



Interferometric Detection and Orbit Modeling of the Subcomponent in the Hot-dust System κ Tuc A: A Low-mass Star on an Eccentric Orbit in a Hierarchical-quintuple System

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Abstract

The system κ Tuc A is part of a hierarchical-quintuple system and is a prime target for studies of hot-exozodiacal dust, because a time-variable near-infrared excess has been detected. We observed the system with the Multi Aperture mid-Infrared Spectroscopic Experiment (MATISSE) and GRAVITY at the Very Large Telescope Interferometer, and detected the stellar companion to the primary κ Tuc Aa that was previously inferred by astrometry, κ Tuc Ab. Its L -band flux ratio to the primary is 1.32% and its signature in the MATISSE closure phases is mostly smaller than $\pm 2^\circ$, which makes κ Tuc Ab the highest-contrast companion ever detected with MATISSE closure phases. We verified with GRAVITY that relative astrometry with milliarcsecond precision can be retrieved from MATISSE closure phases. Using multiple epochs of observations, we obtain a full orbital solution for κ Tuc Ab. Its orbit has an eccentricity of 0.94 and a semimajor axis of 4.8 au. The orbit of κ Tuc Ab and the orbit of the wider separation companion κ Tuc B are mutually inclined. Based on the measured flux ratio of κ Tuc Ab to Aa and their dynamical mass, we estimate the spectral type of κ Tuc Ab to be M3.5 V to M4.5 V. While the then unknown star κ Tuc Ab might have caused the putative detection of hot-exozodiacal dust around κ Tuc Aa in 2012 and 2014, this cannot be for the detection in 2019, giving rise to an intriguing system architecture. This motivates studies investigating the interplay of the low-mass star on an eccentric orbit, the hot-exozodiacal dust, and a possible planetesimal reservoir.

Unified Astronomy Thesaurus concepts: Multiple stars (1081); M dwarf stars (982); Elliptical orbits (457); Exozodiacal dust (500); Long baseline interferometry (932)

1. Introduction

Stellar surveys using near-infrared interferometry have repeatedly found signatures in interferometric observables (O. Absil et al. 2013; S. Ertel et al. 2014, 2016; P. D. Nuñez et al. 2017; O. Absil et al. 2021) that are, since their first detection by O. Absil et al. (2006), commonly attributed to the presence of hot-exozodiacal dust (a *hot exozodi*) in the close vicinity of the star (see for reviews Q. Kral et al. 2017 and S. Ertel et al. 2025). Since stellar companions to the host star can cause a similar signature, they can be a source of confusion (e.g., K. Tsishchankava et al. 2025). Thus, stars with known companions are usually excluded from surveys searching for hot exozodis a priori (e.g., O. Absil et al. 2013; S. Ertel et al. 2014), and the obtained data are checked for signs of new companions (e.g., L. Marion et al. 2014).

However, stars might host unknown companions, as those can avoid interferometric detection for several reasons. The strength of the companion signature in interferometric measurements generally depends on the telescope positions projected onto the sky (e.g., L. Marion et al. 2014, K. Tsishchankava et al. 2025) and gets attenuated by spatial filtering (e.g., J. J. Wang et al. 2021) and possibly spectral-bandwidth smearing (e.g., M. Zhao et al. 2007; R. Lachaume & J. P. Berger 2013). Furthermore, a detection requires a sufficient sampling of the spatial Fourier frequencies for companions with large projected distances (O. Absil et al. 2010), and sufficient angular resolution in the case of small projected distances.

The system of κ Tuc A is uniquely important for the study of hot exozodis because it has long been thought to host dust whose brightness varies on a yearly timescale (S. Ertel et al. 2014, 2016). Constraints on temporal variability can aid in determining the origin of hot exozodis (e.g., T. D. Pearce et al. 2022) and hence κ Tuc A is continuously monitored. The primary component, κ Tuc Aa, is of spectral type F6 with an effective temperature of ~ 6500 K (K. Fuhrmann et al. 2017).



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and is located at a distance of ~ 21 pc (see Section 4.1). Its suggested age is ~ 2 Gyr, and it has slightly evolved off the main sequence (A. Tokovinin 2020). Together with κ Tuc B at a projected separation of ~ 5 as, κ Tuc A forms the system of κ Tuc¹³ (HD 7788, HIP 5896) that is gravitationally bound to the binary system HD 7693 (HIP 5842) at 318 as separation (for a detailed description see A. Tokovinin 2020).

Based on data obtained in the H -band with the Precision Integrated-Optics Near-infrared Imaging Experiment (PIO-NIER; J. B. Le Bouquin et al. 2011) at the Very Large Telescope Interferometer (VLTI; X. Haubois et al. 2020), S. Ertel et al. (2014) announced a hot exozodi around κ Tuc Aa based on observations from 2012 July, after L. Marion et al. (2014) did not find a companion within a distance of 100 mas using the same data. Subsequently, S. Ertel et al. (2016) detected no near-infrared excess that could be interpreted as a hot exozodi based on observations of 2013 August, but detected an excess again based on observations from 2014 November. Lastly, based on observations with the Multi Aperture mid-Infrared Spectroscopic Experiment (MATISSE; B. Lopez et al. 2022) at the VLTI in 2019 July, a hot exozodi was detected in the L band, and no obvious companion signal was reported (F. Kirchschlager et al. 2020).

However, A. Tokovinin (2020) announced a previously unknown astrometric companion to κ Tuc Aa, κ Tuc Ab, based on residuals in the orbital solution of κ Tuc B, and differences between Hipparcos (F. van Leeuwen 2007) and Gaia (Gaia Collaboration et al. 2016) proper motions (T. D. Brandt 2018, 2019); hence κ Tuc is a triple system, that forms together with the binary HD 7693 a quintuple system. The astrometric companion κ Tuc Ab was suspected to be of low mass and, assuming a circular orbit, to have a period of ~ 20 yr. Despite this analysis using astrometry from Gaia, κ Tuc A is not listed in the Gaia non-single star catalog (Gaia Collaboration et al. 2023a; B. Holl et al. 2023).

In this article, we present interferometric detections of the astrometric companion to κ Tuc Aa, κ Tuc Ab, using MATISSE and GRAVITY (GRAVITY Collaboration et al. 2017) at the VLTI; we show that the companion is a low-mass star on a highly eccentric orbit. In Section 2, we describe our observations, the data reduction and selection, and discuss sources of uncertainty for astrometric analysis. After we present the detection and verify with GRAVITY that MATISSE delivers accurate relative astrometry of the companion (Section 3), we determine the companion's position over time in our multi-epoch data and tightly constrain its orbit and spectral type (Section 4). We discuss the performance in measuring relative astrometry of companions with MATISSE, the now confirmed triple system of κ Tuc, the impact of the new companion on previous detections of a hot exozodi around κ Tuc Aa, and provide an outlook into further studies of this peculiar system (Section 5). A summary concludes this study (Section 6), which is solely dedicated to the analysis of the companion; we refer the investigation of the hot exozodi to a forthcoming paper. In this article, we use the term κ Tuc A to refer to the binary system of the components κ Tuc Aa and Ab, and use the terms κ Tuc Aa and κ Tuc Ab to refer to the individual components if necessary.

2. Observations

The light collected with the VLTI Auxiliary Telescopes (ATs, B. Koehler & C. Flebus 2000) and their New Adaptive Optics Module for Interferometry (NAOMI; J. Woillez et al. 2019) was injected into the interferometric instruments MATISSE and GRAVITY. Both instruments combine the light of four telescopes to perform spectrally dispersed measurements of interferometric fringes for six pairs of telescopes. All observations with their different set-ups are summarized in Table 1, including observations that failed or are not of sufficient quality for our analysis; they were performed under ESO programs 0103.C-0725, 109.23HL, 110.24AJ, 111.24S6, 114.27F3, 114.28HE, and 114.28HE.

2.1. MATISSE

MATISSE operates in the mid-infrared bands L , M , and N . As the system of κ Tuc A is too faint to obtain reliable M - and N -band measurements with the ATs, we focus completely on the L band. New MATISSE observations were executed between 2022 August and 2024 November. They are complemented by two observations obtained in 2019 July by F. Kirchschlager et al. (2020). While observations from 2019 were performed in stand-alone mode (i.e., fringe coherencing in the L band), the new observations were performed in GRA4MAT mode (J. Woillez et al. 2024) employing the GRAVITY fringe tracker operating in the K band (S. Lacour et al. 2019). Each observation of κ Tuc A was accompanied by one or two observations of calibrator stars. Those were optimized for the L -band calibration and selected from the MDFO catalog (P. Cruzalèbes et al. 2019) with diameters from the JSDC catalog (A. Chelli et al. 2016). Each of our MATISSE observations begins with four 1 minute exposures performed without chopping (hereafter *non-chopped*), each with a different configuration of the two beam commuting devices (BCDs).¹⁴ Subsequently, eight 1 minute exposures are conducted with chopping (hereafter *chopped*), which allows for an improved correction of the thermal background. Four of these are performed with the BCD configurations IN-IN and OUT-OUT, respectively. Exceptions to this are the observations of 2019, for which no chopping was performed. Moreover, in 2022, using GRA4MAT in combination with chopping delivered unreliable data. While the operation and stability of the GR4MAT mode were improved by early 2023 (M. Nowak et al. 2024; J. Woillez et al. 2024), a low atmospheric coherence time can still lead to unreliable chopped data. This was the case for the execution on 2023 June 21. The observations of 2022 were performed in MED-LM spectral resolution (resolving power $R = \lambda/\delta\lambda = 499$, with wavelength λ and spectral resolution element $\delta\lambda$) while others were performed with LOW-LM spectral resolution ($R = 31.5$, B. Lopez et al. 2022, Table 2) to maximize the signal-to-noise ratio for a search for hot exozodis.

2.2. GRAVITY

The last observation with MATISSE on 2024 November 23 was accompanied by observations during the same night with GRAVITY, which operates in the near-infrared K band. These

¹³ From the SIMBAD Astronomical Database (M. Wenger et al. 2000).

