Radial velocities: Direct application of Pierre Connes’ shift-finding algorithm to cross-correlation functions

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ABSTRACT

Context. Pipelines of state-of-the-art spectrographs dedicated to planet detection provide, for each exposure, series of cross-correlation functions (CCFs) built with a binary mask (BM), as well as the absolute radial velocity (RV) derived from the Gaussian fit of a weighted average CCF\textsubscript{tot} of the CCFs.

Aims. Our aim was to test the benefits of the application of the shift-finding algorithm developed by Pierre Connes directly to the total CCF\textsubscript{tot}, and to compare the resulting RV shifts (DRVs) with the results of the Gaussian fits. In a second step, we investigated how the individual DRV profiles along the velocity grid derived from the shift-finding algorithm can be used as an easy tool for detection of stellar line shape variations.

Methods. We developed the corresponding algorithm and tested it on 1151 archived spectra of the K2.5 V star HD 40307 obtained with ESO/ESPRRESSO during a one-week campaign in 2018. Tests were performed based on the comparison of DRVs with RVs from Gaussian fits. DRV profiles along the velocity grid (DRV(i)) were scrutinized and compared with direct CCF\textsubscript{tot} ratios.

Results. The dispersion of residuals from a linear fit to RVs from 406 spectra recorded within a single night, a measure of mean error, was found to be \(\sigma=1.03\) and 0.83 ms\textsuperscript{-1} for the Gaussian fit and the new algorithm, respectively, which is a significant 20% improvement in accuracy. The two full one-week series obtained during the campaign were also fitted with a three-planet system Keplerian model. The residual divergence between data and best-fit model is significantly smaller for the new algorithm than for the Gaussian fit. Such a difference was found to be associated in a large part with an increase of \(\sim 1.3\) m.s\textsuperscript{-1} in the difference between the two types of RV values between the third and fourth nights. Interestingly, the DRV(i) profiles reveal at the same time a significant variation of line shape.

Conclusions. The shift-finding algorithm is a fast and easy tool that provides additional diagnostics on the RV measurements in series of exposures. For observations made in the same instrumental configuration, and if line shapes are not varying significantly, it increases the accuracy of velocity variation determinations. On the other hand, departures from constancy of the DRV(i) profiles, as well as varying differences between RVs from this new method and RVs from a Gaussian fit can detect and report in a simple way line shape variations due to stellar activity.

Key words. techniques: radial velocities-stars: activity-methods: data analysis-planets and satellites: detection

1. Introduction

Since the discovery of 51 Pegasi b, the first exoplanet detected around a main-sequence star (Mayor & Queloz\textsuperscript{[1995]}, many other planets (1065, 22 September 2023) have been detected with the indirect method of monitoring the radial velocity (RV), which monitors the reflex motion of the star, and their projected masses determined (m sin i). Since the reflex RV is proportional to the planet mass \(m\), there is a great interest to increase the precision of RV measurements, in order to approach the case of an Earth twin planet in the habitable zone, about 10 cm.s\textsuperscript{-1}. Modern spectrographs, such as ESPRESSO at the Very Large Telescope (Pepe et al.\textsuperscript{[2021]} or HARPS North and South (Pepe et al.\textsuperscript{[2000]}), Cosentino et al.\textsuperscript{[2012]}, have reached unprecedented stability and precision in wavelength assignment of observed spectra, well below 1 ms\textsuperscript{-1}. Another way to increase the precision is to add new wavelength domains to the optical domain. This is the case of new near-IR (NIR) spectrographs like SPIROU (Donati et al.\textsuperscript{[2020]} and NIRPS (Bouchy et al.\textsuperscript{[2017]}). Instead of discarding spectral regions contaminated by telluric absorptions, their correction and use is now also increasing the RV accuracy, moderately in the visible (see, e.g., Ivanova et al.\textsuperscript{[2023]} for ESPRESSO), and strongly in the NIR (see Cook et al.\textsuperscript{[2022]} for SPIROU).

However, now that spectrometers have reached a precision well below 1 ms\textsuperscript{-1}, it appears that the time variations of the blueshifts associated with convective granulation and supergranulation of the star atmosphere are the limiting factors for the detection of low mass planets by means of RV methods (Munier et al.\textsuperscript{[2015]} because they affect the shifts of the stellar lines from which we attempt to derive a change in Doppler shift of spectral lines as a proxy of the dynamical dr/dt. The granulation is the irregular cellular pattern at the surface of stars that arises because stars have a convective envelope in their photospheres where the hotter bubbles of gas rise (blueshift) and the cooler bubbles sink (redshift). The imbalance between the contributions of hot gran-
Two main processes affecting the RV measurements connected to GBS may be identified, acting on different timescales. The first is related to stochastic fluctuations of granulation and supergranulation convective blueshift. The lifetime of one granule is on the order of a few minutes, and the number of granules on the visible disk of a star is on the order of $10^2-10^3$ for a star like the Sun; the average RV will not be rigorously constant, but rather will display stochastic fluctuations. The magnitude of these fluctuations has been estimated from model simulations by Meunier & Lagrange (2020) for stars from F6 to K4 spectral classes: peak-to-peak fluctuations on the order of 2 to 0.5 ms$^{-1}$. The second process is the attenuation of granulation blueshift. It has been shown from solar observations that the convective granulation blueshift is inhibited or attenuated by magnetic activity, which manifests itself on the Sun by solar spots, faculae, and plages (Meunier 2021). From the analysis of solar Dopplergrams and magnetograms obtained with the MDI instrument on board SOHO, Meunier et al. (2010) measured along a whole solar cycle (11 years) that the average RV of the integrated solar disk is increasing with solar activity (due to the attenuation of the granulation blueshift) from 0 (quiet Sun as a reference) to 8 ms$^{-1}$, almost 100 times larger than the reflex motion induced by Earth around a G star. Therefore, as said above, the granulation and supergranulation and their time variations are the limiting factors for the detection of Earth-size planets via RV methods (Meunier et al. 2015).

Coming back to the pioneering work of Dravins et al. (1981) studying high-resolution solar spectra, they argued that the bottoms of strong absorption lines should show smaller shifts since they form higher up in the atmosphere where the granulation is not distinctly visible, and that the lines in different wavelength regions with different granular-intergranular contrast or different atmospheric opacity should show differing amounts of line asymmetries and shifts. Therefore, they explained physically why the solar lines are distorted, as evidenced by their bisector showing a characteristic C shape. At that time, however, they did not discuss changes in these distortions, but quite soon exo-planet hunters used the bisector analysis to attempt to discriminate between dynamical RV changes due to the presence of exo-planets and spurious, activity connected, RV changes (e.g., Queloz et al. 2001).

One of the methods used to analyze a RV time series of observations of a particular star is based on the construction of a binary mask (BM) around selected stellar lines and the computation of the cross-correlation function (CCF) between mask windows and the observed stellar lines. Gaussian fitting of the weighted sum of the various CCFs (hereafter CCF$_{tot}$) provides the absolute radial velocity RVabs. At present, official pipelines of the most sophisticated spectrographs (e.g., the ESPRESSO pipeline) make available the results of the Gaussian fit of the CCF$_{tot}$ and also the CCFs for each order and their weighted sum CCF$_{tot}$. Users can directly use the pipeline RVs for planetary orbit modeling. These pipeline values also provide on-the-fly quality checks of the measurements.

There are other techniques of precise RV (pRV) measurements than the BM/CCF method, some of them reaching a high degree of complexity and outperforming the use of CCFs. Template fitting is also largely developed and used in pipelines (Zechelester et al. 2018, Astudillo-Defru et al. 2015). Data-driven techniques (Bedell et al. 2019) and line-by-line (LBL) analyses initiated by Dumusque (2018) and developed further by Artigau et al. (2022), as well as the YARARA approach of Cretignier et al. (2021), are other sophisticated post-processing methods reaching very high accuracy. We do not detail the different methods here, except for the line-by-line algorithm, because there is one common point with our work, namely the use of the shift-finding algorithm developed by Pierre Connes (1985). In the field of pRV measurements, Artigau et al. (2022) have developed a method that is very efficient at eliminating the outliers, whatever their cause. First they built a high signal-to-noise ratio (S/N) template spectrum of the star, by taking the median of all observed spectra. Each stellar spectrum is BERV-registered. Then, each current spectrum is compared line-by-line to the template, and one RV value (actually, a change in RV with respect to the line template) is derived for each line with the Connes shift-finding algorithm, revisited by Bouchy et al. (2001). A histogram of the DRV values for the current spectrum is built, and sigma-clipping is done, eliminating all DRV values defined as outliers. Outliers may come from telluric residuals, cosmic rays, detector defects, and other features. The stellar activity, responsible for spurious shifts, is mitigated by using a Gaussian process fitted to the time series of an activity indicator, linked to the variation of the average FWHM of all lines (in the velocity scale). The CCF method has some advantages. Compared to individual lines, merged CCFs have very high signal and S/N. Moreover, the RV extraction does not need auxiliary data or post-processing using such data. As such, it is appropriate for on-the-fly measurements or analysis of limited measurements of the same target, and for pipeline products. Finally, full CCFs can be used to investigate the line shape and its variability in addition to the simple Gaussian fits.

The idea that we explore in this paper is to apply the shift-finding algorithm to the CCF$_{tot}$ and not to individual lines, at variance with Artigau et al. (2022). It can be seen as an algorithm of intermediate complexity between the Gaussian fit of pipeline-based CCFs and the LBL method. It combines the advantage of the CCF technique, in particular the high signal, and the optimal extraction of RV change from the comparison between two spectra. It should be rather simple for the users to explore the capabilities of this technique with the corresponding Python software available along with this article, using either archived data or their own observations. We do not pretend that it would give more precise RV values than the most sophisticated methods mentioned above. Our aim is to show that it can do better than the CCF Gaussian fit, and bring some on-the-fly warning information on spectral line shape variations. The overall objective of this paper is to describe the algorithm, and explore its capabilities on a particular example of a RV time series. In homage to the pioneering works of Pierre Connes in the field of exoplanets and other instrumentation for astronomy (e.g., Fourier transform spectroscopy), we named this algorithm the Exoplanets Pierre Connes’ Algorithm (EPiCA).

In Section 2 we recall the shift-finding approach and the two basic formulas of his work. The first formula is for retrieving the change in RV between two spectra, and the second formula gives an intrinsic maximum precision provided by a piece of spectrum and the number of photons collected. In Section 3 we recall the classical RV method, using the change in minima of the Gaus-
sian fit to CCF. It is the one used in the official ESO pipeline. In Section 4 we describe our algorithm, and validate it by a simulation exercise. In Section 5 our method is applied to a time series of RV measurements on star HD 40307, which is known to host planets. The achieved accuracy on the RV variation is tested in two ways, by comparing the RV dispersion with that resulting from a Gaussian fit on the one hand, and by comparing the best fit to the three-planet Keplerian model based on RVs from the algorithm and that based on RVs from a Gaussian fit. In Section 6 we describe how the method allows an easy detection of line shape variability. A large part of the data analysis of this paper is derived from the Ivanova (2023) PhD manuscript. We provide a Python code implementing this new algorithm, freely accessible through the GitHub repository.

