Connecting photometric and spectroscopic granulation signals with CHEOPS and ESPRESSO

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ABSTRACT

Context. Stellar granulation generates fluctuations in photometric and spectroscopic data whose properties depend on the stellar type, composition, and evolutionary state. Characterizing granulation is key for understanding stellar atmospheres and detecting planets. Aims. We aim to detect the signatures of stellar granulation, link spectroscopic and photometric signatures of convection for main-sequence stars, and test predictions from 3D hydrodynamic models. Methods. For the first time, we observed two bright stars (Teff = 5833 and 6205 K) with high-precision observations taken simultaneously with CHEOPS and ESPRESSO. We analyzed the properties of the stellar granulation signal in each individual dataset. We compared them to Kepler observations and 3D hydrodynamic models. While isolating the granulation-induced changes by attenuating and filtering the p-mode oscillation signals, we studied the relationship between photometric and spectroscopic observables. Results. The signature of stellar granulation is detected and precisely characterized for the hotter F star in the CHEOPS and ESPRESSO observations. For the cooler G star, we obtain a clear detection in the CHEOPS dataset only. The TESS observations are blind to this stellar signal. Based on CHEOPS observations, we show that the inferred properties of stellar granulation are in agreement with both Kepler observations and hydrodynamic models. Comparing their periodograms, we observe a strong link between spectroscopic and photometric observables. Correlations of this stellar signal in the time domain (flux versus radial velocities, RV) and with specific spectroscopic observables (shape of the cross-correlation functions) are however difficult to isolate due to S/N dependent variations. Conclusions. In the context of the upcoming PLATO mission and the extreme precision RV surveys, a thorough understanding of the properties of the stellar granulation signal is needed. The CHEOPS and ESPRESSO observations pave the way for detailed analyses of this stellar process.

Key words. methods: data analysis – Sun: granulation – stars: atmospheres – techniques: photometric – techniques: radial velocities

1. Introduction

Stellar convection transports energy from the stellar interior to its surface in late-type stars. The properties of this complex and multiscale plasma mixing process are key for understanding stellar structure and evolution, as the dynamics of the convective cells shape angular momentum transport within the star, impact the thermal stellar stratification, mix the chemical elements, and generate the surface acoustics modes (see e.g., Dravins & Nordlund 1990a; Stein & Nordlund 2001; Alvan et al. 2014; Houdek & Dupret 2015; Salaris & Cassisi 2017; Brun & Browning 2017; Philidet et al. 2020).

This stellar phenomenon is well-studied for the Sun where it is visible in the form of granules. For other stars, granulation is studied through indirect techniques. Two of them are photometry—brightness fluctuations—and spectroscopy—radial velocity (RV) changes.

Through photometric observations, the properties of granulation as a function of stellar parameters have been revealed: CoRoT observations have shown that the granulation timescale and amplitudes decrease with the increasing characteristic...
Kepler targets from dwarfs to red giants with an overall very standard deviation and autocorrelation time match those of been used to generate synthetic brightness fluctuations whose series (Sulis et al. 2020b) of solar granulation. They have also ate disk-integrated spectra (Cegla et al. 2019) and RV time difficult to generate), they have been recently used to gener-

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1985; Nordlund & Dravins 1990; Dravins & Nordlund 1990b).

magneto-hydrodynamical (MHD) simulations of stellar con-

vection have been developed since the 1980s (Nordlund 1982,

et al. 1994; Pallé et al. 1999; Garcia et al. 2005; Appourchaux et al. 2013; Tremblay et al. 2013; Beeck et al. 2013, 2015; Samadi et al. 2013), numerous studies based on Kepler observations (Mathur et al. 2011; Bastien et al. 2013, 2016; Kallinger et al. 2014; Pande et al. 2018; Bugnet et al. 2018; Tayar et al. 2019; Sulis et al. 2020a; Rodríguez-Díaz et al. 2022) have also shown that the granulation properties are dependent on the stellar fundamental parameters \( T_{\text{eff}}, \log g, \) and \([\text{Fe/H}]).\) Granule size increases with lower stellar surface grav-ities and/or larger effective temperatures, and therefore with a decreasing \(\nu_{\text{max}}.\) The stellar photometric signal is the net con-

tribution of all the bright granules and dark intergranular lanes on the stellar surface, which reduces the disk-integrated fluctuations (compared to the scale of the granules) and therefore depends on the stellar radius (Trampedach et al. 1998; Ludwig 2006).

In spectroscopic observations, granulation produces shifts and asymmetries in the spectral lines (i.e., the line bisectors, see Dravins et al. 1981, 2021; Nordlund 1985; Dravins 1987; Asplund et al. 2000; Gray 2009; Nordlund et al. 2009). Studying RV time series of a small sample of main-sequence and sub-
giant stars, Bastien et al. (2014) found a correlation between the RV root-mean-square (RMS) evolving on timescales shorter than 8 h (or the “8-h RV scatter”) and the stellar surface gravity. This implies a narrow relation between the RV amplitudes driven by stellar granulation signals and the associated intensities (Bastien et al. 2013; Kallinger et al. 2016). As a result, various empirical relations that predict the amplitude of the granulation signal in RV from photometric observations have been derived (see e.g., Bastien et al. 2014; Cegla et al. 2014; Oshagh et al. 2017), but they have shown significant discrepancies in the predicted RV.

Three-dimensional (3D) hydrodynamical (HD) and magneto-hydrodynamical (MHD) simulations of stellar con-

vection have been developed since the 1980s (Nordlund 1982, 1985; Nordlund & Dravins 1990; Dravins & Nordlund 1990b). While computationally expensive (leading to long time series difficult to generate), they have been recently used to gener-

ate disk-integrated spectra (Cegla et al. 2019) and RV time series (Sulis et al. 2020b) of solar granulation. They have also been used to generate synthetic brightness fluctuations whose standard deviation and autocorrelation time match those of Kepler targets from dwarfs to red giants with an overall very good agreement (Rodríguez-Díaz et al. 2022). Moreover, Cegla et al. (2019) predicted correlations between the photometric and spectroscopic signals of stellar granulation, but this has yet to be confirmed with high-precision observations. They also predict that such observed correlations may allow us to mitigate a significant fraction of the granulation variability in RV observations (Cegla et al. 2019).

The variability induced by granulation constitutes a signif-

icant noise source hampering the detection of smaller stellar signals, like low-amplitude acoustic or gravity modes (see e.g., García & Ballot 2019 for solar-like oscillations, Rodríguez et al. 2016 for M-dwarfs pulsations, and Appourchaux et al. 2010 for \(g\)-modes in the Sun) and planetary signals (Dumusque et al. 2011; Meunier et al. 2015; Meunier & Lagrange 2020). From solar observations, we learn that granulation can generate vari-

ability with RMS around 40 parts-per-million (ppm) in photom-

etry (Dravins 1988, Fröhlich et al. 1997; Aigrain et al. 2004; Sulis et al. 2020a) and around 30–46 cm s\(^{-1}\) in RVs (Elsworth et al. 1994; Pallé et al. 1999; García et al. 2005; Appourchaux et al. 2018; Collier Cameron et al. 2019; Dumusque et al. 2021).

This is significant compared to the signals expected from Earth-like planets around Sun-like stars: a transit depth of 84 ppm and a Keplerian RV signal of 9 cm s\(^{-1}\) amplitude (Perryman 2018). Since the correlation timescales of the granulation-induced noise are similar to the ingress/egress transit duration of long orbital period exoplanets, this stellar signal affects the planetary parameters inferred on the individual transits (Sulis et al. 2020a). Thus, the correlated noise due to stellar granulation can be seen as a source of information to study stellar physics properties but at the same time as a nuisance signal for the detection of exoplanets and stellar oscillation modes. In both cases it needs to be understood, quantified and if possible mitigated.

In this paper, we have three objectives. First, we aim to detect the signatures of stellar granulation based on the granulation indicators that have been recently developed, to test their pre-
dictions against high-precision CHEOPS measurements, and to compare the performances of CHEOPS for probing the photo-
metric signature of stellar granulation to Kepler and TESS data. Second, we aim to study the link between the spectroscopic and photometric signatures of convection for main-sequence stars with high-precision ESPRESSO observations, taken contempo-

raneously with CHEOPS. Third, we aim to test the predictions from 3D hydrodynamical models of convection.

For these purposes, we present the analyses of high-precision CHEOPS and ESPRESSO measurements of two bright stars with different effective temperatures.

The paper is organized as follows. We describe the data reduction methodologies in Sect. 2. We refine the stellar param-

eters of these two targets in Sect. 3. We analyze the stellar granulation signals for each CHEOPS, TESS and ESPRESSO observations in Sect. 4. We study the links between granula-

tion and stellar properties in Sect. 5. We compare our results with the predictions from 3D hydrodynamical convection mod-

els in Sect. 6. We constrain the link between spectroscopic and photometric signatures in Sect. 7. We investigate the relation-

ship between the shape of the cross-correlation functions, flux (as measured by CHEOPS), and RV in Sect. 8. We conclude in Sect. 9.

2. Observations and data reduction

We selected HD 67458 \((T_{\text{eff}} = 5833 \, \text{K})\) and HD 88595 \((T_{\text{eff}} = 6205 \, \text{K})\) as good targets based on their stellar parameters, their low apparent magnitudes, their moderate level of magnetic activity, the a priori absence of identified planets, and the excel-

lent CHEOPS and ESPRESSO visibility windows during the time that was allocated to our program. Our dataset includes 35 CHEOPS orbits, six dedicated nights at ESPRESSO/VLT, and five TESS sectors of observation. We note that this is the first time that high-precision spectroscopic data with ESPRESSO have been taken during several full nights for single stars.

2.1. CHEOPS

CHEOPS (Benz et al. 2021) observed the two bright stars in the visible wavelength range \((330–1100 \, \text{nm})\). HD 67458 was observed during three visits of \(T \sim 8.15 \, \text{h}\) each, with a time sampling of \(\Delta t = 34.3 \, \text{s}\). Each of these measurements resulted from 7 individual images taken with an exposure time of \(t_{\text{exp}} = 4.9 \, \text{s}\) and stacked on-board by coadding them pixel-by-pixel. HD 88595 was observed during four visits of \(T \sim 8.15 \, \text{h}\) each, with a time sampling of \(\Delta t = 37 \, \text{s}\). Each of these measurements

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resulted from 10 stacked images taken with an exposure time of \( \tau_{\text{exp}} = 3.7 \) s.

The duty cycle of each visit was close to 90%, with some gaps present within the light curves. The origin of these gaps is due to Earth occultations and the South Atlantic Anomaly (SAA) crossing of the satellite. Each series has one or two large gaps <17.5 min and five to ten short gaps <2 min. In total, the three visits of HD 67458 contain \( N = [789, 807, 834] \) measurements, while the four visits of HD 88595 contain \( N = [718, 698, 728, 738] \) measurements.

All CHEOPS observations were processed with the Data Reduction Pipeline (DRP, version 13.1.0), which is described in Hoy et al. (2020). We used the light curves provided by the DRP. We test different apertures to minimize the contribution from the background contaminants, and finally choose the default aperture of 25 pixels radius.

We detrended each CHEOPS visit from the satellite systematics using the Pycheops software\(^1\) (version 1.0.6, Maxted et al. 2022). We first corrected for contaminating flux from background sources, with the contamination estimation in Pycheops based on the Gaia DR2 catalog. We then performed a 5\( \sigma \) clipping to each visit, before detrending from the \( x \) and \( y \) centroid variations, roll angle, background, and smear systematics. The main characteristics of these observations are listed in Table 1, and the detrended light curves are shown in the top rows of Fig. 1.

### 2.2. ESPRESSO

ESPRESSO (Pepe et al. 2013) observed the two targets in high-resolution spectroscopy (\( R \sim 140,000 \)) in the wavelength range \( \lambda \in [380, 780] \) nm, during six full nights\(^3\). Each measurement resulted from an exposure time of \( \tau_{\text{exp}} = 60 \) s. The ESPRESSO observations have been taken simultaneously or contemporaneously with the CHEOPS observations (see Fig. 2). They are the first ESPRESSO observations taken during full nights for such a program.

Among these six nights of observations at the VLT, one\(^2\) encountered significant technical problems (PLC-ADC communication issues). We remove this RV time series from the study. For both stars, we found \( \log R'_{\text{HK}} \sim -4.9 \), which is consistent with relatively inactive stars (Holl 2008). Moreover, as no significant variation of this activity indicator is observed during the nights, the stellar magnetic activity is probably not at the origin of the variability observed in the data of HD 67458.

### 2.3. TESS

TESS (Ricker et al. 2015) observed the two stars in the red-optical bandpass (600–1100 nm). HD 67458 was observed in sectors [7, 8, 34], and HD 88595 in sectors [9, 35].

In this work we made use of the short-cadence light curves released by the TESS team. However, we do not use

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\(^1\) https://github.com/pmaxted/pycheops

\(^2\) Program IDs: 106.2186.001 to 106.2186.006.

\(^3\) Program ID: 106.2186.005 (UTC time: 2021/02/15).

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Table 1. CHEOPS observations.

| Target   | Visit ref. number | File key                          | Starting date [UTC] | \( T \) | \( \tau \) | \( N \) | DC [%] | \( \sigma_{\text{TOT}} \) [ppm] |
|----------|-------------------|-----------------------------------|----------------------|------|--------|------|-------|------------------|
| HD 67458 | Visit 1           | CH_PR100022_TG001101_V0200        | 2021-01-17           | 8.15 | 34.3   | 789  | 92.5  | 114             |
|          | Visit 2           | CH_PR100022_TG001301_V0200        | 2021-01-18           | 8.61 | 34.3   | 834  | 92.5  | 110             |
|          | Visit 3           | CH_PR100022_TG001201_V0200        | 2021-01-21           | 8.15 | 34.3   | 807  | 94.6  | 125             |
| HD 88595 | Visit 1           | CH_PR100022_TG001601_V0200        | 2021-02-13           | 8.06 | 37     | 728  | 93.5  | 100             |
|          | Visit 2           | CH_PR100022_TG001501_V0200        | 2021-02-14           | 8.15 | 37     | 698  | 88.6  | 104             |
|          | Visit 3           | CH_PR100022_TG001401_V0200        | 2021-02-15           | 8.14 | 37     | 718  | 91.2  | 108             |
|          | Visit 4           | CH_PR100022_TG001701_V0200        | 2021-02-22           | 8.14 | 37     | 738  | 93.8  | 103             |

Notes. Columns are: file keys referring to the files name in the CHEOPS database, dates (UTC), total observation duration (\( T \)), integration time (\( \tau \)), number of observations (\( N \)), duty cycle (DC), and standard deviation of the light curve (\( \sigma_{\text{TOT}} \)).