¹⁴ The two BCDs switch the light paths of the four telescopes pairwise and can be positioned either IN the light path or OUT of it, respectively. Thus, there are four configurations of the BCDs: IN-IN, IN-OUT, OUT-IN, and OUT-OUT.

Table 1
VLTI/MATISSE and GRAVITY Observations of κ Tuc A

Date	Science OB Execution Time	AT Configuration	Instrument	GRA4MAT	Spectral Resolution	Chopping	Calibrator(s)
2019 Jul 9	08:21:18–08:33:51	Medium	MATISSE	No	LOW-LM	No	HD 3750, HD 8094
2019 Jul 11	08:51:42–09:06:17	Medium	MATISSE	No	LOW-LM	No	HD 4138, HD 8315
2022 Aug 27	08:05:35–08:34:27	Medium	MATISSE	Yes	MED-LM	Yes ^a	HD 2354, HD 1025
2022 Oct 28	01:18:04–01:56:56	Medium	MATISSE	Yes	MED-LM	Yes ^a	(HD 2354), HD 1025
2022 Oct 29	03:14:03–03:41:03	Medium	MATISSE	Yes	MED-LM	Yes ^a	HD 2354, HD 1025
2023 Jun 17	10:06:33–10:34:34	Medium	MATISSE	Yes	LOW-LM	Yes	HD 8810
2023 Jun 21	07:43:15–08:11:59	Medium-Large	MATISSE	Yes	LOW-LM	Yes ^a	HD 8810
2023 Jul 13	07:32:38–07:58:49	Medium	MATISSE	Yes	LOW-LM	Yes	HD 8810
2023 Aug 13	04:50:39–05:18:11	Medium	MATISSE	Yes	LOW-LM	Yes	HD 8810
2024 Oct 25	06:00:19–06:24:58	Large	MATISSE	Yes	LOW-LM	Yes	HD 5457, HD 8810
2024 Oct 26	02:42:33–03:09:24	Large	MATISSE	Yes	LOW-LM	Yes	HD 5457, HD 8810
2024 Oct 26	06:34:47–07:01:24	Large	MATISSE	Yes	LOW-LM	Yes	HD 5457
2024 Oct 29	05:41:08–06:13:33	Small	MATISSE	Yes	LOW-LM	Yes	HD 5457, HD 8810
2024 Oct 29	06:39:23–07:04:20	Small	MATISSE	Yes	LOW-LM	Yes	HD 8810 ^b
2024 Oct 29/30	23:54:39–00:20:17	Small	MATISSE	Yes	LOW-LM	Yes	HD 5457, HD 8810
2024 Nov 6	03:54:09–04:22:19	Medium	MATISSE	Yes	LOW-LM	Yes	HD 5457, HD 8810
2024 Nov 6	04:51:43–05:17:04	Medium	MATISSE	Yes	LOW-LM	Yes	HD 8810 ^b
2024 Nov 7	00:15:41–00:40:39	Medium	MATISSE	Yes	LOW-LM	Yes	HD 5457, HD 8810
2024 Nov 23	02:56:37–03:27:37	Large	MATISSE	Yes	LOW-LM	Yes	HD 5457
2024 Nov 23	01:15:23–01:43:51	Large	GRAVITY	...	HIGH	...	HD 2354
Discarded observations							
2022 Oct 29	00:02:51–00:30:24	Medium	MATISSE	Yes	MED-LM	Yes	...
2023 Jun 17	09:10:34–09:38:22	Medium	MATISSE	Yes	LOW-LM	Yes	...
2023 Jul 13	08:27:10–08:54:03	Medium	MATISSE	Yes	LOW-LM	Yes	...
2023 Jul 13	09:22:24–09:53:26	Medium	MATISSE	Yes	LOW-LM	Yes	...

Notes. The listed execution times give the time interval in Universal Time (UT) used to execute the whole observing block (OB) of the science target. When two calibrators are listed, both are used together to determine the instrumental transfer function. Calibrators in parentheses are discarded. The VLTI telescope positions for the listed AT-configurations are A0-B2-C1-D0 (small), D0-G2-J3-K0 (medium), A0-G2-J2-J3 (medium-large, an intermediate, nonstandard configuration), and A0-G1-J2-K0 (large).

^a Chopped data is not reliable.

^b Calibrator observation from the leading observation used.

observations were performed in single-field on-axis mode: the system was bright enough such that the light was split between the fringe tracker and the spectrograph. For the spectrograph, we selected HIGH spectral resolution ($R \sim 4000$) to maximize the coherence length and avoid bandwidth smearing (see Appendix A). The observation of κ Tuc A was succeeded by the observation of the calibrator star HD 2354, which we selected with the SearchCal tool from the Jean-Marie Mariotti Center (JMMC) that includes the JMDC (A. Chelli et al. 2016; G. Duvert 2016) and JSDC (A. Chelli et al. 2016) catalogs. Each science and calibrator observation consisted of 24 frames of 30 s on target (total of 12 minutes), and 12 frames of 30 s on-sky (total of 6 minutes).

2.3. Data Reduction and Selection

We reduce raw MATISSE data (including archival data from 2019) using the MATISSE data reduction software (see F. Millour et al. 2016) in version 2.0.2. To run the reduction and calibrate the reduced data, we use the Python package `mat_tools`.¹⁵ Following standard data reduction, the calibrated non-chopped exposures would be merged into a single 4 minute exposure, the chopped exposures into an 8 minute exposure, both averaging observations with different

BCD positions. However, this causes significant smearing of the companion signal due to sky rotation. To avoid this, we use the four individual 1 minute non-chopped exposures. We prefer them over the chopped exposures because their signal-to-noise ratio is higher, as chopping reduces the time on target, and we will focus the analysis on the closure phases (see Section 3) that do not profit from chopping and thermal-background subtraction, as they are derived from the position of the fringes on the detector. The default merging of a full BCD sequence of non-chopped exposures corrects the closure phases for instrumental systematic effects to a precision of $\lesssim 1^\circ$. As we keep the exposures separate, we have to rely on the comparison with calibrator observations to correct for systematic effects. On 2024 November 23 the BCD sequence was executed twice, thus resulting in eight individual exposures. On 2019 July 9 the OUT–OUT exposure failed, while on 2019 July 11 the IN–IN exposure failed, thus resulting in only three exposures for each of the dates.

For the LOW-LM spectral resolution of MATISSE, our analysis encompasses wavelengths between $3.1 \mu\text{m}$ and $3.9 \mu\text{m}$, which provides comprehensive coverage of the L band while avoiding the band edges with a low signal-to-noise ratio. For the observations from 2019, the lower boundary is $3.28 \mu\text{m}$ due to a specific instrument setup. For the MED-LM spectral resolution, we analyze wavelengths between $3.35 \mu\text{m}$ and $3.9 \mu\text{m}$; the region for wavelengths $< 3.35 \mu\text{m}$ is

¹⁵ <https://github.com/Matisse-Consortium/tools>

contaminated by several telluric lines and is particularly noisy for the observation of 2022 August 27. We refrain from smoothing the MED-LM data down to LOW-LM resolution using a sliding average as offered by the data reduction software because this process attenuates the companion signal.

GRAVITY observations were reduced using the GRAVITY data reduction software (V. Lapeyriere et al. 2014) in version 1.6.6 with standard parameters. As with MATISSE data, significant smearing of the companion signal occurs if all frames are combined into one exposure. Therefore, we group four frames into exposures of 2 minute length and yield six individual data sets. We test grouping six frames into exposures of 3 minutes, which does not significantly change the retrieved astrometry of the companion (Section 3.2) compared to the 2 minute exposures. This also confirms that 1 minute for MATISSE exposures is short enough to avoid significant smearing by sky rotation. We analyze wavelengths between $2.05 \mu\text{m}$ and $2.35 \mu\text{m}$, avoiding band edges with a low signal-to-noise ratio. All calibrated Oifits files (G. Duvert et al. 2017) from both MATISSE and GRAVITY observations that are used for analysis are available at the Optical Interferometry Database (OIDB).¹⁶

2.4. Uncertainty of Spatial Frequencies

The spatial frequency at which the source brightness distribution is probed is defined as B/λ , which is the ratio of the absolute separation vector of two telescopes projected onto the sky (the baseline B) and the observing wavelength λ . Therefore, the finite precision on the baselines and wavelengths leads to uncertainties of the spatial frequencies that limit the precision of the astrometric analysis. However, it is neither considered by the MATISSE nor the GRAVITY data reduction software.

The relative uncertainty of the wavelength calibration for GRAVITY in HIGH spectral resolution is $\Delta\lambda/\lambda = 2 \times 10^{-4}$ (A. Gallenne et al. 2023), based on daily calibration using the internal laser metrology (S. Gillissen et al. 2012). For MATISSE in MED-LM and HIGH-LM resolution, the wavelength calibration is precise to the extent of one detector pixel (MATISSE Consortium 2025, private communication).¹⁷ One resolution element of the MATISSE LM-band arm is sampled by approximately five pixels. Thus, assuming a wavelength of $3.5 \mu\text{m}$ centered in the L band, in case of the MED-LM resolution, 1 pixel covers a wavelength interval of $\approx 0.0014 \mu\text{m}$, which results in $\Delta\lambda/\lambda \approx 4 \times 10^{-4}$.

