Orbital and atmospheric characterization of the planet within the gap of the PDS 70 transition disk

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Received 06 June 2018 / Accepted 08 July 2018

1. Introduction

Our knowledge of the formation mechanism and evolution of planets has developed by leaps and bounds since the first detection of an exoplanet by Mayor & Queloz (1995) around the main-sequence star 51 Peg. However, constraining the formation timescales, the location of planet formation, and the physical properties of such objects remains a challenge and to date has mostly been based on indirect arguments using measured properties of protoplanetary disks. What is really needed is a detection of planets around young stars still surrounded by a disk. Modern coronagraphic angular differential imaging surveys that utilize extremely adaptive optics, such as the SpHERE INfrared survey for Exoplanets (SHINE; Chauvin et al. 2017), provide the necessary spatial resolution and sensitivity to find such young planetary systems.

In Keppler et al. (2018) we reported the first bona fide detection of a giant planet inside the gap of the transition disk around the star PDS 70 together with the characterization of its protoplanetary disk. PDS 70 is a K7-type 5.4 Myr young pre-main sequence member of the Upper Centaurus-Lupus group (Riaud et al. 2006; Pecaut & Mamajek 2016) at a distance of 113.43 ± 0.52 pc (Gaia Collaboration 2016, 2018). Our determination of the stellar parameters are explained in detail in Appendix A. The planet was detected in five epochs with VLT/SPHERE (Beuzit et al. 2008), VLT/NaCo (Lenzen et al. 2003; Rouset et al. 2003), and Gemini/NICI (Chun et al. 2008) covering a wavelength range from $H$ to $L'$ band. In this paper we present new deep K-band imaging and first $Y-H$ spectroscopic data with SPHERE with the goal of putting constraints on the orbital parameters and properties of PDS 70 b.

2. Observations and data reduction

2.1. Observations

We observed PDS 70 during the SPHERE/SHINE GTO program on the night of February 24, 2018. The data were taken in the IRDIFS-EXT pupil tracking mode using the
The measured contrasts of PDS 70 b from all data sets (SPHERE, SPHERE-IFS, IRDIS, IFS) were varied in contrast and position based on a predefined grid created from a first initial estimate of the planet’s contrast and position. For every parameter combination of the inserted negative planet the data were reduced with the SPEX Data Center pipeline (Delorme et al. 2017), which uses the Data Reduction and Handling software (v0.15.0, Pavlov et al. 2008) and additional IDL routines for the IFS data reduction (Mesa et al. 2015). The modeling and subtraction of the stellar speckle pattern for both the IRDIS and IFS data set were performed with a smart Principal Component Analysis (sPCA) algorithm based on Absil et al. (2013) using the same setup as described in Kepller et al. (2018). Figure 1 shows the high-quality IRDIS combined K1-K2 image of PDS 70. The outer disk and the planetary companion inside the gap are clearly visible. In addition, there are several disk related features present, which are described in Appendix B. For this image the data were processed with a classical ADI reduction technique (Marois et al. 2006) to obtain flux values for our data sets taken in L′ band at 3.8 µm, we modeled the stellar SED with simple blackbodies to account for the observed infrared excess (Hashimoto et al. 2012; Dong et al. 2012). The final SED of the planet is shown in Fig. 2. The IFS SED of the planet is shown in Fig. 2. The IFS spectrum has a steep slope and displays a few features only, mainly water values are listed in Table C.1.

3. Results

3.1. Atmospheric modeling

We performed atmospheric simulations for PDS 70 b with the self-consistent 1D radiative-convective equilibrium tool petitCODE (Mollière et al. 2015, 2017), which resulted in three different grids of self-luminous cloudy planetary model atmospheres (see Table 1). These grids mainly differ in the treatment of clouds: petitCODE(1) does not consider scattering and includes only Mg2SiO4 cloud opacities; petitCODE(2) adds scattering; petitCODE(3) contains four more cloud species including iron (Na2S, KCl, Mg2SiO4, Fe). Additionally, we also use the publicly available cloud-free petitCODE model grid (here called petitCODE(0)); see Samland et al. 2017 for a detailed description of this grid) and the public PHOENIX BT-Setti grid (Allard 2014; Baraffe et al. 2015).

