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HD 43587: a primary CoRoT target under a Maunder minimum phase?

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Abstract. One of the most enigmatic phenomena in the solar activity history is the so-called Maunder minimum, which consists of the lowest sunspot's counting ever registered for the Sun, and never so far confirmed for other stars. Since the spectroscopic measurements from the Mt. Wilson survey, the solar analog HD43587 has shown a very low and apparently invariant activity level, which makes it a Maunder minimum candidate. We use an activity measurements dataset available in the literature, and compute the activity S-index from HARPS and NARVAL spectra, to infer a activity cycle period. Besides, we analyze the CoRoT light-curve of HD43587, and apply gyrochronology and activity calibrations, to determine its rotation period. Finally, based on an evolutionary model and the inferred rotation period, we use the EULAG-MHD code to perform global MHD simulations of HD43587 with the aim of getting some insights about its dynamo process. We confirm the almost flat activity profile, with an activity cycle period $P_{\rm cyc} = 10.44 \pm 3.03$ yrs deduced from the S-index time series. It was impossible to define a rotation period from the light-curve, however, gyrochronology and activity calibrations allow us to infer an indirect estimate of $\overline{P}_{\rm rot} = 22.62 \pm 2.94$ d. We conclude that this object might be experiencing a "natural" decrease in magnetic activity as a consequence of its age. Nevertheless, the possibility that HD43587 is in a Maunder minimum phase cannot be ruled out.

Resumo. Um dos mais enigmáticos fenômenos na história da atividade solar é o conhecido mínimo de Maunder, que consiste na menor contagem de manchas registradas no Sol, e jamais confirmada em outras estrelas. Desde as medidas espectroscópicas do levantamento do Mt. Wilson, a análoga solar HD43587 tem mostrado um nível de atividade muito baixo e aparentemente invariante. Utilizamos um conjunto de dados de medidas de atividade disponível na literatura e calculamos o índice de atividade, S_{MW} , a partir dos espectros HARPS e NARVAL, para calcular um período de ciclo de atividade. Além disso, analisamos a curva de luz CoRoT de HD43587 e aplicamos a girocronologia, bem como as calibrações de atividade para determinar seu período de rotação. Finalmente, com base em um modelo evolutivo e no período de rotação inferido, usamos o código EULAG-MHD para realizar simulações globais de MHD para HD43587 com o objetivo de obter um melhor detalhamento do seu processo de dínamo. Confirmamos o perfil de atividade fixo, com um período de ciclo de atividade $P_{\rm cyc} = 10,44 \pm 3,03$ anos deduzido da série temporal do S_{MW} . Foi impossível definir um período de rotação a partir da curva da luz, no entanto, as calibrações de girocronologia e atividade permitem realizar uma estimativa indireta de $\overline{P}_{\rm rot} = 22.62 \pm 2.94$ d. Concluímos que esse objeto pode estar sofrendo uma diminuição "natural" da atividade magnética como conseqüência de sua idade. No entanto, a possibilidade de HD43587 estar em mínimo de Maunder não pode ser descartada.

Keywords. Stars: activity – Stars: evolution – Stars: chromospheres

1. Introduction

The stellar chromospheric activity (hereafter activity) has been a subject of intense investigation and discussion in the last decades. Measurements of solar activity have been done since the XVI century, primarily counting sunspots and, recently, using stellar spectral analysis (Eddy 1976). One of the most intriguing phenomena observed solar activity evolution is the long period phase, called Maunder Minimum (MM hereafter) when almost no sunspot, were observed on the solar surface (Eddy 1976), for about 70 yrs between the 16th and the 17th centuries. The MM remains an open problem for astronomers until today. The first survey of spectroscopic measurements, which occurred from 1960 to mid-1990, was the HK project at Mount Wilson Observatory, using Ca II H&K lines centered at 3969Å and 3934Å, respectively (Duncan et al. 1991; Wright 2004). Nevertheless, the S-index (S_{MW}) presents not only the chromospheric activity but also the photospheric contribution. Then Noyes et al. (1984) presented the well-known R'_{HK} -index, that subtract the photospheric contribution from S_{MW} measurements. Since the Mount Wilson survey, several long-term surveys have been performed. The main ones were: the California and Carnegie planet search (Wright 2004; Isaacson & Fischer 2010), the Solar and Stellar activity program at Lowell Observatory (Radick et al. 2018), the Magellan survey (Arriagada 2011) and some others. In the majority of them was used S_{MW} , as the standard index to measure the chromospheric activity (or an S-index calibrated to S_{MW} scale).

