The GAPS programme at TNG

XXIII. HD 164922 d: close-in super-Earth discovered with HARPS-N in a system with a long-period Saturn mass companion

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ABSTRACT

Context. Observations of exoplanetary systems demonstrate that a wide variety of planetary architectures are possible. Determining the rate of occurrence of Solar System analogues – with inner terrestrial planets and outer gas giants – remains an open question.

Aims. Within the framework of the Global Architecture of Planetary Systems (GAPS) project, we collected more than 300 spectra with HARPS-N at the Telescopio Nazionale Galileo for the bright G9V star HD 164922. This target is known to host one gas giant planet in a wide orbit (Pb ~1200 days, semi-major axis ~2 au) and a Neptune-mass planet with a period of Pb ~76 days. We aimed to investigate the presence of additional low-mass companions in the inner region of the system.

Methods. We compared the radial velocities (RV) and the activity indices derived from the HARPS-N time series to measure the rotation period of the star and used a Gaussian process regression to describe the behaviour of the stellar activity. We then combined a model of planetary and stellar activity signals in an RV time series composed of almost 700 high-precision RVs, both from HARPS-N and literature data. We performed a dynamical analysis to evaluate the stability of the system and the allowed regions for additional potential companions. We performed experiments on the injection and recovery of additional planetary signals to gauge the sensitivity thresholds in minimum mass and orbital separation imposed by our data.

Results. Thanks to the high sensitivity of the HARPS-N dataset, we detected an additional inner super-Earth with an RV semi-amplitude of \( \Delta v \sim 1.3 \pm 0.2 \) m s\(^{-1}\) and a minimum mass of \( m_\text{p} \sin i = 4 \pm 1 M_\oplus \). It orbits HD 164922 with a period of 12,458 ± 0.003 days. We disentangled the planetary signal from activity and measured a stellar rotational period of \( \sim 42 \) days. The dynamical analysis shows the long-term stability of the orbits of the three-planet system and allows us to identify the permitted regions for additional planets in the semi-major axis range 0.18–0.21 au and 0.6–1.4 au. The latter partially includes the habitable zone of the system. We did not detect any planet in these regions, down to minimum detectable masses of 5 and 18 \( M_\oplus \), respectively. A larger region of allowed planets is expected beyond the orbit of planet b, where our sampling rules out bodies with minimum mass >50 \( M_\oplus \). The planetary orbital parameters and the location of the snow line suggest that this system has been shaped by a gas disk migration process that halted after its dissipation.

Key words. planets and satellites: detection – planetary systems – stars: individual: HD 164922 – techniques: radial velocities

1. Introduction

Giant planets are known to play a dominant role in the dynamical evolution of the planetary systems since they produce gravitational interactions able to compromise the presence of low-mass planets, even preventing their formation (Armitage 2003; Matsumura et al. 2013; Izidoro et al. 2015; Sánchez et al. 2018). This is supported by the observational evidence, in particular from transit surveys, showing that terrestrial and super-Earth planets are generally found in multiple, often packed systems with other low-mass companions (e.g. Batalha et al. 2013; Weiss et al. 2018), while it seems more challenging to find systems showing both low-mass and giant planets (see e.g. the summary in Agnew et al. 2017). Up to a few years ago, these results strengthened the idea that the Solar System architecture is not common, even if this could be the result of observing bias. Transit surveys are more sensitive toward packed coplanar configurations, disfavouring the detection of multiple systems containing giant planets. Theoretical simulations on dynamics and orbital stability show that, under specific conditions, inner rocky planet formation, and survival in systems with an outer gas giant is actually allowed, even within the habitable zone (Thébault et al. 2002; Mandell et al. 2007;
Agnew et al. 2017, 2018). For exoplanetary systems, it is only recently that these simulations have been corroborated by observations (e.g. Zhu & Wu 2018; Bryan et al. 2019), favoured by a long observation baseline and cutting-edge instrumentation. During the first decade of the exoplanets search, a large fraction of giant planets in intermediate orbit (larger than 1 au) were detected without the support of high-precision radial velocities (RV) since their RV signal allowed their detection even with medium performance instrumentation (e.g. Hatzes et al. 2000: coudé spectrograph at CFHT, Hamilton at Lick Observatory, coudé spectrograph at ESO-La Silla, coudé spectrograph McDonald Observatory, RV precisions between 11 and 22 m s$^{-1}$; Mayor et al. 2004: CORALIE at ESO-La Silla, RV precision of 3 m s$^{-1}$). On the other hand, due to the low sensitivity of those data and their sparse sampling, the possible presence of additional low-mass companions could not be revealed. Indeed, with the state-of-the-art instrumentation currently operational (e.g. the spectrographs HIRES, HARPS, HARPS-N, ESPRESSO) it is possible to search for inner low-mass planets in systems with gas giant companions (see e.g. Barbuto et al. 2018). The increasing sensitivity also implies reaching the current limit in low-mass planet detection, represented by the achievable RV precision and the stellar activity “noise”. In recent years, a lot of computational efforts have been made to develop methods to efficiently remove the stellar contribution, which may be significant even in quiet stars. One of the most frequently employed techniques involves Gaussian process (GP) regression (e.g. Haywood et al. 2014 and references therein). An optimised observing strategy is also crucial both to reduce the impact of the stellar noise (e.g. Dumusque et al. 2011a,b) and to improve the efficiency of the modelling methods. A well-sampled and large dataset enhances our ability to model and thus mitigate the contribution of the stellar activity on the RV time series.

Since 2012, the Global Architecture of Planetary System (GAPS, Covino et al. 2013; Benatti et al. 2016) project has been carrying out a radial velocity survey with the High Accuracy Radial velocity Planet Searcher (HARPS-N) high-resolution spectrograph (Cosentino et al. 2014) mounted at the Italian Telescope Nazionale Galileo (TNG, La Palma, Canary Islands). One of the first goals of the GAPS programme was the search for close-in, low-mass planets in systems hosting giant planets at wide separation. Within this framework, we observed the bright G9V star HD 164922 ($m_V = 6.99$), known to host a long-period gas giant (planet b, $P_b = 1201$ days, $a_b \sim 2.2$ au, $m_b \sin i_b = 107.6$ $M_{\oplus}$ $\sim 0.3$ $M_{\text{Jup}}$), detected by Butler et al. (2006) and a temperate Neptune-mass planet (planet c, $P_c = 75.76$ days, $a_c \sim 0.35$ au, and $m_c \sin i_c = 12.9$ $M_{\oplus}$), declared by Fulton et al. 2016 (hereinafter F2016) after we started to follow-up the star. The mean value of the chromospheric activity index $\log R'_{\text{HK}}$ is approximately $-5.05$, as reported by several authors. This indicates that the target is rather quiet from the viewpoint of stellar activity, also confirmed by a comparison with the same index for the quiet Sun ($\log R'_{\text{HK,\,mini}} = -4.98 \pm 0.01$, see e.g. Egeland et al. 2017). Nevertheless, the robust detection of the planet c required a considerable amount of RV measurements, for a total of almost 400, mainly provided by the HIRES spectrograph at the Keck Observatory, and with a dedicated monitoring with the Levy spectrograph mounted at the Automated Planet Finder (APF) of the Lick Observatory. In this work, we present the detection of a super-Earth orbiting at a distance of 0.1 au with a dataset of more than 300 high-precision RVs measured from HARPS-N spectra, with the support of the RVs from the literature.

