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RELATIONSHIP BETWEEN CHROMOSPHERIC EMISSION INDICATORS FROM F TO M STARS: ROLE OF PLAGES AND FILAMENTS

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Abstract. Different types of relationships between the Hα and Ca II chromospheric emissions have been reported in solar-type stars. In particular, the time series of emissions in these two lines are anti-correlated for a few percent of the stars, contrary to what is observed for the Sun or from the global correlations between averaged indexes, and some time series are also completely uncorrelated. We had previously proposed that this could be due to the possible presence of filaments. We will present a detailed analysis of this relationship at short and long timescales between these chromospheric emissions for a very large sample of F-G-K stars. We also characterise the complex and surprising relationship between the average activity levels of both indexes, in particular for low-activity stars. The comparison with synthetic Hα and Ca II time-series for different assumptions for plage and filament properties based on criteria at different timescales allows to discuss their impact on the different indicators. We then extend this work to a large sample of M dwarfs and include the relationship of these indicators with the Na doublet emission, which shows that different processes may dominate the relationship between the different indicators.

Keywords: Stars: activity – Stars: solar-type – Stars: chromospheres - techniques: spectroscopy – planetary systems

1 Introduction

Chromospheric emissions in stars are very widely used to characterise stellar variability due to active regions, and plages in particular. On the Sun, the emission in Ca and Hα in plages are for example correlated with each other (Harvey & White 1999), as are the indices intergrated over the disk (Livingston et al. 2007). However, Cincunegui et al. (2007) analysed a sample of FGKM stars and found that for a few percents of those stars, the emissions were anticorrelated, which was a puzzle. This was later also observed by Gomes da Silva et al. (2011), Gomes da Silva et al. (2014) and Scandariato et al. (2017). A possible interpretation for solar-type stars was proposed by Meunier & Delfosse (2009), suggesting that the presence of filaments, at a level higher than in the solar case, could be responsible for such behaviour: being in absorption in Hα, their impact on the integrated Hα emission may counterbalance the contribution of plages, degrading the correlation between the two emissions. In addition, for M dwarfs, it has been suggested (Cram & Mullan 1979) that for those stars, the Hα emission should go into absorption when the activity level is increasing, before going into emission at a higher activity level. There is therefore some theoretical possibility for plage properties in M dwarfs to be responsible for an anticorrelation. The relationship between such a local law and the integrated emission is however not direct. It is of great importance to understand the relationship between such activity indicators, because they may provide a better understanding of the magnetic structures in the chromosphere of those stars, such as plages and possibly filaments. They are also widely used to eliminate false positives when searching for exoplanets with the radial velocity technique, and it is therefore necessary to evaluate if they provide similar informations or not.

In this work, we analyse two large samples of FGK stars and of M dwarfs to study the relation between the different chromospheric emissions at different timescales. A dedicated analysis of the long-term analysis of those emission for M dwarfs in the same sample is presented in Mignon et al. (2022), focusing on the search for new cycles. After a description of the samples, we describe a few results obtained from this analysis as well as a first comparison with simple models.

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2 The data samples

The FGK sample is composed of 441 stars, with at least 10 nights of observations with HARPS (the data are retrieved from the ESO archive), including 152 stars with more than 4 seasons. Seasons cover a maximum of 100 days in duration. This data set represents 26579 nights of observations. The median time span is 9.1 years, and 97% of the stars have a time span longer than 1000 days. We computed the S-index from the Ca II H & K lines as well as a similar index in Hα. We refer to Meunier et al. (2022) for more details.

The M sample is composed of 177 stars, with at least 10 nights of observations with HARPS, including 57 stars with more than 4 seasons. Seasons cover a maximum of 150 days in duration. The data set represents 9942 nights of observations. The median time span is 7.4 years, and 88% of the stars have a time span longer than 1000 days. We computed the S-index from the Ca II H & K lines as well as a similar index in Hα and in the Na doublet. We refer to Meunier et al. (2023) for more details.

