SF2A 2022
J. Richard, A. Siebert, E. Lagadec, N. Lagarde, O. Venot, J. Malzac, J.-B. Marquette, M. N'Diaye, D. Briot (eds)

A STEP TO THE SIDE: F-TYPE STARS, SOLAR-TYPE STARS, AND THE SUN

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Abstract. Fast rotating late F-type stars are fascinating objects which can be seen as the missing link between the cool dwarfs like the Sun and intermediate mass stars. Their shallow convective envelope still allows the excitation of detectable stochastic acoustic modes (p modes) as in cooler solar-like stars, while stochastically excited gravity modes (g modes) may have enough amplitude at the stellar surface to be detectable. By characterising the properties of these modes or by analysing the light curve modulations due to spots and faculae, targets with short rotation periods (below eight days) have been studied with the NASA *Kepler* mission. Understanding the rotational behaviour of such targets, from the surface to the core, will shed light on the similarities and differences that exist with G-type solar analogs. Studying these stars on both modelling and observational levels could also help to improve our knowledge about large-scale dynamical mechanisms at stake in main-sequence solar-like stars, such as angular momentum transport, dynamo cycles, or surface magnetic braking.

Keywords: stars, solar-type, F-type, gravity waves, star-planet interactions

1 Introduction

Located in the transition region between the two populations, late F-type stars are key to our understanding of both solar-type stars and intermediate-mass stars. Precise characterisation of their rotational dynamics, from the surface to the core, would be an important achievement in order to provide a better description of stellar internal dynamics on different timescales. Different techniques (e.g. photometry, spectroscopy, seismology) allow measuring stellar surface rotation while we emphasise that constraints on the core rotation can only be obtained through the characterisation of low-frequency low-signal-to-noise gravity modes (g modes, see e.g. Christensen-Dalsgaard 2014). Figure 1 shows a typical power spectral density (PSD) obtained for a late F-type star observed by the *Kepler* (Borucki et al. 2010) mission and exhibiting stochastically excited p modes. Starting from a modelling point of view, we summarise in Section 2 the results of the deep-shell hydrodynamical 3D simulations of a 1.3 $M_\odot$ F-type solar-like star performed in Breton et al. (2022). We then select in Section 3 a sample of seismic late F-type stars and we briefly discuss the potential opened by the analysis of systems exhibiting characteristic signatures of non-transiting companions.

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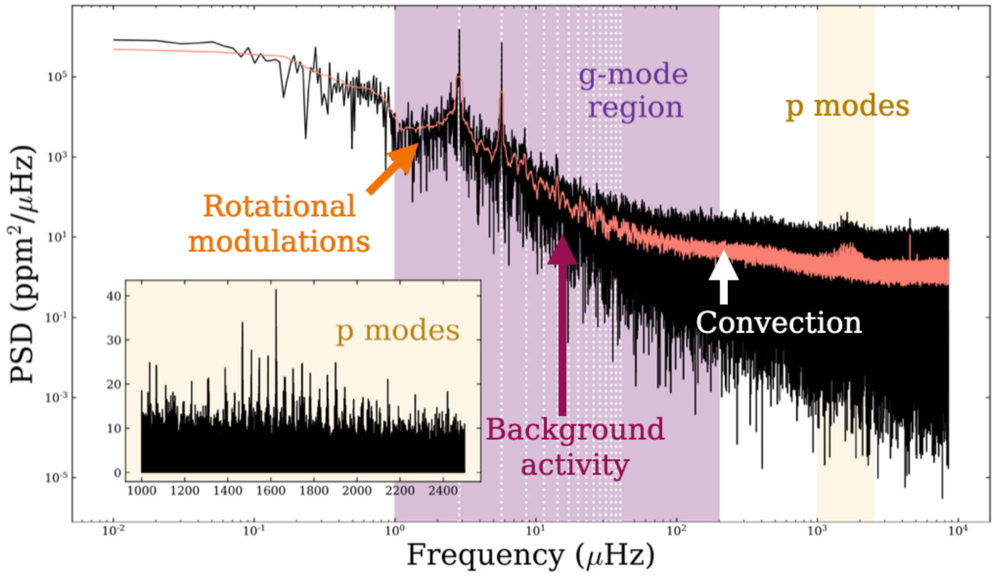

Fig. 1. PSD of the *Kepler* target KIC 7206837. The location of p modes, rotational modulations, convective signal and background activity are emphasised. The frequency range where g modes are expected is highlighted in purple.