In this context, it is widely discussed how singular is the activity evolution of the Sun. The problem of extremely low activity in main sequence stars is still a puzzle for the stellar astrophysics. It is known that young stars have a strong activity (do Nascimento et al. 2014), and if these stars present an extremely low activity for several decades, it could be one evidence of a Maunder Minimum phase in another star other than the Sun (Schröder et al. 2012). In the meantime, the solar activity cycle is 11 years and many solar-like stars should have an activity-cycle measurable (Baliunas et al. 1995). We investigate the low spectroscopic activity of the solar analog HD43587 over 50 years of measurements. We focused on the continuous low activity level obtained from spectroscopic measurements, and presented by the time-averaged value $\langle S_{MW} \rangle = 0.1543$.

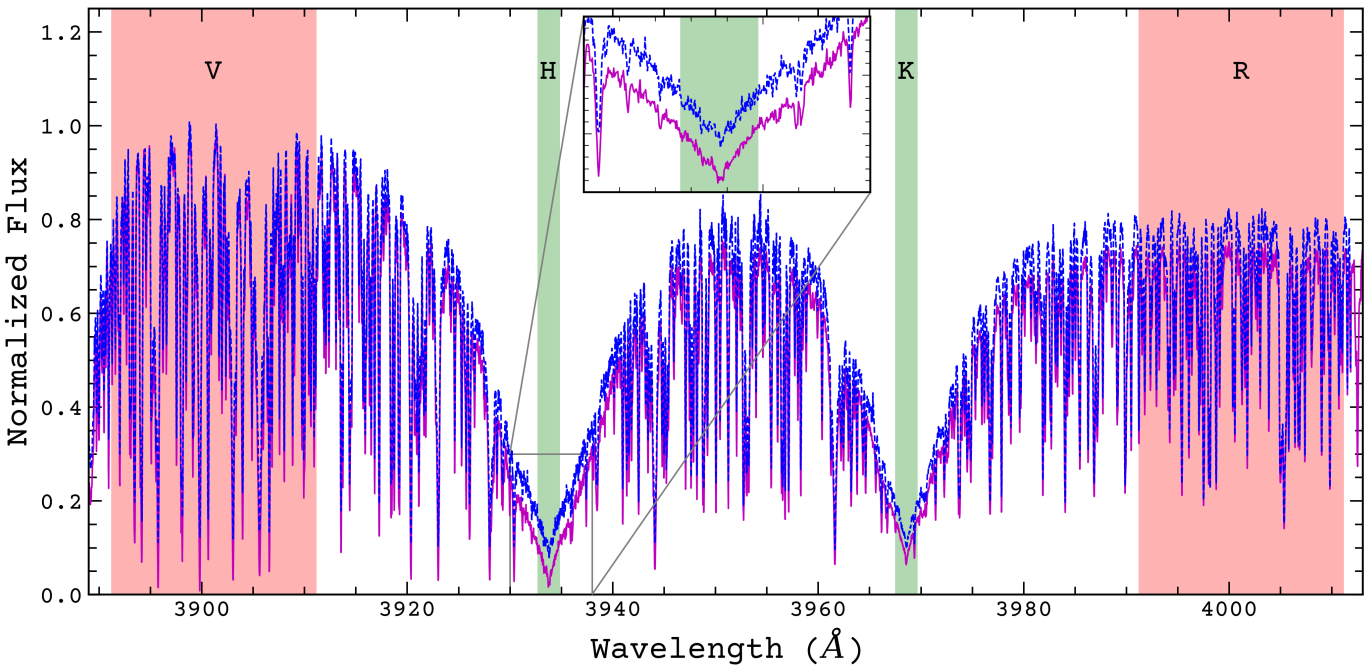

Figure 1. HD 43587 spectra from NARVAL spectrograph. The magenta line corresponds to the spectrum with the maximum S_{MW} value of the dataset, observed on February 13th 2010. The blue line corresponds to the spectrum with the minimum S_{MW} value, observed on January 18th 2010. Both spectra were normalized from 3889 Å to 4013 Å. An upward shift in flux of 0.05 was applied in the blue spectra to better visualization. The inset panel shows the region between 3930 Å and 3938 Å in detail.

