Fast-Moving Structures in the Debris Disk Around AU Microscopii

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In the nineteen-eighties, infrared excess emissions were discovered around main-sequence stars; subsequent direct-imaging observations revealed orbiting disks of cold dust as the source[1]. These debris disks are byproducts of planet formation and often exhibit morphological and brightness asymmetries that may result from gravitational perturbation by planets. This relation was proven correct for the β Pic system, in which the known planet generates an observable warp in the disk[2–5]. The nearby, young, unusually active late-type star AU Microscopii hosts a well-studied edge-on debris disk in which earlier studies in the visible and near-infrared have reported asymmetric localized structures in the form of intensity variations along the midplane beyond 20 au[6–9]. Here we present new high-contrast imaging observations revealing a series of five large-scale structures in the southeast side of the disk, at projected separations of 10–60 au, persisting over intervals of 1–4 years. All these features appear to move away from the star at projected speeds of 4–10 km/s, suggesting highly eccentric or unbound trajectories. The localization, the morphology and the rapid evolution of these features is puzzling, leaving their exact nature and origin unknown for the time being.

The system AU Microscopii (AU Mic) is peculiar in many respects. The star is a flaring[10] cool M1Ve type dwarf at a distance of only 9.94 ± 0.13 pc, and is a member of the β Pic Moving Group, with an age of 23 ± 3 Myr[11]. Its extended (~200 au) edge-on, optically thin debris disk was first imaged at visible

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wavelengths from the ground[12]. The current picture of the system assumes a birth ring of planetesimals located at 35–40 au[13] and gas-depleted[14]. Beyond this radius, the disk is populated by small dust particles ($> 0.05\,\mu$m)[9], likely driven outward by stellar wind; radiation pressure alone would be insufficient to explain the disk's extent[13]. Following the discovery image, the system was intensively observed in 2004/2005 from the ground and space[6–9]. Several intensity inhomogeneities in the form of clumps were reported far from the star at physical separations of 20–40 au. Most were located in the fainter, southeast side of the disk while the northwest side was more uniform and approximately twice as bright. The exact positions of these structures slightly differ from one author to the other, possibly due to wavelength dependencies[9]. More recently, observations obtained in August 2010 and July 2011 using Hubble Space Telescope (HST) confirmed the presence of structures in the AU Mic debris disk[15].

AU Mic was one of the prime test targets during the commissionning of SPHERE[16], the planet finder instrument installed at the Very Large Telescope (VLT). It was observed on August 10th, 2014, in the J band (1.25μm) with SPHERE's near IR camera IRDIS. Owing to good and stable atmospheric conditions (seeing $\approx$1.25$''$, wind < 10 m/s), the adaptive optics delivered high Strehl ratios (corresponding to 90–95% at the SPHERE reference wavelength $\lambda = 1.65\,\mu$m), which resulted in high focal-plane contrasts of 9.10^{-5} at $\sim$0.5$''$ on average.

The disk is detected out to 7$''$ ($\sim$70 au), as limited by the detector field of view, and as close as 0.17$''$ ($\sim$1.7 au), below which the disk is attenuated by the coronagraph (Figure 1). We measured a position angle (PA) of $129.5° \pm 0.3°$ in the southeast side. The northwest side PA differs by $1.7° \pm 0.4°$ (see Methods). While the general shape agrees with previous observations, the new SPHERE images show the morphology of the whole disk with unprecedented resolution and detail.

The most striking features revealed by the SPHERE observations are the arch- or wave-like structures close to the star in the southeastern side (annotated A to E in Figure 1). The features A, B, and C located above the midplane, are closer than the ones reported earlier, and do no resemble anything previously observed in circumstellar disks. Two additional fainter structures, D and E, are observed at larger projected separations, closer to and overlapping with the midplane. Yet, they show a wavy morphology (Figure 1 and Figure 3). The projected separations of these five structures span the range of $\sim$10 to 55 au (approximately 1.02$''$, 1.70$''$, 2.96$''$, 4.10$''$, 5.52$''$). The typical projected radial extents of the features range between $\sim$5 (for A, the closest) to 10 au (for E, the farthest) while they reach an elevation above the disk midplane of $\sim$1.5 to 0.5 au, respectively (Extended Data Figure 2). Features A and B are recovered with the visible light arm of SPHERE, as well (Methods).

