Radial-velocity Precision of ESPRESSO Through the Analysis of the Solar Twin HIP 11915

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Abstract

Different stellar phenomena affect radial velocities (RVs), causing variations large enough to make it difficult to identify planet signals from the stellar variability. RV variations caused by stellar oscillations and granulation can be reduced through some methods, but the impact of rotationally modulated magnetic activity on RV, due to stellar active regions, is harder to correct. New instrumentnom changes an improvement in precision of one order of magnitude, from about 1 m s$^{-1}$ to about 10 cm s$^{-1}$
In this context, we report our first results from 24 spectroscopic Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO)/Very-Large Telescope observations of the solar twin star HIP 11915, spread over 60 nights. We used a Gaussian Process approach and found for HIP 11915 a RV residual rms scatter of about 20 cm s$^{-1}$, representing an upper limit for the performance of ESPRESSO.

Unified Astronomy Thesaurus concepts: Radial velocity (1332); Astronomy data analysis (1858)

1. Introduction

The radial-velocity (RV) method has been used to discover exoplanets, or to confirm exoplanets detected by the transit method and estimate their mass. Earth analogs orbiting the habitable zone of a Sun-like star induce an RV signal on the order of 10 cm s$^{-1}$ (e.g., Langellier et al. 2021). However, the measured RV variations are not entirely due to planets; stellar activity, oscillations, and granulation also cause changes in RV (e.g., Fischer et al. 2016). The effect of stellar oscillations and granulation on RV can be reduced by adopting exposure times tailored to the star’s spectral type (Chaplin et al. 2019), or modeling through magnetohydrodynamical simulations (Cegla et al. 2016). Yet, the impact of rotationally modulated stellar activity is hard to predict, as stellar activity cycles are not strictly periodic and have complex shapes. Furthermore, the presence of active regions on the stellar surface can induce RV signals, which can sometimes be misinterpreted as planet signals (e.g., Figueira et al. 2010; Haywood et al. 2014; Diaz et al. 2018).

Thus, a better understanding and characterization of the impact of stellar activity on RV is crucial for the progress in our ability to detect exoplanets (Blackwood et al. 2020). After the discovery of the first exoplanet around solar-type stars (Mayor & Queloz 1995), Saar & Donahue (1997) discussed the possible impact of apparent changes in RV due to the effects of stellar magnetic activity. Further, Hatzes (2002) and Desert et al. (2007) also presented characterization of the likely effects of stellar active regions. More recently the interest has been renewed (e.g., Dumasque et al. 2014; Borgniet et al. 2015; Korhonen et al. 2015; Bauer et al. 2018; Haywood et al. 2020), as planet searches are focusing in small exoplanets, for which the stellar activity imposes serious limitations in their detection.

Observations and models show the dependence of the RV activity on the activity cycle phase (e.g., Borgniet et al. 2015; Korhonen et al. 2015), being the lowest at the activity cycle minimum. There have been important advances in the treatment of star-induced RV variability, through reconstructing the geometry of active regions (e.g., Dumasque et al. 2014) or semiempirically through a Gaussian process (GP) fit (e.g., Haywood et al. 2014). GP regression (Roberts et al. 2012; Rajpaul et al. 2015) has become one of the most successful tools in the analysis of stellar activity in RV time series (Dumasque et al. 2017).

The aim of this work is to test the accuracy of the RV uncertainties estimated by the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) data reduction pipeline, reported to be at a precision level of 10 cm s$^{-1}$ (Pepe et al. 2021). For this, we analyze RV observations of the solar twin HIP 11915, which is currently in the minimum of its magnetic activity cycle. We account for rotationally modulated stellar activity using GP regression. Details regarding the data are in Section 2. In Section 3 we present the method to analyze the RV. We discuss our results in Section 4.