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\footnote{https://github.com/pmaxted/pycheops}

\footnote{Program IDs: 106.2186.001 to 106.2186.006.}

\footnote{Program ID: 106.2186.005 (UTC time: 2021/02/15).
Fig. 1. Detrended CHEOPS light curves (top row), ESPRESSO radial velocity time series (middle row), and TESS light curves (bottom row) for HD 67458 (left panels) and HD 88595 (right panels). In each panel, the colors indicate a different set of observations (CHEOPS visits, ESPRESSO nights, TESS sectors). Observations are y-shifted for visibility, and the dates of each time series are normalized to start at 0 (with a display that goes from the earliest date on the top, to the latest one on the bottom).

the Presearch Data Conditioning Simple Aperture Photometry (PDCSAP) flux because sometimes they are affected by some systematic errors due to over-corrections and/or injection of spurious signals. The light curves we used were obtained applying Cotrending Basis Vectors (CBVs) to the Simple Aperture Photometry (SAP) flux as done in Nardiello et al. (2021). The CBV were obtained by using the SAP light curves of the stars in the same Camera/CCD in which the targets are located and following the procedure described in detail in Nardiello et al. (2019, 2020). For the analysis of the light curves, we rejected the points with DQUALITY>0, as recommended by the TESS Science Data Products Description Document\(^5\). Additionally, we clipped out the points corresponding to a sky background value >3040 e\(^-\)/s in sector 35 (since this sector was affected by known technical issues such as thermal stability and telescope pointing). We finally clipped out the 3\(\sigma\) outliers of each sectors for both targets. The main characteristics of these observations are listed in

\(^5\) https://archive.stsci.edu/files/live/sites/mast/files/home/missions-and-data/active-missions/tess/_documents/EXP-TESS-ARC-ICD-TM-0014-Rev-F.pdf
and kept the subseries for which the duty cycle was >90\%. We obtained \( L = 172 \) subseries for HD 67458, and \( L = 113 \) for HD 88595.

For comparison with the CHEOPS observations in the following, we extracted subseries of 8-h duration from each TESS sector. Then, we removed the subseries affected by large gaps and kept the subseries for which the duty cycle was >90\%. We obtained \( L = 172 \) subseries for HD 67458, and \( L = 113 \) for HD 88595.

### 2.4. The Sun as a reference star

As a reference star, we refer throughout the paper to the Sun that has been observed continuously from space with the Solar and Heliospheric Observatory (SoHO) since 1996. On board SoHO, the VIRGO instrument measures the solar spectral irradiance with the three channels sun photometer (SPM) at wavelength of 402 (blue), 500 (green) and 862 (red) nm (Fröhlich et al. 1995, 1997; Jiménez et al. 2002). In parallel, the GOLF spectrophotometer observes the solar disk-integrated position of the Sodium doublet lines at \( \lambda = 5895.9 \) and 5889.9 Å, from which it extracts the projected radial velocities (Boumier & Dame 1993; Gabriel et al. 1995; Garcia et al. 2005; Appourchaux et al. 2018). Together, VIRGO and GOLF observations form a unique set of high-precision solar observations with an excellent duty cycle of almost 96\% over the past 26 yr. In the following, we use both datasets sampled at one point per minute, taken out of the initial higher cadence sequences.

For GOLF observations, we used the level-2 GOLF data\(^6\) calibrated as described in Appourchaux et al. (2018). To be conservative, we only selected the year 1996 from this dataset since, after that, the detector was affected by an instrumental failure. This year corresponds to a solar cycle minima, leading then to a negligible impact of the magnetic regions (which is out-of-scope of the present study). We divided this time series into subseries of 8-h duration to compare them with our ESPRESSO set of observations. From the total number of available 8-h subseries, we selected 75 subseries with a condition of regular sampling (i.e., we only took the subseries that avoid gaps).

For VIRGO observations, we also selected the observations taken in 1996 to be consistent with the selected GOLF data. We corrected them from the instrumental degradation over time (Appourchaux et al. 2005).

### Table 2. ESPRESSO observations.

| Target   | Night ref. number | Starting date [UTC] | \( T \) [h] | Min/Max airmass | \( N \) | \( \sigma_{\text{RV}} \) [m s\(^{-1}\)] | DC [%] | \( \sigma_{\text{TOT}} \) [m s\(^{-1}\)] | \( \log R'_{\text{HK}} \) |
|----------|-------------------|---------------------|------------|----------------|------|-----------------|-------|-----------------|----------------|
| HD 67458 | Night 1           | 2021-01-17          | 4.85       | 1.20           | 155  | [0.4, 1.1]      | 91.8  | 2.6             | -4.97          |
|          | Night 2           | 2021-01-18          | 8.48       | 1.8            | 273  | [0.5, 2.7]      | 87.5  | 2.0             | -5.20          |
|          | Night 3           | 2021-01-21          | 4.75       | 1.7            | 126  | [0.4, 0.9]      | 72.0  | 1.1             | -4.96          |
| HD 88595 | Night 1           | 2021-02-14          | 8.8        | 2.3            | 308  | [0.7, 2.3]      | 95.0  | 2.54            | -4.96          |
|          | Night 2           | 2021-02-22          | 9.0        | 1.9            | 313  | [0.7, 3.7]      | 94.0  | 2.26            | -4.97          |

**Notes.** Columns are: date of observation (UTC), total observation duration (\( T \)), Min and Max values of airmass during the data acquisition, number of observations (\( N \)), Min and Max RV errorbars (\( \sigma_{\text{RV}} \)), duty cycle (DC), standard deviation of the detrended RV time series (\( \sigma_{\text{TOT}} \)), and median value of the \( \log R'_{\text{HK}} \) activity indicator.

### Table 3. TESS observations.

| Target    | Sector number | Starting date [UTC] | \( T \) [days] | \( \tau \) [s] | \( N \) | DC [%] | \( \sigma_{\text{TOT}} \) [ppm] |
|-----------|---------------|---------------------|----------------|---------------|------|-------|-------------------------------|
| HD 67458  | 7             | 2019-01-08          | 24.4           | 120           | 16 283 | 92.5 | 134                           |
|           | 8             | 2019-02-02          | 24.6           | 120           | 13 369 | 75.5 | 275                           |
|           | 34            | 2021-01-14          | 25.0           | 120           | 16 802 | 93.2 | 92                            |
| HD 88595  | 9             | 2019-02-28          | 24.0           | 120           | 15 164 | 87.6 | 175                           |
|           | 35            | 2021-02-09          | 23.8           | 120           | 12 866 | 74.9 | 269                           |

**Notes.** Columns are: date of observation (UTC), total observation duration (\( T \)), integration time (\( \tau \)), number of observations (\( N \)), duty cycle (DC), and standard deviation of the light curve (\( \sigma_{\text{TOT}} \)).

![Fig. 2. Contemporaneous observations of HD 67458 (two first rows) and HD 88595 (two last rows) taken with CHEOPS and ESPRESSO (same color code as in Fig. 1: black, gray, red and blue dots). For each star, there are two simultaneous sets of CHEOPS/ESPRESSO observations shown with the dashed and dotted vertical lines.](www.ias.u-psud.fr/golf/templates/access.html)
following the recipe described in Sect. 2 of Sulis et al. (2020a). We then divided them into 8-h subseries to mimic the duration of CHEOPS observations, and we picked 265 of these subseries with a condition of regular sampling. Throughout the paper, we use these VIRGO and GOLF subseries as references for comparing the properties of solar granulation with our two main-sequence targets.

In addition, we also compare our set of observations in Sect. 4.1 with ground-based solar observations taken by the HARPS-N spectrograph, for which the first three years of observations (2015–2018) have been made recently available (Collier Cameron et al. 2019; Demusque et al. 2021). We extracted 298 daily subseries from this released dataset. The HARPS-N subseries have a median duration $T \sim 6.75$ h and a sampling rate $\Delta t \sim 5.4$ min. In Appendix C, we compare these different sets of solar observations.

### 3. Derivation of stellar parameters

First concerning the stellar atmospheric parameters, we coadded the individual exposures taken with ESPRESSO (see Sect. 2.2) after correcting for each individual radial velocity shift. This was done for each target in order to create a combined spectra with higher signal-to-noise ratio. We used each ESPRESSO master spectrum to derive the stellar spectroscopic parameters ($T_{\text{eff}}$, $\log g$, micro-turbulence, [Fe/H]) and the respective uncertainties following the ARES+MOOG methodology as described in Sousa et al. (2021); Sousa (2014); Santos et al. (2013). The ARES code (Sousa et al. 2007, 2015) was used to measure in a consistent way the equivalent widths of iron lines included in the line list presented in Sousa et al. (2008). Briefly, ARES+MOOG performs a minimization process looking for the ionization and excitation equilibrium to find convergence on the best set of spectroscopic parameters. For the computation of the iron abundances we make use of a grid of Kurucz model atmospheres (Kurucz 1993) and the radiative transfer code MOOG (v2019; Sneden 1973). In addition we have also used the IDL package Spectroscopy Made Easy (SME) to do the spectral analysis for these stars (Valenti & Piskunov 1996; Piskunov & Valenti 2017). This code utilizes an input of stellar parameters to perform radiative transit calculations in order to synthesize models, that through an iterative minimizing procedure with the observed spectrum as a template, arrive at a set of final stellar parameters. In this process one varies one parameter while keeping the other fixed and works with several different atmospheric models and atomic and molecular line lists from (VALD; Piskunov et al. 1995). In this case we utilized again a grid of Kurucz model atmospheres (Kurucz 1993).

For HD 67458 both spectral analyses provided completely consistent parameters and we selected the values given by ARES+MOOG. For HD88595 we rely on the parameters derived by SME, mostly because of the higher $v \sin i$ for this star which degrades a bit the precise measurements of the equivalent widths in the ARES+MOOG method. The adopted spectroscopic parameters are listed in Table 4.

We determined the stellar radii of HD 67458 and HD 88595 using a modified IRFM method in a Markov-chain Monte Carlo (MCMC) approach (IRFM; Blackwell & Shallis 1977; Schanche et al. 2020). This was done by computing the bolometric fluxes for the targets by fitting stellar atmospheric models to broadband photometry that are converted to effective temperatures and angular diameters using the physical relationships between these parameters. Utilizing the target’s parallaxes, we subsequently determined the radii from the angular diameters. For HD 67458 and HD 88595, we use Gaia, 2MASS, and WISE broadband photometry (Skrutskie et al. 2006; Wright et al. 2010; Gaia Collaboration 2021) with the ATLAS catalog of stellar atmospheric models (Castelli & Kurucz 2003), and the offset-corrected Gaia EDR3 parallax (Lindegren et al. 2021) and find $R_\ast = 1.021 \pm 0.020 R_\odot$ and $R_\ast = 1.616 \pm 0.017 R_\odot$, respectively. These radii are reported in Table 4.

Adopting $T_{\text{eff}}$, [Fe/H], and $R_\ast$ as basic input set, we then derived the isochronal mass $M_\ast$ and age $t_\ast$ of each star from two different stellar evolutionary models. In detail, we used the isochrone placement algorithm (Bonfanti et al. 2015, 2016), which interpolates the input parameters within precomputed grids of PARSEC (Marigo et al. 2017) isochrones and tracks, to retrieve a first pair of mass and age values. To improve the convergence, we also accounted for the stellar $v \sin i$, coupling the isochronal interpolation scheme with gyrochronology as outlined in Bonfanti et al. (2016). The second pair of mass and age values, instead, was computed through CLES (Code Liégeois d’Évolution Stellaire; Scuflaire et al. 2008), which builds the best-fit stellar track according to the input parameters following the Levenberg-Marquardt minimization scheme as explained in Salmon et al. (2021). Finally, for each star and for each output parameter, we merged the two respective distributions derived from PARSEC and CLES, after checking their mutual consistency through a $\chi^2$-based criterion (see Bonfanti et al. 2021 for further details). We obtained $M_\ast = 0.935^{+0.042}_{-0.021} M_\odot$ (resp. $M_\ast = 1.351^{+0.031}_{-0.025} M_\odot$) and $t_\ast = 7.7 \pm 2.1$ Gyr (resp. $t_\ast = 2.8 \pm 0.4$ Gyr) for HD 67458 (resp. HD 88595). The computed stellar parameters are listed in Table 4.

The uncertainties associated with each of the stellar parameters are those obtained by the above procedure, which is the one applied to all CHEOPS exoplanet host targets (see again Bonfanti et al. 2021, for full details). This procedure is performed here on two bright main-sequence stars with high quality spectra, detailed abundances, and numerous and accurate broadband photometric measurements. Concerning the stellar surface gravity, we want to recall that its spectroscopic determination is prone to several problems that directly affect the accuracy of the derived value. Problems such as the assumption of plane parallel stellar atmosphere models, or the use of the ionization balance derived value. Problems such as the assumption of plane parallel stellar atmosphere models, or the use of the ionization balance where few optimal lines of ionized iron is present, can affect strongly the accuracy of the spectroscopic analysis for the $\log g$. Fortunately these do not strongly affect the determination of other atmospheric parameters. For example, it was demonstrated that when using equivalent-width methods the other atmospheric parameters are mostly independent from the surface gravity (e.g., Torres et al. 2012). In our procedure to derive the stellar radius, mass, and age, the spectroscopic surface gravity is only marginally used as a prior for the radius determination (where it is allowed to vary within the MCMC), but is not used anymore in deriving mass and age. Given these considerations, for HD 88595 the spectroscopic log $g$ is reasonably consistent with the one computed from the derived mass and radius values (see Table 4), which in turn very well agree with the asteroseismic

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7 https://dace.unige.ch/sun/
8 https://github.com/sousasag/ARES
9 Padova & Trieste Stellar Evolutionary Code: http://stev.oapd.inaf.it/cgi-bin/cmd
from Table 4, this gives a stellar inclination of $i \times \text{timescales}$ (Sect. 4.1). We then analyze how they behave over short timescales (from some minutes to several hours), and how their amplitudes evolve over different ESPRESSO datasets.

Stellar granulation generates stochastic fluctuations in both photometric and spectroscopic observations. These fluctuations are correlated over timescales from some minutes to several hours, and their amplitudes evolve on short timescales for both stars, typically over $\nu_{\text{max}}$ [MHz]. This work

$v_{\text{max}}$ measured for this star (see Sect. 4.3). Concerning the solar-like star HD 67458, the spectroscopic log $g$ and the one derived from mass and radius are in perfect agreement (see Table 4).

