The discontinuous nature of chromospheric activity evolution

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Abstract Chromospheric activity has been thought to decay smoothly with time and, hence, to be a viable age indicator. Measurements in solar type stars in open clusters seem to point to a different conclusion: chromospheric activity undergoes a fast transition from Hyades level to that of the Sun after about 1 Gyr of mainsequence lifetime and any decaying trend before or after this transition must be much less significant than the short term variations.

Keywords sample article;

Introduction

In the atmosphere of the Sun and of the stars similar to it, several processes take place, which make the temperature of the atmosphere higher than it would be if radiative equilibrium held. Such non–radiative heating mechanisms are powered by convection and magnetic field. In the outer layers of these stars, the temperature is increasing towards the surface, and the main cooling mechanism is radiative loss through strong resonance lines, such as Ca II H and K, Mg II h and k, H_{α} . (see e.g. Hall 2008, for a review). This region is referred to as chromosphere, the radiation emitted in it is called chromospheric activity (hereafter CA), and the strength of the emission cores in some of the aforementioned resonance lines are a good CA indicator.

Solar-type stars loose angular momentum due to magnetised stellar winds, and CA is believed to decay with time as a consequence. This trend is superimposed to short term CA variations, such as those that

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caused the Maunder-minimum in the Sun, activity cycles equivalent to the 11-year long solar one, and, in the most active stars, rotational modulation (Wilson 1963; Skumanich 1972; Noyes et al. 1984; Simon et al. 1985).

Due to its decay, CA is a potential age indicator and several efforts have been undertaken in order to calibrate it (see e.g. Soderblom et al. 1991; Lachaume et al. 1999; Mamajek & Hillenbrand 2008, and references therein). But results coming from the analysis of solar type stars in open clusters are challenging the view of a smooth, decreasing trend modulating CA cycles. We do not question the main picture described above on CA decay, but it appears that this occurs mainly in one major event, in which it spans the Vaughan—Preston gap, and any evolution before and after such event is less important than the variation due to activity cycles.

Rotation is probably better correlated with stellar ages (see e.g. Barnes 2009; Cardini & Cassatella 2007), since it is not affected by any cyclic variation. However, rotation periods measurements are not possible for inactive stars, for which we can only have an estimation of the projected rotation velocity, which is not sufficient to to draw any firm conclusion on the nature of the angular momentum evolution.

The matter deserves close attention, because chromospheric ages have been used in important studies on chemical enrichment and star formation in the Galactic disk (Rocha-Pinto et al. 2000a,b), and the age of stars hosting planetary systems (Saffe et al. 2005). We should reach a definitive conclusion on whether CA is or not a good age indicator, and this can be better achieved by observing more solar—type stars in open clusters and by determining more precisely their ages.

Intense investigation has long been conducted on the topic, especially by using the large amount of data collected in Mount Wilson campaign (Wilson 1968) and in the planet-search surveys (Isaacson 2009). However,

only the possibility of observing at high signal to noise and high resolution solar type stars in old and distant open clusters, provided by the 8– and 10–m class telescopes, could make us progress in this field, and it is the key to address still unanswered questions.

In the present work, I will report on the results that led us to reconsider the viability of CA as age indicator. It is also shown that data used to calibrate chromospheric ages do not contradict our conclusions.

1 Data sample

The complete sample on which our conclusions are based consists of 40 main-sequence stars in 7 open clusters and the Sun. The nature of single, dwarf members of the parent clusters were established, for the 40 target stars, in published photometric, propermotion and radial-velocity studies (Herzog et al. 1975; Latham et al. 1992; Nordstroem et al. 1996; Meibom et al 2002; Mermilliod & Mayor 1990; Twarog et al. 1993), and, only for IC 4756 and NGC 5822, from our own radial-velocity measurements (Pace et al. 2010). The data about 15 stars in the Hyades cluster consist of spectra taken with HIRES at Keck, kindly made available to us by D. Paulson, A. Hatzes and P. Cochran. The rest of the data consists of spectra taken with UVES at VLT in two different runs. In the first (ESO run 66D-0457, P.I. L. Pasquini) the targets were: 7 in Praesepe, 2 in NGC 3680, 5 in IC 4651, and 6 in M 67. In the second run (ESO run 73D-0655, P.I. G. Pace) 2 stars were observed in NGC 5822 and 3 in IC 4756.