3 Analysis of the time series

3.1 Average indices

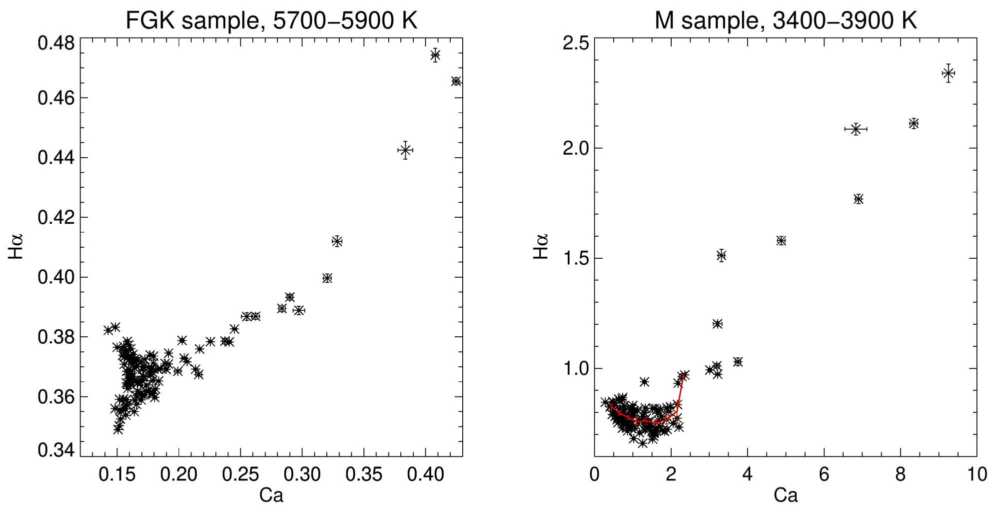

Fig. 1. Left: Average of the Hα versus Ca emission for stars in our FGK sample in the 5700-5900 K $T_{\rm eff}$ range, from Meunier et al. (2022). **Right:** Average of the Hα versus Ca emission for stars in our M sample in the 3400-3900 K $T_{\rm eff}$ range, after a shift in the vertical direction to normalise the levels, from Meunier et al. (2023).

Before analysing the temporal variability, we derived the flux-flux relation from the average over time of the various indices. Because they are not normalised, we performed this analysis in bins in $T_{\rm eff}$. The analysis of the FGK stars sample shows a general correlation between Ca and Hα. However, at low activity levels and for stars with $T_{\rm eff}$ in the range 5300-6100 K, there is a departure from that correlation, with a spread in Hα level that may correspond to two branches (an example is shown in the left panel in Fig. 1), a lower branch corresponding to the prolongation of the active regime and a correlation, and an upper branch with an increasing Hα level towards low activity levels. This behaviour remains to be understood. For M dwarfs, there is a very good correlation between each pair of indices for active stars. However, in the low activity regime, we observe a stagnation and even a negative slope for the lowest activity levels for Hα versus Ca (illustrated in the right panel in Fig. 1 with a zoom n low activity stars) and versus Na: this is observed for stars with $T_{\rm eff}$ in the 3400-3900 K range only, and does not seem to be present below, i.e. with fully convective stars. This property may be related to the theoretical prediction of Cram & Mullan (1979). It has been observed by Scandariato et al. (2017). The same lower enveloppe was also observed by Rauscher & Marcy (2006) and Walkowicz & Hawley (2009). Furthermore, we also observe a change in slope between low and high activity levels in the Na versus Ca relationship, which also remains to be understood.

3.2 Relationships between indices

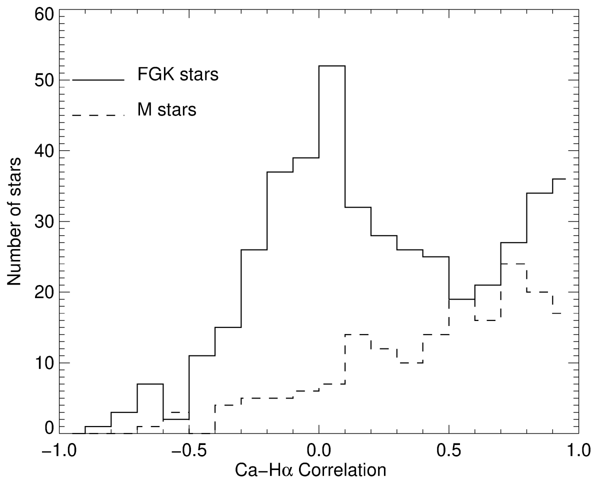

Fig. 2. Distribution of the Ca-Hα correlation for our sample of FGK stars (solid line) and M stars (dashed line), from Meunier et al. (2022) and Meunier et al. (2023).

