, exhibit relatively smaller shifts (Salabert et al. 2011). This frequency-dependent behavior serves as a diagnostic for understanding the Sun’s internal dynamics and magnetic activity.

5.1. Comparison with KIC 6106415

When comparing the asteroseismic oscillation frequencies of KIC 6106415 with those measured by GOLF, several notable similarities emerge. Higher-frequency modes in KIC 6106415 exhibit more pronounced temporal variations, a behavior also observed in the Sun. This suggests that similar physical processes—such as perturbations in the acoustic cavity due to surface magnetic fields and temperature fluctuations—govern frequency shifts in both KIC 6106415 and the Sun. However, the amplitude of these variations in KIC 6106415 is significantly larger than in the Sun. This difference likely reflects a more dynamic magnetic environment in KIC 6106415’s outer layers, which is consistent with the detection of frequent stellar flares in its light curve.

To further analyze these temporal variations, the oscillation frequencies of KIC 6106415 were divided into high-frequency and low-frequency regimes, using a threshold midway between the observed minimum and maximum frequencies. The high-frequency modes, which are more sensitive to the star’s outer convective layers, displayed larger temporal shifts, correlating with variations in magnetic activity. In contrast, the low-frequency modes, which probe deeper interior regions, exhibited smaller shifts, reinforcing the hypothesis that the primary drivers of these variations originate in the outer convective zones.

Additionally, the temporal evolution of KIC 6106415’s oscillation frequencies suggests the presence of a magnetic activity cycle. The periodic peaks and troughs in frequency amplitudes hint at a repeating pattern analogous to the solar cycle but operating on a shorter timescale, likely due to the star’s faster rotation rate. This supports the potential of using asteroseismology to infer magnetic activity cycles in solar-type stars.

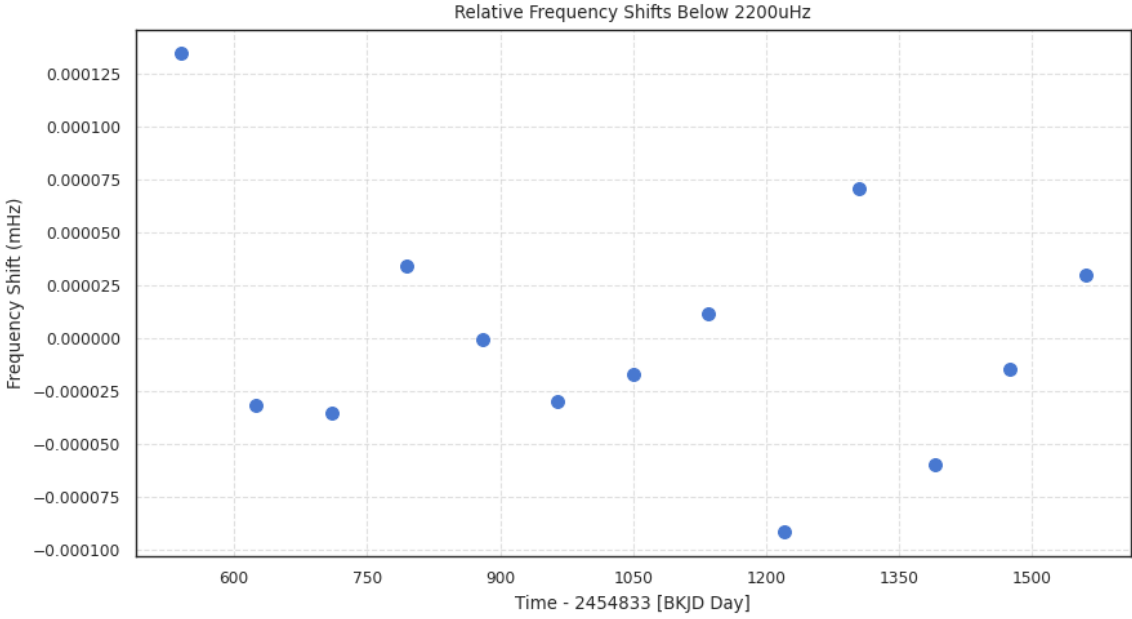


Figure 11. Frequency Variations below 2200 μ Hz. Temporal changes in frequency are lower than the corresponding higher frequencies.