To verify this behavior for the LOW-LM resolution, we analyze 38 wavelength calibrations between 2019 July 26 and 2024 September 10 and find that the standard deviation of the wavelength associated with a single pixel is $\approx 0.019 \mu\text{m}$. This is slightly smaller than the wavelength coverage of one pixel in the central L band of $\approx 0.022 \mu\text{m}$. Therefore, we confirm that the wavelength calibration is precise to the extent of one detector pixel also in LOW-LM resolution and adopt this for further analysis. This results in a relative wavelength uncertainty for LOW-LM of $\Delta\lambda/\lambda \approx 6.3 \times 10^{-3}$. To estimate the baseline precision, we consider the *imaging baselines* (J. Woillez & S. Lacour 2013). The estimated relative precision of the VLTI imaging baselines is 5×10^{-5} (ESO 2025, private communication), which is already smaller than the wavelength uncertainty of GRAVITY. Additionally, this

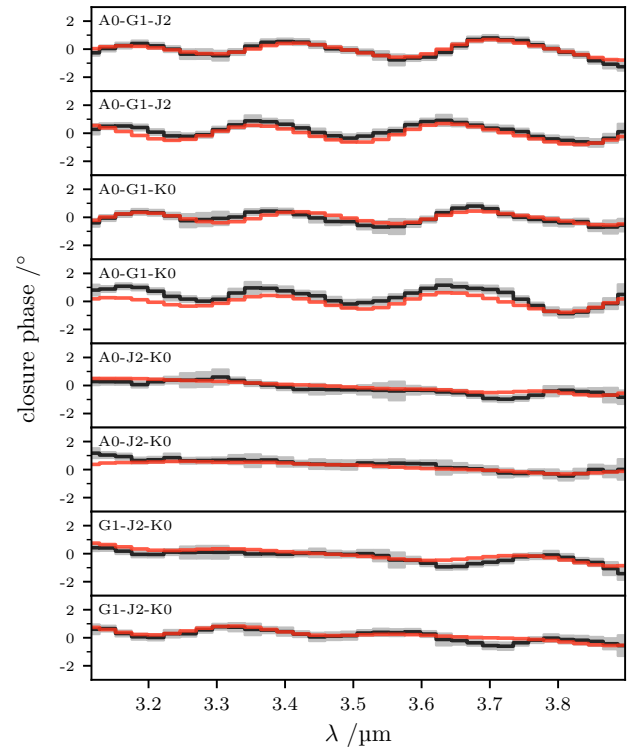


Figure 1. MATISSE closure phases obtained on 2024 November 23 in BCD position OUT–OUT (black) with uncertainties in gray. The BCD cycle was executed twice, delivering two measurements for each telescope triplet, which is denoted in each panel by the combination of AT positions (e.g., A0-G1-J2 for the positions A0, G1, and J2). The two BCD cycles were recorded with a pause of 8 minutes in between, during which the chopping sequence was performed. Due to sky rotation during this period, the measurements deviate slightly from each other. A binary model was fitted to the data of all four BCD positions (of which three are not shown for clarity of illustration) with the best-fit model shown in red.

uncertainty applies to each baseline individually. That is, some baseline lengths are underestimated, while others are overestimated, which further mitigates the impact in a joint analysis of data from all telescope pairs. Therefore, we neglect the baseline uncertainty, and thus the relative uncertainty of the spatial frequencies is given by the relative wavelength uncertainty $\Delta\lambda/\lambda$.

3. Detection of a High-contrast Companion

The closure phases from both MATISSE and GRAVITY show an oscillating signal (see Figures 1, 2), indicating that the source brightness distribution is not point-symmetric. A stellar companion to the primary star would cause such an oscillating signal, with the amplitude being related to the binary flux ratio (e.g., J. B. Le Bouquin & O. Absil 2012; K. Tsishchankava et al. 2025). Given that an astrometric companion to κ Tuc Aa has already been inferred (A. Tokovinin 2020), we assume a stellar companion, κ Tuc Ab, to be the source of the asymmetry. This assumption is validated in retrospect by the analysis of the whole observational sample (Section 4).

A companion would also cause an oscillating signal in the (squared) visibilities, which is present in our data. However, visibilities are affected by a uniform circumstellar dust distribution that causes a visibility deficit compared to the signal from the stellar photosphere alone (e.g., O. Absil et al. 2006; E. di Folco et al. 2007). Such a dust distribution is point-symmetric and thus has no effect on the closure phases. As the

¹⁶ <http://oidb.jmmc.fr>

¹⁷ This information is contained in the commissioning document VLT-TRE-MAT-15860-9141 v1.0.

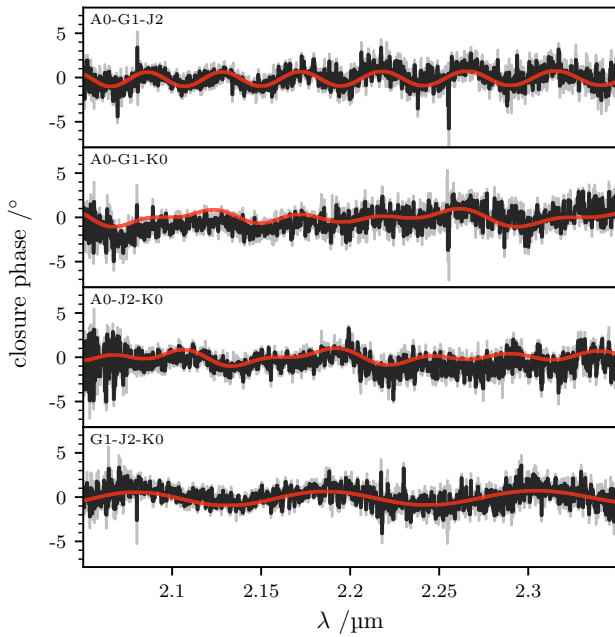


Figure 2. GRAVITY closure phases from the observation of 2024 November 23 for the first of six 2 minute exposures (black) with uncertainties in gray. Each panel belongs to one telescope triplet. A binary model was fitted to the data of all six exposures (of which five are not shown for clarity of illustration) with the best-fit model shown in red.

companion signal is clearly pronounced in the closure phases, visibilities are not needed to improve a marginal companion detection (e.g., L. Marion et al. 2014), and we restrict our analysis to the closure phases to reduce bias by possible circumstellar dust.

Few investigations were dedicated to detecting high-contrast companions with MATISSE. B. Lopez et al. (2022) demonstrated this capability during commissioning, observing a known binary with a flux ratio f from companion to primary of $\sim 2\%$, while J. Varga et al. (2025) detected a new companion, albeit with a larger flux ratio of $f \sim 10\%$. However, the detections of high-contrast companions and their relative astrometry retrieved from MATISSE observations have not been verified independently. For this purpose, we use the joint GRAVITY and MATISSE observations from 2024 November 23.

3.1. Companion Search and Detection

We search for the signature of a companion to κ Tuc Aa separately in the MATISSE and GRAVITY closure phases obtained on 2024 November 23 using the numerical modeling suite PMOIRED v1.3.1 (A. Mérand 2022; A. Mérand et al. 2024). We model the system with a central uniform disk with a diameter of 0.739 mas (S. Ertel et al. 2014) for the primary and an off-axis point source for the companion. For a companion search in interferometric data, the χ^2 -map for the companion position typically shows several local minima (e.g., O. Absil et al. 2011; L. Marion et al. 2014; A. Gallenne et al. 2015). Thus, we use the CANDID grid search algorithm (embedded in PMOIRED, A. Gallenne et al. 2015) with a grid spacing of 2 mas to find the global best-fit solution. PMOIRED takes the effect of spectral-bandwidth smearing into account, which affects our MATISSE observations with LOW-LM spectral resolution (see Appendix A, including how bandwidth smearing is treated by PMOIRED).

Measurements from the VLTI are highly correlated (e.g., R. Lachaume et al. 2019; R. Lachaume 2021). S. Ertel et al. (2014) determined that for squared visibilities, the dominating source of correlation is among the spectrally dispersed data belonging to a certain baseline. We extend this finding to the closure phases and assume all closure phases belonging to a certain telescope triplet are fully correlated. We compute the final fit results using a bootstrapping procedure (B. Efron 1979, 1982) with the initial fit parameters set to the global solution from the grid search. The bootstrapping routine accounts for the correlation by keeping all data belonging to a certain triplet for a certain exposure together, thus sampling triplets instead of individual data points. We draw 2000 data samples in each bootstrapping fit, which is sufficient to yield stable results. We take the final best-fit parameters to be the median values from the 2000 results and compute their uncertainties by averaging the differences between the median and the 0.16 and 0.84 quantiles, respectively. This procedure yields similar best-fit values compared to the global solution from the CANDID grid search, but increases uncertainties.

We detect the signal of a companion in the MATISSE closure phases (see Figure 1). Assessing the numerical significance of a detection is challenging due to the correlation among the data. However, considering that the binary flux ratio obtained from the closure phases $f_{\text{CP}} = (1.01 \pm 0.06)\%$ is highly significant and the model reproduces well the closure phase oscillations across telescope triplets, we consider this a highly significant detection. Analyzing the GRAVITY closure phases, we detect the companion signal as well and confirm the MATISSE detection. The flux ratio of $f_{\text{CP}} = (0.70 \pm 0.02)\%$ is again highly significant, and the oscillations are well reproduced (see Figure 2).

3.2. Astrometry: MATISSE versus GRAVITY

Besides the binary flux ratio, the model fit predicts the companion position relative to the primary, expressed by the position angle (PA),¹⁸ and the separation ρ . We find for the position angle $\text{PA} = (255.71 \pm 0.09)^\circ$ from MATISSE and $\text{PA} = (255.64 \pm 0.02)^\circ$ from GRAVITY, showing excellent agreement. In the case of the separation ρ , the relative uncertainty of the spatial frequencies, given here by the relative uncertainty of the wavelength $\Delta\lambda/\lambda$ (Section 2.4), acts as a scaling factor and limits its precision. We compute the final uncertainty of ρ by quadratically adding the contributions from the bootstrapping fit $\Delta\rho_{\text{fit}}$ and the relative uncertainty of the wavelengths, thus

$$\Delta\rho = \sqrt{(\Delta\rho_{\text{fit}})^2 + \left(\frac{\Delta\lambda}{\lambda}\rho\right)^2}. \quad (1)$$

We find from MATISSE $\rho = (171.5 \pm 1.1)$ mas and from GRAVITY $\rho = (172.66 \pm 0.04)$ mas. The difference between the two results for ρ is only marginally larger than the uncertainty of the less precise value from MATISSE. We conclude that GRAVITY and MATISSE deliver consistent measurements, and the astrometry retrieved from MATISSE observations is robust to milliarcsecond precision.

¹⁸ The primary star is in the coordinate center, $\text{PA} = 0^\circ$ is to the north and increases counterclockwise.

