

LETTER TO THE EDITOR

The persistent Be enigma: The case of HD 212044

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ABSTRACT

We present an analysis of the Be star HD 212044 that reveals intriguing correlations between photometric variations, circumstellar disk emission, and frequencies. Our findings, based on data from the Transiting Exoplanet Survey Satellite (TESS) mission, show an unexpectedly strong negative correlation between photometric brightness and $H\alpha$ equivalent width, challenging the established understanding of the behavior of Be star seen at low inclination angles. Notably, beating episodes precede brightening events. This study suggests that the variability of HD 212044 may be due to additional mechanisms.

Key words. stars: emission-line, Be – stars: mass-loss – stars: oscillations

1. Introduction

Be stars are rapidly rotating objects on or near the main sequence that possess decretion disks, regions where emission lines and infrared excesses are observed (Rivinius et al. 2013). These stars often exhibit short-term variability (≈ 0.5 –2 days) due to non-radial pulsation (NRP) modes, specifically g - and p -modes (Rivinius et al. 2003). The circumstellar disks are fed aperiodically by Be stars through outbursts of varying intensity, during which line emissions are enhanced. However, the rapid rotation of Be stars alone is insufficient to account for the observed mass ejection, even though these stars do not reach break-up velocity (Zorec et al. 2016).

Non-radial pulsation has been proposed as a mechanism that provides the additional momentum and energy needed to expel photospheric matter (Rivinius et al. 1998b,c,d). However, establishing a clear correlation between pulsations and mass ejections remains challenging, and a comprehensive cause-and-effect model is still lacking. A rare case in which NRPs directly influenced mass-loss episodes was presented for the Be star μ Cen (Rivinius et al. 1998b,c,d). The authors found that the vector sum of the frequency amplitudes was largest during $H\alpha$ outbursts, suggesting that when the combined amplitude of the frequencies exceeds a certain threshold, mass is transferred to the circumstellar disk, after which the individual amplitudes are damped. In the past 15 years, space photometry has enabled continuous monitoring of Be stars, allowing for detailed studies of their variability. For instance, Huat et al. (2009) correlated amplitude variations in the primary NRP frequencies of HD 49330 with an outburst observed by the Convection Rotation and planetary Transits (CoRoT) satellite. Similarly, Howarth & Stevens (2014) utilized data from the Solar Mass Ejection Imager (SMEI), Wide Field Infrared Explorer (WIRE), and Microvariability and Oscillations of Stars (MOST) satellites

to observe an emission-line episode in ζ Oph, which coincided with increased intensity in photometric NRP frequencies. However, only a single episode was captured.

Our group has actively contributed to this field by observing significant NRP frequency and amplitude variations during medium-sized outbursts in HD 172219, recorded by the CoRoT satellite (Andrade et al. 2017). These variations have been interpreted as evidence of a temporary transfer and consumption of pulsation energy that actively contributes to the outburst. Furthermore, Labadie-Bartz et al. (2022) investigated 430 Be stars observed with the Transiting Exoplanet Survey Satellite (TESS) and have identified synchronized amplitude enhancements, or beatings of NRP frequencies with episodes of photometric enhancement and line emission, further enriching our understanding of these phenomena.

A series of studies led by D. Baade has further explored the mechanism behind mass ejection in Be stars. Utilizing space photometry, spectroscopic observations from the European Southern Observatory (ESO), and data from the Be Star Spectra (BeSS) database, they conducted an empirical analysis of Be outbursts and circumstellar disk feeding driven by NRP variability in several bright Be stars (Baade et al. 2016, 2018a,b; Rivinius et al. 2016; Borre et al. 2020; Labadie-Bartz et al. 2021). They propose two distinct mechanisms: one that regulates mass transfer from the star to the disk based on a combination of NRP frequencies and another that affects matter dynamics within the decretion disk. Despite these insights, the trigger for the activation of the NRP mechanism remains unclear.

