

# The GAPS programme at TNG LXVIII. Characterization of the outer substellar companion around HD 72659 with a multitechnique approach\*

A. Ruggieri<sup>1,2★</sup>, A. Sozzetti<sup>3</sup>, S. Desidera<sup>2</sup>, D. Mesa<sup>2</sup>, R. Gratton<sup>2</sup>, F. Marzari<sup>2,4</sup>, M. Bonavita<sup>5</sup>, K. Biazzo<sup>6</sup>, V. D’Orazi<sup>2,7</sup>, C. Ginski<sup>8,9,10</sup>, M. Meyer<sup>11</sup>, L. Malavolta<sup>2,12</sup>, M. Pinamonti<sup>3</sup>, D. Barbato<sup>2</sup>, C. Lazzoni<sup>2</sup>, A. F. Lanza<sup>1</sup>, L. Mancini<sup>3</sup>, L. Naponiello<sup>3</sup>, D. Nardiello<sup>2,12</sup>, T. Zingales<sup>2,12</sup>, M. Rainer<sup>13</sup>, G. Scandariato<sup>1</sup>, P. Giacobbe<sup>3</sup>, R. Cosentino<sup>14</sup>, A. Fiorenzano<sup>14</sup> and R. Claudi<sup>2,15</sup>

*Affiliations are listed at the end of the paper*

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## ABSTRACT

Before discovering the first exoplanets, the radial velocity (RV) method had been used for decades to discover binary stars. Despite significant advancements in this technique, it is limited by the intrinsic mass-inclination degeneracy that can be broken when combining RVs with astrometry, which allows us to determine the orbital inclination, or direct imaging, from which we can estimate the true mass of the target. HD 72659 is a solar analogue known to host a gas giant on a  $\sim 10$ -yr orbit and a massive outer companion. This work aims to confirm HD 72659 c, which was recently announced using data from HIRES and HARPS spectrographs in combination with *Gaia*’s astrometric data. We monitored HD 72659 with HARPS-N in the framework of the GAPS project since 2012. We now combined our 91 spectra with literature data and *Gaia* DR3 high-precision astrometry to constrain the mass and the orbit of this object ( $M_c \sim 19 M_J$ ,  $a \sim 21$  au) that falls in the Brown Dwarf desert. Moreover, we analysed our high-resolution imaging observation taken with SPHERE, but since the target was not detected, we could only derive upper limits on its mass. We characterize the orbital parameters of HD 72659 c, confirming the literature mass of this object but finding a period twice as high as previously reported, and we also refine the parameters of planet b with reduced uncertainties compared to previous works. Finally, we analyse and discuss the dynamic configuration of this system, finding that the Kozai–Lidov mechanism may be at work.

**Key words:** techniques: radial velocities – astrometry – planets and satellites: detection – stars: imaging – stars: individual: HD 72659 – stars: solar-type.

## 1 INTRODUCTION

For years, the radial velocity (RV) technique was used to detect binary stars (e.g. Duquennoy & Mayor 1991, and references therein). As technology advanced and instrumental precision increased, this allowed us to find exoplanets and brown dwarfs (BDs) as well (e.g. Campbell, Walker & Yang 1988; Mayor & Queloz 1995). Today, we

have almost 30 yr of high-precision RV data for some stars and are thus beginning to probe the long-orbital-period part of the parameter space (that is, periods larger than a few thousand days) despite several limitations due to well-known selection effects (e.g. Bryan et al. 2016). In particular, long-period planets cause lower RV variations onto their host stars compared to their short-period counterparts of equal mass. In addition, they require systematic monitoring for longer time spans while keeping instruments stable, which is not a trivial task. Lastly, RV suffers from mass-inclination degeneracy and only gives us the minimum mass of the putative companion. For this reason, some of the most massive planets known today might be BDs on nearly face-on orbits. In this context, important help comes from astrometry and direct imaging since these two methods are biased in favor of long-period planets, and allow us to derive the true mass and the three-dimensional orbit of our targets (e.g. Perryman 2018). It is not yet clear at what point a sub-stellar companion must be considered a BD and no longer a planet, with the Deuterium-burning limit being around  $13 M_J$  (Saumon & Marley 2008; Spiegel, Burrows & Milsom 2011), which is also the reference value used by the IAU

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\* E-mail: [alessandro.ruggieri@inaf.it](mailto:alessandro.ruggieri@inaf.it)

Working Group Definition. However, there are objects below this mass limit found in systems likely formed via cloud fragmentation and vice versa, indicating that the formation path is probably a better discriminant than the object’s mass. Notorious examples include AB Pic b Chauvin et al. (2005) and HD 168443 (Marcy et al. 1999, 2001; Pilyavsky et al. 2011). Nevertheless, in many cases, the mass of the object is used as a discriminant because it is often harder to reconstruct the exact formation and evolution history of a single planetary system, especially if this is old, rather than determining its true mass. A third issue that represents a challenge for the current status of our knowledge is how these massive objects affect the other planets that might be present in the system. In recent years, there has been a lot of effort in searching for new BDs with different techniques, especially in systems with additional planets (e.g. Wilson et al. 2016; Ryu et al. 2017; Fontanive et al. 2019; Kiefer et al. 2019; Rickman et al. 2019; Sozzetti 2023; Šubjak et al. 2023), showing the great interest in the field. This task is made difficult by the estimated low occurrence rates of such objects, which should be around a few percent (e.g. Borgniet et al. 2019; Nielsen et al. 2019; Vigan et al. 2021). This phenomenon is known as the ‘brown dwarf desert’, indicating the paucity of this type of companions at low and mid periods. Since the combination of RVs and astrometry yields the true mass of substellar companions and direct imaging, in principle, allows us to derive their spectra, the sum of this information is a great tool to test formation and evolution mechanisms, leading to a better understanding of this phenomenon. Nevertheless, it has been proven that wide BDs do affect the presence and evolution of the other planets in their systems, for example, through the Kozai–Lidov mechanism (Fontanive et al. 2019). Many of the mentioned works have been possible thanks to SPHERE at the Very Large Telescope (VLT; Beuzit et al. 2019), one of the best direct imaging instruments currently available. Other comparable facilities are mounted at the Keck and Gemini Observatories, leading to the first direct detection of a multiple planetary system around HR 8799 with this technique (Marois et al. 2008), and at the Subaru Telescope (e.g. Carson et al. 2013).

HD 72659 is a solar-analogue star, having the same mass, chemical composition, a mass only 3 per cent larger, and a similar or larger age (see Section 3). The star hosts a first planet ( $m_p \sin i \sim 2.8 M_J$ ,  $P \sim 10$  yr) that was discovered more than 20 yr ago by Butler et al. (2003) and its orbit is today very well constrained (Butler et al. 2006; Moutou et al. 2011). What’s more, Moutou et al. (2011) underline that stellar activity is not correlated with radial velocities and that they find no significant peak in the periodogram of the residuals. However, a long-period signal is visible in our data set, which includes HIRES, HARPS, HRS, and HARPS-N data, covering a time span of about 23 years. Indeed, this trend has also been noted by Bryan et al. (2016), who tried to fit a 2-planets solution. They limited the mass of this new companion to  $1.3 \leq M \leq 133 M_J$  and the semi-major axis to  $7.6 \leq a \leq 35$  au. The values that we retrieved in this work fall in these ranges. Feng et al. (2022) announced a second companion for this star, combining GAIA–Hipparcos PMa and RVs (HIRES + HARPS). They reported a mass of  $18.81 M_J$ , which, as we will show in the next sections, is compatible with our results. However, they reported a period of about 18 000 d, much lower than, but formally compatible with, the nominal value that we found from RVs alone. On the contrary, our results from RV + astrometry are not compatible with theirs (see the next sections for more details). Motivated by the high mass of this second object and by a previous shallow imaging observation with SPHERE, we decided to observe HD 72659 again with the same instrument to directly detect its substellar companion, HD 72659 c. Hosting two massive planets with long orbital periods,

this system has the potential to become an interesting benchmark case for dynamic studies. In addition, HD 72659 has a mass of  $\sim 1 M_\odot$ , so the presence of two potentially massive objects was surprising since massive objects require more massive disks, which are typical for higher-mass stars (e.g. Mordasini et al. 2012).

In Section 2, we describe our RV and astrometric data, plus our new SPHERE observations. In Section 3, we describe the stellar parameters that we derive from our HARPS-N data. In Section 4, we describe the tools used in our analysis. In Section 5, we describe our results from RV, astrometric, and imaging analysis about the external substellar companion of HD 72659, followed by a discussion of the dynamics of the system. Finally, in Section 6, we summarize our conclusions.

## 2 OBSERVATIONS AND DATA ANALYSIS

### 2.1 High-resolution spectroscopy

#### 2.1.1 HARPS-N

We observed HD 72659 in the framework of the Global Architecture of Planetary Systems (GAPS) programme (Covino et al. 2013) with HARPS-N (High Accuracy Radial velocity Planet Searcher for the Northern hemisphere) at the Telescopio Nazionale Galileo (TNG; Cosentino et al. 2012). This is a 3.58-m Italian telescope located at the Roque de los Muchachos observatory in the Canary Islands. HARPS-N is a state-of-the-art spectrograph with a resolution of  $R = 115\,000$  that works in the visible part of the electromagnetic spectrum (from 390 to 690 nm). The instrument operates in a vacuum with a temperature stability of  $\pm 0.001$  K, ensuring high short- and long-term precision. As part of the Known Planet (KP) sub-programme (Benatti et al. 2020, Pinamonti et al., in preparation), we collected 91 spectra for HD 72659 from 2013 January 3 to 2023 April 11, observing the target quite intensively between 2013 to 2017, collecting 68 spectra with main goal of searching for inner low-mass planets. Observations were continued at low cadence in the following years with the main goal of characterizing the long-term signal. Radial velocities (RVs) have been extracted using the YABI<sup>1</sup> online tool (Hunter et al. 2015), which runs the HARPS-N pipeline, using a G2 mask for the cross-correlation function (CCF). The tool also exploits the procedure by Lovis et al. (2011) to derive the Mount Wilson calibrated chromospheric activity index  $S_{MW}$ . The median RV uncertainty of our observations is  $0.62 \text{ m s}^{-1}$ . We removed from our data set the observation taken on 2022 March 18, as a clear outlier since the corresponding RV value differs by  $\sim 30 \text{ m s}^{-1}$  from the observations done in the same period. Moreover, the associated RV uncertainty is  $4.37 \text{ m s}^{-1}$ , which is 7 times larger than the median value, and the signal-to-noise ratio (SNR) in the 6th order ( $\lambda = 402$  nm) is 4.80, much lower than the median value of 43.55. The full RV time series is available in Table A1 in the appendix and it is available at CDS via anonymous ftp to [cdsarc.u-strasbg.fr](https://cdsarc.u-strasbg.fr) (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/MNRAS>.