Table 2
Position and Flux of the Companion κ Tuc Ab Relative to the Primary Star κ Tuc Aa

Date	MJD	ρ /mas	ϵ_ρ /mas	PA $^\circ$	ϵ_{PA} $^\circ$	f_{CP} /%	f /%	Instrument
2019 Jul 9 and 11	58674.366	326.2 ± 2.2	8.1	233.62 ± 0.10	-0.78	0.51 ± 0.05	1.29 ± 0.13	MATISSE
2022 Aug 27	59818.347	228.1 ± 0.2	-0.2	217.10 ± 0.04	0.04	0.95 ± 0.04	1.47 ± 0.07	MATISSE
2022 Oct 28	59880.071	211.0 ± 0.2	0.03	215.29 ± 0.07	-0.07	0.90 ± 0.06	1.3 ± 0.09	MATISSE
2022 Oct 29	59881.143	210.7 ± 0.2	0.03	215.27 ± 0.05	-0.06	0.81 ± 0.03	1.18 ± 0.05	MATISSE
2023 Jun 17	60112.433	112.1 ± 0.7	-0.4	203.34 ± 0.17	0.04	0.87 ± 0.10	0.97 ± 0.11	MATISSE
2023 Jun 21	60116.332	109.7 ± 0.7	-0.3	202.75 ± 0.12	-0.13	1.28 ± 0.06	1.41 ± 0.06	MATISSE
2023 Jul 13	60138.324	94.3 ± 0.6	-0.7	200.78 ± 0.16	0.65	1.52 ± 0.15	1.63 ± 0.16	MATISSE
2023 Aug 13	60169.213	69.7 ± 0.5	0.1	193.37 ± 0.27	-0.46	1.26 ± 0.07	1.31 ± 0.07	MATISSE
2024 Oct 25	60608.260	164.2 ± 1.0	-0.7	257.00 ± 0.03	-0.01	1.06 ± 0.03	1.32 ± 0.04	MATISSE
2024 Oct 26	60609.124	164.2 ± 1.0	-1.0	257.09 ± 0.03	0.09	1.26 ± 0.05	1.57 ± 0.06	MATISSE
2024 Oct 26	60609.285	163.8 ± 1.0	-1.2	256.96 ± 0.02	0.01	1.17 ± 0.03	1.45 ± 0.03	MATISSE
2024 Oct 29	60612.251	165.4 ± 1.1	-0.7	256.59 ± 0.07	-0.20	0.99 ± 0.04	1.24 ± 0.04	MATISSE
2024 Oct 29	60612.287	164.8 ± 1.1	-1.0	256.62 ± 0.09	-0.29	1.01 ± 0.05	1.27 ± 0.07	MATISSE
2024 Oct 29/30	60613.006	165.2 ± 1.1	-0.9	256.81 ± 0.10	0.04	1.11 ± 0.02	1.39 ± 0.02	MATISSE
2024 Nov 6	60620.174	167.0 ± 1.1	-1.2	256.47 ± 0.06	0.03	1.2 ± 0.06	1.52 ± 0.08	MATISSE
2024 Nov 6	60620.212	167.1 ± 1.1	-1.3	256.16 ± 0.11	-0.20	0.69 ± 0.09	0.87 ± 0.11	MATISSE
2024 Nov 7	60621.021	167.2 ± 1.1	-1.3	256.45 ± 0.04	0.01	1.04 ± 0.04	1.31 ± 0.05	MATISSE
2024 Nov 23	60637.132	171.5 ± 1.1	-1.1	255.71 ± 0.09	0.04	1.01 ± 0.06	1.29 ± 0.08	MATISSE
2024 Nov 23	60637.063	172.66 ± 0.04	0.04	255.64 ± 0.02	-0.04	0.70 ± 0.02	1.87 ± 0.05	GRAVITY

Note. The MJD of a certain epoch is computed by averaging the MJDs of all corresponding subexposures. The 2019 epoch was excluded from the orbit analysis.

4. Multi-epoch Analysis

Using the same procedure as discussed in Section 3.1, we detect a companion accompanying the primary star in all MATISSE observations and determine its flux ratio and position relative to the primary star (Table 2).

4.1. Orbit Fit

The companion positions are reasonable for all epochs except the two observations from 2019: when analyzed individually, the results are inconsistent with each other. When analyzed jointly with a grid search region primed to the predictions based on all other epochs, we find a position consistent with the predictions that we list in Table 2. However, this position is sensitive to small changes in the analyzed wavelength interval and changes up to ~ 20 mas. The analysis of the 2019 data generally suffers from a smaller wavelength coverage, leading to fewer spatial frequencies being probed and only three instead of four successful 1 minute exposures (see Section 2.3). Furthermore, the companion signal for this large separation of $\gtrsim 300$ mas is strongly attenuated by both bandwidth smearing and spatial filtering (see later in this section and Appendix C). Therefore, we exclude the 2019 epoch in the subsequent orbit analysis.

To constrain the physical extension of the orbit, the distance to the system is required. The astrometry solution of κ Tuc A from Gaia DR3 (Gaia Collaboration et al. 2016, 2023b) is unreliable. This is indicated by its RUWE value of ≈ 10.4 , which should be ≈ 1 for a reliable solution (L. Lindegren et al. 2021). Thus, we apply the reliable solution of κ Tuc B with $\text{RUWE} \approx 1.2$. Its parallax of (47.65 ± 0.02) mas translates to a distance of (20.986 ± 0.009) pc.

To constrain the companion's orbital parameters, we use the numerical tool *orbitize!* v3.1.0 (S. Blunt et al. 2020, 2024). The parameter space is explored via the Markov chain Monte Carlo (MCMC) method with parallel tempering (R. H. Swendsen & J.-S. Wang 1986; C. J. Geyer 1991;

D. J. Earl & M. W. Deem 2005) using the embedded tool *ptemcee* (W. D. Voudsen et al. 2016; W. Voudsen et al. 2021) that is based on *emcee* (D. Foreman-Mackey et al. 2013); see Appendix B for details on the MCMC setup, such as the priors and the corner plot.

We achieve fully converged chains and show a selection of 100 orbits from the posterior distribution in Figure 3. We take the best-fit orbital parameters to be the median values from the posterior distribution. We take the uncertainties as the differences between the median and the 0.16 and 0.84 quantiles, respectively, which hence enclose 68% of the distributed values (Table 3). There are measurements of the radial velocity of κ Tuc Aa (B. Nordström et al. 2004; A. Tokovinin et al. 2015; A. Tokovinin 2015, 2020; K. Fuhrmann et al. 2017), but no radial velocity signal due to the companion was reported by A. Tokovinin (2020). Without constraining radial velocity data of κ Tuc Aa, we cannot determine the movement of the companion along the line of sight and hence the results for the argument of periastron ω and the position angle of the ascending node Ω are degenerate to a shift of 180° (e.g., H. Beust et al. 2014). The dimensionless quantity τ parametrizes the periastron passage and is defined by $\tau = (t_p - t_{\text{ref}})/P_{\text{orb}}$, where t_{ref} is an arbitrary reference date, 58849 MJD (2020 January 1) for *orbitize!* default settings, t_p is the next time of periastron passage after t_{ref} , and P_{orb} is the orbital period computed by Kepler's third law. Further parameters are the combined mass of primary and companion M_{tot} , and the orbit's semimajor axis a , eccentricity e , and inclination i .

The well-constrained orbit of the companion verifies that the off-axis point source detected in various epochs belongs to the same astronomical object that is not a moving background source but is gravitationally bound to κ Tuc Aa. The orbit is highly eccentric with $e = 0.9356$. While the apoastron is at a distance from the primary of ≈ 9.3 au, the periastron is at only ≈ 0.3 au, approximately at ~ 40 stellar radii of κ Tuc Aa (based on the angular diameter and parallax). This coincides

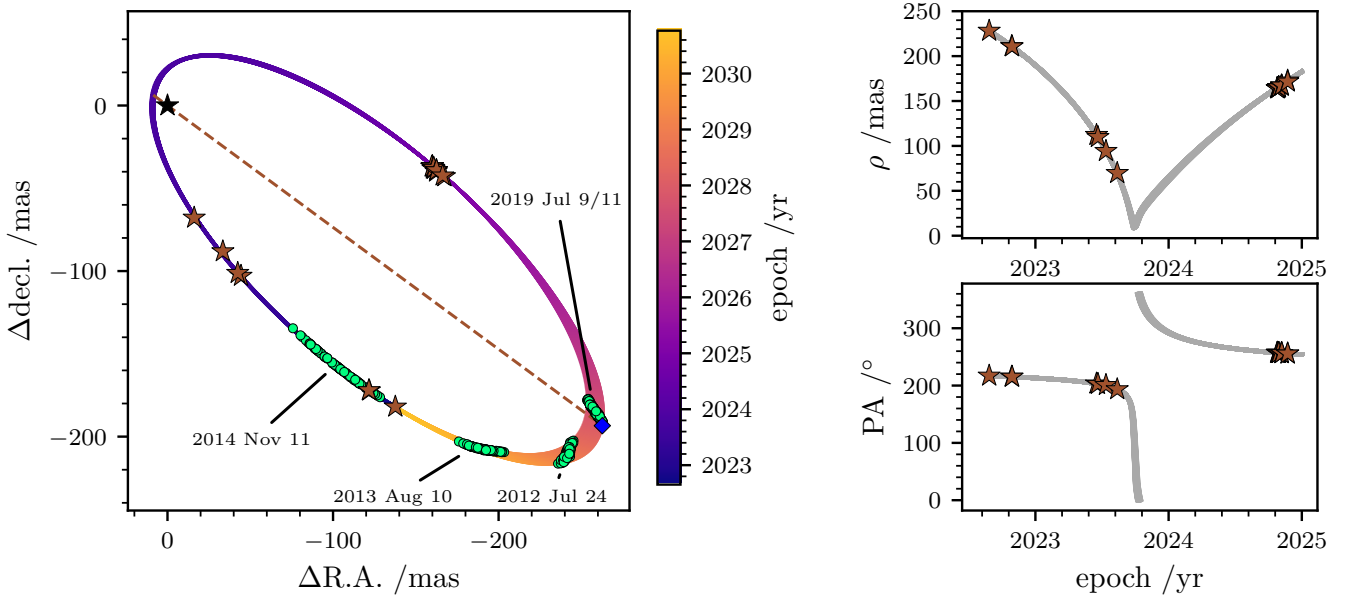


Figure 3. One hundred orbits randomly selected from the posterior distribution computed by an MCMC fit to relative astrometry (brown stars). Left: orbits show the displacement of the companion κ Tuc Ab in decl. and R.A. ($\Delta\text{decl.}$, $\Delta\text{R.A.}$) with the primary star κ Tuc Aa in the coordinate center (black star). Colors indicate the position of κ Tuc Ab along the orbits, starting with our first detection on 2022 August 27, and ending after one orbital period. The dashed brown line connects the peri- and apoastron for the best-fit orbital parameters. The blue diamond indicates the tentative position for 2019 July 9/11, which was not used to constrain the orbit. In several past PIONIER and MATISSE observations, κ Tuc Ab was not detected (see Section 5.3), and green points show for the selected orbits its predicted past positions at these epochs that are denoted by text insets. Right: gray curves show for the same orbits as on the left the companion separation ρ and the PA of κ Tuc Ab with PA = 0° to the north and increasing counterclockwise. Figure created with a modified `orbitize!` plot routine.