In this context, the current Letter unveils a new and significant case involving the Be star HD 212044. Utilizing data from TESS and the BeSS database, we observed episodes of correlation between $H\alpha$ outbursts, photometric variability, and frequency behavior. What is particularly intriguing is that these correlations appear in a mirror-like pattern, contrary to expectations for a star observed at a low inclination angle.

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2. Observations

2.1. TESS photometry

The TESS observations analyzed in this study were obtained for HD 212044 at a 20-s cadence during observation cycles 2, 5, and 6. These observations cover sectors 16 and 17, from September 12, 2019, to November 2, 2019; sectors 56 and 57, from September 1, 2022, to October 29, 2022; and sectors 76 and 77, from February 26 to April 23, 2024. The usable data duration for each pair of sectors was 51, 57, and 40 days, respectively (only the first 12 days of data are usable for sector 77 due to a significant interruption in data collection afterward).

We utilized Simple Aperture Photometry (SAP) light curves from NASA's Ames Research Center, which included essential calibration and cleaning steps (Smith et al. 2017). The SAP flux was preferred over the Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP) flux because the latter often removes astrophysical variability on relatively long timescales (Labadie-Bartz et al. 2022), potentially obscuring outburst events in Be stars.

2.2. Frequency analysis

To identify periodicities in the TESS light curves, we employed the iterative pre-whitening method developed by Degroote et al. (2009), implemented in the IVS Python package from the Institute of Astronomy at KU Leuven¹. This method, combined with Lomb-Scargle periodograms (Scargle 1982), iteratively identifies the highest amplitude frequency present in the data. The light curve is refined at each stage using a nonlinear least-squares fit that incorporates the current frequency and those identified in previous iterations. This process continues until the signal-to-noise ratio (S/N) falls below 5, a threshold that indicates that all significant periodicities have been detected. Using an S/N threshold of ≥ 5 aligns with the criteria used in earlier analyses of *Kepler*/K2² data by Baran et al. (2015) and Burssens et al. (2019).

The frequency spectrum for HD 212044 reveals two distinct groups of frequencies commonly observed in Be stars: one group between 1.0 and 1.4 day⁻¹ and another between 2.0 and 2.5 day⁻¹. These groups are displayed in Fig. A.1.

We applied wavelet analysis (Haar 1910) to understand how these frequencies evolve, which offers significant advantages over traditional Fourier analysis by providing simultaneous analysis in both the time and frequency domains. While Fourier analysis can determine the frequency content of a signal, it does not reveal when these frequencies occur, making it less suitable for nonstationary signals in which spectral components change over time. Wavelet analysis overcomes this limitation by decomposing the signal into components across different scales and positions, thereby revealing the time-dependent spectral structure of the signal (Daubechies & Heil 1992).

2.3. BeSS spectra database

The BeSS database, a freely accessible repository maintained by the LESIA laboratory at the Observatoire de Paris-Meudon (Neiner et al. 2011), contains spectra of Be stars, Herbig Ae/Be

stars, and B[e] supergiants acquired by both professional and amateur astronomers. This comprehensive database includes hundreds of thousands of spectra from over a thousand Be stars. For our analysis, we selected medium- to high-resolution spectra of HD 212044 from the BeSS database, which was obtained concurrently with the TESS observations.

3. HD 212044

Popper (1938) was the first to classify HD 212044 as a Be star. He noted that its brightness fluctuates irregularly by approximately 0.2 magnitudes, and identified prominent H α and H β emission lines, along with weak absorption for H γ , leading to its initial classification as a B2ek spectral type. Subsequent studies have suggested different spectral classifications: Westerlund (1957) classified it as O9eV, while Jaschek et al. (1980) proposed B1 IVe. Later, Halbedel (1996) assigned a spectral type of B0e, with a projected rotational velocity ($v \sin i$) of 150 km/s ($\sigma = 2$ km/s).