Our UVES spectra have a resolution of $R\approx100\,000$ in the spectral range from $4\,800$ to $6\,800$ Å, and $R\approx60\,000$ in the spectral range $3\,200$ to $4\,600$ Å. After summing the spectra of the same star, we achieved S/N ratios per pixel ranging from about 50 to about 150. Due to the higher apparent brightness of its stars, the quality of Praesepe spectra is remarkably high. The Hyades spectra we used have a resolution of $R\approx60\,000$ and a signal-to-noise ratio per pixel ranging from 100 to 200, and from 20 to 30 at the core of the Ca II K line.

2 Data analysis

The procedure we adopted to measure chromospheric activity is described in detail elsewhere (Pace & Pasquini 2004; Pace et al. 2009). Here I present a complete summary.

As an indicator of chromospheric activity we used F'_K , i.e. the energy flux of the Ca II K line emitted per unit surface in the chromosphere. We also computed the value normalised to bolometric emission:

$$\log R_K' = \log \left(F_K' / \sigma T_{eff}^4 \right).$$

The spectra were normalised by dividing their intensity by the counts at the pseudo continuum point 3950.5–Å.

The normalised flux was integrated over a 1-Å wide region centred on the Ca II K line. This region coincides with the chromospheric emission peak. The result of this integration is the 1-Å K index and includes a contribution from the photosphere. The stars in NGC 3680, IC 4651, M 67, IC 4756 and NGC 5822 showed the interstellar K absorption line which affected the chromospheric K-line feature. As for NGC 3680, IC 4651, and M 67, we could evaluate the contribution of the interstellar absorption, by observing hot stars in each of these clusters, and correct for it. This was not possible, instead, for stars in IC 4756 and NGC 5822. To measure the 1-Å K index in these stars, we integrated the normalised flux only in the uncontaminated part of their profile. The Praesepe stars are unaffected by interstellar absorption thus allowing us to calculate a ratio between the flux measured over the 1-Å and that measured over the portion of the feature which is unaffected by interstellar line in all stars. The initial measures for the affected stars were then multiplied by this factor to give a final corrected 1-A K index. The errors involved in the measurement of the 1-Å K index were evaluated to be within 6%.

For the Sun, we used the 1-Å K index measurements made by White & Livingston (1981). They monitored solar chromospheric activity from the first minimum to the maximum of the 21^{st} solar-activity cycle.

Subtraction of the photospheric contribution to the 1-Å K index was made as follows. For the Sun, we computed the photospheric correction using a solar–photosphere synthetic spectrum (courtesy of P. Bonifacio). For the other stars, the photospheric contribution was computed by scaling the solar photospheric contribution by a factor that depends on the stellar parameters. These scaling factors were computed using the spectral synthesis code of MOOG (Sneden 1973, version 2002), and Kurucz's grid of models (Kurucz 1993). Stellar parameters, namely temperature, gravity, microturbulence and metallicity, were known from our chemical analyses in Pace et al. (2008, 2010) and, for Hyades stars, from Paulson et al. (2003).

In order to transform the 1–Å K index, which is an equivalent width, into an intrinsic flux, namely F_K' , we multiplied the former by the flux at the stellar surface of the pseudo–continuum radiation at 3950.5–Å, which was obtained from the stellar temperatures using relationships published in Sousa et al. (2008); Pasquini (1985); and Pasquini et al. (1988).

The employment of stellar temperatures from spectroscopic analysis of iron lines instead of published

colours avoids the use of uncertain reddening estimations.

The results of the reviewed analysis of the old sample and of the analysis of the new sample, published in Pace et al. (2009), were used to produce the diagram of CA as a function of temperature shown in Figure 1.

