Stars and their variability observed from space
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THE RELEVANCE OF PARTIAL IONIZATION IN THE OUTER LAYERS OF F STARS

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Abstract. The present-day quality of asteroseismic data enables us to probe the complex outer layers of Sun-like stars. F stars are particularly interesting, given their diversity of magnetic and rotational behaviours. Using a seismic diagnostic based on the phase shift of the acoustic waves, we found a trend, in the form of a power-law dependence, that correlates the ionisation processes occurring in these external layers with the rotation periods of the stars. In addition, we have studied the internal structure of the outer layers of 10 main-sequence F stars; we found that the rotational characteristics of those stars can be distinguished by the relative location of the partial ionisation region of heavy elements and the base of the convective zone. Since the region near the base of the convective zone (the tachocline) is known to have a strong influence in the expected dynamo-driven mechanism, these results might be important for improving and extending our understanding of the relations between magnetism and rotation in those stars.

Keywords: Chemical processes: partial ionisation, stars: rotation, oscillations, low-mass stars

1 Introduction

Main-sequence stars of spectral type F exhibit a diversity of rotational and magnetic properties that makes them interesting targets for studies of stellar structure and evolution. Late-F stars are generally slow rotators ($P_{\rm rot} \gtrsim 10$ days) whereas early-F stars are generally rapid rotators ($P_{\rm rot} \lesssim 10$ days). These two distinct rotational regimes for stars on the main sequence were observed and studied by Kraft (1967). The transition between the two regimes occurs around type F5, and can be considered abrupt since it consists of a decrease in rotational velocity from ∼20 to ∼80 km s^{-1} for stars with masses in the range $1.2 - 1.4$ M$_\odot$. Concerning magnetic activity, slow rotators are usually less active than rapid rotators. It is also worth remembering that we are dealing with stars with convective external envelopes for which the magnetic field is thought to be amplified by a dynamo mechanism acting at the tachocline – the shear layer located between the radiative and convective zones (e.g., Spiegel & Zahn 1992; Brun & Browning 2017).

In this work, we probe the outer convective layers of 10 main-sequence F-type stars using a seismic diagnostic that is particularly sensitive to partial ionisation processes occurring in their more external layers. The stars were chosen from the *Kepler Legacy* sample (Lund et al. 2017). We separated the stars into two subgroups. One consists of the cooler stars, the other consists of the hotter stars – as shown in Table 1. The non-linear seismic diagnostic used to analyse the 10 stars is a robust one based on the phase shift of the acoustic waves reflected by the surface of the star. This phase shift $\alpha(\omega)$ enters the eigenfrequency equation resulting from the asymptotic analysis (e.g., Duvall 1982)

$$F(W) = \pi \left(\frac{\alpha(\omega) + n}{\omega} \right) , \tag{1.1}$$

where ω is the angular frequency, $W = \omega/(l + 1/2)$ determines the penetration depth of the acoustic mode, l is the degree and n the radial order of the mode. The function $F(W)$ is determined by the profile of the speed of sound in the stellar interiors. After some manipulation of the eigenfrequency equation 1.1, it is possible to define a non-linear seismic diagnostic (Brodskii & Vorontsov 1987),

$$\beta(\omega) = \frac{\omega - n\left(\frac{\partial\omega}{\partial n}\right) - L\left(\frac{\partial\omega}{\partial L}\right)}{\left(\frac{\partial\omega}{\partial n}\right)} , \tag{1.2}$$

that is suitable for obtaining information about the relevant partial ionisation processes occurring in the outer stellar convective layers. This diagnostic was studied extensively in the solar case (e.g., Vorontsov & Zharkov

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Table 1. Observational parameters

Star Id.	$T_{\rm eff}$ (K)	[Fe/H] (dex)
C1	6033 ± 77	-0.23 ± 0.1
C2	6177 ± 77	-0.07 ± 0.1
C3	6122 ± 77	-0.08 ± 0.1
C4	6140 ± 77	-0.19 ± 0.1
C5	6179 ± 77	-0.08 ± 0.1
H1	6479 ± 77	0.01 ± 0.1
H2	6344 ± 77	0.02 ± 0.1
H3	6326 ± 77	0.01 ± 0.1
H4	6538 ± 77	0.16 ± 0.1
H5	6331 ± 77	-0.05 ± 0.1