Zorec et al. (2016) estimated that most Be stars rotate at 77% or less of their critical velocity. For a B0V star, they derived a critical velocity of 544 km/s, and 77% of this means a maximum rotational velocity of 420 km/s. Given the observed $v \sin i$ of 150 km/s, this corresponds to an inclination angle of at least 21°. The H α profiles recorded in the BeSS database at different epochs and with varying intensities are consistent with this low to moderate inclination angle (see H α profiles in Fig. B.1), as supported by comparisons with profiles from studies such as Sigut & Ghafourian (2023). Adelman et al. (2000) identified HD 212044 as a γ Cas variable based on observation from the HIPPARCOS satellite.

Labadie-Bartz et al. (2018) conducted a study of the photometric behavior of 160 classical Be stars using the Kilodegree Extremely Little Telescope (KELT; Pepper et al. 2012), complemented by spectroscopic observations from the Apache Point Observatory Galactic Evolution Experiment 1 (APOGEE-1) of the Brackett series (Eisenstein et al. 2011; Chojnowski et al. 2015, 2017) and data from the BeSS database (Neiner et al. 2011). Over approximately two and a half years (2012–2014), numerous outbursts were observed in HD 212044, accompanied by significant equivalent width (EW) variability. Labadie-Bartz et al. (2018) report that the star never appeared quiescent during this period, with visible and infrared emission lines consistently indicating a strong disk signature. H α measurements from the BeSS database, spanning from 2002 to 2016, recorded EW variations ranging from -1.2 to -23.5 Å. In the BeSS data concurrent with the TESS observations analyzed in the present Letter, the H α EW varied between -15 and -22 Å.

4. Correlations between Balmer emission, photometric level, and frequency beatings

We investigated correlations among variations in Balmer emission, photometric levels, and changes in frequency intensities in HD 212044 across the six TESS sectors. The abscissas are presented in BTJD³ = BJD⁴ – 2457000 days. Each figure shows the continuous monitoring for two consecutive TESS sectors and reveals strong variability.

Panel a of Figs. 1 and 2 displays the TESS SAP photometric flux, with the orange line representing the long-period trend.

¹ Code available at <https://github.com/IvS-KULeuven/IvSPythonRepository>

² *Kepler*/K2 is the redesigned mission after the *Kepler* spacecraft lost the second of four gyroscope-like reaction wheels, compromising its ability to maintain precise pointing.

³ Barycentric TESS Julian Date.

⁴ Barycentric Julian Date.