#### 2.1.2 Archive and literature data

In addition to our HARPS-N set, we searched the literature for additional data. We used the HIRES (High-Resolution Echelle Spectrometer) data published by Rosenthal et al. (2021), comprising

<sup>1</sup><https://ia2.inaf.it/>

**Table 1.** Main characteristics of the RV observations of HD 72659.

Data set	N. of obs.	Start date	End date	Time span (yr)	$\langle\sigma_{RV}\rangle$ (m s <sup>-1</sup> )
HIRES	66	1998/01/25	2019/10/24	21.74	1.44
HARPS	65	2004/02/23	2021/06/05	17.28	1.86
HARPS-N	90	2013/01/03	2023/04/11	10.27	0.74
HRS	32	2003/12/03	2007/11/27	2.96	9.14
Total	253	1998/01/25	2023/04/11	25.21	2.27

**Table 2.** Proper motion anomaly data for HD 72659.

Parameter	HD 72659	Reference
HIPPARCOS (epoch 1991.25) $\Delta\mu_\alpha$ (mas yr <sup>-1</sup> )	+0.059 ± 0.690	Brandt (2021)
HIPPARCOS (epoch 1991.25) $\Delta\mu_\delta$ (mas yr <sup>-1</sup> )	-1.138 ± 0.601	Brandt (2021)
<i>Gaia</i> (epoch 2016.0) $\Delta\mu_\alpha$ (mas yr <sup>-1</sup> )	+0.311 ± 0.043	Brandt (2021)
<i>Gaia</i> (epoch 2016.0) $\Delta\mu_\delta$ (mas yr <sup>-1</sup> )	+0.662 ± 0.029	Brandt (2021)

66 RV data and 47  $S_{MW}$  measurements<sup>2</sup>. As described by Butler et al. (2017), HIRES underwent a CCD upgrade procedure in 2004 August, so we used different offsets and jitter terms for data taken before and after such an event.

Furthermore, we downloaded 66 HARPS (High Accuracy Radial velocity Planet Searcher) spectra available in the ESO archive (reduced with the instrument pipeline) and extracted the various activity indices ( $S_{MW}$ , BIS, FWHM of the CCF,  $H\alpha$ , Na I) using the PYTHON tool ACTIN2 (Gomes da Silva et al. 2018, 2021). We removed the first of the two spectra taken on 2008 March 22, as the reported exposure time is only 5 s. We considered separately the data taken before and after the HARPS upgrade described in Lo Curto et al. (2015).

Finally, we also adopted the data collected with the Hobby–Eberly Telescope (HET) at MacDonald observatory using the High Resolution Spectrograph (HRS; Tull 1998) instrument and published by Wittenmyer et al. (2009). From these, we removed all the data points with RV uncertainty larger than 10 m s<sup>-1</sup> due to their lower quality compared to the rest of the set, leaving us with 32 of the initial 53 measurements. Table 1 shows the main characteristics of the RV data sets used in our analysis.

## 2.2 Gaia–Hipparcos PMa

We combined the information obtained from the RV analysis with tangential acceleration information from absolute astrometry, in particular the proper motion anomaly (PMa) from the cross-calibrated Hipparcos–Gaia early data release 3 (EDR3) catalogue of astrometric accelerations by Brandt (2021). The PMa vector components ( $\Delta\mu_\alpha$ ,  $\Delta\mu_\delta$ ) at the mean epochs of the Hipparcos and Gaia EDR3 catalogues were obtained subtracting from the quasi-instantaneous proper motions of the two catalogues the long-term proper motion vector defined as the catalogues’ positional difference divided by the time baseline ( $\sim 25$  yr). The latter quantity is typically considered as an accurate representation of the tangential velocity of the barycentre of the system in the limit of orbital periods of the companion shorter than the time baseline between the two catalogues. This assumption might be considered questionable given the limited phase coverage of the scaled Hipparcos–Gaia positional difference,

spanning only  $\sim 25$  per cent of the orbital period of HD 72659 c. However, as long as the astrometric acceleration and overall magnitude of the orbital proper motion are small compared to the stellar proper motion (as is our case), the combined analysis of RVs and PMa can still be successfully performed, as demonstrated by a number of recent analyses (e.g. Bardalez Gagliuffi et al. 2021; Currie et al. 2023; Ruggieri et al. 2024).

We note that the reported signal-to-noise ratio of the PMa at the highly sensitive *Gaia* DR3 mean epoch for HD 72659 is  $\sim 16$ , which indicates the presence of a very significant astrometric acceleration. The  $\Delta\mu$  values that we used in our RV + astrometry analysis are listed in Table 2.

## 2.3 High-contrast direct imaging

Our target was observed with SPHERE at VLT (Beuzit et al. 2019) on 2015 December 31, during the GTO survey SHINE [ESO ID: 096.C-0241(C); Desidera et al. 2021]. The observation was part of a filler program aiming at stars hosting RV-discovered exoplanets (Hagelberg et al., in preparation). The data were reduced through the SPHERE Data Center (Delorme et al. 2017), exploiting the instrument pipeline (Pavlov et al. 2008b) and the SpeCal procedures (Galicher et al. 2018). Considering the relatively shallow detection limits due to the short integration time and small field rotation, and the fact that the mass of the companion was likely high due to the RV trend and the high-SNR astrometric acceleration, we applied for a new and deeper observation.

HD 72659 was observed again with SPHERE following our accepted proposal (ESO ID: 112.25JY, PI: A. Ruggieri) on the night of 2024 January 21, exploiting the IRDIFS\_EXT observing mode. In this mode we observed both with IFS (Claudi et al. 2008) covering  $Y$ ,  $J$ , and  $H$  spectral bands between 0.95 and 1.65 microns and with a field of view (FOV) of 17 arcsec  $\times$  17 arcsec, and with IRDIS (Dohlen et al. 2008) operating in the K spectral band using the K12 filter pairs (wavelength K1 = 2.110 microns; wavelength K2 = 2.251 microns; Vigan et al. 2010) on a circular FOV of  $\sim 5$  arcsec. The observations were performed exploiting the SPHERE extreme adaptive optics system SAXO (Fusco et al. 2006). Before and after the science coronagraphic data, we also acquired frames with the stellar PSF offset with respect to the coronagraph to perform photometric calibration. To this aim, we used a neutral density filter to avoid saturation of the detector. Moreover, we also acquired frames with satellite spots at symmetrical positions with respect to the central star

<sup>2</sup>The first 19 data points have been taken before the CCD upgrade described in Butler et al. (2017) and, in the data file published, the  $S_{MW}$  values are not listed.

**Table 3.** Main characteristics of the SPHERE observations of HD 72659.

Date	Obs. mode	Coronagraph	DIMM seeing	$\tau_0$ (ms)	wind speed (m s <sup>-1</sup> )	Field rotation	DIT	Total exposure
2015-12-31	IRDIFS	N_ALC_YJH_S	0.72''	3.0	3.58	9.6°	64 s	1024 s
2024-01-21	IRDIFS_EXT	N_ALC_YJH_S	0.72''	7.8	7.60	28.49°	64 s	3072 s

to precisely define the position of the star behind the coronagraph (Marois, Véran & Correia 2012). The science data were acquired in pupil-stabilized mode, allowing the rotation of the FOV during the acquisition to be able to implement the angular differential method (ADI, Marois et al. 2006). In total, we acquired 48 frames with a detector integration time (DIT) of 64 s for a total exposure time of 3072 s. The total rotation of the FOV during the observation was 28.49 deg. The data were reduced using the SPHERE data reduction and handling pipeline (DRH; Pavlov, Feldt & Henning 2008a). Finally, we performed speckle subtraction to reduce the noise from the star and highlight the signal from the star at the same time. To this aim, we applied at the same time both ADI and spectral differential imaging (SDI; Racine, Nadeau & Doyon 1999), implementing the principal components analysis (PCA, Soummer, Pueyo & Larkin 2012). Table 3 contains the technical information for both the old and new SPHERE observations.