In order to compare the data to the petitCODE models we use the same tools as described in Samland et al. (2017), using the python MCMC code emcee (Foreman-Mackey et al. 2013) on N-dimensional model grids linearly interpolated at each evaluation. We assume a Gaussian likelihood function and take into account the spectral correlation of the IFS spectra (Greco & Brandt 2016). For an additional independent confirmation of the results obtained using petitCODE, we also used cloudy models from the Exo-REM code. The models
and corresponding simulations are described in Charnay et al. (2018). Exo-REM assumes non-equilibrium chemistry, and silicate and iron clouds. For the model grid Exo-REM(1) the cloud particles are fixed at 20 \( \mu \)m and the vertical distribution takes into account vertical mixing (with a parametrized \( K_z \)) and sedimentation. The Exo-REM(2) model uses a cloud distribution with a fixed sedimentation parameter \( f_{sed} = 1 \) as in the model by Ackerman & Marley (2001) and petitCODE. Table 2 provides a compilation of the best-fit values and Fig. 2 shows the respective spectra. The values quoted correspond to the peak of the respective marginalized posterior probability distribution. The cloud-free models fail to represent the data and result in unphysical parameters. In contrast, the cloudy models provide a much better representation of the data. The results obtained by the petitCODE and Exo-REM models are consistent with each other. However, because of higher cloud opacities in the Exo-REM(2) models the log \( g \) values are less constrained and the water feature at 1.4 \( \mu \)m is less pronounced. Therefore, the resulting spectrum is closer to a blackbody and the resulting mass is less constrained. All these models indicate a relatively low temperature and surface gravity, but in some cases unrealistically high radii. Evolutionary models predict radii smaller than 2 \( R_J \) for planetary-mass objects (Mordasini et al. 2017). The radius can be pushed toward lower values if cloud opacities are removed, for example by removing iron (petitCODE(2)). However, a direct comparison for the same model parameters is very small. In petitCODE(1) this is shown in an exaggerated way by artificially removing scattering from the models, which leads to a significant reduction in radius. In general, we find a wide range of models that are compatible with the current data. The parts of the spectrum most suitable for ruling out models are the possible water absorption feature with the current data. The parts of the spectrum most suitable for ruling out models are the possible water absorption feature with the current data. The parts of the spectrum most suitable for ruling out models are the possible water absorption feature with the current data. The parts of the spectrum most suitable for ruling out models are the possible water absorption feature with the current data. The parts of the spectrum most suitable for ruling out models are the possible water absorption feature with the current data.

### Table 1. Model grids used as input for MCMC exploration.

| Model       | \( T_{eff} \) (K) | \( \Delta T \) (K) | \( g \) (cgs) | \( \Delta g \) (cgs) | \( (M/H) \) | \( \Delta (M/H) \) (dex) | \( f_{sed} \) | \( \Delta f_{sed} \) | Remarks                  |
|-------------|-------------------|-------------------|--------------|-------------------|-------------|-----------------------------|--------------|-------------------|--------------------------|
| BT-Settl    | 1200–3000         | 100               | 3.0–5.5      | 0.5               | 0.0         | –                           | –            | –                 | –                        |
| petitCODE(0)| 500–1700          | 50                | 3.0–6.0      | 0.5               | –1.0 to 1.4 | 0.2                         | –            | –                 | Cloud-free               |
| petitCODE(1)| 1000–1500         | 100               | 2.0–5.0      | 1.0               | –1.0 to 1.0 | 1.0                         | 1.5          | –                 | –                        |
| petitCODE(2)| 1000–1500         | 100               | 2.0–5.0      | 0.5               | 0.0–1.5     | 0.5                         | 0.5–6.0      | 1.0               | with scattering, w/o Fe clouds |
| petitCODE(3)| 1000–2000         | 200               | 3.5–5.0      | 0.5               | –0.3 to 0.3 | 0.3                         | 1.5          | –                 | With scattering, with Fe clouds |
| Exo-REM(1)  | 400–2000          | 100               | 3.0–5.0      | 0.1               | 0.32, 1.0  | 3.32                        | –            | –                 | Cloud particle size fixed to 20 \( \mu \)m |
| Exo-REM(2)  | 400–2000          | 100               | 3.0–5.0      | 0.1               | 0.32, 1.0, 3.32 | 1.0          | –            | –                        |

Notes. The radius of the planet was included as an additional analytic fit-parameter regardless of the model, ranging from 0.1 \( R_J \) to 5 \( R_J \). \(^{a}\) Except additional grid point at 0.5.