2 Interior 3D simulation modelling

In Breton et al. (2022), we performed the first 3D deep-shell hydrodynamical simulations of 1.3 $M_\odot$ stars rotating at different rotation rates (1, 3, and 5 $\Omega_\odot$) in order to study the behaviour of internal gravity waves (IGW) excited by convective motions. We find mode amplitudes several orders of magnitudes larger than in similar simulations performed on a solar model (Alvan et al. 2014). Our results suggest that it could be easier to obtain constraints on the internal rotation for these F-type solar-like stars than for the Sun or cooler solar analogs. We emphasise the key role that rotation plays concerning the model dynamics, for both the convective envelope and the radiative interior. Models rotating at 3 and 5 $\Omega_\odot$ exhibit a low-frequency IGW excitation rate much larger than the models at 1 $\Omega_\odot$, which is consistent with the predictions of Augustson et al. (2020).

We also note that, in our different models, the Rossby number measured in the simulation is significantly higher than the predictions of the scaling laws derived by Noraz et al. (2022). We remind that the 1.3 $M_\odot$ value corresponds to the upper edge of the validity domain for which these scaling laws were derived. We therefore underline that a special attention should be brought to F-type stars falling in this range of mass when searching for possible anti-solar rotators (see e.g. Brun et al. 2017, 2022).

3 Late F-type stars in Kepler

3.1 A seismic sample

With the results of our 3D simulations in mind, we consider seismic stars with effective temperature $T_{\rm eff}$ in the range 6200 − 6800 K and logarithm of surface gravity in the range $3.9 < \log g < 4.4$ in order to build a sample composed of F-type solar-like pulsators observed with the *Kepler* short cadence mode. All the stars in our sample have been studied either by Mathur et al. (2014), Lund et al. (2017), or Hall et al. (2021) and exhibit stochastically-excited p modes. We selected $T_{\rm eff}$ and $\log g$ measurements from Mathur et al. (2017) and Silva Aguirre et al. (2017). The sample is shown in Figure 2 in a $T_{\rm eff}$ vs $\log g$ diagram. When available, photometric surface rotation measurements from Santos et al. (2021) are shown. Most of the stars in the sample have rotation periods below 10 days.

3.2 Looking for non-transiting companions

Searching for signatures of g modes in our working sample, we detect two targets (referred as Target 1 and Target 2) with strong low-frequency modulations not related to surface rotation (0.6 and 0.9 days, respectively).

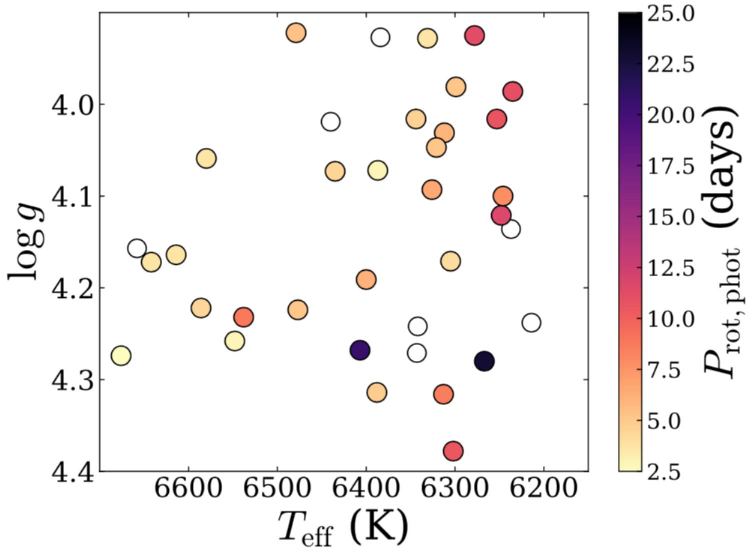

Fig. 2. Seismic late F-type sample in a $T_{\rm eff}$ vs $\log g$ diagram. The surface rotation rate measured by Santos et al. (2021) is color coded. Unfilled circles correspond to stars where no photometric surface rotation measurements were available in the catalog.

