

$\zeta^1 + \zeta^2$ Reticuli binary system: a puzzling chromospheric activity pattern

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ABSTRACT

We perform, for the first time, a detailed long-term activity study of the binary system ζ Ret. We use all available HARPS spectra obtained between the years 2003 and 2016. We build a time series of the Mount Wilson S index for both stars, then we analyse these series by using Lomb–Scargle periodograms. The components ζ^1 Ret and ζ^2 Ret that belong to this binary system are physically very similar to each other and also similar to our Sun, which makes it a remarkable system. We detect in the solar-analogue star ζ^2 Ret a long-term activity cycle with a period of ~ 10 yr, similar to the solar one (~ 11 yr). It is worthwhile to mention that this object satisfies previous criteria for a flat star and for a cycling star simultaneously. Another interesting feature of this binary system is a high ~ 0.220 dex difference between the average $\log(R'_{\text{HK}})$ activity levels of both stars. Our study clearly shows that ζ^1 Ret is significantly more active than ζ^2 Ret. In addition, ζ^1 Ret shows an erratic variability in its stellar activity. In this work, we explore different scenarios trying to explain this rare behaviour in a pair of coeval stars, which could help to explain the difference in this and other binary systems. From these results, we also warn that for the development of activity–age calibrations (which commonly use binary systems and/or stellar clusters as calibrators) the whole history of activity available for the stars involved should be taken into account.

Key words: stars: activity – binaries: general – stars: chromospheres – stars: individual: ζ^1 Reticuli, ζ^2 Reticuli – stars: solar-type.

1 INTRODUCTION

Stellar activity studies have several applications. They can be used to disentangle stellar and planetary signals in radial-velocity surveys (e.g. Robertson et al. 2013; Carolo et al. 2014; Díaz et al. 2016). Also, studying the long-term magnetic activity of stars with physical characteristics similar to the Sun (T_{eff} , $\log g$, age, etc.) could help to place our Sun in context (e.g. Hall, Lockwood & Skiff 2007; Hall, Henry & Lockwood 2009). In addition, they can be used to better understand star–planet interactions (e.g. Canto Martins et al. 2011; Krejčová & Budaj 2012; Miller et al. 2015).

The first stellar activity studies were initiated by Olin Wilson in 1966, which gave rise to the HK project (Wilson 1978). This pro-

gramme was carried out at the Mt Wilson Observatory and continued until 2003. It has been the main source of many activity-related projects (e.g. Vaughan, Preston & Wilson 1978; Duncan et al. 1991; Gray & Baliunas 1995; Baliunas et al. 1998). These works have allowed better understanding of stellar magnetic phenomena beyond solar activity. By using the Ca II H&K line cores as activity proxies through the standard Mt Wilson index (S), Baliunas et al. (1998) grouped a sample of 2200 stars into three classes corresponding to different long-term activity behaviour. They found that stars with moderate activity showed cycles with periods between 2.5 and 21 yr, while very active stars displayed fluctuations of activity rather than cycles, in general, corresponding to young stars with high rotation velocities. Finally, inactive stars are found in a phase that may be similar to the solar Maunder minimum¹ (hereafter MM).

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¹ The period between 1645 and 1715 during which solar activity was greatly reduced (e.g. Eddy 1976).

Currently, new activity cycles have been reported by several authors (e.g. Metcalfe et al. 2010; DeWarf, Datin & Guinan 2010; Buccino et al. 2014; Egeland et al. 2015). These activity cycles have been found in main-sequence and even post-main-sequence stars with spectral types ranging from F to M (Baliunas et al. 1998), including solar analogue/twins and stars with planets (e.g. Flores et al. 2016). In addition, several stars seem to have multiple activity cycles (e.g. Baliunas et al. 1995; Hall et al. 2007; Oláh et al. 2009; Metcalfe et al. 2013; Egeland et al. 2015; Flores et al. 2017).

Samples of binary systems were included in stellar activity studies and also used to obtain activity–rotation–age calibrations. Observational data (Reipurth et al. 2007; Vogt et al. 2012; King et al. 2012) and numerical simulations (e.g. Reipurth & Mikkola 2012) support the idea that most binary stars are formed from a common molecular cloud (i.e. coeval stars); therefore it is expected that components of binary systems present similar properties such as age and chemical composition. As stellar activity is thought to be produced by a global-scale dynamo action that is powered by the rotational velocity (or angular momentum) and turbulent convection (e.g. Parker 1955; Steenbeck, Krause & Rädler 1966; Robinson & Durney 1982; Strugarek et al. 2017), it decays during stellar lifetime as a consequence of magnetic braking and angular momentum loss due to stellar wind. Thus, a difference in activity between similar components of a binary system led to some initial interpretations such as the measurement of different phases of long-term variations (e.g. Baliunas et al. 1995, 1998; Donahue 1998), one component possibly leaving the main sequence, or the rotational modulation (Donahue 1998); nowadays the origin of the difference in activity is not fully understood.

By using a sample of binary systems and star-cluster members, Mamajek & Hillenbrand (2008) (hereafter MH08) derived an improved activity–age relation that allows one to obtain a chromospheric age by means of the chromospheric activity measured from the Ca II H&K emission lines. To do so, they also took into account the relation between R'_{HK} and colour (i.e. mass), which until that time had not been considered (e.g. Soderblom, Duncan & Johnson 1991; Donahue 1993; Lachaume et al. 1999). However, the validity of these activity–age calibrations is still under discussion in the literature (e.g. Pace 2013; Lorenzo-Oliveira, Porto de Mello & Schiavon 2016).

In 2015, we started a programme aiming to study stellar activity in solar-analogue and solar-twin stars using the extensive data base of HARPS spectra. Our initial sample comprised solar-twin stars taken from Nissen (2015). Currently, we have extended our sample to other particular stars and also to binary systems with similar components. Some results of this new programme have recently been published (see Flores et al. 2016, 2017, for details).