### 3 STELLAR PARAMETERS

#### 3.1 Spectroscopic parameters

We derived spectroscopic stellar parameters for HD 72659 using HARPS-N spectra, employing the same procedure described in Ruggieri et al. (2024). Through equivalent width (EW) measurements and the force-fitting abundance method, we adopted the q2 PYTHON code (Ramírez et al. 2014), allowing the use in silence mode of the 2019 version of the MOOG radiative transfer code (Sneden 1973). Using the Castelli & Kurucz (2003) grid of model atmospheres and the line list by D’Orazi et al. (2020), effective temperature and surface gravity were derived via excitation/ionization equilibrium of Fe I and Fe II lines. Microturbulence values were obtained by minimizing the trend between the reduced EW of Fe I lines and the corresponding iron abundance. The outcome of this standard procedure gives us the final iron abundance. Errors in stellar parameters were evaluated using q2, considering dependencies among parameters. Internal errors on metallicity result from the quadrature sum of errors from EW measurements and uncertainties related to stellar parameters. Then, we measured the projected rotational velocity  $v \sin i_*$  using the spectral synthesis technique and the iSpec package (Blanco-Cuaresma et al. 2014), where stellar parameters were fixed to those previously derived (see Ruggieri et al. 2024 for details on the procedure). The star results to be a slow rotator ( $1.6 \pm 0.9$  km s<sup>-1</sup>). The corresponding inferred rotation period is highly uncertain,  $P_{\text{rot}} = 43.0 \pm 24.3$  d. Another estimate of  $P_{\text{rot}}$  can be obtained from  $\log R'_{\text{HK}}$  value<sup>3</sup> finding  $20.7 \pm 1.3$  d (using the expression by Noyes et al. 1984) and  $21.9 \pm 1.9$  d (using the expressions by Mamajek & Hillenbrand 2008). From our adopted age value in Section 3.2, the

<sup>3</sup>For the estimate of the expected rotation period, we used the  $\log R'_{\text{HK}}$  derived from Sindex using the  $B-V$  colour of the star (0.612 from Hipparcos catalogue), which results  $\log R'_{\text{HK}} = -5.00$  to be consistent with the formalism by Mamajek & Hillenbrand (2008). In Section 3.2, we will instead adopt the  $\log R_{\text{HK}}$  value derived following Lorenzo-Oliveira et al. (2018), which is more suitable to our target star.

**Table 4.** Stellar parameters of HD 72659.

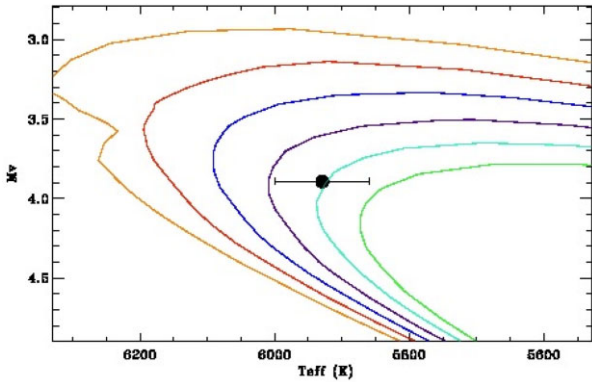
Parameter	Value	Ref.
Parallax (mas)	$19.258 \pm 0.027$	1
Spectral type	G2V	2
$V$ (mag)	7.46	2
$B - V$ (mag)	0.612	2
$\mu_{\alpha^*}$ (mas yr <sup>-1</sup> )	$-112.313 \pm 0.026$	1
$\mu_{\delta}$ (mas yr <sup>-1</sup> )	$-96.386 \pm 0.018$	1
$U$ (km s <sup>-1</sup> )	$7.17 \pm 0.11$	3
$V$ (km s <sup>-1</sup> )	$-2.04 \pm 0.12$	3
$W$ (km s <sup>-1</sup> )	$-39.99 \pm 0.09$	3
ecc (galorb)	0.07	4
zmax (kpc)	0.59	4
RV (km s <sup>-1</sup> )	$-18.203^{+0.024}_{-0.029}$	5
$T_{\text{eff}}$ (spec.) (K)	$5929 \pm 61$	5
$\log g_*$ (cgs)	$4.23 \pm 0.14$	5
[Fe/H] (dex)	$-0.02 \pm 0.06$	5
$\xi$ (km s <sup>-1</sup> )	$1.15 \pm 0.08$	5
$M_*$ ( $M_{\odot}$ )	$1.033 \pm 0.025$	5
$R_*$ ( $R_{\odot}$ )	$1.36 \pm 0.06$	5
Age (Gyr)	$8.0 \pm 1.0$	5
$v \sin i_*$ (km s <sup>-1</sup> )	$1.6 \pm 0.9$	5
$S_{\text{MW}}$ (HARPS-N)	$0.157 \pm 0.003$	5
$\log R'_{\text{HK}}$ (HARPS-N)	$-5.00 \pm 0.02$	5
$EW_{\text{Li}}$ (Å)	$36.5 \pm 1.0$	5
$A(\text{Li})_{\text{NLTE}}$	$2.25 \pm 0.05$	5
$\log L_X$	$< 28.78$	6

Note. References: 1: Gaia DR3; 2: Moutou et al. (2011); 3: Gaia Collaboration (2021); 4: Mackereth & Bovy (2018); 5: this work; 6: Kashyap, Drake & Saar (2008).

expected rotation period is 24 and 32 d for Mamajek & Hillenbrand (2008) and Ye et al. (2024), respectively. These values and especially their uncertainties should be taken with caution, considering the ambiguities in the rotational evolution of old solar-type stars (van Saders et al. 2016; Hall et al. 2021). In any case, it is plausible that the rotation period of HD 72659 is in the range 20–30 d. Table 4 shows the results for all stellar parameters.

#### 3.2 Stellar age

We used different methods to derive the age of HD 72659. First, because HD 72659 evolved outside the main sequence, we can determine its mass and age well through isochrone fitting. Using PARSEC isochrones (Bressan et al. 2012) and the metallicity derived from HARPS-N spectra ( $[\text{Fe}/\text{H}] = -0.02 \pm 0.06$ ), we inferred an age of  $8.0 \pm 1.0$  Gyr and, thus, a mass of  $1.033 \pm 0.025 M_{\odot}$ . Fig. 1 shows the result of the isochrone fitting. Secondly, since the target spectrum shows the presence of the lithium line at  $\sim 6707.8$  Å, we estimated from the Li EW an abundance compatible with the age of the M67 open cluster ( $\sim 4.5$  Gyr; Pasquini et al. 2009), where correction by Lind, Asplund & Barklem (2009) for NLTE effects was considered. Next, following the procedure by Biazzo et al. (2022), we derived the abundance of the  $s$ -process yttrium element and the  $\alpha$  magnesium and aluminum elements, as ratios  $[\text{Y}/\text{Mg}]$  and



**Figure 1.** Isochrone fit for HD 72659. PARSEC isochrones of metallicity  $[\text{Fe}/\text{H}]=-0.02$  and ages 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0 Gyr are shown.

$[\text{Y}/\text{Al}]$  are considered to be helpful chemical clocks, in particular for solar analogs (Casali et al. 2020). Thanks to these elemental ratios, we derived a mean age of  $6.2 \pm 1.0$  Gyr (see Ruggieri et al. 2024 for details). Successively, we estimated the star’s age from the value of the Ca II H&K activity index using the equations by Lorenzo-Oliveira et al. (2018), which are specifically valid for solar twins. In particular, using the value of  $T_{\text{eff}}$  and  $S_{\text{MW}}$  in Table 4, we obtained  $\log R'_{\text{HK}}(T_{\text{eff}}) = -5.04 \pm 0.025$ , from which we calculated an age of  $5.4 \pm 1.2$  Gyr. We notice that this value of  $\log R'_{\text{HK}}$  is slightly different from the value in Table 4 because the correction for the photospheric flux contribution is evaluated as a function of  $T_{\text{eff}}$  and not  $B - V$  as usual (cf. Lorenzo-Oliveira et al. 2018). The X-ray emission does not provide significant constraints, as the upper limit the X-ray luminosity by Kashyap et al. (2008) corresponds to an age older than 1.2 Gyr using Mamajek & Hillenbrand (2008) calibration. Finally, we used the technique proposed in Almeida-Fernandes & Rocha-Pinto (2018) to calculate the age probability distribution from the U, V, and W components of spatial motion. The expected age according to equation 16b of the authors is 7.11 Gyr, the peak of the distribution is at 4.96 Gyr, and the kinematical age (according to the definition of the same authors) is 5.50 Gyr. For all these estimates, the uncertainty is 3 Gyr. Among all these methods, we consider elemental ratios and isochrones the most reliable since HD 72659 is very similar to the Sun in mass and chemical composition. In addition, age estimates from kinematics suffer from large uncertainties when applied to single stars and those from chromospheric activity are affected by magnetic cycles and rotation, which is dubious in our case. Considering the age obtained from the isochrone fitting and the elemental ratios, we find that the two are consistent with each other at  $1.3\sigma$ . In the following, we adopt the age obtained from the isochrones, although we note that, due to a partial discrepancy with the nominal values obtained with the other methods, the true age could likely be in the lower part of the error bar.

## 4 DATA ANALYSIS

### 4.1 Periodograms

We used the ASTROPY PYTHON package to extract the GLS (Generalized Lomb–Scargle periodogram, Zechmeister & Kürster 2009) of our RV time series (including both old and new data). In the following, we first extracted the GLS to each data set individually to account for the different offsets and then applied it to the whole data

set after subtracting each offset from the corresponding individual set. We calculated False Alarm Probabilities (FAPs) using the implemented bootstrap method. In practice, the periodogram is calculated repeatedly on many resamplings, each time keeping the temporal coordinates unchanged, while the RV values are drawn randomly from the observed values. See the astropy documentation for more details.

### 4.2 RV orbital fit

For the RV analysis in this work, we used the 9.1 version of PYORBIT<sup>4</sup> (Malavolta et al. 2016, 2018) to perform a Monte Carlo Markov Chain (MCMC) analysis of our RV data. To do this, the programme exploits the global optimization algorithm PYDE<sup>5</sup> (Storn & Price 1997) and the affine invariant MCMC sampler EMCEE<sup>6</sup> (Foreman-Mackey et al. 2013). We applied different offset and jitter terms to data taken with different instruments. For each planet, the code fits the data using a Keplerian curve with the following parameters: the RV semi-amplitude  $K$ , the orbital period  $P$ , the mean longitude  $L = \omega + M_0$  (setting  $\Omega = 0$  as shown in Section 4.2 in Ford 2006),  $\sqrt{e} \sin \omega$ , and  $\sqrt{e} \cos \omega$ , where  $\omega$  is the argument of periastron of the planet and  $e$  the orbital eccentricity (following the parametrization by Eastman, Gaudi & Agol 2013). The semi-major axis and the minimum mass ( $m \sin i$ ) are then derived using the stellar mass. We used uniform priors for all parameters considered. In total, we have 22 parameters to be fitted: 6 offset terms, 6 jitter terms, and 5 parameters for each planet, giving a total of 88 walkers. We ran the algorithm for 200 k steps and verified that chains have converged with the integrated autocorrelation analysis (Goodman & Weare 2010), the Gelman–Rubin diagnostic using a reference value of 1.01 (Gelman & Rubin 1992), and visual inspection. As explained in Section 5.2, we fit the data with different models and then compared them using the Bayesian Information Criterion (BIC, Schwarz 1978) value and the results by Kass & Raftery (1995).