Finally, analyzing the TESS observations based on the generalized Lomb-Scargle periodograms (Zechmeister & Kürster 2009), we were able to constrain the rotation period of the F star ($P_{\text{rot}} \approx 3.1151 \pm 0.0003$ days) and the G star ($P_{\text{rot}} \approx 10.57 \pm 0.06$ days). We report these rotation periods in Table 4 and the details in Appendix A. Using the known $v \sin i$ and $R_\star$ from Table 4, this gives a stellar inclination of $i \approx 16^\circ$ for the F star, and $i \approx 26^\circ$ for the G star. Both stars are then seen nearly pole-on.

4. Granulation signals in high-precision photometric and spectroscopic observations

Stellar granulation generates stochastic fluctuations in both photometric and spectroscopic observations. These fluctuations are correlated over timescales from some minutes to several hours, depending on the stellar parameters. The objective of this section is to identify the contribution of the stellar granulation among the various sources of noise present in the CHEOPS, TESS and ESPRESSO datasets.

We first look at the behavior of these fluctuations in the time domain, and how their amplitudes evolve over different timescales (Sect. 4.1). We then analyze how they behave when using the common observational strategies to mitigate them (i.e., long exposure time for RV data acquisition or light curve binning over short timescales), and we discuss these behaviors in the context of small exoplanets detection (Sect. 4.2). We conclude this section by analyzing the observations in the frequency domain (periodograms), and in particular we show how the instrumental noise (dominated by photon noise) impacts the characterization of the stellar granulation signal (Sect. 4.3). The main conclusions are summarized in a table at the end of this section.

4.1. Amplitude of the granulation signal

We assume that each time series results from the contribution of three phenomena: instrumental noise, stellar oscillations, and stellar granulation. We neglect stellar magnetic activity because (i) the chromospheric activity indicator log $R'_{\text{HK}}$ indicates that the two stars are relatively inactive (log $R'_{\text{HK}} \approx -4.9$), (ii) no correlation between log $R'_{\text{HK}}$ and RV is observed, and (iii) our observations are very close in time so any signature of magnetic activity (spot or plages) should act as a trend over the nightly datasets. The instrumental noises are dominated here by the photon noise and affect differently the CHEOPS, TESS and ESPRESSO observations. The stellar oscillations (or p-modes) evolve on short timescales for both stars, typically over 10 min or less. The stellar granulation, which we seek to identify here, evolves on longer timescales. We expect the amplitudes of the

Table 4. Properties of the stars HD 67458 and HD 88595.

| Parameters                  | Values                          | Source                        |
|-----------------------------|---------------------------------|-------------------------------|
| Target names                | HD 67458 HIP 39710 TIC 154234114| Simbad\(^{(a)}\)               |
|                            | HD 88595 HIP 50013 TIC 5506063  | Gaia archive\(^{(b)}\)       |
| Spectral type               | G0V                             | This work (spectroscopy)      |
| Right Ascension (ep=J2000)  | 08 07 00.522                    | This work (spectroscopy)      |
| Declination (ep=J2000)      | −29 24 10.57                     | This work (spectroscopy)      |
| Gaia G-band magnitude       | 6.64                            | This work (spectroscopy)      |
| Distance [pc]               | 25.68                           | This work (IRFM)              |
| Effective Temperature (K)   | 5833 ± 62                       | This work (spectroscopy)      |
| Metallicity [Fe/H]          | −0.18 ± 0.04                    | This work (spectroscopy)      |
| [Mg/H]                     | −0.14 ± 0.06                    | This work (spectroscopy)      |
| [Si/H]                     | −0.21 ± 0.04                    | This work (spectroscopy)      |
| [Ti/H]                     | −0.17 ± 0.06                    | This work (spectroscopy)      |
| log $g$ [cgs]               | 4.37 ± 0.10                     | This work (spectroscopy)      |
| Radius ($R_\star$)         | 1.021 ± 0.020                    | This work (IRFM)              |
| Mass ($M_\star$)           | 0.935$^{+0.042}_{-0.043}$       | This work (isochrones)       |
| Age [Gyr]                  | 7.7 ± 2.1                       | This work (isochrones)       |
| $v_{\text{max}}$ [MHz]     | 2756 ± 169                      | Eq. (2), This work (ESPRESSO) |
| Mean log $R'_{\text{HK}}$  | −4.99 ± 0.14                    | This work (spectroscopy)      |
| Rotation period [days]      | 10.57 ± 0.06                    | This work (TESS photometry)   |
| $v \sin i$ [km s\(^{-1}\)] | 2.179 ± 0.2                     | HARPS\(^{(d)}\), This work   |
| Stellar inclination [degrees]| ~26                            | This work                     |

Notes. \(^{(a)}\)SIMBAD astronomical database from the Centre de Données astronomiques de Strasbourg (http://simbad.u-strasbg.fr/simbad/). \(^{(b)}\)Archive of the Gaia mission of the European Space Agency (https://gea.esac.esa.int/archive/). \(^{(c)}\)Values are in agreement with the Gaia Early Data Release 3 (catalog http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=I/352 from Bailer-Jones et al. 2021). \(^{(d)}\)HARPS data initially published in Soto & Jenkins (2018) and reanalyzed in this work.
stochastic fluctuations generated by the stellar granulation to follow a Gaussian distribution (see Sect. 2.3 of Sulis et al. 2020a), and to decrease with increasing stellar surface gravity (Bastien et al. 2013). We therefore expect the overall amplitude of the granulation signal to be comparable to the solar values extracted from the visible wavelengths for HD 67458, and to be larger for HD 88595. Since the granulation signal amplitude decreases at redder wavelengths (Planck’s law), we expect the amplitude of the granulation signal to be smaller in the TESS passband than in the CHEOPS one.

We start by extracting the contribution of photon noise, which dominates the high-frequency part of our time series. To this end, we filter each time series with a high-passband filter with cut-off frequencies \( \nu_{\text{cut}} \). We visually determine these cut-off frequencies \( \nu_{\text{cut}} \) for each dataset by examining the flat regions of the different periodograms (see details in Sect. 4.3). We then measure the standard deviation of each filtered time series (\( \sigma_{w} \)) that corresponds to one visit (CHEOPS), one night (ESPRRESSO), or one sector (TESS). For TESS, we report the median value of the standard deviations calculated on each 8-h subseries contained in a given sector. For HD 67458, we obtain: \( \sigma_w = [79, 81, 93] \) ppm (CHEOPS), \( \sigma_w = [97, 93, 85] \) ppm (TESS), and \( \sigma_w = [2.1, 1.6, 0.95] \) m/s (ESPRRESSO). For HD 88595, we obtain: \( \sigma_w = [77, 75, 77, 78] \) ppm (CHEOPS), \( \sigma_w = [181, 177] \) ppm (TESS), and \( \sigma_w = [1.37, 1.49] \) m/s\(^{-1} \) (ESPRRESSO).

For CHEOPS observations, the observed white Gaussian noise (WGN) amplitudes are in remarkably good agreement with the predictions from the CHEOPS Exposure Time Calculator\(^{10} \). Indeed, including contributions of instrumental (readout, smearing, quantization and dark current), background (sky and straylight) and photon noise (which is by far the dominating factor), the ETC predicts white noise levels at the cadence of the downloaded images of 85 ppm and 71 ppm for HD 67458 and HD 88595, respectively. We observe larger white noise levels for TESS observations (especially for HD 88595) than for CHEOPS. This is also in agreement with expectations based on the characteristics of the two satellites (equivalent collective area, photometric performances at a given stellar magnitude, see e.g., Futyan et al. 2020). For ESPRESSO observations, the observed white noise amplitudes do vary significantly between the different nights of HD 67458. This would mean than the global dispersion \( \sigma_{\text{TOT}} \) (given in Table 2) is driven by short term instrumental noise. In order to identify whether these variations were of instrumental origin, we looked at many indicators such as atmospheric conditions, signal-to-noise ratio, instrumental drifts, or pipeline quality controls. Unfortunately, we could not clearly identify a source for this high-frequency variability. However, this excess white noise with no apparent structure will not affect the conclusions presented in the rest of this study.

We continue with the extraction of the granulation signal. To this end, we use a slight modification of the 8-h flicker (or F8) metric, defined in Bastien et al. (2013). We start by binning each time series into 5-min intervals (and not 30-min as originally defined in Bastien et al. 2013), since we would miss the typical timescales of stellar granulation. We then use a 8-h length boxcar filter\(^{11} \) to remove the long term stellar activity (we note the small impact of this additional step since the length of our subseries are short). Results are shown and compared to the Sun in photometry (right) and spectroscopy (left) in Fig. 3.

The solar photometric values are extracted from the narrow passbands of the VIRGO red, green and blue SPM channels. To compare CHEOPS and VIRGO observations, as done in Basri et al. (2010) and Salabert et al. (2016) for Kepler, we therefore need to consider a combination of the red (862 nm) and green (500 nm) channels. The CHEOPS values for HD 67458 are then expected to fall in the interval defined by the red and green histograms of Fig. 3. The TESS passband being redder, the TESS values for HD 67458 are expected to fall closer to the red histogram. This is however not what we observe, with F8 values of [67, 55, 58] ppm for the three CHEOPS visits, and F8e [50, 106] ppm for the whole set of 8-h subseries from TESS observations. We explain these discrepancies by two reasons. First, the level of white noise is significantly larger in both CHEOPS and TESS observations than in solar observations. Then, the discrepancy with solar observations is larger for TESS observations since the granulation amplitude decrease

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10 https://cheops.unige.ch/pht2/exposure-time-calculator

11 We use the function convolution.Box1DKernel available from the Python package www.astropy.org
4.2. Mitigation of the granulation signal

To reduce the contribution of the stellar oscillations and granulation for the detection and characterization of exoplanets, the common strategy is to average the observations. In radial velocity, this results in the use of a longer exposure time than the stellar $p$-modes timescales (see Chaplin et al. 2019 for a recent optimization of this exposure time), followed by a binning of data points taken over the course of a night to reduce stellar granulation signals (Hatzes et al. 2011; Dumusque et al. 2011). In photometry, this results in binning the data points over some minutes, depending on the characteristics of the studied planetary transit. Below, we first study how the high precision ESPRESSO observations behave when using this mitigation strategy, then we turn to the CHEOPS photometric observations. In both cases, we compare with the expected signal amplitude of an Earth-like planet that would orbit in the habitable zone (HZ) of the two stars.

In Fig. 5, we show the decreases of the RV amplitudes as a function of the binning timescale $\tau$. We compare them with the decrease expected for WGNs of the same variance, that we take as a reference to determine if the RV RMS at a given $\tau$ is dominated by white noise or by stellar signals. The decrease of WGNs behaves as $\sigma_{\text{TOT}} \sqrt{N_{\text{bin}}/N}$, with $N_{\text{bin}}$ the number of binned data points.

For the solar-like star HD 67458 (top panel), we observe a different behavior for the three nights: one is consistent with the behavior of a white noise, while the two others are not. At $\tau = 20$ min we get an RV RMS of $\sim 0.4$ m s$^{-1}$ for the last night (magenta line) and the WGNs, while we get an RV RMS of $0.7-0.8$ m s$^{-1}$ for the other nights (red and green lines). To determine if these two behaviors are consistent with solar observations, we compute the RV RMS as a function of $\tau$ for each of the 75 GOLF solar 8-h subseries and for each corresponding WGN. We see that solar RV RMS measurements show a large dispersion but do not match the decrease observed for a WGN. The RV RMS derived on HD 67458 dataset are statistically compatible with solar data at large $\tau$. Comparing with the RV semi-amplitude of an Earth-mass planet in the habitable-zone ($K \sim 9$ cm s$^{-1}$ for HD 67458, see Appendix B), this demonstrates that this strategy is not robust to mitigate enough the short-timescale stellar signal. This is in total agreement with Meunier et al. (2015), who found that we need to bin over $\tau > 8$ h to get down to the level of an Earth-like RV signature. For the F star HD 88595 (bottom panel), we observe for both nights a behavior inconsistent with a WGN. At $\tau = 20$ min, we read RV RMS values of $1.7$ and $1.1$ m s$^{-1}$ for the first and second nights, while we read an RMS of $0.7$ m s$^{-1}$ for the WGN. This demonstrates the failure of this observational strategy for a slightly evolved star as HD 88595, with an RV dispersion remaining above 50 cm/s even after a binning of $\tau = 150$ min. For comparison the RV semi-amplitude of an Earth-mass planet in the habitable-zone of this star would be $K \sim 5.6$ cm s$^{-1}$ (see Appendix B).

While it is clear that the RV RMS at large $\tau$ is not driven by WGN, it remains to estimate the contribution of the stellar oscillation modes. Following Chaplin et al. (2019), we estimate the exposure time needed to mitigate the contribution of these modes down to the 10 cm s$^{-1}$ level for our two stars. We find $\tau_{\text{osc}} \sim 12$ min and $\sim 85$ min for HD 67458 and HD 88595, respectively (see dotted vertical lines in Fig. 5). Since Chaplin et al. (2019)'s methodology does not include the contribution of the stellar granulation signal (stochastic correlated

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12 We note that the reported RV RMS are also consistent with the predictions based on solar-like RV simulations from Meunier et al. (2015), with values around 30 to 40 cm s$^{-1}$ for a solar-like star at $\tau = 1$ h.

13 https://github.com/grd349/ChaplinFilter
In Fig. 7, we show the Lomb-Scargle periodograms (Scargle 1982) of each CHEOPS, ESPRESSO and TESS datasets. To fit these periodograms, classical models are Harvey-functions (Harvey 1988). These functions are defined as the sum of Lorentzian functions parameterized by different timescales and amplitudes to distinguish the stellar activity components that dominate different frequency regions in the periodogram (generally attributed from high to low frequencies to: instrumental noise, stellar oscillation modes, granulation, supergranulation, and active regions). Some debates about the exact shape of these Lorentzian functions and the number of free parameters to use exist (see e.g., Mathur et al. 2011; Kallinger et al. 2014). In this

Fig. 5. Effect of temporal binning on the RV RMS of HD 67458 (top) and HD 88595 (bottom). Each color (red, green and magenta) represents one night of ESPRESSO observations. The behavior of WGNs having the same variance as the considered dataset is shown by the colored dotted lines. RMS values obtained on the 75 solar GOLF subseries are shown in yellow in the top panel, and the corresponding WGNs in blue (median values are shown by the yellow and blue solid lines). The RV semi-amplitude of an Earth-like planet orbiting in the HZ of each star are shown by the dashed horizontal lines. The exposure times needed to mitigate the $p$-modes oscillations down to the $\sim 10$ cm s$^{-1}$ level are shown by the dotted vertical lines.