Table 3Parameters of the Orbit of the Companion κ Tuc Ab from the MCMC Fit

Parameter	Value
a / au	$4.822^{+0.077}_{-0.071}$
e	$0.9356^{+0.0024}_{-0.0024}$
i / $^\circ$	$126.13^{+0.80}_{-0.83}$
ω / $^\circ$	$(120.9 \text{ or } +180)^{+1.5}_{-1.4}$
Ω / $^\circ$	$(189.0 \text{ or } +180)^{+1.1}_{-1.0}$
τ	$0.4611^{+0.0057}_{-0.0057}$
t_p / MJD	$60219.8^{+1.8}_{-1.8}$
P_{orb} / yr	$8.14^{+0.11}_{-0.10}$
M_{tot} / $M_\odot$	$1.69^{+0.11}_{-0.10}$

Note. The parameter M_{tot} represents the combined mass of κ Tuc Aa and Ab.

with the location of hot dust as deduced by F. Kirchschrager et al. (2020). The most recent periastron passage occurred approximately between 2023 October 1 and 5 (see Table 3 for t_p). The next periastron passage will occur approximately between 2031 October 14 and 2032 January 2; precise measurements of the companion’s location near the passage will further constrain the orbit (e.g., I. Waisberg et al. 2025). In addition, during the passage, the radial velocity signal of κ Tuc Aa will be well detectable with various instruments; the semi-amplitude is $K \sim 8 \text{ km s}^{-1}$. Determining the sign of the radial velocity during the passage will break the degeneracy of ω and Ω .

We compute the residuals of the orbit solution for the companion separation, ϵ_ρ , and the PA, ϵ_{PA} , by respectively subtracting the values predicted by the best-fit orbital model from those deduced from the closure phases (Table 2). Excluding the epoch of 2019, which was not used for the modeling, the residuals of the separation ϵ_ρ are on the order of the estimated uncertainties $\Delta\rho$. The residuals of the position

angle ϵ_{PA} are up to several times larger than the estimated uncertainties (see Section 5.1).

4.2. Companion Brightness and Spectral Type

For both MATISSE and GRAVITY, the flux of an off-axis source, such as the detected companion, gets attenuated compared to a centered source by spatial filtering. We correct the thereby biased flux ratio of companion to primary star f_{CP} as derived from the closure phases to yield the nonattenuated flux ratio f (Table 2). In the case of MATISSE, which employs pinholes for spatial filtering, we describe and verify the resulting attenuation for the first time in Appendix C. The final L -band flux ratio is obtained by computing the nonweighted average of all corrected values of f to $f_L = (1.32 \pm 0.04)\%$, with the uncertainty being the standard error of the mean.

The dependence of the flux ratio f_{CP} on the companion separation ρ in the L band can be explained solely by the instrument characteristics. Thus, the companion’s intrinsic brightness is constant with separation, and hence it has to be self-luminous; an externally heated object such as a dust clump would change temperature and thus color and luminosity along its eccentric orbit because the cooling timescale is much shorter than the orbital timescale (A. Bensberg & S. Wolf 2022; T. D. Pearce et al. 2022). Together with the well-constrained orbit, this confirms that the off-axis source is a stellar companion to κ Tuc Aa as we assumed: κ Tuc Ab.

To estimate the spectral type of this self-luminous companion κ Tuc Ab, we use the dynamical mass of the system. The mass estimate for κ Tuc Aa is $1.36 M_\odot$, derived by K. Fuhrmann et al. (2017) using the V -band magnitude of κ Tuc A; by using it, we neglect any contamination by κ Tuc Ab in the V -band measurement. Subtracting the mass of κ Tuc Aa from the total mass M_{tot} yields $\sim(0.33 \pm 0.10)M_\odot$ for the mass

of κ Tuc Ab. This indicates a spectral type between M2.0 V and M5.0 V (C. Cifuentes et al. 2020, Table 6).

In contrast to MATISSE, GRAVITY uses single-mode optical fibers for spatial filtering. When using Equation A4 of J. J. Wang et al. (2021, Appendix A) to correct for spatial filtering, assuming a wavelength of $2.2\ \mu\text{m}$ and a telescope diameter of 1.8 m for the ATs, we yield a K -band flux ratio of $f_K = (1.87 \pm 0.05)\%$ from our single observation (see Section 3.1). This is larger than the flux ratio in the L band, which contradicts the fact that κ Tuc Aa is of spectral type F and κ Tuc Ab is of type M. However, the equation of J. J. Wang et al. (2021) assumes the source being perfectly centered on the fiber and no wave front disturbances due to atmospheric effects. The flux ratios determined from our MATISSE observations scatter considerably around the theoretically expected values (Figure 5), likely due to imperfect centering and atmospheric effects. Thus, we conclude that with only one GRAVITY observation, we cannot reliably determine the K -band flux ratio. However, GRAVITY and MATISSE use individual mechanisms to center the source, and an assessment of GRAVITY's behavior for systems with companion separations $\rho \gtrsim 200$ mas and different binary brightness ratios, both under different atmospheric conditions, is needed.

Instead of the flux ratio in the K band, we use the measured ratio in the L band of 1.32% and PHOENIX synthetic spectra (HiRes spectra with solar metallicity, T. O. Husser et al. 2013)¹⁹ to estimate the K -band flux ratio. For κ Tuc Aa, we utilize a spectrum for an effective temperature of 6500 K and a logarithmic surface gravity of $\log(g) = 4.0$. For κ Tuc Ab, we explore spectra for intermediate-type M dwarfs with effective temperatures between 3000 K and 3400 K and $\log(g) = 5.0$. Given the measured L -band flux ratio, the K -band flux ratio would be $\approx 1.1\%$ consistent across the explored spectra. Given the companion separation and the measured flux ratio determined from the closure phases (Table 2), this is consistent with a fiber offset of 45 mas from κ Tuc Aa in the direction of κ Tuc Ab. An imperfectly corrected wave front would further reduce this required offset because the fiber injection of the on-axis primary would decrease while the injection of the off-axis companion would increase.

We use this K -band flux ratio of 1.1% to do a flux-based determination of the spectral type, neglecting differences between the photometric bands K and K_s . The apparent magnitude of the multiple system κ Tuc in the K_s band from the Two Micron All Sky Survey (2MASS; M. F. Skrutskie et al. 2006) is $m_{K_s,AB} = 3.876$ (R. M. Cutri et al. 2003; M. F. Skrutskie et al. 2003); this is likely the joint magnitude of κ Tuc Aa, Ab, and B as the latter does not have its own 2MASS identifier and the component κ Tuc Ab was only recently inferred. Thus, we first correct for the magnitude of κ Tuc B and find for the binary κ Tuc A the magnitude $m_{K_s,A} \approx 4.15$ (see Appendix D). Using the flux ratio of κ Tuc Ab to Aa, $f_K \approx 1.1\%$, this results in an apparent magnitude of κ Tuc Ab of $m_{K_s,Ab} \approx 9.1$ and an absolute magnitude of $M_{K_s,Ab} \approx 7.4$. This indicates a spectral type between M3.5 V and M4.5 V (C. Cifuentes et al. 2020, Table 7). The corresponding mass from their Table 6 agrees with the mass of $\approx 0.24 M_\odot$ estimated with the mass–luminosity relation of G. F. Benedict et al. (2016, Equation (11)) and the estimate

from our dynamical mass. Therefore, the mass and flux-based estimates of the spectral type agree, supporting the consistency of our analysis.

At most times, κ Tuc Ab is located at separations of $\rho \gtrsim 200$ mas to κ Tuc Aa. With a contrast to the primary of $\sim 10^{-2}$, it is easily detectable by high-contrast facilities such as the Very Large Telescope (VLT) instruments SPHERE (J. L. Beuzit et al. 2019), HiRISE (A. Vigan et al. 2024), or ERIS (R. Davies et al. 2023; J. Hayoz et al. 2025) that can measure more precise fluxes across different photometric bands. This would allow for a more precise determination of the spectral type.

5. Discussion

5.1. Astrometric Measurements with MATISSE

We interferometrically detected for the first time a stellar companion to κ Tuc Aa, κ Tuc Ab, that was previously inferred by astrometry (A. Tokovinin 2020). Using the combined mass of the stars and their flux ratio, we constrained the spectral type of κ Tuc Ab to be between M3.5 V and M4.5 V. The companion signature in the closure phases is mostly smaller than $\pm 2^\circ$, and the smallest inferred binary flux ratio in the L band based on this signal is $\sim 0.5\%$. The true flux ratio derived from the whole observational sample after correcting for spatial filtering is $(1.32 \pm 0.04)\%$. This makes κ Tuc Ab, to our knowledge, the stellar companion with the highest contrast ever detected using MATISSE closure phases. The companion is also detected in most of our (squared) visibility measurements, but we refrained from including them in the analysis to prevent any possible circumstellar material, such as a hot-dust distribution, from degrading the retrieved relative astrometry.