### 4.3 Combined fits: RVs and astrometry

We combined our RV results with astrometric data with the DEMCMC algorithm (Ter Braak 2006; Eastman et al. 2013) described in Sozzetti (2023), following the same procedure as in Ruggieri et al. (2024). This allows us to derive the values of the orbital inclination  $i$ , the longitude of the ascending node  $\Omega$ , and the mass ratio  $q$ . We adopted uninformative priors for the model parameters derived by the RV-only analysis and uniform priors on  $\cos(i)$ ,  $\Omega$ , and  $q$ .

## 5 THE SUBSTELLAR COMPANION OF HD 72659

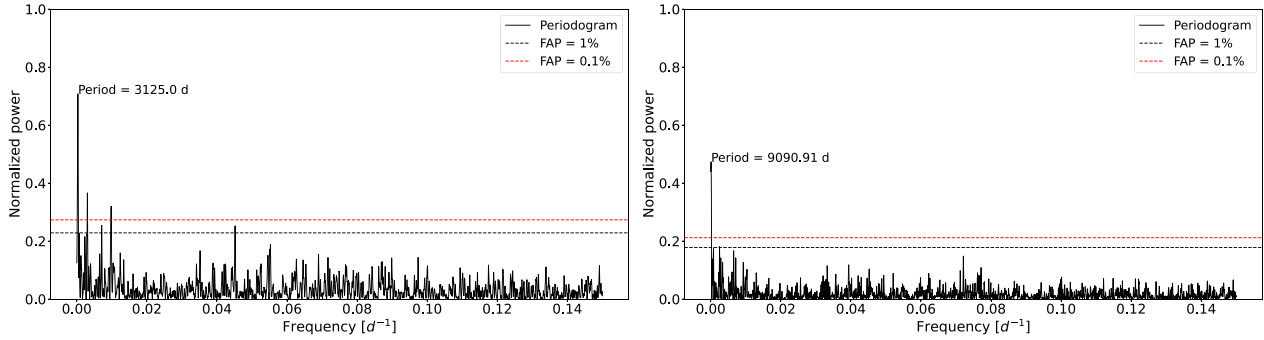
### 5.1 Periodogram analysis

As shown in Fig. 2 (left panel), in the GLS of the RVs of HD 72659, we find the peak corresponding to planet b to be extremely clear, even though at slightly lower periods, probably because the GLS pipeline fits a sinusoidal curve with no eccentricity. In the residuals, after fitting a simple sinusoidal with the automatic pipeline at the nominal peak found by the previous GLS, we can see a longer-term signal (Fig. 2, right panel). The nominal peak is at a much

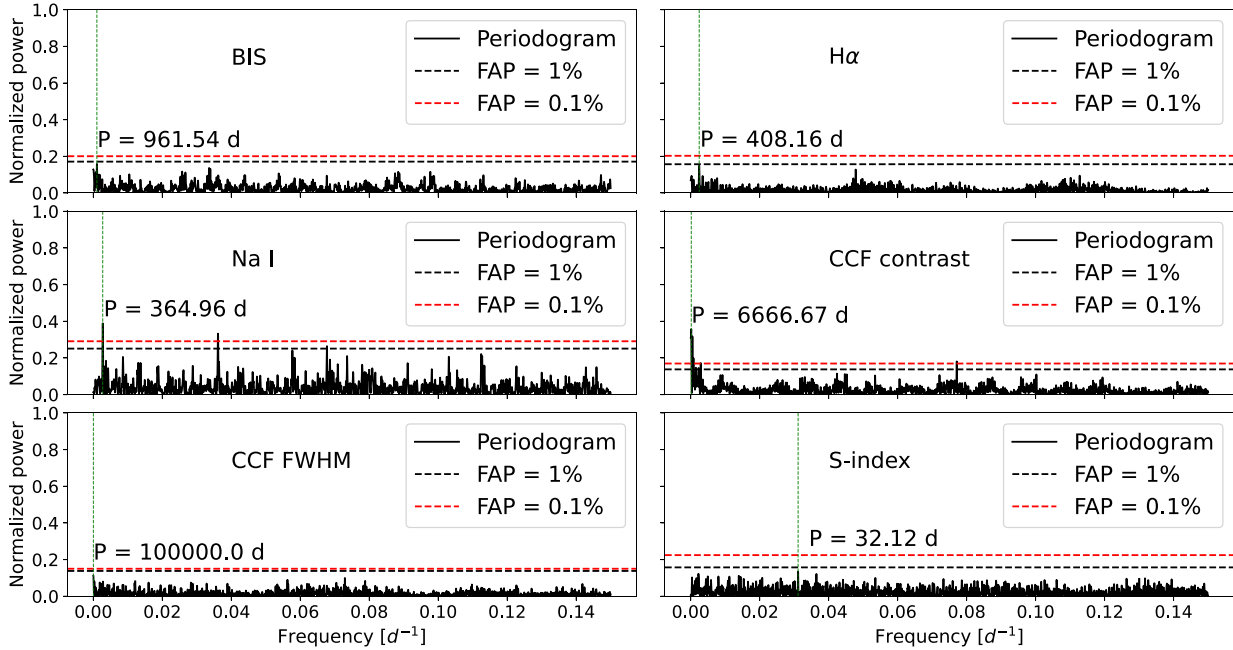
<sup>4</sup><https://pyorbit.readthedocs.io/>

<sup>5</sup><https://github.com/hpparvi/PyDE>

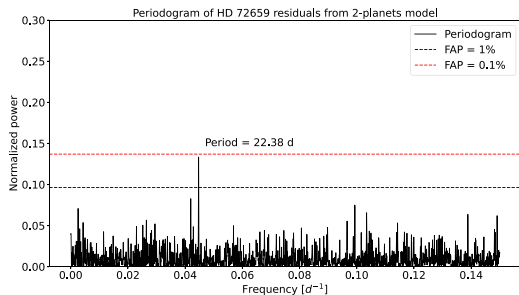
<sup>6</sup><https://emcee.readthedocs.io/en/stable/>



**Figure 2.** GLS of RV data of HD 72659, before (left) and after (right) subtracting the signal from planet b.



**Figure 3.** GLS of activity data of HD 72659.



**Figure 4.** GLS of the RV residuals for HD 72659 after removing the signals corresponding to planets b and c.

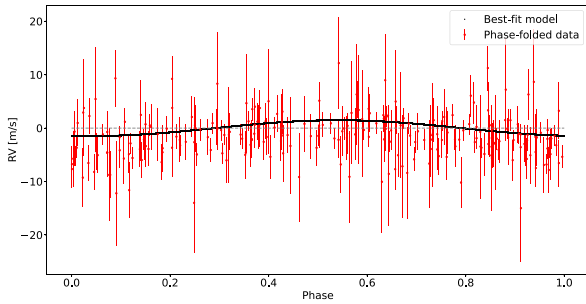
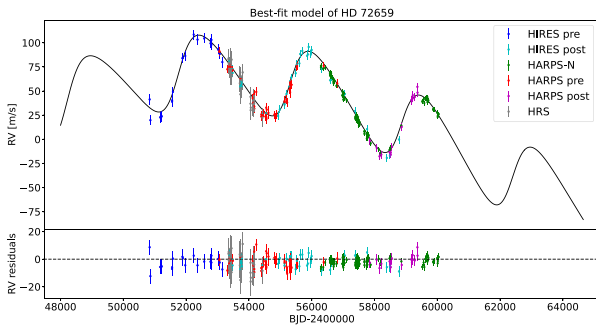
shorter period than later found with the full RV analysis, again likely due to the eccentricity matter and because the time span of the observations is much shorter than the real period of planet c. As far as the activity is concerned, we extracted the GLS of the  $S_{MW}$ , BIS, CCF contrast, CCF FWHM,  $H\alpha$ , and Na I activity indicators

(for HARPS data, the  $S_{MW}$ ,  $H\alpha$ , and Na I indices have been derived from the spectra using the tool ACTIN2 by Gomes da Silva et al. 2021). All the periodograms for these activity indices are shown in Fig. 3. As we can see, the only formally meaningful peaks are found in the sodium and CCF contrast time series. We therefore checked whether these data showed any correlations with RVs. Considering Na I, the Spearman's rank coefficient is  $|r| < 0.1$  both for HARPS and HARPS-N data, indicating no correlation. For the CCF contrast, we obtained  $r = 0.285$  for HARPS and  $r = -0.447$  for HARPS-N, indicating a possibly weak anti-correlation in the second case. However, as described in Benatti et al. (2017), during the first part of the observations the instrument was affected by a small defocus that was fixed in 2014 March. Thus, removing the data taken before that date, we obtain for the HARPS-N data set  $r = 0.137$ , once again indicating no correlation between RVs and the CCF contrast. We therefore confirm that there does not seem to be neither rotational modulations nor any significant activity cycle that might affect the RV time series.