2. Data

In this section we briefly present some features of the solar analog HD43587. We also summarize the photometric and observational data used.

The star HD43587 (i.e. HD43587Aa) belongs to a quadruple system formed by two distant main sequence visual binaries (see Table 1 in Ferreira et al. (2020)). This system is localized in the Orion constellation. This system has been observed by many authors (Duncan et al. 1991; Baliunas et al. 1995; Catala et al. 2006; Morel et al. 2013). HD43587 was a CoRoT primary target, in the seismology program (ID CoRoT 3474). This object was observed during the LRa03 for 145 days, performed between October 2009 and March 2010 (Boumier et al. 2014). Afterward, complementary observations were performed by the spectrograph HARPS *(High Accuracy Radial velocity Planet Search)*, mounted on the 3.6m telescope in La Silla Observatory/ESO (Boumier et al. 2014). It also has been monitored by several surveys along 50 yrs, as detailed below.

The observational spectroscopic data considered, were obtained in part from long-term surveys already published, as well as from HARPS and NARVAL spectra. The already published data are listed following:

- NSO/MWO: measurements obtained from MWO between 1966 and 1983 (Duncan et al. 1991). Besides, we used largely dataset updated from National Solar Observatory (NSO) with S_{MW} measurements until 1995[1];
- NARVAL: We used the 50 high-resolution spectra obtained from archive available on NARVAL/Polarbase (Petit et al. 2014);
- HARPS: 3 high-resolution spectra from HARPS/ESO, obtained from (Morel et al. 2013);
- California and Carnegie Planet Search: S_{MW} measurements from this program at Keck Observatory, available in Wright (2004).
- Lowell Observatory: The S_{MW} measurements performed between 1994 and 2016, available in Radick et al. (2018).

It is important to underline a crucial feature of this star, that has been considered as a good MM candidate by many authors (Baliunas et al. 1995; Lubin et al. 2010; Schröder et al. 2012; Morel et al. 2013). Its long activity timeseries indicates an invariant flat S_{MW} profile along 50 yrs. Its time-averaged activity index is $\langle S_{MW} \rangle = 0.1543$, while for the Sun $\langle S_{MW} \rangle_{\odot} = 0.167$.

Castro et al. (2019) presented an evolution status analysis of this object, using two evolution codes, TGEC (Hui-Bon-Hoa 2008) and CESTAM (Marques et al. 2013). Data from spectroscopic, photometric and seismic constraints were used (see the main results in Table 1 in Ferreira et al. (2020)). These results confirm the solar analog status of HD43587, and indicate a star slightly more massive and older than the Sun, which is in good agreement with its long-standing low activity level.

We used the well-know S_{MW} as proposed by Duncan et al. (1991); Wright (2004), to compute this proxy from spectra archive we use a linear fit calibration between the instrumental S-index and S_{MW} for the Mount Wilson standard stars. Fortunately, many authors already published these S-index calibrations. Taking this into account, we used 50 NARVAL[2] high-resolution spectra observed in September 2009, January 2010, and February 2010, consisting of 5 spectra per night, totalizing 10 nights. The spectra correspondent to maximum and minimum S_{MW} are presented in Fig. 1. The S_{MW} from NARVAL spectra was calculated following the calibrations proposed by Marsden et al. (2014). We also used three high-resolution HARPS spec-

[1] https://www.nso.edu/data/historical-data/mount-wilson-observatory-hk-project/

[2] Mounted at the Telescope Bernard Lyot (TBL) located at Pic du Midi, France.