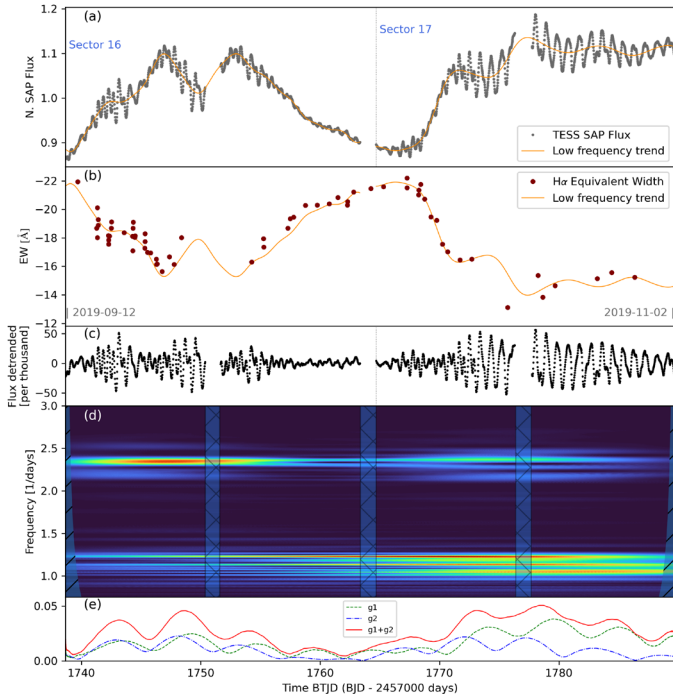


Fig. 1. Variability of HD 212044 during TESS sectors 16 and 17. (a) Normalized TESS SAP flux, with the orange line indicating the low-frequency trend. (b) H α EW measurements (red points). The orange line represents the low-frequency trend line from panel (a), mirrored to match the EW variations. (c) Detrended flux, highlighting frequency beatings (see Sect. 4). (d) Wavelet analysis of the TESS signal, showing the frequency content over time. (e) Amplitude modulation corresponding to the beatings and intensity variations in the five frequencies with the highest amplitudes of the first (in green) and second (in blue) frequency groups. The red curve represents the vector sum combined effect of the two groups. Abscissas are in BTJD = BJD – 2457000 (details in Sect. 4).

This trend line was constructed using frequencies below 0.5 d^{-1} , along with their respective phases and amplitudes. Panel b shows the EW of H α over time from the BeSS database spectra (Neiner et al. 2011); it has the same trend line when a linear fit is applied to the EW data points. Panel c presents the TESS light curve with long-period trends removed, where the beating effect between the main frequencies becomes evident. Panel d provides a wavelet analysis of the TESS signal, showing intensity increases in the main frequencies accompanying the beatings. Finally, panel e displays the intensity variations of the two observed frequency groups, with the green line representing the amplitude modulation among the five frequencies; the highest amplitudes are in the first group, and the blue line shows the same for the second group. The red line illustrates the combined effect, which is stronger during the beating of the frequencies observed in the third panel. Figure 3 displays the same panels without the EW measurements, due to the lack of H α observations during TESS 76 and 77 sectors.

Outbursts in Be stars are complex phenomena and have been extensively studied, primarily to understand the mechanisms driving mass ejection and disk formation. Research has focused on the roles of rapid rotation and NRPs, the variability in photometric and spectroscopic signatures during these events, and the long-term evolution of circumstellar disks resulting from episodic mass-loss processes (see, e.g., Sect. 4 of Rivinius et al. 2013). With this Letter we aim to provide additional insights into these processes based on the observed variability of HD 212044.

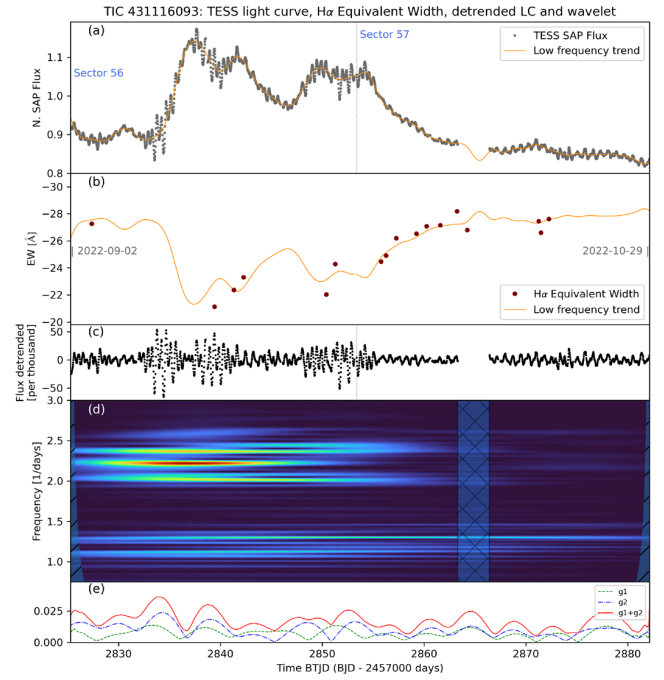


Fig. 2. Same as Fig. 1 but for TESS sectors 56 and 57 data.