### Table 2. Parameters of best-fit models based on the grids listed in Table 1.

| Model       | \( T_{eff} \) (K) | \( \log g \) (cgs) | \( (M/H) \) (dex) | \( f_{sed} \) | \( \text{Radius} \) \( R_J \) | \( \text{Mass} \) \( M_J \) | \( K \) flux | \( L' \) flux |
|-------------|-------------------|-------------------|------------------|--------------|-----------------------------|-----------------------------|------------|-------------|
| BT-Settl    | 1590              | 3.5               | –                | 1.4          | 2.4                         | Yes                         | Yes        |
| petitCODE(0)| 1155              | 5.5               | –1.0             | 2.7          | 890.0                       | No                          | (Yes)      |
| petitCODE(1)| 1050              | \( \leq 2.0 \)    | \( \geq 1.0 \)   | 1.5\(^{a}\)  | 2.0                         | 0.2                         | Yes        |
| petitCODE(2)| 1100              | 2.65              | 1.0              | 1.24         | 3.3                         | 1.9                         | Yes        |
| petitCODE(3)| 1190              | \( \leq 3.5 \)    | 0.0              | \( \leq 1.5 \)| 2.7                         | 8.9                         | Yes        |
| Exo-REM(1)  | 1000              | 3.5               | 1.0              | 3.7          | 17                          | Yes                         | Yes        |
| Exo-REM(2)  | 1100              | 4.1               | 1.0              | 3.3          | 55                          | Yes                         | Yes        |

Notes. The last two columns indicate qualitatively whether the corresponding model is compatible with the photometric points in \( K \) and \( L' \) band, whereas all models describe the \( Y \)- to \( H \)-band data well. \(^{a}\) Only grid value. \(^{b}\) As derived from \( \log g \) and \( \text{radius} \).
3.2. Orbital properties of PDS 70 b

The detailed results of the relative astrometry and photometry extracted from our observation from February 2018 are listed in Table C.1 together with the earlier epochs presented in Keppler et al. (2018). A first verification of the relative position of PDS 70 b with what we could expect for a stationary background contaminant is shown in Fig. 3. The latest SPHERE observations of February 24, 2018, confirms that the companion orbiting inside the gap of the transition disk around PDS 70 is comoving with the central star. This third possibility is especially interesting in the light of possible features in our reduced images that could present spiral arm structures close to the planet (Fig. 1). There also appears to be an increase in HCO\(^+\) velocity dispersion close to the location of the planet in the ALMA data presented by Long et al. (2018).

We applied the Markov chain Monte Carlo (MCMC) Bayesian analysis technique (Ford 2005, 2006) developed for applied the Markov chain Monte Carlo (MCMC) Bayesian analysis clearly demonstrates that cloud-free models do not provide a good fit to the data. In contrast, we find a range of solutions favoring solutions compatible with low-eccentric solutions as shown by the \((a, e)\) correlation diagram. The elements \(\Omega\) and \(\omega\) are poorly constrained as low-eccentric solutions are favored and as pole-on solutions are also likely possible. Time periastron is poorly constrained. The inclination distribution clearly favors retrograde orbits \((i > 90^\circ)\), which is compatible with the observed clockwise orbital motion resolved with SPHERE, NaCo, and NICI. To consider the disk geometry described by Keppler et al. (2018), we decided to explore the MCMC solutions compatible with a planet-disk coplanar configuration. We restrained the PDS 70 b solution set given by the MCMC to those solutions with orbital plane making a tilt angle less than 5\(^\circ\) with respect to the disk midplane described by Keppler et al. (2018), i.e., \(i = 180^\circ − 49.8^\circ\) and \(PA = 158.6^\circ\). The results are shown in Fig. D.2 and Table D.1 together with the relative astrometry of PDS 70 b reported with 200 orbital solutions randomly drawn from our MCMC distributions in Fig. D.4. Figure D.3 shows the posterior distribution (out of Fig. D.1) of the tilt angle with the disk plane assuming \(i_{\text{disk}} = 130.2^\circ\) and \(PA = 158.6^\circ\). The distribution peaks around 50\(^\circ\), which remains consistent with a likely coplanar planet-disk configuration (or a moderate tilt angle) given the uncertainties. Given the small fraction of orbit covered by our observations, a broad range of orbital configurations are possible including coplanar solutions that could explain the formation of the broad disk cavity carved by PDS 70 b.