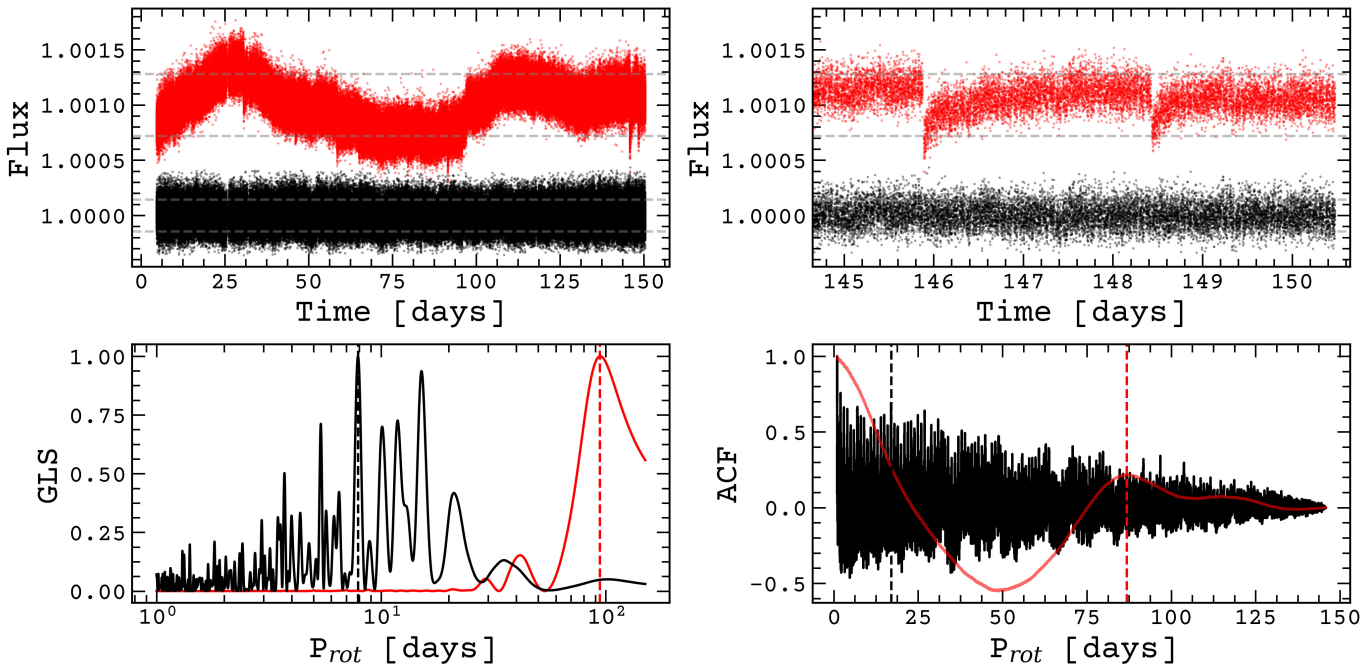

Figure 2. CoRoT light curve of HD43587. Left top panel: raw light curve including discontinuities (red dots) and the detrended light curve (black dots). Right top panel: detail of the discontinuities at the end of the light curve (red dots) and the flat aspect of the curve after the reduction (black dots). Left bottom panel: GLS periodograms for the two cases of reduction (raw in red and detrended in black). Right bottom panel: ACF periodogram for the same two reductions

tra collected between December 2010 and January 2011 (Morel et al. 2013). The S_{MW} was computed following the calibrations proposed by Lovis et al. (2011). A complete detailed description is presented in Ferreira et al. (2020).

3. Results and discussion

3.1. Photometric observation from HD43587's CoRoT light curve

From the photometric CoRoT data we investigate the variability of the HD43587's light curve. Seeking to determine the rotational period, we computed the Generalized Lomb-Scargle (GLS) periodogram (Zechmeister & Kürster 2009) as well as the Autocorrelation Function (Brockwell 2002), as shown in Fig. 2. After performing the data reduction (see section 3.1 in Ferreira et al. (2020)), we obtained $P_{\rm rot}$ = 93.98 d with the GLS and $P_{\rm rot}$ = 86.81 d with the ACF, as indicated by the vertical red dashed lines in the lower panels of figure 2. This consists clearly in inadequate periods for solar analog stars, as shown by do Nascimento et al. (2014).

We also derived the photometric activity proxy, by computing the standard deviation of the light curve corrected after subtracting the photon noise S_{ph} (Mathur et al. 2014). We obtained S_{ph} = 102 ppm, which returns a rotational period of 43.38 d, which is a $P_{\rm rot}$ compatible with a subgiant star for this stellar-mass (Mathur et al. 2014).

3.2. Spectroscopic stellar activity timeseries

We computed the S-index for a dataset of spectra archives from the spectrograph NARVAL and HARPS. We used our python code, developed according to the method proposed by Duncan et al. (1991); Wright (2004); Marsden et al. (2014). Then we use the calibrations to convert the instrumental S-index to S_{MW}, as described in the previous section. Afterward, we combined the entire S_{MW} time-series with the previous data. The whole time-series consists of 1524 measurements obtained between 1966 and 2016.