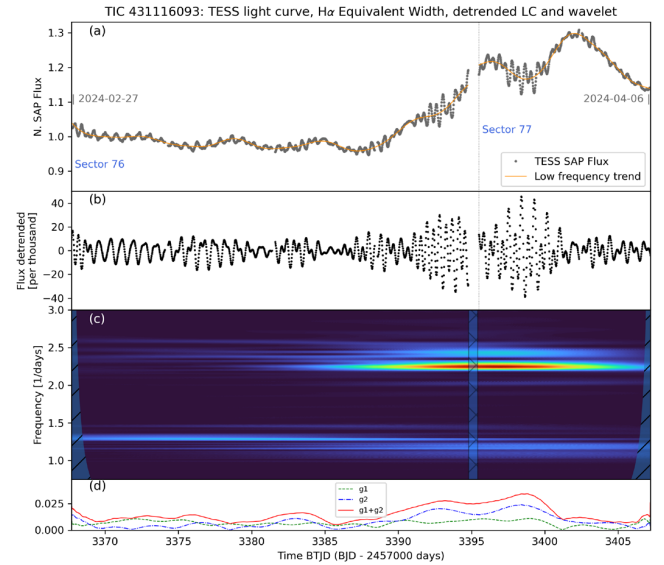


Fig. 3. Same as Fig. 1 but for TESS sectors 76 and 77 data. Only a portion of sector 77 is usable, and no H α measurements are available in the BeSS database during this epoch.

Figures 1–3 illustrate the photometric and spectroscopic variations of HD 212044, providing a valuable opportunity to study the dynamic processes occurring within the circumstellar environment of a Be star. During the observed periods, several medium-sized outbursts occurred.

A notable finding is the anticorrelation between photometric brightness and H α intensity, which challenges expectations for a low-inclination star like HD 212044. According to Harmanec (1983), correlations between photometric and spectroscopic features in Be stars generally fall into two categories. The first category shows a positive correlation, where stronger H α emission is associated with a brighter star in the Paschen continuum – typical for stars seen at low inclination angles. The second

category shows a negative correlation, where stronger H α emission corresponds to a fainter star, a pattern commonly found in shell stars seen nearly edge-on (i.e., at high inclination). Moreover, Sigut & Patel (2013) concluded that the correlation changes from positive to negative for a critical angle (i_{crit}) of 75°.

Haubois et al. (2012) demonstrated that a viscous accretion disk, characteristic of Be stars, should exhibit behaviors similar to the categories defined by Harmanec (1983). Their study (see their Fig. 12) showed that, for a disk observed at an inclination angle of 30°, the disk appears brighter in the visible spectrum during its buildup phase. The opposite effect is seen for a disk observed edge-on at an inclination angle of 90° (see also Sigut & Patel 2013; Sigut & Ghafourian 2023).

HD 212044, a star with a low to moderate inclination angle, exhibits an inverse relationship between the variations in the photometric brightness and H α intensity. This is inconsistent with the studies cited above. For instance, TESS observations during sectors 16 and 17 (Fig. 1) show a minimum in photometric brightness at the beginning of the observations (around BTJD 1740) coinciding with a peak in H α EW, followed by a progressive decline in H α and two brightness maxima. A brightness minimum follows, mirrored by a pronounced H α EW maximum at the beginning of sector 17 (around BTJD 1770).

Furthermore, panels a and c of Figs. 1 and 2 reveal a clear correlation between the beating of frequencies and photometric brightness, providing further insight into the outburst mechanisms. This correlation between the beating of frequencies and the brightness of a Be star is reminiscent of the behavior observed for μ Cen by Rivinius et al. (1998b,c,d, 2001). For μ Cen, which is also seen at an intermediate inclination angle (30° < i < 45°), these authors obtained approximately 500 high-quality spectra from ESO between 1987 and 1999, from which they identified six NRP periods. They demonstrated a correlation between constructive mode interference of the NRP periods and line-emission outbursts (see also Fig. 3 in Rivinius et al. 1998a). Remarkably, they successfully predicted outbursts of μ Cen in 1997 by modeling the stellar variability of a multimode combination of NRPs. Thus, at least for the Be star μ Cen, NRPs play a significant role in the observed mass ejection as seen through line emission. However, HD 212044 may involve additional mechanisms and requires further investigation.