This paper is organised as follows: in Sect. 2 we describe the characteristics of our HARPS-N observations, from which we obtained the stellar parameters presented in Sect. 3. The first evaluation of the frequency content in our data, along with a comparison with those available in the literature, are presented in Sect. 4. In Sect. 5, we show the best-fit results of our RV modelling through Gaussian process regression. In Sect. 6, we provide an evaluation on the system stability with some clues on the planet migration history from the present architecture and we draw our conclusions in Sect. 7.

2. HARPS-N dataset

We observed, at high cadence, HD 164922 with HARPS-N for five seasons, from March 2013 to October 2017, with an additional set of ten spectra collected between May and June 2018. HARPS-N is a cross-dispersed high-resolution ($R = 115 000$) echelle spectrograph, in the range 3830–6930 Å. A constant control of its pressure and temperature prevents spectral drifts due to environmental parameters variations. HARPS-N is fed by two fibres: the target feeds the first fibre while the second one can be illuminated either by the sky or a simultaneous calibration source. To obtain high precision in our RV measurements, we exploited the latter technique. We collected a total of 314 spectra with a mean signal-to-noise ratio ($S/N$) of 200 at 5500 Å and a mean integration time of 600 s. Figure 1 shows the cumulative distribution of the time lag between consecutive data points in our sampling. To account for spectra collected with a time difference slightly larger than one day, as it can happen the night following one observation, we binned the distribution at 1.5 days. Within the same season, $\sim 80\%$ of our spectra were collected with a time lag less or equal to one week, while $65\%$ were taken in contiguous nights or in the same night. The largest difference is 46 days while in the second, third, and fourth seasons we collected two spectra in the same night, with a time lag of about three hours.

The spectra were reduced through the HARPS-N Data Reduction Software (DRS), including the radial velocity extraction based on the Cross-Correlation Function (CCF) method (see Pepe et al. 2002 and the references therein), where the observed spectrum is correlated with a K5 template, called “mask”, depicting the features of a star with spectral type K5V. The offline version of the HARPS-N DRS, which is implemented at the INAF Trieste Observatory$^1$, can be run by the users to re-process the data through the YABI workflow interface (Hunter et al. 2012), with the possibility of modifying the

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$^1$ http://ia2.inaf.it
default parameters obtaining thus a custom reduction. The resulting CCF is the weighted and scaled average of the lines contained in the correlation mask, and can be used as a proxy for common line profile changes. For this reason, it can be analysed through several diagnostics in order to investigate effects related to stellar activity. For instance, Lanza et al. (2018) describe a procedure for deriving a set of CCF asymmetry indicators such as the Bisector Inverse Slope (BIS, e.g. Queloz et al. 2001), the $V_{\text{asy}(\text{mod})}$ (re-adapted from the original definition by Figueira et al. 2013), and the $\Delta V$ (Nardetto et al. 2006). With YABI, it is also possible to calculate the chromospheric activity index from the H&K lines of Ca II (S-index and $log\alpha$) as the Bisector Inverse Slope (BIS, e.g. Queloz et al. 2001), the $V_{\text{asy}(\text{mod})}$ (re-adapted from the original definition by Figueira et al. 2013), and the $\Delta V$ (Nardetto et al. 2006). With YABI, it is also possible to calculate the chromospheric activity index from the H&K lines of Ca II (S-index and $log\alpha$) as the Bisector Inverse Slope (BIS, e.g. Queloz et al. 2001), the $V_{\text{asy}(\text{mod})}$ (re-adapted from the original definition by Figueira et al. 2013), and the $\Delta V$ (Nardetto et al. 2006). With YABI, it is also possible to calculate the chromospheric activity index from the H&K lines of Ca II (S-index and $log\alpha$). By using the definition in Dravins et al. (1999), we were able to estimate the perspective acceleration in the HD 164922, adopting the parallax and the proper motions listed in Table 2. We therefore noticed that this target shows the non-negligible value of $0.26 \, \text{m s}^{-1} \, \text{year}^{-1}$, so we decided to apply this correction to our RVs (this is not taken into account by the HARPS-N DRS). The following analysis is therefore performed on the corrected RVs, shown in Fig. 2. The mean uncertainty of the RV measurements is $0.4 \, \text{m s}^{-1}$.

### 3. Stellar parameters

The main stellar parameters of HD 164922 are collected in Table 2, either reported from the literature or specifically estimated in this present work. The astrometric parameters (astrometers, proper motions and parallax) are taken from the Gaia Data Release 2 (Gaia Collaboration 2018; Lindegren et al. 2018), that we used to evaluate the perspective acceleration in the previous section.

To estimate the photospheric parameters, we produced a coadded spectrum from 212 HARPS-N spectra of our dataset with higher S/N. We also excluded spectra collected before JD 2 456 740 (March 2014), which are affected by a certain degree of de-focussing (we note that this issue had a negligible impact on the HARPS-N RVs, see Benatti et al. 2017). The S/N of the coadded spectrum reached the high value of 2800. At this level we were mainly limited by systematic errors of the atmospheric parameters determination method rather than by the quality of this spectrum. We obtained a first determination of the atmospheric parameters using CCFpams (Malavolta et al. 2017). By using the most recent release of the MOOG code (Sneden 1973) and following the approach described in Biazzo et al. (2011) with the line list presented in Biazzo et al. (2012), we measured the stellar effective temperature ($T_{\text{eff}}$), surface gravity ($log\,g$), iron abundance ([Fe/H]), and microturbulence velocity ($v_{\text{mac}}$) from line equivalent widths (see Table 2). The projected rotational velocity was estimated with the same code and applying the spectral synthesis method after fixing the macroturbulence. Assuming $v_{\text{mac}} = 2.6 \, \text{km s}^{-1}$ from the relationship by Doyle et al. (2014) based on asteroseismic analysis of main sequence stars observed by the NASA – Kepler satellite and depending

### Table 1. Time series of the HARPS-N spectra for HD 164922.

| BJD$_{\text{TDB}}$−2 450 000 | RV | RV$_{\text{err}}$ | log $R'_{\text{HK}}$ | log $R'_{\text{HK,err}}$ | BIS | BIS$_{\text{err}}$ | $\Delta V$ | $\Delta V_{\text{err}}$ | $V_{\text{asy}(\text{mod})}$ | $V_{\text{asy}(\text{mod,err})}$ | Hz | Hz$_{\text{err}}$ |
|-----------------------------|----|-----------------|---------------------|-------------------------|-----|-----------------|--------|----------------|---------------------|-----------------------------|----|----------------|
| 6362.761620                 | 20.3668 | 0.0002 | −5.0539 | 0.0016 | −3.9170 | 1.4220 | −0.0073 | 0.0075 | 0.0120 | 0.0200 | 0.4333 | 0.0023 |
| 6363.696888                 | 20.3650 | 0.0004 | −5.0649 | 0.0036 | −3.9440 | 1.7310 | −0.0078 | 0.0076 | 0.0133 | 0.0023 | 0.4331 | 0.0041 |
| 6365.766007                 | 20.3704 | 0.0002 | −5.0556 | 0.0016 | −3.0150 | 1.3040 | −0.0071 | 0.0075 | 0.0113 | 0.0021 | 0.4336 | 0.0024 |
| 6375.730565                 | 20.3680 | 0.0005 | −5.0693 | 0.0040 | −6.5920 | 1.4980 | −0.0093 | 0.0076 | 0.0152 | 0.0023 | 0.4340 | 0.0045 |
| 6404.703976                 | 20.3719 | 0.0004 | −5.0687 | 0.0029 | −4.8380 | 1.6760 | −0.0083 | 0.0076 | 0.0146 | 0.0022 | 0.4328 | 0.0035 |
| 6405.637835                 | 20.3725 | 0.0003 | −5.0585 | 0.0026 | −3.6740 | 1.4560 | −0.0075 | 0.0074 | 0.0128 | 0.0022 | 0.4328 | 0.0031 |

### Notes.
Columns are: radial velocity (RV), log $R'_{\text{HK}}$, bisector span (BIS), $\Delta V$, $V_{\text{asy}(\text{mod})}$ and Hz indices with the corresponding uncertainties. Full table available at the CDS.