2. The shift-finding method to measure star radial velocity changes.

This method is fully described in a seminal paper (Connes 1985). At that time no exoplanet had been discovered, in spite of various attempts. In this paper the author said that the best way to discover an exoplanet would be an indirect method: monitoring for periodic variations of the radial velocity RV of a star. He was even more specific, saying that this could be achieved by measuring the spectrum of the star with a high-resolution spectrometer, with an echelle-grating spectrograph, cross-dispersed, and a CCD detector. He also said that it may be illusory to measure the absolute RV of a star, dR/dt, (R, distance of the star to the observer) with an accuracy of 1 ms⁻¹ from the observation of a star spectrum, because it is only a proxy of the mechanical dR/dt. For instance, the Einstein effect cannot be estimated accurately enough to predict its magnitude for a given star which surface gravity may be known by other means: its spectral type. This general relativity Einstein effect is mimicking exactly a Doppler shift, and cannot be disentangled from a Doppler effect. It is on the order of 600 ms⁻¹ for the Sun (González Hernández et al. 2020).

However, the variation of RV with time may be accurately measured, making the difference of two determinations of RV at two epochs: the Einstein effect, a constant for a given star, disappears from the difference. This is why Pierre Connes called his method accelerometry. However, it is a somewhat improper denomination, since acceleration is a

\[ \frac{\Delta V}{c} = \frac{\delta sp(i)}{s p(i) \delta A(i)/\delta s p(i)} \]

(3)

Then all the \( \frac{\delta sp(i)}{s p(i)} \) have to be combined accounting for their individual errors \( \sigma(i) \). In the case of Gaussian errors, it is known that the optimal combination is to use weights \( \frac{1}{\sigma^2(i)} \), while the error \( \sigma(RV) \) on the combined retrieved RV is such that

\[ \frac{1}{\sigma^2} = \sum \frac{1}{\sigma(i)^2} \]

(4)

The variance \( \sigma^2(i) \) of \( \frac{\delta sp(i)}{s p(i)} \) can be calculated by the relation

\[ \Var(aX+bY) = a^2 \Var(X) + b^2 \Var(Y) \]

where a and b are constants and X and Y are random variables, applied to Equation 5

\[ \sigma^2(i) = \frac{1}{s p(i) \delta A(i)/\delta s p(i)}^2 \Var(A(i)) \]

(5)

\[ + \frac{1}{s p(i) \delta A(i)/\delta s p(i)}^2 \Var(A_n(i)) \]

Fig. 1. Principle of shift-finding algorithm of Pierre Connes. Example of a spectral line at three epochs. Epoch 0 - reference (black), Epoch 1 - shifted by +2 kms⁻¹ (red), Epoch 2 - shifted by +15 kms⁻¹ (blue). The intensity change is measured within the d.l slice. This figure is similar to Fig. 4 in Connes (1985).

the axis is the wavelength along the 2D array detector lines, with continuous coordinate sp (for spectel)

- the spectel index is i

- the intensity of the spectrum is \( A_0 \) at epoch 0, and \( A_n \) at another epoch n. This intensity is to be measured in electrons created by light. Both spectra \( A_0 \) and \( A_n \) must be identical, only shifted with respect to one another by a small displacement \( \delta sp \).

The intensity in one pixel i (or one spectel) is changing by

\[ dA(i) = A_n(i) - A_0(i) = -\frac{\partial A_0(i)}{\delta sp(i)} \delta sp(i) \]

(1)

and so it is possible to extract for each pixel i (or spectel) the wavelength shift \( \delta sp(i) \). We call it the first formula of Connes, replacing \( A_0 \) by \( A' \):

\[ \delta sp(i) = \frac{A_0(i) - A(i)}{dA(i)/\delta sp(i)} \]

(2)

Equation 2 can be transformed into a Doppler shift and the corresponding change \( \delta V(i) \) of the radial velocity of the star between two epochs:

\[ \frac{\delta V}{c} = \frac{\delta sp(i)}{s p(i) \delta A(i)/\delta s p(i)} \]

(3)

In the following, we have new notations:

2 https://theses.hal.science/tel-04504477
3 https://github.com/aeclft/EPIC/A
The variance of a number of photoelectrons $A$ is equal to $A$. In most practical cases, the reference spectrum $A(i)$ is built from many spectra and $\text{Var}(A(i))$ becomes much smaller than $\text{Var}(A_n(i))$. Hence equation \[8\] will be

$$\sigma^2(i) = \left( \frac{1}{s p(i) \partial A(i)/\partial s p(i)} \right)^2 A_n(i).$$ \[6\]

Here it is assumed that $A(i)$ is a perfect noise-free spectrum. This is always the case when a template median spectrum is built from several tens of observations, as practiced commonly by high-precision RV programs. In the case of the comparison of two spectra of similar intensities (for instance, taking the first of a time series as a reference), then a factor 2 should be added as a multiplier in equation \[6\].

Following the notations of Bouchy et al. (2001) who revisited the Connes approach, the next step is to introduce the weight function $W(i)$:

$$W(i) = \frac{1}{\sigma(i)^2} = \frac{s p(i) \partial A(i)/\partial s p(i)}{A_n(i)}.$$ \[7\]

The velocity change then is

$$\frac{\delta V}{c} = \frac{\sum \frac{\partial \bar{W}(i)}{\partial V} W(i)}{\sum W(i)} = \frac{\sum (A(i) - \bar{A}(i)) W(i)}{\sum W(i)}.$$ \[8\]

Connes (1985) also showed that the uncertainty on a RV measurement can be calculated a priori on the basis of photon noise. Even if there is no velocity change between epochs due to the motion, we can find a small velocity change caused by the noise perturbation of spectrum at epoch $n$. In the following we consider only the photon noise, neglecting the readout noise from the detector. The approach is based on the quality factor $Q$ which can be computed for any star, and is independent from the absolute flux (if we neglect the detector noise contribution). The quality factor $Q$ depends on the wavelength structure of the spectrum and $\delta V_{\text{min}}$ is the photon noise limit which can be achieved to determine the absolute wavelength position of a piece of an observed spectrum in radial velocity units

$$\delta V_{\text{min}} = \frac{c}{Q \sqrt{N_c}},$$ \[9\]

where $c$ is the speed of light, $N_c$ is the total number of photoelectrons counted over the whole spectral range considered, and $Q$ is the quality factor equal to

$$Q = \frac{\sqrt{\sum W(i)}}{\sqrt{\sum \bar{W}(i)}}.$$ \[10\]

We call it the second formula of Connes. It should be noted that the observed spectra are given in ADU units. In order to convert into a number of electrons, one must multiply by the gain of the CCF read-out system, the number of electrons per ADU, which is included in the headers of ESPRESSO spectra (0.9 electrons per ADU in the present case):

$$\delta V_{\text{min}} = \frac{c}{Q \sqrt{N_c}} = \frac{c}{Q \sqrt{0.9 \times N_{\text{ADU}}}}.$$ \[11\]

Connes (1985) demonstrated mathematically that this algorithm is optimal (the best possible), and makes use of all photons and information contained in the spectrum in an optimal way. This fact has been later recognized many times by scientists working on the subject, for instance those who used the Cross-Correlation Function of the spectrum with a spectral line which wavelength is well defined. It can either be a laboratory measured transition wavelength, or better the wavelength of an observed stellar spectral line, to account for gravitational redshift and mean convective granulation blueshift. An ensemble of such lines is called a binary mask (BM).

The algorithm has other features:

- It does not need a very accurate wavelength spectral calibration of all pixels/spectra, although it requires a great stability of the spectrometer between the two epochs.
- The pixels need not to be equally spaced and with a uniform size

However, the algorithm does not work properly when RV$_1$ and RV$_2$ are quite different, which occurs because of the Earth’s 30 kms$^{-1}$ orbital motion, inducing a shift on the detector of many pixels: the formula \[1\] may not be used any more, because the same pixel samples at epoch E$_2$ a quite different portion of the spectrum, with a different slope, than at epoch E$_1$ (Figure \[1\]). The typical width of a spectral line is on the order of 3-10 kms$^{-1}$; see Figure \[1\] with simulation of +2 and +15 kms$^{-1}$ shifts. However, this difficulty can be circumvented by using the formula (1), not applied to a pixel and trying to determine the shift in pixel units, but to a spectel, a wavelength element, and to use a wavelength scale in the frame of reference of the star target. An approximation of this requirement may just to correct the wavelength scale of the measured spectra from the BERV (Barycentric Earth Radial Velocity). This was done for instance for example in Dupuis et al. (2018), who applied the Connes formula in a line-by-line template matching analysis. We note that none of the two formulas of Connes is giving an estimate of RV.

3. The Cross-Correlation Function (CCF) algorithm to determine a radial velocity RV.

Baranne et al. (1996) designed the spectrometer ELODIE, partially inspired by the work of Connes (1985), and stimulated by Michel Mayor. ELODIE is a cross-dispersed spectrometer and CCD. Installed at Observatoire de Haute Provence, it allowed the rapid discovery of 51 Pegasi b, the first exo-planet found around a Sun-like star, detected by the RV indirect method (Mayor & Queloz 1995). Earlier on, planets had been detected around a pulsar (Wolszczan & Frail 1992).

In Baranne et al. (1996) there is a description of the CCF algorithm applied to the series of stellar lines. The stellar spectrum intensity is digitized on pixels, each with an assigned wavelength. A box-car shaped “emission” line is 0 everywhere, and 1 in a small wavelength interval (for instance one pixel) centered on the absolute wavelength chosen for the transition responsible for the stellar line. The correlation function is computed on a fixed grid of potential absolute RV values (in kms$^{-1}$). Each point of the CCF is the portion of the stellar spectrum which is included in the box-car. Usually the CCF is fitted by a Gaussian, and the wavelength of the Gaussian minimum reveals a “proxy” of the dynamical absolute radial velocity of the star. A series of emission lines constitutes a Binary Mask. Piling-up together all individual CCFs of one optical Echelle order of the spectrometer, to get one single CCF per order has the great advantage to average out some artifacts, for example pixel-to-pixel response nonuniformity (PRNU); optical fringes caused by the optics of the spectrometer, imprinted on the observed spectrum; and the blaze effect, which results in a bias when the CCF on one single line is fitted by a Gaussian.