To confirm the presence and reliability of these features we revisited older observations with HST/STIS in 2010/2011, in which a bump in the midplane was reported in the southeast side at a projected separation of ∼13 au[15]. We re-analyzed these data to yield separate images for the 2010 and 2011 epochs, augmented with unsharp masking to render the structures more visible. Both epochs show that this bump is equivalent to feature B seen in the 2014 SPHERE image but situated ∼4 au closer to the star (Figure 1), and similarly feature A is also visible from the 2011 epoch. A more careful look reveals that the HST re-processed images also contain more features all the along the midplane. Not only do the features in the SPHERE and HST images match with high fidelity across all three epochs, but they also appear radially offset between epochs, suggestive of a motion away from the star as shown in Figure 2.

To precisely register the features we plot the disk spine's transversal excursions from the midplane and its intensity as a function of separation from the star (Figure 3). We note that these two methods do not trace exactly the same physical structures, since the intensity maxima do not coincide with the excursion peaks for the outer features (Figure 3a an Figure 3b). Nevertheless, both methods show a persistent pattern shifting away from the star in a 4-year time frame. The five features are clearly identifiable as peaks in the excursion plot. As a general trend, the features get fainter, broader, and closer to the midplane with increasing stellocentric distance (Figure 3 and Extended Data Figure 2). Feature A is inside the blind area of the HST 2010 image. Finally, we conclude that all structures identified in 2014 are recovered in 2010 and 2011 and appear to have moved away from the star toward the southeast direction as a coherent series of patterns. The fact that the two HST epochs alone (biases being minimal) already exhibit a noticeable motion is a very strong argument in favor of a real phenomenon. This motion is opposite to that of background objects given AU Mic's proper motion. The color dependence of the grains' scattering properties cannot account for such a large displacement between the visible and the IR.

From the three available epochs we obtained the projected speeds associated with each feature considering the excursions from the midplane (Figure 4). To remain conservative the registration errors are peak-to-valley instead of 1-sigma dispersion. The measured speeds are in the range 4–11 km/s. Assuming stellar mass in the range of $0.6 \pm 0.2 M_{\odot}$, the projected speeds of all features beyond A are inconsistent with circular orbits. The speeds of features B and C are compatible with elliptical orbits, but require minimum eccentricities of ∼0.5 and ∼0.97 even for the high end of the stellar mass range. Features D and E are fainter and less distinct than the closer features, which makes their speed measurements more delicate. However, given the error bars, they exceed the local system escape velocity for all stellar mass assumptions. To a lower extent, feature C has a similar behavior for the lowest stellar mass assumption. If confirmed with future measurements, these speeds may indicate that at least two (an possibly three) of the features are on unbound trajectories leaving the system.

Several mechanisms were considered to produce structures in a dusty disk, some involving gas-rich disk, spiral waves, resonances with planetary-mass objects, stellar activity, or outflows from planets (see Methods).

But the distinct morphology of the features, their high apparent speeds incompatible with low-eccentricity orbits, and their spatial localization on only one side of the disk are at odds with most scenarios. Therefore, we cannot offer a single explanation for these features and additional data are needed to do so. New HST and IRDIS imaging can monitor the morphological, photometric, and astrometric temporal evolution of the features, determine whether their motion slows down or accelerates and whether they expand with time, and possibly observe the generation of new features. ZIMPOL measurements of scattering polarization can constrain the phase angle and thus the line-of-sight configuration of the features relative to the disk. ALMA observations can improve constraints on the disks residual gas content. Monitoring the flaring activity of AU Mic may allow to test the link between the generation of features in the dust distribution to coronal mass ejections. Finally, Hα differential imaging may reveal signs of accretion if proto-planets are residing in the system.

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Figure 1: High-contrast images of the AU Mic debris disk. Images are shown for the 3 epochs (2010.69, 2011.63, 2014.69) at the same spatial scale; the location of AU Mic marked with a yellow star symbol. In the two upper panels (a, b), the HST/STIS data were processed with multi-roll PSF-template subtraction and unsharp mask. SPHERE/IRDIS images are displayed in panels c, d, and e, for three differential imaging techniques (see Methods). The intensity maps are multiplied by the square of the stellocentric distance to counteract the high dynamic range of the data and make the disk structures visible at all separations.