### Table 2. Stellar parameters of HD 164922.

| Parameter | Value | Ref. |
|-----------|-------|------|
| RA (J2015.5) [deg] | 270.630 ± 0.016 | a |
| Dec (J2015.5) [deg] | 26.310 ± 0.024 | a |
| pmRA [mas yr$^{-1}$] | 389.653 ± 0.033 | a |
| pmDec [mas yr$^{-1}$] | −602.313 ± 0.433 | a |
| Parallax [mas] | 45.422 ± 0.031 | a |
| Distance [pc] | 22.00$^{+0.01}_{-0.02}$ | b |
| Spectral type | G9V | c |
| $v_{\text{TG}}$ | 6.99 | c |
| $B-V$ | 0.799 ± 0.005 | d |
| $v_{\text{mac}}$ [m s$^{-1}$] | 0.26 ± 0.01 | e |
| Systemic RV [km s$^{-1}$] | 20.3634 ± 0.0007 | e |
| $T_{\text{eff}}$ [K] | 5390 ± 30 | e |
| $log\,g$ [cm s$^{-2}$] | 4.46 ± 0.13 | e |
| [Fe/H] [dex] | 0.18 ± 0.08 | e |
| $v_{\text{mac}}$ [m s$^{-1}$] | 0.80 ± 0.03 | e |
| $v\sin\,i$ [km s$^{-1}$] | <2.0 | e |
| log $R'_{\text{HK}}$ | −5.075 ± 0.010 | e |
| $P_{\text{rot}}$ [d] | 42.3$^{+1.3}_{-0.7}$ | e |
| $L/L_{\odot}$ | 0.71 ± 0.15 | e |
| Mass [$M_{\odot}$] | 0.926$^{+0.029}_{-0.035}$ | e |
| Radius [$R_{\odot}$] | 0.946$^{+0.014}_{-0.015}$ | e |
| Age [Gyr] | 9.58$^{+1.99}_{-1.55}$ | e |

### References.

(a) Gaia Collaboration (2018); (b) Bailer-Jones et al. (2018); (c) Butler et al. (2006); (d) van Leeuwen (2007); (e) this work.
on $T_{\text{eff}}$ and $\log g$, we find a projected rotational velocity of $v\sin i = 0.7 \pm 0.5$ km s$^{-1}$. This value is consistent with the determination by Brewer et al. (2016), obtained through the spectral synthesis modelling of HIRES data from a large sample of dwarfs and subgiants stars. However, since the velocity resolution of HARPS-N is about 2.0 km s$^{-1}$ we cannot assert that we resolve the actual stellar rotation velocity. We estimated the stellar luminosity by combining parallax measurements with the bolometric corrections to obtain the bolometric magnitude. By using a bolometric correction BC = $-0.164 \pm 0.11$ deduced here by following Buzzoni et al. (2010), we obtained $L/L_\odot = 0.71 \pm 0.15$. To obtain the mass, radius and age of our target we used the web interface of the Bayesian tool PARAM2 version1.3 (da Silva et al. 2006; Rodrigues et al. 2014), based on the PARSEC isochrones (Bressan et al. 2012). The input parameters are $T_{\text{eff}}$, [Fe/H], and $\log g$ all used as priors to compute the probability density function of the stellar parameters. We found that the resulting fundamental parameters of this star are: age = $9.2 \pm 2.5$ Gyr, stellar mass $M = 0.93 \pm 0.05$ $M_\odot$ and radius $R = 0.95 \pm 0.1 R_\odot$.

The systemic RV and the activity index of the Ca II H&K lines, $\log R'_{\text{HK}}$, are finally obtained from our HARPS-N dataset. The former is obtained from the orbital fit presented in Sect. 5.2. The evaluation of the $\log R'_{\text{HK}}$ is not affected by the interstellar reddening being our target within 75 pc (see e.g. Mamajek & Hillenbrand 2008), and its small value, $-5.075 \pm 0.010$, suggests that HD 164922 is a quiet star. According to the empirical relations by Noyes et al. (1984) and Mamajek & Hillenbrand (2008) we should expect a rotation period ranging between 43 and 48 days. In Table 2 we report the adopted $P_{\text{rot}}$, $42.3^{+1.3}_{-0.5}$ days, as derived in Sect. 4.2.

4. HARPS-N time series analysis

In this section, we present a first evaluation of the HARPS-N time series of HD 164922, obtained as described in Sect. 2. This investigation was performed in preparation for the GP analysis presented in Sect. 5.

4.1. Periodogram analysis

We carried out a preliminary two-planets fit of the HARPS-N RVs time series using the MPFIT IDL package3, implemented as in Desidera et al. (2011), starting from the orbital solution reported by F2016 and depicted by a grey solid line in Fig. 2. Subsequently, we computed the Generalised Lomb-Scargle (GLS) periodogram (Zechmeister & Kürster 2009) of the RV residuals, shown in Fig. 3 together with the corresponding window function, in the inset plot. Except for the 1-yr signal located at the lower frequencies, two main periodicities are visible: the dominant one is found at 0.0239 days$^{-1}$ (i.e. 41.63 d in the time domain, red dashed line), the second one at 0.0803 days$^{-1}$ (12.46 d, blue dashed line), both of them with a False Alarm Probability (FAP) less than 10$^{-4}$, evaluated with 10 000 bootstrap random permutations. The large peak at $-41.6$ d could be the signature of the stellar rotation, as expected by the empirical activity-rotation relationships (Sect. 3), while the second peak could suggest the presence of a short period planetary companion. For sake of completeness, the periodicity at about 0.165 days$^{-1}$ shows a high value of the FAP (15%). In order to understand whether the main periodicities are related to the stellar activity, we evaluated the GLS for the BIS, the $\log R'_{\text{HK}}$ and the available asymmetry indices, as presented by Lanza et al. (2008). The GLS of all these parameters are reported in Fig. 4, where the dashed lines follow the same colour code as in Fig. 3. No significant peak can be found close to the 12.46 d periodicity. Based on the FAP evaluation, none of the periodogram peaks appears significant, with the only exception of the 23.4 days in the periodogram of Hα (FAP = 0.01%).

We finally evaluated the Spearman correlation coefficient between the RV residuals of the two-planets fit and the considered activity indices but no correlation was found. This might be explained by the dominant contribution of the faculae to the RVs rather than starspots (e.g. Dumusque 2016 and Collier Cameron et al. 2019 for the solar case).

4.2. GP regression of the $\log R'_{\text{HK}}$ index

To confirm the hypothesis that the rotation period of the star is about 42 days, we performed a GP regression analysis of the time series of the $\log R'_{\text{HK}}$ index. We used a quasi-periodic model for the correlated signal of stellar origin. We first removed all the spectra with S/N $< 20$ in the region of the Ca II lines, to work with a more reliable determination of the $\log R'_{\text{HK}}$ value. The Monte Carlo analysis has been done with the open source Bayesian inference tool MULTINEST v3.10 (e.g. Feroz et al. 2019), through the PYMULTINEST python wrapper.