This stellar signal may bias the inferred parameters of long-period transiting exoplanets (from which few transits may be observable, see e.g., Sulis et al. 2020a). Indeed, their amplitudes are comparable to the transit depth of Earth-size planets, which are 80.6 ppm for HD 67458 and 32.2 ppm HD 88595 (see Appendix B). Moreover, these signals’ amplitudes remain significant (brightness RMS $\in [32–76]$ ppm) even after a binning of $\tau \sim 7.5–8.4$ min, which are the typical durations of the transit ingresses of Earth-size planets in the HZ (see Appendix B). Accessing how this stellar signal is correlated is therefore important to infer accurate and precise exoplanet parameters.

4.3. Periodograms of the granulation signal

The power spectral density of stellar granulation is well-known to act as a red-like noise, that is a power increase in a given frequency range. For main-sequence stars, this frequency range correspond to $\nu > 10$ $\mu$Hz.

In Fig. 7, we show the Lomb-Scargle periodograms (Scargle 1982) of each CHEOPS, ESPRESSO and TESS datasets. To fit these periodograms, classical models are Harvey-functions (Harvey 1988). These functions are defined as the sum of Lorentzian functions parameterized by different timescales and amplitudes to distinguish the stellar activity components that dominate different frequency regions in the periodogram (generally attributed from high to low frequencies to: instrumental noise, stellar oscillation modes, granulation, supergranulation, and active regions). Some debates about the exact shape of these Lorentzian functions and the number of free parameters to use exist (see e.g., Mathur et al. 2011; Kallinger et al. 2014). In this
work, we chose to model each periodogram shown in Fig. 7 with a Harvey-function of the form (Kallinger et al. 2014):

\[
P_H(\nu^i):= \eta^2(\nu^i) \left( \sum_{i=1}^{2} \frac{a_i}{1 + \left( \frac{\nu^i - \nu_{\text{max}}}{2\sigma_{\text{osc}}} \right)^2} \right) + \sigma_H^2(\nu),
\]

where the set of parameters \(a_i, b_i, c_i\) collects the amplitude, characteristic frequency and power of the Harvey functions for the stellar granulation signal \((i = 1)\) and the low frequency region \((i = 2)\). Parameters \(P_{\text{osc}}, \nu_{\text{max}}, \sigma_{\text{osc}}\) refer to the oscillation \(p\)-modes signals, which are only clearly detected in the ESPRESSO observations of HD 88595 (see the middle right panel of Fig. 7). Parameter \(\sigma_H^2\) refers to the variance of the high-frequency noise component, assumed to be a WGN in model.
Table 5. Best-fitting parameters \(\{a_1, b_1, c_1\}\) associated to the stellar granulation component in the Harvey functions given in Eq. (1) and found for CHEOPS, ESPRESSO and TESS datasets of HD 67458 and HD 88595.

| Target | Instrument | \(a_1\) | \(b_1\) | \(c_1\) |
|--------|------------|--------|--------|--------|
| HD 67458 | CHEOPS  | 0.64 ± 0.01 | 2005 ± 44 | 3.04 ± 0.19 |
| HD 88595 | ESPRESSO  | 938 ± 15 | 110 ± 12 | 3.44 ± 0.02 |
| HD 88595 | TESS  | 0  | 0  | 0  |
| HD 88595 | ESPRESSO  | 1.44 ± 0.02 | 875 ± 18 | 2 ± 0.01 |
| HD 88595 | TESS  | 2000 ± 3 | 270.0 ± 0.3 | 2.0 ± 0.01 |
| Sun | VIRGO + WGN  | 0.86 ± 0.08 | 2065.9 ± 147 | 3.8 ± 0.66 |

Notes. The best-fitting parameters found for the solar VIRGO data without and with white noise added are shown in the two last rows. Symbol \(\emptyset\) highlights the nondetection cases (i.e., parameters \(\{a_1, b_1, c_1\}\) consistent with zero within their 1σ uncertainties). Parameter \(a_1\) is in units of ppm\(^2/\mu Hz\) or ppm/\(\mu Hz^2\), and parameter \(b_1\) in units of \(\mu Hz\).

Eq. (1). Notation \(v_1^*\) means that positive Fourier frequencies are considered, and \(\eta := \text{sinc}(\frac{v}{\nu_{Ny}})\) is an attenuation factor based on the Nyquist frequency (defined for a regular sampling with time step \(\Delta t\) as \(v_{Ny} = 1/2\Delta t\)). For each star and each periodogram, we infer the parameters of model Eq. (1) using first a nonlinear least-squares minimization\(^\text{14}\). Then, we use the EMCEE package (Foreman-Mackey et al. 2013) to calculate with MCMC the probability distribution for each parameters, from which we take the median values and the 1σ uncertainties. We note that uniform priors are used to fit all the parameters of the model except the power index \(c_1\) which we consider \(\leq\)10 to avoid being too sensitive to large local variations between two peaks of the periodogram. Estimated values that are relevant to the granulation signals \(\{a_1, b_1, c_1\}\) are reported in Table 5. The best-fitting models are shown in Fig. 7 (yellow lines). From these fits, we conclude that the signature of granulation is evident from both CHEOPS and ESPRESSO observations of HD 88595. For HD 67458, only the CHEOPS observations show a clear granulation signal. We note an increase of the periodogram at frequency \(v < 200 \mu Hz\) for both stars that could be the signature of supergranulation in the ESPRESSO data, but the length of our observations are too short to conclude on the nature of this signal. On the contrary, TESS is blind to the granulation signal due to the high level of WGN and the small amplitude of this signal in this passband (see Fig. 4).

We also find an oscillation frequency at maximum power \(v_{max} = 1534 \pm 85 \mu Hz\) from ESPRESSO observations of HD 88595, which is consistent with the prediction from the asteroseismic scaling relation (Kjeldsen & Bedding 1995):

\[
v_{max} \equiv v_{max,0} \left(\frac{M_\star}{M_\odot}\right) \left(\frac{R_\star}{R_\odot}\right)^2 \left(\frac{T_{eff}}{7500}\right)^{-1/2},
\]

where \(v_{max,0} = 1542.5 \pm 60 \mu Hz\), with \(T_{\star,0} = 5777 K\) and \(v_{max,0} = 3090 \mu Hz\) (Huber et al. 2011) and stellar parameters from Table 4.

In each panel of Fig. 7, we have indicated the cut-off frequencies \(v_{cut}\) that delineate the white noise and granulation regimes (green vertical lines). In the CHEOPS and ESPRESSO datasets, \(v_{cut}\) correspond to periods in the interval [244, 810] s.

In the TESS dataset, \(v_{cut}\) corresponds to periods around 100 min. We note that, in the dataset of ESPRESSO observations of HD 88595, the approximation of white noise is only partially true (the high frequency part of the periodogram is not perfectly flat). These levels of white noise impact the detection of the granulation signal, with the periodogram slope in the frequency region of stellar granulation that decreases with the increase of WGN. Without correction of this WGN, the inferred Harvey parameters from model Eq. (1) may show discrepancies around their expected values in the Hertzsprung-Russell (HR) diagram. To illustrate this effect, we compare the periodograms of CHEOPS observations of the solar-like star HD 67458 and of the solar VIRGO observations with WGN added (because intrinsically the WGN component is very low in solar data). For this comparison, we compute the averaged periodogram defined as in Sulis et al. (2017):

\[
P_L(v_{\nu}) := \frac{1}{L} \sum_{c=1}^{L} P^c(v_{\nu}),
\]

with \(P^c\) the periodogram computed on \(L = 3\) solar 8-h sub-series taken randomly in the VIRGO sample. For the case with WGN, we added to each \(L\) solar subseries a WGN with standard deviation \(\sigma_w\). The value of \(\sigma_w\) has been scaled until the high-frequency region of the VIRGO periodograms matches the one of CHEOPS observations. This corresponds to \(\sigma_w \approx 30\) ppm. The averaged periodograms of the solar data (with and without WGN added) as well as the best-fitting Harvey functions are shown in Fig. 8. The best-fitting parameters related to the solar granulation signal component in Eq. (1) are given in Table 5. We see the impact of WGN on the Harvey parameters and particularly the decrease of the power index value \(c_1\) parameter with the increase of \(\sigma_w\). When parameter \(c_1\) is fixed in Eq. (1) (for example \(c_1 = 2\) corresponds to a standard Harvey model), this can bias the comparison of the best-fitting Harvey parameters derived for stars with different apparent magnitude (i.e., different levels of white noise). Since Harvey functions are classical empirical functions used to model the stars’ power spectral density, when we compare the inferred Harvey parameters for stars of different apparent magnitude, one needs to be careful about the impact of this white noise on the fitted parameters. The interpolation of the inferred parameters to their value at a “reference level” of white noise is necessary to avoid any bias.

5. Relationship between granulation and stellar properties

5.1. Computing the flicker index

In this section, we make use of the flicker index (Sulis et al. 2020a). This index is a granulation indicator that has been defined as the slope of the averaged periodogram \(P_L\) in Eq. (3) in the frequency region where the granulation signal dominates. Related to the parameter \(c_1\) in Harvey functions (Eq. (1)), this index has been shown to be correlated to the stellar fundamental parameters once it is corrected from the influence of the high-frequency white noise component.

To compute the averaged periodograms of TESS observations, we consider all the available 8-h subseries that have a duty cycle \(\geq 90\%\). This corresponds to \(L = 172\) subseries for HD 67458, and \(L = 113\) for HD 88595. Since the duty cycle...
We then fit each averaged periodogram with a model defined as a sum of power laws functions of the form:

\[
\log P_L(\nu_i^*) = \sum_{i=1}^{3} -a_i \log(\nu_i^*) + \beta_i,
\]  

(4)

with \(a_i = \{a_H, a_g, a_L\}\) the periodogram slopes in three particular frequency regimes split by two cut-off frequencies \(f_{\text{cut}, H}\) and \(f_{\text{cut}, g}\), and \(\beta_i = \{\beta_H, \beta_g, \beta_L\}\) the corresponding amplitudes. Model (4) takes the form of straight lines in the log-log space. Parameters \(\{a_H, \beta_H\}\) represent the periodogram in the high frequency regime (dominated by the photon/instrumental noises, and also stellar oscillations for ESPRESSO observations of HD 88595), parameters \(\{a_g, \beta_g\}\) in the regime dominated by the granulation signal, and parameters \(\{a_L, \beta_L\}\) in the regime dominated by low-frequency stellar signal. We note that photometric and RV observations are expected to be sensitive to different noise sources in the low frequency region (e.g., the signal of supergranulation is large in RV observations but negligible in photometric observations, see Sect. 7.1).

Therefore, model (4) has eight free parameters (indices \(a\) and amplitudes \(\beta\) for each three PSD regimes, plus two cut-off frequencies \(f_{\text{cut}, H}\) and \(f_{\text{cut}, g}\) that mark these three regimes out). Using the MCMC scheme described in Sect. 4.2 of Sulis et al. (2020a), we fit model (4) to each averaged periodogram. An example MCMC posterior is shown in Fig. 9. The best fitting parameters for the flicker indexes (\(a_i\)), the flicker power amplitudes (\(\beta_i\)) and the two cut-off frequencies are listed in Table 7.

For reference, the flicker index inferred from the VIRGO averaged periodogram in the frequency range \(\nu \in [550, 2083] \mu\text{Hz}\) is \(a_H = 1.33 \pm 0.03\) (for the red SPM channel). We note that consistent indexes are found for all SPM channels, as shown in Sulis et al. (2020a). The flicker index inferred from GOLF averaged periodogram in the frequency range \(\nu \in [550, 1236] \mu\text{Hz}\) is \(a_H = 1.34 \pm 0.14\), consistent with VIRGO observations.
Note the difference in the cut-off frequency $f_H$ between the two instruments.

From Table 7, we read a flicker index for the solar-like star HD 67458 smaller than the one found on solar VIRGO data. As discussed in Sect. 4.2, this is due to the large level of white noise in CHEOPS data. For comparing different stellar observations, we need to correct the flicker index values for this effect. This will be done in Sect. 5.2. On the other hand, the flicker index deduced from the ESPRESSO periodogram of HD 67458 is consistent with zero, leading us to the conclusion that the granulation signal is this dataset is not clearly identified. On the contrary, indexes inferred from CHEOPS and ESPRESSO averaged periodograms of HD 88595 are both large (i.e., $\alpha_g > 0$), and are consistent within their 1$\sigma$ errors.

Finally, the flicker indexes inferred from TESS averaged periodograms of HD 67458 and HD 88595 are $\alpha_g < 0.1$, both consistent with a nondetection. Analyzing the two TESS sectors of HD 88595 allows, however, a marginal detection of the granulation signal with $\alpha_g = 0.26 \pm 0.36$ for sector 9 (non-detection), and $\alpha_g = 0.71 \pm 0.39$ for sector 35 (marginal detection). We investigate the influence of the high-frequency noise level, the duration of the subseries, and the temporal sampling on the inferred flicker index in Appendix E.

5.2. Comparison with Kepler bright stars

To compare the flicker indexes for stars of different apparent magnitudes (i.e., different white noise levels), we have to interpolate the behavior of the periodogram’s slope at a constant white noise level. Following Sulis et al. (2020a), we target the level $\sigma_w = 30$ ppm (hereafter $\sigma_{30}$), which was arbitrarily chosen as a good compromise for all studied stars (since all estimates of $\sigma_w$ are above 30 ppm). For each photometric dataset (VIRGO’s three SPM channels, CHEOPS observations), we then applied the following procedure.

(a) We added a synthetic white Gaussian noise of standard deviation $\sigma_{i}^{(0)}$ to each $L$ available light curves.
(b) We compute the averaged periodogram $P_{L}^{(0)}$ with Eq. (3) using these $L$ new light curves.
(c) We evaluate the flicker index $\tilde{\alpha}_{i}(\sigma_{i}^{(0)})$ by fitting model (4) to $P_{L}^{(0)}$.
(d) We performed steps (a) to (c) for $\sigma_{i}^{(0)} = 0$ (initial conditions) to $\sigma_{i}^{(0)} = 1000$ ppm.