4. Summary and conclusions

We presented new deep SPHERE/IRDIS imaging data and, for the first time, SPHERE/IFS spectroscopy of the planetary mass companion orbiting inside the gap of the transition disk around PDS 70. With the accurate distance provided by Gaia DR2 we derived new estimates for the stellar mass \((0.76 \pm 0.02 \, M_\odot)\) and age \((5.4 \pm 1.0 \, \text{Myr})\). Taking into account the data sets presented in Keppler et al. (2018) we achieve an orbital coverage of 6 yr. Our MCMC Bayesian analysis favors a circular ~22 au wide and a disk coplanar orbit, which translates to an orbital period of 118 yr. The new imaging data show rich details in the structure of the circumstellar disk. Several arcs and potential spirals can be identified (see Fig. B.1). Determining the way these features are connected to the presence of the planet is beyond the scope of this study. With the new IFS spectroscopic data and photometric measurements from previous IRDIS, NaCo, and NICI observations we were able to construct aSED of the planet covering a wavelength range of 0.96–3.8 \(\mu\)m. We computed three sets of cloudy model grids with the petitCODE and two models with Exo-REM with different treatment of clouds. These model grids and the BT-Settl grid were fitted to the planet’s SED. The atmospheric analysis clearly demonstrates that cloud-free models do not provide a good fit to the data.
of cloudy models that can describe the spectrophotometric data reasonably well, and result in a temperature range of 1000–1600 K and log g no larger than 3.5 dex. The radius varies significantly between 1.4 and 3.7 $R_\oplus$ based on the model assumptions and is in some cases higher than what we expect from evolutionary models. The planet’s mass derived from the best-fit values ranges from 2 to 17 $M_\oplus$, which is similar to the masses derived from evolutionary models by Kepler et al. (2018). This paper provides the first step toward a comprehensive characterization of the orbit and atmospheric parameters of an embedded young planet. Observations with JWST and ALMA will provide additional constraints on the nature of this object, especially in the presence of a circumplanetary disk.

Acknowledgements. SPHERE is an instrument designed and built by a consortium consisting of IPAG (Grenoble, France), MPIA (Heidelberg, Germany), LAM (Marseille, France), LESIA (Paris, France), Laboratoire Lagrange (Nice, France), INAF-Osservatorio di Padova (Italy) and ESO (Switzerland), ETH Zurich (Switzerland), NOVA (Netherlands), ONERA (France) and ASTRON (Netherlands) in collaboration with ESO. SPHERE was funded by ESO, with additional contributions from CNRS (France), MPIA, INAF (Italy), FINES (Switzerland) and NOVA (Netherlands). SPHERE also received funding from the European Commission Sixth and Seventh Framework Programmes as part of the Optical Infrared Coordination Network for Astronomy (OPTICON) under grant number RI3-Ct-2004-010566 for FP6 (2004–2008), grant number 226604 for FP7 (2009–2012) and grant number 312430 for FP7 (2013–2016). We also acknowledge financial support from the Programme National de Planetologie (PNP) and the Programme National de Physique Stellaire (PNPS) of CNRS-INSU in France. This work has also been supported by a grant from the French Labex OSUG@2020 (Investissements d’avenir-ANR10 LABX56). The project is supported by CNRS, by the Agence Nationale de la Recherche (ANR-14-CE33-0018). It has also been carried out within the frame of the National Centre for Competence in Research PlanetS supported by the Swiss National Science Foundation (SNSF). M.R.M., H.M.S., and S.D. are pleased to acknowledge the financial support of the SNSF. Finally, this work has made use of the the SPHERE Data Centre, jointly operated by OSUG/IPAG (Grenoble), PYTHEAS/LAM/CESAM (Marseille), OCA/Lagrange (Nice), and Observatoire de Paris/LESIA (Paris). We thank P. Delorme and E. Lagadec (SPHERE Data Centre) for their efficient help during the data reduction process. This work has made use of the SPHERE Data CENTRE, jointly operated by OSUG/IPAG (Grenoble), PYTHEAS/LAM/CESAM (Marseille), OCA/Lagrange (Nice) and Observatoire de Paris/LESIA (Paris) and supported by a grant from Labex OSUG@2020 (Investissements d’avenir-ANR10 LABX56). A.M. acknowledges the support of the DFG priority program SPP 1992 “Exploring the Diversity of Extragalactic Planets” (MU 4172/1-1). F.Me. and M.B. acknowledge funding from ANR of France under contract number ANR-16-CE31-0013. D.M. acknowledges support from the ESO-Government of Chile Joint Committee program “Direct imaging and characterization of exoplanets.” J.L.B. acknowledges the support of the UK Science and Technology Facilities Council. A.Z. acknowledges support from the CONICYT+PAI/Convocatoria nacional subvención la instalación en la academia, convocatoria 2017+Folio PAI77170087. We thank the anonymous referee for the constructive report on the manuscript. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC). https://www.cosmos.esa.int/web/gaia/dpac/consortium. Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multi–lateral Agreement. This research has made use of NASA’s Astrophysics Data System Bibliographic Services of the SIMBAD database, operated at CDS, Strasbourg. Based on observations obtained at the Gemini Observatory (acquired through the Gemini Observatory Archive), which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), Ministère de la Recherche de Technologie et Innovation Productiva (Argentina), and Ministério da Ciência, Tecnologia e Inovação (Brazil).
Appendix A: Determination of host star properties