One remarkable object in our current sample is the ζ Reticuli binary system (hereafter ζ Ret). A Bayesian analysis of the proper motions indicates a very high probability (near 100 per cent) that the pair is physically connected (Shaya & Olling 2011). The spectral types of their components are very similar to each other (G2 V G1 V, as noted in the *Hipparcos* data base) and also similar to the Sun, being both solar analogues (see Saffe et al. 2016, for details). In addition, the $(B - V)$ colours of the stars ζ^1 Ret and ζ^2 Ret are 0.64 ± 0.01 and 0.60 ± 0.01 mag, according to Perryman et al. (1997). This makes ζ Ret a unique laboratory that allows one to carry out a detailed test of stellar activity. ζ Ret is a wide binary system, with a separation of ~ 3700 au (Mason et al. 2001), which rules out any physical interaction between the components. The star ζ^2 Ret (=HD 20807) has a debris disc at ≈ 100 au, which was detected through a mid-IR excess (Trilling et al. 2008) and

Table 1. HARPS ID observing programmes used in this work.

ESO HARPS programmes	
078.C-0833(A)	074.C-0364(A)
077.C-0530(A)	060.A-9036(A)
078.C-0044(A)	076.C-0878(A)
079.C-0681(A)	074.C-0012(B)
072.C-0513(B)	072.C-0488(E)
074.C-0012(A)	183.C-0972(A)
073.C-0784(B)	074.C-0012(B)
072.C-0513(D)	192.C-0852(A)

then confirmed by direct imaging (Eiroa et al. 2010). In contrast, *Spitzer* and *Herschel* observations of ζ^1 Ret (=HD 20766) have not revealed the presence of IR excess (Bryden et al. 2006; Trilling et al. 2008; Eiroa et al. 2013). Additionally, both stars have been monitored by the Anglo-Australian Planet Search (AAPS) radial-velocity survey,² (Tinney et al. 2001) and included in the ESO CES and HARPS GTO planet search programmes (e.g. Sousa et al. 2008; Zechmeister et al. 2013) giving, at the moment, no planet detection.

There is a previous stellar activity study of the star ζ^2 Ret in the literature, which was carried out by Lovis et al. (2011). In this work the authors report 99 stars with magnetic cycles, finding a period of 1133^{+1090}_{-65} d for ζ^2 Ret by using more than 6 yr of observations (ζ^1 Ret was not analysed). Fortunately, the HARPS monitoring of both components of this binary system continued, providing a large data set that can now be used to make a detailed long-term stellar activity study in this system. In this way, we are starting to study possibly different long-term activity levels observed in binary systems with similar components, which are difficult to explain. In addition, the solar-analogue nature of both stars ζ^1 Ret and ζ^2 Ret could also be used to compare them directly with our Sun, which has been done for few stars, such as 18 Sco (Hall et al. 2007) and HD 45184 (Flores et al. 2016). Recently, solar activity is under discussion in the stellar context. Given its activity and rotation period, many authors suggest that the Sun could be in a transitional phase with an atypical activity cycle in the stellar dynamo theory (Böhm-Vitense 2007; Metcalfe, Egeland & van Saders 2016). All these works have encouraged the present study of the ζ Ret binary system.

This study is organized as follows. In Section 2 we describe the observations and data reduction, while in Section 3 we describe our main results. In Section 4 we provide a discussion, and finally in Section 5 we summarize our main conclusions.

2 OBSERVATIONS AND DATA REDUCTION

Stellar spectra of the binary system ζ Ret were taken between 2003 and 2016 with the HARPS (High Accuracy Radial velocity Planet Searcher) spectrograph attached to the La Silla 3.6-m ESO telescope. These public high-resolution spectra ($R \sim 115,000$) were obtained from the ESO HARPS archive,³ (Mayor et al. 2003) under the programmes listed in Table 1. They have been automatically processed by the HARPS pipeline.⁴ These spectra typically cover a spectral range from ~ 3780 to ~ 6910 Å and present a signal-to-noise (S/N) ratio of ~ 150 at ~ 6440 Å for both stars.

² <http://newt.phys.unsw.edu.au/~cgt/planet/Targets.html>

³ <https://www.eso.org/sci/facilities/lasilla/>

⁴ <http://www.eso.org/sci/facilities/lasilla/instruments/harps/doc.html>

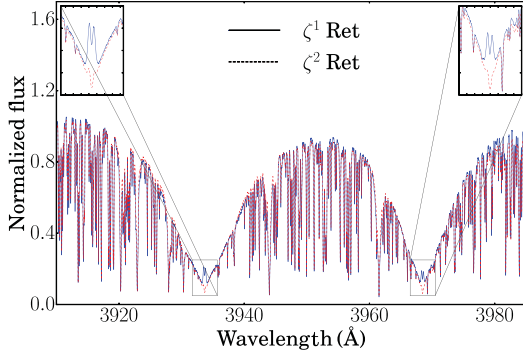


Figure 1. Average Ca II H&K profiles for ζ^1 Ret (blue solid line) and ζ^2 Ret (red dotted line). For clarity, we include a zoom in the Ca II H&K spectral cores.

In order to compute the S index, HARPS spectra were corrected by radial velocity by using standard IRAF⁵ tasks. Thus, we discarded the spectra with low S/N ($\lesssim 100$) and measured the Ca II H&K line-core fluxes of 337 HARPS spectra (being 68 for ζ^1 Ret and 269 for ζ^2 Ret). To do so, for each spectrum we integrated the flux in two windows centred at the cores of the Ca II lines, weighted with triangular profiles of 1.09 Å full width at half-maximum (FWHM), and computed the ratio of these fluxes to the mean continuum flux, integrated in two passbands of width 20 Å centred at 3891 and 4001 Å. Finally, we converted this ratio into S , following Lovis et al. (2011), as in our previous works (Flores et al. 2016, 2017).