Table 7. Best-fitting parameters of model (4) fitted to CHEOPS and ESPRESSO averaged periodograms of HD 67458 and HD 88595.

\begin{tabular}{|l|c|c|}
\hline
Target & Parameter & Photometry & Spectroscopy \\
\hline
HD 67458 & $\alpha_g$ & $0.57^{+0.12}_{-0.13}$ & $0.02^{+0.43}_{-0.28}$ \\
 & $\beta_g$ & $-4.88^{+0.74}_{-0.42}$ & $-12.60^{+8.82}_{-2.08}$ \\
 & $f_{ii}$ & $3636^{1645}_{-377}$ & $1680^{+711}_{-125}$ \\
 & $f_g$ & $480^{+26}_{-23}$ & $442^{+89}_{-132}$ \\
HD 88595 & $\alpha_g$ & $0.61^{+0.49}_{-0.25}$ & $0.77^{+38}_{-0.28}$ \\
 & $\beta_g$ & $-8.08^{+3.59}_{-1.80}$ & $-18.49^{+2.75}_{-2.15}$ \\
 & $f_{ii}$ & $1036^{+450}_{-29}$ & $1104^{+7}_{-3}$ \\
 & $f_g$ & $351^{+2}_{-37}$ & $209^{+111}_{-5}$ \\
\hline
Sun & $\alpha_g$ & $1.33 \pm 0.03$ & $1.34 \pm 0.14$ \\
\hline
\end{tabular}

Notes. Frequencies $f_{ii}$ and $f_g$ are expressed in $\mu$Hz. The last row indicates the flicker index based on solar VIRGO and GOLF averaged periodograms.

We note that we do not find coefficients $\{a_i, b_i, c_i\}$ consistent with the predictions from Eq. (6) of Sulis et al. (2020a). This may be due to the small number ($<5$) of targets with mass $<1 M_\odot$ and/or $>1.5 M_\odot$ that were used to derive the Eq. (6) of Sulis et al. (2020a). This may also be due to uncertainties on the stellar parameters of the Kepler sample or to the few number of CHEOPS visits that leads to an approximate interpolation of the curve $\tilde{\alpha}_{i}(\sigma_{i})$ involved in Eq. (5).
magnetic fields and therefore no plage or spot but they showed a remarkable agreement with bolometric light variations of Kepler targets (Rodríguez Díaz et al. 2022). Previous studies have also used these kind of models to study the granulation signal (see e.g., Ludwig 2006; Ludwig & Steffen 2013; Trampedach et al. 2013; Tremblay et al. 2013; Samadi et al. 2013), and compared their results with observations. However, those studies could not reproduce the observational trends with high accuracy or without introducing the Mach number, a quantity that is very difficult to compute for observational data.

Therefore, we generated long time series of box-in-a-star type 3D hydrodynamical simulations across the HR diagram using the STAGGER-code (Nordlund & Galsgaard 1995; Magic et al. 2013). This code solves the equations for the conservation of mass, momentum, and energy, as well as the radiative transfer equation assuming local thermodynamic equilibrium (LTE). For more information about the code we refer to Rodríguez Díaz et al. (2022) and references therein. The box-in-a-star type means that the 3D models are centered around the stellar photospheres. That is, they cover the photosphere, the superadiabatic region, and the quasi-adiabatic deeper convective layers, where a flat entropy profile is ensured at the bottom boundary. These layers are distributed in a specific 3D Cartesian geometry.

The 3D models are defined by three stellar parameters: the effective temperature \(T_{\text{eff}}\), the surface gravity \(\log g\), and the metallicity [Fe/H]. \(T_{\text{eff}}\) is defined by the entropy value at the bottom boundary of the models, while [Fe/H] is defined by the abundance of chemical elements present in the models.

Each model contains typically 10 granules, whose sizes are a few tens of pressure scale heights. This means that the sizes of the granular cells are bigger for models representing early-type stars or evolved stars.

Realistic radiative transfer is performed using long characteristic along several rays at different inclinations across the simulation domain in order to account for heating and cooling in the energy equation (e.g., Stein & Nordlund 2003). These radiative intensities are integrated in wavelengths and inclinations to give bolometric fluxes which can be compared to observations. To compare with observations, this quantity has to be rescaled by the number of granules visible on the disk, as Trampedach et al. (1998) and Ludwig (2006) proposed. With this scaling, Rodríguez Díaz et al. (2022) was able to determine the standard deviation of the stellar disk-integrated intensity from the small box models. We refer the reader to Rodríguez Díaz et al. (2022) for a more detailed description of the method.

Rodríguez Díaz et al. (2022) found that at solar metallicity the standard deviation of the flux scales like \(\sigma_{\text{HD}} \sim \nu_{\text{max}}^{-0.567}\), and the characteristic timescale follows \(\tau_{\text{ACF}} \sim \nu_{\text{max}}^{-0.997}\) (see Table 4 in their paper). We note that the characteristic timescale is defined as the autocorrelation time of the entire time series. It is a different timescale than the one related to the flicker frequency \(f_0\) (measured on the observed periodogram). For consistency with how we evaluate the granulation amplitude in Sect. 4.1, we have also determined a relation for F8 based on these 3D HD models (see Appendix D for details). We found \(F8_{\text{HD}} \propto \nu_{\text{max}}^{0.530}\).

Using such scaling and the parameters given in Table 4, the two values predicted by the 3D simulations are \(F8_{\text{HD}} \approx 48\) ppm (HD 67458) and \(F8_{\text{HD}} \approx 66\) ppm (HD 88595). The predicted characteristic timescales are \(\tau_{\text{ACF}} \approx 203.2\) s (HD 67458) and \(\tau_{\text{ACF}} \approx 369.3\) s (HD 88595). For HD 67458, the F8 values inferred from CHEOPS dataset are larger than the predictions from HD simulations, indicating that white noises are dominating the dataset. For HD 88595, the inferred and predicted F8 are in very good agreement (see Sect. 4.1 and Table 6).
6.2. Flicker indexes and relationship with the stellar properties

From the total sample of 27 stars simulated with the 3D models in Rodríguez Díaz et al. (2022), we select the 17 main-sequence stars. The selected stars have $T_{\text{eff}} \in [4727, 6485]$ K, $\log g \in [3.25, 4.44]$ cgs, and $[\text{Fe/H}] \in [-2, 0.5]$.

The length of all the synthetic time series correspond to at least 1000 convective turnover times, with these turnover times that are adapted to the stellar properties of the synthetic target stars. For all of these target stars, we compute the classical periodogram and scale the two cut-off frequencies $f_g$ and $f_c \geq f_H$ with the stellar parameters, with $f_c$ the corner frequency that marks the $p$-modes frequency dominance regime out (see Sulis et al. 2020a). We finally evaluate the flicker indexes as in Sect. 5.1 based on these synthetic periodograms of stellar granulation. Results are shown with the square symbols in Fig. 11. The color code indicates the stellar metallicity (not given for Kepler stars). We note that the HD simulated time series do not contain white noise, but only granulation signals and are therefore used as reference.

The flicker index indicators $\alpha_g$ derived from the HD convection models are in good agreement with the bright Kepler and CHEOPS targets. In line with Rodríguez Díaz et al. (2022), this demonstrates the success of these 3D models in reproducing realistic photometric time series of stellar granulation. However, we have noted a larger dispersion of the simulations compared to observations for stars with $\log g = 4.0$. This dispersion seems to be strongly correlated with the stellar metallicity: low metallicity shows smaller flicker index. While the results are different at other $\log g$ values, this needs to be investigated further based on a larger synthetic stellar population.

The flicker frequency $f_g$ derived from the HD convection models are also in good agreement with the values inferred from Kepler and CHEOPS observations. We note however a slight shift compared to Kepler values at $\log g = 4.0$.

7. Link between the spectroscopic and photometric signatures

Only a few variations of the physical granulation properties were observed during the solar magnetic cycles (Garcia et al. 2005), with 2% variation in the density and mean granules’ area observed during the solar cycle (Ballot et al. 2021). This cannot be directly verified on other stars since their surfaces cannot be resolved on the scale of the granulation cells. However, this can also be confirmed indirectly by studying variations in their power spectra (Seleznyov et al. 2011; Muller et al. 2018; Sulis et al. 2020a). A comparison of the current periodogram of HD 88595 with future observations taken in a few years would allow us to confirm if the granulation signal is indeed stationary with the stellar magnetic cycle. Without having any dataset – to our knowledge – to verify this statement, we assume in this section that photometric observations of the granulation signal can allow us to predict its signature (amplitude and timescales) in spectroscopic observations (e.g., in line with techniques that have been developed for magnetic activity, such the FF' technique described in Aigrain et al. 2012). This is important since high-precision photometric surveys allow the accumulation of ten to hundred of continuous 1-day observation of stars from space missions, while RV ground-based surveys typically have poor sampling to characterize this noise source for exoplanet detection (typically: one to three data points per night spread over long term campaigns).

7.1. Comparison of the periodograms

In the left panel of Fig. 12, we compare the (arbitrarily normalized) averaged periodograms of solar VIRGO (red) and GOLF (black) observations. We observe comparable periodogram's

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17 We note that this normalization factor has no impact on the inferred flicker index values, which are based on the periodograms’ slope and not their amplitudes.
slopes on data taken in photometry and spectrophotometry with flicker indexes $a_g = 1.33 \pm 0.03$ and $a_g = 1.34 \pm 0.14$, respectively (see Sect. 5.1). In both dataset, the level of white noise is low and does not affect the characterization of the stellar granulation signal. We note that, in the frequency region where the supergranulation starts to dominate ($\nu<200$ $\mu$Hz), the periodogram of brightness becomes flat while it still increases in the periodogram of RV.

In the two other panels, we show the averaged periodograms of CHEOPS and ESPRESSO observations of HD 67 458 and HD 88 595. The flicker index deduced from the ESPRESSO periodogram of HD 67 458 is consistent with zero (see Table 7), but its value remain consistent within their 1$\sigma$ errorbars with the flicker index inferred from CHEOPS observations. While we assert a marginal detection of the granulation signal for this star, this could explain the visual good match of the two periodograms; the white noise being too large to infer a precise flicker index value. More subseries ($\tau \approx 3$) would be needed to improve the precision on this parameter. On the other hand, the flicker indexes of HD 88 595 inferred on CHEOPS ($a_g = 0.61^{+0.05}_{-0.05}$) and ESPRESSO data ($a_g = 0.77^{+0.08}_{-0.28}$; see Table 7) are in complete agreement within their 1$\sigma$ errorbars.

This indicates that the properties (i.e., correlation timescales where this signal dominates, amplitudes distribution, and type of correlation with the flicker index) of the stellar granulation signal in RV data could be predicted from high-precision photometric observations (CHEOPS and PLATO) of bright stars.

### 7.2. Prediction from empirical laws

Some relations between the amplitudes of the stellar granulation signal in spectroscopy (RV RMS) and photometry (F8 metric) have been derived in the literature. We aim to test these predictions with the CHEOPS and ESPRESSO datasets of HD 67 458 and HD 88 595.

A first relation has been derived in Bastien et al. (2014), based on a small sample of 12 stars observed first by Kepler and later by RV ground-based surveys at the Keck and Lick observatories. The stars in this sample have been characterized as “chromospherically quiet stars” since they showed low-amplitude photometric variability ($\leq 3$ ppt) in their Kepler light curves. However, the RV precision was limited to $9 \leq 4$ m s$^{-1}$ leading to a difficult characterization of the stellar granulation signal. Fitting a linear law between F8 and the corresponding RV RMS for each stars, the relation:

$$\text{RV RMS} = (31.99 \pm 3.95) \times F8 + (3.46 \pm 1.19)$$

has been derived with RV RMS in m s$^{-1}$ and F8 in ppt (see also Sect. 3.5 of Tayar et al. 2019).

A second relation has been derived in Cegla et al. (2014), but based on indirect RV measurements. This study used a statistically more robust stellar sample (944 stars) observed by Kepler in photometry and with the GALEX survey (Martin et al. 2005) in far ultraviolet (FUV). From the FUV observations, the authors converted the data to chromospheric activity proxies ($\log R'_{\text{HK}}$) using the conversion extracted from Findedeisen et al. (2011), and then converted again to an RV RMS using the relation given in Saar et al. (2003)\(^8\). This work led to the linear relations:

$$\begin{align*}
\text{RV RMS} &= 18.04 \times F8 + 0.98 \text{ if } T_{\text{eff}} < 6000 \text{ K}. \\
\text{RV RMS} &= 84.23 \times F8 - 3.35 \text{ if } T_{\text{eff}} \geq 6000 \text{ K}.
\end{align*}$$

These relations were derived from targets deemed to be on the so-called flicker floor in Cegla et al. (2014) and therefore convection dominated; stars with large amplitude photometric variations did not show a clear correlation between F8 and RV RMS.

Finally, Oshagh et al. (2017) extended the work of Bastien et al. (2014) with 9 new targets observed with K2 and HARPS. However, their HARPS RV measurements contained only few data points (<12) and the RV RMS remained large (>10 m s$^{-1}$) meaning the RV signal was dominated by other noise sources than granulation (e.g., active regions). We then do not consider this study in the present work.

We note that in Eqs. (6) and (7) the F8 metric has been derived based on the initial definition, that is using data binned into 30-min intervals ($\tau$). However, this $\tau$ is not optimal for main-sequence stars since the granulation timescales are shorter than 30 min. We therefore investigated different binning intervals. To reduce the contribution of the high-frequency noises, we found that a data binning of $\tau = 15$ min and $\tau = 5$ min (as in Sect. 4.1) was sufficient to extract the signal of granulation in the CHEOPS data of HD 67 458 and HD 88 595, respectively. In particular, since ESPRESSO data of HD 67 458 are dominated by photon noise we have to use a more drastic data binning than in Sect. 4.1 to reduce its contribution in the measured RV data and makes an

\(^8\) We note that they found similar RV RMS based on another work of Wright (2005), but higher RV RMS values when using predictions from Santos et al. (2000).
stellar lines due to their larger brightness and surface area, to a "C"-shaped bisector in most stellar absorption lines; the We know from solar observations that granulation gives rise should be defined with mean and standard deviation parame-
– a priori – as Gaussian colored noise with amplitudes that
certainty interval is given while the granulation signal behaves
predictions of Cegla et al. (2014) are rough estimates (i.e., no
lar parameters. This leads us to the conclusion that, although the
RV RMS with Eq. (7) using an F8 metric coming from the stel-
involved in the study of Tayar et al. (2019), who computed the
ality in Fig. 13. The dots represent the predicted values from
due to the weighting in the CCF template mask, the "C"-shaped
shape of the cross-correlation functions (CCFs) and RVs,
and both RV and brightness (Cegla et al. 2019; Dravins et al.
Consequently, in this section we explore variations in the
the cross-correlation functions (CCCs) and RVs, as
measured from the ESPRESSO observations, and brightness as measured from CHEOPS. We examine CCFs rather than
individual stellar lines due to the increase in S/N; we note that
due to the weighting in the CCF template mask, the "C"-shaped
bisection of the individual lines is not preserved in the CCF, but
the overall shape should respond to the corresponding temporal
variations experienced by the individual lines.
Before we can explore the impact of granulation, we must
exclude the impact of the p-mode oscillations; this is particu-
larly important in RV-space where they may dominate over the
granulation-induced shifts. We take two approaches to disentan-
gling the granulation and p-mode effects.