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2 http://stev.oapd.inaf.it/cgi-bin/param_1.3
3 A non-linear least squares curve fitting presented by Markwardt (2009), available at http://purl.com/net/mpfit

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(Buchner et al. 2014), including the publicly available GP python module GEORGEv0.2.1 (Ambikasaran et al. 2015). The formalism used for the GP regression is the same described in Affer et al. (2016), with the quasi-periodic kernel described by the following covariance matrix:

$$k(t, t') = h^2 \cdot \exp \left( -\frac{(t - t')^2}{2\lambda^2} - \frac{\sin^2(\pi(t - t')/\theta)}{2w^2} \right) + (\sigma^{2}_{\log R'_{\text{HK}}}(t)) \cdot \delta_{t,t'},$$

where $t$ and $t'$ indicate different epochs, $\sigma^{2}_{\log R'_{\text{HK}}}$ is the uncertainty of the $R'_{\text{HK}}$ index at the time $t$ added quadratically to the diagonal of the covariance matrix, and $\delta_{t,t'}$ is the Kronecker delta. Finally, $h$, $\lambda$, $\theta$, and $w$ are the hyper-parameters: $\theta$ represents the periodic time-scale of the modeled signal, and corresponds to the stellar rotation period; $h$ denotes the scale amplitude of the correlated signal; $w$ describes the level of high-frequency variation within a complete stellar rotation; $\lambda$ represents the decay timescale in days of the correlations and can be physically related to the active region lifetimes (see e.g. Haywood et al. 2014). We performed a run using a uniform prior on $\theta$ between 15 and 100 days, large enough to span the range of the possible rotation periods. The resulting posterior distribution for $\theta$ shows a maximum centred at $42.3^{+1.3}_{-0.7}$ days, which is close to the expected rotation period as derived from the empirical relation with the value of $\log R'_{\text{HK}}$. Also the maximum a posteriori probability (MAP) value of $\theta$ is 42.2 days. The hyper-parameter $\lambda$ is $33.6^{+1.7}_{-1.3}$ days ($\text{MAP} = 35.3$ days). This value is comparable to $\theta$, thus it indicates that the correlated signal due to the stellar activity changes within a single rotation period and is well described by a quasi-periodic signal modulated over the stellar rotation period. To complete our analysis on the activity indicators, we run similar models both for the BIS and the $V_{\text{asy}}$.

4.3. Comparison with data from the literature

As a final check before starting the GP modelling of our RV data, we analysed the rich RV dataset available in the literature for HD 164922. We considered the official HIRES/Keck data release (Butler et al. 2017) and the Levy/APF RVs published by F2016. Both HIRES and Levy spectrographs adopted the Iodine cell method (Butler et al. 1996) to obtain high precision radial velocity measurements. With this technique a rich forest of I$_2$ lines is overimposed on the stellar spectrum as a stable reference in the wavelength range between 5000 and 6200 Å. Similarly to F2016, we considered the HIRES dataset as two separate time series because of the major upgrade of the spectrograph in 2004, labelling them as “pre” and “post” the modification. The HIRES$_{\text{pre}}$ dataset includes 51 spectra collected through 8 yr with a mean RV error of 1.23 m s$^{-1}$. The HIRES$_{\text{post}}$ dataset includes 248 RVs spanning 10 yr with a mean internal error of 1.11 m s$^{-1}$. Both of them clearly show the modulation of the long period giant planet. The perspective acceleration in the HIRES data is already taken into account by the standard RV extraction pipeline (e.g. Howard et al. 2010). The 73 data from the Levy spectrograph show an RV error of 2.13 m s$^{-1}$ and do not allow to sample the full orbit of the planet b, since they were specifically collected to recover the planet c (the time span is $1.28$ yr).

The full HIRES+Levy+HARPS-N dataset for HD 164922 is probably one of the richest high-precision RV collections known in the literature, since it is composed by 684 data. It is shown in Fig. 5 together with the two-planet fit (grey solid line) obtained as in Sect. 4.1. The GLS of the corresponding residuals is shown separately for the HIRES$_{\text{pre}}$, HIRES$_{\text{post}}$ and Levy datasets in Fig. 6. As a reference, we overplotted the location of the periodicities found in the HARPS-N residuals with the corresponding harmonics (same colour code as in Fig. 3). We observe

Fig. 4. Generalised Lomb-Scargle periodogram of the HARPS-N time series of activity indicators (bisector span, $\log R'_{\text{HK}}$, $\Delta V$, $V_{\text{asy}}$ and $H_{\alpha}$). Reference lines have the same colour code than in Fig. 3.

Fig. 5. Full RV dataset available in the literature for HD 164922. The grey solid line represents the two-planet model obtained from the solution in F2016 with the corresponding residuals (lower panel). The colour code is defined in the legend.
a periodicity close to 41.63 d in the HIRES pre dataset, and some power both in the HIRES post and Levy GLS, even if the peaks are not significantly higher than the background noise. This is expected because of the typical lack of coherence of the stellar rotation modulation. The signal at 12.46 d is not recovered in the HIRES pre data because of the sparse sampling, while it is recognized among the peaks in the HIRES post GLS. In the Levy GLS the periodicity at 12.46 d is clearly found, while the dominant peak (at about 9.13 days) seems to be spurious after an inspection with 10000 bootstrap random permutations, similarly for the peak at 5.3 days in the HIRES pre GLS (FAP > 5%).

Due to the large time span of the dataset from the literature, that is useful to constrain the orbit of planet b, we included those data in the GP modelling presented in the next section. As a final note, during the preparation of the present work, we learned of an alternative RV extraction of HIRES data from Tal-Or et al. (2019). After the comparison between the two datasets, that showed a typical difference of the RVs of about 0.5 m s$^{-1}$, we decided to proceed with the data from the official pipeline by Butler et al. (2017).

5. Analysis of the radial velocity datasets

For the RV analysis, we used the same tools described in Sect. 4.2, with 800 random walkers and a sampling efficiency of 0.8. The covariance matrix is similar to Eq. (1), but in this case, we added quadratically an uncorrelated noise term defined as:

$$(\sigma_{RV}^2(t) + \sigma_j^2) \cdot \delta_{ij}.$$  

(2)

In this case, $\sigma_{RV}(t)$ is the RV uncertainty at the time $t$ and $\sigma_j$ is the additional noise we used to take into account instrumental effects and further noise sources. We performed a GP analysis of the data from HIRES ("pre" and "post"), Levy, and HARPS-N data. The final, multi-instrument dataset is composed by 684 RVs covering a time span of nearly 22 yr, for which a GP regression including two or more Keplerian signals represents a huge computational effort (from a few weeks to months).

5.1. Two-planet model

First of all, we explored the model composed from two Keplerian signals (i.e. planet b and c) including the correlated term due to the stellar activity, modelled by a GP quasi-periodic kernel. The priors for the GP hyper-parameters and for the planetary orbital parameters are reported in Table 3. For $\lambda$ and $\omega$ we chose the same conservative priors used to model the log $R_{HK}$ time series in Sect. 4.2, while we extended the prior on $\theta$ in the range 30–50 days. We consider this a choice justified by the large temporal extent of the dataset, since we can expect a change in the measured value of the stellar rotation period over 22 yr, according to the evolution of the activity cycle.