**Table 5.** Comparison between the various models used to fit RV data.

Model	N. of planets	$\dot{\gamma}$ (ms <sup>-1</sup> d <sup>-1</sup> )	$\ddot{\gamma}$ (ms <sup>-1</sup> d <sup>-2</sup> )	$K_c$ (m s <sup>-1</sup> )	$P_c$ (d)	$m_c \sin i_c$ (M <sub>J</sub> )	BIC
M1	1	–	–	–	–	–	1917
M2	2	–	–	$74^{+28}_{-23}$	$27960^{+9834}_{-8683}$	$11.1^{+5.5}_{-4.1}$	1574
M3	1	$(-1.267 \pm 0.031) \cdot 10^{-2}$	–	$\geq 45.52$	$\geq 14372$	$\geq 5.34$	1593
M4	1	$(-2.70^{+0.64}_{-0.67}) \cdot 10^{-3}$	$\dot{\gamma} = (-1.016 \pm 0.068) \cdot 10^{-6}$	$\geq 71.26$	$\geq 52622$	$\geq 12.88$	1549

*Note.* Linear coefficient, quadratic coefficient, RV semi-amplitude, orbital period, and minimum mass derived for HD 72659 c using different models. The second column lists the number of planets included in the model, while the last one shows the corresponding BIC values.


**Figure 5.** Phase-folded data and Keplerian model for the 22-d signal present in the residuals.

**Figure 6.** Best-fit model for HD 72659 obtained using two Keplerian terms.

## 5.2 RV orbital fit

For our analysis, we used six different offsets and jitters: HIRES pre-upgrade, HIRES post-upgrade, HARPS-N, HARPS pre-upgrade, HARPS post-upgrade, and HRS. We fitted our data with a one-planet model (Model 1, M1), a 2-planets model (Model 2, M2), and one planet plus linear (Model 3, M3) or quadratic trend (Model 4, M4). We then compared the results from these based on the BIC criterion by Kass & Raftery (1995) and derived lower limits for the RV semi-amplitude  $K$ , orbital period  $P$ , and minimum mass  $m \sin i$  of the outer planet using our polynomial coefficients and the equations by Kipping et al. (2011).

The results obtained with all these models for HD 72659 are shown in Table 5, where we also reported the BIC value for the model with only planet b for comparison. As we can see from the Table, when using a Keplerian term for the outer planet (M2) in this system, we found a highly unconstrained period as our data cover  $\sim 1/3$  of the nominal value. Nevertheless, we note that our result agrees with the one by Feng et al. (2022) within  $1.1\sigma$ . When using a linear polynomial instead (M3), we found smaller nominal values for  $K$ ,  $P$ , and  $m \sin i$ , but since these are just lower limits, they are in

**Table 6.** Planetary parameters obtained from the RV analysis using two Keplerian terms.

Parameter	HD 72659 b	HD 72659 c
$m_p \sin i$ (M <sub>J</sub> )	$2.851 \pm 0.057$	$11.1^{+5.5}_{-4.1}$
P (d)	$3549 \pm 10$	$27960^{+9834}_{-8683}$
a (au)	$4.607 \pm 0.039$	$18.3^{+4.1}_{-4.0}$
e	$0.2393 \pm 0.0098$	$0.104^{+0.14}_{-0.074}$
$\omega$ (deg)	$-95.9 \pm 2.6$	$-112^{+212}_{-35}$
K (m s <sup>-1</sup> )	$38.23 \pm 0.46$	$74^{+28}_{-23}$
$T_0$ [BJD–2450000]	$3594 \pm 22$	$10299^{+1674}_{-1582}$
jitter HARPS-N (m s <sup>-1</sup> )		$2.07^{+0.20}_{-0.18}$
jitter HIRES (m s <sup>-1</sup> )	$4.86^{+1.20}_{-0.93}$	(pre-upgrade)
	$3.66^{+0.53}_{-0.44}$	(post-upgrade)
jitter HARPS (m s <sup>-1</sup> )	$3.53^{+0.56}_{-0.49}$	(pre-upgrade)
	$3.58^{+0.90}_{-0.69}$	(post-upgrade)
jitter HRS (m s <sup>-1</sup> )		$2.0^{+2.1}_{-1.4}$

*Note.* Physical and orbital parameters for the planets of HD 72659 derived from RV fitting. The reported values are the medians of the resulting distributions and the error bars are the 15th and 84th percentile, respectively. The parameter  $T_0$  is the time of the periastron passage calculated with reference time BJD = 2453000.

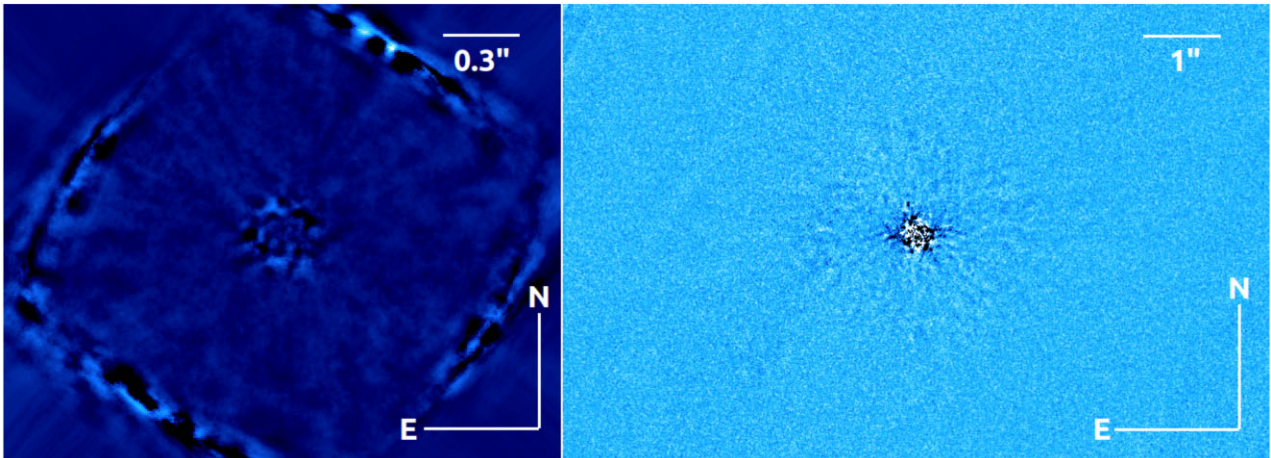
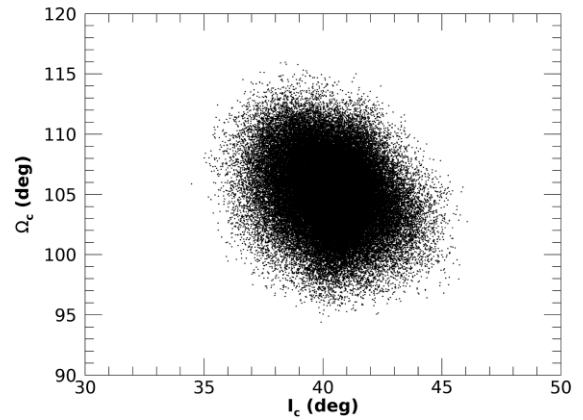
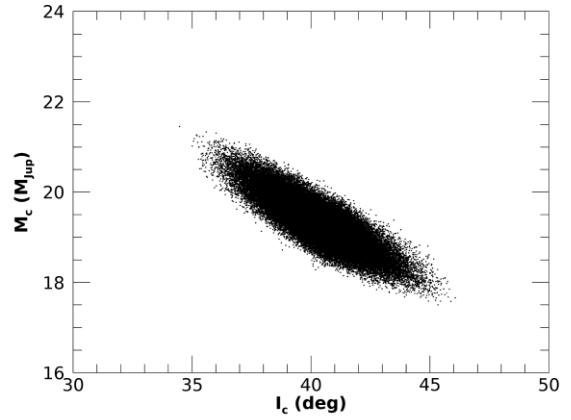
overall agreement with the previous model. In contrast, when using a second-order polynomial, we obtained a much longer orbital period that is incompatible at a  $> 2.5\sigma$  level, even though the  $m \sin i$  is compatible with our previous estimates. As we can see from the BIC values shown in Table 5, the one-planet model is by far the worst at fitting the data. Adding a second Keplerian significantly improves the fit and is favoured over a first-order polynomial, indicating that a curvature is present in our data set. However, the quadratic trend is the most favoured since we only see a relatively small fraction of the orbit of this object.

We conclude that RVs alone are not enough to accurately determine the orbital and physical properties of this object and thus resort to a combined RV + astrometry analysis. Before doing so, we searched for additional signals in the residuals of the quadratic and 2-planet models, finding in both cases a significant (FAP  $\sim 0.1$  per cent) peak at 22 d, as shown in Fig. 4. Thus, we repeated the analysis, fitting the data with three Keplerian terms, setting a flat prior for the period of the third one in the range [2, 100] d and assuming a circular orbit. The results for planets b and c are consistent with the previous models, while the third Keplerian corresponds to a  $6.7 \pm 1.3 M_{\oplus}$  planet with  $P_d = 22.3754 \pm 0.0083$  d. This model is statistically favored over the 2-planets one with  $\Delta\text{BIC} = 53$ . However, we refute this putative third planet based on the following considerations. First