Figure 2: Extraction of disk substructure from the southeastern side. Panels a–c show the images from Figure 1a–c after unsharp masking, subtraction of the smooth main body of the disk, and stretching in the vertical direction by a factor of two (cf. Methods). The same persistent pattern is recovered in all three epochs, though at shifted locations, implying motion away from the star. Panel d shows a contour plot of the two HST epochs after more aggressive spatial filtering (Methods), which produces sharp residual features highlighting the differential motion of each feature.

Figure 3: Disk features across three epochs. Precise registration of the disk spine in the southeast side reveals vertical excursions (a) and intensity variations (multiplied by the square of the separation from the star, b). The SPHERE profile is an average of three data reductions (ADI, KLIP, subtraction of azimuthally averaged profile). To illustrate the evolution with time, the profiles are shifted vertically in proportion to the time intervals between epochs. Disk features are identified as five local maxima (marked A–E). Dashed orange lines roughly illustrate the possible trajectory of each feature. Feature A is undetected in 2010, as being too close to the star.

Figure 4: Projected speeds of the disk features. The projected speeds of the five features A–E (green, red, orange, blue, magenta) are plotted against the projected distance from the star. Several orbits are shown for different mass assumptions (0.4, 0.6 and 0.8 solar mass) and several eccentricities: e=0 (dotted lines), e=0.9 (dashed lines). The solid lines stand for the maximum local system escape speed. Horizontal bars correspond to the range of projected separations between two epochs, while the vertical dotted lines stand for the speed uncertainty (PTV).

Code availability Data reduction are performed with IDL and custom routines (including IDP3 available from the Mikulski Archive for Space Telescopes at STScI).

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Methods

Observations and data reduction

SPHERE is a highly specialized instrument dedicated to high contrast imaging, built by a wide consortium of European laboratories and recently installed at the VLT[16]. It is based on the SAXO extreme adaptive optics system, with a 41×41 actuator wavefront control. Several coronagraphic devices for stellar diffraction suppression are provided, including apodized Lyot coronagraphs.

AU Mic was observed on August 11th, 2014, with the differential imaging camera IRDIS, in the J band for a total integration time of 2560 s. IRDIS, offers two square fields of view (about $12''$ each) on the same detector to allow for spectral differential imaging, but since the broadband J filter was used for both channels, they provided redundancy in this case. The star was masked with an Apodized Lyot Coronagraph of which the focal mask occults an area of 185 mas in diameter and the pupil mask transmits ∼67% of the light.

Data reduction follows a standard procedure including cosmetics (correction for flat-field, bad pixels, dark current, and distortion). Individual frame registration is not required as the sequence is very stable and a dedicated hardware in SPHERE is taking care of the positioning of the star onto the coronagraph in real time, reaching 0.5 mas accuracy[17].

We then took advantage of the field rotation during the observation ($\sim 77^\circ$) to suppress the residual starlight in coronagraphic images and reveal the faint scattered light from the debris disk via angular differential imaging (ADI). We explored several ADI techniques, including classical ADI, LOCI[18] and KLIP[19] with various parameter settings. The final images were obtained with a LOCI (Figure 1e) frame selection criterion of 0.75 FWHM, and an optimization zone of 10,000 PSF footprints (using sectors of annuli 12 FWHM in the radial dimension), while the KLIP image (Figure 1d) is calculated for separations shorter than 600 pixels ($7.35''$), and is built from the subtraction of 5 modes out of 160 (a conservative value to avoid strong attenuation of the disk). Since ADI techniques achieve their high contrast performance at the cost of flux losses to the disk image which remain difficult to calibrate[20], we also reduced the data with less powerful but more conservative methods, such as frame-by-frame reference star subtraction or subtraction of an azimuthally averaged radial profile. Owing to the high quality and stability of the data, these methods performed similarly well as the ADI techniques in terms of detecting the disk at separations larger than ∼0.7–1.0". Doing so, the processed images reach a 5-σ contrast as large as 4.10^{-6} at $\sim 0.5''$. All data reduction methods recover the disk features A–E consistently and at the very same locations.

The limit of detection to point sources is presented in Extended Data Figure 1, as measured within the disk using the method of fake point sources injection to calibrate for the self-subtraction inherent to ADI. The contrast achieved in the image at a projected separation of $1''$ would have enabled the detection of a planet with 1 to 6 times the mass of Jupiter depending which evolutionary and atmospheric model is considered[21,22] and assuming an age of 20 Myr. This threshold potentially lowers to a Saturn mass object at a projected separation of $4''$ (about the location of the planetesimal belt), but the models are not reliable for such low mass.