2. Observations and Data Reductions

The new high-resolution spectrograph ESPRESSO (Pepe et al. 2014, 2021) of ESO’s Very-Large Telescope (VLT) started operations at the ESO Paranal observatory in 2018 September. It is designed and built to detect and characterize Earth analogs within the habitable zones of their host stars, reaching RV precision of 10 cm s$^{-1}$. More details regarding ESPRESSO may be found in the general description of the ESPRESSO instrument, reported on the actual on-sky performance described by Pepe et al. (2021).
The solar twin star HIP 11915 was selected from our former HARPS planet survey around solar twins, from which a Jupiter-twin planet was found (Bedell et al. 2015). The star has been carefully characterized in our previous works (dos Santos et al. 2016; Spina et al. 2018; Galarza et al. 2021), with improved CaII H&K activity indices derived by Lorenz-Oliveira et al. (2018). In Table 1 we summarize the main fundamental parameters derived for HIP 11915. Within the ESO program 0102.C-0523 (PI: Jorge Meléndez), we obtained a total of 24 observations of HIP 11915 from 2018 November to 2019 January. Measurements were taken in ESPRESSO’s High-Resolution 1-UT mode to reach a high resolving power \(R = \lambda/\Delta\lambda = 140,000\). We reduced the spectra using the 1.3.2\(^{\text{5}}\) version of the ESOReflex environment (Freudling et al. 2013). The data reduction includes the standard procedures such as corrections for bias, flat-field and background light, wavelength calibration, extraction of the spectrum, merging of the Echelle orders, and barycentric and instrumental drift corrections. The resulting spectra are given in counts and calibrated in flux. The wavelength calibration is performed combining a Thorium–Argon hollow-cathode lamp and a white-light illuminated Fabry–Pérot. The former provides wavelength accuracy, and the latter ensures wavelength precision. The pipeline also provides a cross-correlation function (CCF), computed with respect to a binary template mask. Then, the RV is obtained from a Gaussian fit to the CCF. For each exposure, we extracted the RV and activity indicators from the CCF (FWHM and CCF CONTRAST). The activity index \(S\) is measured from the extracted spectra, following prescriptions given in Wright et al. (2004). The contrast of the CCF, expressed as a percentage, is the relative depth of the CCF at its central wavelength, used to measure temporal changes (Lafarga et al. 2020). Maldonado et al. (2019) found significant correlations between the contrast with the main optical activity indicators for the Sun-as-a-star observations.

Table 1

| Parameter | Value | References |
|-----------|-------|------------|
| Spectral Type | G5V | (1) |
| V(mag) | 8.615 | (2) |
| \(T_{\text{eff}}(K)\) | 5773 ± 2 | (3) |
| \([\text{Fe/H}]\) | −0.057 ± 0.003 | (3) |
| \(\log g\) | 4.470 ± 0.008 | (3) |
| \(\log R_{\text{H}}(T_{\text{eff}})\) | −4.923 ± 0.028 | (4) |
| Age (Gyr) | 3.87 ± 0.39 | (3) |
| Mass (\(M_\odot\)) | 0.991 ± 0.003 | (3) |
| \(P_{\text{rot}}/\sin(i)\)(days) | 42.0 ± 8.6 | (5) |
| Number of observations | 24 |

References. (1) Houk & Smith-Moore (1988), (2) Ramírez et al. (2012), (3) Galarza et al. (2021), (4) Lorenzo-Oliveira et al. (2018), (5) Lorenzo-Oliveira et al. (2019).

3. RV Performance Through GP Analysis

The star-induced RV variability is difficult to model deterministically, and has motivated the use of GP regression (Haywood et al. 2014; Rajpaul et al. 2015). GP is a powerful statistical technique, in which intrinsic stellar variability is treated as correlated noise described by a covariance functional

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\text{form, while the hyperparameters describe the physical phenomena to be modeled. A kernel function is chosen to model these covariances as a function between two measurements at a time (Haywood et al. 2014; Rajpaul et al. 2015; Faria et al. 2016).}

3.1. GP Model

For a given activity indicator \(i\), we define a combination of covariance functions between two measurements at time \(t\) and \(t'\) of the observations, to build our quasiperiodic (QP) activity model:

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k(t, t') = \mathcal{I}_{\text{const}} + \mathcal{A} \exp \left( -\frac{\|r - r'\|}{2\ell^2} \right) - \Gamma \sin^2 \left( \frac{\pi}{P_{\text{rot}}} \|t - t'\| \right) + \sigma^2 \delta_{t, t'},
\]

where \(\mathcal{I}_{\text{const}}\) gives a constant scale to match the observed mean activity level of the star, while \(\mathcal{A}\) represents the amplitude of the rotation signal. The timescale of rising and decay of active regions is interpreted by \(\ell\), the harmonic nature of the time series is represented by \(\Gamma\), the white-noise term is \(\sigma^2 \delta_{t, t'}\), and \(P_{\text{rot}}\) is the rotational period, where \(P_{\text{rot}}\) was initially determined by using generalized Lomb–Scargle periodograms (GLS; Zechmeister & Kürster 2009). We use a log-normal prior distribution for the hyperparameters (HP): \(\mathcal{I}_{\text{const}} = \mu = (i), \sigma = \sigma(i), P_{\text{rot}} = \mu = P_{\text{rot}}, \sigma = 0.2 \times P_{\text{rot}}\), and \(\Gamma = (\mu = -2.3, \sigma = 1.4, \text{as in Angus et al. 2018})\). We use the emcee (Foreman-Mackey et al. 2013) Python implementation of the affine-invariant Markov chain Monte Carlo method (MCMC) following Angus et al. (2018) to estimate the posterior distribution of all GP HP. In brief, we start the MCMC process with 64 walkers to sample the parameter space, and are initialized with an optimal solution obtained by maximum likelihood optimization. Then, every 100 steps, we evaluate the convergence of chains and check its autocorrelation timescale (\(\tau_{\text{chain}}\)) and the consistency of walkers solutions through Gelman–Rubin statistics (\(\hat{R}\)) (Gelman & Rubin 1992). We consider that the walkers have converged when \(\tau_{\text{chain}}\) is less than 10% of the total chain length, \(\tau_{\text{chain}}\) is stable concerning the previous chain evaluation within 1%, and \(\hat{R}\) less than 1.03. Finally, we discard the initial iterations (3 × \(\tau_{\text{chain}}\)) and randomly resample 5000 samples to represent our estimate of posterior probability distribution of all GP HP.

3.2. Fitting the RV

To model the RV of HIP 11915 we fit the activity indicator \(i\) and the RV consecutively. We fit the RV using the same GP kernel function of Equation (1) with the \(\Gamma\), \(P_{\text{rot}}\) and \(\ell\) fixed at the median value from the activity indicator \(i\) fit. The GP regression fit to the CONTRAST and to the RV are shown in Figure 1. The resulting HP estimates are displayed in the last column of Table 2 as the median and 16% confidence interval of these uncorrelated samples. We also applied the same procedure to the FWHM and the S Index and its resulting HP estimates for the RV are displayed in the bottom part of the Table 2.

The root mean square (rms) of the residuals is 25 cm s\(^{-1}\), 23 cm s\(^{-1}\) and 23 cm s\(^{-1}\) for the rms \(\text{res}_{\text{CONTRAST, RV}}\), \(\text{rms res}_{\text{FWHM, RV}}\) and \(\text{rms res}_{S \text{ Index, RV}}\) respectively. These values can be compared to the average RV uncertainty of 27 cm s\(^{-1}\). They

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\(^{5}\) https://www.eso.org/sci/software/esoreflex/
are also in agreement with the posterior estimate for the white-noise term parameters of 20 cm s$^{-1}$, yet at the level of few tens of cm s$^{-1}$. In Figure 2, we show all the residuals for each fit. The values reached for the RV precision are robust, since the GP was applied independently for each activity indicator.

To test the stability of the values found for the total sample, we resampled 30 times, choosing the observations randomly, keeping 2/3 of the total sample. The results remained relatively stable, deviating $+6$ cm s$^{-1}$ from the original values, except for the FWHM which had the largest deviation, 11 cm s$^{-1}$. The HP also remained stable in tests, most of them resulting in the same value found for the total sample. The HP $\ell$ and $\Gamma$ present greater variation in results, from ~60 days to ~200 days and ~0.5 to ~2.5, respectively.