In a word, the piled-up CCF algorithm is quite robust to several
artifacts. Any pattern which is fixed in the wavelength frame of the spectrometer, while the star spectrum is moving by up to ±30 km s\(^{-1}\), will be detrimental (producing a bias on RV) for all methods which compare directly the motion of the spectrum, as the shift-finding algorithm or others, like template matching. This is the case of several artifacts (e.g., PRNU, dark current nonuniformity, DCNU), optical fringes, and micro-telescopes (large tellurics are just avoided by standard Binary Masks). For template matching, when the template is built from many observations with full yearly excursion of BERV, it will somewhat smooth out artifacts. Also, for CCF building some weights are usually assigned to each line of the Binary Mask (Pepe et al. 2002). For instance, Lafarga et al. (2020) use as a weight for each line the ratio between the contrast and the width of the line, where the contrast is the relative depth of the line and is given for each line of the official ESPRESSO BM. Then, all orders are combined together through the optimal combination of Gaussian errors, with a weight equal to \(1/\sigma_{\text{err}}^2\). The uncertainty estimate for this order \(\sigma_{\text{err}}\) is given by the second formula of Connes applied to the CCF, as described in Boisse et al. (2010). Another way to combine the CCFs from all Echelle orders is just to add them together to get a single CCF\(_{\text{tot}}\) per exposure, since each of the order CCF has been obtained from the addition of all CCFs of the BM lines inside this order, already weighted for each line. This is indeed the case of the official ESO/ESPRESSO pipeline at VLT. While a good pipeline is supposed to correct many artifacts quoted above (PRNU, DCNU, optical fringes, micro-telescopes, stray light, etc.), one should still worry about the residuals after the correction of these effects by the pipeline. Artigau et al. (2022) have improved the RV data by eliminating outliers (resulting from residuals after pipeline corrections) with a Line-by-Line analysis of Barnard’s star acquired with SPIRou spectrometer at CFHT.

4. Proposed algorithm: applying the first formula of Connes to piled-up CCFs.

4.1. Description of the new EPICA algorithm.

We propose to combine the optimal retrieval, photon noise limited, algorithm of Connes (equation 8) with the robustness of the piled-up CCF. We call it the “CF1 to CCF” algorithm (CF1, Connes formula 1) or the EPICA method. Instead of applying the 1\(^{\text{st}}\) formula of Connes to a measured spectrum at two epochs, we apply it to the two CCF\(_{\text{tot}}\) computed for those two epochs, yielding CCF1 and CCF2. The trick is that the CCF is not computed on the wavelength scale provided by the laboratory calibrated spectrometer, but on the wavelength scale produced after correction from the barycentric Earth radial velocity (BERV). In the Solar System barycentric frame of reference, the radial velocity of a star is constant, except for the small variations induced by the potential presence of exo-planets. Today, conversions from geocentric to barycentric velocities have reached accuracy on the order of \(\text{cm s}^{-1}\) (Wright & Eastman 2014) and are not a limiting factor. Therefore, there is only a small displacement of the two curves CCF1 and CCF2, suitable to use the Pierre Connes algorithm (equation 1) valid for small displacements. To the best of our knowledge, this method has never been used or described before. In practice, in the CCF fits files taken from the ESO archive the CCF matrix has 171 columns, while there are only 170 Echelle optical orders. The last column of the CCF matrix is an order-merged CCF\(_{\text{tot}}\) produced by the pipeline itself. We have verified that this CCF\(_{\text{tot}}\) is computed by adding together all CCF per order for the exposure. We applied the EPICA algorithm to this order-merged CCF\(_{\text{tot}}\) of the pipeline (last column numbered 170 in the code, where numbering starts at zero). One particular exposure spectrum 1 is taken as a reference, providing CCF1\(_{\text{tot}}\). Each other exposure 2 provides a CCF2\(_{\text{tot}}\), and the 1\(^{\text{st}}\) formula of Connes (Equ. 8) is applied, yielding the change of RV, DRV, between exposure 1 and exposure 2. The CCF2\(_{\text{tot}}\) must be normalized to CCF1\(_{\text{tot}}\) before applying Equ. 8 (both CCF1\(_{\text{tot}}\) and CCF2\(_{\text{tot}}\) must have the same integral). However, we note that all computations required for Equ. 8 use CCF2\(_{\text{tot}}\) before its normalization to compute the weighting function W(i) and the quality factor Q (the “on the fly” quality factor and W, for each exposure).

4.2. Validation; simulation of shift-finding algorithm applied to an observed CCF.

Here we are testing the 1st and 2nd formulae of Connes (equations 8 and 9), applied to an observed CCF. For this simulation, we have used a series of 200 exposures taken on star HD 40307 (taken during the night from 24 to 25 December, 2018 (called night 24 elsewhere in this paper). We have added all 200 spectra together, spectel to spectel, for order 104, and computed the CCFs on a given grid \(V_{\text{rad}}\) of radial velocities (figure 2, black curve). The S/N for one spectel is about 1,000 for this reference spectrum S1. The wavelength scale WS1 was the spectrometer wavelength scale for exposure number 100. Order 104 (covering wavelength range 5523.8 – 5606.7 Å) was selected because this order is not affected by tellurics, and the signal is rather high with one single exposure. The S/N for one point of the CCF is about 4,000.

Then, a synthetic spectrum S2 was derived from the stacked spectrum S1 just by modifying the wavelength scale, as if the star had changed its velocity by \(+100\text{ ms}^{-1}\) : same intensities but on a RV shifted scale WS2.

In order to mimic what would be the values of spectrum S2 sampled on the grid WS1, we interpolate the spectrum S2 vs WS2 on all the points of the grid WS1. The CCF2 of the spectrum S2 sampled on WS1 is done on the same grid \(V_{\text{rad}}\) of radial velocities, yielding the green CCF curve of Figure 2. Also displayed in Figure 2 (in red) is the weight attached to each point of the \(V_{\text{rad}}\) grid (equation 8), according to the photon noise limit of Pierre

\[4\text{ Prog.ID:0102.D-0346(A); PI: Bouchy}\]
Connes first formula, here applied to the CCF1. The double-peak shape of the weight curve (in red) just shows the relative contribution (weight) of each point of the CCF to determine a shift: the weight is depending on the square of the derivative (with respect to the \( V_{rad} \) grid):

\[
weight(i) = 1/\sigma^2(i) = \left( \frac{\partial A_0(i)}{\partial sp} \right)^2 \frac{1}{2\Delta v}
\]

(12)

When the first formula of Connes is applied to the CCF1 and CCF2, a radial velocity change \( DRV \) of 99.613 ms\(^{-1}\) is returned, while the second formula of Connes giving the uncertainty applied to CCF1 (or CCF2) is 0.366 ms\(^{-1}\). The retrieved DRV is near the +100 ms\(^{-1}\) simulated RV shift, with a difference from 100 ms\(^{-1}\) near the nominal error bar. Therefore, this simulation exercise validates this new algorithm, and the uncertainty associated with it. It can be pointed out that, while applying a shift-finding algorithm to the comparison of spectra as a function of wavelength includes an approximation (finding a shift instead of a stretch), applying the same shift-finding algorithm to a CCF does not imply the same approximation, because the scale of the CCF is a radial velocity, and computing the CCF accounts exactly for the Doppler stretching.

4.3. Basic differences between the two RV retrieval algorithms.

The ESO/ESPaSSO pipeline algorithm for RV retrieval is to fit the curve CCF\(_{tot}\) (similar to green and black curves in Figure 2) by a symmetric Gaussian and assign as absolute RV value the position of the center of the Gaussian. Therefore, only one single information is derived from the full CCF\(_{tot}\) curve. Actually, as shown by González Hernández et al. (2020) for the Sun (integrated disk through observation of the Moon), the exact position of this symmetry axis of a Gaussian fit to a single solar line depends somewhat on the wavelength extent of the fitting domain, which shows that the spectral lines are not rigorously symmetric. Inasmuch as the curve CCF\(_{tot}\) is an average image of all piled-up solar lines of the Binary Mask, it is likely that such a dependence also exists for the CCF\(_{tot}\). Then, RV changes of a star are just computed by subtracting a constant from all RV measurements.

On the other hand, the Connes algorithm does not claim to determine an absolute value of RV for each spectrum and corresponding CCF\(_{tot}\), but only the change \( DRV \) of RV between two spectra and their corresponding CCF\(_{tot}\). Actually, each point of the CCF\(_{tot}\) gives an estimate of DRV, which can be combined together in an optimal way (mathematically) by applying the weight function of equation (12) (red curve of figure 2). This is what we have done in the following. However, there is potentially the possibility to study separately various parts of the spectral lines (or their image trough the CCF\(_{tot}\)). In particular, the red side and the blue side could give different estimates of the RV change, if stellar activity deforms the spectral lines and CCF\(_{tot}\) in a nonsymmetrical way. In summary, it is clear that the ESO pipeline for ESPRESSO must give, for each observed spectrum, one single number, an estimate of the absolute radial velocity of the star (in the barycentric system), revealed by its Doppler effect; and this is indeed what is provided by the present version of the ESO ESPRESSO pipeline when fitting CCF\(_{tot}\) by a symmetric Gaussian.

When a change of RV between two spectra (taken at two epochs) must be evaluated, the simplest method consists of comparing RV\(_1\) and RV\(_2\) from the pipeline, and this is exactly what is done routinely during the search for exoplanets by most of scientific teams. However, the two spectra contain an enormous amount of information: they could be compared, in the extreme limit, spectel by spectel, with the Pierre Connes approach, each spectel giving an estimate of the DRV = RV\(_2\) − RV\(_1\). This could be a way to detect some spectral regions which are affected by stellar processes changing the shape of the spectral lines (including variations of convective Granulation Blue Shift, GBS). Unfortunately, there are some artifacts spoiling this extreme approach: PRNU, DCNU not perfectly known and accounted for; optical fringes, which may change with the orientation of the telescope; uncorrected micro tellurics, to name a few. These outliers are well detected by the Artigau et al. (2022) technique which explains its success in increasing the accuracy of RV. On the other hand, using CCF order-by-order and even CCF\(_{tot}\), mitigates these artifacts by averaging them out: the CCF method is quite robust. With the proposed EPiCA method (applying the Connes approach to the CCF\(_{tot}\)), there is a hope to combine the robustness of the CCF approach (which combines many lines together, and partially smoothes out some artifacts) and the sophistication of the Pierre Connes’ approach.

We note two other interesting studies that are using also CCF\(_{tot}\), with the aim (the same aim as us) to try to discriminate planetary reflex Doppler shifts from stellar variability. Simola et al. (2019) are adding one more parameter in the Gaussian fit to the CCF, the skewness (asymmetry). Collier Cameron et al. (2021) use the autocorrelation function (ACF) and departures from an average of all ACF, which requires a lot of observations. Here we explore an alternate route, by studying in detail how the CCF\(_{tot}\) behaves, with the help of the Pierre Connes shift-finding algorithm and the full details provided by the DRV curves.

5. Application to HD 40307 ESPRESSO data and three-planet model.

5.1. Overview.

Ideally, in order to compare two methods yielding changes of RV, one should use a planet-less star with a constant RV, and compute the standard deviation of a series of measurements of RV changes around the mean which should be 0. On the other hand, we wished to use ESPRESSO data which provide an absolute wavelength scale of excellent quality (Pepe et al. 2021), possibly the best in the world, and extensive series of measurements. Looking at the available ESPRESSO data, we noticed a quite exceptional series of 1151 exposures spread over 7 days of star HD 40307. HD 40307 is a K2.5V type star with visual magnitude 7.147 and distance 13 parsec. It was observed during 6 nights from 22 December to 28 December 2018 by ESPRESSO. The series of exposures were made in HR mode which resolution varies between 100 000 and 160 000 across the spectrum. It had originally been planned to search for an asteroseismology signal (finally, not found yet on this star), but has the advantage of providing a unique way to get an estimate of the true error made on RV changes, based directly from data on the dispersion of RV change residuals to a linear best fit during a short period of time. For this asteroseismological campaign the exposure time was set to 30 seconds for all 1151 exposures, and the sampling period was about 78 seconds.