Concerning the two Keplerian signals we chose not to impose Gaussian priors centered on the orbital solution obtained by F2016: this would be too restrictive, given the inclusion of so many new data extending the time span by more than five years. Moreover, since the HIRES data are included in our analysis, it would be improper to adopt an informative prior based on the same data. Finally, we included a linear term as a free parameter of the model to investigate the presence of a long-term additional signal. The results are reported in Table 3. We first notice that the introduction of the HIRES datasets have necessarily impacted on the activity description of the star, with respect to the analysis performed in Sect. 4.2 for HARPS-N data only. On a 22-yr timespan, we could expect rotation period variations due to differential rotation or variation of the magnetic activity cycle, so the hyper-parameter $\theta$ changed slightly from the expected 42.3 to 41 days. This can also explain the higher uncertainty on $\theta$, with respect to the GP regression in the case of the HARPS-N time series only, obtained in five years of intensive monitoring.

The GLS of the residuals (Fig. 7) shows the same periodicities identified in Fig. 3, that is the signature of the stellar activity (0.02394 ± 2 × 10$^{-5}$ days$^{-1}$ corresponding to 41.77 ± 0.03 days) and the signal at 0.08027 ± 2 × 10$^{-5}$ days$^{-1}$, corresponding to a period of 12.457 ± 0.030 days. If we subtract from these residuals the model of the stellar activity as obtained by the GP regression, the final time series does not show any periodicity, not even the one at ~12.46 days. In this case, the flexibility of the GP regression, likely implied that the activity-induced term has absorbed the candidate third planetary signal. For this reason we modelled the data including one additional Keplerian signal to investigate the nature of the periodicity at ~12.46 days, as described in the next sub-section.

5.2. Three-planet model

The presence in our data of the robust additional signal at nearly 12.46 days led us to include a third Keplerian signal in the global stellar activity+planet model. We kept fixed the priors for both the activity and the two known planets with respect to the model presented in Sect. 5.1, while the priors for the parameters of the candidate planet d are reported in Table 3. Despite the very precise determination of the signal in the GLS periodogram in
Table 3. Priors and percentiles (16th, 50th, and 84th) of the posterior distributions concerning the analysis of the full RV dataset using a GP quasi-periodic kernel.

| Jump parameter | Prior                  | Best-fit values | $N = 2$ planets | $N = 3$ planets (Adopted solution) |
|----------------|------------------------|-----------------|----------------|-----------------------------------|
| $h$ [m s$^{-1}$] | $U(0, 10)$             | $2.7 \pm 0.2$   | $2.5 \pm 0.2$   |
| $A$ [days]     | $U(0, 2000)$           | $29 \pm 9$      | $23^{+8}_{-7}$  |
| $w$            | $U(0, 1)$              | $0.20^{+0.05}_{-0.04}$ | $0.3 \pm 0.1$   |
| $\theta$ [days]| $U(30, 50)$            | $42^{+8}_{-9}$  | $41^{+7}_{-9}$  |
| $K_b$ [m s$^{-1}$] | $U(0, 10)$           | $6.7 \pm 0.3$   | $6.7 \pm 0.3$   |
| $P_b$ [days]   | $U(1150, 1250)$        | $1206 \pm 5$    | $1207^{+5}_{-6}$|
| $T_{0,b}$ [BJD-2 450 000] | $U(6700, 8050)$ | $7965^{+21}_{-20}$ | $7978^{+20}_{-26}$ |
| $\sqrt{e_b} \cos \omega_b$ | $U(-1, 1)$        | $-0.196^{+0.182}_{-0.112}$ | $-0.24^{+0.15}_{-0.10}$ |
| $\sqrt{e_b} \sin \omega_b$ | $U(-1, 1)$        | $0.004^{+0.137}_{-0.143}$ | $0.10^{+0.15}_{-0.11}$ |
| $e_b$          | Derived                | $0.06^{+0.05}_{-0.04}$ | $0.08^{+0.05}_{-0.05}$ |
| $\omega_b$ [rad] | Derived                | $0.27^{+0.26}_{-0.10}$ | $2.03^{+0.83}_{-0.70}$ |
| $m_b \sin i_b$ [M$_b$] | Derived            | $116^{+10}_{-12}$ | $0.12$          |
| $a_b$ [au]     | Derived                | $2.16 \pm 0.03$ | $2.16 \pm 0.03$ |
| $K_c$ [m s$^{-1}$] | $U(0, 5)$           | $2.2 \pm 0.3$   | $2.2 \pm 0.2$   |
| $P_c$ [days]   | $U(71, 81)$            | $75.73 \pm 0.06$| $75.74^{+0.06}_{-0.05}$ |
| $T_{0,c}$ [BJD-2 450 000] | $U(7500, 7590)$   | $7565.2^{+2.7}_{-2.9}$ | $7564.7^{+2.7}_{-2.2}$ |
| $\sqrt{e_c} \cos \omega_c$ | $U(-1, 1)$        | $0.09^{+0.23}_{-0.25}$ | $0.13 \pm 0.22$  |
| $\sqrt{e_c} \sin \omega_c$ | $U(-1, 1)$        | $-0.013^{+0.245}_{-0.247}$ | $-0.05 \pm 0.18$  |
| $e_c$          | Derived                | $0.09^{+0.10}_{-0.07}$ | $0.12^{+0.11}_{-0.09}$ |
| $\omega_c$ [rad] | Derived                | $-0.10^{+1.77}_{-1.66}$ | $-0.50^{+1.39}_{-1.34}$ |
| $m_c \sin i_c$ [M$_b$] | Derived            | $13^{+3}_{-2}$  | $0.341 \pm 0.004$ |
| $a_c$ [au]     | Derived                | $1.3 \pm 0.2$   | $1.3 \pm 0.2$   |
| $K_d$ [m s$^{-1}$] | $U(0.5)$           | $1.3 \pm 0.2$   | $1.3 \pm 0.2$   |
| $P_d$ [days]   | $U(10, 15)$            | $12.458 \pm 0.003$| $12.458 \pm 0.003$ |
| $T_{0,d}$ [BJD-2 450 000] | $U(7500, 7518)$   | $7503.9^{+0.4}_{-0.8}$ | $7503.9^{+0.4}_{-0.8}$ |
| $\sqrt{e_d} \cos \omega_d$ | $U(-1, 1)$        | $0.03^{+0.26}_{-0.18}$ | $0.12^{+0.11}_{-0.08}$ |
| $\sqrt{e_d} \sin \omega_d$ | $U(-1, 1)$        | $-0.20^{+0.27}_{-0.18}$ | $-0.83^{+2.29}_{-1.34}$ |
| $e_d$          | Derived                | $0.12^{+0.13}_{-0.08}$ | $0.12^{+0.13}_{-0.08}$ |
| $\omega_d$ [rad] | Derived                | $-0.83^{+2.29}_{-1.34}$ | $-0.83^{+2.29}_{-1.34}$ |
| $m_d \sin i_d$ [M$_d$] | Derived            | $4 \pm 1$       | $4 \pm 1$       |
| $a_d$ [au]     | Derived                | $0.103 \pm 0.001$| $0.103 \pm 0.001$ |
| $\dot{y}$ [m s$^{-1}$d$^{-1}$] | $U(-1, 1)$        | $0.0006 \pm 0.0002$ | $0.0006^{+0.0003}_{-0.0002}$ |

Uncorrelated jitter

| $\sigma_{\dot{y},\text{Keck-pre}}$ [m s$^{-1}$] | $U(0, 5)$        | $1.1^{+0.5}_{-0.6}$ | $1.3 \pm 0.6$   |
| $\sigma_{\dot{y},\text{Keck-post}}$ [m s$^{-1}$] | $U(0, 5)$        | $1.6 \pm 0.1$     | $1.7 \pm 0.1$   |
| $\sigma_{\dot{y},\text{HARPS-N}}$ [m s$^{-1}$] | $U(0, 5)$        | $1.3^{+0.5}_{-0.6}$ | $1.3^{+0.4}_{-0.5}$ |
| $\sigma_{\dot{y},\text{AFFP}}$ [m s$^{-1}$]    | $U(0, 5)$        | $1.23 \pm 0.09$   | $1.3 \pm 0.1$   |