We complement our analysis with X-ray observations sensitive in the 0.2–10.0 keV band. To do so, we search the HEASARC⁶ (see acknowledgements section) data base using the coordinates of both components of the system. As a result, we found only one observation per star in the XMM-Newton Serendipitous Source Catalogue⁷ (Rosen et al. 2016). These individual measurements correspond to the dates 2006 August 5 and 2002 May 3 for ζ^1 Ret and ζ^2 Ret, respectively. In order to obtain X-rays fluxes (F_X), source data were extracted from a circular aperture of fixed radius (28 arcsec) centred on the detection position, while background data were accumulated from a co-centred annular region with inner and outer radii of 60 arcsec and 180 arcsec, respectively. In this way, we estimated F_X values of $(5.11 \pm 0.08) \cdot 10^{-13}$ and $(0.25 \pm 0.32) \cdot 10^{-13}$ for ζ^1 Ret and ζ^2 Ret, respectively.

3 RESULTS

3.1 Chromospheric activity of the ζ Ret binary system

The average of the Ca II H&K profiles for both components of ζ Ret are shown in Fig. 1. A clear difference between both stars can be seen from their Ca II H&K line cores. On the other hand, in Figs 2 and 3 we show the time series for both components. Due to the high sampling frequency of HARPS and in order to diminish the scatter probably produced by rotational modulation of individual active regions (Baliunas et al. 1995), we have followed the same procedure detailed in our previous works (Flores et al. 2016, 2017).

⁵ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

⁶ <https://heasarc.gsfc.nasa.gov/docs/archive.html>

⁷ <http://xcatdb.unistra.fr/3xmmdr6>

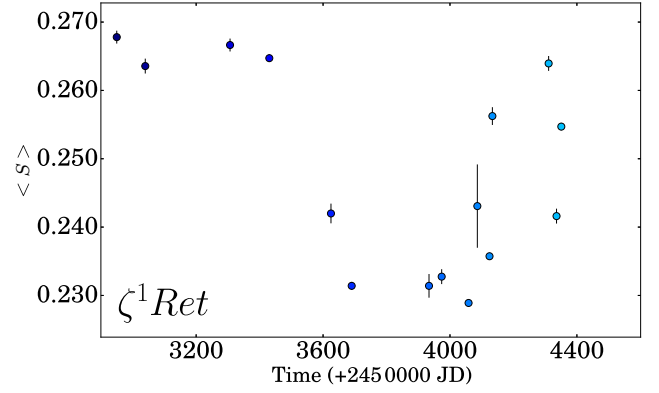


Figure 2. Time series of the Mt Wilson indexes for ζ^1 Ret. Different coloured circles correspond to the same observing season of Fig. 3.

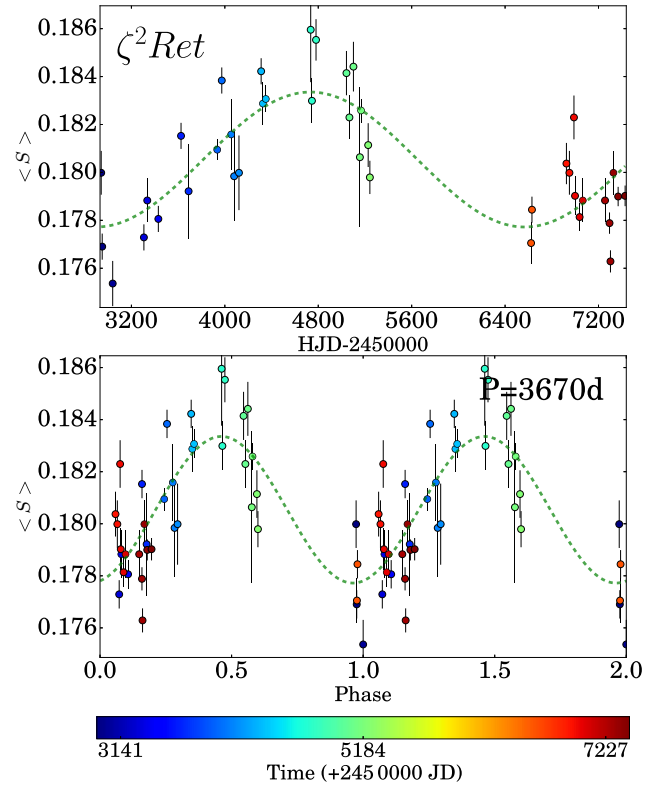


Figure 3. Top panel: Time series of the Mt Wilson index for ζ^2 Ret. The dotted green line indicates the cycle calculated in this work. Lower panel: Mt Wilson index phased (shown between 0 and 2) with a 10 yr period.

Data points are the average values of observations associated with the same observing season (HARPS monthly means), while error bars of the average values correspond to the standard deviation of the mean. We note that ζ^1 Ret presents higher activity levels than ζ^2 Ret for all (individual or average) measurements.

To study the long-term activity of both components by using the Ca II H&K lines, we compute the Lomb–Scargle periodogram (Horne & Baliunas 1986). As a result, we obtain a long period of 3670 ± 170 d (~ 10 yr) with a Monte Carlo FAP⁸ (false alarm probability) of 3.2×10^{-6} for ζ^2 Ret (see top panel of Fig. 4). We use a cut-off in FAP for the detection of periodicities of 0.1 per cent

⁸ See details in Buccino & Mauas (2009).