Using GRAVITY, we validated the relative astrometry retrieved from MATISSE closure phases and verified that MATISSE is able to deliver milliarcsecond precision on a companion's location in LOW-LM spectral resolution ($R = 31.5$). With this spectral setting, the main source of uncertainty is the limited precision of the wavelength calibration that directly affects the retrievable precision of the companion separation. Furthermore, depending on the employed baselines and the separation, bandwidth smearing can attenuate the companion's visibility and closure phase signal. Employing higher spectral resolutions than LOW-LM lifts these issues. However, this decreases the signal-to-noise ratio, which can be detrimental for observations of faint primary stars and high-contrast companions.

Based on our best-fit orbital solution, the residuals of the PA are up to several times larger than the estimated uncertainties (see Section 4.1). This suggests that the uncertainties of the PAs are underestimated. Possibly, there are systematic effects such as the discussed efficiency of centering the source within the spatial filter (see Section 4.2), or single observations are insufficient to estimate the uncertainties via bootstrapping due to the high correlation among the data (see Section 3.1). For the companion separation, both effects could be masked as the uncertainty of the spatial frequencies dominates the error budget for most of the epochs.

5.2. The Triple System of κ Tuc

A. Tokovinin (2020) fitted the orbit of κ Tuc B around κ Tuc A and identified residuals in agreement with the proper motion anomaly of κ Tuc A from T. D. Brandt (2018), which they interpreted as signs of an astrometric companion to κ Tuc

¹⁹ <https://phoenix.astro.physik.uni-goettingen.de/>

Aa. Based on the assumption of a circular orbit of this companion, A. Tokovinin (2020) presented a companion mass of $0.2 M_{\odot}$ as a plausible estimate, but noted that the PA residuals for κ Tuc B did not suggest a circular orbit. We find for the interferometrically detected companion a highly eccentric orbit and a mass of $(0.33 \pm 10) M_{\odot}$, close to the estimate of A. Tokovinin (2020), while using the same mass estimate for κ Tuc Aa. Thus, we conclude that the detected companion and the inferred astrometric companion are the same object, κ Tuc Ab.

However, our orbit constraints predict that the binary κ Tuc Aa, Ab experienced periastron passage approximately at the time of the Gaia observation of DR2.²⁰ Thus, the measured positions of κ Tuc Aa (with the individual positions foreseen to be published in DR4) do not follow a straight line, which renders the DR2 proper motions unreliable. Furthermore, the periastron passage could be the cause of the unreliable astrometric solution of κ Tuc Aa in Gaia DR3.

In constraining the orbit of κ Tuc B around A, A. Tokovinin (2020) set the orbital period to 1200 yr to yield a total system mass of $2.22 M_{\odot}$ that equals the sum of $1.36 M_{\odot}$ for κ Tuc Aa (K. Fuhrmann et al. 2017) and $0.86 M_{\odot}$ for κ Tuc B (M. J. Pecaut & E. E. Mamajek 2013). Using our mass constraint for the combined system of κ Tuc Aa and Ab and the semimajor axis of (7.03 ± 0.07) as from A. Tokovinin (2020), while neglecting any mass uncertainty of κ Tuc B, we deduce the orbital period of κ Tuc B to be (1122 ± 28) yr. We use the inclination i and position angle of the ascending node Ω of the orbit of κ Tuc B around A from A. Tokovinin (2020) and those from κ Tuc Ab around Aa from Table 3 to compute the mutual inclination between these orbits (F. C. Fekel 1981). Due to the degeneracy of Ω , the mutual inclination is equally degenerate and can be either $(36.2 \pm 1.0)^{\circ}$ or $(94.2 \pm 1.2)^{\circ}$. Based on the stability criterion of A. Mylläri et al. (2018, Equation (13)) with the parameter $A = 2.4$ for absolute stability and a strictness factor of $\lambda = 10$, and the unfavorable smaller mutual inclination of 36.2 , the current configuration of the triple system κ Tuc is stable for ~ 10 Gyr, which is longer than the remaining lifetime of κ Tuc Aa. Furthermore, tidal circularization of the orbit of κ Tuc Ab is negligible due to the long timescales (P. Goldreich & S. Soter 1966; P. Bodenheimer et al. 2001). However, the distance between κ Tuc Aa and Ab at periastron is only ≈ 0.3 au. Assuming the configuration is unchanged when κ Tuc Aa enters its late-stage evolution, the expansion of κ Tuc Aa will alter the orbital dynamics.

5.3. Previous Nondetections and Implications for Hot-exozodiacal Dust

The system of κ Tuc A was observed with PIONIER on 2012 July 24 (S. Ertel et al. 2014; L. Marion et al. 2014), 2013 August 10, and 2014 November 11 (S. Ertel et al. 2016). Only the data from 2012 were searched for signals from stellar companions; the search region was restricted to a separation of < 100 mas, where clear companion signals are expected with PIONIER (O. Absil et al. 2011; L. Marion et al. 2014). According to our orbit constraints, κ Tuc Ab was located outside this search region for all PIONIER epochs (see green points in Figure 3).

For the 2012 and 2014 epochs, but not for 2013, a small deficit of the measured squared visibility²¹ compared to the prediction from the stellar photosphere alone was detected. With no companion detected, this deficit was attributed to the presence of a hot exozodi with a flux ratio of $\sim 1\%$ compared to κ Tuc Aa, with the dust potentially being of variable brightness due to the nondetection in 2013 (S. Ertel et al. 2014, 2016).

To assess whether κ Tuc Ab could have been the cause of the measured deficits, we estimate the attenuation of its flux due to spatial filtering. The transmission over the PIONIER field of view can be approximated by a Gaussian with a full width at half maximum (FWHM) of 400 mas, assuming seeing of 0.8 as (O. Absil et al. 2011). For the smallest possible separation in 2014 of ~ 150 mas (see Figure 3), about 70% of the flux of κ Tuc Ab would have been transmitted. Assuming a flux ratio of κ Tuc Ab to Aa in the H band of 1% (estimated from the L -band flux ratio and synthetic spectra, see Section 4.2), this would have been reduced by spatial filtering to $\sim 0.7\%$. The maximum deficit in squared visibility that can be caused by a companion star is approximately 4 times the flux ratio, thus $\Delta V^2 \lesssim 2.8 \times 10^{-2}$. Even considering that this would be reduced by bandwidth smearing or worse transmission than assumed, it is likely still similar to the deficit in squared visibility deduced by S. Ertel et al. (2016) of $\Delta V^2 = (2.32 \pm 0.34) \times 10^{-2}$ (twice the flux ratio associated with the hot exozodi in their modeling, see their Figure 1). Thus, the companion could have been the origin of the measured deficit in squared visibility and the hot-exozodi detection.

In 2013, the smallest possible separation was ~ 270 mas (see Figure 3), causing a transmission of $\sim 30\%$. In 2012, the separation was ~ 320 mas, causing a transmission of $\sim 20\%$. The separation in both epochs was so large that the fringe packets associated with the primary and the companion were not overlapping for some of the baselines (ranging from ~ 9 m to 31 m) while they were still covered by the minimum scan length of PIONIER (L. Marion et al. 2014, Sect. 3.2). This special case is not considered by the PIONIER data reduction software pndrs (J. B. Le Bouquin et al. 2011). A detailed assessment of this case would require an in-depth investigation of the PIONIER data reduction process. Furthermore, a more accurate description of how the electromagnetic wave front couples into the optical fiber (e.g., C. Ruilier & F. Cassaing 2001; J. J. Wang et al. 2021) under the actual atmospheric conditions compared to the Gaussian approximation by O. Absil et al. (2011) is needed. Both are beyond the scope of this article. While it appears unlikely to us that κ Tuc Ab could have caused the entire deficit in squared visibility of $\Delta V^2 = (2.86 \pm 0.34) \times 10^{-2}$ measured in 2012 (S. Ertel et al. 2014), we cannot judge by how much κ Tuc Ab influenced the hot-exozodi detection in 2012. If the 2012 detection was caused by κ Tuc Ab, the nondetection in 2013 could be explained by an unfavorable sampling of the spatial frequencies or the baseline orientation projected onto the sky.

For the MATISSE observations on 2019 July 9 and 11, κ Tuc Ab cannot explain the deep deficit of the visibility amplitude measured by F. Kirchschlager et al. (2020). The visibility amplitudes (of our new reductions) show that the deficit compared to the expected signal from κ Tuc Aa is

²⁰ Characteristic epoch 2015.62062 for decl., 2015.65609 for R.A., see T. D. Brandt (2018, 2019).

²¹ PIONIER only measures the squared visibility and not the visibility amplitude.

nearly constant over spatial frequency, consistent with an over-resolved brightness distribution (e.g., E. di Folco et al. 2007; S. Ertel et al. 2014) as modeled by F. Kirchschrager et al. (2020). Furthermore, the visibility amplitudes for the shorter ~ 35 m baselines (not affected by bandwidth smearing) at this lower overall visibility level appear modulated by an oscillating signal, in agreement with an off-axis point source with a flux ratio of $\sim 0.5\%$ to the primary (a companion with flux ratio f causes a modulation in visibility amplitudes of $\Delta|V| \leq 2f$; e.g., K. Tsishchankava et al. 2025). This agrees well with our estimate for the attenuated flux ratio based on the closure phases (Table 2).

We conclude that, while κ Tuc Ab left imprints in the visibility amplitudes analyzed by F. Kirchschrager et al. (2020), it cannot account for the overall measured deficit in the visibility amplitude that has been attributed to a hot exozodi.

5.4. Implications for the Planetary System

The coexistence of κ Tuc Ab with a hot exozodi motivates dynamical studies of how the binary star interacts with the planetary system. The periastron of κ Tuc Ab coincides with the constrained location of the hot exozodi (F. Kirchschrager et al. 2020) and generally where hot exozodis are found (O. Absil et al. 2006; R. L. Akeson et al. 2009; D. Defrère et al. 2011; J. Lebreton et al. 2013; F. Kirchschrager et al. 2017; T. A. Stuber et al. 2023a; K. Ollmann et al. 2025), which will have a strong influence on the dust dynamics and lifetime during periastron passage: For instance, the added emission of κ Tuc Ab will reduce sublimation timescales (e.g., H. Kobayashi et al. 2009; J. Lebreton et al. 2013; É. Sezestre et al. 2019; T. D. Pearce et al. 2020) and its gravitational effect might disrupt the orbits of dust grains and reduce the efficiency of any potential dust-trapping mechanism around the primary κ Tuc Aa, such as gas drag (J. Lebreton et al. 2013; T. D. Pearce et al. 2020), magnetic field lines (A. Czechowski & I. Mann 2010; K. Y. L. Su et al. 2013; G. H. Rieke et al. 2016; J. Stamm et al. 2019; H. Kimura et al. 2020), or the differential Doppler effect (J. A. Burns et al. 1979; E. T. Rusk 1987; É. Sezestre et al. 2019). Furthermore, κ Tuc Ab might trap dust in its own vicinity.