The star HD 40307 harbors a multi-planetary system. It was reported by Mayor et al. (2009) that it hosts 3 super-Earth-type planets, with orbital periods \( P_1 = 4.311 \) days, \( P_2 = 9.6 \) days and \( P_3 = 9.6 \) days.
night 25 (in short for 25 december). The most recent analysis made by Coffinet et al. [2019] confirm the findings of Diaz et al. [2016]; they found 3 exoplanets from Mayor et al. [2009] and also the additional planet f from Tuomi et al. [2013], but as well as Diaz et al. [2016] cast doubt on the presence of planets e and g. After subtraction of a long-term signal, which probably represents a magnetic cycle of the star, the signal around the period of 200 days has a very low significance and the signal around 34.6 days is absent. In our analysis, we considered only the three planets b, c, d, and f. Because its period of 51.76 days is considerably longer than the short duration (7 days) of the time series and would not make any significant difference in a model fit to data.

5.2. Comparison of the two RV time series obtained with the two methods.

We now compare the two RV time series: the official ESPRESSO, containing the RV assigned to each exposure recording one spectrum of HD 40307 (the pipeline series), and the time series that we obtained from our new EPiCA method, CF1 applied to CCF$_{tot}$. They are plotted in Figure 3, not as a function of time, but as a function of exposure number; the data are concatenated. From the pipeline RV data was subtracted a constant radial velocity of 31.3668 km/s, while the EPiCA series displays the RV change between each exposure and exposure $n'10$ taken as an arbitrary reference. Therefore, the overall offset between the two time series is arbitrary and has no particular significance. Both time series show a rather sharp decrease after exposure 615, which is the last one of the night 25 (in short for 25 december). This is due to the presence of planets, as we shall see later. The offset between the two series is partially due to the difference of reference exposure: $n'0$ for ESPRESSO pipeline, $n' 10$ (first of night 24) for Connes CF1 applied to CCF$_{tot}$. But the offset is not constant, as can be seen when plotting the difference between the two time series (Fig. 3). There is a change of $\pm 1.3 \text{ms}^{-1}$ between nights 25 and 26.

Therefore, one of the two methods is giving some wrong results by about 1.3 ms$^{-1}$ (or may be both of them), which do not correspond to a true change of the dynamical radial velocity $\text{d}R/\text{dt}$. We suspect that this is the effect of stellar processes, and more precisely of granulation bluelshift (GBS) changes, on a timescale of a few hours, together with the fact that both methods are differently sensitive to stellar processes.

5.3. Comparison of RV dispersion over one night from a linear fit.

One criterion for RV retrieval method comparison is the use of a time series of measurements when the star is not moving at all. The precision of the RV method is quantified by the standard deviation $\sigma$ of the RVs (the square root of the variance) of the series of measurements (this is the definition of the precision). In our case of the HD 40307 time series, the star is moving because of planets, and RV is changing. However, we may restrict the time series to a particular night and a limited duration in such a way that the RV variation is small and close to linear. In this configuration, we may accommodate with planet-induced star motion by subtracting a linear fit and computing the standard deviation of the residuals, as a quality indicator of the method. Actually, this linear fit may also include spurious RV variations due to stellar variability affecting the Doppler shift of the disk-integrated spectrum.

The first night contains only 10 measurements and is not suitable for this statistical exercise. The third night (25 December) displays a significant number of outliers, affecting the second half of the 200 measurements (figure 5). This behavior has been assigned to an instability of the cooling system of the ESPRESSO blue detector (Figueira et al. [2021]). Therefore, the night of 24 December containing 406 measurements was selected for further comparison of the two methods.

As said above, we compare in Figure 5 the EPiCA results with the results from (symmetric) Gaussian fits to CCF$_{tot}$ (the RVs from the pipeline). Although not easily visible by eye, there is a gain (i.e., a reduction) in RV dispersion in the case of the EPiCA method. The cloud of data points can be seen on figures 4 and 5 at night 24 and day 2.2.

In order to compare quantitatively the two methods we made a linear fit to the 406 values of RVs of night December 24th for both measurement methods and removed a linear trend (due to planets and/or stellar processes) to keep only the residuals, and compute the dispersion around the average value. We made two histograms of the residual RV values with the same bins and compared them, as shown in Figure 5. The figure clearly shows the gain in precision with the EPiCA method, quantified by the widths of Gaussian fits to the two histograms. For this series of exposures, the semi-width of the Gaussian (at 1/\sigma) is reduced with the EPiCA method with respect to the pipeline, from 1.46 to 1.17 ms$^{-1}$, corresponding to a reduction of the dispersion (the actual mean error on RV changes measurements) from $\sigma = 1.03$ to 0.83 ms$^{-1}$, a significant 20% improvement of the precision.

The result is not very surprising, since P. Connes demonstrated that his first formula is the optimal way to measure Doppler shifts, by taking into account the totality of information contained in the two spectra (or here, the CCF$_{tot}$). On the other hand, as we discuss below, the hypothesis underlying the Connes formulation is an absence of variability of the shape of the spectra (or here CCF$_{tot}$), except for a single shift. Only pure Doppler shifts are allowed. We interpret this decrease in the RV dispersion during a short duration as evidence for the absence of strong variations of the stellar line shapes, at least of the absence of shape variations strong enough to cancel the benefit of the application of the CF1 formulation.

5.4. A three-planet best fit to the official pipeline ESPRESSO RV time series.

We now examine a second quality indicator of an RV changes retrieval method, totally independent of the first one, namely the true error computed from dispersion, discussed in the previous section. Our goal is to investigate whether or not the EPiCA method may be less sensitive than the Gaussian fit to spurious changes of RV due to stellar activity. The idea is that the RV changes due to planets do obey strictly to Kepler’s laws, while RV changes due to stellar activity are more random (but still stochastic). Therefore, we may produce a quality indicator indicating how well a series of measurements reproduce a pure Kepler’s law model of RV changes. To do so, we have used the entire HD 40307 time series. For each method, we have determined some best-fit parameters of the three-planet system, and computed the absolute dispersion during a short duration as evidence for the absence of strong variations of the stellar line shapes, at least of the absence of shape variations strong enough to cancel the benefit of the application of the CF1 formulation.
Fig. 3. The two RV time-series and their difference. Top: Comparison between the RVs derived from the Gaussian fit and the EPiCA method. The data (RV changes in m/s) are plotted as a function of exposure number. The pipeline RVs are plotted with their error bars, in a different color for each night. They were derived by subtracting from all pipeline RV data contained in each spectrum fits file the value of the first exposure: 31.3668 km/s. Red points are obtained by the EPiCA method applied to the CCFs of the current exposure and the first exposure of night 24 (exposure no10 when all nights are concatenated), taken as a reference. A constant 2 ms$^{-1}$ was subtracted for clarity. Bottom: Differences between the two time series of RV changes: Gaussian fit - EPiCA (CF1 applied to CCF$_{tot}$). This difference shows an abrupt decrease (∼1.3 ms$^{-1}$) after exposure no615, corresponding to the transition from night 25 to night 26, which remains after that.

## Table 1. Characteristics of three planets in the HD 40307 system from the HARPS 2008 campaign

<table>
<thead>
<tr>
<th></th>
<th>HD 40307b</th>
<th>HD 40307c</th>
<th>HD 40307d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude and error [m/s$^{-1}$]</td>
<td>1.84±0.14</td>
<td>2.29±0.13</td>
<td>2.31±0.14</td>
</tr>
<tr>
<td>Nominal period and error [day]</td>
<td>4.3114±0.0002</td>
<td>9.6210±0.0008</td>
<td>20.412±0.004</td>
</tr>
<tr>
<td>Zero crossing time T$_0$ at epoch 2008 (bjd-2.4e6)</td>
<td>54562.77±0.08</td>
<td>54551.53±0.15</td>
<td>54532.42±0.2</td>
</tr>
<tr>
<td>$m_2sini$ (M$_E$) (Mayor et al., 2009)</td>
<td>4.2</td>
<td>6.9</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Difference between data and best-fit model as the second quality indicator. In Table 1 we summarize some parameters of the three planets detected around HD 40307.
Fig. 4. Comparison of pipeline RV time series with three-planets modeling. The black dots represent the time series of changes of RV values contained in the official pipeline, obtained by subtracting the RV value of the first exposure of the first night. The thick pale gray solid line is the extrapolation of the sum of the three sine waves as determined from 2008 HARPS data. It does not closely fit the data because the extrapolation over nine years is sensitive to small errors in the periods. The dashed gray lines is the same as the solid gray line, but with planet b period shorter by 0.0004 d, corresponding to twice the claimed error bar for the period of planet b. The solid black line is the best fit to the pipeline RV data by adjusting the phases of the three planets.

5.4.1. Best-fit strategy and result of RV official pipeline ESPRESSO RV time series.

Our first analysis is done only on ESPRESSO 2018 data, without archive HARPS data. ESPRESSO data set consists only of 6 days, so it is not possible to detect a signal from the 4th (HD 40307 f), since it would induce only a too small drift over 6 days. We have assumed that planets are on circular orbits as it is mentioned in Table B.1 from Díaz et al. (2016).

Therefore, we kept fixed the amplitudes and periods of three planets at their most recently published values from Contet et al. (2019), where the authors corrected the HARPS wavelength calibration from the CCD stitching, a gap in blocks of pixels composing the full CCD. We know the time $T_0$, the origin of the sinusoidal wave at epoch 2008 from the exoplanet.eu (see Table B.1). With these time values of ascending zero crossing in March-April 2008, we can extrapolate in time all 3 sine waves with the defined periods up to the epoch of 2018 observations, getting the curve $V_r_{nominal}$ (pale gray, thick solid line) in Figure 4 compared to ESPRESSO data. We see a major discrepancy, easily explained: an error on any of the periods, propagated over ten years, will make $V_r_{nominal}$ not representing well the data of 2018. Also represented with a dashed gray line is the extrapolation with a period of planet b shorter by 0.0004 d, twice the claimed error bar. We are still far away from a reasonable fit.

Therefore, we have to adjust the exact times of ascending zero crossing near the time of observations, for each of the sine functions in order to get a good fit of data. Actually, we take as unknown in the fitting process the exact phase of each of the sine function at a reference time ($BJD_{ref} = 2458474.5$), taken as the time 0 of the plot of Figures 4 to 11. It is adjusted by a classical Levenberg-Marquardt scheme within IGOR software. We also have to let free a constant offset parameter $w_0$, added to the three sine functions, since we deal only with variations of RV.

On Figure 5 is plotted the best-fit curve, in black, while the three sine waves for the three planets are represented by dashed lines around the zero line. It is clear that the drop in RV between night 25 (day 3.2) and the next night 26 is mainly due to planet b, with smaller contributions from planets c and d.