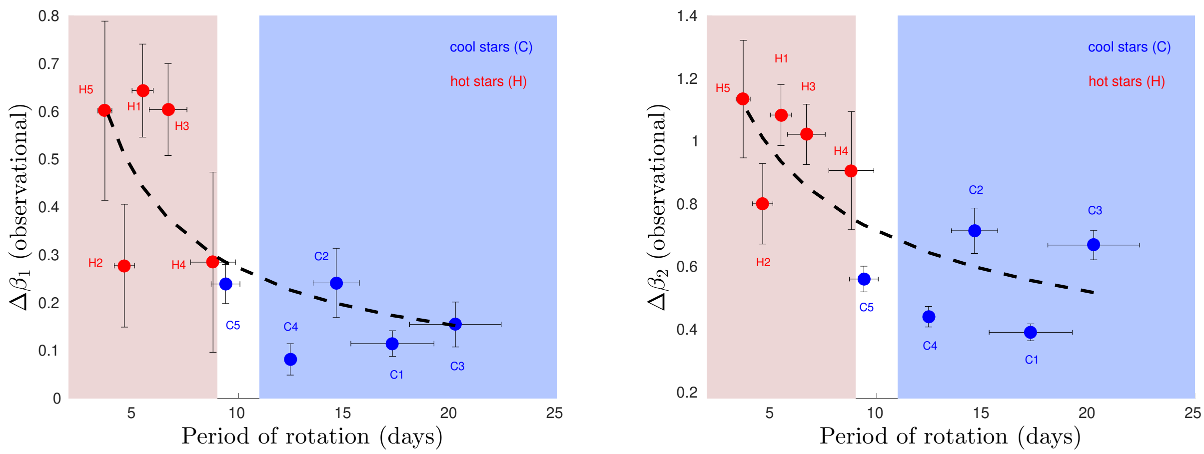

Fig. 1. The ionisation indices $\Delta\beta_1$ and $\Delta\beta_2$ plotted against the rotation period of the selected stars. The dashed line represents the result of a power law fit, $\Delta\beta_i = a \times P_{\rm rot}^b$ to the data ($i = 1, 2$). Specifically, $\Delta\beta_1 = 1.777 \times P_{\rm rot}^{(-0.8176)}$ and $\Delta\beta_2 = 2.023 \times P_{\rm rot}^{(-0.4536)}$. The vertical white bar signalises the values of the rotation period around which the transition between the two rotational regimes on the main sequence occurs (the Kraft break). Rotation periods were taken from Benomar et al. (2015) and Kiefer et al. (2017).

1989; Lopes & Gough 2001), enabling a measurement of the solar helium abundance and contributing to the calibration of the equation of state (Pamiatnykh et al. 1991). More recently, Brito & Lopes (2017a), studying the theoretical envelopes of *Kepler* F stars, used the diagnostic $\beta(\omega)$ to define two seismic ionisation indices ($\Delta\beta_1$ and $\Delta\beta_2$) that can be related to the magnitude of the partial ionisation processes in the envelopes of Sun-like stars. It was noticed that the ionisation indices have larger values for hot stars than for cool ones. Owing to the differences in the rotational behaviours of cool and hot stars we plotted the ionisation indices against the rotation period of the stars being studied and found a correlation in the form of a power law (Fig. 1) which strongly suggests that partial ionisation might be acting as an important factor for understanding better the complex relations between rotation and magnetism.

2 How partial ionisation correlates with the rotational regimes for main-sequence F stars

In order to explore further the importance of partial ionisation and how it might influence the macroscopic properties of stars, we need new tools. To that end, we defined a mean effective ionic charge, $\overline{Q}$, (Brito & Lopes 2017b), which is simply the sum of the average ionic charges of each atomic species considered in the theoretical models of our sample of 10 main-sequence F stars. For computating $\overline{Q}$ in this particular case, we considered three heavy elements (carbon, nitrogen, and oxygen) alongside hydrogen and helium,

$$\overline{Q} = \langle Q_{\rm H}\rangle + \langle Q_{\rm He}\rangle + \langle Q_{\rm C}\rangle + \langle Q_{\rm N}\rangle + \langle Q_{\rm O}\rangle, \qquad (2.1)$$