8.1. Data binning
First, we bin the individual CCFs following Chaplin et al. (2019),
to optimally average out the p-modes. Using the OscFilter
script provided by Chaplin et al. (2019), we predicted in Sect. 4.2
that an exposure time of ~12 min should result in a remaining
RMS (due to the p-modes) of 10 cm s⁻¹ for HD 67458. How-
ever, to reach a similar (p-mode) RMS for the hotter and slightly
evolved HD 88595 would require binning over ~85 min. We note
that we have not propagated the uncertainties in the stellar
parameters through OscFilter nor accounted for the variabil-
ity in mode amplitudes. From Table 1 of Chaplin et al. (2019),
we expect these uncertainties to be of order a few minutes for

approximation comparison with the literature possible. We then
derive the RV RMS following the relations given in Eqs. (6) and
(7). Results are shown in Table 8. Clearly, comparing these pre-
dictions with the RV RMS found on our ESPRESSO time series
(see last columns) are in favor of Eq. (7) derived by Cegla et al.
(2014).
We note however the high sensitivity of this relation to the
length of the temporal binning \( \tau \) used to compute Eq. (7). Indeed,
computing the F8 metric with \( \tau = [5,15,30] \) min in Eq. (7) leads
to a predicted RV RMS of [2.0, 1.61, 1.4] m s⁻¹ for HD 67458,
[1.46, 1.34, 1.26] m s⁻¹ for the Sun, and [2.27, 1.65, −0.10] m s⁻¹
for HD 88595 (the last value representing a limit of Eq. (7) for F8
values <39.77 ppm). The choice of \( \tau \) for computing the F8 met-
ric does not significantly affect the predictions for the Sun (where
the level of high-frequency noise in VIRGO data is negligible). For
HD 67458, using a too short temporal binning for computing
the F8 metric of the solar-like star HD 67458 makes the time
series completely dominated by the high-frequency noise.
Using a temporal binning of 30-min, as in Cegla et al. (2014),
leads to predicted RV RMS of similar order of magnitude. For
the F star HD 88595, the relation in Eq. (7) is not adapted to
\( \tau > 15 \) min. Computing the F8 metric based on a temporal bin-
ning that is adapted to the granulation timescales, as proposed
in Bugnet et al. (2018), may allow the photometric versus RV
relation derived in Cegla et al. (2014) to be refined.
In addition, we compare the measured RV RMS of our two
targets and the Sun with the stellar surface gravity and metal-
licity in Fig. 13. The dots represent the predicted values from
Eq. (7), both are in agreement with ESPRESSO observations
(see the interval delimited by the dashed horizontal lines), as
shown in Table 8. In this figure, we also represent the targets
involved in the study of Tayar et al. (2019), who computed the
RV RMS with Eq. (7) using an F8 metric coming from the stel-
lar parameters. This leads us to the conclusion that, although the
predictions of Cegla et al. (2014) are rough estimates (i.e., no
confidence interval is given while the granulation signal behaves – a priori – as Gaussian colored noise with amplitudes that
should be defined with mean and standard deviation paramet-
eries, see Sulis et al. 2020a), they lead to values that are quite consistent with CHEOPS and ESPRESSO observations.

8. Analysis of CCF shape
We know from solar observations that granulation gives rise to a "C"-shaped bisection in most stellar absorption lines; the
uprising/blue-shifted granules contribute more overall to the
stellar lines due to their larger brightness and surface area,
while the dark downfailing and red-shifted intergranular lanes
serve to depress the redward wing. As the granules evolve over
time, and the ratio of grain to intergranular lane changes, we
expect to see a corresponding change in line shape, symmetry and overall brightness. Such changes in line shape may then
manifest as RV shifts. Both 3D MHD and HD simulations
predict correlations between granulation-induced line shape
and both RV and brightness (Cegla et al. 2019; Dravins et al.
2021). Consequently, in this section we explore variations in
the shape of the cross-correlation functions (CCFs) and RVs,
as measured from the ESPRESSO observations, and brightness
as measured from CHEOPS. We examine CCFs rather than
individual stellar lines due to the increase in S/N; we note that
due to the weighting in the CCF template mask, the "C"-shaped
bisection of the individual lines is not preserved in the CCF, but
the overall shape should respond to the corresponding temporal
variations experienced by the individual lines.
Before we can explore the impact of granulation, we must
exclude the impact of the p-mode oscillations; this is particu-
larly important in RV-space where they may dominate over the
granulation-induced shifts. We take two approaches to disentan-
gling the granulation and p-mode effects.

Table 8. Radial velocity RMS for HD 67458, HD 88595, and the Sun as predicted from Eqs. (6) and (7) based on the F8 metric computed on our CHEOPS and VIRGO observations.

| Target   | RV RMS predicted from Eq. (6) | RV RMS predicted from Eq. (7) | Measured RV RMS |
|----------|-------------------------------|-------------------------------|-----------------|
| HD 67458 | 4.31 ± 1.19                   | 1.46                          | 1.1, 2.6        |
| HD 88595 | 5.59 ± 1.22                   | 2.27                          | 2.26, 2.54      |
| Sun      | 4.10 ± 1.19                   | 1.34                          | [0.87, 1.63]    |

Notes. The last column shows the RV RMS measured on ESPRESSO observations (see Table 2). Radial velocity RMS for the Sun are based on the 75 GOLF subseries. All RV units are in m s⁻¹.

Fig. 13. Radial velocity RMS as a function of the stellar surface gravity. Individual small dots represent the values for the 129 055 stars of the APOGEE sample studied in Tayar et al. (2019). For this stellar sample, the RV RMS was computed based on Eq. (7) (Cegla et al. 2014). The two big dots represent the RV RMS predicted from Eq. (7) for HD 67458 and HD 88595. The star symbol represents the RV RMS predicted from Eq. (7) for the Sun. The color code for all targets represents the stellar metallicity [Fe/H]. The blue and red horizontal dashed lines show the RV RMS values inferred from ESPRESSO observations of HD 88595 and HD 67458, respectively.
Table 9. Correlations with RV as assessed by Spearman’s Rank ($\rho_s$) for the binned datasets.

| Indicator | Night 1 (88) | Night 2 (68) | Night 3 (87) | Night 1 (263) | Night 2 (285) |
|-----------|--------------|--------------|--------------|--------------|--------------|
| FWHM      | -0.75        | -0.92        | -0.77        | -0.31        | 0.71         |
| Contrast  | -0.68        | -0.86        | -0.83        | -0.26        | -0.14        |
| EW        | -0.67        | -0.89        | -0.82        | -0.26        | 0.26         |
| BIS       | 0.35         | 0.05         | 0.56         | -0.77        | 0.31         |
| Curvature | -0.11        | 0.1          | 0.82         | -0.77        | -0.77        |
| $A_b$     | -0.28        | 0.01         | -0.15        | 0.6          | 0.94         |
| Flux      | N.O          | -0.56        | 0.73         | 0.0          | 0.03         |

Notes. Also listed in brackets is the average S/N from echelle order 10 per night; strong correlations with low S/N may be spurious (HD 67458), see for example Fig. 14. “N.O” means there was no overlap between CHEOPS and ESPRESSO observation for this night (see Fig. 2).

HD 67458, but they may be as large as 50 min or more for HD 88595. For HD 67458, we account for this uncertainty by averaging over 20 min time bins; unfortunately, with 85 min time bins for HD 88595 we are left with only 6 points per night so we do not attempt to account for this uncertainty here.

For each time bin, we sum all the CCFs that fall within the bin and then continuum normalize; uncertainties on the CCF flux are propagated accordingly. We then fit a Gaussian to the binned CCFs to determine the RV, full width at half maximum (FWHM), and contrast. To investigate any potential trends with S/N, we add the individual S/N, provided by the DRS for each order, in quadrature. We follow Cegla et al. (2019) and measure FWHM, contrast, equivalent width (EW), bisector inverse span (BIS), bisector curvature, and bisector amplitude ($A_b$). Both the BIS and bisector curvature split the CCF bisector into discrete regions. Here we use the standard definitions for BIS and curvature (BIS: top region is bounded by 10–40% of the line depth, bottom region by 55–90% of the line depth; curvature: top region is 20–30%, middle is 40–55%, 75–95% of the line depth); we explore optimizing these definitions in Appendix G. For nights with overlapping simultaneous CHEOPS and ESPRESSO observations, we average the CHEOPS light curves over the same time bins as the ESPRESSO data.

In each instance, we explore the relationship between the shape indicator or brightness and RV on a night by night basis for each target. If we are able to detect the impact of granulation on the CCF shape, we expect to see correlations between the shape indicators, flux and RV that are consistent across the various observing nights and independent of S/N. Irregardless of the observations here, the CCF contrast, and to a lesser extent FWHM, is often correlated with S/N, especially at low S/N due to difficulties in accurately subtracting the background (bias level, dark current, diffuse inter-order background, sky background, etc.). Hence, any correlation between shape indicator and RV that is S/N-dependent should be taken with caution.

We use the Spearman’s Rank correlation coefficient ($\rho_s$) to assess, in a nonparametric way, the strength of any potential correlations between the shape indicator and the measured RV shift.

The results are shown in Table 9, and a subset of these are shown in Figs. 14 and 15 for HD 67458 and HD 88595, respectively.

For HD 67458, the FWHM, contrast, and EW show clear correlations with RV that are consistent across all three nights (see Fig. 14); however, these correlations are dependent on the S/N, as shown by the data color-coded, with the S/N from the 10th echelle order (there does not appear to be a dependence on airmass). The remaining shape indicators do not show any

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19 We are able to improve the correlation between BIS or curvature and RV by tweaking the top, bottom, and middle definitions, which may indicate we are identifying regions more sensitive to granulation. However, these regions change across nights and further exploration is needed to determine the root cause; see Appendix G for more details.

20 We use the `spearmanr` function from the scipy Python library.
consistent or strong correlations with RV. The flux appears to correlate with RV, but changes from anticorrelated in the second night to positively correlated in the third night. The peak-to-peak RV variation of $\sim 5 \, \text{m s}^{-1}$ is also potentially larger than we might expect based on solar observations of granulation. For all these reasons, the correlations we do see are likely due to difficulties in accurately subtracting the sky background, rather than driven by true convection changes. Future observations under more ideal observing conditions may be key to confirm the nature of the observed correlations; alternatively, a more refined treatment of the \( p \)-modes may also help.

For HD 88595, with the exception of the bisector curvature, we do not see any strong correlations that are consistent across nights (see Fig. 15). Even with the bisector curvature there are still some inconsistencies; although the strength (and sign) of the correlation is similar, there are offsets in the actual values of the curvature and RV. We find that the bisectors between the two nights show a different shape, indicating the overall shape of the CCF is different between nights (see Fig. G.1). We also note that for the flux-RV exploration in the first night, there is a lack of CHEOPS observations at the start of the night that means there is no overlap in the first time bin and limited overlap in the second bin (the latter corresponding to the data point in bottom right subplot of Fig. 15 with the highest flux).

At this stage, it is not clear if these differences in behavior between nights are driven by changes in the instrumental PSF or stellar changes happening on longer timescales, such as supergranulation. The two nights are separated in time by $\sim 8$ days and although we would expect the supergranular lifetime to be longer than on the Sun (which is just under 2 days) this seems likely too long for the supergranulation to remain correlated; that said, there is not a strong enough understanding of stellar supergranulation to completely rule this out. If supergranulation were the dominant effect here (rather than the short-term granulation), then there might be tentative evidence for correlations across the nights (that often differ in sign from the nightly behavior). Unfortunately, the long duration required to mitigate the \( p \)-modes significantly reduces our sampling and prevents us from making strong conclusions here.

### 8.2. Data filtering

Motivated by the large timespans required to bin out the \( p \)-modes for HD 88595 (and likelihood for a large uncertainty on the optimal binning), we also attempt to filter out the \( p \)-mode impact in the RVs and shape indicators. For this, we apply a Butterworth filter provided by the Python library scipy. Here, we use the individual RVs, the FWHM and contrast provided by the ESPRESSO DRS. We fit each of the remaining shape indicators for each individual CCF. For nights where there is an overlap between CHEOPS and ESPRESSO observations, we (linearly) interpolate the CHEOPS lightcurves onto the ESPRESSO timeshifts. Then, on a night by night basis, we apply the Butterworth filter to the RV and shape indicator time-series with a cutoff frequency corresponding to 5 min and increasing in 5 min intervals up to 80 and 255 min for HD 67458 and HD 88595, respectively (with the latter being approximately three times the estimated time to bin the \( p \)-modes down to 10 cm s\(^{-1}\) RMS for this target). For each cutoff frequency, we assess the correlation strength between the filter RV and indicator time-series following the Spearman’s Rank correlation coefficient. We repeat this analysis on the unfiltered (unbinned) data.

We examine the behavior of each indicator for all observed nights for each target, as well as the behavior of all indicators across a given night. If we are filtering out the \( p \)-modes with increasing cutoff frequency, then a given indicator should increase in correlation strength in a consistent manner across the nights. However, we do run the risk of over-filtering and flattening the signal, and therefore artificially creating a correlation (e.g., if both the RV and shape indicator or flux are constant over time then they will have a perfect correlation). If all indicators grow in correlation strength in a similar way with cutoff frequency, but behave differently on different nights, this may be a sign we are over-filtering the data.

In general we find, for both targets and all nights, the correlation strength between RV and most shape indicators or flux tends to grow as a function of cutoff frequency, as shown in Figs. 16 and 17. However, the behavior of the correlation strength as a function of cutoff frequency is largely inconsistent across nights for most indicators, for both targets. This is consistent with the binned analysis in Sect. 8.1, where the sign of the correlations which did not trend with S/N changed across nights. The inconsistencies across nights here casts doubt on the detection of granulation-induced shape changes and the increase in correlation strength with cutoff frequency may indeed be due to simply flattening both time-series. The exception to this is the relationships with contrast and bisector curvature for HD 88595, where the correlation with RV increases in strength for cutoff frequencies corresponding to longer timescales in a similar manner across both nights. This also adds further evidence that the strong correlation between bisector curvature and RV in the

![Fig. 15. Same as Fig. 14, but for HD 88595. For this star, the CCFs are binned over 85 min.](image-url)
binned data in Sect. 8.1 (Fig. 15) might be indeed be due to granulation.