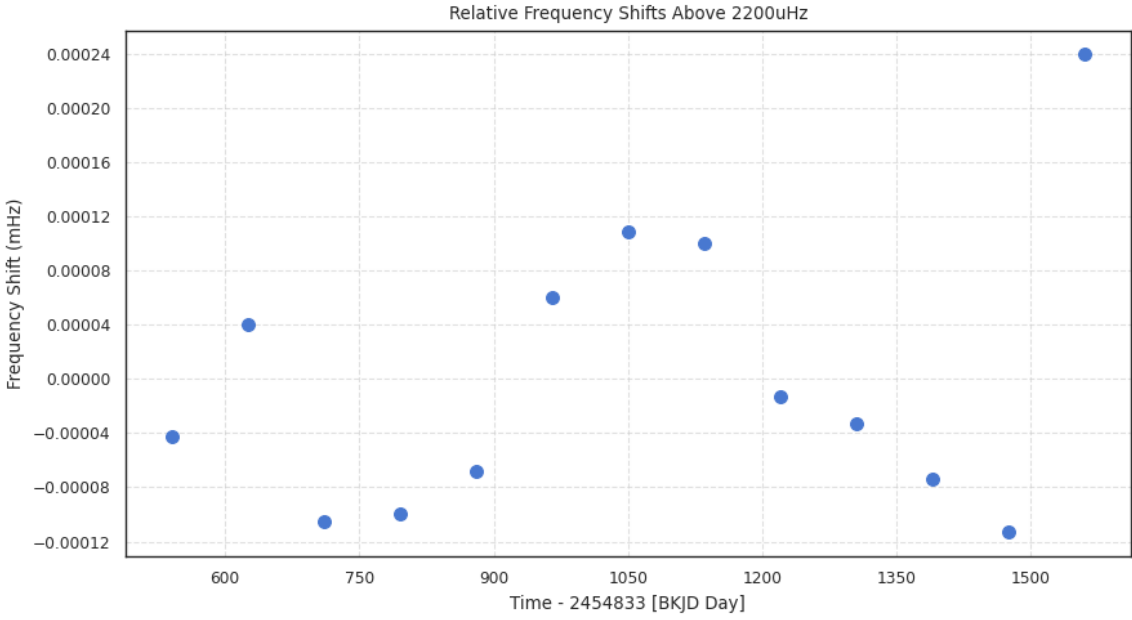


Figure 12. Frequency Variations above 2200 μ Hz.

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5.2. Estimating Starspot Numbers from Frequency Shifts

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Figure 13 shows how the starspot numbers vary according to the relative frequency shifts after averaging over all n and ℓ values. The findings were consistent with expectation that the greater frequency variations aligned with greater sunspot numbers. After performing linear regression to extract the slope and intercept from this plot, a best fit line for estimating the starspot values was constructed according to

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$$S = \delta\nu \cdot a + b \tag{1}$$

169 where S represents the estimated starspot number, $\delta\nu$ is the frequency shift, $mathita$ is the slope derived from the
 170 regression fit, b is the intercept. Figure 14 shows the measured frequency shifts from the peakbagging results and
 171 the estimated starspot numbers from this equation. As expected, the largest shifts corresponded to a higher starspot
 172 number, consistent with the greater rotational period of the KIC 6106145.

173 5.3. Conclusion

174 Overall, the comparison between KIC 6106415 and the GOLF data underscores the universality of certain aster-
 175 oseismic phenomena across solar-type stars, while also revealing intriguing differences in the magnitude and nature