Figure 2 presents data for HD 212044 during TESS sectors 56 and 57. Although H α EW measurements are less frequent than in sectors 16 and 17, the average emission level is stronger. A similar anticorrelation between photometric brightness and emission, as seen in Fig. 1, is evident: following two brightening episodes, an emission enhancement occurs around the middle of sector 57, beginning at approximately BTJD 2855 (second panel from the top). As in sectors 16 and 17, the beating of the main frequencies aligns with the brightness enhancement in the last three panels. Figure 3 shows the same general photometric behavior observed in the previous years.

5. Conclusions

The advent of stellar space photometry through missions like CoRoT, *Kepler*, and TESS has dramatically enhanced our understanding of stellar variability. In this study, we utilized TESS observations to explore the Be star HD 212044 and identified correlations between photometric levels, circumstellar disk line emission, and frequencies. Our analysis reveals an unexpected and strong negative correlation between photometric brightness and H α EW at a low inclination angle, very far from the i_{crit} =

75° where the correlation regime changes. This finding challenges the current understanding of Be stars, particularly those observed at low inclination angles. This unusual behavior suggests that additional or alternative mechanisms may influence the variability of HD 212044 beyond what is typically observed in similar stars. Further studies are needed to explore these findings in more detail and to clarify the underlying processes driving this star's behavior. Our results provide new insights into the complex interactions between pulsation modes, mass ejection, and disk dynamics in Be stars.