We used a Markov chain Monte Carlo approach to find the posterior distribution for the PDS 70 host star parameters, adopting the `emcee` code (Foreman-Mackey et al. 2013). The unknown parameters are the stellar mass, age, extinction, and parallax\(^1\), and we assumed solar metallicity. The photometric measurements used for the fit, and the independently determined effective temperature \(T_{\text{eff}}\) and radius are listed in Table A.1. We perform a simultaneous fit of all these observables. The uncertainties are treated as Gaussians and we assume no covariance between them.

We used a Gaussian prior from `Gaia` for the distance and a Gaussian prior with mean 0.01 mag and sigma 0.07 mag, truncated at \(A_V = 0\) mag, for the extinction (Pecaut & Mamajek 2016). Given \(A_V\), we computed the extinction in all the adopted bands by assuming a Cardelli et al. (1989) extinction law. We used a Chabrier (2003) initial mass function (IMF) prior on the mass and a uniform prior on the age. The stellar models adopted to compute the expected observables, given the fit parameters, are from the MIST project (Paxton et al. 2011, 2013, 2015; Dotter 2016; Choi et al. 2016). These models were extensively tested against young cluster data, and against pre-main sequence stars in multiple systems, with measured dynamical masses, and compared to other stellar evolutionary models (see Choi et al. 2016 for details). The result of the fit constrains the age of PDS 70 to 5.4 ± 1.0 Myr and its mass to 0.76 ± 0.02 \(M_\odot\). The best-fit parameter values are given by the 50\% quantile (the median) and their uncertainties are based on the 16\% and 84\% quantile of the marginalized posterior probability distribution. The stellar parameters are identical to the values used by Kepler et al. (2018). We note that the derived stellar age of PDS 70 is significantly younger than the median age derived for UCL with 16 ± 2 Myr and an age spread of 7 Myr by Pecaut & Mamajek (2016). For the computation of the median age Pecaut & Mamajek (2016) excluded K- and M-type stars for the reason of stellar activity which might bias the derived age. When the entire sample of stars is considered a median age of 9 ± 1 Myr is derived. The authors provide an age of 8 Myr for PDS 70 based on evolutionary models. Furthermore, the kinematic parallax for PDS 70 therein is larger by ∼15\% compared to the new `Gaia` parallax. Thus, the luminosity on which the age determination is based is underestimated and, subsequently, the age is overestimated.

Appendix B: Disk seen with IRDIS

Figure B.1 shows the IRDIS combined \(K_s, K_{\text{ff}}\) image using classical ADI. The image shows the outer disk ring, with a radius of approximately 54 au, with the western (near) side being brighter than the eastern (far) side, as in Hashimoto et al. (2012) and Kepler et al. (2018). The image reveals a highly structured disk with several features: 1) a double ring structure along the west side, which is clearly pronounced along the northwest arc, and which is less clear but still visible along the southwest side; 2) a possible connection from the outer disk to the central region; 3, 4) a possible spiral-shaped feature close to the coronagraph; and 5) two arc-like features in the gap on the southeast side of the central region. Whereas features 1 and 2 have already been tentatively seen in previous observations (see Figs. 5 and 9 in Kepler et al. 2018), our new and unprecedentedly deep data set allows us to identify extended structures well within the gap (features 3–5). Future observations at high resolution, i.e., with interferometry, will be needed to prove the existence and to investigate the nature of these features, which, if real, would provide an excellent laboratory for probing theoretical predictions of planet-disk interactions.