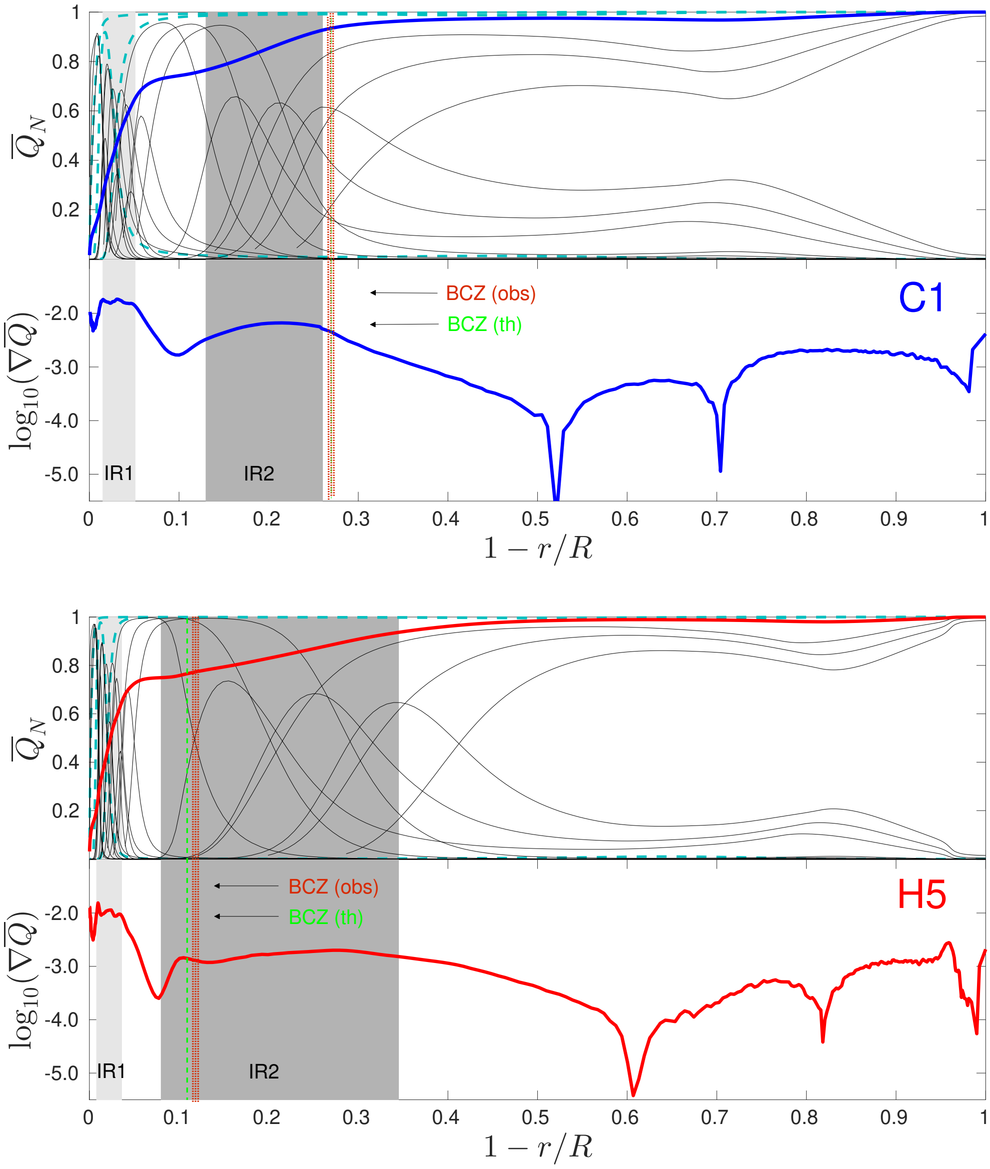

Fig. 2. Detailed representation of the partial ionisation processes occurring in the interior of a cool star (top; in blue) and of a hot star (bottom; in red). The ionisation fractions of light elements (H, He) are indicated by dashed lines, and the ionisation fractions of heavy elements are indicated with thin solid black lines (see Brito & Lopes 2017b). The mean effective ionic charge normalised to its maximum value, $\overline{Q}_N = \overline{Q}/\max\overline{Q}$, is given by the thick solid lines (blue, red) in each case. Below, the corresponding gradient of the ionic charge is also given by a thick solid line in each case. The partial ionisation regions IR1 and IR2 represent the locations where the effective mean ionic charge increases significantly. IR1 coincides with the partial ionisation region of helium, while IR2 is associated with partial ionisation of heavier elements. Both regions are marked with vertical grey bars. The locations of the base of the convective envelopes for both stars are also shown. The red vertical dashed line represents the observed value. The thickness of the line indicates $r_{\rm bcz}$ approximately within a 1-σ error bar. Dashed vertical green lines represent the theoretical value of $r_{\rm bcz}$. All quantities are plotted as a function of the star's fractional radius.