The published images of the optical HST observations from 2010 and 2011 represent a combination of both epochs[15], in which the strongest feature (B) was already identified. For the purpose of tracking our disk features A–E through time, these data were re-reduced to yield separate images for both epochs. Following the original recipe for data reduction (multi-roll PSF-template subtraction) augmented with an additional high-pass filtering (unsharp masking), we recover features B–E reliably in both epochs. In 2010, feature A resides inside the blind area resulting from the multi-roll technique. The HST images are obtained with STIS in a filter-less mode, the spectral range being set by the detector spectral response across a very broad band (200–1100 nm).

For Figures 2a–c, the images shown in Figure 1a–c were unsharp-masked on a spatial scale of $0.76''$. The main body of the disk was approximated as a brightness distribution with a broken linear horizontal profile (with a break at $3''$, the approximate radius of the source ring) and a Gaussian vertical profile. The linear trends were chosen on the basis of the disks brightness profile along the midplane. This distribution was subtracted to reveal the inhomogeneous substructure. The same distribution was used for both HST epochs, preserving their extreme reliability. In Figure 2d, a more aggressive asymmetric kernel of $0.76'' \times 0.25''$ was used for unsharp masking on the two HST images to highlight sharp horizontal gradients suitable to visualize the differential motion.

On August 13th, 2014, we obtained a follow-up observation of AU Mic with ZIMPOL, the rapid-switching imaging polarimeter. A total of 1 h of integration time was taken in the the I'-band filter (713–866 nm) in imaging mode (no polarimetry) with pupil tracking so as to allow for ADI data reduction. Since the high-sensitivity detector mode is currently only available in slow polarimetry mode, which does not support pupil tracking, the noisier high-gain detector mode was used. AU Mic was heavily saturated and produced some charge bleeding in the vertical direction, but the compromised region does not affect the disk detection. A total of 40° of field rotation was captured during the observation. After correcting for cosmetics as for the IRDIS data, we applied various ADI data reduction techniques to suppress the stellar halo. In Extended Data Figure 2, we show the results for LOCI data reduction with 'conservative' parameter settings[23] including a frame selection criterion of 0.5 FWHM and an optimization area of 10,000 PSF footprints (same geometry as for IRDIS). The AO correction is more difficult at shorter wavelengths, and thus yields a lower Strehl ratio in the optical than in the IR. On the other hand, the shorter wavelengths yield a higher angular resolution ($\lambda/D \approx 19$ mas in I' as compared to $\sim$32 mas in J-band) and thus a greater potential to resolve fine structure. As Extended Data Figure 2 demonstrates, the location and overall morphology of the A and B features as seen in the IRDIS images are very well reproduced in the ZIMPOL images, including the wave-like connection of feature A to the disk plane. Both images show an additional pattern in between feature B and the midplane. This structure may represent further wave-like features like A–E at a lower amplitude but will require future investigation and modeling.

Disk morphology

From a morphological point of view, the southeast and northwest sides of the disk are very different. The former contains many structures above the midplane while the latter is brighter, thinner and features an abrupt change of direction near $1.5''$. The disk Position Angle (PA), measured from North to East, is determined in both SPHERE and HST images using the same method developed earlier for edge-on disks[4]. The image is rotated with an initial guess for the PA to place the disk midplane approximately horizontal and a profile function (Gaussian or Lorentzian) is fitted vertically to retrieve the midplane centroid versus the angular separation. We used regions where the disk contains as few features as possible ($3''$ to $6''$ here). The true disk PA is the image rotation for which the slope of the disk centroid is flat. The measurement is repeated separately for the two sides since the AU Mic disk is highly asymmetric. We found $PA_{SE} = 129.5 \pm 0.2^\circ$ and $PA_{NW} = 311.2 \pm 0.3^\circ$ respectively for the southeast and northwest sides. Similarly in the HST images we obtained $PA_{SE} = 129.0 \pm 0.5^\circ$ and $PA_{NW} = 310.5 \pm 0.2^\circ$. Although the error is relatively large, the measurements are likely discrepant in the northwest side between SPHERE and HST by $0.7 \pm 0.4^\circ$. We suspect that the determination of the PA in the southeast is in fact perturbed by the presence of the features appearing at different locations between 2010-2011 and 2014. Thus, we considered that the northwest side gives a more reliable measurement of PA so we compensated the HST image with a rotation of 0.7° to realign all the epochs. We note that for both HST and SPHERE the true North uncertainty is $\sim$0.1° so the uncertainty on the disk PA is reflecting our ability to locate the disk midplane and is also possibly impacted by the color dependence of the grains. In addition, the two sides are clearly misaligned by $1.7 \pm 0.4^\circ$ in the SPHERE image and respectively $1.5 \pm 0.5^\circ$ in the HST image. Once the disk PA is set, the centroid of the disk cross-section versus separation defines the disk spine in which the features are visible as excursions from the midplane (Extended Data Figure 3). This spine includes both the main disk and the features which explains that they may appear in Extended Data Figure 3 at different elevations than in Figure 1. To register the radial locations of features we used a model profile combining a Gaussian and a first-order polynomial in some delimited regions (red lines in Extended Data Figure 3). The measurement is repeated for various data reductions including PA uncertainty to estimate the errors on the location of the features. The registration of features and associated errors are listed in Extended Data Table 1.