\(^1\) The parallax of PDS 70 is treated as an unknown parameter in our fit to the host star’s properties, together with mass, age and \(A_V\). However, we imposed a parallax prior, using `Gaia` DR2, which strongly constrains the allowed distance values. As a result, the best-fit distance value reported here from the MCMC posterior draws is identical to the value provided by the `Gaia` collaboration.

### Table A.1. Stellar parameters of PDS 70.

| Parameter | Unit | Value | References |
|-----------|------|-------|------------|
| Distance  | pc   | 113.43 ± 0.52 | 1 |
| \(T_{\text{eff}}\) | K    | 3972 ± 36 | 2 |
| Radius    | \(R_\odot\) | 1.26 ± 0.15 | Computed from 2 |
| \(B\)     | mag  | 13.494 ± 0.146 | 3 |
| \(V\)     | mag  | 12.233 ± 0.123 | 3 |
| \(g'\)    | mag  | 12.881 ± 0.136 | 3 |
| \(r'\)    | mag  | 11.696 ± 0.106 | 3 |
| \(i'\)    | mag  | 11.129 ± 0.079 | 3 |
| \(J\)     | mag  | 9.553 ± 0.024 | 4 |
| \(H\)     | mag  | 8.823 ± 0.040 | 4 |
| \(K_s\)   | mag  | 8.542 ± 0.023 | 4 |
| Age       | Myr  | 5.4 ± 1.0 | This work |
| Mass      | \(M_\odot\) | 0.76 ± 0.02 | This work |
| \(A_V\)   | mag  | 0.05±0.05 | This work |

### References

(1) Gaia Collaboration (2016, 2018); (2) Pecaut & Mamajek (2016); (3) Henden et al. (2015); (4) Cutri et al. (2003).

![Fig. B.1. IRDIS combined K, K_s image of PDS 70 using classical ADI. To increase the dynamic range of the faint disk structures, the companion’s full intensity range is not shown. The black lines indicate the structures discussed in the above text. North is up, east is to the left.](image-url)
Appendix C: Astrometric and photometric detailed results

Table C.1. Relative astrometry and photometry of PDS 70 b as derived from the sPCA reduction.

| Date       | Instr. | Filter | \(\Delta \alpha\) (mas) | \(\Delta \delta\) (mas) | Sep. (mas) | PA (deg) | \(\Delta m\) | mag | \(m_{\text{app}}\) | Peak \(S/N\) |
|------------|--------|--------|--------------------------|--------------------------|------------|----------|-------------|-----|----------------|-------------|
| 2012-03-31 | NICI   | \(L'\) | 58.7 ± 10.7              | −182.7 ± 22.2            | 191.9 ± 21.4 | 162.2 ± 3.7 | 6.59 ± 0.42 | 14.50 ± 0.42 | 5.6 |
| 2015-05-03 | IRDIS  | \(H2\) | 83.1 ± 3.9               | −173.5 ± 4.3             | 192.3 ± 4.2 | 154.5 ± 1.2 | 9.35 ± 0.18 | 18.17 ± 0.18 | 6.3 |
| 2015-05-03 | IRDIS  | \(H3\) | 83.9 ± 3.6               | −178.5 ± 4.0             | 197.2 ± 4.0 | 154.9 ± 1.1 | 9.24 ± 0.17 | 18.06 ± 0.17 | 8.1 |
| 2015-05-31 | IRDIS  | \(H2\) | 89.4 ± 6.0               | −178.3 ± 7.1             | 199.5 ± 6.9 | 153.4 ± 1.8 | 9.12 ± 0.24 | 17.94 ± 0.24 | 11.4 |
| 2015-05-31 | IRDIS  | \(H3\) | 86.9 ± 6.2               | −174.0 ± 6.4             | 194.5 ± 6.3 | 153.5 ± 1.8 | 9.13 ± 0.16 | 17.95 ± 0.17 | 6.8 |
| 2016-05-14 | IRDIS  | \(K1\) | 90.2 ± 7.3               | −170.8 ± 8.6             | 193.2 ± 8.3 | 152.2 ± 2.3 | 7.81 ± 0.31 | 16.35 ± 0.31 | 5.5 |
| 2016-05-14 | IRDIS  | \(K2\) | 95.2 ± 4.8               | −175.0 ± 7.7             | 199.2 ± 7.1 | 151.5 ± 1.6 | 7.67 ± 0.24 | 16.21 ± 0.24 | 3.6 |
| 2016-06-01 | NaCo   | \(L'\) | 94.5 ± 22.0              | −164.4 ± 27.6            | 189.6 ± 26.3 | 150.6 ± 7.1 | 6.84 ± 0.62 | 14.75 ± 0.62 | 2.7 |
| 2018-02-24 | IRDIS  | \(K1\) | 109.6 ± 7.9              | −157.7 ± 7.9             | 192.1 ± 7.9 | 147.0 ± 2.4 | 8.10 ± 0.05 | 16.65 ± 0.06 | 16.3 |
| 2018-02-24 | IRDIS  | \(K2\) | 110.0 ± 7.9              | −157.6 ± 8.0             | 192.2 ± 8.0 | 146.8 ± 2.4 | 7.90 ± 0.05 | 16.44 ± 0.05 | 13.7 |