However, the periastron passage is rapid, and κ Tuc Ab spends most of the time at larger distances of several astronomical units from the primary. If the hot dust is short-lived and continuously supplied, for instance by exocomets, the hot exozodi would quickly recover from any impact by the periastron passage. While cometary supply as the sole cause of hot exozodis is disfavored, because it requires unphysically large comet-inflow rates (T. D. Pearce et al. 2022), this periodic dust-level effect could still occur if some efficient trapping mechanism were also present. Whereas the large apoastron of κ Tuc Ab allows for a change in the dominant physical processes in the primary's close circumstellar environment, κ Tuc Ab might interact with a possible cold debris disk (e.g., B. C. Matthews et al. 2014; A. M. Hughes et al. 2018; M. Wyatt 2020) at tens of astronomical units. While no far-infrared excess of the κ Tuc A system has been found (A. Gáspár et al. 2013; B. Sibthorpe et al. 2018), which agrees with the statistical lack of far-infrared detected debris disks in binary systems (D. R. Rodriguez & B. Zuckerman 2012; D. R. Rodriguez et al. 2015; B. Yelverton et al. 2019), the existence of the hot exozodi gives rise to the possibility of a dust reservoir formed by a planetesimal population further

out than the apoastron of κ Tuc Ab; at those distances also the gravitational influence of the wider companion κ Tuc B might have to be considered. The gravitational influence of both κ Tuc Ab and B would shape the planetesimal distribution (e.g., V. Faramaz et al. 2014; T. D. Pearce & M. C. Wyatt 2014; Z. Regály et al. 2018; J. A. Sende & T. Löhne 2019; T. A. Stuber et al. 2023b) and provide means to scatter planetesimals onto orbits that graze the primary (V. Faramaz et al. 2015, 2017) where they could replenish the hot-dust distribution. Even a planetesimal distribution that is penetrated by the orbit of κ Tuc Ab cannot be excluded (T. D. Pearce et al. 2021).

Lastly, while the radiation pressure (see J. A. Burns et al. 1979; B. A. S. Gustafson 1994 for reviews on forces acting on dust grains) exerted by the emission of M dwarfs is not effective in repelling dust grains, their stellar winds can be effective in repelling or dragging dust grains (e.g., P. Plavchan et al. 2005, 2009; J. C. Augereau & H. Beust 2006; L. E. Strubbe & E. I. Chiang 2006; M. Reidemeister et al. 2011; C. Schüppler et al. 2014, 2015; B. C. Matthews et al. 2015), which affects the interplay of transport and collisional processes in the entire system.

6. Summary

We detected a low-mass stellar companion to κ Tuc Aa with infrared interferometry using the VLTI instruments MATISSE and GRAVITY. With an L -band contrast of 1.32%, this is the highest-contrast stellar companion ever detected with MATISSE. Furthermore, we demonstrated that MATISSE is able to deliver relative astrometry with milliarcsecond precision in imaging mode, which we validated with GRAVITY. Measuring precise flux ratios for such binaries with contrasts of $\sim 1 \times 10^{-2}$ and separations of $\gtrsim 100$ mas is challenging with single observations for both MATISSE and GRAVITY, probably due to imperfect centering of the source and atmospheric conditions; multiple observations are advised to statistically mitigate this issue.

The new companion κ Tuc Ab is an M dwarf of spectral type M3.5 V to M4.5 V that moves around κ Tuc Aa with a period of ≈ 8.14 yr on a highly eccentric orbit with $e \approx 0.94$ and a semimajor axis of ≈ 4.8 au. While κ Tuc Ab might have caused the putative detection of hot-exozodiacal dust around κ Tuc Aa in 2012 and 2014, it cannot negate the hot-dust detection in 2019.

This coexistence of hot dust and the stellar companion motivates dynamical studies of this intriguing planetary system, governing, for instance, how κ Tuc Ab interacts with the hot-dust distribution during its periastron passage or how it might excite unseen planetesimals onto cometary orbits that can replenish the dust in situ.

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Facility: VLTI (GRAVITY, MATISSE, NAOMI).

Software: Aspro (L. Bourguès & G. Duvert 2016), astropy (Astropy Collaboration et al. 2013, 2018, 2022), emcee (D. Foreman-Mackey et al. 2013), Ipython (F. Perez & B. E. Granger 2007), GRAVITY data reduction software (V. Lapeyrière et al. 2014), Jupyter notebooks (T. Kluyver et al. 2016), MATISSE data reduction software (F. Millour et al. 2016), Matplotlib (J. D. Hunter 2007), NumPy (C. R. Harris et al. 2020), OI DB (<http://oidb.jmmc.fr>), OIFITS (G. Duvert et al. 2017), OIFits Explorer (<https://www.jmmc.fr/english/tools/data-analysis/oifits-explorer/>), orbitize! (S. Blunt et al. 2020), PMOIRE (A. Mérand 2022; A. Mérand et al. 2024), ptmcee (W. D. Voudsen et al. 2016; W. Voudsen et al. 2021), python (<https://www.python.org/>), SearchCal (<https://www.jmmc.fr/english/tools/proposal-preparation/search-cal/>), SIMBAD Astronomical Database (M. Wenger et al. 2000), VizieR (F. Ochsenbein et al. 2000).

²² <https://www.cosmos.esa.int/gaia>

²³ <https://www.cosmos.esa.int/web/gaia/dpac/consortium>

²⁴ <https://www.jmmc.fr/suv>

Appendix A Treatment of Bandwidth Smearing by PMOIRE

Modeling of interferometric data often treats light as monochromatic. However, for a finite resolving power $R = \lambda/\delta\lambda$, the spectral resolution element $\delta\lambda$ (also called spectral bandwidth or spectral channel) has a finite length. In this case, bandwidth smearing occurs if the angular separation ρ between two sources along the projected baseline becomes comparable to the width of a fringe packet associated with a single point source, thus $\rho \gtrsim R\lambda/B$ (see, e.g., R. Lachaume & J. P. Berger 2013 for a detailed description). For our observations, this is relevant only for MATISSE observations in LOW-LM spectral resolution.

In the case of a binary star with fixed separation, the fringe visibility and phase are modulated with increasing spatial frequencies B/λ . PMOIRE models bandwidth smearing by convolving the simulated observables in the spectral domain with a Gaussian. Its FWHM equals the spectral resolution element $\delta\lambda$, which is specified by its oversampling by detector pixels (set by the `wl` keyword in `setupFit` of PMOIRE); for the LM-band arm of MATISSE, the oversampling is ≈ 5 . If smearing occurs over several detector pixels, the observables have to be computed at a higher spectral resolution (set by the `smear` keyword) before convolution and then reduced to the correct sampling afterwards. This effect was not considered for our case, because the high oversampling by MATISSE already causes the observables to be computed at a sufficiently high resolution.

If bandwidth smearing is not accounted for, the binary flux ratio can be underestimated. Furthermore, for different baseline lengths, the modulation amplitude gets damped by different degrees, which biases a joint analysis of multiple baselines. For our largest separation (2019 July, $\rho \sim 300$ mas), accounting for bandwidth smearing with PMOIRE increases the determined flux ratio from $(0.13 \pm 0.01)\%$ to $(0.51 \pm 0.05)\%$. Our treatment is validated by the remaining trend of binary flux ratio with separation that agrees with the expected behavior caused by spatial filtering inside MATISSE (Appendix C).

Appendix B MCMC Setup

For our MCMC setup, we use default `orbitize!` priors for the following orbital parameters: uniform in $[0, 1]$ for the eccentricity e and dimensionless epoch of periastron passage τ , uniform in $[0, 2\pi]$ for the argument of periastron ω , log-uniform in $[10^{-2} \text{ au}, 10^{-4} \text{ au}]$ for the semimajor axis a , and $\sin i$ for the inclination i with i uniform in $[0, \pi]$. For the position angle of ascending node Ω , we choose a prior uniform in $[0, \pi]$ to restrict the orbits to one of the degenerate modes and aid convergence. For the parallax of the system, we apply a Gaussian prior with a mean of 47.65 mas and a standard deviation of 0.02 mas. For the total system mass of primary and companion M_{tot} , we apply a prior uniform in $[1M_{\odot}, 2.5M_{\odot}]$; this interval ranges from the lower mass end of F-type stars up to the upper mass end of a pair of F- and M-type stars. As verified by the resulting posterior, this allowed mass interval well encloses the constrained mass and hence is not overly restrictive. Furthermore, as the coverage of the orbital phase is $>40\%$, the use of Campbell orbital