Finally, we also found that the disk spine shows an excursion of $0.07''$ (equiv. $\sim$5–6 pixels) southwest to the star inside a radius of 0.6–$0.7''$, a characteristic that is clearly seen in a zoomed image (Extended Data

Figure 4). It is unlikely to be a result of ADI bias, which is expected to be symmetrical about the disk midplane. Similar excursions were observed in a number of debris disks which could represent the opening of the disk's source ring as viewed at an inclination close to, but not equal to, 90°. In such a situation, anisotropic forward-scattering is expected to render the near-side edge of the ring much brighter than the far-side edge, which accounts for the asymmetry. A complete analysis of the disk photometry is deferred to future work since a careful modeling of ADI bias effects is crucial in that case, especially close to the star[20].

With the most aggressive algorithms (those that remove the starlight most efficiently like KLIP and LOCI) the three features closest to the star appear as arches; that is, the structures are clearly separated from the midplane by a void of scattered light. As a qualitative sanity check, fake bumps were added to the data inside the disk midplane to investigate qualitatively whether ADI could produce a depletion between the midplane and the top of the bump, mimicking arches. We found no such effects and conclude that this is likely a real characteristic to be confirmed with deeper follow-up observations.

As a complement to Fig. 3 and Fig. 4, we have plotted the stellocentric distance versus time for each feature in Extended Data Figure 5. The structures are well aligned over the three epochs, error bars being smaller than the plotted symbols in some cases. Once the data points are fitted with linear trends and extended back in time, three out of five features (A, B, C) lie on nearly parallel tracks, and suggests a timeframe of ∼15 years (where lines intersect the Y axis). In fact, the observed structures are necessarily recent, otherwise they would have propagated and smeared all around the star due to secular evolution. Brightness asymmetries reported in the literature in 2004 may coincide with the tracks for features C and D, though it is difficult to determine reliably if they are the same features since they are seen as intensity variations rather than excursion from the midplane.

Physical interpretation of disk features

A majority of known debris disks exhibit structural features such as eccentricities, warps, and brightness asymmetries, which are assumed to be induced by planets via secular gravitational perturbation. However, such features either appear static over observational time scales or remain coupled to the Keplerian motion of the disk, which is incompatible with the fast motion measured for two/three of the five features observed. There are mandatory observational facts with which a physical interpretation must comply, at least qualitatively, which are: 1) spatial localization of the features on one side of the disk and above the midplane, 2) timeframe for the evolution, 3) increase of projected speeds at larger projected separations, 4) larger projected radial widths away from the star, 5) increase of intensities at shorter projected separations, 6) variable elevations.

While a number of mechanisms occur in massive protoplanetary disks that can impact the dust distribution and generate structures with speeds of a few to a few tens of km/s, they rely on the presence of gas.

Although some debris disks retain a significant amount of gas[24] , it is likely a low-mass component in the AU Mic system[14] compared to the estimated total mass of dust[9]. For these reasons gas-induced scenarios (radiation-driven disk wind, protostellar jets, ...) are considered unlikely here.