RV offset

| $\gamma_{\text{Keck-pre}}$ [m s$^{-1}$] | $U(-5, 5)$ | $0.4^{+0.8}_{-0.7}$ | $0.6^{+0.6}_{-0.8}$ |
| $\gamma_{\text{Keck-post}}$ [m s$^{-1}$] | $U(-5, 5)$ | $0.1 \pm 0.5$      | $0.2 \pm 0.4$     |
| $\gamma_{\text{HARPS-N}}$ [m s$^{-1}$]    | $U(20000, 20700)$ | $20363.2 \pm 0.7$ | $20363.4^{+0.5}_{-0.7}$ |
| $\gamma_{\text{AFFP}}$ [m s$^{-1}$]      | $U(-10, 10)$ | $2.1^{+0.8}_{-0.9}$ | $2.1 \pm 0.6$    |

Bayesian evidence $\ln Z$

| $\Delta \ln Z$ with respect to $N = 2$ pl. model | $-1634.2 \pm 0.1$ | $-1626.8 \pm 0.1$ |

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Fig. 7, we used a uniform prior for the orbital period in a relatively wide range with the specific aim to avoid biasing the solution toward that value.

Table 3 shows the result of the fit. The description of the correlated activity term is consistent with the one obtained for the two-planet model. The orbital period of the planetary candidate is 12.458 ± 0.003 days, the RV semi-amplitude is 1.3 ± 0.2 m s⁻¹ (6σ significance), and the minimum mass, $m_d \sin i_d = 4 \pm 1 M_{\oplus}$, is 4σ significant.

The best-fit values of the Keplerian parameters are consistent with those by F2016 within 1σ, except for the eccentricity of planet b that we find to be lower and significantly consistent with zero ($e_b = 0.08^{+0.06}_{-0.08}$ with respect to 0.126 ± 0.049 in F2016). A more constrained eccentricity consistent with zero is also found for planet c (i.e. $0.12^{+0.11}_{-0.09}$ versus 0.22 ± 0.13 from F2016). The model returned a small but significant acceleration term which is found to be correlated to the RV offsets associated to the four instruments. We evaluated the difference of the proper motion components from HIPPARCOS and Gaia DR2 with respect to the reference proper motion from the catalog of accelerations by Brandt (2018). In both cases, the $\Delta \mu_{\alpha, \delta}$ are lower than 1 mas yr⁻¹ and compatible with zero within 1σ, hinting at a non-existent or negligible anomaly from a purely linear motion on the plane of the sky.

Upper panel of Fig. 8 shows the GLS of the resulting RV residuals after removing the three planetary signals and the instrumental offsets from the original dataset. Except for the periodicity at ∼42 days and its first harmonics, we notice a peak close to 1-yr signal (0.0028 d⁻¹, which was also present in the two-planet fit residuals in Fig. 7). We performed a pre-whitening operation (where the signal of the most prominent periodicity in the GLS is subtracted from the time series and the main signal in the GLS is evaluated for the residuals and subtracted again until no peaks are above 3σ from the noise) and after the iterative subtraction of the 42 days (GLS in the middle panel of Fig. 8) and the 1-yr signals, the resulting periodogram shows no significant periodicities (lower panel). The origin of the 1-yr periodicity will be discussed in Sect. 6.1. As pointed out in the previous sub-section, the signal of the third planet at about 12.46 days is absorbed in the GP regression, while we demonstrated that it is actually present in our data and must be included in the model. Indeed, the GLS of the RV residuals after the removal of the two known planets and the stellar contribution clearly show the signal of planet d (Fig. 9). The RV phased diagram of the newly detected planet companion is shown in Fig. 10. This plot shows the crucial contribution of HARPS-N (blue diamonds) to recover the small amplitude $K_d$, which is of the same order of the RV uncertainties of the HIRES datasets. Finally, we show in Fig. 11 a portion of the time series where both HARPS-N (blue dots) and HIRES post (red dots) data are present. Here the stellar contribution to the RVs is fitted by our GP quasi-periodic model (orange line), while the shaded region indicates the 1σ confidence interval.

To verify that the GP regression does not alter the planetary parameters of the newly detected planet, we set up simple simulations. We assume that our determined planetary parameters of the two known planets are accurate and that the planet we discovered is well retrieved. We considered only the HARPS-N residuals after removing the three Keplerians, with the activity signal left in the data. We then injected the signal of the third planet in the data using our best-fit solution, then creating three mock datasets by randomly shifting each data point within the error bars (including the jitter term we found for HARPS-N,
For a well defined time \( t \), the KR method, a locally linear model is used to fit the RVs years, which can be better described by different indices. With account possible variation of the activity behaviour over the divided the dataset into the six observing seasons, to take into 

Zoom on the GP quasi-periodic modelling of the stellar signal contribution to the RV times series. The orange line represents the best-fit curve, while the grey shaded area is the confidence interval of 1σ. In this part of the sampling, HARPS-N (blue dots) and HIRESpost (red dots) data overlap.

Fig. 11. Zoom on the GP quasi-periodic modelling of the stellar signal contribution to the RV times series. The orange line represents the best-fit curve, while the grey shaded area is the confidence interval of 1σ. In this part of the sampling, HARPS-N (blue dots) and HIRESpost (red dots) data overlap.

5.3. Additional tests

Because the 42-day periodicity persisted through the HIRES/HARPS-N observation time span, we performed a test to confirm that this signature is actually related to stellar activity. Specifically, we analysed the RV residuals of the three-planets fit with the kernel regression (KR) technique, recently applied by Lanza et al. (2018) on a sample of GAPS targets characterised by slow rotation and weak stellar activity. Lanza et al. (2018) show that the KR can model the dependence of the RVs as a function of time and the activity indices (e.g. CCF asymmetry indicators and the \( \log R'_{\text{HK}} \)), allowing to evaluate the impact of stellar activity on the observed RV time series.

We applied this method to the HARPS-N dataset with the following activity indicators: BIS, \( \Delta V \), \( V_{\text{asy(mod)}} \), CCF Full Width at Half Maximum (FWHM), CCF contrast and \( \log R'_{\text{HK}} \). We subdivided the dataset into the six observing seasons, to take into account possible variation of the activity behaviour over the years, which can be better described by different indices. With the KR method, a locally linear model is used to fit the RVs for a well defined time \( t \). In this way, KR takes into account the temporal variation of the correlation between the RVs and the activity indices, which is expected to be non-linear (Desort et al. 2007). The significance level of the KR modelling for each indicator is estimated through the Fisher-Snedecor statistic, proposed by Mortier & Collier Cameron (2017) to discriminate stellar activity from genuine planetary signals of the GLS. Since the activity signals are supposed to be unstable, showing phase incoherence, this method allows to evaluate possible phase-period-amplitude variations of the signal of interest in the classical GLS periodogram calculated as a function of time, that is, with the increasing number of data. Figure 13 shows the SBGLS for the HARPS-N time series of HD 164922 after the removal of the two-planets model, where periodicities are plotted with respect to the increasing number of observations, while the third coordinate represents the Bayesian probability of a specific signal. After gathering \( \sim 100 \) data points, both the signal of planet d and the rotation period become clearly distinguishable and are seen to strengthen with the increasing number of observations. After 150 data, the first harmonics of \( \sim 42 \) days are retrieved accurately and precisely, with no interference with the GP.