The 0.6-day modulation of Target 1 (and its first harmonic) can be seen in the PSD represented in Figure 3. These modulations can be interpreted as probable evidence for the presence of a non-transiting close companion (Breton, Dyrek et al., in prep). The stellar inclination angle $i_\star$ can be constrained from seismology by the inclination angle of the orbit i is unknown. An example of the possible geometry of the considered systems is schematised in Figure 4. The exclusion region corresponds to the range of i where a transit should occur. Radial velocity observations can only yield a value for the $M_p \sin i$ parameter, where M_p is the mass of the planet. For a given value of $M_p \sin i$, this can therefore be consistent with a brown dwarf companion (at low i) or a planetary companion (at high i). Such a detection represents an interesting perspective in order to characterise star-planet interactions in systems with inclined orbits (Barker & Ogilvie 2009) and the possible tidal excitation of g modes (see e.g. Fuller 2017) that could be triggered over secular periods of times if their characteristic damping timescale is large enough (in a different context, the case of magnetostrophic oscillations kept in resonance by tidal interaction has been discussed by Lanza 2022). A follow-up campaign performed with the High Accuracy Radial velocity Planet Searcher for the Northern hemisphere (HARPS-N, Cosentino et al. 2012) instrument is currently underway in order to better characterise Target 1.

4 Conclusion

This work explored a few of the numerous perspectives to characterise late F-type stars and their environment, with a focus on IGWs and tidal interactions. Late F-type stars represent a population of primary importance in order to improve our understanding of the transition from solar-type stars to intermediate-mass stars.

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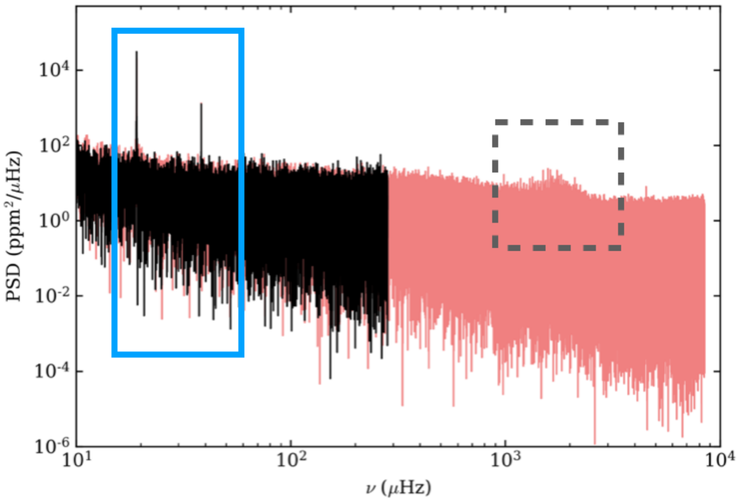

Fig. 3. PSD of Target 1. *Kepler* long cadence data are shown in black, and short cadence in red. Grey dashes show the p-mode hump location while the blue frame highlights the location of the signals associated with the non-transiting companion.

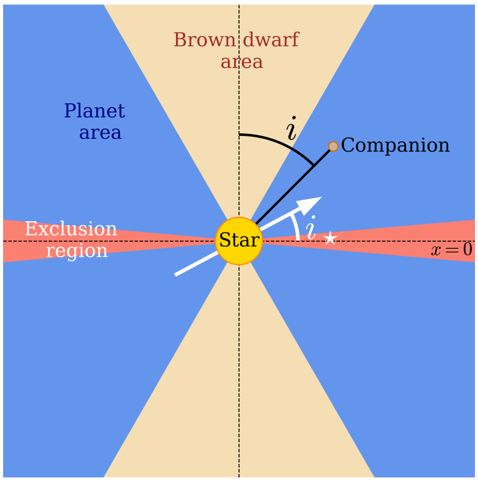

Fig. 4. Possible configuration of the studied non-transiting systems. The observer is located in the $x = 0$ plane. The white arrow represents the stellar rotation axis, with corresponding inclination angle $i_\star$. A possible position for the companion is shown as an illustration at inclination angle i.

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