One possible assumption would be that the measured speeds represent the phase speed of a pattern propagating through the disk, which could significantly exceed the physical speed of the constituent disk particles. Indeed, protoplanetary disks may exhibit spiral density waves whose outer arms ”travel” at super-Keplerian speeds, as a response to gravitational instabilities or planets orbiting inside the disk[25]. Given AU Mic’s youth, it must have dispersed its primordial gas only recently; thus, some disk structures could conceivably have survived as ”fossils”. Whether this is physically plausible remains to be investigated. Resonances can induce wave-like structure even in gas-less disks. Saturns rings feature edge waves along the orbits of embedded moons, though they follow Keplerian orbits[26]. Lindblad resonances, on the other hand, produce spirals phase-locked to a planet, which exhibit super-Keplerian phase speeds. However, a spiral would have to ”wrap” around the star several times to reproduce the observed train of features on the southeastern side, which is at odds with the lack of features on the northwestern side.

Local intensity enhancements on one single side could be interpreted as an series of concentric eccentric rings resulting from massive collisions of asteroid-like objects[27]. However, the typical timescale to produce several eccentric rings is of the order of 100 years, too long compared to our measurements for the moving structures in the AU Mic disk.

Rather than phase speed, the observed motion may represent physical motion at super-Keplerian velocities. Dust blowout by stellar radiation or wind constitutes an integral part of the mechanism that produces debris disks, and is well capable of boosting small grains to escape speeds. Given AU Mics high activity level, flares from coronal mass ejections could occasionally impact the planetesimal ring and produce distinct dust clouds at different azimuths. A warped ring of planetesimals as in beta Pictoris[5] could account for the elevation. Due to anisotropic scattering, the near-side clouds could appear bright while those on the far side remain undetected, explaining the one-sided apparent distribution. Similarly, the interaction of episodic flares with a planet’s magnetosphere or a dusty circumplanetary disk, on a Keplerian orbit, may explain the spatial localization of the features as a train of dust cloud[29]. Circumplanetary disks are also capable of releasing outflows[28]. In both of these scenarios, the combination of orbital motion of the dust source and the outward force would explain the velocity dispersion shown in Figure 4.

In the planetary outflow scenario, given that features A and E could have been released ∼15 years apart (Extended Data Figure 5) and that projected speeds vary from ∼4 to 10 km/s, we can constrain the minimal separation of a planet to ∼10–15 au. On the other hand, dust clearing observed at distances closer than ∼35–40 au could be the result of a planet orbiting inside the planetesimal belt. Therefore, in this range

10–40 au, where a hypothetical planet may reside, the SPHERE data reach a contrast of 1.10^{-6} to 8.10^{-8}, which, for the DUSTY model[21], places an upper limit at 6 and 3.5 Jupiter masses, respectively.

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Extended Data Figure 1: Limit of detection to point sources. The contrast is measured at 5 sigma using fake planets introduced in the data at discrete positions (circles) along the disk midplane to account for the self-subtraction of the ADI/KLIP algorithm. The dashed line defines the edge of the coronagraphic mask at $0.09''$.

Extended Data Figure 2: Comparison of IRDIS and ZIMPOL images. Panels (a) and (b) show zoomed-in regions of the KLIP and LOCI reductions of the IRDIS IR data, whereas (c) is taken from the conservative LOCI reduction of the ZIMPOL optical data. Features A and B are reproduced accurately in the ZIMPOL data. An additional substructure between feature B and the midplane is also detected as indicated by arrows.

Extended Data Figure 3: Spine of the disk measured in SPHERE IRDIS data. The spine is measured in several reductions (noADI, ADI, KLIP) of the SPHERE IRDIS 2014 data. Average values and dispersions are plotted as a blue line. A Gaussian + first-order polynomial model is fitted in each region where a local maxima is identified to register precisely the five features.

Extended Data Figure 4: Central part of the SPHERE IRDIS image. The upper panel (a) shows a $12''$ field of view of the SPHERE IRDIS image processed with the KLIP algorithm and the lower panel (b) is a magnified version to indicate the bow-like deviation of the disk to the southeast in the central area (for separations shorter than $\sim 0.7''$). The horizontal dotted lines materialize the disk midplane.

Extended Data Figure 5: Positions of the disk features over time. Positions of features measured in SPHERE and HST images are plotted as circles together with error bars (in some cases, the errors are smaller than the symbol size). Linear fits on these three epochs illustrate the possible track of each feature. The black symbols show the location at which various inhomogeneities were reported in literature based on older data[6−9]. The color coding is the same as in Figure 4.