The result of the KR modelling provides an independent confirmation that the RV signal observed at \( \sim 42 \) days is ascribable to the rotation of the star, while the decreasing of the dispersion for each season together with the RV dispersion before (\( \sigma \)) and after (\( \sigma_{\text{KRres}} \)) the correction.

**Notes.** The indexing showing a better correlation is reported for each observing season together with the RV dispersion before (\( \sigma \)) and after (\( \sigma_{\text{KRres}} \)) the correction.

![Table 4. Summary of the results of the kernel regression (KR) technique on the HARPS-N RV residuals of the three-planets fit as function of time and of activity indicators.](image)

| Season  | BJD - 2 450 000 | Best index | \( \sigma \) [m s\(^{-1}\)] | \( \sigma_{\text{KRres}} \) [m s\(^{-1}\)] |
|---------|----------------|-------------|-----------------|-----------------|
| 1       | <6660          | BIS         | 2.49            | 1.08            |
| 2       | 6660–7000      | \( V_{\text{asy(mod)}} \) | 1.46            | 0.75            |
| 3       | 7000–7350      | BIS         | 2.09            | 0.89            |
| 4       | 7350–7750      | \( \log R'_{\text{HK}} \) | 2.39            | 1.0             |
| 5       | 7750–8100      | BIS         | 3.27            | 1.29            |
| 6       | >8100          | \( \log R'_{\text{HK}} \) | 1.41            | 0.45            |

**Table 4. Summary of the results of the kernel regression (KR) technique on the HARPS-N RV residuals of the three-planets fit as function of time and of activity indicators.**

Fig. 12. **Top panel:** HARPS-N RV residuals of the three-planet fit for HD 164922 (second season, same timespan as in Fig. 11) as modelled through the KR with respect to the time and the \( V_{\text{asy(mod)}} \). **Bottom panel:** corresponding residuals of the RV dispersion (from 2.73 to 0.72 ms\(^{-1}\)) for the whole time series, while the decreasing of the dispersion for each season is reported in Table 4) as well as of the power of all the periodicities identified in Fig. 8. The result of the KR modelling provides an independent confirmation that the RV signal observed at \( \sim 42 \) days is ascribable to the stellar activity and validates the solution of the GP analysis of the \( \log R'_{\text{HK}} \) index presented in Sect. 4.2.

We also employed the Stacked Bayesian General Lomb-Scargle periodogram (SBGLS), proposed by Mortier & Collier Cameron (2017) to discriminate stellar activity from genuine planetary signals of the GLS. Since the activity signals are supposed to be unstable, showing phase incoherence, this method allows to evaluate possible phase-period-amplitude variations of the signal of interest in the classical GLS periodogram calculated as a function of time, that is, with the increasing number of data. Figure 13 shows the SBGLS for the HARPS-N time series of HD 164922 after the removal of the two-planets model, where periodicities are plotted with respect to the increasing number of observations, while the third coordinate represents the Bayesian probability of a specific signal. After gathering \( \sim 100 \) data points, both the signal of planet d and the rotation period become clearly distinguishable and are seen to strengthen with the increasing number of observations. After 150 data, the first harmonics of the rotation period can also be seen. While the 42-day signal is highly significant but not clearly peaked (i.e. the distribution of
the system. With the same method, we investigated the possible broader range without affecting the overall dynamical stability of is significantly wider. It means that its orbit can be varied on a row stable zones while the stability region for the outer planet 

The results are reported in Fig. 14, showing a high Bayesian probability.

As mentioned in Sect. 5.2, the GLS of the HARPS-N RVs reveals the presence of a periodicity of ~357 days, that we analysed on the light of this latter result. Rather than being due to a planet, this signal has more probably the same origin of the spurious 1-yr signal first reported and characterised by Dumusque et al. (2015) by using HARPS data. For HARPS-N data this feature is also suspected in the GLS periodograms presented in Barbato et al. (2020). As in Fig. 3 from Dumusque et al. (2015), we verified that the RV signal is in opposition of phase with the Earth orbital motion around the Sun, showing a correlation with the Barcyentric Earth Radial Velocity (BERV). In the case of HARPS, CCD imperfections lead to a deformation of specific spectral lines passing by the crossing block stitching of the detector. The long observation baseline of HD 164922 with HARPS-N allows to detect this spurious signal since we sample a large variation of the BERV (±20 km s⁻¹). However, the treatment or the removal of this signal is beyond the scope of the present paper.

6. System architecture

In this section, we evaluate the stability of the HD 164922 system and put detection thresholds on additional planets. With this information and the evaluation of the water snow line, we try to infer which formation and migration scenarios could have shaped the current orbital architecture.

6.1. Orbital stability

The long-term stability of the HD 164922 system has been tested as in Benatti et al. (2017), starting from the stellar and planetary parameters in Tables 2 and 3 through the exploration of the phase space around the nominal positions (semi-major axis vs eccentricity) of the three planet companions. We exploited the Frequency Map Analysis (FMA; Laskar 1993; Šidlichovský & Nesvorný 1996; Marzari et al. 2003) tool to evaluate a possible chaotic behaviour of the orbits with short term numerical integrations by analysing the variation of the secular frequencies of the system. We measured the diffusion speed in the phase space, identified by the parameter $c_v$, as the dispersion of the main secular frequency of the system over running windows covering the integration timespan. The results are reported in Fig. 14 for each planet, starting, left to right, from the super-Earth close to the star, then the Neptune-mass planet and finally the Saturn-mass planet in the outer region. In each of the three models, two of the planets are kept on fixed orbits, the nominal ones, while the orbital parameters of the third planet are randomly changed within a wide interval of values to explore its range of stability in semi-major axis and eccentricity. In each plot, we show the nominal position of the planet and the stability properties of the region around it. The two inner low-mass planets lie within narrow stable zones while the stability region for the outer planet is significantly wider. It means that its orbit can be varied on a broader range without affecting the overall dynamical stability of the system. With the same method, we investigated the possible stable zones for an additional fourth unseen planet. We set the three known planets on their nominal orbits and randomly select the initial orbital elements of the fourth potential planet adopting for it a mass equal to 1 $M_\oplus$. We focussed on the regions between planet d and c (0.1–0.3 au) and between planet c and b (0.4–1.5 au). We did not consider orbits for the fourth planet with semi-major axis smaller than 0.1 au due to the excessive computing load related to the short orbital period.

We found a narrow stable region ranging between 0.18 and 0.21 au, corresponding to an interval of orbital periods from ~30 and ~36 days, therefore, a putative planet with a period of ~42 days should not be permitted, further strengthening our interpretation of the RV signal at this period as the rotation period of the star. A second allowable region is located between 0.6 and 1.4 au (300–500 days), including the habitable zone (HZ) that we evaluated to be 0.95–1.68 au for the conservative HZ, and 0.75–1.76 au in the optimistic case. The calculation was performed by using the public tool4 based on Kopparapu et al. (2013, 2014), assuming a planet of 1 $M_\oplus$ and adopting $T_\text{eff}$ and stellar luminosity from Table 2.

