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HIP 102152b: A low-mass planet candidate around an old solar twin

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Abstract. We present the discovery of a short-period low-mass exoplanet candidate around the 8–Gyr solar twin HIP 102152 as part of the Solar Twin Planet Search survey. The system was observed over 7 years with the ESO/HARPS spectrograph, and besides the rotational modulations of stellar activity, we did not find correlations with the proposed exoplanet's orbital period. To probe the physical and orbital characteristics of HIP 102152b, and assess the significance of red noise that account for stellar activity signatures, we employed a joint Keplerian and Gaussian Process model. The results are consistent with a mini-Neptune ($m \sin i = 8 \pm 1$ $M_\oplus$) on a circular orbit with $P_{b,orb} = 23$ days, and no radial velocity slope was observed due to acceleration from an outer massive companion in this system. Even exceptionally similar to the Sun in terms of refractory/volatile species abundances, HIP 102152 is severely lithium-depleted, a possible indication that this heavy material from the protoplanetary disc was used in the formation of planetesimals and other planets, including HIP 102152b.

Resumo. Apresentamos a descoberta de um candidato a exoplaneta de baixa massa e curto período orbital orbitando a gêmea solar HIP 102152 de 8-Gyr como parte do levantamento Solar Twin Planet Search. O sistema foi observado ao longo de 7 anos com o espectrógrafo ESO/HARPS, e além de modulações rotacionais por atividade estelar, não encontramos correlações com o período orbital do exoplaneta proposto. Para determinar as características físicas e orbitais de HIP 102152b, e avaliar a significância de ruído vermelho que responde por assinaturas de atividade estelar, empregamos um modelo conjunto Kepleriano e por Processos Gaussianos. Os resultados são consistentes com um mini-Netuno ($m \sin i = 8 \pm 1$ $M_\oplus$) em uma órbita circular de período $P_{b,orb} = 23$ dias, e nenhuma inclinação de velocidade radial foi observada devido à aceleração de um companheiro massivo externo neste sistema. Mesmo excepcionalmente semelhante ao Sol em termos de abundância de espécies refratárias/voláteis, HIP 102152 é severamente depletado em lítio, uma possível indicação de que este material pesado do disco protoplanetário fora utilizado na formação de planetesimais e outros planetas, incluindo HIP 102152b.

Keywords. planets and satellites: individual: HIP 102152b – stars: solar-type – techniques: radial velocities

1. Introduction

HIP 102152 is a solar twin ($T_{\rm eff} = 5718$ K, [Fe/H] = −0.016, and $\log g = 4.325$; Spina et al. 2018), placed near the end of the main sequence ($t = 8.2$ Gyr), and presents a rotation period of 35.7 days (Lorenzo-Oliveira et al. 2020). Due to its severe lithium depletion (Monroe et al. 2013), and low activity levels ($\log R'_{\rm HK} = -5.12$) but high radial velocity root mean square errors, it was identified as a promising planet-hosting system (Bedell 2017).

2. Data Analysis

HIP 102152 was observed with the ESO/High Accuracy Radial Velocity Planet Searcher (HARPS) spectrograph mounted at the 3.6–m telescope in La Silla Observatory between October 2011 and May 2019, retrieved through the ESO Advanced Data Products (ADP[1]). From a generalised Lomb-Scargle analysis (GLS; Zechmeister & Kürster 2009), we detected a periodic signal of ∼23–d in the radial velocity time-series, and besides known stellar activity, no modulation of the indicators proxies was observed at this period, nor correlation with the radial velocity measurements (see Figs. 1 and 2).

Following the hypothesis of planetary nature, we employed a joint Keplerian plus Gaussian Process model and estimated the significance of the results via Markov chain sampling, where observations at two different epochs are correlated via the *kernel*

$$\Sigma_{ij} = \eta_1^2 \cdot \exp\left[-\frac{|t_i - t_j|}{2 \cdot \eta_2^2} - \frac{2 \cdot \sin^2\left(\frac{\pi \cdot |t_i - t_j|)}{\eta_3}\right)}{\eta_4^2}\right], \quad (1)$$

a function of the stellar activity Doppler amplitude signal (η_1), the time-scale for growth and decay of active regions in a star's surface (which is often comparable to the star's rotational period, η_2), the recurrence time-scale for active regions (η_3), and a smoothing parameter (η_4) (Hatzes 2019). For the Keplerian side, both the eccentricity (in the orthogonal basis with the periastron argument: $\sqrt{e} \sin \omega$ and $\sqrt{e} \cos \omega$) and the radial velocity slope ($\dot{\gamma}$) were set to freely vary in a unitary disc and infinitely respectively, and we included separated jitter parameters for data taken before and after the ESO/HARPS upgrade in mid-2015. The other model variables include the GLS orbital period (P), the planet's Doppler amplitude (K), and the time of inferior conjunction (T_c).