5.4.2. Refining the periods by comparing 2008 and 2018 data

For each of the sine curves, knowing the phase at $BJD_{ref}$ then allows us to compute the time $T_{2b}$ (respectively $T_{2c}$, $T_{2d}$) of start of the period ($\sin = 0$ and becoming positive) just before $BJD_{ref}$. The values are displayed in Table B.1 with their uncertainties. We find in the literature that a similar sinus function at a reference time (BJD = 2454562.77 ± 0.08 BJD, on April 5, 2008. Therefore, we may determine a precise value of the average orbital period of planet b between epochs April 2008 and
December 2018, knowing that it must be an integer number of periods between $T_{0b}$ and $T_{2b}$. The elapsed time difference $T_{2b} - T_{0b} = 3909.0964 \pm 0.088$ days. Here we take as the uncertainty the quadratic sum of the two uncertainties, respectively 0.08 and 0.037 days for $T_{0b}$ and $T_{2b}$. Dividing the elapsed time difference by the nominal period 4.3114 gives a number of orbits of planet b of $906.688$ (Table B.1), while it should be an integer number. We designate by $K_{b}$ the nominal period 4.3114 gives a number of orbits of planet b of 906 full orbits, while with 906 full orbits, the period is $P_{906} = 4.31467 \pm 1.0 \times 10^{-4}$ days (Table B.1). These two values encompass the original value of the period found at discovery announcement 4.3115 ± 0.0002 and the more recent value $P_{906} = 4.31414 \pm 0.0002$. Therefore we favor the $P_{906}$ which is about 2.2 times nearer this value than $P_{907} = 4.3114$ than $P_{906}$. Still, this new accurate value $P_{906}$ is different from the nominal 2008 period $P_{908} = 4.31414 \pm 0.0002$ by 0.0015 $d$, outside the claimed error bar $err_{P_{908}} = 0.0002$ by a factor of 7. The planet b may have changed its average period from interactions with other planets between 2008 and 2018. Alternately, the uncertainty of 0.0002 $d$ claimed for 2008 data was underestimated, but some arguments developed in Appendix B suggests that this is unlikely the case. Actually, similar results are found with both methods applied to 2018 observations, Gaussian fit (pipeline) or EPiCA (see next section). This is a potentially very interesting result, because it could reveal the influence of other planets on the orbit of planet b. However, since it is irrelevant to the comparison between the two RV methods, we defer this subject to Appendix B for further discussion.

The same procedure was done for planets c and d, and the results are in Tables B.2 and B.3 respectively. Clearly, $K_{per}$ is nearer an integer number than for planet b, and the most likely values are $K_{per} = 407$ for planet c, and $K_{per} = 193$ for planet d.

### 5.5. A three-planet best fit to the EPICA derived time series.

We want to find out if the use of EPICA method (CF1 applied on CCF$_{tot}$) is able to produce an improvement in the case of a planetary system. To do so, we applied exactly the same fitting methods as in section 5.4.2 by replacing pipeline results by EPICA results. Figure 7 illustrates the fit by a model with three planets to data computed by EPICA (CF1 on CCF$_{tot}$).

On figure 8 are compared the best-fit curves for the three planets obtained with the two methods, pipeline and EPICA. While there is not much difference for planet b, there is some substantial time shift for planets c and d.

The same exercise to compute the period from the elapsed time between two zero crossings (from negative to positive) of the sine wave was done for the best fit to RV data retrieved with EPICA method. The results (also shown in Table B.1, B.2, B.3) for the two methods are not very different. For planet b, and with the EPICA method we find the same period offset as the nominal period found at 2008 epoch. We have summarized in Table 7 the new results of the periods of the three planets both for the best fit to pipeline data and EPICA data. The results of both methods are similar. We have also indicated the difference of period between the nominal (old) value, and the new value found from the CF1 method. As mentioned above, this difference for planet b is 7.5 times larger than the previously claimed error bar. For planets c and d, the difference is 2.5 and 2 larger than the claimed error bar. In summary, joining the 2008 and 2018 data is providing more accurate periods than those which were determined with 2008 observations only, and this is valid for both methods.

### 5.6. Comparison of the residuals to three-planet best fit between the two methods.

On figure 9 are represented (black points) the residuals ($\delta$RV time series after subtraction of the best-fit model) for the RVs from the pipeline (Gaussian fit), and similarly (red points) on figure 10 the residuals for the EPICA method. By eye, it seems that the EPICA method is better aligned on the Zero line (solid black line) than for the $\delta$RV time series from the pipeline.

This visual impression is confirmed by the following statistical analysis, summarized in Table 3 and in figure 11. The first night (December 22) contained only 10 exposures, and is not in Table 3. The second night (24) is the longest one and contained 406 exposures. It shows the smallest standard deviation, quite similar for the two methods. The third night (200 exposures) had a specific problem. An instrumental noise due to a blue detector
Table 2. Characteristics of three planets in the HD 40307 system from the HARPS 2009 campaign. New periods are computed based on pipeline data and on CF1 method results.

<table>
<thead>
<tr>
<th></th>
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<th>HD 40307d</th>
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<td>9.6210 ± 0.0008</td>
<td>20.412 ± 0.004</td>
</tr>
<tr>
<td>New period and error [day] from pipeline data</td>
<td>4.3099 ± 0.0001</td>
<td>9.6174 ± 0.0005</td>
<td>20.383 ± 0.0045</td>
</tr>
<tr>
<td>New period and error [day] from CF1 method</td>
<td>4.30984 ± 0.00001</td>
<td>9.619 ± 0.0004</td>
<td>20.4194 ± 0.0006</td>
</tr>
<tr>
<td>Difference nominal- CF1 [day]</td>
<td>0.0015</td>
<td>0.002</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Fig. 9. Residuals after subtraction of the best-fit model from the $\delta_{\nu}$ official Gaussian fit (black points). It seems by eye that the average of groups of points do not always lie on the zero line. There is a bias that depends on the day of observation (numbers represent the night of December 2018 when HD 40307 was observed.)

Fig. 10. Residuals after subtraction of the best-fit model from the CF1 to CCF$_{tot}$ time series (red points). It seems by eye better aligned on the Zero line (solid black line) than for the $\delta_{\nu}$ time series of Fig. 9.

Fig. 11. Mean residual for each night as a function of time (BJD-BJD$_{ref}$). Black: Gaussian fit. Red: EPiCA method (CF1 on CCF$_{tot}$). The error bars are computed as the standard deviation divided by sqrt(number of exposures). The two points for night 25 (around 3.2 days) are not independent.

6. EPiCA method and detection of changes in the spectral shape of stellar lines.

As detailed above, the EPiCA method provides, for each point $i$ of the radial velocity grid used in the building of the CCF$_{tot}$, an estimate of the change of radial velocity $\text{DRV}(i)$, with an associated error bar, between two exposures at epochs E1 and E2. In previous sections we considered only the change of RV obtained by combining optimally the various values of $\text{DRV}(i)$. However, it is also possible to examine the curve $\text{DRV}(i)$ in detail, as a function of point $i$. If there is no change in the CCF$_{tot}$ shape between the two exposures, the DRV estimate should be constant across the RV grid. If it is not constant, then it means that the spectral lines shape have changed between the two epochs E1 and E2. Since CCF$_{tot}$ is an “image”, combination of all spectral lines in the stellar spectrum, this change must reflect at least a physical effect that is dominating in the average “image”, even if it is not present identically in all the spectral lines.
Table 3. Statistics per night on standard deviation and mean residual, both in ms$^{-1}$. Keeping the 200 exposures for night 25, the mean absolute residual (averaged over the five nights), and the standard deviation are computed in the two last lines.

<table>
<thead>
<tr>
<th>Date</th>
<th>N$^a$ of exposures, exposure N$^b$</th>
<th>$S_{dev}$ pipeline</th>
<th>$S_{dev}$ CF1</th>
<th>Residual pipeline</th>
<th>Residual CF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>406 [10,415]</td>
<td>1.014</td>
<td>1.03</td>
<td>-0.094</td>
<td>-0.014</td>
</tr>
<tr>
<td>25</td>
<td>100 [416,515] (**)</td>
<td>1.13</td>
<td>1.04</td>
<td>0.45</td>
<td>0.098</td>
</tr>
<tr>
<td>25</td>
<td>200 [416,615] (**)</td>
<td>1.87</td>
<td>2.26</td>
<td>0.482</td>
<td>0.072</td>
</tr>
<tr>
<td>26</td>
<td>174 [616,789]</td>
<td>1.26</td>
<td>1.11</td>
<td>-0.616</td>
<td>-0.147</td>
</tr>
<tr>
<td>27</td>
<td>176 [790,965]</td>
<td>1.19</td>
<td>1.91</td>
<td>0.344</td>
<td>0.203</td>
</tr>
<tr>
<td>28</td>
<td>185 [966,1150]</td>
<td>1.13</td>
<td>1.68</td>
<td>-0.09</td>
<td>-0.12</td>
</tr>
</tbody>
</table>

mean of absolute value of five nightly averaged residuals ms$^{-1}$ 0.32 0.11

RMS of five nightly averaged residuals ms$^{-1}$ 0.39 0.13

Fig. 12. Model-data comparison using CCF ratios. Top: Expected ratio of two CCFs with unchanged shape and various Doppler shifts (colored lines), and ratios using the four periods of night 24 (black lines). The same curve is observed for ratios of parts 2, 3, and 4 to part 1. It does not resemble the expected variation for a simple shift and indicates a change in shape during the first and second parts of the night. Bottom: Ratios of pairs formed by the first two consecutive stacked CCFs obtained during the same night, for nights 24 to 28 (numbers indicated on the plot for 26 to 28). One CCF is drawn (gray line). There is a systematic bump centered on the CCF, indicative of an increase in signal near the center during the first and second parts of each daily pair. The increase is larger for the latest nights. The ratio for the two last parts of night 24 is shown for comparison (pink line). There is no increase in this case, a sign of absence of shape variation during this period.

In order to increase the S/N (up to about 3,000), we have stacked the CCF$_{tot}$ by 100 consecutive exposures whenever possible (taken over about 2 hours), and a little less otherwise. Night 24 contains 406 exposures, and is divided in 4 periods. There are 200 exposures for night 25, thus divided in two periods; night 26 has 174 exposures, divided in two parts; same for night 27 with 176 exposures and night 28 with 185 exposures. Hereafter we name for night XX and first (resp. second) series of exposures by C-XX-1 (resp. C-XX-2). Before any computation of a ratio, the two curves were normalized to each other, to account for photometric changes and to get a value around 1 at the extremities of the curves, corresponding to the shoulders of CCF$_{tot}$.
Changes in the spectral shapes can also be detected directly by dividing a CCF of one exposure by the one of a different exposure. This can be done also using CCFs averaged over several exposures. In this section we have taken advantage of the unique series of short exposures to explore the application of EPiCA for this purpose and to compare with divisions. We explain why the diagnostic using EPiCA is easier to perform.