where

$$\langle Q_{\rm elem}\rangle \equiv \sum_{j=1}^{q_{\rm elem}} j\, x_{j,{\rm elem}} \;, \tag{2.2}$$

is the mean ionic charge of each element. $x_{j,{\rm elem}}$ is the number of atoms of element "elem" in the ionisation state j divided by the total number of atoms of the element "elem". By taking the gradient of $\overline{Q}$ it is possible

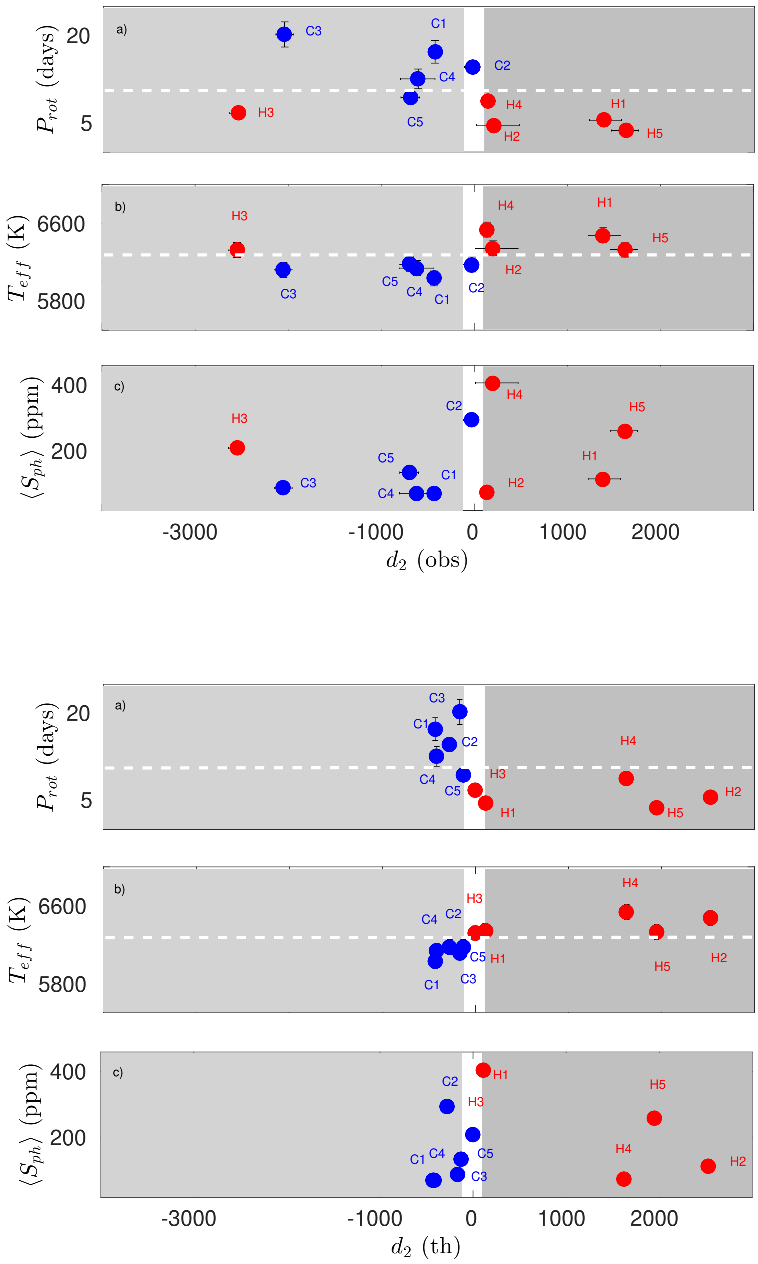

Fig. 3. d_2 represents the difference between the acoustic depths of the location of the region IR2 and the acoustic depth of the location of the BCZ (Eq. 2.3). A negative value means that the location of the region IR2 is above the base of the convective zone, i.e., IR2 is closer to the surface than the BCZ. A zero value occurs when the two zones coincide. A positive value means that the region IR2 is located (mostly) below the BCZ. The white vertical bar marks the overlap of IR2 (at its central point) and BCZ. White horizontal dashed lines correspond to the threshold values of the Kraft break for the rotation period ($\sim$ 10 days) and $T_{\rm eff}$ ($\sim$ 6250 K). d_2 is plotted against: a) the rotation period ($P_{\rm rot}$), b) the effective temperature ($T_{\rm eff}$), and c) the magnetic photometric index ($S_{\rm ph}$). Top panel: The observed value for the location of the base of the convective zone was used. Bottom panel: The theoretical value for the location of the base of the convective zone was used.