Notes. For completeness we list the values from the first five epochs from Kepler et al. (2018). The astrometric values are corrected for true north, and account for the instrument anamorphism (Maire et al. 2016). The true north correction for the IRDIS data recorded on February 24, 2018, is \(−1.76° ± 0.06°\). For true north values from earlier epochs, see Table 4 in Kepler et al. (2018).

Appendix D: Markov chain Monte Carlo results

Table D.1. MCMC solutions for the orbital parameters of PDS 70 b.

| Parameter | Unit | Unrestrained solutions | Solutions for restrained \(i\) and \(\Omega\) |
|-----------|------|------------------------|---------------------------------------------|
|           |      | Peak       | Median      | Lower     | Upper      | Peak       | Median      | Lower     | Upper      |
| \(a\)     | au   | 22.2       | 25.1        | 12.5      | 28.4       | 21.2       | 23.8        | 13.3      | 27.0       |
| \(e\)     |      | 0.03       | 0.17        | 0.0       | 0.25       | 0.03       | 0.18        | 0.0       | 0.27       |
| \(i\)     | °    | 151.1      | 150.1       | 137.5     | 165.2      | 131.1      | 131.0       | 128.3     | 133.6      |
| \(\Omega\) | °    | −128.1     | 0.0         | −180.0    | 51.0       | 159.6      | 158.4       | 156.2     | 163.9      |
| \(\omega\) | °    | −130.9     | 0.0         | −180.0    | 59.9       | −12.7      | 2.5         | −144.7    | 52.3       |
| \(t_p\)   | yr   | 2041.9     | 2020.1      | 2001.4    | 2069.0     | 2009.1     | 2013.4      | 1973.1    | 2029.1     |

Notes. The left part of the table lists the values obtained without any prior information taken into account. The right part of the table lists the solution for the restrained case. The lower and upper values correspond to the 68% confidence interval.
Fig. D.1. Results of the MCMC fit of the SPHERE, NaCo, and NICI combined astrometric data of PDS 70 b reported in terms of statistical distribution matrix of the orbital elements $a$, $e$, $i$, $\Omega$, $\omega$, and $t_p$. The red line in the histograms and the black star in the correlation plots indicate the position of the best LSLM $\chi^2$ model obtained for comparison.
Fig. D.2. Results of the MCMC fit of the SPHERE, NaCo, and NICI combined astrometric data of PDS 70 b reported in terms of statistical distribution matrix of the orbital elements $a$, $e$, $i$, $\Omega$, $\omega$, and $t_p$. We restrained the PDS70 b solution set given by the MCMC to solutions with orbital plane making a tilt angle of less than $5^\circ$ with respect to the disk midplane described by Keppler et al. (2018), i.e., $i = 180^\circ - 49.8^\circ$ and PA = 158.6$^\circ$.

Fig. D.3. Posterior distribution (from Fig. D.1) of the tilt angle. The distribution peaks around 50$^\circ$, which remains consistent with a likely coplanar planet-disk configuration. The red line indicates the position of the best LSLM $\chi^2$ model obtained for comparison.
Relative astrometry of PDS 70b solutions drawn from the MCMC distribution for the coplanar planet-disk configuration. One of the most likely solutions from our MCMC analysis is shown as an illustration (in red).