**Table 7.** Orbital parameters and true mass for HD 72659 c from the combined RV + astrometry analysis.

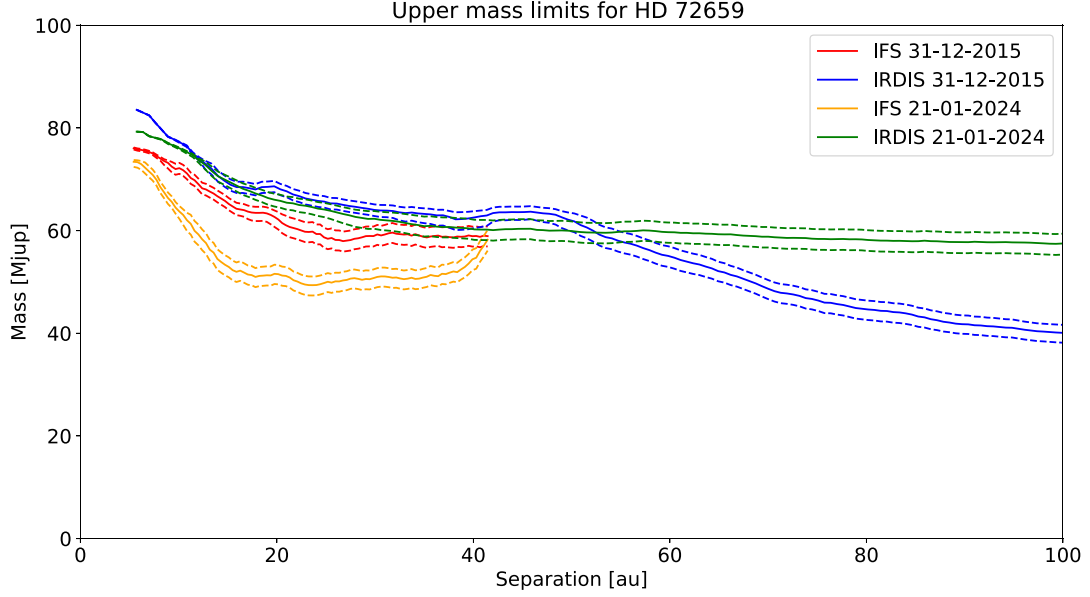
Parameter	Prior	Value
$P_c$ (yr)	$\mathcal{U}(30.0, 150.0)$	$97.1^{+3.4}_{-2.5}$
$T_{0,c}$ (yr)	$\mathcal{U}(0.0, 3000.0)$	$2033.4^{+0.2}_{-0.3}$
$a_c$ (au)	$\mathcal{U}(10.0, 30.0)$	$21.5^{+0.5}_{-0.4}$
$e_c$	$\mathcal{U}(0.0, 1.0)$	$0.114^{+0.002}_{-0.003}$
$\omega_c$ (deg)	$\mathcal{U}(0.0, 360.0)$	$133^{+2}_{-2}$
$i_c$ (deg)	$\cos(i_d), \mathcal{U}(0.0, 180.0)$	$40^{+2}_{-2}$
$\Omega_c$ (deg)	$\mathcal{U}(0.0, 360.0)$	$105^{+3}_{-4}$
$q_c$	$\mathcal{U}(0.0, 0.1)$	$0.0179^{+0.0007}_{-0.0003}$
$M_c$ ( $M_{\text{Jup}}$ )	(derived)	$19.4^{+0.8}_{-0.5}$

of all, we extracted the GLS of the S-index time series and found the highest peaks for HARPS-N and HARPS data at 29 and 22 d, respectively, although both have FAPs  $> 1$  per cent. No such signal is present in the HIRES data as this is the most sparse set. In any case, despite the low significance of these peaks, there is an indication that the 22 d signal seen in the RVs might be related to stellar activity, considering that these periodicities are in the range of the expected rotation period for the star estimated in Section 3. Furthermore, the jitter terms associated with each RV data set do not diminish when adding a third Keplerian to the fit and the same holds for the uncertainties on the orbital parameters of planets b and c. If this was a real signal, we would expect them to decrease, while in our case they are identical to the 2-planets case. What's more, the jitters range from 1.8 to 5  $\text{m s}^{-1}$  while  $K_d = 1.48 \pm 0.29 \text{ m s}^{-1}$ , meaning that the signal has a lower amplitude than the jitters. On top of that, as shown in Fig. 5, the phase-folded model for this presumed object does not follow the data as well as one would expect. Considering all this, we do not further consider the presence of a third planet in the rest of the paper and leave a potentially more detailed analysis for future work. The results obtained with the two Keplerian terms are listed in Table 6 and the best-fitting model is shown in Fig. 6.

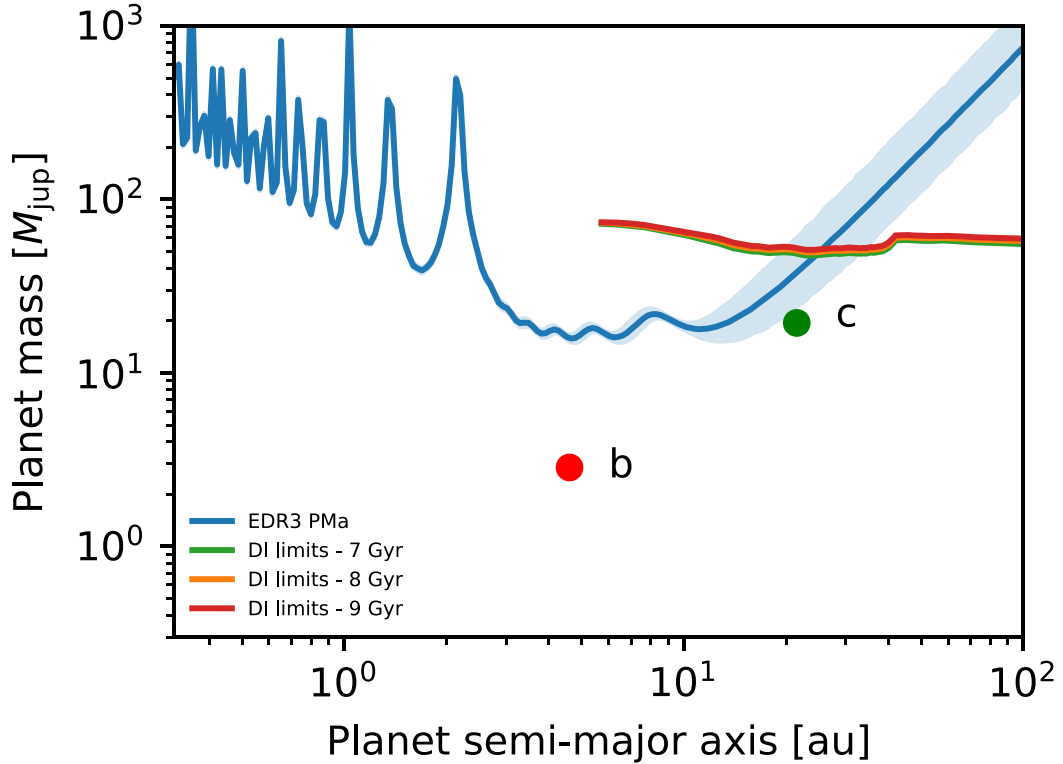
**Figure 8.** Deepest imaging observations taken with SPHERE, both with IFS (left) and IRDIS (right).**Figure 7.** Joint posterior distributions for inclination, longitude of the ascending node and true mass for HD 72659 c.

### 5.3 Orbital parameters and true mass from combined fits

Following the same approach adopted in the combined astrometry+RV analysis described in Ruggieri et al. (2024), we ran the DE-MCMC analysis with the PMA + RV model fitted to the HIPPARCOS–Gaia absolute astrometry of HD 72659 from Table 2 and the offset-corrected RV data set with the signal of HD 72659 b removed. We do note that, with  $a_b = 4.60$  au, the orbital



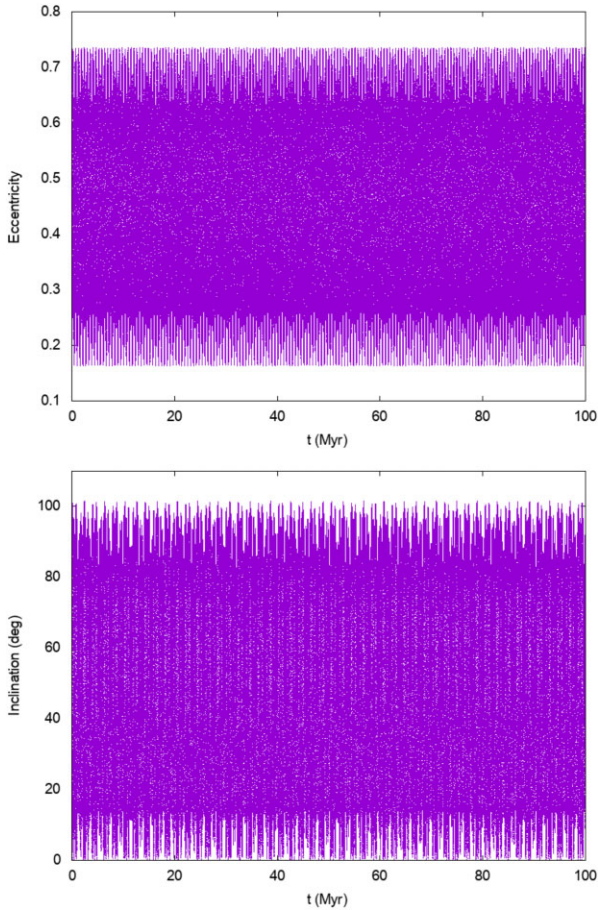
**Figure 9.** Upper mass limits for HD 72659 c, as a function of separation from the central star, derived from the previous and new SPHERE observations obtained using the AMES-COND models. The dashed lines represent the  $1\sigma$  uncertainty.