to identify and locate the relevant ionisation zones in stellar interiors. Fig. 2 shows the mean effective ionic charge for a representative cool star (top panel) and for a representative hot star (bottom panel) in our sample. These figures are very interesting, for several reasons. First, they illustrate that in the more external regions of these stars we can see the influence of two main ionisation regions. IR1 corresponds to a region where hydrogen and helium are the main contributors to the variation of the ionic charge, and we therefore named IR1 as the partial ionisation region of light elements. The other relevant ionisation region represented, IR2, is completely dominated by the ionisation of heavy elements, because at that depth light elements are already fully ionised. We therefore named IR2 as the partial ionisation region of heavy elements. Secondly, another aspect that stands out in these figures is the location of the base of the convective zone. For cool stars, the base of the convective zone is located predominantly *outside* the ionisation region IR2, whereas for hot stars the base of the convective zone is located predominantly *inside* the ionisation region IR2.

Finally, this interesting structural detail that differentiates the two subgroups of stars, cool and hot, can be quantified by the introduction of an indicator that we called the acoustic distance d_2. This indicator gives us the relative position between the region IR2 and the base of the convective zone. We define it as follows,

$$d_2 = \tau_{\rm IR2} - \tau_{\rm BCZ} \, . \tag{2.3}$$

With the help of this indicator we can distinguish the rotational regimes for main-sequence F stars. Thus, the structure of a slowly-rotating F star is characterised by a negative value of d_2 ($d_2 < 0$), whereas the structure of a rapidly-rotating F star is characterised by a positive value of d_2 ($d_2 > 0$). The most interesting case is the transitional one, where the transition between the two main rotational regimes occurs. This case corresponds to $d_2 \approx 0$, meaning that the base of the convective zone is located well within the central region of the partial ionisation zone of heavy elements. To investigate this relation further, we plotted the effective temperatures, the rotation periods, and a photometric activity index (Mathur et al. 2014) against the distance d_2 (Fig. 3). It is noteworthy that this Figure shows that the distance d_2 does indeed separate the two main rotational regimes for our sample of 10 main-sequence F stars. The different types of stellar structure and rotational regime thus appear to be related to the microphysics of stellar interiors, specifically to the partial ionisation processes occurring in the upper layers.

3 Conclusions

In this work we studied the internal ionisation profiles of a sample of 10 main-sequence F stars and correlate them with the two distinct rotational regimes observed among these stars. More specifically, we relate the two rotational regimes with the relative location of the base of the convective zone and the region where heavy elements ionise. For a detailed reading about this result we refer to the paper Brito & Lopes (2019).

From a physical standpoint we would like to highlight that the relevant regions of partial ionisation are regions of large variations of ionic charges. At the same time it is well-known that electric charges are among the main ingredients needed for the generation of magnetic fields, and that these play an important role in the mechanisms of redistribution of angular momentum (e.g., Aerts et al. 2019). Also interesting is the fact that there is an overlapping of $T_{\rm eff}$ and mass for the hotter stars in this study and γ Doradus stars. The latter are known to be gravity mode oscillators with the pulsations being driven by the convective flux blocking mechanism at the base of their convective envelope (e.g., Guzik et al. 2000; Samadi et al. 2015). Therefore, the relative location of partial ionisation zones and convective boundaries seems to be worthy of special attention in future studies of stellar interiors.

The computation of the observed seismic diagnostic used in this work to establish a connection between ionisation and rotation greatly benefits from a large number of high-precision detected oscillation mode frequencies. We hope that in a nearby future, the observational data from the TESS (Ricker et al. 2014) and PLATO (Rauer et al. 2014) missions allow us to extend this study to other spectral types and probe further for this connection between ionisation, rotation and magnetism.

We are grateful to Conny Aerts for drawing our attention to F-type gravity-mode pulsators that, we hope, will allow us to place this study in a broader context in the future.

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