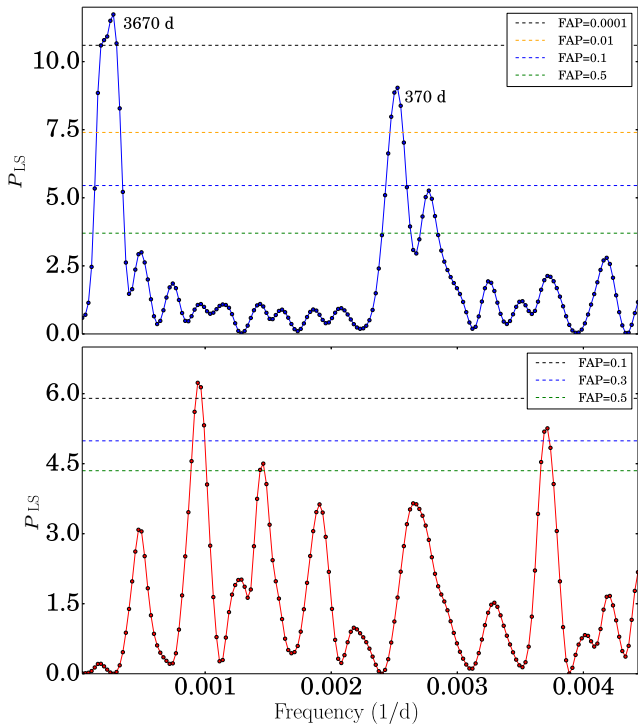


Figure 4. Top panel: Lomb–Scargle periodogram of the HARPS data set plotted in Fig. 3. Lower panel: Lomb–Scargle periodogram after subtracting the ~ 10 yr long-term period. Dashed horizontal coloured lines correspond to different values of FAP.

(0.001), similar to previous works (e.g. Baliunas 1995; Suárez Mascareño, Rebolo & González Hernández 2016). Together with the most significant peak, there appears a short less significant period (~ 370 d) that could correspond to an alias. Thus, this possibility was explored by subtracting the main periodic variation and recalculating the periodogram, which was carried out following Suárez Mascareño et al. (2016). The second peak is not present in the new periodogram (Fig. 4, lower panel), indicating that it is not a real period. On the other hand, there is no evidence for a long-term activity cycle in ζ^1 Ret from a Lomb–Scargle analysis. However, we caution that our temporal coverage for ζ^1 Ret is ~ 3.3 yr. Thus, more observations are desirable in order to detect a possible long-term activity cycle, given that up to now this star has shown erratic rather than cyclic behaviour.

The fitted harmonic curve with a period of ~ 10 yr calculated in this work was obtained as a least-squares fit to the monthly means (see Buccino & Mauas 2009, for details). A good agreement can be seen between observational data points and the fitted curve.

From a visual inspection of Figs 2 and 3, a clear difference in morphology between both time series is also readily evident. In a previous work, we showed that both stars present very similar stellar parameters (see table 2 in Saffe et al. 2016). In order to compare their chromospheric activity levels, we computed the R'_{HK} index by subtracting the photospheric contribution, following Noyes et al. (1984). The resulting $\log(R'_{\text{HK}})$ mean values are -4.64 ± 0.014 dex and -4.86 ± 0.013 dex for ζ^1 Ret and ζ^2 Ret, respectively. The uncertainties in $\log(R'_{\text{HK}})$ were estimated by adding quadratically the error related to $(B - V)$ and an additional instrumental noise of ~ 0.01 dex, which was estimated following Lovis et al. (2011). Thus, according to activity regions defined by Henry et al. (1996), ζ^1 Ret corresponds to an active star and ζ^2 Ret to an inactive one.

Table 2. Activity measurements from the literature for the ζ Ret binary system.

Reference	ζ^1 Ret $\log(R'_{\text{HK}})$	ζ^2 Ret $\log(R'_{\text{HK}})$
Henry et al. (1996)	−4.65	−4.79
Jenkins et al. (2006)	−4.58	−4.84
Martínez-Arnáiz et al. (2010)	−4.86	–
Lovis et al. (2011)	–	−4.90
Zechmeister et al. (2013)	−4.67	−4.89
This work	−4.64	−4.86

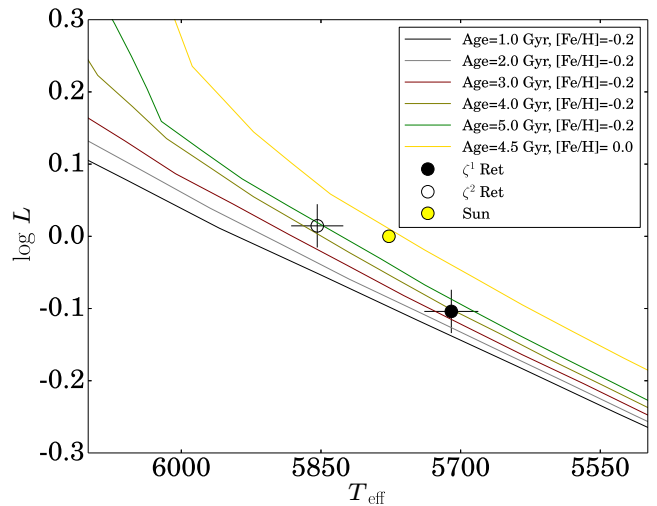


Figure 5. Luminosity versus T_{eff} for ζ^1 Ret (full circle), ζ^2 Ret (empty circle) and for the Sun (yellow circle). The continuous lines indicate the isochrones corresponding to different ages and metallicities, as predicted by Yonsei–Yale (Yi et al. 2001; Demarque et al. 2004). For instance, the yellow line corresponds to the isochrone with an age of 4.5 Gyr and solar metallicity ($[\text{Fe}/\text{H}] = 0$).

For comparison, in Table 2 we show activity measurements from the literature for the ζ Ret binary system. It is interesting to note that for ζ^2 Ret MH08 used a mean activity index of -4.79 dex (taken from Henry et al. 1996) in order to derive an improved activity–age relation, which is the highest value reported for this star.