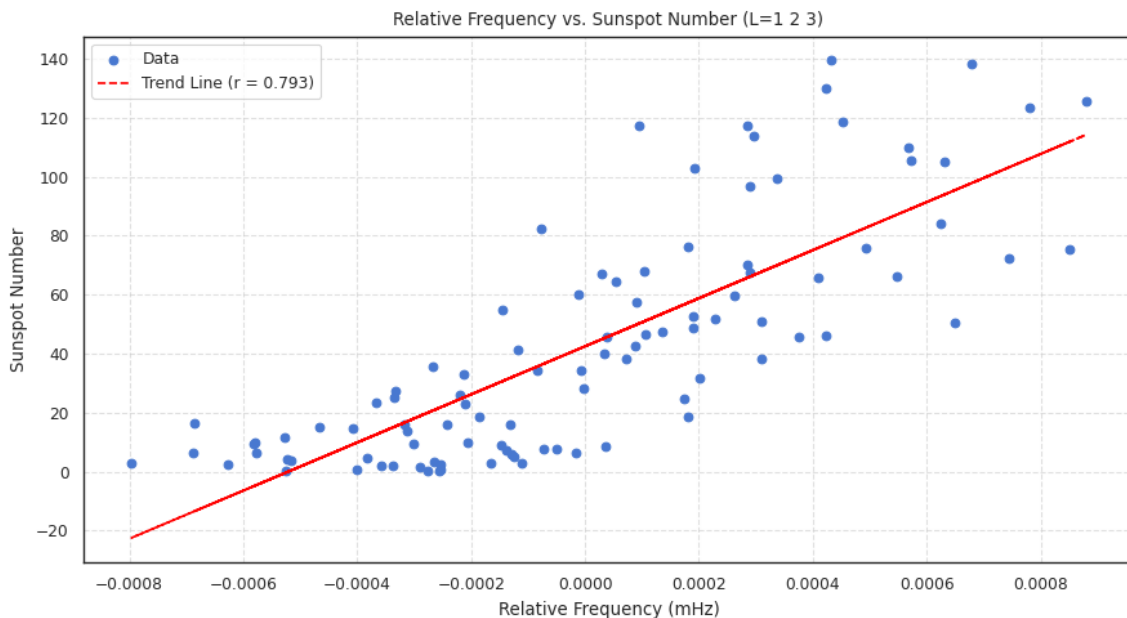


Figure 13. Relative Frequency Variations plotted against Sunspot Numbers from GOLF data.

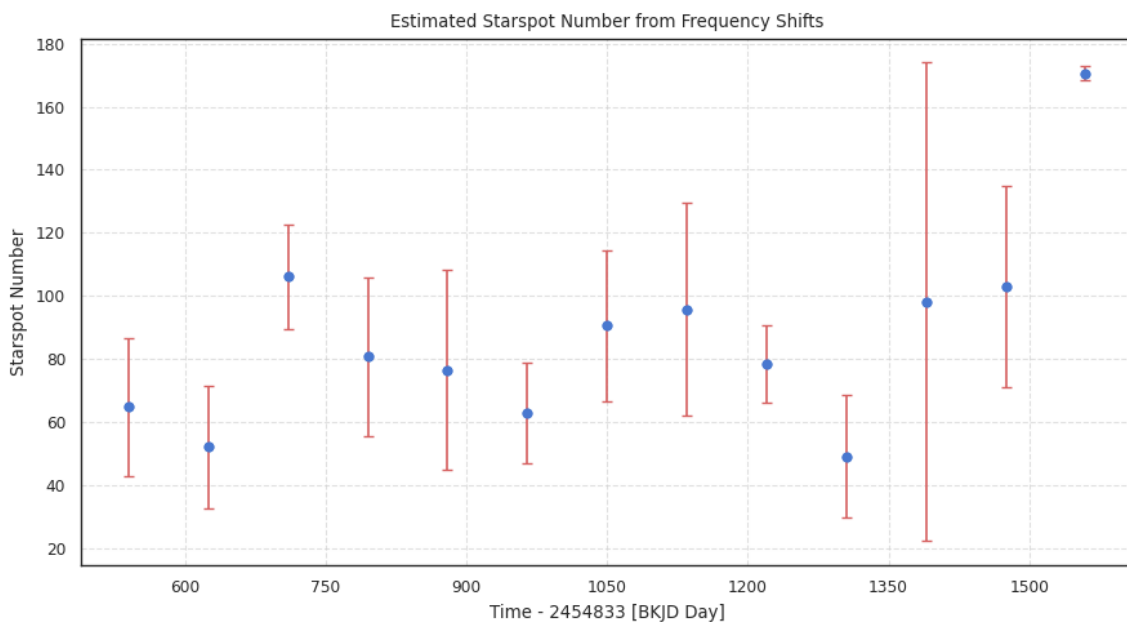


Figure 14. Projected starspot number as a function of time.

of magnetic activity. The larger frequency shifts observed in KIC 6106415 suggest that it may represent a different evolutionary stage or possess a more robust convective envelope, leading to stronger magnetic fields. These findings offer valuable insights into stellar dynamo processes and the complex interplay between magnetic activity and stellar oscillations in solar-type stars.

6. ACKNOWLEDGMENTS

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Facilities: Coffies, NASA, GOLF, Kepler

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