In this section, we concentrate on the analysis of all time series. A visual inspection of the time series show that although many are solar-like, i.e. with good to moderate correlation, many others are different. In addition to a few stars with strong anticorrelations in both stellar samples, we also observe, especially in the FGK sample, stars with a correlation close to zero between Ca and Hα typically: those low correlations are not due to the measurement uncertainties but to an intrinsic behaviour. There are for example many FGK stars with a well-defined long-term variability in Ca (long-term cycle), while the Hα emission does not exhibit this long-term variability but rather a more short-term dispersion. Figure 2 shows the difference in correlation distribution between the two samples. In addition, for M dwarfs, since we studied three indices, we also have 3 pairs of indices. If we focus on the comparison with Ca emission, we find that 44% of the stars have both correlations (Ca-Na and Ca-Hα) above 0.5. Other stars fall into typically three categories: 1/ the Ca-Na correlation remains good, and the Ca-Hα is degraded, with low correlations or anticorrelations, those are mostly relatively quiet stars; 2/ the Ca-Hα correlation remains good, and the Ca-Na correlation is degraded, those are more active stars; 3/ Stars for which all correlations are weak. The picture is therefore quite complex. In particular, it is not clear why the Ca-Na correlation is poor for some stars. Finally, in both samples, low Ca-Hα correlation tends to be quiet stars, while the correlation is in most cases very good for active stars. There is on the other hand no correlation between those correlations and $T_{\rm eff}$, and the relationship with metallicity is complex to interpret.

We also studied those correlations at two specific timescales, in order to provide additional criteria: we computed them at short timescales within seasons (ST), and at long timescales, based on the average indices over each season (LT). For FGK stars, we found that long-term correlations tend to be reinforced (closer to 1 or -1) while short-term correlations tend to be closer to zero compared to the global correlations. This was not observed for M dwarfs however, with a more similar behaviour at the different timescales. The same was true for the amplitude of the signal, with less difference in behaviour between short-term and long-term variabilities for M compared to FGK stars.

4 Simulations

For both samples, we first performed simulation based on synthetic time series as follows: The observed Ca time series were used as a reference, and a synthetic Hα time series is then built based on a conversion factor (the proper level and noise is then added) representing the relation between Ca and Hα emission in a plage. Several factors were tested based on several assumptions for plage properties, but all assuming a similar behavior for all plages of a given star. We then compared the correlation at different scales as well as the amplitude of the variability of the resulting Hα time series with observations. We found that although a good agreement was found for certain stars, in many cases no assumption would give a good agreement at all time scales simultaneously. In addition, it was difficult to reproduce the low correlation stars, especially for M dwarfs. For FGK stars, we also performed based on a large set of synthetic time series produced in Meunier et al. (2019), with similar results.

For FGK stars, we also explored the possibility for the presence of filaments to explain the observations. We first identified the important properties of filaments that should significantly impact the Hα time series: size, contrast, number, lifetime, keeping in mind that the solar level is insufficient to create anticorrelation; position in latitude and in longitude (in particular wih respect to the latitude of active regions). With very simple toy models, we found that a level around 20 times the solar level is necessary to reach anticorrelation. It is easier to reach long-term anticorrelations with filaments far from active regions in latitude. On the other hand, it is easier to obtain short-term correlations if filaments are close to active regions in longitude. These differences in behaviour are particularly interesting since we observed that correlations at different timescales differ, which is not easy to obtain with plages only.

Finally, for M dwarfs, we also implemented toy models to explore the Ca-Hα relationship, in order to study the link between a local law such as the one proposed by Cram & Mullan (1979), and the integrated emission, as for example discussed in Stauffer & Hartmann (1986). These results are still preliminary, but they already show that the relationship between the two is not obvious if we also wish to reproduce other properties such as the proper sign in correlations. There is probably a need for a correlation between plage size and Ca local emission, and for plages with various properties present at the surface of given star to explain the observations.

5 Conclusions

Our results allowed to derive interesting new properties of the relationship between chromospheric indices. The study of their behaviour at different timescales proved to be fruitful. There are a number of similarities between FGK and M dwarfs, for example the existence a large range of correlations, but also differences, such as different amounts of weak correlations and different short-term and long-term properties compared to the global correlations. Filaments remain an interesting possibility to explain the correlations for FGK stars, which is interesting because they are related to magnetic configuration of the stars, forming on line of inverse polarity (Meunier & Delfosse 2011). On the other hand, there is currently no diagnosis for stellar filaments, apart for prominences on very young stars such as in Jardine et al. (2020), so this could open new possibilities. In a future work, we will implement more sophisticated models for both types of stars to be able to explain all observed properties.

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