It would be useful to know the stellar age of this binary system. To do so, we estimated the ages of both stars using Yonsei–Yale isochrones (Yi et al. 2001; Demarque et al. 2004) as described in Meléndez et al. (2012) and Ramírez, Allende Prieto & Lambert (2013), employing the q^2 PYTHON package (Ramírez et al. 2014). By adopting the spectroscopic fundamental parameters of Saffe et al. (2016), V magnitudes from the *Hipparcos* and *Tycho* catalogues (ESA 1997), and revised parallaxes from van Leeuwen (2007), we estimated an age of 4.0 ± 1.7 Gyr and 4.7 ± 1.4 Gyr for ζ^1 Ret and ζ^2 Ret, respectively, i.e. an average age of ~ 4.4 Gyr. For comparison, we also derived the ages of both stars using a Bayesian approach through the PARAM⁹ code (da Silva et al. 2006), using the PARSEC isochrones of Bressan et al. (2012). With this method, we find ages of 4.1 ± 1.9 Gyr and 5.5 ± 1.1 Gyr for ζ^1 Ret and ζ^2 Ret, respectively, in agreement with the previous determination. In Fig. 5 we present Yonsei–Yale isochrones (Yi et al. 2001; Demarque et al. 2004) corresponding to different ages and metallicities (continuous

⁹ <http://stev.oapd.inaf.it/cgi-bin/param>

lines), together with the positions of the Sun (yellow circle), the star ζ^1 Ret (full circle) and ζ^2 Ret (empty circle). The rotational velocities of both stars are $v \sin i \sim 2.7 \pm 0.1 \text{ km s}^{-1}$ for ζ^1 Ret and $v \sin i \sim 2.7 \pm 0.3 \text{ km s}^{-1}$ for ζ^2 Ret according to Reiners & Schmitt (2003), who caution that very low projected rotational velocities ($v \sin i < 3 \text{ km s}^{-1}$) must be interpreted as upper limits. These low velocities, together with the non-detection of the lithium line at 6707.8 \AA , point towards an age similar to our Sun, while the high activity (particularly of ζ^1 Ret) would indicate a younger age for the system.

It is interesting to note that both set of isochrones seems to indicate that ζ^2 Ret is slightly older than ζ^1 Ret (but they agree within the uncertainties). Thus, we explore the possibility that both stars do present different ages. To do so, we estimated the expected activity using the activity–age relations of MH08 in order to compare to the activity measured. Using the ages from Yonsei–Yale, the resulting $\log(R'_{\text{HK}})$ values are -4.95 ± 0.19 dex and -5.12 ± 0.15 dex, while using the ages from the PARSEC isochrones we obtained -4.96 ± 0.21 dex and -5.20 ± 0.12 dex, for the stars ζ^1 Ret and ζ^2 Ret, respectively. Thus, the expected activity values were lower than those observed in both stars (-4.64 ± 0.014 dex and -4.86 ± 0.013 dex for ζ^1 Ret and ζ^2 Ret). If these expected values were in better agreement with the observed ones, this would give some support to the idea that ζ Ret is not a coeval system.

4 DISCUSSION

4.1 Possible scenarios to explain the activity differences in binary systems

Up to now, a difference in the activity level between similar stars of a binary system has usually been attributed to one of the following scenarios:

(i) Measurement of different phases of long-term variations in both stars (e.g. Baliunas et al. 1995, 1998; Donahue 1998). This would correspond, for example, to having one star near a maximum and its companion near a minimum, with their average activity levels being similar to each other. However, in this case we analyse time variations of both stars over years, ζ^2 Ret always being more inactive than ζ^1 Ret.

(ii) Different rotational modulation of both stars (e.g. Donahue 1998). In order to avoid the scatter probably associated with rotational modulation, we have used HARPS monthly means data. Therefore, the measurement of time series shows that the stellar rotation is not the cause of these differences.

(iii) Differences in rotation rate (Noyes et al. 1984; Barnes 2007; Mamajek & Hillenbrand 2008; Wright et al. 2011). To analyse this possibility, we estimated both ‘projected’ and ‘empirical’ rotation periods of ζ Ret, in order to compare them. The ‘projected’ rotation periods were estimated following the formula $P_{\text{rot}}/\sin i = (2\pi R_*)/(\nu \sin i)$, where $\sin i$ is the inclination between the rotational axis and a perpendicular plane to the observer, R_* is the stellar radius and $\nu \sin i$ is the projected rotational velocity measured from the spectra. We note that $P_{\text{rot}}/\sin i$ is a lower limit to the rotational period. We used spectroscopic $v \sin i$ values of Reiners & Schmitt (2003) and estimated R_* values from the Bayesian method through the PARAM code ($0.87 \pm 0.01 R_{\odot}$ and $0.95 \pm 0.01 R_{\odot}$ for ζ^1 Ret and ζ^2 Ret, respectively). In this way, we obtained projected rotation periods of 16.4 ± 3.2 d and 17.9 ± 3.5 d for both stars, being similar within the errors. These uncertainties include the dispersion in the estimation of R_* and the errors associated with $v \sin i$ values.

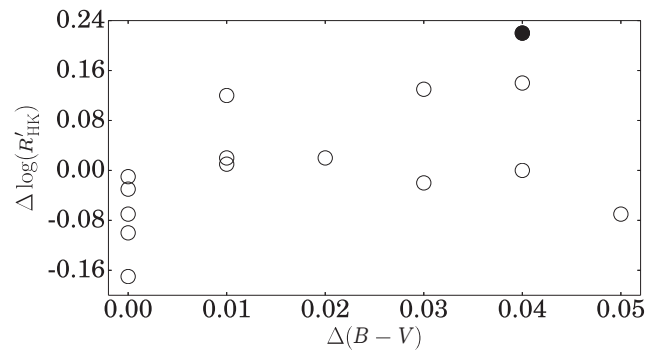


Figure 6. Position of near-identical pairs of MH08 in the $\Delta \log(R'_{\text{HK}})$ – $\Delta(B - V)$ diagram (empty circles). The position of the ζ Ret binary system, with the activity levels calculated in this work, is also included in the figure (full circle).

Thus, we derived the ‘empirical’ rotation periods, i.e. rotation periods expected from the MH08 calibration (see their equation 5) given the known activity and $(B - V)$ colour. As a result, we obtained 13.2 ± 2.8 d and 16.5 ± 1.8 d for ζ^1 Ret and ζ^2 Ret, respectively. The errors include the uncertainties of $\log(R'_{\text{HK}})$, $(B - V)$ and the scatter of the MH08 calibration. The empirical rotation period of ζ^1 Ret seems to be shorter than the corresponding value for ζ^2 Ret. However, when we consider the uncertainties they are indistinguishable.