This allows us to compile a long-term activity series calibrated to the MW scale, which is presented in the upper panel of Fig. 3. The long flat-activity profile, $\langle S_{MW}\rangle$ = 0.154 and $\log\langle R'_{\rm HK}\rangle$ = −4.97 is reinforced by the very low variability of the S_{MW}, quantified by the standard deviation of σ_S = 0.0043. Besides, we seek to determine a suitable activity cycle length for HD43587. We used the GLS analysis and we obtained the periodogram of the whole S_{MW} time series, which is represented by the solid gray line in the bottom left panel of Fig. 3. We used a gaussian fit (solid red line) to find the cycle period without the long term trend. We then inferred a suitable cycle period, $P_{\rm cyc}$ = 10.44 ± 3.03 yrs.

3.3. Stellar Rotation

In order to determine the reasonable rotation period for HD43587, we first used the whole activity time-series of S_{MW} and compute the GLS periodogram. We then analyzed the densest region in the dataset, formed by 195 points over 184 days between 46340.99 to 46525.65 days (JD-2400000), see Fig. 3. The inferred period lies below the 10% false alarm probability, and thus was discarded as true rotation period.

We also estimated the $P_{\rm rot}$ using gyrochronology as proposed by Barnes (2009) and Meibom et al. (2009). We used the two ages determined by Castro et al. (2019),inferred from two different evolution codes, from TGEC 6.76 ± 0.12 Gyr and from CESTAM 5.7 ± 0.1 Gyr. The color index used is $B - V$ = 0.61 (van Leeuwen 2007). Then we found two rotation periods: $P^T_{\rm rot}$ = 25.04 ± 4.41 d with TGEC age, and $P^C_{\rm rot}$ = 22.91 ± 3.72 d with CESTAM age.