**Figure 10.** Upper limits in mass for the long-period substellar companion of HD 72659 derived from our SPHERE observation and PMA sensitivity curves calculated following Kervella, Arenou & Thévenin (2022). The positions of planet b (from RVs only) and planet c (as derived from our RV + astrometry analysis) are also shown.

separation of HD 72659 b, falls in the region of highest sensitivity of the PMA technique. However, based on the analytical formulation of Kervella et al. (2019), at  $a \simeq 5$  au the measured PMA should be due to a companion with  $M_b = 19 \pm 6 M_J$  (see also Fig. 10). Given the  $m_b \sin(i)$  value obtained by the RV-only analysis, this

would imply quite a low inclination orbit ( $i \sim 9$  deg). We therefore initially assumed that the observed PMA is entirely due to the effect of orbital motion induced by HD 72659 c. The best-fitting orbital solution for HD 72659 c is reported in Table 7. We obtain a formally precise solution, despite only seeing a long-term trend in the RV



**Figure 11.** Evolution with time of the eccentricity (top panel) and inclination (bottom panel) of planet b perturbed by planet c.

data covering  $\sim 20$  per cent of the period. In particular, we obtained an orbital inclination  $i_c = 40 \pm 2$  deg (for a retrograde orbit) and a mass ratio  $q_c = 0.0179^{+0.0007}_{-0.0004}$ , corresponding to a true mass of  $M_c = 19.4^{+0.8}_{-0.5} M_{\text{Jup}}$ , formally identifying HD 72659 c as a low-mass brown dwarf. The joint posteriors of the parameters mentioned above are shown in Fig. 7. The true mass HD 72659 c we obtain sits at the lower boundary of the  $1\sigma$  mass interval predicted by the sensitivity curve in Fig. 10, with a central true mass value at  $a \sim 20$  au closer to  $30 M_{\text{Jup}}$ .

We also explored the possibility of a significant contribution to the observed PMa from HD 72659 b by fitting a two-companion model to the combined RV + astrometry data set. In particular, we ran the DE-MCMC analysis using the same broad priors for  $i_b$  and  $i_c$  and forcing  $i_c$  in the range  $10 - 15$  deg (or  $165 - 180$  deg for a prograde orbit), the latter case corresponding to a range of true values of  $M_b$  that would encompass that indicated by the sensitivity curve shown in Fig. 10 given the semi-major axis of HD 72659 b's orbit. Even imposing the tight priors on the spectroscopically determined orbital elements for HD 72659 b, which are precisely determined by the RV-only analysis, convergence was not achieved in either case, with a vanishingly small value of  $q_b$  and unconstrained values for  $P_c$ . We conclude that the signal of HD 72659 b is not present in the Hipparcos–Gaia absolute astrometry, therefore its true mass is likely within a factor of a few from its minimum value. In this respect, we cannot rule out a close to coplanar configuration between HD 72659 b and HD 72659 c, as in this case, assuming  $i_b \sim 40$  deg, the true

mass of the former would be  $M_b \sim 4.5 M_{\text{J}}$ , still far from being large enough to produce a detectable astrometric acceleration.

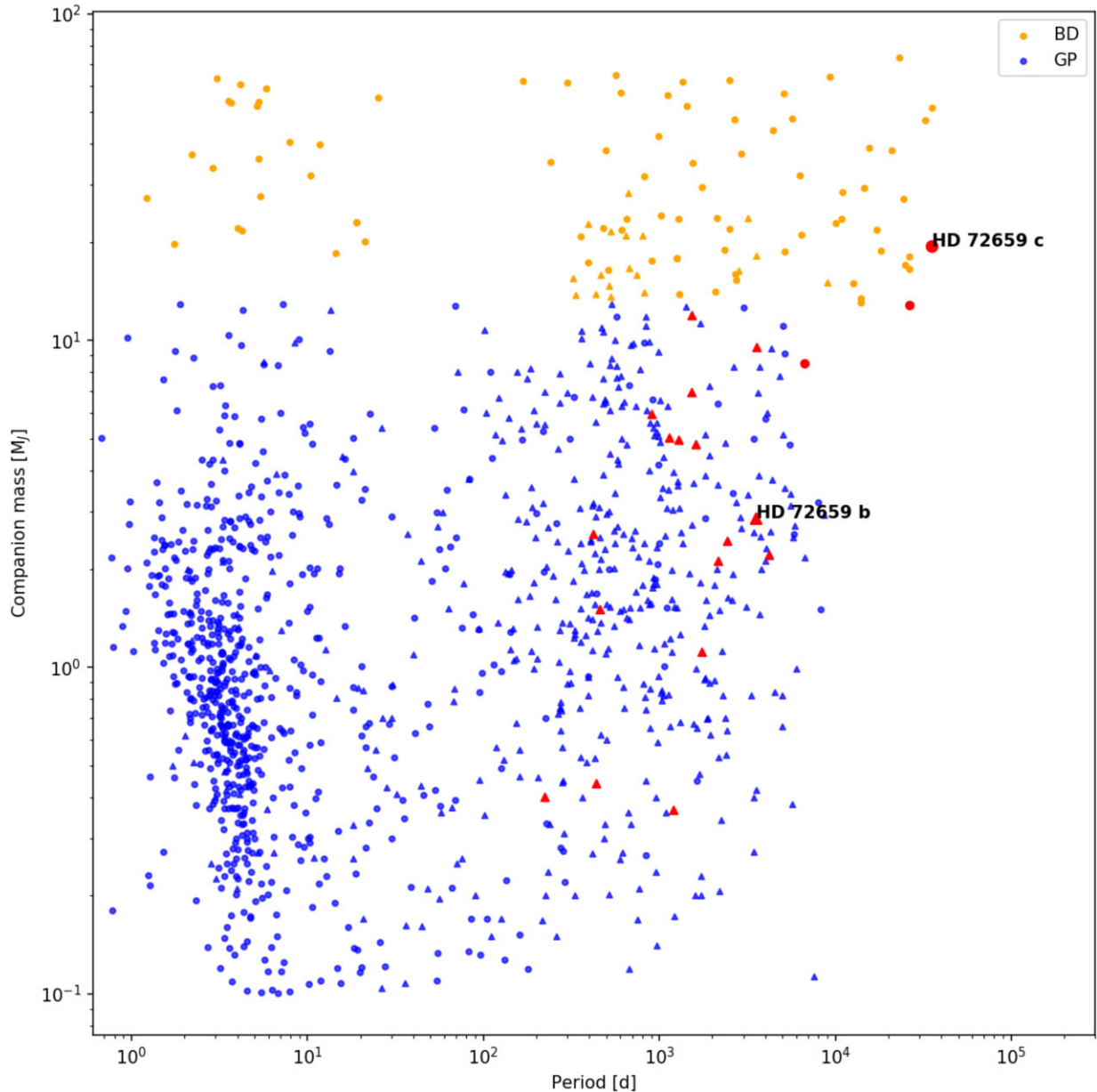
#### 5.4 Result from direct imaging

We reduced our new SPHERE observation as described in Section 2.3, the result is shown in Fig. 8. As we can see, there is no clear trace of HD 72659 c nor of any other stellar or sub-stellar companion. We derived the contrast curve by calculating the standard deviation for pixels at the same separation from the central star and dividing this value by the normalization factor obtained using the offset PSF described in Section 2.3. We then evaluated the self-subtraction caused by the speckle subtraction method used by injecting in our data set simulated planets with known contrast at different separations from the central star. These results were then used to correct the contrast previously obtained. Starting from the contrast we were then able to calculate the mass limits of possible companions around this star using the AMES-COND atmospheric models (Allard et al. 2003) and assuming an age of  $8.0 \pm 1.0$  Gyr as derived in Section 3. Fig. 9 shows the results for both SPHERE observations using both IFS and IRDIS. As we can see, the new observation is deeper, especially with IFS. We note that the higher mass limits obtained at large separation with IRDIS in the new observation are not surprising, as they were obtained in *K* band, where the background level is higher than in the *H* band used for the previous observation. In this observation, we were more interested in searching companions at short separations from the host star, so the loss in sensitivity at larger separations was considered acceptable. Therefore, from now on, we will only consider the results obtained from our new observations, giving an upper limit on the mass of HD 72659 c of about  $50 M_{\text{J}}$  at the expected orbital separation for this object. Fig. 10 contains the imaging detection limits, the PMa sensitivity curve as derived by Kervella et al. (2022), and the position of the two planets. Since the object is not detected in SPHERE data, its position on this plot should be below (i.e. at lower masses than) the red line ( $\sim 50 M_{\text{J}}$ ). This is compatible with the astrometric result discussed in the previous section.

#### 5.5 The intriguing dynamics of the system

Both planets b and c exhibit significant eccentricities, suggesting a complex evolutionary history. Mutual secular perturbations between the two planets in a coplanar configuration result in a maximum eccentricity of only 0.01 for each planet – far below the observed values. Two alternative explanations are possible: (1) the system may have experienced a phase of planet–planet scattering, during which one planet was ejected, leaving the remaining two on eccentric orbits; or (2) the two planets may have a significant mutual inclination, leading to Kozai–Lidov oscillations. In the first scenario, following the planet–planet scattering event that increased the eccentricities to their current values, secular perturbations would cause modest eccentricity variations—ranging from 0.08 to 0.125 for planet c and from 0.22 to 0.29 for planet b, as resulting from a dedicated dynamical simulation in case of nearly coplanar orbits. In contrast, the Kozai–Lidov mechanism would result in a much richer dynamical evolution. According to Naoz (2016), this process can induce large variations in both eccentricity and inclination, with potential transitions between prograde and retrograde orbits, and even chaotic behaviour.

To explore the possible dynamics of the system under the assumption that it resides in a Kozai–Lidov state, we performed numerical integrations using the RADAU integrator (Everhart



**Figure 12.** Mass-period plot of known exoplanets and BDs. Triangles indicate that only the minimum mass is known, while the true mass has been derived for objects indicated with dots. Blue indicates planets and orange indicates BDs (below or above  $13 M_J$ ). All the GAPS KP objects are shown in red.