When we compare both projected and empirical rotation periods, they are similar within the errors. Thus, a rotation difference between ζ^1 Ret and ζ^2 Ret cannot be ruled out, due to their relatively large uncertainties. The uncertainties of the $v \sin i$ measurements are too large to conclusively show a difference in the rotation period. We point out that both estimations show that ζ^1 Ret rotates faster than ζ^2 Ret. It would be desirable, for instance, to count with a suitable set of spectroscopic or photometric observations in order to better estimate a period by using the rotational modulation in future work.

(iv) MH08 point out that pronounced activity discrepancies (~ 0.1 – 0.2 dex) in coeval stars could be associated with differences in $(B - V)$ colour. Thus, we wonder if it is possible to explain the observed activity difference between both components of ζ Ret. With this aim in mind, we compared this difference with those from the sample of near-identical pairs of MH08. In Fig. 6 we plot $\Delta \log(R'_{\text{HK}})$ versus $\Delta(B - V)$, where the binary system ζ Ret is shown with a full circle. Following MH08, the order in the Δ differences corresponds to $B - A$, the B star being that with the higher $(B - V)$ value in the pair. We note that ζ Ret appears above all of the near-identical pairs of MH08. This is the first indication of a somewhat rare behaviour of this pair. Thus, we applied the MH08 activity–age calibration by adopting a common age of 4.5 ± 2.0 Gyr and a $(B - V)$ difference of 0.04 ± 0.02 , and compare these ‘expected’ activity values with the observed ones. If we assume the greater possible age for the pair (i.e. 6.5 Gyr) and also the maximum possible $(B - V)$ difference between them (0.06 mag), then we reach a maximum difference of 0.17 ± 0.05 dex in $\log(R'_{\text{HK}})$ (-5.11 and -5.28 dex for both stars). As a result, we find that the MH08 calibration would roughly reach the observed difference in $\log(R'_{\text{HK}})$ (0.220 ± 0.027 dex), but simultaneously estimating very low activity levels for each star, which is not observed. This shows that the ζ Ret binary system seems to be outside of the ‘normal’ behaviour of the near-identical pairs of MH08.

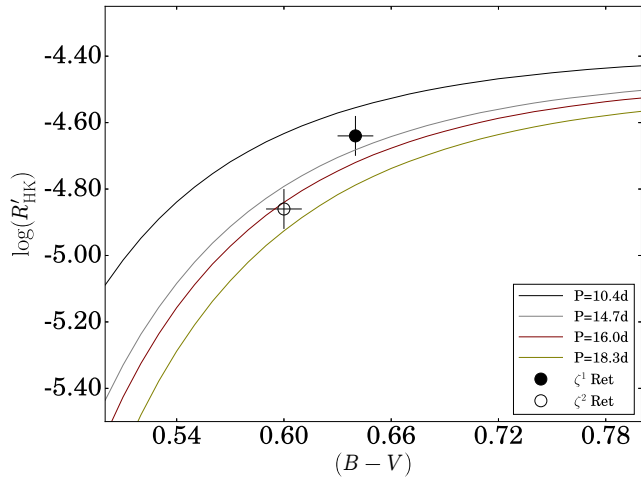


Figure 7. Activity versus $(B - V)$ for different rotational periods. Adopting P_1 and P_2 as the rotational periods of ζ^1 Ret and ζ^2 Ret, the colour curves correspond to periods of $P_1 - 1\sigma$ (10.4 d), $P_1 + 1\sigma$ (14.7 d), $P_2 - 1\sigma$ (16.0 d) and $P_2 + 1\sigma$ (18.3 d). We also indicate the position of ζ^1 Ret (full circle) and ζ^2 Ret (empty circle).

Also, in Fig. 7 we plot activity versus $(B - V)$. Full and empty circles show the positions of the stars ζ^1 Ret and ζ^2 Ret, respectively. Coloured curves correspond to different rotation periods, according to the MH08 calibration. Curves are shown for the $\pm 1\sigma$ region around the MH08 empirical rotation period for ζ^1 Ret and ζ^2 Ret using the observed $(B - V)$ and activity. When including the rotation period uncertainties, we obtain a region rather than a single curve for each star.

Previously, we mentioned that the MH08 calibration suggests rotation periods of 13.2 ± 2.8 and 16.5 ± 1.8 d, compatible with the activity levels of the stars ζ^1 Ret and ζ^2 Ret, respectively. If we suppose that both stars do present the same rotation period (e.g. ~ 15 d), this would imply mean activity levels of -4.69 ± 0.06 and -4.80 ± 0.06 dex for both stars, i.e. a difference of $\sim 0.11 \pm 0.12$ dex. Thus, it seems unlikely to explain the measured activity difference of 0.220 dex only by adopting a difference in $(B - V)$ between both stars. For instance, as can be seen in Fig. 7, the stars ζ^1 Ret and ζ^2 Ret are located above and below the curves corresponding to periods of 16.0 d and 14.7 d. This would point towards different rotational periods for both stars. Thus, the MH08 calibration could (in principle) explain the difference observed in activity, by considering the compound effect of $(B - V)$ together with the assumption of different rotational periods for the stars (the mentioned 13.2 ± 2.8 and 16.5 ± 1.8 d, respectively). However, to our knowledge there is no observational evidence of different rotational rates in these stars. A better estimation of the rotational periods would help to support (or rule out) this compound scenario trying to explain the activity difference in this binary system.