6.2. Detectability limits

We computed the detection threshold for the HARPS-N dataset following the Bayesian approach from Tuomi et al. (2014). We applied this technique on the RV residuals after subtracting the signals of the three planets and including in the model the GP to take into account the stellar activity contribution. The resulting detectability map is shown in Fig. 15. Planets b, c and d (red circles) are located above the detection threshold, as expected. HD 164922 d is just above the minimum mass detection threshold, which corresponds to $m_\text{P}\sin i = 2.3 M_\oplus$ in the interval 12 < $P_{\text{orb}}$ < 13 days. We can also compute the minimum mass threshold in the orbitally-stable regions identified in Sect. 6.1: we obtain a minimum mass limit of 5.0 $M_\oplus$ for the 30–36 days region, 18 $M_\oplus$ for the 300–500 days region, and a few tens of $M_\oplus$ for the $P > 1200$ d region. In the figure, we indicated with green areas the allowed regions for additional companions in the system, as defined in Sect. 6.1, while the inner part of the system that we did not explored is represented in grey.

6.3. Snow line position of the HD 164922 system

In order to investigate the planetary migration scenario of the HD 164922 system, we estimated the position of the water snow

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4 http://depts.washington.edu/naivpl/sites/default/files/hz.shtml
where $\Sigma$ is the surface density of the disk, $\eta$ is the accretion rate, $M_\star$ is the stellar mass. The factor $\eta$ provides a range of disk masses for a fixed stellar mass (“relative disk mass”, Kennedy & Kenyon 2008) and is varied to account for the observed range of disk masses at fixed stellar mass. Observations (e.g. Natta et al. 2000) stated that this parameter ranges from 0.5 up to 5 for disk masses between 0.01 and 0.1 $M_\star$. In the case of HD 164922, we considered $\eta = 4$. The midplane temperature of accreting protoplanetary disk irradiated by the central star is given by:

$$T_{\text{mid}}^4 = T_{\text{mid,acc}}^4 + T_{\text{irr}}^4,$$  

(4)

where $T_{\text{mid,acc}}$ is the temperature profile of the midplane due to the mass accretion and the corresponding viscous heating of the disk, and $T_{\text{irr}}$ is the temperature profile of the disk due to the irradiation heating (Sasselov & Lecar 2000; Lecar et al. 2006; Kennedy & Kenyon 2008). For $T_{\text{irr}}$ we considered the scale law obtained by Sasselov & Lecar (2000)$^5$, while for the contribution due to the accretion we considered the standard relation reported in Eq. (1) in Bell et al. (1997) and the dust opacity according to Hubeny (1990)$^6$. For simplicity, we assumed that the dust opacities are constant throughout the disk. To evaluate $T_{\text{mid,acc}}$, we obtained the stellar parameters of HD 164922 in the pre-main sequence (PMS) phase at about 1 Myr of age, exploiting the PARSEC evolutionary tracks. We adopted the set of models with a metallicity of [Fe/H] = 0.18 (from Table 2), corresponding to $X = 0.73$, $Y = 0.25$ and $Z = 0.02$ (Asplund et al. 2004). From this set of models we selected the parameters for masses of 0.90, 0.95 and 1.00 $M_\odot$ at the age of 1 Myr. Stellar parameters were obtained interpolating the values for masses, temperatures, and radii of the three chosen models and they resulted to be $R_{\text{1Myr}} = 2.31 R_\odot$, $T_{\text{eff,1Myr}} = 4443.3$ K. For the accretion rate, we considered the typical value for the MMSN of $10^{-7} M_\odot$ yr$^{-1}$.

Both the passive and the accreting disk temperature profiles are shown in Fig. 16, together with the location of the snow line and the position of the three planets of the HD 164922 system. The snow line position is found to be at 1.03 au for the passive disk and at 1.38 au for the accreting and irradiated disk, thus located about halfway between planet c and b.

$$T_{\text{mid,acc}} = \frac{1}{8} \pi T_{\text{eff,acc}}^4,$$

where $T_{\text{eff,acc}}$ is the effective temperature of a given ring of a disk, defined as $T_{\text{eff,acc}} = \frac{1}{8} \frac{GM_\star M}{\pi a^3}$, where $M$ is the accretion rate, $R_\star$ is the stellar radius, and $\sigma$ is the Stefan’s constant.

$^5$ $T_{\text{eff}}(t) = T_0 \sigma t^{-3/4}$, with $T_0 \propto M_\star^{10/4}$ (e.g. for $M_\star = 0.5 M_\odot$, $T_0$ is equal to 140 K), where the opacity $k$ is 0 $\leq k < 2$.

$^6$ $T_{\text{mid,acc}} = \frac{1}{8} \pi T_{\text{eff,acc}}^4$, where $T_{\text{eff,acc}}$ is the effective temperature of a given ring of a disk.
6.4. Discussion

According to our GP regression, the eccentricities of the three planetary companions of HD 164922 are all consistent with zero (Table 3) and the RV analysis over a time span of 22 yr excludes the presence of outer companions with a mass larger than \( \sim 30 \ M_\oplus \) up to 5 au (with a period of about 4000 days, cf Fig. 15), a result corroborated by the negligible value of the \( \Delta \mu a, \delta \). The lack of a massive perturbing body and the low planetary eccentricities indicate that a migration through the protoplanetary disk could have acted in shaping the present system architecture. Planet b probably formed beyond the water snow line. Due to its relatively low mass it is supposed to have quickly migrated closer to the star until the disk dissipation. The formation of the two low-mass planets, instead, occurred within the region of the disk, stimulating then the planet formation process. Pebbles formation and their consequent drifting toward the inner and the inside-out model (Chatterjee & Tan 2014), that invokes a proportional reduction of the heat flux. For example, adopting a value of 170 K for the sublimation temperature of water ice. The edges of the corresponding snow lines are indicated with dotted vertical lines and their distances. The separation of the planets in the system is also shown as a reference. The size of the symbols is proportional to the planetary masses.

7. Conclusions

One of the largest high-precision RV datasets available in the literature allowed us to claim the presence of an additional close-in super-Earth with minimum mass \( m_d \sin i_d = 4 \pm 1 \ M_\oplus \) in the HD 164922 planetary system, known to host a sub-Neptune-mass planet and a distant Saturn-mass planet. We monitored this target in the framework of the GAPS programme focussed on finding close-in low-mass companions in systems with outer giant planets. Thanks to the dedicated monitoring and the high precision RV measurements ensured by HARPS-N, we took full advantage of the GP regression analysis. With such a technique, we could robustly model the stellar activity as a quasi-periodic signal both from the \( \log R' HK \) index and the RV time series. The subtraction of this contribution to the RVs allowed us to recover the low-amplitude Keplerian signal of the additional companion at a 6\( \sigma \) level \( (K_d = 1.3 \pm 0.2 \ m \ s^{-1}) \). The application of the Kernel Regression technique to the residuals of the three-planets fit confirmed that the signal content can be properly described as a function of time and the activity indices.

The analysis of the system architecture allowed us to infer that the most probable planet migration process is through the gas of the protoplanetary disk. The challenging detection of HD 164922 d is an example of the observational effort invoked by Zhu & Wu (2018) to find low-mass planets in systems with cold gaseous planets with state-of-the-art instrumentation, because of the very high probability that those systems could host low-mass planets in their interiors. Unfortunately, this target will not be observed with the NASA Transiting Exoplanets Survey Satellite (TESS, Ricker et al. 2015) satellite, at least not in Cycle 2, to verify if it transits. Dedicated observations with the ESA CHaracterizing ExOPlanet Satellite (CHEOPS, Broeg et al. 2013) could be proposed, but they can be severely affected by the uncertainty on the transit time. For instance, at the beginning of 2021 it could be of the order of 0.9 days by using our ephemeris in Table 3. A former attempt to search for transits of planets b and c was reported in F2016 with APT photometry (about 1000 data spread over 10 yr), with no evidence of such events or photometric variability between 1 and 100 days.