The relationship between flux and RV (as a function of cut-off frequency) is also somewhat consistent across nights; we note that the \( p \)-values associated with the Spearman rank correlations strengths indicate that a window size of \( 100-150 \) min or more may be required to reject the null hypothesis, that means we may only be able to trust the correlations with a large filtering window. This behavior might explain why we were unable to detect an RV-flux correlation in the \( 80 \)-min binned data in Sect. 8.1. Interestingly, the difference in strength of the \( p \)-values associated with the Spearman rank correlation may further indicate the difference in data quality between nights (e.g., Fig. 5 shows how the RV RMS of the first nights is consistently larger than for the second night).

Nonetheless, a further refinement of the treatment of the \( p \)-modes is required to confidently confirm the nature of this behavior; this is beyond the scope of this paper and will be the subject of a future study. Additionally, future observations would also be useful to confirm the origin of the CCF shape differences between nights and the relationship between granulation-induced RV shifts and flux.

9. Conclusions

The first goal of this paper was to detect the stellar granulation signal of two bright stars for the first time with high-precision photometric CHEOPS observations taken simultaneously or contemporaneously with high-resolution spectroscopic ESPRESSO observations. We detected the stellar granulation signal for the F star HD 88595 in both datasets, but only in the CHEOPS dataset for the solar-like star HD 67458 (Sect. 4). In particular, we observed significant variabilities between the three nights of observations of HD 67458 with ESPRESSO. Although we could not clearly identify the origin of these variabilities, we showed that they are induced by an excess of white noise in the observations masking the signatures of the stellar granulation (Sect. 4.1). We demonstrated the sensitivity of high-precision photometric CHEOPS observations to this stellar signal, which was not detected on TESS observations (large photon noise and small amplitude of the granulation signal in the TESS passband).

We also showed that the temporal binning of RV time series (i.e., the technique that is classically used to mitigate the amplitude of this stellar signal) is limited as this signal remains correlated over timescales \( \tau > 10-15 \) min (Sect. 4.2). In particular, to reach the RV amplitude level of Earth-mass planets in the HZ of our two stars, we estimated that observations would need to be binned over \( \tau \geq 180 \) min for the G star (in agreement with the predictions of Meunier et al. 2015) and over \( \tau \gg 250 \) min for the F star.

Computing the flicker index indicator, defined as the slope of the periodograms, we demonstrated that both this indicator and the flicker frequency are correlated with the stellar parameters (Sect. 5), which is in agreement with previous studies (Sulis et al. 2020a) based on \textit{Kepler} observations.

The second goal of this study was to test the predictions from 3D hydrodynamic models of convection (Sect. 6). We observed photometric amplitudes with CHEOPS that are consistent with the expectation from 3D models: 48 ppm for the solar-like star and 66 ppm for the F star. The flicker index and flicker frequency derived on synthetic granulation time series generated by these 3D model predictions are also in agreement with both \textit{Kepler} and CHEOPS observations.

The last goal of this study was to link the spectroscopic and photometric signatures of convection for main-sequence stars with high-precision observations (Sect. 7). We observed a very good match between the periodograms of CHEOPS and ESPRESSO observations for the F star in the frequency regime dominated by stellar granulation. This was quantitatively confirmed by similar flicker indexes inferred on both datasets and...
this indicates that the spectroscopic signal of stellar granulation can be predicted by photometric observations. Unfortunately, the RV precision of the ESPRESSO observations of the solar-like star HD 67458 was not good enough to precisely characterize this stellar signal (the errorbars were between 0.4 and 2.7 m s$^{-1}$ against a signal with amplitude <1 m s$^{-1}$). Additional RV observations with precision <1 m s$^{-1}$ are then still needed to confirm the strong link that we already observed in the Sun with VIRGO and GOLF observations.

Comparing the RV RMS predictions from photometric measurements lead us to invalidate the empirical relations derived in Bastien et al. (2014), while confirming the relations derived in Cegla et al. (2014). We however demonstrated the high sensitivity of the data binning – used to extract the photometric granulation signal – on these RV RMS predictions. We argued that the amplitude of this stellar signal needs to be adapted on the stellar dependent granulation timescales and high-frequency noise level that affects its characterization. A perspective of this study will be to use a more robust technique to do so, as the one developed in Bugnet et al. (2018). Indeed, in the context of the upcoming ESA PLATO mission and the extreme precision radial velocity (EPRV) surveys, the interplay between the photometric and spectroscopic observables will be key for mitigating this stellar noise source that limits the detection and characterization of both stellar oscillations and exoplanet signatures. In line with Sulis et al. (2020a), we expect a high sensitivity to this stellar phenomenon with the future high-precision photometric PLATO observations (at least in the 24-camera mode).

Finally, we also explored whether it was possible to detect the impact of granulation-induced changes on the CCF shape, corresponding induced RV shifts and brightness changes (Sect. 8). This analysis was complicated by the presence of $p$-modes excited by the granulation and occurring on similar timescales. The RV shifts induced by the $p$-modes dominate over the granulation and efforts to mitigate and/or disentangle the $p$-modes likely also squash the granulation signal. Moreover, the long timescales required to bin or filter out the $p$-modes for the hotter F star (HD 88595) mean that even though the granulation signal is also expected to be larger, it is still equally tricky to disentangle. Nonetheless, there are potential hints that the CCF bisector curvature may provide information on the granulation signal, at least for the F star. If the $p$-modes are sufficiently filtered (i.e., with a cutoff frequency corresponding to ≈100–150 min or more), there also appears to be a correlation observed between flux and RV for the F star that is consistent across nights. Unfortunately, the G star (HD 67458) observations seem to limited by signal-to-noise as the apparent correlations between shape and RV are signal-to-noise dependent. Future observations are needed to further determine the impact of granulation on the overall brightness, CCF shape and net RV shifts. Additionally, a more refined treatment of the $p$-modes may also be key to further unveiling the granulation behavior; this is currently under analysis and will be the subject of a forthcoming paper.

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Appendix A: Rotation period estimates based on TESS observations

To measure the stellar rotation period of HD 88595 and HD 67458, we use the TESS light curves introduced in Sect. 2.3. We analyze the light curves using the Generalized Lomb-Scargle periodogram (Zechmeister & Kürster 2009), after having masked out the most obvious outliers and after applying a linear detrending in time to each sector.

Appendix A.1: HD 88595

This star has been observed in sectors 9 and 35. For the latter we detect a clear peak around ~3 days, while for the former we get a broader comb of aliases between 1 and 10 days. The joint analysis of the two sectors returns a period of 3.1151 ± 0.0003 days and a photometric amplitude of 83 ± 4 ppm. The detected period would be consistent with rotation and with \( \delta = v \sin i = 7.2 \text{ km s}^{-1} \) assuming that the inclination of the rotation axis is \( i = 16^\circ \), and obtain the star is seen nearly pole on. In such a scenario, the active regions on the stellar surface are always visible (unless they have nearly equatorial latitudes), and this would explain why the star has a low photometric signal despite being a fast rotator.

Appendix A.2: HD 67458

This star has been observed in sectors 7, 8, and 34. The light curve obtained in sector 8 is the most problematic. The data release note\(^{21}\) reports noisy quaternions, and the periodogram is difficult to interpret. For these reasons we exclude this sector from our analysis.

The periodogram of sector 7 suggests a periodicity of 5.80 ± 0.03 days, while for sector 34 we get a period of 10.57 ± 0.06 days. In both cases the photometric amplitude is ~100 ppm. The joint analysis of the two sectors show significant peaks at these two periods in the periodogram. Since the two periods are roughly in a 1:2 proportion, we thus argue that the period detected in sector 7 is the first harmonic of the true rotation period. The detected period of 10.57 ± 0.06 days would be consistent with rotation and with \( v \sin i = 2.179 \text{ km s}^{-1} \) assuming an inclination of ~26\(^\circ\), meaning this star is also seen nearly pole-on.

Appendix B: Exoplanets in the habitable zone

As a reference in the paper, we evaluate the planetary timescales (transit and in-egress durations, orbital period) and amplitudes (transit depth, RV semi-amplitude) of an Earth-like planet (1 \( M_\oplus \), 1 \( R_\oplus \)) that would orbit in the HZ of HD 67458 and HD 88595. For that purpose, we assume an impact parameter \( b = 0 \), an eccentricity \( e = 0 \), and the inclination to be \( i = 90^\circ \). We use the stellar parameters given in Table 4 and the classical equations given in Perryman (2018).

We compute the transit depth as

\[
\delta = \left( \frac{R_p}{R_*} \right)^2,
\]

and obtain \( \delta = 80.6 \text{ ppm} \) for HD 67458, and \( \delta = 32.18 \text{ ppm} \) for HD 88596.

We compute the orbital separation of the planet in the middle of the HZ as

\[
a = \sqrt{ \frac{L_*}{L_\odot} } \]

with \( L_* = 4\pi\sigma R_*^2 T_{\text{eff}}^4 \) the stellar luminosity in SI from the Stefan-Boltzmann law, \( \sigma = 5.67 \times 10^{-8} \text{ kg s}^{-2} \text{ K}^{-4} \) the Stefan-Boltzmann constant, and \( L_\odot = 3.828 \times 10^{26} \text{ W} \) the solar luminosity according to IAU. We obtain \( a = 1.04 \text{ AU} \) for HD 67458 and \( a = 1.86 \text{ AU} \) for HD 88595. Using Kepler’s 3rd law, we derive the corresponding orbital periods and find \( P = 402.3 \text{ days} \) for HD 67458 and \( P = 802.2 \text{ days} \) for HD 88595.

We express the total transit duration as

\[
T_T \approx \frac{P}{\pi} \left( R_* + R_p \right),
\]

and obtain \( T_T = 14.12 \text{ hours} \) for HD 67458, and \( T_T = 24.8 \text{ hours} \) for HD 88595.

The duration of full transit is computed as

\[
T_f = \frac{P}{\pi} \left( R_* - R_p \right),
\]

which gives a duration of the transit ingress expressed as

\[
T_{in} = \frac{T_f - T_T}{2}.
\]

We obtain \( T_{in} = 7.5 \text{ min} \) for HD 67458, and \( T_{in} = 8.4 \text{ min} \) for HD 88595.

Finally, the RV semi-amplitude of an Earth-mass planet is expressed in m/s as (Lovis & Fischer 2010)

\[
K = 28.4329 \left( \frac{M_p}{M_\oplus} \right)^{-0.5} \left( \frac{a}{1 \text{ AU}} \right)^{-0.5},
\]

with \( M_J \) the Jupiter mass. We obtain \( K = 9 \text{ cm/s} \) for HD 67458 and \( K = 5.6 \text{ cm/s} \) for HD 88595.

Appendix C: Solar granulation as seen from different instruments

Stellar activity is wavelength-dependent. To evaluate this dependence with solar observations, we compare in this section the periodograms of VIRGO/SoHO solar irradiance (see Sec. 2.4) with HMI/SDO photometric observations (see description in Sulis et al. 2020a). We also compare the GOLF/SoHO spectroheliometric data (see Sec. 2.4) with HARPS-N spectroscopic observations\(^{22}\) (Collier Cameron et al. 2019, Dumusque et al. 2021).

For each dataset, we compute the averaged periodogram based on 1-day regularly sampled time series of VIRGO (year:1996), HMI (year:2008), and GOLF observations (year:1996). Since HARPS-N observations (years:2015-2018) are taken from the ground, they are irregularly sampled and their durations are around 6-8-hours. For this reason, the Lomb-Scargle periodogram (Scargle 1982) is used to compute \( P_L \) in Eq. (3) for HARPS-N data, while the classical periodogram (Schuster 1898) is used for the other datasets.

The resulting averaged periodograms are shown in Fig. C.1. We observe a very good match between the slopes of the different periodograms in the frequency region dominated by the stellar granulation signal. While the amplitudes of this signal are wavelength-dependent (see Fig 3 for example), the flicker index, which is based on the periodogram’s slope, is not (at least, in first approximation). This makes this indicator a useful diagnostic tool for granulation studies.

\(^{21}\) https://archive.stsci.edu/missions/tess/doc/tess_drn/tess_sector_34_drn50_v02.sspdf

\(^{22}\) http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/648/A103
Appendix D: F8 scaling relation from 3D stellar atmosphere models

Since one of the scaling relations provided by Rodríguez Díaz et al. (2022) was for the standard deviation ($\sigma_{\text{HD}}$), we calculated a new scaling relation for F8, so we can compare directly with our two CHEOPS targets.

Table D.1 summarizes the F8 values for the models used and Fig D.1 shows the F8 values for the 3D stellar atmosphere models at solar metallicity and with $\log g \geq 3.0$, together with a fit for the scaling relation, which is of the form:

$$\log_{10} F8_{\text{HD}} = a \log_{10} v_{\text{max}} + b.$$ 

We find $a = -0.530 \pm 0.040$ and $b = 3.506 \pm 0.112$ leading to the relation $F8_{\text{HD}} \propto v_{\text{max}}^{-0.530}$ that we used, instead on the RMS based relation $\sigma_{\text{HD}} \propto v_{\text{max}}^{-0.567}$ initially published in Rodríguez Díaz et al. (2022).

Fig. D.1: F8 values obtained for 3D stellar atmosphere models at solar metallicity compared to $v_{\text{max}}$, and the derived scaling relation.

Appendix E: Influence of observational parameters on the flicker index

The flicker index is linked to several observational settings that affect its estimation. In this section, we investigate how the length of the subseries, the temporal sampling, and the level of high-frequency noise impact the inferred flicker indexes.

The flicker index is estimated from the averaged periodogram (3), which is computed based on short-duration subseries. To evaluate the influence of the different parameters, we use VIRGO solar observations (see Sec. 2.4).

Fig. E.1 shows the flicker index as a function of the number of 1-day subseries ($L$) for different parameters. In all panels, the reference setting if $\Delta t = 1$ min, $T = 1$ day and $\sigma_w < 30$ ppm (VIRGO high-frequency noise level). The inferred flicker indexes converge toward a fixed estimate with the increase of $L$ (see red horizontal lines). We note this “asymptotic” estimate $\alpha_{g,\infty}$ in the following.