We also used the GP approach applied to the recently released ESO Phase 3 (pipeline version 2.2.1 or higher), to test if different pipelines to reduce the data interfere with the results. The results remained relatively stable, the rms of the residuals is 24 cm s$^{-1}$, 41 cm s$^{-1}$ and 44 cm s$^{-1}$ for the rms $\text{res}_{\text{CONTRAST,RV}}$, $\text{rms}_{\text{FWHM,RV}}$ and $\text{rms}_{\text{Index,RV}}$, respectively.

### 4. Conclusions

In this work we report results about the ESPRESSO RV precision. Using the solar twin HIP 11915 data (~60 days) from the ESPRESSO spectrograph at the VLT, we applied the Gaussian Process regression with a quasiperiodic kernel to obtain the residuals from the fits. We found an average value of

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**Table 2**

Summary of Hyperparameters, Upper and Lower Bounds of the Priors, and its Initial Guesses used for MCMC Sampling for the CONTRAST (CONT) and RV Fits of ESPRESSO Data

| Fit | MCMC Initial Guess | Priors Bounds | Fit Value |
|-----|-------------------|---------------|-----------|
| CONT HP | $\mathcal{I}_{\text{CONTR}}$ [%] | mean(CONT) | (60.628, 60.761) | 60.710 $\pm$ 0.021 |
|      | $\sigma_{\text{CONTR}}$ [%] | mean(CONT error) | (0.0022, 0.0226) | 0.0134 $\pm$ 0.0043 |
|      | $\lambda_{\text{CONTR}}$ [days] | var(CONT) | (0.034, 0.174) | 0.059 $\pm$ 0.010 |
|      | $\Gamma$ | (2, 365) | 68.8 $\pm$ 27.8 |
|      | $P_{\text{rot}}$ [days] | (−10, 2) | 2.5 $\pm$ 0.9 |
|      | $\mu$ [km s$^{-1}$] | (15, 50) | 27.4 $^{+11}_{−8}$ |
|      | $\sigma_{\text{CONTR}}$ [km s$^{-1}$] | mean(RV) | (14.436, 14.446) | 14.441 $\pm$ 0.002 |
|      | $\lambda_{\text{CONTR}}$ [km s$^{-1}$] | var(RV) | (10$^{-4}$, 5 $\times$ 10$^{-4}$) | 0.0002 $\pm$ 0.0001 |
| RV HP | $\sigma_{\text{FWHM,RV}}$ [km s$^{-1}$] | mean(RV) | (0.0032, 0.0160) | 0.0039 $\pm$ 0.0008 |
|      | $\lambda_{\text{FWHM,RV}}$ [km s$^{-1}$] | var(RV) | (0.0002, 0.0006) | 0.0037 $\pm$ 0.0003 |
|      | $\sigma_{\text{Index,RV}}$ [km s$^{-1}$] | mean(RV) | (14.436, 14.446) | 14.441 $\pm$ 0.001 |
|      | $\lambda_{\text{Index,RV}}$ [km s$^{-1}$] | var(RV) | (10$^{-4}$, 5 $\times$ 10$^{-4}$) | 0.0002 $\pm$ 0.0001 |

**Note.** The last column shows the resulting median value of the MCMC samples and their corresponding error.
24 cm s$^{-1}$ for the rms of our residuals, that represents an upper limit for the performance of ESPRESSO for this range of observation. HIP 11915 is a solar twin star, observed during the minimum of its activity cycle, and the low activity level of the star has helped to evaluate the performance of ESPRESSO, demonstrating that the instrument can achieve low-to-mid 20 cm s$^{-1}$ on quiet stars.

With long-term repeated measurements, it may be possible to improve the RV precision for the HIP 11915. This is a great target for the searches of Earth analogs, since it has a Jupiter twin (Bedell et al. 2015), has a chemical composition depleted in rocky-forming elements, similar to the Sun (Galarza et al. 2021), and a precision at the level of 20 cm s$^{-1}$ can be achieved.

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Figure 2. Residuals in RVs of the GP fit for each activity indicator with its rms scatter. In each panel, the GP was trained on: Top: CONTRAST; middle: FWHM; bottom: $S$ Index.

Facilities: ESO: VLT 8.2 m Unit Telescopes, Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPResso).

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