In the light of the results obtained in this work, it is clear that the case of the ζ Ret binary system is a challenge for activity–age calibrations: the greater the contrast in their chromospheric activity levels, the greater the difference in their stellar ages. Following the calibration of MH08, the difference in chromospheric age between both stars amounts to ~ 2 Gyr, which clearly exceeds the expected dispersion of $\lesssim 1$ Gyr for the case of binary stars (Donahue 1998; Mamajek & Hillenbrand 2008). The ζ Ret binary system is considered by MH08 in the group of ‘near-identical’ pairs (see their table 3). We mentioned above that the difference in $(B - V)$ colour alone could not explain the activity levels of both stars. Thus, when

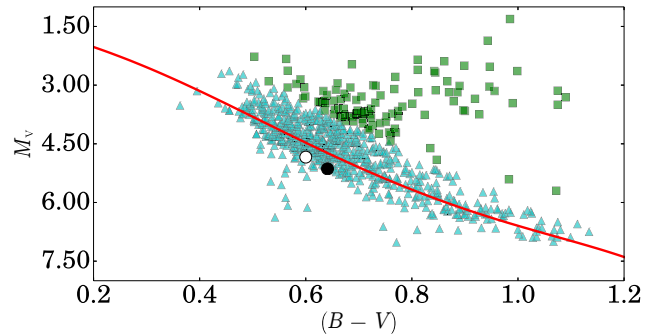


Figure 8. Position of ζ^1 Ret (black circle) and ζ^2 Ret (white circle) stars in the M_v – $(B - V)$ diagram. The continuous red line shows the fit to main-sequence stars (triangles). Evolved stars are indicated with squares.

dealing with stellar clusters, which are usually used for activity–age studies, one should carefully check not only for $(B - V)$ colour, mass and metallicity biases, but also for long-term high activity differences such as those found in ζ Ret.

(v) Evolved stars have significantly lower chromospheric activity levels compared to main-sequence stars (see e.g. Wright 2004, for details). Thus, the possibility that only ζ^2 Ret has evolved off the main sequence is another tentative cause for its lower activity level. The estimated surface gravity of this star is $\log g = 4.54$ (Saffe et al. 2016). Wright (2004) defines as ‘unambiguously evolved’ those stars with $\Delta M_v > 1$, where ΔM_v is the difference between the absolute magnitude M_v and the function $M_v(B - V)$, which is a fit to main-sequence stars as a function of the colour $(B - V)$. Similar to the plot of Wright (2004), in Fig. 8 we present M_v versus $(B - V)$ for the stars included in the work of Fischer & Valenti (2005). The triangles correspond to main-sequence stars (fitted using a continuous red line), while the squares correspond to stars that satisfy Wright’s criteria as evolved. The circles (black and white) show the position of the stars ζ^1 Ret and ζ^2 Ret with ΔM_v values of ~ -0.40 and ~ -0.37 mag, respectively. Thus, there is no evidence for an evolved status for the stars in this binary system.

(vi) The separation of 3700 au between both stars (Mason et al. 2001) allows us to discard a possible interaction between ζ^1 Ret and ζ^2 Ret. The non-detection of planets orbiting both stars (e.g. Sousa et al. 2008; Zechmeister et al. 2013) rules out a possible SPI (star–planet interaction) activity effect.

The presence of a dust disc orbiting around ζ^2 Ret (Trilling et al. 2008; Eiroa et al. 2010) is intriguing. A possible (current) interaction between the disc and the star seems unlikely, due to the separation between them (~ 100 au, Eiroa et al. 2010). On the other hand, it is difficult to determine if the presence of a dust disc could possibly alter the rotational evolution of the stars. To our knowledge, there is no statistical study comparing rotational rates in the presence of a dust disc.

(vii) Vaughan & Preston (1980) noted that solar-neighbourhood stars could be roughly divided into two populations, namely active and inactive stars. The separation between these populations is made by the so-called Vaughan–Preston gap (hereafter VP gap), located around $\log(R'_{HK}) \sim -4.75$ dex, which is a region of intermediate activity containing very few stars (Vaughan & Preston 1980; Henry et al. 1996; Pace et al. 2009). Henry et al. (1996) suggest that this region is a transition zone rather than a gap. The stars ζ^1 Ret and ζ^2 Ret present $\log(R'_{HK})$ values of -4.64 dex and -4.86 dex, respectively, being then considered as active and inactive stars on different sides of the VP gap.

Different works have tried to explain the presence of the VP gap. For instance, Rocha-Pinto & Maciel (1998) suggest an abrupt change in metallicity between both populations of active and inactive stars; however, the components of our binary system present almost identical metal contents (Saffe et al. 2016). Berdyugina, Pelt & Tuominen (2002) suggest that the VP gap represents a transition from a multiple-mode dynamo to a single-mode dynamo. Then, Pace & Pasquini (2004) proposed that most active stars are usually young, and then a fast decay of chromospheric activity occurs roughly between 0.6 and 1.5 Gyr of main-sequence lifetime, after which a kind of plateau appears. They propose that the abrupt decline in activity with age could explain the VP gap. Thus, Pace et al. (2009) propose that the chromospheric activity does not evolve smoothly with time: stars change from active to inactive crossing the VP gap on time-scales that might be as short as 200 Myr.

Following this idea, we can interpret that only ζ^2 Ret would have very recently crossed the VP gap (in the last ~ 200 Myr) while ζ^1 Ret is close to crossing it. We consider that this is a plausible scenario, which has never been proposed before to explain a difference of activity in a binary system. If this is the case, both stars should present an age lower than ~ 1.5 Gyr, which corresponds to the time when most stars seem to cross the VP gap, according to Pace et al. (2009). However, the estimated common age for ζ Ret is ~ 4.6 yr, according to the isochrone method. Thus, if additional binary stars straddling the gap were found with ages > 1.5 Gyr (as the ζ Ret binary system appears to be), it would be a reason to be suspicious of Pace & Pasquini's result that stars cross the gap at ages between 0.6 and 1.5 Gyr.

(viii) It has been suggested that the existence of a remarkable difference in the activity behaviour among binary components could be associated with a similar MM state in the star with lower activity (Donahue 1998; Wright 2004). However, current criteria to identify MM candidates are still under discussion (e.g. Wright 2004; Judge & Saar 2007).