Doing this study, we found a small change of the spectral shape during the first two hours of exposures (about 100 exposures, first quarter of night 24 and half of the total observation period for nights 25, 26, 27, 28), a change similar for all five nights, and diagnosed with both CCF ratios and with EPiCA. Because of this systematic, repetitive behavior and the similarity of shape variations for the five nights, we separated their study from the study of the other types of spectral shape variability.

The former effect is described in the first part of this section, and, in order to avoid the inclusion of its type of variability, we restricted the analyses presented in the second section to comparisons between either the two first parts, or the second parts of the nights.

6.1. Change of spectral shape between the first and subsequent periods of time within the same night

6.1.1. Using CCF ratios

If there is a simple shift between two curves CCF1 and CCF2, their ratio should present a characteristic shape displayed as smooth colored curves on figure 12 (top), the results of a simulation using the curve C-24-1 (first stack of night 24) and shifting it by -20, -10, -5, +5 ms⁻¹. By comparison, the computed ratio C-24-2/C-24-1 (after normalization) is characterized by a centered bump, quite different from any of the model curves. The ratio curves C-24-3/C-24-1 and C-24-4/C-24-1 are very similar to the ratio curve C-24-2/C-24-1, showing that the shape of C-24-3 and C-24-4 are very similar to the shape of C-24-2: the variation producing the bump occurred only between the first and second parts of the night 24, and the shape did not change afterwards during this night 24. This is confirmed by the ratios between part 2 and 3, and also part 3 and 4 of night 24, displayed in Fig. 12 (bottom panel), which are constant within the fluctuation level observed for all ratios. Actually, we found out a similar central bump (and thus systematic behavior) when making the ratios of second part to first part of the night C-XX-2/C-XX-1 for the other nights XX=24 to 28, as shown on figure 12 (bottom), with the central bump increasing from day to day. Such a centered bump in the ratios of CCF is the signature that the so-called contrast (relative depth) is decreasing with time between the two CCF. A change of contrast is often used classically as a stellar activity indicator.

This is quite possibly the case here for HD40307. However, in the present case, because of the somewhat systematic behavior of contrast change along each night of observation on a timescale of ≈ two hours, we cannot completely exclude that this effect is connected to an artifact of so far unidentified origin.

6.1.2. Using EPiCA

In this subsection we examine how the change of contrast along a night revealed by the ratios of CCF of the previous section translates into the shape of DRV(i) curves derived from EPiCA.

Fig. 13 displays several profiles along the velocity grid DRV(i) obtained with EPiCA for pairs of the same types of time periods as used in the previous analysis based on CCF ratios. For this figure, the two members of each pair belong to the same night. Error bars are computed for each pair based on the second Connes formula (Equation 9) and reflect the weights associated with the slope of the CCF. A typical series of weights is superimposed with the slope of the CCF. A typical series of weights is superimposed. The two most central values differ from the division by the very small derivative (equation 3) and additional uncertainties due to BM coarse velocity sampling (500 ms⁻¹) and the corresponding area is marked by a rectangle.

In the case of a pure Doppler shift (i.e., in the absence of a change in stellar line spectral shape), the DRV(i) curve should be flat. This is indeed the case (see top of figure 13 for the two DRV(i) profiles for night 24 which are inter-comparing the second and third, then third and fourth parts). They are flat, within the error bars: there is no change of contrast, as revealed by the ratios of curves on figure 12 (bottom); the instrument has stabilized. On the contrary, the other DRV(i) curves of figure 13 depart significantly from a flat, constant, value. For all pairs of periods containing the first and second parts of the night, the profiles exhibit departures from zero on both sides of the central velocity. Moreover, the amplitude of these features increases from night 24 to night 28, forming extended spikes. Also, there is a difference of average level between the two sides of the curve DRV(i): it is positive on the blue side (≤3.14 km⁻¹), and negative on the red side. This is consistent with what is expected from the Connes algorithm applied to this particular case of change in shape (i.e., when the CCFtot becomes shallower) between stack 1 and stack 2 (decrease in contrast); the increase in intensity of the blue side is interpreted by the algorithm as a redshift, while the increase in intensity of the red side is interpreted as a blueshift. This case is similar to one of the model exercises performed by Cretignier et al. (2020), comparing the Gaussian...
fit of a spectral line with the algorithm of Connes, as we do here (their figure B3). Namely, it is the third row of their figure B3, where they model a decrease in depth (or contrast) induced by temperature-sensitive lines. All in all, both approaches (ratio curves and DRV(i) curves) are consistent, pointing to a small decrease in the contrast of CCF along each night.

6.2. Change of spectral shape between two consecutive nights

Whatever the cause of the observed change in contrast between the first part of the night (=2 hours or 100 exposures) and the rest of the same night, we have also studied the change of shape from one day to the next by comparing two stacked CCF\textsubscript{tot} taken similarly along each of the two nights (i.e., using pairs of type C-25-1/C-24-1, C-25-2/C-24-2, C-26-1/C-25-1, C-26-2/C-25-2, etcetera).

6.2.1. Using CCF ratios

The CCF\textsubscript{tot} ratios for two consecutive nights are displayed on figure 14. There are two curves for each couple of days, one for the pair of first CCF\textsubscript{tot} of the nights, one for the pair of second CCF\textsubscript{tot} of the nights. The two curves for pairs of the same two nights are very similar, even in their detailed structure, in spite of the fact that they are built from different, and fully independent data sets, bringing some confidence in their credibility. The curves are different from day to day. The ratios are close to constant, except for the pairs 25/26 which are characterized by positive and negative values far above the noise. This large change between the two nights (quantified by the standard deviation over 81 points of the ratio) happens at the time of the largest RV change (= -4 m s\textsuperscript{-1}) predicted by the planetary model (figure 4), but, of interest here, also at the time of the abrupt change (by = -1.3 m s\textsuperscript{-1}), figure 5 of the difference between the two time series, Gaussian fit to CCF\textsubscript{tot} and EPiCA method. Importantly, the change of shape of the ratio observed from day 25 to day 26 is quite different from the model prediction for a simple shift (see a model for a shift of = -5 m s\textsuperscript{-1} superimposed for comparison in Fig. 13). This observed departure from a pure Doppler shift clearly indicates a significant change of spectral shape between night 25 and night 26, quantified by sdev= 8.3 \times 10^{-4}. The other night ratios show smaller changes, quantified (in decreasing order) by sdev=5.6 \times 10^{-3} (27/26), 4.7 \times 10^{-4} (25/24), 4.4 \times 10^{-4} (28/27). The ratios for pairs of the same night 24, 24-24-3 and 24-3-24-2 have a sdev= 1.9 \times 10^{-5}, representative of the noise level for such ratios. The two red and black curves of 27/26, and also the ones of 28/27 ratios are different from each other near the center, because of the contrast artifact which is more severe for nights 27 and 28 than for the previous nights, as shown in Figure 12 (bottom).

Fig. 15. Same as Fig. 13 for four pairs of stacks that are one day apart over the five nights from night 24 to 28. Each pair consists of using either the first or the second parts of night. Over the five nights from night 24 to 28. Each pair consists of using either the first or the second part of night. O

6.2.2. Using EPiCA

Similarly to the previous section using the CCF ratios, we searched for changes of spectral shape from one night to the other using EPiCA and the same parts of the night. Figure 15 shows the results separately for each pair of consecutive nights. The two series of profiles, using the first or the second time periods of the two consecutive nights, are very similar, despite being derived from independent data sets, in the same way CCF ratios were similar. The DRV curves for the pairs of nights 24-25, 26-27 and 27-28 show somewhat constant values near 0 for both the blue and red sides (still restricting to the data points with low error). This is consistent with a pure, very small Doppler shift. In the case of the two DRV curves between night 25 and 26, their shape is very different from the other DRV curves, and, clearly, these DRV curves of the pair 25-26 stand alone. One would expect a flat profile at about -4 m s\textsuperscript{-1} in both the blue and red side, according to the planetary model. However, the two sides of the curves are very different from each other. The blue side is negative, which is consistent with the planetary motion between day 25 and 26 (figure 4), but decreases strongly below -4 m s\textsuperscript{-1}; we discarded from the discussion the two spikes near the center. The red side is also not constant, and decreases but is globally positive. Such behavior is showing that the shape of the CCF\textsubscript{tot} profile has changed substantially between night 25 and night 26. This is totally in line with the change of shape characterized by the ratios of CCF\textsubscript{tot} displayed on figure 14, where also the pairs of ratios between nights 25 and 26 stand alone among one day apart ratios, with a pronounced change of shape, not symmetrical with the center of the line.

6.3. Conclusion about the line shape variations and the two methods of detection

In summary, we found that the DRV(i), the Doppler velocity shift between two CCF\textsubscript{tot} is sometimes very far from being constant...
along the RV grid points i. This is the proof that the spectral lines are changing their shape, in addition to any Doppler shift, on a timescale of ≈2 hours or a little shorter. With the help of the ratio curves, we detected a somewhat systematic effect: a central “bump” builds up between the first stack of the night, and the second stack, along each of the five nights, possibly of stellar origin or resulting from an artifact. Whatever its origin is, we mitigate this effect by comparing CCF<sub>tot</sub> taken at the same relative time during the nightly operation and one day apart. Doing so, we detected a significant variation of shape, between night 25 and night 26, exactly at the time of the abrupt change of the difference between the RV time series deduced from the Gaussian fit and the EPiCA method (decrease by ≈1.3 ms<sup>−1</sup>). This suggests that the change of shape modifies differently the results of the Gaussian fit and the shift-finding algorithm. We assign this change of shape to the stellar activity.

For both types of detection, it is interesting to compare with the lineshape simulations of [Cretignier et al. (2020)]<sup>3</sup> displayed in their figure B3. First, the authors conclude that, adding a symmetric perturbation to a symmetric spectral line, both methods, Gaussian fit and Connes’s formalism (equivalent to EPiCA) are robust, and the retrieved RV does not change. On the contrary, if a symmetric perturbation to a nonsymmetric line (which happens at least whenever there is a blend of a smaller line on one side of the line), then both algorithms are retrieving a somewhat biased change of RV. The “bump” centered in figure 6.1.1 resembles a case of a symmetric perturbation, such as a change of contrast. It is very likely that a fraction of lines from the binary mask has blends. But since secondary line blends are distributed at random, the CCF<sub>tot</sub> will be much more symmetric than a single blended line, and it is likely that both methods are robust to this artifact, yielding small biases if any. The case of the addition of a nonsymmetric perturbation is not shown in their exercise, but, from their exercises of addition of a symmetric perturbation, we certainly may expect that a biased DRV will be retrieved for both methods. Actually, the (largest) change of shape observed from night 25 to night 26 is strongly asymmetric (figure 5), and therefore we may expect that the DRV retrieved by the two methods will both be biased erroneously away from the true dynamical change of RV due to planets. Because this peculiar behavior between night 25 and 26 corresponds exactly to the abrupt change of the difference between the two time series (drop by ≈1.3 ms<sup>−1</sup>), the classical Gaussian fit and the EPiCA method, as displayed on figure 3, this difference in the time series of ≈1.3 ms<sup>−1</sup> is certainly the difference of biases between the two methods.