The first column shows the influence of the time sampling on the flicker index. From top to bottom, the subseries are sampled at $\Delta t = 1$ min, 5 min, and 10 min. For a solar-like star, we see that a too long temporal sampling, as $\Delta t \geq 5$ min, affects the flicker index value since the high-frequency cut-off is cropped. The convergence of the inferred index toward $\alpha_{g,\infty}$ is fast ($L \leq 10$), for all $\Delta t$, and no specific bias is observed at low $L$ (the asymptotic index $\alpha_{g,\infty}$ is within the $1\sigma$ errorbars). We note that, while $\Delta t$ is not expected to affect the flicker indexes obtained from CHEOPS and the future PLATO space data (since they both have $\Delta t < 5$ min), it can be critical for ground-based RV observations where the exposure time is, in general, $\geq 5$ min.

The second column shows the influence of the subseries duration on the inferred flicker index. From top to bottom, the subseries have duration of 5 days, 1 day, and 8 hours. Again, we observe a fast convergence of the flicker index toward $\alpha_{g,\infty}$ for all $T$. It indicates that the relatively short length of our CHEOPS observations (8 hours) are enough to infer accurate flicker index. However, the low number of visits (3 to 4) may slightly bias our inferred values. We note that long observations (e.g., $T = 5$ days) does not improve the flicker index convergence toward $\alpha_{g,\infty}$.

The last column shows the influence of the high-frequency noise level on the inferred flicker index. From top to bottom, we added to VIRGO observation a WGN of standard deviation $\sigma_w = 0$ ppm (our reference), 85 ppm ($\approx$ CHEOPS high-frequency noise level), and 96 ppm ($\approx$ TESS high-frequency noise level).

Fig. E.1: F8 values obtained for 3D stellar atmosphere models at solar metallicity compared to $v_{\text{max}}$, and the derived scaling relation.
Table D.1: Stellar and physical parameters of the 3D stellar models at solar metallicity used to determine the scaling relation of F8. From left to right: model name, target effective temperature (target $T_{\text{eff}}$, in K) corresponding to the $T_{\text{eff}}$ that we aimed to achieve for each model, mean $T_{\text{eff}}$ (K) from the time series, surface gravity in logarithm scale (log$g$) (cm/s$^2$), metallicity [Fe/H], $v_{\text{max}}$ ($\mu$Hz), standard deviation of the brightness fluctuations ($\sigma_{\text{HD}}$) (ppm), and F8$_{\text{HD}}$ (ppm).

| Model       | Target $T_{\text{eff}}$ | $T_{\text{eff}}$ | log$g$ | [Fe/H] | $v_{\text{max}}$ | $\sigma_{\text{HD}}$ | F8$_{\text{HD}}$ |
|-------------|-------------------------|------------------|--------|--------|------------------|-----------------------|------------------|
| t50g30m00   | 5000                    | 4960             | 3.00   | 0.0    | 121.516          | 219                   | 286              |
| t47g32m00   | 4750                    | 4727             | 3.25   | 0.0    | 221.351          | 199                   | 220              |
| t55g35m00   | 5500                    | 5516             | 3.50   | 0.0    | 364.387          | 136                   | 145              |
| t50g35m00   | 5000                    | 4958             | 3.50   | 0.0    | 384.345          | 142                   | 153              |
| t65g40m00   | 6500                    | 6413             | 4.00   | 0.0    | 1068.672         | 88                    | 83               |
| t60g40m00   | 6000                    | 5962             | 4.00   | 0.0    | 1108.355         | 83                    | 88               |
| t55g40m00   | 5500                    | 5462             | 4.00   | 0.0    | 1157.975         | 81                    | 85               |
| t577g44m00  | 5777                    | 5759             | 4.44   | 0.0    | 3106             | 38                    | 46               |

noise level). As discussed in Sec. 5.2, the index values logically decrease with the level of this high-frequency noise (that was largely dominated by photon noise for our two stars observed by CHEOPS).

Appendix F: Flicker indexes of Kepler and CHEOPS bright targets

In Table F.1, we show the results from the flicker analyses on some targets described in the present study. Kepler targets comes from Sulis et al. (2020a). The table shows the cut-off frequencies ($f_c$ and $f_b$) and flicker indexes ($\alpha_4$) inferred from the MCMC analyses for a time series affected by a high-frequency noise level $\sigma_w$ (see Sec. 5.1). The errorbars indicated in the table are the more conservative ones. The flicker index interpolated at the high-frequency noise level of 30 ppm is indicated by $\alpha_4^{30\text{ ppm}}$. Stellar parameters for Kepler targets ($M_\star, R_\star, T_{\text{eff}}, \log g, \text{mag}$) are from the Kepler_stellar17.csv.gz catalog available at https://archive.stsci.edu/kepler/catalogs.html.

Appendix G: Bisector inverse span and curvature optimization

We explore the impact of optimizing the BIS and curvature region definitions by searching for the regions of the bisector most sensitive to changes in net RV. This analysis is performed only on the binned data in Sec. 8.1 as the CCF shape could potentially be impacted by the p-modes in the individual data. For the optimal BIS and curvature range exploration, we employ two approaches: in the first instance we employ an MCMC (implemented with EMCEE; Foreman-Mackey et al. 2013) to explore the top and bottom (middle) definitions, and in the second case we search a fixed grid.

For the MCMC approach, we start 100 walkers in a tight Gaussian ball near the standard definitions and let the walkers explore the parameter space for 1000 steps (excluding a burn-in of 100 steps). We set uniform priors to avoid the continuum and CCF core (excluding the top 10% and bottom 95% of the CCF) and to ensure the various regions are separate. We aim to minimize the residuals between the measured RV and that predicted by a linear fit with the given indicator. We note that this assumes a linear relationship between RV and indicators or flux, which may well not be the case; it also does not account for any potential time lags between RV and shape indicator. As such, this approach may not identify the regions of the bisector most sensitive to granulation, but it is a good first parameter space to search.

In the second approach, we loop over various top and bottom (middle) region definitions in steps of 5% of the CCF depth, requiring the range of a given region to be at least as large as one step size and that the regions do not overlap. Similar to the MCMC approach, we limit the search to 10-95% of the CCF depth. The “optimal” region definitions were then those that maximized the correlation (as determined by the Spearman’s Rank test) between the BIS or curvature and RV. This approach has the advantage that we maximally search all possible region definitions (and do not need to worry about convergence), but the disadvantage of having a fixed step size. If the relationship between BIS or curvature and RV is linear, then this is equivalent to the previous approach.

We consider instances where both approaches agree to be the most reliable. We find there are often multiple top, bottom, and middle definitions that could be considered optimal and the sign of the correlation can change depending on either the region definition or the night of observations. We note that a change in correlation sign can happen simply from moving to different regions within the bisector and should not be cause for alarm. Nonetheless the inconsistencies across nights indicate that we likely do not identify the regions of the CCF bisector most sensitive to granulation (and may be sensitive primarily to instrumental or telluric noise and/or low-number statistics). Nonetheless, we outline the individual results below.

Appendix G.1: BIS results

The CCF bisector for HD 67458 is fairly straight with a slight blue-ward bend near the top, and does not change significantly between nights (see Fig. G.1). Both nights 1 and 2 are optimized to instrumental or telluric noise and/or low-number statistics). Alternatively, an optimized CCF mask or a line-by-line approach may be needed as the current CCF template smears
Fig. E.1: Inferred flicker indexes as a function of the number of subseries ($L$) used to compute the averaged periodogram in Eq. (3) based on VIRGO solar data. Left column: influence of the time sampling, $\Delta t = 1, 5, 10$ min (from top to bottom). Middle column: influence of the duration of the subseries, $T = 5$ day, 1 day, 8-hours (from top to bottom). Right column: influence of the high-frequency noise level, $\sigma_W < 30$ ppm (VIRGO data, top), $\sigma_W = 82$ ppm (level measured on CHEOPS HD 67458 periodogram), $\sigma_W = 92$ ppm (approximately the level measured on TESS HD 67458 periodogram). The red horizontal line indicates the flicker index value for large $L (\alpha_{g,\infty})$.

out too much of the bisector curvature; this is the subject of a forthcoming analysis for a follow-up paper.

As noted in Sec. 8, the bisectors for HD 88595 change significantly in shape between the two nights observed (see Fig. G.1). The bisector on night 1 is more vertical, with less blue-shift near the CCF core compared to night 2; this is in agreement with the fact that the FWHM is larger and contrast shallower for night 1 (see Fig. 15). The broader CCF in night 2 might be linked to the lower RV precision we find for this night. The backwards bend in the bisector is far more prominent for this star, indicative of the more vigorous convection with larger contrasts between granules and inter-granular lanes; this bend occurs at a similar depth in both nights. Since binning to help mitigate the effects of the p-modes only leaves 6 points per night, efforts to find the bisector ranges most sensitive to granulation via maximizing the correlation with RV should be taken with extreme caution. For night 1, the MCMC approach points toward a 'top' region of $\sim 10-30\%$ (above the bend in the bisector) and a 'bottom' region of $\sim 70-75\%$ and a Spearman’s rank correlation coefficient near -0.9, while the nested loop approach points toward $\sim 20-40\%$ (top) and $\sim 30-60\%$ (bottom) with a correlation coefficient closer to -1. Interestingly, ranges of 55-60% and 60-65% can lead to a positive correlation coefficient near 1. For night 2, both approaches find optimal regions near 35-45% and 70-80% for the top and bottom, respectively, and a positive correlation coefficient near 1. With the nested loop approach we find a similar correlation sign and strength with a narrow region defined very near the CCF core (85-90% and 90-95%) that might simply be tracing centroid shift rather than any true asymmetry change. The differences between lines is probably being driven by whatever is driving the larger shape changes between the nights, potentially linked to observing conditions since a broader CCF also leaders to poorer RV precision.

Appendix G.2: Bisector curvature results

For HD 67458, on night 1 we find strong correlations between RV and bisector curvature regions (with a Spearman’s rank
Table F.1: Results from the flicker analyses on some targets described in the present study. This table is available in its entirety in machine-readable form (315 targets) at the CDS. We note that values $\tilde{\alpha}(\sigma_{30}) < 0.2$ have been replaced by “-1” in the CDS table.

| Target        | Mission | $f_c$ [µHz] | $f_0$ [µHz] | $\sigma_w$ [ppm] | $\alpha_\sigma$ | $\tilde{\alpha}(\sigma_{30})$ | $M_\star$ [$M_\odot$] | $R_\star$ [$R_\odot$] | $T_{eff}$ [K] | $\log g$ [cgs] | mag |
|---------------|---------|-------------|-------------|-------------------|-----------------|-------------------------------|----------------------|------------------|----------------|----------------|-----|
| HD 67458     | CHEOPS  | 3638        | 480         | 81                | 0.526 ± 0.120   | 0.888             | 0.94 ± 0.04                | 1.02 ± 0.02       | 5833 ± 62       | 4.37 ± 0.10     | 6.8 |
| HD 88595     | CHEOPS  | 1036        | 351         | 77                | 0.608 ± 0.493   | 2.079             | 1.35 ± 0.06                | 1.02 ± 0.02       | 6205 ± 35       | 3.99 ± 0.06     | 6.5 |
| KIC 1430163  | Kepler  | 824         | 378         | 115               | 0.61 ± 0.05     | 1.35              | 1.29 ± 0.08                | 1.46 ± 0.06       | 6586 ± 85       | 4.22 ± 0.01     | 9.6 |
| KIC 2837475  | Kepler  | 837         | 350         | 83                | 0.99 ± 0.24     | 1.60              | 1.34 ± 0.07                | 1.58 ± 0.05       | 6642 ± 92       | 4.16 ± 0.01     | 8.5 |
| KIC 3424541  | Kepler  | 448         | 251         | 142               | 1.36 ± 0.14     | 2.36              | 1.37 ± 0.21                | 2.45 ± 0.16       | 6100 ± 96       | 3.80 ± 0.02     | 9.7 |
| KIC 3427720  | Kepler  | 2029        | 607         | 95                | 0.34 ± 0.06     | 0.78              | 1.03 ± 0.08                | 1.09 ± 0.04       | 6045 ± 81       | 4.38 ± 0.01     | 9.1 |
| KIC 3456181  | Kepler  | 642         | 392         | 124               | 0.60 ± 0.47     | 1.15              | 1.27 ± 0.18                | 2.03 ± 0.15       | 6372 ± 77       | 3.93 ± 0.01     | 9.7 |
| KIC 3656476  | Kepler  | 1415        | 385         | 116               | 0.65 ± 0.03     | 1.37              | 1.03 ± 0.10                | 1.30 ± 0.06       | 5666 ± 76       | 4.22 ± 0.01     | 9.5 |
| KIC 3733735  | Kepler  | 1320        | 360         | 84                | 0.86 ± 0.04     | 1.52              | 1.30 ± 0.07                | 1.38 ± 0.05       | 6676 ± 80       | 4.27 ± 0.01     | 8.4 |
| KIC 3735871  | Kepler  | 2176        | 357         | 110               | 0.27 ± 0.01     | 0.65              | 1.05 ± 0.08                | 1.09 ± 0.04       | 6108 ± 92       | 4.39 ± 0.02     | 9.7 |

For HD 88595, there are numerous combinations of top, middle, and bottom region definitions that yield similar results, likely owing to the low number of data points for each night of the binned data. For night 1, the optimal combinations found with the MCMC approach were narrowly defined top regions at the blue-ward bend of the bisector (~25-30% of the CCF depth), a large middle region spanning most of the bisector (~40-80%), and a narrow region near the bottom (~80-90%); this combination yielded Spearman’s rank correlation coefficients near -0.9. The nested loop approach yielded 272 different combinations that were equally strongly correlated, both positively and negatively, between RV and curvature; combinations that probed the top two thirds were negatively correlated, while combinations probing the bottom two thirds were positively correlated. For night 2, the MCMC approach led to optimal regions defined with a narrow region above the blue-ward bisector bend (~10-20%), a region just below the bend (~35-55%), and a region near the bottom of the bisector (~70-95%), with a correlation coefficient near -0.9. The nested loop approach yielded 26 combinations of similar strength; 25 of which led to anticorrelations near -1 (the exception, with a positive correlation, was regions 40-55%, 65-75%, and 75-80%).

On one hand, since we can optimize the BIS and bisector curvature regions to reveal strong correlations with RV, it is possible that we might be probing the impact of granulation. However, since the bisectors do not seem to behave in a coherent way across the nights, it is difficult to confirm the driving force behind the changes we see. Forthcoming work will include a refined treatment of the p-modes and an optimization to mitigate the effects of the current CCF template masks smearing out the individual line shapes and curvatures. This work would also benefit from further observations, potentially at higher resolution.