The first stellar analogies to the MM come from stars with relatively constant activity levels, called 'flat' stars ($\sigma_S/\bar{S} < 1.5$ per cent) in Baliunas & Jastrow (1990) and Baliunas et al. (1995). It is interesting to note that ζ^2 Ret satisfies Baliunas's criteria for a flat star ($\sigma_S/\bar{S} \sim 1.4$ per cent) and for a cycling star (FAP $\leq 10^{-2}$) simultaneously. Thus, some authors have considered as MM candidates those stars with $\log(R'_{\text{HK}}) < -5.1$ dex (e.g. Henry et al. 1996). Due to this criterion being established from a sample in which almost all were evolved stars (Wright 2004), it has been proposed that this low activity value should be higher than -5.1 dex, and that UV and X-ray data could also be used to identify MM candidates (Judge & Saar 2007). In addition, Wright (2004) suggested that MM states in main-sequence stars should not be constrained to the $\log(R'_{\text{HK}}) < -5.1$ dex condition, proposing (in section 4.1) that a higher value of $\log(R'_{\text{HK}}) \sim -5.0$ dex may represent the minimum level of activity in main-sequence stars. Thus, the author suggests the search for the absence of activity variations or appreciable activity differences between components of binary systems as an useful test to identify MM states. Considering that ζ^1 Ret and ζ^2 Ret satisfy this final condition, we explored the possibility that the low activity of ζ^2 Ret could be attributed to a similar solar MM phase.

It is well known that during this period, the sunspot number¹⁰ was extremely reduced, although it did not disappear (Ribes &

Nesme-Ribes 1993). In addition, some evidence has been found suggesting that the solar cycle was still in progress during the MM (e.g. Beer, Tobias & Weiss 1998; Soon & Yaskell 2003; Vaquero et al. 2015). After the solar MM ended, it was followed by a gradual increase in cycle amplitudes of the cyclic variability (Hathaway 2015). In this way, following the interpretation of Donahue (1998) and Wright (2004), maybe ζ^2 Ret is not in an MM state; instead, this component could be emerging from (or going to) it and at the same time, showing a stellar activity cycle with a period similar to the solar case.

We tried to compare the average difference in activity between ζ^1 Ret and ζ^2 Ret ($\sim 0.220 \pm 0.027$ dex) with an estimation of the decrease in activity of the Sun during its MM state. This is a difficult task, given that there are only estimations and no direct measurements of the solar chromospheric index from the mentioned period. Egeland et al. (2017) found a mean activity of the Sun of $\log(R'_{\text{HK}}) = -4.9427 \pm 0.0072$ by taking data from the cycles 15 to 24. If we adopt for the Sun the value of $\log(R'_{\text{HK}}) \sim -5.0$ suggested by Wright (2004) as the minimum level of activity in main-sequence stars, then we roughly estimate a decrease of ~ 0.06 dex for the Sun. This would indicate that the activity difference between ζ^1 Ret and ζ^2 Ret would be possibly greater than the activity decrease of the Sun in its MM state. Thus, a possible decrease in activity in the star ζ^2 Ret could not be ruled out.

In order to search for evidence of this behaviour from an independent source, we also explored the available X-ray data¹¹ following the Judge & Saar (2007) suggestion. To do so, we estimated F_X values of $(5.11 \pm 0.08) 10^{-13}$ and $(0.25 \pm 0.32) 10^{-13}$ erg s⁻¹ cm⁻² for ζ^1 Ret and ζ^2 Ret in the 2–10 keV band. This seems to indicate that ζ^1 Ret is more intense than ζ^2 Ret, as also suggested by the Ca II H&K fluxes. Thus, the difference between the stellar activity for both components and the activity cycle detected here allow us to suppose that ζ^2 Ret is possibly emerging from a similar MM state. In this way, before the stellar cycle that we are now observing (~ 10 yr), perhaps the mean stellar activity of ζ^2 Ret was even lower. We stress, however, that long-term Ca II H&K and X-ray data (including for the Sun) would be desirable in order to more properly identify ζ^2 Ret as an MM candidate.

5 CONCLUSIONS

We performed, for the first time, a detailed long-term activity study of the binary system ζ Ret by using HARPS spectra, covering measurements between the years 2003 and 2016. Both stars are physically very similar and are also both solar analogues. We detected a periodic modulation of ~ 10 yr in the star ζ^2 Ret with a mean S index (0.180) similar to that of the Sun. We also note that this object satisfies previous criteria for a flat star and for a cycling star simultaneously. On the other hand, ζ^1 Ret showed a higher activity level (in Ca II H&K and X-ray) with an erratic rather than a cyclic modulation.

We discussed possible scenarios in order to account for the activity difference observed in the ζ Ret binary system. On one hand, a different rotational rate between both stars cannot be totally ruled out as a possible cause. However, this would require a more precise determination of the rotation periods of ζ^1 Ret and ζ^2 Ret. On the other hand, we showed that the difference in $(B - V)$ alone is unlikely to explain the activity difference, in the context of the

¹⁰ The sunspot number, a key indicator of solar activity, has a strong correlation with the Ca II H&K chromospheric activity proxy (e.g. Bertello et al. 2016).

¹¹ As previously indicated, these individual observations were taken at different dates.

activity–colour–rotation [MH08](#) calibrations. However, adopting the compound effect of a difference in $(B - V)$ of 0.06 mag (at the limit of the observed 0.04 ± 0.02 mag), together with the assumption of different rotational periods (estimated as 13.2 ± 2.8 and 16.5 ± 1.8 d for both stars), could in principle explain the activity difference observed. Finally, we also propose that the star ζ^2 Ret is possibly emerging from (or going to) a state similar to the MM, as another possible scenario. We wonder if a similar activity difference could also be observed in other binary systems, which would help to verify or rule out these possible scenarios. This requires continued monitoring of this and other binary systems, if they are available, with new HARPS data. In addition, these measurements can be complemented with observations from the Complejo Astronómico El Leoncito (CASLEO) observatory, also situated in the Southern hemisphere.

Finally, when dealing with activity–age calibrators, we suggest carefully checking not only for $(B - V)$ colour, mass and metallicity, but also for possible long-term activity variations such as those found in the ζ Ret binary system.

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