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References

- Adelman, S. J., Mayer, M. R., & Rosidivito, M. A. 2000, *Inf. Bull. Variable Stars*, **5008**, 1
- Andrade, L., Janot-Pacheco, E., Emilio, M., et al. 2017, *A&A*, **603**, A41
- Baade, D., Rivinius, T., Pigulski, A., et al. 2016, *A&A*, **588**, A56
- Baade, D., Pigulski, A., Rivinius, T., et al. 2018a, *A&A*, **610**, A70
- Baade, D., Pigulski, A., Rivinius, T., et al. 2018b, *A&A*, **620**, A145
- Baran, A. S., Koen, C., & Pokrzywka, B. 2015, *MNRAS*, **448**, L16
- Borre, C. C., Baade, D., Pigulski, A., et al. 2020, *A&A*, **635**, A140
- Bursens, S., Bowman, D., Aerts, C., et al. 2019, *MNRAS*, **489**, 1304
- Chojnowski, S. D., Whelan, D. G., Wisniewski, J. P., et al. 2015, *AJ*, **149**, 7
- Chojnowski, S. D., Wisniewski, J. P., Whelan, D. G., et al. 2017, *AJ*, **153**, 174
- Daubechies, I., & Heil, C. 1992, *Comput. Phys.*, **6**, 697
- Degroote, P., Aerts, C., Ollivier, M., et al. 2009, *A&A*, **506**, 471
- Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, *AJ*, **142**, 72
- Haar, A. 1910, *Math. Ann.*, **69**, 331
- Halbedel, E. M. 1996, *PASP*, **108**, 833
- Harmanec, P. 1983, *Hvar Obs. Bull.*, **7**, 55
- Haubois, X., Carciofi, A. C., Rivinius, T., Okazaki, A. T., & Bjorkman, J. E. 2012, *ApJ*, **756**, 156
- Howarth, I. D., & Stevens, I. R. 2014, *MNRAS*, **445**, 2878
- Huat, A. L., Hubert, A. M., Baudin, F., et al. 2009, *A&A*, **506**, 95
- Jaschek, M., Hubert-Delplace, A. M., Hubert, H., & Jaschek, C. 1980, *A&AS*, **42**, 103
- Labadie-Bartz, J., Chojnowski, S. D., Whelan, D. G., et al. 2018, *AJ*, **155**, 53
- Labadie-Bartz, J., Baade, D., Carciofi, A. C., et al. 2021, *MNRAS*, **502**, 242
- Labadie-Bartz, J., Carciofi, A. C., Henrique de Amorim, T., et al. 2022, *AJ*, **163**, 226
- Neiner, C., de Batz, B., Cochard, F., et al. 2011, *AJ*, **142**, 149
- Pepper, J., Siverd, R. J., Kuhn, R., et al. 2012, *Am. Astron. Soc. Meet. Abstr.*, **219**, 125.06
- Popper, D. M. 1938, *PASP*, **50**, 175
- Rivinius, T., Baade, D., Stefl, S., et al. 1998a, in *Cyclical Variability in Stellar Winds*, eds. L. Kaper, & A. W. Fullerton, 207
- Rivinius, T., Baade, D., Stefl, S., et al. 1998b, *Be Star Newsletter*, **33**, 15
- Rivinius, T., Baade, D., Stefl, S., et al. 1998c, *A&A*, **333**, 125
- Rivinius, T., Baade, D., Stefl, S., et al. 1998d, *A&A*, **336**, 177
- Rivinius, T., Baade, D., Stefl, S., et al. 2001, *A&A*, **369**, 1058
- Rivinius, T., Baade, D., & Stefl, S. 2003, *A&A*, **411**, 229
- Rivinius, T., Carciofi, A. C., & Martayan, C. 2013, *A&ARv*, **21**, 69
- Rivinius, T., Baade, D., & Carciofi, A. C. 2016, *A&A*, **593**, A106
- Scargle, J. D. 1982, *ApJ*, **263**, 835
- Sigut, T. A. A., & Ghafourian, N. R. 2023, *ApJ*, **948**, 34
- Sigut, T. A. A., & Patel, P. 2013, *ApJ*, **765**, 41
- Smith, J. C., Morris, R. L., Jenkins, J. M., et al. 2017, *Kepler Data Processing Handbook: Finding Optimal Apertures in Kepler Data*, Kepler Science Document KSCI-19081-002
- Steff, S., Baade, D., Rivinius, T., et al. 1998, *ASP Conf. Ser.*, **135**, 348
- Westerlund, B. 1957, *Arkiv Astron.*, **2**, 83
- Zorec, J., Frémat, Y., Domiciano de Souza, A., et al. 2016, *A&A*, **595**, A132