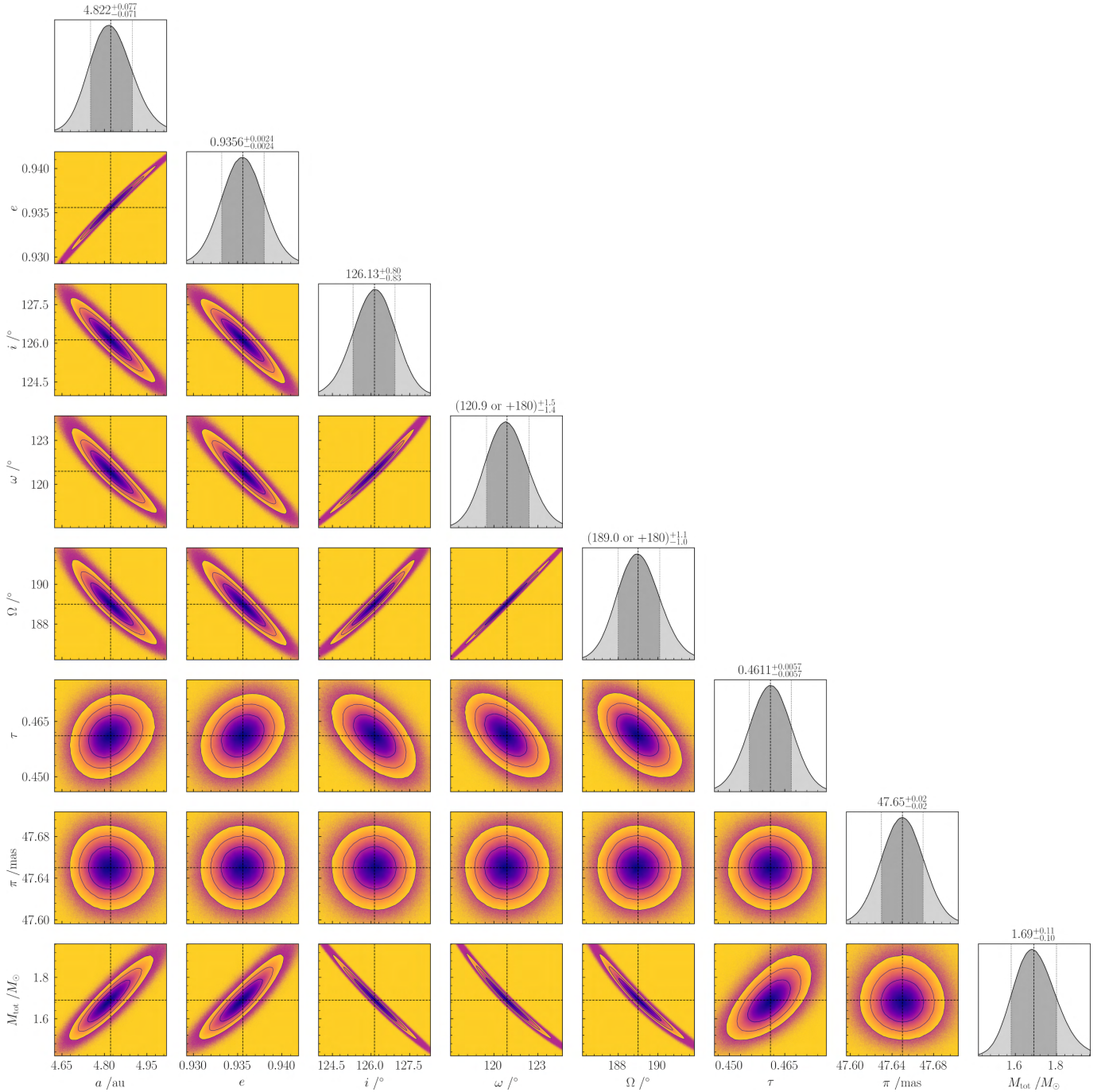


Figure 4. Corner plot showing the converged *orbitize!* posterior sample thinned by a factor of 10 (i.e., 10^7 samples). We show gray 200-bin histograms for each orbital element along the diagonal with a KDE overplotted in black. Dashed and dotted lines mark the median and 0.16/0.84 quantiles computed from the complete posterior sample. The solid contours in the off-diagonal panels show the 2σ , 1.5σ , and 1σ equivalent levels estimated from two-dimensional KDEs, containing $\approx 86.5\%$, $\approx 67.5\%$, and $\approx 39.3\%$ of the samples, with σ being the standard deviation of a circular bivariate Gaussian. Samples are scattered below the 2σ equivalent levels, and the two-dimensional KDEs are shown with filled contours above this level.

elements and uniform priors does not bias our results (L. B. Lucy 2014; K. K. O’Neil et al. 2019).

We employ 1000 walkers, each using 20 temperatures (the *orbitize!* default). Walkers at higher temperatures explore a flattened (*tempered*) posterior distribution that can more easily be sampled. Periodically, there are swaps in the position of walkers of adjacent temperatures, promoting the exploration of the entire parameter space, also for low-temperature walkers. Only the samples of the lowest-temperature walkers that explore the unaltered posterior distribution are analyzed.

First, we perform a blind run with walker positions randomly initialized within the prior constraints and perform a total of 5×10^8 steps. We apply a *thinning* of 100, that is, only every 100th step is saved. Thus, the chain length of each of the 1000 lowest-temperature walkers for each orbital parameter equals 5000. The chains appear visually converged after ~ 500 steps. For each parameter, we estimate from the chains the integrated autocorrelation time t , that is, the number of adjacent steps in the chain that are correlated. The autocorrelation times range from $t \approx 2.5$ for the parallax up to $t \approx 39$ for the eccentricity.

As our chains are much longer than $50t$, our estimates of t are reliable (D. Foreman-Mackey & Contributors 2021), and the final walker positions are independent from the start positions. We conclude that the chains are fully converged.

From the final walker positions of this first run, we start a second run with 10^8 steps, without thinning, to sample the posterior distribution for analysis. The individual chain length is 10^5 , and autocorrelation times are $t \approx 8$ for the parallax and $t \approx 6$ for all other parameters. Figure 4 shows the posterior distribution (thinned by a factor of 10 for computational reasons), computed following the procedure of G. Weible et al. (2025) and using kernel density estimates (KDE) computed with `KDEpy.FFTKDE`,²⁵ which is based on the `statsmodels`²⁶ implementation (S. Seabold & J. Perktold 2010).

Appendix C

Spatial Filtering and Attenuation of Off-axis Sources for MATISSE

MATISSE uses pinholes at an intermediate focus to spatially filter the incoming beam of each telescope. The

pinholes' angular diameter for the LM-band arm is $1.5\lambda/D$ in the pupil plane. If the point-spread function of a source is not centered on the pinhole, for instance, in the case of a companion separated from the centered primary star, less light is transmitted through the pinhole compared to the case of the fully centered point-spread function. We estimate the transmission T for an off-axis source by computing the transmitted flux of an Airy disk through the pinhole, divided by the transmitted flux of an Airy disk centered on the pinhole. Then we correct the flux ratio affected by spatial attenuation f_{CP} via $f = f_{CP}/T$ (Table 1) and compute the final flux ratio in the L band as the mean of all measurements with its standard error $f_L \approx (1.32 \pm 0.04)\%$; the standard deviation of the measurement sample is $\approx 0.18\%$. Assuming f_L as the nonattenuated flux ratio for a point-spread function centered on the pinhole, we compare the predicted attenuated flux ratios with our measurements in Figure 5 and find good agreement. Furthermore, this is consistent with a spatial attenuation following a Gaussian profile with a FWHM of ≈ 540 mas as obtained from a least-squares fit to the measurements. Thus, this can be used as an approximation of the flux attenuation by

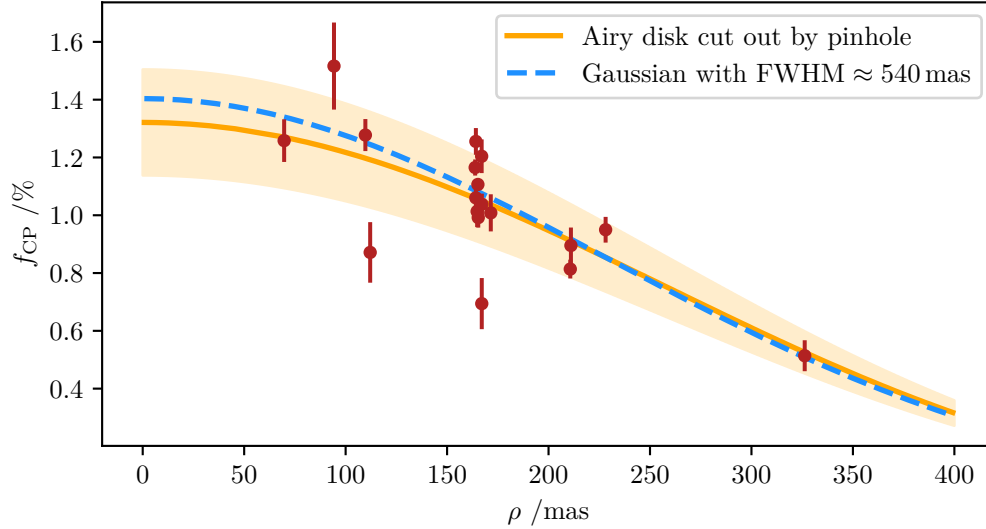


Figure 5. Attenuated flux ratios f_{CP} (red points) as measured directly from the interferometric closure phases, compared to the prediction assuming transmission loss by spatially filtering an Airy disk separated from the pinhole center by ρ (solid orange line). The nonattenuated flux ratio for $\rho = 0$ mas is computed from the mean of the flux ratios corrected from attenuation; the faint orange region covers their standard deviation. This treatment is consistent with a Gaussian description of the attenuation (dashed blue line).

²⁵ <https://kdepy.readthedocs.io/en/latest/API.html#fftkde>

²⁶ <https://www.statsmodels.org/stable/dev/index.html>

spatial filtering. However, this treatment is only possible if attenuation by spectral-bandwidth smearing is either negligible or has been accounted for in the interferometric analysis (see Appendix A). A reason for the remaining scatter in Figure 5 could be inaccuracies in centering the Airy disk in the pinhole.

Appendix D

Determination of the K_s -band Magnitude of the Binary κ Tuc A

To determine the K_s -band magnitude of the binary κ Tuc A, $m_{K_s,A}$, from the joint magnitude of κ Tuc A and B, $m_{K_s,AB} = 3.876$ (R. M. Cutri et al. 2003), we first estimate the K_s -band magnitude of κ Tuc B, $m_{K_s,B}$. With its V -band magnitude of $m_{V,B} = 7.58$ and spectral type of K1 V (C. J. Corbally 1984), we obtain the color from M. J. Pecaut & E. E. Mamajek (2013) as $m_V - m_{K_s} = 2.06^{27}$, which results in $m_{K_s,B} = 5.52$. Using standard magnitude relations, we compute the magnitude of κ Tuc A from $m_{K_s,AB}$ and $m_{K_s,B}$ to be $m_{K_s,A} = 4.15$.

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