3 Discussion.

It was already pointed out back in the eighties that the distribution of CA is markedly bimodal (Vaughan & Prest 1980). Namely very few stars are less active than the Hyades and significantly more active than the Sun. This underpopulated range of values is usually referred to as Vaughan-Preston (VP) gap. Hartmann et al. (1984) explained it as a combined effect of CA saturation in active stars and a basal level in the CA indicator used by VP, due to the photospheric flux. These, it was claimed, enhance the impression of a gap. A variation in the local stellar birthrate was also invoked. Other studies consider the VP gap a result of the nature of the CA evolution (e.g. Durney et al. 1981; Middelkoop 1982). Our Figure 1 corroborates the latter hypothesis: all stars younger than 1.2 Gyr, except one, lie above the gap, all stars older than 1.4 Gyr with the exception of one, lie below it, indicating a drop of CA level in a very short time. The two exceptions are probably due to a particular phase of the activity cycle. It is worth noticing that the stars in either side of the gap differ not only in CA level, but also in its trend as a function of temperature: $\log R'_K$ (or equivalently $\log R'_{HK}$) depends weakly on the temperature for stars above the gap, while it has a distinct decreasing trend for stars below. This can be seen from our Figure 1, and it appears clearer when a larger temperature range is considered, like, for instance, in Mamajek & Hillenbrand (2008, see Figure 4 therein). Furthermore, short–term temporal variations of CA are large and irregular for active stars and small and regular for inactive ones (Vaughan 1980). There must be a major event at a given time of the stellar main sequence life time, that changes the way radiative heating mechanisms occur in the chromosphere, and, as a consequence, their dependence on stellar parameters as well as the shape and length of CA cycles.

Fawzy et al. (2002) present theoretical calculations that reproduce the observed trend of CA with stellar temperature. They invoke two heating mechanisms: the magnetic–wave and the acoustic–wave heating. Theoretical chromospheric fluxes for the former mechanism match the observed flux of the active stars, while theoretical fluxes for the latter mechanism match

the observed flux of the inactive stars. In order to provide a physical explanation for the occurrence of the VP gap, Durney et al. (1981) proposed a transition from a complex to a simpler magnetic-field morphology which occurs at the time when the rotation decreases enough to reach a threshold value. More recently, Barnes (2003) detected two sequences in the period-versuscolour diagram of open clusters, and he associated them with two different rotation morphologies, intertwined with stellar magnetic fields. Böhm-Vitense (2007) suggested a change of dynamo mechanism to explain the of ct that stars occupy two very distinct sequences in a rotation period-versus-cycle period diagram. Not all of these works can be used to explain our results. What is relevant for the present discussion is the possibility of a change in the nature of the dynamo mechanism taking place at a specific point of the main-sequence lifetime of solar-type stars.

The most important conclusion of our analysis is that, before and after the fast drop of CA from above to below the VP gap in only 200 Myr, its alleged smooth decay must be much less important than short term variations. We noted first in Pace & Pasquini (2004) that CA in intermediate age clusters had already dropped to the solar level. After the reanalysis of the data using temperature determined spectroscopically from iron lines, 1 out of the 7 stars in the two intermediate age clusters IC 4651 and NGC 3680 turned out to lie in the VP gap. In addition, the membership of one of the two stars in NGC 3680 has been questioned Anthony-Twarog et al. (2009). However, the data still point undoubtedly to a lack of evolution after 1.4 Gyr, since 5 out of 6 secure intermediate age stars have CA levels equal or lower to those spanned by the Sun and by M 67 stars (empty dots in Figure 1). This conclusion is also corroborated by the work of Lyra & Porto de Mello (2005). The other part of the conclusions, that regarding the time interval between 0.7 and 1.2 Gyr (filled dots in Figure 1), was achieved after the analysis of 5 stars in NGC 5822 and IC 4756, together with the older data on Hyades and Praesepe (Pace et al. 2009). We could show that metallicity is unlikely to play a major role, since there is no significant difference between three almost coeval open clusters at different metallicities: Praesepe, at [Fe/H]=0.27 (Pace et al. 2008), Hyades, at [Fe/H]=0.13 (Paulson et al. 2003), and IC 4756 at [Fe/H]=0.01 (Pace et al. 2010). The quoted iron abundance for Praesepe is somewhat different from other published works (see e.g. Anthony-Twarog et al. 2009). However, this result is based on the high-quality spectra described in Section 1, the iron abundance was obtained adopting both spectroscopic and photometric