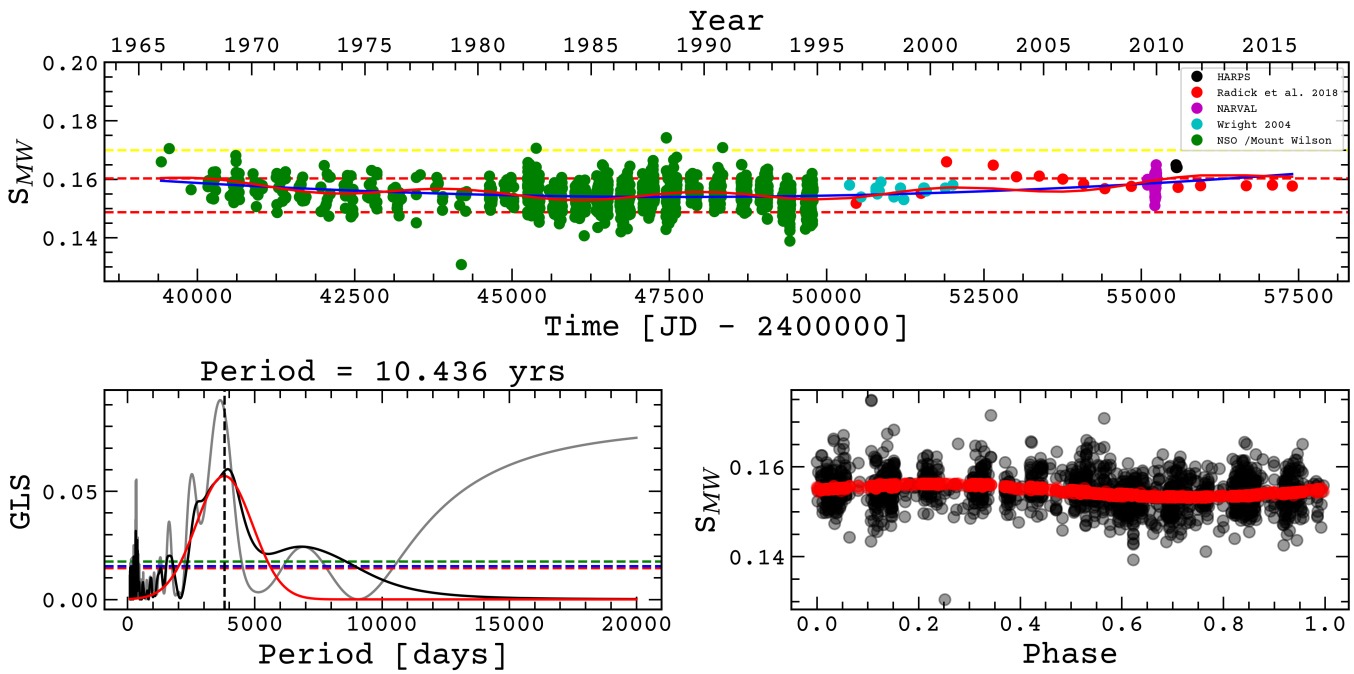

Figure 3. Entire spectroscopic chromospheric activity measurements with the S_{index} calibrated to the Mt. Wilson Scale for HD43587 between 1966 and 2016. The upper panel displays all measurements from Duncan et al. (1991); Wright (2004); **?**); Radick et al. (2018), combined with the computed S_{MW} from the NARVAl and HARPS spectra archives. The red solid line is the sinusoidal curve fitting for 10.436 yrs, the blue solid line is the long-term trend found to be larger than 50 yrs. The yellow dashed line shows the mean S_{MW} for the Sun. The bottom left panel shows the GLS periodogram of the whole S_{MW} time series (solid gray line), and removing the long trend larger than 50 years (solid black line). The gaussian fit (solid red line) of this second periodogram indicates an activity-cycle of 10.436 years (vertical black dashed line). The bottom right panel shows the phase of the S_{MW} (black circles) and the folded fit with the found period (red circles).

Furthermore, we derived a theoretical Rossby number Ro, from activity-rotation calibrations proposed by Noyes et al. (1984). This is defined as the ratio of the rotation period, $P_{\rm rot}$, to the convective turnover time, τ_c. We used the inferred $P_{\rm rot}$ from TGEC models age and $\tau_c = 12.8 \pm 1.0$ d, therefore $\mathrm{Ro}^T = 1.96 \pm 0.38$. We also deduce a $P_{\rm rot}$ from the S_{MW} according to the semiempirical calibrations from Noyes et al. (1984). We then applied the calculations to the whole dataset and we obtained a mean Rossby number with its standard deviation $\mathrm{Ro}^N = 2.05 \pm 0.05$. We calculate the τ_c which depends on (B-V) using Eq. (4) of Noyes et al. (1984). From the result $\tau_c = 9.67$ d, and the definition of the Rossby number $\mathrm{Ro} = P_{\rm rot}/\tau_c$, we derived a mean $P^N_{\rm rot} = 19.79 \pm 0.69$ d. Thereafter, we can estimate an average rotation period, $\overline{P}_{\rm rot} = 22.58 \pm 2.94$ d for HD43587, which is adequate to the rotation of a solar analog star.

3.4. Simulations results

We simulated the object HD43587 with the EULAG-MHD code, which considered a fiducial fit for its stratification. This code solves the equations of Lipps & Hemler (1982), adapted to the MHD and inviscid regime. The set of equations, as well as the boundary and initial conditions, are fully described in Guerrero et al. (2016) and Ferreira et al. (2020). We performed three simulations with the same stratification and different $P_{\rm rot}$, with P21 = 21 d, P25 = 25 d and P29 = 29 d.

The Fig. 4 is the main result of simulations. The colored contours represent the radial magnetic field averaged over longitude, $\overline{B}_r$, and the solid (dashed) contour lines reproduce the positive (negative) mean toroidal magnetic field, $\overline{B}_\varphi$. The simulations result in oscillatory magnetic fields with polarity reversals. From these simulations, we are able to reproduce cyclic dynamo action, including field reversals, including a differential rotation smaller than in the Sun, and a magnetic field which at the top boundary is similar to the radial field observed at the solar surface ($\sim 10^{-3}$ Tesla). The difference observed about 10% in $\langle S_{MW}\rangle$ between the Sun and HD43587 might be correlated to a diminished differential rotation which in the Sun is at least twice larger than in simulations P25 and P21. These cases are the ones that better reproduce the cycle period of HD43587 inferred from the spectroscopic chromospheric activity.

4. Conclusions and summary

In this study, combining high-resolution spectra archive and already published data, we investigated the chromospheric activity evolution of the solar analog star HD43587. It allows us to build a large S_{MW} time-series from several surveys and calculate S_{MW} from NARVAL and HARPS databases. The derived $\langle S_{MW}\rangle = 0.154$ and $\log\langle R'_{\rm HK}\rangle = -4.97$ indicate a low chromospheric activity, beyond the limit of the Vaughan-Preston gap (Brandenburg et al. 2017). Moreover, the GLS analysis of the activity time series, provides us a reliable 10.44 yrs cycle period (see Fig. 3), which is very close to the solar value. The indirect determinations of a rotation period give $\overline{P}_{\rm rot} = 22.62 \pm 2.94$ d.