Which method provides the smaller bias? Extensive simulations are beyond the scope of this paper. Whatever the answer, we may emphasize that EPiCA is a more direct and easier way to detect shape variations. Departures from flat DRV(i) curves are an easy diagnostic of shape variation, they cannot be confused with effects of a pure Doppler shift, and there is no need for a comparison with a model, as in the case of CCF ratios. We also argue that the EPiCA method is easier and has more flexibility in the analysis of departures from a single Doppler shift between two epochs than the comparison of CCF bisectors. By essence, the bisector is making a link between both sides of the spectral lines (or the CCF image), while the Connes algorithm is applied independently to each point of the line (or the CCF image). The bisector says nothing about the length of segment joining the two sides of the line: the center of the segment may not move, while the length of the segment may change without being noticed by the bisector analysis. One may oppose that in this case there is no bias in RV, but symmetric variations like those detected at the beginning of the observing periods would not be detected.

The variation of stellar line shape from night 25 to night 26 is likely a result of stochastic changes of the convective granulation bluethish (GBS) averaged over the stellar disk [Meunier & Lagrange 2020; Meunier 2021]. Model results of these authors indicate an amplitude of RV Doppler shift fluctuations of ≈0.2 m.s<sup>−1</sup> for a star of K4 type (similar to HD4030, type K2.5), when granulation only is considered on timescales of 15 - 50 minutes, and up to ≈1 m.s<sup>−1</sup> for super-granulation changes (on a ≈one day timescale). Such a super-granulation change could explain the important departure from constancy of the DRV(i) curve, and the corresponding change by ≈1.3 m.s<sup>−1</sup> between the difference of RV retrieved either from the Gaussian fit or from EPiCA method, and remaining during the following nights 27 and 28.

7. Summary and discussion

In this paper we described and tested a new way to estimate the change in radial velocity DRV between two epochs from the comparison of the two stellar spectra. This algorithm is based on the first formula of Pierre Connes: its aim is exactly this, and was shown to be the (mathematically) optimal way to retrieve DRV. Instead of applying the shift-finding algorithm to two spectra, as it was originally designed, or to individual spectral lines, as in some line-by-line techniques, it is applied here to the weighted sum of all CCFs obtained separately for each order, CCF<sub>tot</sub>, which represents an average image of all spectral stellar features. If the computation of CCF<sub>tot</sub> is done on a wavelength scale associated with the Solar System barycentric frame (i.e., using the corresponding barycentric velocity grid), the reflex motions induced by planets are small and one can stop at the first-order term of the Taylor expansion involved in the formalism of equation 2. This new EPiCA method is simple to implement and appropriate when pipeline data products of the spectrograph include CCF<sub>tot</sub> in the Solar System barycentric frame. It combines the advantage of the shift-finding algorithm and the robustness of CCF construction.

To test the algorithm, we used a series of spectra acquired during a one-week observing campaign on star HD 40307, which is known to host at least three planets, and we compared the two RV time series obtained from the CCF<sub>tot</sub> profiles by means of a Gaussian fit, on the one hand, and our new EPiCA algorithm, on the other hand. In order to compare quantitatively the two methods, two different quality indicators of the retrieved RV time series were computed. First, a single-night series was examined. The RV series were fitted to a linear relationship representing the first-order Doppler variation under the influence of planets, but also any RV change that could be due to stellar activity. The first-order approach is justified by the short duration for the analysis. The dispersion of the residuals to the linear fit, which is a measure of the mean error, was found to be σ = 1.03 and 0.83 ms<sup>−1</sup> respectively for the pipeline and the EPiCA algorithm, a significant 20% improvement of the precision on RV changes. We interpret this decrease in the RV dispersion as evidence for the absence of strong variations of the stellar line shapes during this time interval, at least for the absence of variations strong enough to cancel the benefit of the application of the Connes shift-finding algorithm which makes an optimal use of all the spectral information, but requires unchanged profiles.

In a second test, we made use of the whole series obtained over the campaign, and the computed RVs were fitted to a three-
planet Keplerian model. The periods and reflex-amplitudes were fixed to the previously determined values, but the phases were adjusted. Based on the nightly averaged residuals to the respective best fits (figure 11), we computed a second quality indicator, defined as the mean over five nights of the absolute value of nightly mean residual. This average bias was found to decrease significantly with the new algorithm. We found 0.32 and 0.11 ms$^{-1}$ respectively for the pipeline and the EPiCA algorithm (i.e., a factor of 3 of decrease). Inasmuch as a three-planet Keplerian best fit is the dynamical “truth” and is not affected by stellar activity, it appears that the EPiCA algorithm (at least in the HD 40307 study case) is nearer the truth than the Gaussian fit. As a side result, we found a somewhat intriguing new value of the orbital period of planet b, averaged over 10 yr from 2008 to 2018.

The main difference between the two RV series, at the origin of the differences in the model fitting, is associated with the significant increase in the difference between the two determinations between night 25 and night 26, of about 1.3 ms$^{-1}$. We come back to this phenomenon below, associated with a quite significant line shape variation. While it is easy to explain the benefit of the EPiCA method in the case of negligible changes of the line shapes, as mentioned above for the first test, it is not totally obvious why the EPiCA method should provide a more accurate estimate of the changes of dynamical RV than the Gaussian fit method for long periods of time and strong line shapes variations, which seems to be the case based on the results of our second test. Admittedly, the comparative tests of the two methods shown in this paper are limited to only one example of one stellar system. However, our results are encouraging and show that such a method deserves to be explored further. It might be worth obtaining a few hours of high-cadence time series, at least once for each star monitored, for the search of exoplanets. It should allow us to estimate whether or not the EPiCA method provides better accuracy in the (likely) case of small line shape variations. A study similar to our second test, on the other hand, on longer duration for a star without planets, would be very useful too. It would give some insight into the relative sensitivity of the two methods to line shape variations specific of the observed object.

About the abrupt change of the offset between the two time series between night 25 and night 26 (figure 12), we assign this significant change of offset by the combination of two effects:

- stellar processes (most likely supergranulation bluetsift, because of the approximately one-day timescale) are present and modify substantially the shape of the spectral lines and the resulting CCF$_{tot}$ between the two nights;
- the two algorithms are not sensitive in the same way to those changes in spectral shapes.

If the results of the second test are interpreted as a reduced sensitivity of the EPiCA algorithm to stellar changes, this lower sensitivity is very likely linked to the basic difference of the two algorithms. The standard Gaussian fit to the CCF$_{tot}$ assumes that the Gaussian is symmetric, while the EPiCA method reveals that the change in shape between two epochs may be strongly asymmetric (see figures 14 and 15). Therefore, always fitting with a symmetric Gaussian a curve that is not symmetric, and that varies in its asymmetry, will introduce a bias in RV, variable from epoch to epoch.

An amplitude of 1.3 ms$^{-1}$ is significantly larger than theoretical estimates of the RV RMS of granulation blueshift (GBS), based on stellar atmosphere models: $\approx 0.1$ ms$^{-1}$ (Ceget et al. 2019); 0.26-0.30 ms$^{-1}$ for a K1 star (Meunier et al. 2023). This is why we believe rather in supergranulation variability. On the other hand, this observed value of change by $\approx 1.3$ ms$^{-1}$ is comparable with faster RV variations observed on star HD 88595 (F7V), as reported in Sulis et al. (2023), which they assign to GBS. Even after binning over 2.5 hours their RV time series (obtained with Gaussian fit to CCF), their resulting RV RMS is still $\approx 1.5$ ms$^{-1}$.

These results imply that the measurement of the offset between the Gaussian fit RV (the pipeline RV) and the shift-finding algorithm RV provide good indicators of significant stellar line shape variability, and it motivated us to go in this direction. Instead of only extracting RV for each exposure, we additionally tested an extension of the EPiCA method to the analysis of the EPiCA profiles along the velocity grid, with the goal of characterizing the stellar line shape variations. Applying the shift-finding algorithm between two CCFs allows us to determine a change in RV (a shift) DRV(i), for each grid point i of the radial velocity. If there is only a simple shift between the epochs of CCF1 and CCF2, the curve DRV(i) should be constant with i. This is what we implicitly assume when we average all DRV(i) values to extract RV. On the contrary, any departure from constancy is a sign of line shape change, and consequently of stellar activity.

The detailed study of the DRV(i) profiles provided several results. First, we detected a somewhat systematic variation in the profile every night, occurring during the first two hours of measurement. The variation is weak and symmetric, and, regardless of its origin, it does not affect the RV determination. In order to avoid any interference with the study of the DRV(i) profiles on the longer term, we limited the study of the day-to-day variability to the inter-comparison of the same periods of the observing run, namely using the first (resp. second) 100 exposures of night N with the first (resp. second) 100 exposures of the following night. We found significant departures from profile constancy between the night 25–night 26 pair, and constancy for the other pairs. The nonconstant profile corresponds exactly to the same interval for which we have the abrupt variation of the difference between the RVs from the Gaussian fit and from EPiCA. It is a second indication that a stellar line shape change has occurred. Here, however, we have more information on the type of variability that happened. In this respect, it is useful to compare with the simulations of DRV(i) done for the LBL analysis by Creti et al. (2020). The shapes of the DRV(i) curves give an idea of the types of distortions the line shape suffered from.

In conclusion, the application of EPiCA to the merged CCFs may be quite useful in several ways. It can provide on-the-fly results as soon as two spectra are collected, along with the pipeline results. It may produce a smaller dispersion of the RV series compared to the Gaussian fit, and, independently, changes in the offset with the Gaussian fit RVs are a warning for line shape variations. Although it cannot compete on the long term with LBL analyses, the use of CCF$_{tot}$ yields a much higher S/N than when the shift-finding algorithm is applied on a line-by-line basis, allowing the detection of global line shape change and stellar activity. It should be recognized however that our method would also benefit from a median template spectrum and better defined derivatives of CCF$_{tot}$ because the noise on DRV(i) would be substantially reduced. Finally, the EPiCA method is rather easy to implement, since CCF$_{tot}$ is already in the ESO data products for ESPRESSO, and the Python codes are provided to the user’s community (see explanations and
Acknowledgements. We thank our referee for his/her very constructive and detailed comments. We deeply thank Nadège Meunier for very detailed discussions about the role of convective granulation blueshift as an important perturbation to radial velocity measurements. We wish to thank Willy Benz suggesting the implications of a possible long term change of the period of HD40307 b. A.I. acknowledges the support of a Vernadski Scholarship for PhD students, sponsored by the French Government and the Ministry of Science and Higher Education of the Russian Federation under the grant 075-15-2020-780 (N13.1902.21.0039).

References

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Appendix A: Where to find ESPRESSO CCF and how to use the code

With the new service of the ESO archive it is possible to obtain not only the raw data, but the ancillary data as well. For ESPRESSO at VLT, one of the type of ancillary data is the ANCILLARY.CCF - 2D array containing the cross correlation function of fibre A with a stellar template spectrum, computed per Echelle order. Each row represents one order, and the X direction is the sampling in velocity space.