Appendix A: Frequency spectra

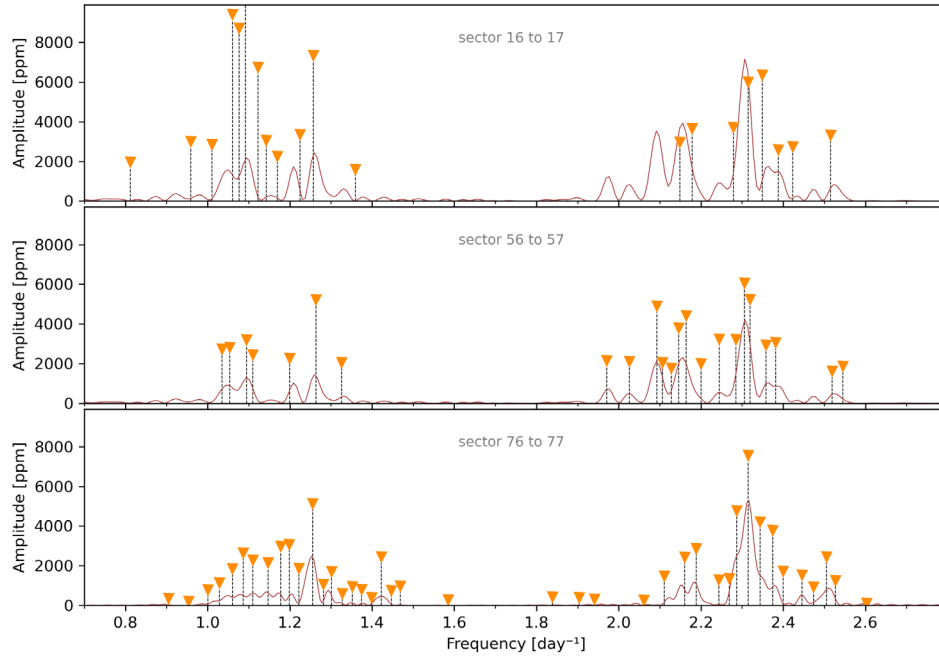


Fig. A.1. Frequency spectrum for each pair of TESS sectors of HD 212044. Orange triangles and dashed lines indicate the frequencies detected using the iterative pre-whitening method, with $S/N \geq 5$. The red line represents a simple Lomb-Scargle periodogram. Two distinct groups of frequencies are evident: a first one primarily between 1.0 and 1.4 d^{-1} , and a second one between 2.0 and 2.5 d^{-1} . Many frequencies remain consistent across the three observation segments. Within the first group, we identify 1.26 d^{-1} as the main frequency, which is strong and stable over the three and a half years spanned by the observations. In contrast, the frequency at 1.09 d^{-1} is very strong during the first cycle, with an amplitude of $11,300 \text{ ppm}$ (beyond the scale of the figure), but its amplitude reduces by more than half in subsequent cycles. We propose that this frequency corresponds to the Stefl frequency (Stefl et al. 1998; Baade et al. 2016), a transient exophotospheric frequency that is enhanced during outbursts and typically appears $\sim 10\%$ below the main pulsation frequency. The dominant pulsation frequency in the second group was detected at 2.35 d^{-1} . The first harmonic of the Stefl frequency is visible at 2.17 d^{-1} .

Appendix B: H α profile

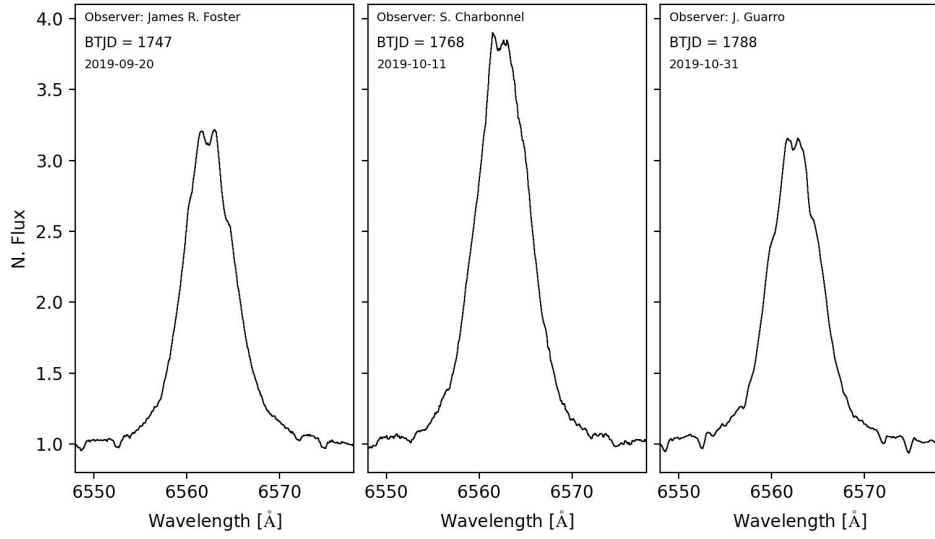


Fig. B.1. H α profiles at different phases during TESS sectors 16 and 17. From left to right: BTJD = 1747 (high TESS flux, low H α flux), BTJD = 1768 (low TESS flux, high H α flux), and BTJD = 1788 (high TESS flux, low H α flux). These H α profiles are typical of a Be star seen at a low inclination angle (Sigut & Ghafourian 2023).