These values of $P_{\rm cyc}$ and $\overline{P}_{\rm rot}$, are consistent for a solar analog star. The inferred Rossby number, $\mathrm{Ro}^N = 2.05 \pm 0.05$ from the calibrations prescribed by Noyes et al. (1984), and $\mathrm{Ro}^T = 1.96 \pm 0.38$ from TGEC modeling, point out a rotation period about twice larger than the convective turnover time which

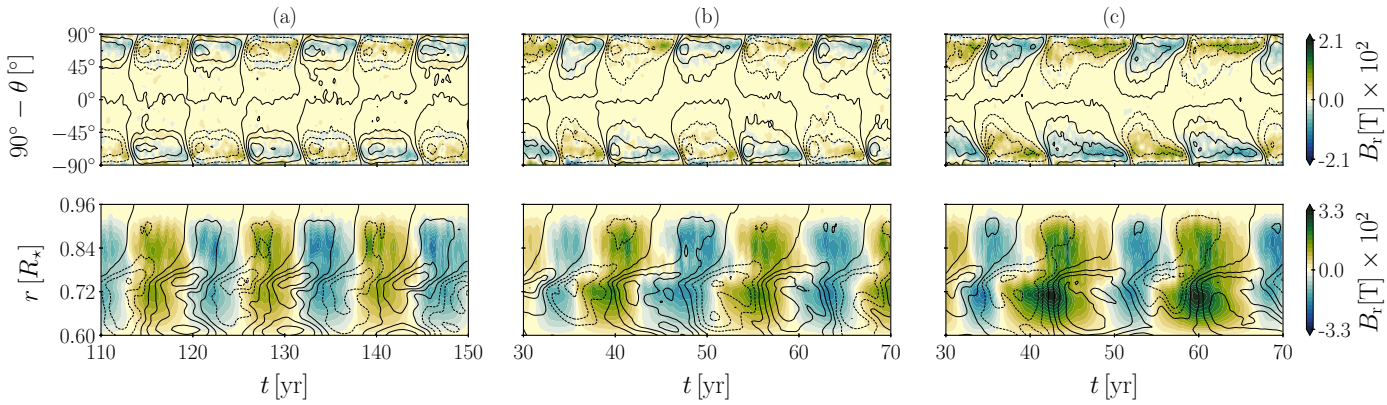

Figure 4. Time-latitude at $r = 0.95\,R_\star$ (upper panels), and time-radius at $\theta = 15°$ latitude (lower panels), butterfly diagrams comparing the magnetic field evolution between simulations (a) P29, (b) P25 and (c) P21. The colored contours show the radial magnetic field intensity. The solid (dashed) lines show the positive (negative) contours of toroidal magnetic field.

might represent a diminished differential rotation (Metcalfe et al. 2016).

From the inferred rotational period and the internal structure of HD43587, we can perform global simulations with the EULAG-MHD code. For all the cases the angular velocity is solar-like, i.e., equator rotates faster than the poles, with relative differential rotation smaller than the solar value. The radial field at the top of the simulations (at $r = 0.96\,R_\star$) is about 10^{-2} T. This is similar to the radial field at the solar photosphere. The better simulation with a $P_{\rm rot} = 21$ d provides us an activity cycle period about 8.6 yrs, which is compatible with the observational value found.

Considering that the possibility that HD43587 is under a Maunder minimum cannot be ruled out, our results indicate that it is a solar analog star, older than the Sun, and undergoing a "natural" decrease of its magnetic activity. This low activity profile probably is due to a small differential rotation in the convective zone. Furthermore, the determination of a Maunder minimum star would only be accurate if we could observe the star coming out of this activity minimum.

These results explain the importance of studying HD43587 in the context of stellar evolution. Some authors have investigated its features and evolutionary status, as well as its magnetic activity evolution. Its similarity with the Sun, whether evolutive, spectroscopic or magnetic, gives a picture of the future evolution of the Sun and makes it a suitable candidate for being an earth-like exoplanet host.

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