3. Results

HIP 102152b signal is consistent with a mini-Neptune ($m \sin i = 8 \pm 1 M_\oplus$) on a circular orbit with period $P = 22.9 \pm 0.01$–d, and no radial velocity slope was observed due to acceleration from an outer massive companion in this system (see Fig. 3). The best-fit model posterior (by combining Normal and Jeffrey priors[2]) was

[1] http://archive.eso.org/wdb/wdb/adp/

[2] The notation $\mathcal{N}(\theta|\mu,\sigma)$ reads out as a Normal distribution of a hyper-parameter θ with mean μ and standard deviation σ, while $\mathcal{J}(\theta|\alpha\beta$

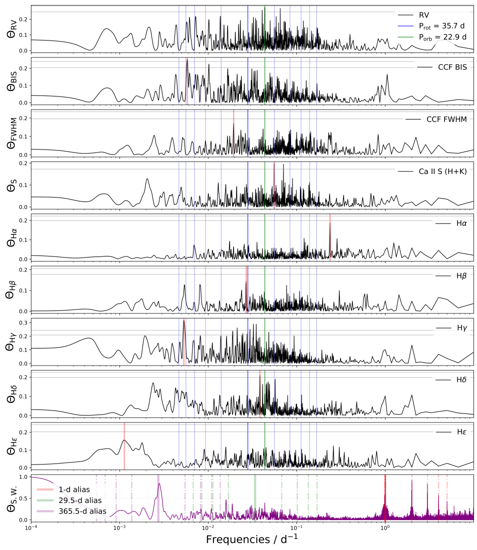

Figure 1. GLS periodograms for the RV measurements and activity indicators proxies of HIP 102152. The central blue vertical line marks the star's rotational period and its lower/upper order harmonic up to 6^{th} degree. The green line marks the planet's orbital period, while the red line is the periodogram peak for each variable. The Spectral Window Function is presented at the bottom in purple, highlighting 1–d, 1–mo., and 1–yr. aliases. The power level for which the false-alarm levels are less than 1% and 5% are indicated as grey horizontal lines in each periodogram estimated from bootstrapping re-sampling.

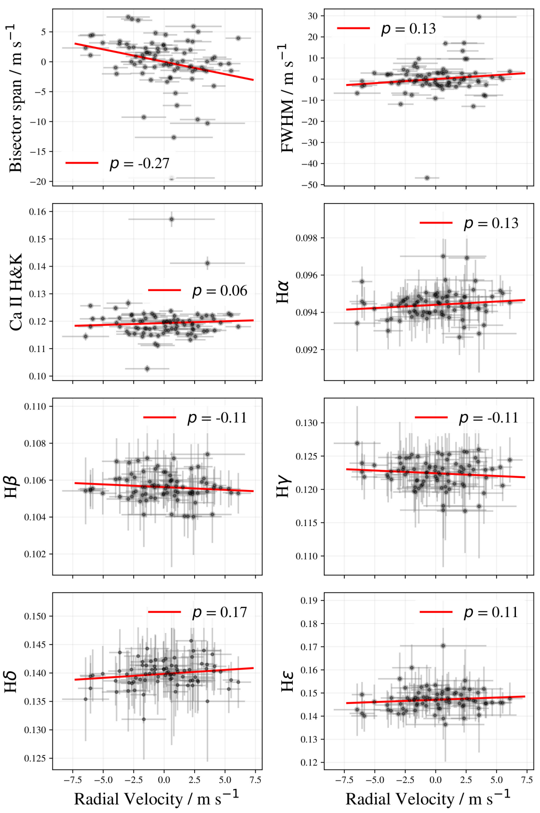

Figure 2. Radial velocity and activity indicators relationship. The red lines represent the best-fit linear correlations, while the Pearson correlation index p is indicated to quantify the significance of the correlations.

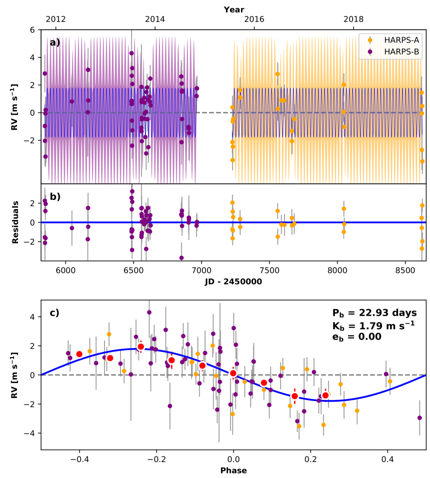

Figure 3. (a) 1–planet joint Keplerian and Gaussian Process model for HIP 102152b. The planet's maximum likelihood is presented in blue, while activity modulations are in purple/yellow, respectively, for data after and before HARPS' upgrade. (b) Residuals to the best-fit model. (c) Radial velocity (RV) phase diagram to the ephemeris of planet b. RVs are binned in 0.08 phase units in red.

obtained with the `RadVel` routine (Fulton et al. 2018), implementing a maximum a posteriori optimisation, and computing confidence intervals from 1000 independent chains, plus requiring a Gelman-Rubin statistics $\hat{R} < 1.01$.

$$\begin{aligned}\pi(V_r|\Theta) \;\propto\; & \mathcal{N}(P|22.9, 0.01) \times \mathcal{N}(K|2, 0.2) \\ & \times\; \mathcal{N}(T_0|x(\max y), 0.01) \\ & \times\; \mathcal{J}(\eta_1|0.01, 100) \times \mathcal{N}(\eta_2|35.7, 1.4) \\ & \times\; \mathcal{N}(\eta_3|30, 0.7) \times \mathcal{N}(\eta_4|0.46, 0.01) \\ & \times\; \mathcal{N}(\sigma_{\mathrm{A,B}}|0, 0.1) \qquad (2)\end{aligned}$$

Four models (circular and eccentric, with and without slope) were compared using the Bayesian/Akaike Information Criterion (BIC/AIC) factors, from which we found out that the circular without radial velocity slope is preferable in describing the modulations by $\Delta(\mathrm{BIC/AIC}) = -13.4/-10.0$ over the second-ranked, which is expected as close-in exoplanets tend to be on circular orbits due to tidal dissipation.

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reads out as a Jeffrey's distributed hyper-parameter θ bounded between α and β.