The information about the velocity space (or grid) can be retrieved through the fits header, “HIERARCH ESO RV STEP” stands for the step in kms$^{-1}$, and “HIERARCH ESO RV START” is the first velocity value in kms$^{-1}$, the number of points at the grid is the same as the length of the CCF array.

The ANCILLARY.CCF has 170 orders, while ESPRESSO has only 170 orders, the last column of ANCILLARY.CCF is the result of adding all the single-order CCFs together. In the current version of code the computation is provided using this column only, but it is planned to extend the code to provide more flexibility and allow users to choose which orders to consider.

In the current configuration the code works only with data provided in the fits format of ESPRESSO CCF files, in the future an extension for more custom formats (nursery array, text data) is being considered. To get started, one needs to specify the path to the reference CCF and the path to the other CCFs (in case of other CCF it is possible to provide path to the fits file if only one CCF is considered, text file with paths or just put the path to the directory if an ensemble of CCFs are considered). It is important to mention that the current version of the code does not check the date of observations and makes a loop on files in accordance to their position in the list/directory: an initial correct compilation list is important to get correct results. The velocity grid is computed by the code itself on the basis of the fits header information. The result is saved as numpy array. All paths should be provided with `.txt` file.

Examples of usage and documentation of further changes can be found at the GitHub repository.

Specific questions about the code should be addressed to anastasia.ivanova@cosmos.ru.

Appendix B: Putative change of period of planet b between 2008 and 2018.

Here we discuss further the intriguing result of an apparent change of period of planet b, between 2008 and 2018. Looking at figures [5]and[7] where the RV data are plotted with the three-planet best fit, it is rather clear that the observed RV drop from night 25 to night 26 by $\approx$ 4 ms$^{-1}$ cannot be entirely due to planet c or planet d, because of their longer periods, and is mostly due to planet b with the shortest period (4.3114 d). Therefore, this sudden drop constrains very much the exact phase of the planet b sine wave, on which is based the finding that its average period has changed between 2010 and 2018. Quantitatively, we explored a potential coupling between the phases of the three planets with the following exercise, applied to the EPICA RV time series. For a 2D ensemble of 11x11 possible phases at BJD$_{ref}$ of planets c and d, the three-planet best fit was run, keeping fixed the phases of planets c and d, yielding the best-fit phase of planet b and Chi$_2^2$. It yields a 2D image of Chi$_2^2$ displayed on figure [B.1] showing some iso-contours of Chi$_2^2$. Two 1D sections of this image are also plotted on figure [B.1] showing both the Chi$_2^2$ values and the phase of planet b (expressed in days, time lag= period x phase). On the top panel, the phase (expressed in days, time lag) of planet d is kept fixed at its three-planet best-fit value, as a function of the time lag of planet c. Similarly, on bottom panel, the same curves of Chi$_2^2$ and time lag of planet b are plotted as a function of time lag of planet d when the time lag of planet c is fixed at its three-planet best fit. While the Chi$_2^2$ increases significantly away from its three-planet best fit, the time lag of planet b does not change very much, at -1.61 $\pm$ 0.03 d: it is very weakly coupled to the exact values of phases of planet c and d. Therefore, we may consider the retrieved phase at BJD$_{ref}$ of planet b as a robust result, almost independent of the phases of the two other planets, within the 2D area of the Chi$_2^2$ contours. Consequently, the determination of T2b, the start time of the sine wave just before BJD$_{ref}$, is also robust at T2b = BJD$_{ref}$ + (4.3114-1.61) $\pm$ 0.03 d, as well as the average period between 2008 and 2018 as determined in section 5.4.2. Including in the best-fit process planet f at 51.6 d period does not change the best-fit values of the phases of other planets.

Changes of periods due to gravitational interactions between planets have been detected, particularly by monitoring the Transit Time Variations (TTV) of transiting planets. This allows to determine the mass of the perturbing planet, as discussed for instance in Nesvorný & Morbidelli (2008). Actually, the period of the perturbed planet (time between two successive transits) changes periodically, typically by $\approx$ 200 s, and with a period of typically $\approx$200 days. In the transit geometry, the measurement of the time between two transits can be determined very accurately (within seconds), and changes of period detected easily. On the contrary, in a system with no transit and monitored with the RV measurements, such changes of period would be much more difficult to detect. Consequently, it cannot be excluded that the HD40307b planet is indeed in this typical TTV configuration. The system around HD40307 was observed from 2003 to 2014 (only 7 observations prior to 2006), a time span of 10.4 yr (Diaz et al. 2016), before the 2018 observations used here. If planet HD40307 b were influenced gravitationally with a periodic change of period, then the reported period at 4.3114$\pm$0.0002 days is the mean period. The reported uncertainty on the period of 0.0002 d, or about 20 s, does not preclude at all a periodic change of its orbital period, even by 200 s typical of TTVs. On the other hand, the comparison of zero crossing times between epochs 2008 (T0b) and 2018 (T2b) yields a mean period averaged over 10 years, which is different from the first one by 0.0015 d, or $\approx$ 130 s. Therefore, the change of period pattern found between 2008 and 2018 is quite different from the typical TTV pattern of $\approx$200 days periodic change of the period by $\approx$200 s. In addition, if the period determined over 2003-2014 had been as the one determined between 2008 and 2018, the difference of periods of 0.0015 day would have accumulated over the 1219 orbits of planet b up to a time lag of 1.828 day, or slightly less than one-half of orbital period. It is very doubtful that such a discrepancy would have gone unnoticed by the various analysis of the period 2003-2014 time span (Diaz et al.2016; Cohened et al. 2019), supporting the analysis reported here. It sounds more like a longer timescale, secular change of the period that could be related to an eccentric planet, a very interesting subject indeed but out of the scope of the present paper, which deals with RV retrieval methods. Both methods yield similar results on this topic. A detailed analysis of the system stability is beyond the scope of the current work. Other scientists are encouraged to examine independently the 2018 observations to verify the phase and period...
Fig. B.1. Study of \( \chi^2 \) when fitting the EPiCA time series with a three-planet model. Left: Iso-contours of \( \chi^2 \) as a function of planets c and d time lag. For each pair of planet c and d time lag with BJD\(_{\text{ref}}\), a best fit of the time lag of planet b is computed, as well as the overall \( \chi^2 \) on the 1151 points. The minimum \( \chi^2 \) is at 3014, the average \( \chi^2 \) per point is 2.6 (ms\(^{-1}\)). Top right: Horizontal cross section of left image, with the variation of the time lag of planet b, and \( \chi^2 \), as a function of the time lag of planet c, when the time lag of planet d is fixed to its overall best-fit value. Bottom right: Same as top, but the roles of planet d and c are inverted. For both panels, the variation of the time lag of planet b is very small, showing an absence of coupling between the phases (or time lags) of the three planets.

results presented here, even taking the standard official RV results contained in the data product. Both time series are available at the GitHub repository.

<table>
<thead>
<tr>
<th>Planet b pipeline</th>
<th>Planet CF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude and error [ms(^{-1})]</td>
<td>1.84± 0.14</td>
</tr>
<tr>
<td>Nominal period and error [day]</td>
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<tr>
<td>Phase at BJD(_{\text{ref}}) (epoch 2018)</td>
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<tr>
<td>Zero crossing time T(_2) at epoch 2018 (bjd-2.4e6)</td>
<td>58471.866±0.037</td>
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<tr>
<td>Elapsed time T(_2)-T(_1) [day]</td>
<td>3909.1±0.09</td>
</tr>
<tr>
<td>( K_{\text{per}} ) number of periods in T(_2)-T(_1)</td>
<td>906.688</td>
</tr>
<tr>
<td>K1</td>
<td>906</td>
</tr>
<tr>
<td>K2</td>
<td>907</td>
</tr>
<tr>
<td>Period and error for K1 [day]</td>
<td>4.3147±0.0001</td>
</tr>
<tr>
<td>Period and error for K2 [day]</td>
<td>4.3099±0.0001</td>
</tr>
</tbody>
</table>

Table B.1. New estimation of period for planet HD 40307 b

<table>
<thead>
<tr>
<th>Planet c pipeline</th>
<th>Planet CF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude and error [ms(^{-1})]</td>
<td>2.29± 0.13</td>
</tr>
<tr>
<td>Nominal period and error [day]</td>
<td>9.6210±0.0008</td>
</tr>
<tr>
<td>Phase at BJD(_{\text{ref}}) (epoch 2018)</td>
<td>0.90041±0.0145</td>
</tr>
<tr>
<td>Zero crossing time T(_2) at epoch 2018 (bjd-2.4e6)</td>
<td>58465.837±0.1396</td>
</tr>
<tr>
<td>Elapsed time T(_2)-T(_1) [day]</td>
<td>3915.747±0.1396</td>
</tr>
<tr>
<td>( K_{\text{per}} ) number of periods in T(_2)-T(_1)</td>
<td>406.85</td>
</tr>
<tr>
<td>K1</td>
<td>406</td>
</tr>
<tr>
<td>K2</td>
<td>407</td>
</tr>
<tr>
<td>Period and error for K1 [day]</td>
<td>9.6411±0.0005</td>
</tr>
<tr>
<td>Period and error for K2 [day]</td>
<td>9.6174±0.0005</td>
</tr>
</tbody>
</table>

Table B.2. New estimation of period for planet HD 40307 c
Table B.3. New estimation of period for planet HD 40307d

<table>
<thead>
<tr>
<th></th>
<th>Planet d pipeline</th>
<th>Planet d CF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude and error [ms⁻¹]</td>
<td>2.31 ± 0.14</td>
<td>2.31 ± 0.14</td>
</tr>
<tr>
<td>Nominal period and error [day]</td>
<td>20.412 ± 0.004</td>
<td>20.412 ± 0.004</td>
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<tr>
<td>Phase at BJDₑₑₑₑ (epoch 2018)</td>
<td>0.39676 ± 0.0419</td>
<td>0.33147 ± 0.0555</td>
</tr>
<tr>
<td>Zero crossing time T₂ at epoch 2018 (bjd-2.4e6)</td>
<td>58466.4</td>
<td>58467.737</td>
</tr>
<tr>
<td>Elapsed time T₂-T₁ [day]</td>
<td>3933.98 ± 1.15</td>
<td>3935.32 ± 1.15</td>
</tr>
<tr>
<td>Kₚₑₑ number of periods in T₂-T₁</td>
<td>192.7287</td>
<td>192.79</td>
</tr>
<tr>
<td>K₁</td>
<td>192</td>
<td>192</td>
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<tr>
<td>K₂</td>
<td>193</td>
<td>193</td>
</tr>
<tr>
<td>Period and error for K₁ [day]</td>
<td>20.489 ± 0.00455</td>
<td>20.4964 ± 0.0059*</td>
</tr>
<tr>
<td>Period and error for K₂ [day]</td>
<td>20.383 ± 0.00457</td>
<td>20.3902 ± 0.0059*</td>
</tr>
</tbody>
</table>