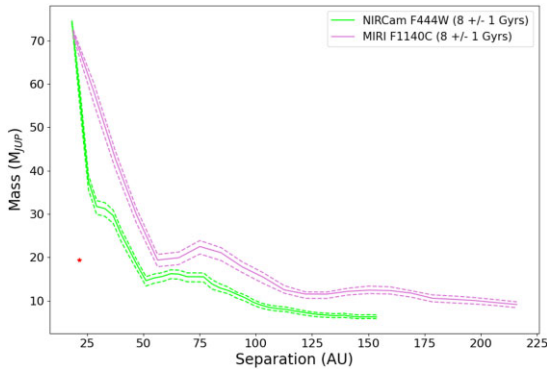
1985). The simulations employed the nominal masses and orbital parameters listed in Table 6 for planet b and Table 7 for planet c, adopting a mutual inclination of  $50^\circ$ . As illustrated in Fig. 11, the eccentricity of planet b varies between approximately 0.16 and 0.72, while its inclination oscillates between  $0^\circ$  and  $100^\circ$ , with the orbit periodically becoming retrograde. This behaviour is consistent with the observed eccentricities of the planets.

Over the 100 Myr duration of the integration, the orbits exhibit semi-periodic evolution without signs of chaotic behavior. A similar dynamical pattern is observed when planet c is initially placed on a retrograde orbit. Random variations in the longitudes of pericentre and ascending node do not significantly affect the inclination evolution, although the eccentricity of planet b can be reduced, reaching a maximum of about 0.4 in some configurations.

The possible misalignment between the orbit of planet c and that of planet b may result from three distinct evolutionary scenarios. In the first, planet c formed concurrently with the primary star as a brown dwarf, while planet b formed later via core accretion within a circumstellar disk that was misaligned with planet c’s orbit (Batygin 2012).

A second viable scenario involves a massive circumstellar disc capable of producing several giant planets with varying masses. Subsequent planet–planet scattering among these bodies could have ejected some of the planets, leaving the survivors on highly inclined orbits (Marzari 2025, and references therein).

A third possibility is that the system experienced a stellar flyby within a dense stellar cluster during its early evolution. In this case, the inclination of planet c could have been excited by a strong gravitational interaction with a passing star (Laugh-



**Figure 13.** Theoretical detection limits for HD 72659 using both the MIRI F1140C and the NIRCam F444W filters on JWST. The red star represents HD 72659 c, while the dashed lines represent the  $1\sigma$  uncertainties.

lin & Adams 1998; Malmberg, Davies & Heggie 2011). For this mechanism to be effective, the flyby must have occurred after the dissipation of the circumstellar disc and near the end of the cluster’s lifetime; otherwise, the disk would have rapidly damped any inclination or eccentricity induced by the encounter (Marzari & Nelson 2009).

## 6 CONCLUSION

In this work, we analysed HD 72659, putting severe constraints on the orbit of its two substellar companions. This was relatively easy for planet b, thanks to more than 20 yr of high-precision RV data, but not as much for the recently discovered companion on the system’s outer edges. Its period is so long that even with our large data set, we were not able to well constrain its orbit with RVs alone. However, the strong Hipparcos–Gaia PMA measured for this object greatly improved our results. In particular, we find a true mass that is compatible with Feng et al. (2022) but, according to our results, they are underestimating the orbital period of HD 72659 c by a factor of  $\sim 2$  with a significance of  $10.4\sigma$  (with respect to our RV+astrometry analysis). This is likely due to our larger data set that includes 91 data points gathered over 10 yr. As we mentioned, the mass that we derive is lower than the value predicted by the Gaia sensitivity curve but formally compatible, and we excluded the possibility that planet b is also contributing to the astrometric signal. This would have implied an almost pole-on orbit, potentially casting doubts about the stability of a system with 2 very massive ( $M \sim 20 M_J$ ) objects. What’s more, our new imaging data showed that there are no previously undetected stellar companions and confirmed that HD 72659 c is, unfortunately, not detectable with SPHERE. Finally, we discussed the dynamics and possible origin of the system, which is of peculiar interest given that the inner planet has a moderate eccentricity while the outer companion is rather massive and not so distant. We concluded that the Kozai–Lidov mechanism might be at play in this system and that there is no chaotic evolution. This situation is somewhat similar to that of HD 11 506 discussed in Ruggieri et al. (2024).

HD 72659 c is placed in the so-called brown dwarfs desert, which is a region of the mass-period space where only a few objects are found. In particular, this system represents a precious case study because it also contains another planet with a high mass and a relatively long period. We note here that this star belongs to the KP sample selected by the GAPS team. This includes 16 stars for which an external gas giant was already known in 2012 and these were monitored

with HARPS-N since then. Out of 16, three of them turned out to have another planet/BD at even longer periods (the other two are HD 75 898 and HD 11 506, see Ruggieri et al. (2024)). This is a significant number of outer companions and we will analyse the matter more in-depth in an upcoming dedicated statistical analysis (Pinamonti et al., in preparation). Fig. 12 shows the mass-period diagram of known exoplanets with our KP objects highlighted.

In the future, there is room for improvement in the analysis of this system. First, we will keep monitoring this target with HARPS-N, covering larger fractions of planet c’s orbit. Secondly, *Gaia* DR4 will provide astrometric time series that will likely be sensitive to the mass and period range of HD 72659 b, possibly helping to constrain the orbital inclination of this planet (and thus the true mass). As far as direct imaging is concerned, we investigated the potential of detecting the outer planet in this system with the *James Webb Space Telescope* (*JWST*) in the near- and mid-infrared. To this end, we computed theoretical contrast curves for MIRI F1140C filter ( $\lambda = 11.30 \mu\text{m}$ ,  $\Delta\lambda = 0.8 \mu\text{m}$ ) and NIRCam F444W filter ( $\lambda = 4.402 \mu\text{m}$ ,  $\Delta\lambda = 1.024 \mu\text{m}$ ) using PanCAKE, a simulation tool that extends the official *JWST* exposure time calculator (Pandeia) to produce more accurate predictions of *JWST* coronagraphic performance (Carter et al. 2021). We simulated a coronagraphic observation with both instruments, assuming an exposure time of 3600 s and a reference star of similar spectral type for Reference Differential Imaging (RDI; Lafrenière et al. 2009) processing, which proved to be the most efficient post-processing technique for *JWST* coronagraphic observations (Carter et al. 2023). The contrast limits were then converted into mass limits using the atmospheric evolutionary model ATMO (Phillips et al. 2020) and assuming a system age of  $8 \pm 1$  Gyr. As shown in Fig. 13, the outer planet lies below the detection thresholds of both instruments. We thus conclude that *JWST* cannot directly detect a planetary companion in such an old system. Nevertheless, future direct detection with the Extremely Large Telescope (ELT) could be possible. Combined with the well-determined metallicity and age of HD 72659, the sum of these aspects in the coming years may allow us to shed further light on the architecture, dynamics, and composition of this system, making it a benchmark case study for directly imaged planetary systems.

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## DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

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## SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](https://www.mnras.org) online.

**Table A1.** RVs, S-index, and BIS time series for HD 72659 derived from HARPS-N spectra, and their associated uncertainties.

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## APPENDIX A: HARPS-N TIME SERIES OF HD 72659

**Table A1.** RVs, S-index, and BIS time series for HD 72659 derived from HARPS-N spectra, and their associated uncertainties. The full version of this table is available online.

BJD–24000000	RV (m s <sup>-1</sup> )	$\sigma_{RV}$ (m s <sup>-1</sup> )	SMW	$\sigma_{SMW}$	BIS (km s <sup>-1</sup> )	$\sigma_{BIS}$ (km s <sup>-1</sup> )
56 295.7024	–18 128.52	0.36	0.152 701	0.000 281	0.015 88	0.000 50
56 296.6934	–18 127.02	0.37	0.152 241	0.000 287	0.015 97	0.000 52
56 366.4057	–18 130.07	0.89	0.155 158	0.000 972	0.013 04	0.001 26
56 424.4005	–18 129.20	0.62	0.154 787	0.000 586	0.020 72	0.000 87
56 582.7663	–18 134.66	0.49	0.157 785	0.000 414	0.021 58	0.000 69
56 584.7678	–18 134.47	0.65	0.157 508	0.000 635	0.036 78	0.000 92
56 585.7432	–18 136.68	0.57	0.158 707	0.000 526	0.022 50	0.000 80
56 586.7532	–18 136.37	0.54	0.158 777	0.000 484	0.022 23	0.000 76
56 602.7091	–18 134.41	0.57	0.159 661	0.000 514	0.012 32	0.000 80
56 603.7258	–18 136.61	0.44	0.158 465	0.000 362	0.021 44	0.000 62

- <sup>1</sup>INAF, Astrophysical Observatory of Catania, Via S. Sofia 78, I-95123 Catania, Italy
- <sup>2</sup>INAF, Astronomical Observatory of Padua, Vicolo dell'Osservatorio 5, I-35122 Padua, Italy
- <sup>3</sup>INAF, Astrophysical Observatory of Turin, Via Osservatorio 20, I-10025 Pino Torinese (TO), Italy
- <sup>4</sup>Department of Physics and Astronomy, University of Padua, via Marzolo 8, I-35131 Padua, Italy
- <sup>5</sup>Institute for Astronomy, University of Edinburgh Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
- <sup>6</sup>INAF, Astronomical Observatory of Rome, Via Frascati 33, I-00178 Monte Porzio Catone (RM), Italy
- <sup>7</sup>Department of Physics, University of Rome Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
- <sup>8</sup>School of Natural Sciences, Center for Astronomy, University of Galway, Galway H91 CF50, Ireland

- <sup>9</sup>Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands
- <sup>10</sup>Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands
- <sup>11</sup>Department of Astronomy, University of Michigan, 1085 S. University, Ann Arbor, MI 48109, USA
- <sup>12</sup>Department of Physics and Astronomy 'Galileo Galilei', University of Padova, Vicolo dell'Osservatorio 3, I-35122 Padova, Italy
- <sup>13</sup>INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate (LC), Italy
- <sup>14</sup>Fundacion Galileo Galilei-*INAF*, Rambla J.A. Fernandez P., 7, E-38712 S.C.Tenerife, Spain
- <sup>15</sup>Mathematics & Physics Department, University of Roma Tre, Via Della Vasca Navale, 84, Roma I-00146, Italy

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