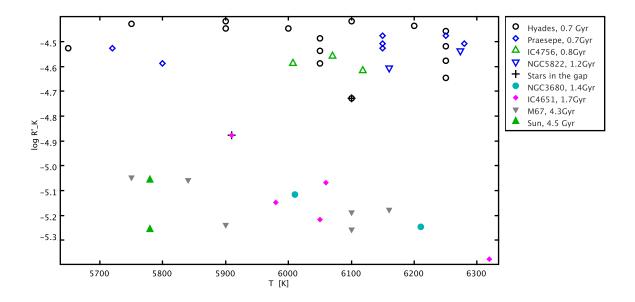


Fig. 1 Diagram of CA as a function of the temperature using $\log R_K'$ as a proxy for CA. For the Sun, 2 datapoints, corresponding to the maximum and the minimum of an activity cycle, are plotted. Datapoints relative to stars above Vaughan-Preston gap are plotted with empty symbols, datapoints below with full symbols. The typical 1σ error is 0.1 dex on the ordinate and 110 K on the abscissa. The ages indicated in the legend are taken by Salaris et al. (2004).

temperatures, several ways of normalizing for the continuum were tried, and even different people performed EW measurements in order to avoid personal bias, and in any case the result was [Fe/H] significantly higher than $0.2~{\rm dex}$.

Our conclusions on CA evolution are still based on few stars per cluster, and they partly rely on the age scale of Salaris et al. (2004), which uses a calibration of a photospheric age indicator made on 11 clusters. In order to strengthen our results, or to disprove them, we need more CA measurements in solar—type stars in open clusters based on high—resolution spectra and direct age determinations of the open clusters used based on improved colour—magnitude diagrams. We should both reobserve the already analysed stars, to obtain a time—averaged CA level, and choose other targets.

The scenario suggested here contradicts the common belief that CA is well correlated with age, however our investigation does not include stars younger than the Hyades, some of which are indeed more active than the Hyades stars. In addition, the fact that young stars are active and old stars are not is not questioned here, and it causes a weak correlation between CA and age. We believe that data used in the literature to prove a deterministic relation between CA and age do not

disprove our alternative view, and that more data are necessary to achieve a definitive conclusion.

For instance Soderblom et al. (1991) used Mount-Wilson data about several solar-type stars in visual binaries and single F dwarfs, with ages from Strömgren photometry in order to prove that the relationship between CA and age is, using their words, deterministic and not statistical. Figure 3 in the aforementioned paper shows that $\log R'_{HK}$ and the logarithm of age are indeed correlated. However we notice, analysing data in Table 1 and 2 therein, that among stars with $\log R'_{HK} > -4.9$, i.e. more active than the Sun, the correlation between $\log R'_{HK}$ and age is not significant, the Pearson correlation coefficient is about 0.1. As for the other stars, i.e. those with $\log R'_{HK} < -4.9$, the Pearson coefficient is 0.35, and its sign is positive, unlike what is expected according to an activity decay. In either group of stars there is, instead, a significant correlation between $\log R'_{HK}$ and the B-V colour, and it has opposite signs.

Another calibration of CA evolution with time is that of Lachaume et al. (1999). From Fig. 4 therein, it can be seen that their result agrees with ours as far as inactive stars are concerned, i.e. CA does not evolve after it has crossed the VP gap. As far as active stars older than the Hyades are concerned, there are 4 to 6 data–points (for two stars it is not possible to say whether or not they are younger than the Hyades and therefore out of the range considered in the present study). For this group, the Pearson coefficient indicates a level of anticorrelation between age and $\log R'_{HK}$ that is weak (-0.27) or fair (-0.57), depending on how many stars we consider.

From Mamajek & Hillenbrand (2008) it is clear that the one open cluster that supports a strict monotonicity of CA time evolution (once short-time scale variations are smoothed out) in the age range between that of the Hyades and that of M 67 and the Sun, is NGC 752. This cluster, according to Salaris et al. (2004), is older than NGC 5822 and younger than NGC 3680, i.e. exactly in the range in which we expect the transition to occur. However, Mamajek & Hillenbrand also show that companions of a binary system tend to have similar CA level, especially if they have similar colours. According to the assumption that CA is a good age indicator, this circumstance is easily interpreted as due to the fact that companions of a binary system are coeval. We suggest that it could be instead related to the nature of the binary systems.

We conclude that data in Soderblom et al. (1991); Lachaume et al. (1999); Mamajek & Hillenbrand (2008) are compatible with the conclusion that, within the age range from 0.7 to 1.2 Gyr and from 1.4 Gyr to solar age, any age—activity relationship must be weaker than the short term variations

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